

## **EVALUATION OF SOIL EROSION PROCESS AND CONSERVATION PRACTICES IN THE PARAGOMINAS-PA MUNICIPALITY (BRAZIL)**

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### **ABSTRACT:**

Over the last decades, the natural environment has been degraded at a much greater speed than its own resilience. Lack of knowledge about soil natural limitations and mismanagement can increase their degradation and nutrient losses by erosion. The objective of this study was to estimate and map soil vulnerability to erosion through the Universal Equation of Revised Soil Loss (RUSLE) and based on the ecodynamic concept of physical and biotic environment analysis, and finally to evaluate conservation practices in the municipality of Paragominas with the economic database of IBGE / SIDRA. In the two analyzed methods the percentage of area with low and high potential and erosivity estimation were similar. The estimation of low and low-moderate loss and vulnerability represents about 77% (15,064 km<sup>2</sup>) of the territory by RUSLE and 60% (11,485 km<sup>2</sup>), by ecodynamic concept. The high to very high soil loss zones represent only 3% (642 km<sup>2</sup>) and 2.7% (584 km<sup>2</sup>), in the RUSLE and ecodynamic concept, respectively. Most of the variables analyzed in both methods presented low estimation values of loss and erosivity potential. The soil and slope attributes, for example, obtained exactly 79% (15,377 km<sup>2</sup> - RUSLE) and 80% (15,572 km<sup>2</sup> - ecodynamic concept), except for the climate and factor R attributes, in both methods the vulnerability potential and erosion, were only 1.5% (292 km<sup>2</sup>) and 1.3% (253 km<sup>2</sup>), based on the ecodynamic concept and RUSLE respectively. The geospatial analysis of the use practices correlated with the economic data showed an intense use of agricultural activities, logging and mining, which caused severe environmental damages, considering that 45% (8,773.3 km<sup>2</sup>) of the municipality have already been deforested and converted into other uses. The municipality still has 47% (9,182 km<sup>2</sup>) of its territory covered by altered primary vegetation and 23% (4,441 km<sup>2</sup>) by secondary vegetation, important information to subsidize decision-making processes related to ecological-economic strategies for the management of natural resources in the study area.

*Key-words: Agriculture, Environmental variables, Potential for soil loss, Amazon*

## **1. INTRODUCTION**

Erosion is a process by which soil and rocks wear out, then transported by natural or anthropogenic agents and deposited elsewhere (Verheijen *et al.*, 2009), it can pollute water, cause land degradation, reduce soil fertility and increase the loss of organic matter (Cerdan *et al.*, 2010). Changes in the management and use of land resulted from human activities can increase soil erosion causing irreversible damage to the environment (Fiorio *et al.*,

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2016; Da Silva *et al.*, 2016). The vegetation withdrawal due to the insertion of plantations can increase up to 600% soil erosion (Chaplot *et al.*, 2005). Soil loss brings concern all over the planet, as it is a source for food production (Abel *et al.*, 2005).

Production of food and other goods for human needs, combined with population growth and agricultural intensification, has resulted in severe land degradation and, particularly, soil erosion. Between 1961 and 2010 the world population duplicated from 3 billion to 6 billion inhabitants, while the crop production increased four times in almost the same area (FAO, 2017). It is estimated that since the beginning of stable agriculture, ca. 430 million hectares were damaged due to soil erosion (Lal, R, 2017).

Agricultural production in Brazil was fostered through a National Development Plan in the 1970s aiming to improve the country economy (Becker, 2005). Such Plan was developed to attract entrepreneurs to the Brazilian Amazon, with the government releasing taxes on rural credits to incentivize investment (Kohlhepp, 2002). That period was marked by huge agricultural, industrial, and silvicultural projects besides infrastructure actions (Hall, 1989; Serra, 1998). The intense advance of the agricultural sector and the territory occupation was evident in many Amazon municipalities, leading to a drastic change in the landscape. For example, Paragominas has already 45% (8,773.3 km<sup>2</sup>) of its land deforested (INPE/Prodes, 2018), causing loss of soil organic matter and nutrients and soil erosion (Angima, 2003). Lack of knowledge about soil limitations and inadequate soil management practices can trigger or speed up its erosion in agricultural areas (Navas *et al.*, 2005). Beyond land use activities, soil loss and degradation are affected by a combination of different environmental factors including geology (rock types), geomorphology (landform), vegetation (e.g. its cover and structure), pedology (soil types), and climate (e.g. rainfall) (Arnesen, 2009). The awareness about risks to environment, economy and livelihoods have resulted in research, technology and production practices to minimize soil erosion (Bakker *et al.*, 2008).

Understanding and quantifying erosion processes are important steps in the decision making process regarding the best management to be adopted. Methods with empirical models are used, for example, the Universal Soil Loss Equation (USLE), which emerged in the late 1970s (Wischmeier & Smith, 1978) in the United States, but it is widely used in Brazil. This method presents great accuracy, as it considers soil type, soil morphology, rainfall, cultivation practices and management, allows quantification and regionalization of the area with higher risk of erosion (Wischmeier & Smith, 1978; Bertoni, 2005; 2012). It was later revised and adapted by several authors “Revised Universal Soil Loss Equation” (RUSLE). Another technique widely used to analyze the natural vulnerability to soil loss was based on the ecodynamic of Tricart (1977), modified by Crepani *et al.*, (2001), which uses the morphogenesis/pedogenesis relation integrated to satellite images, assigning values of vulnerability/stability to each thematic class.

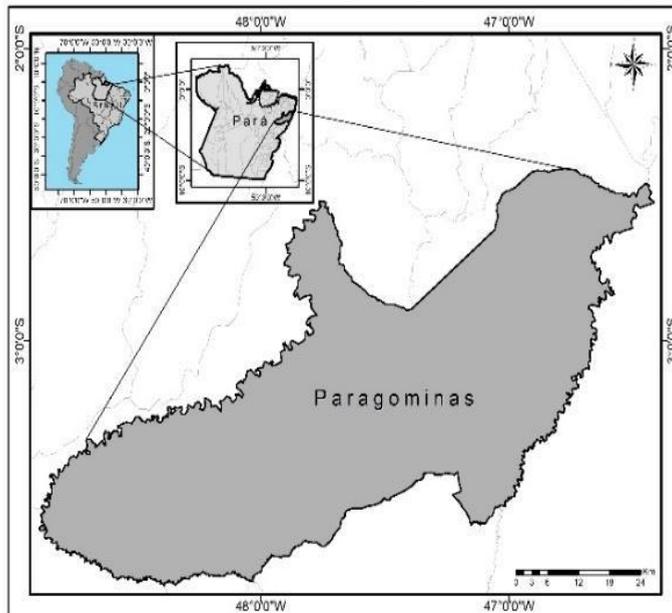
The use of remote sensing and geographic information systems contribute significantly to monitoring, mapping, and managing landscapes (Ferreira, 2008), particularly in large and remote areas. For example, in Brazil where, besides having huge territorial extension, the access to some areas is also a constraint, what emphasizes the need of a constant input in this field in order to monitor effectively (Assad & Sane, 1998; Câmara *et al.*, 2001). This study aims to estimate and map vulnerability to soil erosion through geospatial analysis, by the model of the Universal Equation of Soil Loss Revised (RUSLE), ecodynamic concept of analysis of physical and biotic environment and conservation practices evaluation in Paragominas municipality in the Brazilian Amazon. We analyzed the local attributes of geology, geomorphology, vegetation, pedology, and climate, by means of satellite imagery

analysis, thematic maps, and rainfall data, then a map of land was obtained which represents a range of levels of vulnerability to soil erosion. The analysis presented here can contribute to support decision makers regarding ecological-economic strategies for natural resource management in the study area and other parts of Brazilian Amazon.

## 2. MATERIAL AND METHODS

### 2.1. Study site

Paragominas municipality has an area of 19,465 km<sup>2</sup> and it is placed in Pará state, Brazil. Its original vegetation was mainly formed by Dense Ombrophilous Forest (Watrin, 1992). The predominant soil type is yellow latosol, rich in clay and has low fertility. The climate is warm and humid, with annual average temperature of 26.3°C (**Fig. 1**).



**Fig.1.** Paragominas municipality (Source: authors).

### 2.2. Estimation and mapping of soil erosion

Soil erosion estimations were carried on the concept proposed by Tricart (1977), adapted by Crepani (2001) and by the Revised Universal Soil Loss Equation - RUSLE (Wischmeier and Smith, 1978). Both methods evaluate soil erosion with variables such as: rainfall; soil type; land-use class; geology and geomorphology.

### 2.3. Soil erosion based on the ecodynamic concept

We used the method based on the ecodynamic concept (Tricart, 1977), adapted by Crepani *et al.*, (2001) to Brazil. This concept considers the balance between soil formation processes (pedogenesis) and erosion processes (morphogenesis). It applies a range of soil erosion vulnerability values to the target land areas that are analyzed (stability or instability). Areas where pedogenesis and morphogenesis predominate have a value around 1 and 3, respectively, and areas where both processes are balanced have values around 2 (**Table 1**).

**Table 1.**

<b>Classes of soil erosion vulnerability.</b>	
Class	Vulnerability Value
Low Vulnerability	1 > - 1.6
Low-moderate vulnerability	1.6 - 1.9
Moderate vulnerability	1.9 - 2.1
High-moderate vulnerability	2.1 - 2.4
High vulnerability	2.4 - 3

Source: Elaborated by the author, adapted from Crepani *et al.*, (2001), by ecodynamic concept (Tricart, 1977).

Vulnerability values of soil erosion (between 1 and 3) were assigned based on attributes related to geology, geomorphology, pedology, vegetation types, and climate variables. They resulted in five thematic maps obtained by means of the Map Algebra of ArcGis 10.1 (Esri, 2012). For a given land area, the overall vulnerability (V) was:

$$V = G + SL + S + Vg + C / 5 \tag{1}$$

Where:

G = vulnerability due to Geology, SL = vulnerability due to Slope, S = vulnerability due to Soil, Vg = vulnerability due to Vegetation, and C= vulnerability due to Climate.

### 2.3.1. Geology attribute

Vulnerability due to Geology depends upon rock type. We used the geological database of the Brazilian Geological Service (CPRM, <http://www.cprm.gov.br/>), at a 1:100.000 spatial scale. The CPRM provides data in georeferenced vector format of aerogeophysical projects available in Geobank (<http://geobank.cprm.gov.br/>). Values of soil erosion vulnerability related to rock types in the study area are reported in **Table 2.**

**Table 2.**

<b>Values of soil erosion vulnerability related to rock types.</b>	
Rock types	Value
Quartzites or metaquartzites	1.0
Rhyolite, Granite, Dacite	1.1
Granodiorite, Quartz Diorite, Granulites	1.2
Migmatite, Gneiss	1.3
Phonolite, Nepheline syenite, Trachyte, Syenite	1.4
Andesite, Diorite, Basalt	1.5
Anorthosite, Gabbro, Peridotite	1.6
Mylonitos, Muscovite Quartz, Biotite, Shale chlorites	1.7
Pyroxene, Kimberlite amphibolite, Dunite	1.8
Hornblende, Tremolite, Shale actinolite	1.9
Shale Staurolite, Granatiferous shale	2.0
Phyllite, Metassiltite	2.1
Slate, Metargilite	2.2
Marbles	2.3
Quartz Sandstone or orthoquartzites	2.4
Conglomerates, Subgraywacke	2.5
Greywackes, Arkose	2.6
Siltstones, Mudstones	2.7
Husk	2.8
Calcareous, Dolomites, Marls, Evaporites	2.9
Soft-bottom sediments: Alluvium, Colluvium, Sands, etc.	3.0

Source: Elaborated by the author, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

### 2.3.2. Slope attribute

The source of soil erosion vulnerability related to slope, was adapted by Crepani *et al.*, (2001) study (**Table 3**). These data derive from SRTM (Shuttle Radar Topography Mission) available on EMBRAPA (Brazilian Corporation of Agricultural Research, (<https://www.embrapa.br/territorial/>), calculated using the ArcGis 10.1 Solpe tool.

**Table 3.**

**Values of soil erosion vulnerability related to slope.**

Degree	%	Value/ Vuln.	Degree	%	Value/ Vuln.	Degree	%	Value/ Vuln.
<2	<3.5	1.0	9.9-11.2	17.4-19.8	1.7	19.1-20.4	34.6 - 37.2	2.4
2-3.3	3.5-5.8	1.1	11.2-12.5	19.8-22.2	1.8	20.4-21.7	37.2 - 39.8	2.5
3.3-4.6	5.8-8.2	1.2	12.5-13.8	22.2-24.5	1.9	21.7-23.0	39.8 - 42.4	2.6
4.6-5.9	8.2-10.3	1.3	13.8-15.2	24.5-27.2	2.0	23.0-24.4	42.4 - 45.3	2.7
5.9-7.3	10.3-12.9	1.4	15.2-16.5	27.2-29.6	2.1	24.4-25.7	45.3 - 48.1	2.8
7.3-8.6	12.9-15.1	1.5	16.5-17.8	29.6-32.1	2.2	25.7-27	48.1 - 50	2.9
8.6-9.9	15.1-17.4	1.6	17.8-19.1	32.1-34.6	2.3	>27	>50	3.0

Source: Elaborated by the author, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

### 2.3.3. Pedology attribute

The vulnerability related to the pedology attribute (**Table 4**) refers to mapping of soil units according to Crepani *et al.*, (2001), updated with Prado (2001) nomenclature. This attribute database was obtained from IBGE (Brazilian Institute of Geography and Statistics), based on the new Brazilian System of Soil Classification (EMBRAPA, 1999).

**Table 4.**

**Soil erosion vulnerability values related to soil types.**

Soil Classes	Vuln.	Soil classes	Vuln.
Yellow Latosol	1	Spodosol	2
Red-Yellow Latosol	1	Neosol Litólicos	3
Red Latosol	1	Neossolos Flúvicos	3
Latosol Brunos	1	Neossolos Regolíticos	3
Latosol (...) Humic	1	Neossolos Quartzarênicos	3
Latosol Bruno (...) Humic	1	Vertisol	3
Acrisol	2	Organosols	3
Acrisol Luvisol Alisol Nitosol	2	Gleysol	3
Acrisol Nitosol	2	Gleysols Plinthosol	3
Luvisol	2	Plinthosol	3
Chernozem	2	Rocky Outcrop	3
Planosol	2	-	-

Source: Elaborated by the author, adapted from Crepani *et al.*, (2001), with new nomenclature from Prado (2001).

### 2.3.4. Vegetation and use of class attribute

The definition of values on vulnerability to erosion regarding vegetation attribute was identified under the forest canopy density using satellite imagery determined 21 class units, following the Crepani *et al.*, (2001) definition (**Table 5**).

It was used satellite imagery from Landsat 8 TM, orbits/points 222/62, 222/63, 223/62, and 223/63 (2015 data), with the lowest cloud coverage of the period, available in the website Glovis from NASA. From these satellite imageries were produced a classification using the supervised Maximum Likelihood method. This method uses mean and variance of the data set for the classification decision rule and for this reason a considerable number of pixels is required for each region to be classified. First the use class was defined, then

samples (ROI's) of the areas to be classified in the image were generated (**Table 6**). With the selected ROI's for use class the image was classified using the software ENVI 4.7, afterward vulnerability values of classes were set as follows in **Table 7**.

**Table 5.**

<b>Soil erosion vulnerability values related to vegetation types.</b>	
<b>Vegetation Class</b>	<b>Vuln.</b>
Dense Ombrophilous Forest	1.0
Open Ombrophilous Forest	1.0
Mixed Ombrophilous Forest	1.0
Semideciduous Seasonal Forest	1.4 - 1.7
Campinaranas formation	1.4 - 1.7
Forested Savanna and Steppe Savanna	1.4 - 1.7
Dense tree steppe, with or without palms	1.4 - 1.7
Wooded Savanna and Steppe Savanna da e Wooded Steppe Savanna	2.0
Deciduous Seasonal Forest	2.0
Wooded Campinarana	2.0
Wooded Steppe	2.0
Buritizal with fluvial and/ or lake influence	2.0
Wooded Campinarana with or without palms	2.4 - 2.6
Savanna Park, Wooded Savanna Park	2.4 - 2.6
Campinarana and Steppe with shrub size	2.4 - 2.6
Vegetation under marine influence (Sandbanks)	2.4 - 2.6
Vegetation under fluvial and/or lake influence	2.4 - 2.6
Montane Refuge and High Montane Refuge	2.4 - 2.6
Woody- grassy Savanna, Woody-grassy steppe savanna, and Woody-grassy steppe	3.0
Woody-grassy campinarana	3.0
Vegetation under herbaceous marine influence	3.0
Montano and High-Montano refuges	3.0
Cloud/ Shadow/ exposed soil/ sparse vegetation	3.0

Source: Elaborated by the author, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

### **2.3.5. Climate attribute**

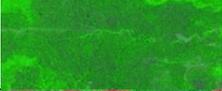
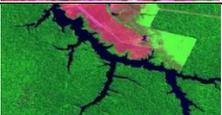
About the attribute climate (pluviometry), 21 classes were classified on soil erosion (**Table 8**). The areas with lower annual pluviometric rate and higher extension of rainy season were classified with values around stability (1.0) to intermediary values of vulnerability/stability (2.0). On the other hand, areas with higher annual pluviosity rate and shorter rainy season vulnerability presented values around 3.0. In order to assign the vulnerability values to the climate, the precipitation data of the last 18 years of the municipality station, was used in the system of the national meteorological institute (INMET-<http://www.inmet.gov.br/portal/>). The average precipitation was calculated between the months of January 2000 and November 2018 (**Fig. 2**).

### **2.4. Revised Universal Soil Loss Equation (RUSLE) method.**

Through the RUSLE equation, the main spatial distribution factors responsible for soil erosion were performed in the GIS environment. Information plans were embedded into the database and manipulated through the geoprocessing tools in ArcGis (**Fig. 3**).

Table 6.

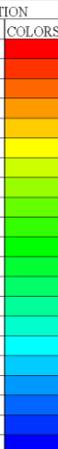
## Land use patterns and Vegetal cover used in the satellite image classification.

Typological classification	Pattern identified in satellite image	Description
Primary Forest		Forests that have passed through interventions in the past, but have their primary structure conserved.
Secondary Forest		Forests that have undergone deforestation or degradation processes and are currently in regeneration.
Pasture		Livestock pasture areas with low biomass, characterized areas with healthy pastures and degraded pastures.
Agriculture		Agricultural plantations mechanized, which presupposes high technological level and family agriculture areas.
Deforestation		Areas in which all vegetation cover was removed, leaving the soil exposed.
Urban area		Areas of urban agglomeration, with industrial estates, streets, buildings and highways.
Hydrography		Drainage with rivers and springs.

Source: Elaborated by the author.

Table 7.

## Soil Vulnerability regarding vegetation.

LANDSCAPE UNITES	AVERAGE	DEGREE OF VULNERABILITY	DEGREE OF SATURATION			
			RED	GREEN	BLUE	COLORS
U1	3.0	VULNERABLE	255	0	0	
U2	2.9		255	51	0	
U3	2.8		255	102	0	
U4	2.7		255	153	0	
U5	2.6		255	204	0	
U6	2.5	MODERATE VULNERABILITY	255	255	0	
U7	2.4		204	255	0	
U8	2.3		153	255	0	
U9	2.2		102	255	0	
U10	2.1		51	255	0	
U11	2.0	MEDIUM STABLE VULNERABILITY	0	255	0	
U12	1.9		0	255	51	
U13	1.8		0	255	102	
U14	1.7		0	255	153	
U15	1.6		0	255	204	
U16	1.5	MODERATE STABLE	0	255	255	
U17	1.4		0	204	255	
U18	1.3		0	153	255	
U19	1.2		0	102	255	
U20	1.1		STABLE	0	51	255
U21	1.0	0		0	255	

Source: Elaborated by the author adapted from Crepani *et al.*, (2001), by ecodynamic concept.

Table 8.

**Soil vulnerability regarding pluviometric rate.**

Pluviometric Intensity mm/month	Vuln.	Pluviometric Intensity mm/month	Vuln.	Pluviometric Intensity mm/month	Vuln.
< 0 50	1.0	200 - 225	1.7	375 - 400	2.4
50 - 75	1.1	225 - 250	1.8	400 - 425	2.5
75 - 100	1.2	250 - 275	1.9	425 - 450	2.6
100 - 125	1.3	275 - 300	2.0	450 - 475	2.7
125 - 150	1.4	300 - 325	2.1	475 - 500	2.8
150 - 175	1.5	325 - 350	2.2	500 - 525	2.9
175 - 200	1.6	350 - 375	2.3	> 525	3.0

Source: Elaborated by the author adapted from Crepani *et al.*, (2001), by ecodynamic concept.

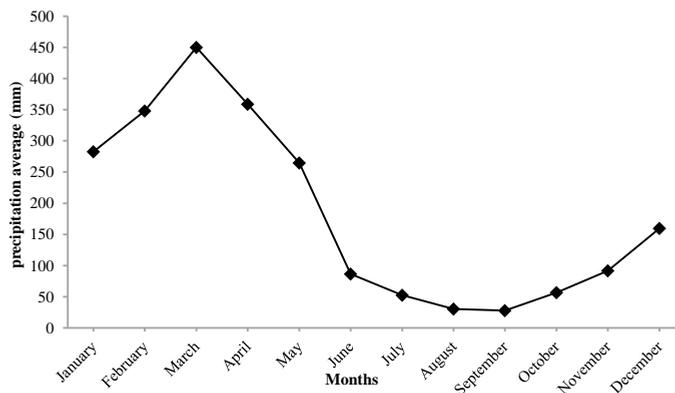


Fig. 2. Precipitation average from 2000 to 2018, INMET data. (source: authors).

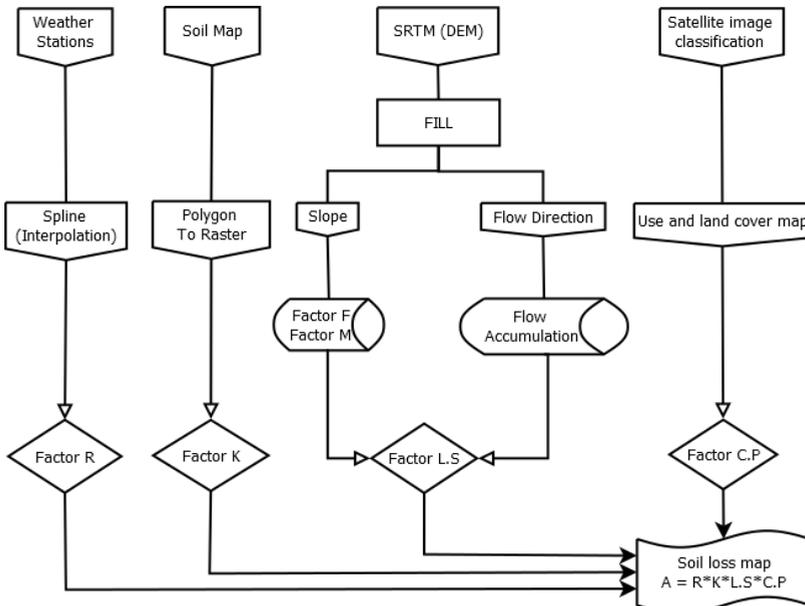


Fig. 3. Flowchart of the technique used in the generation of the soil loss map (source: authors).

(2)

$$A = R \times K \times L \times S \times C \times P$$

Being: A = Soil loss calculated per unit area, (Mg.ha<sup>-1</sup>.ano<sup>-1</sup>); R = Rainfall factor: rainfall erosion index, (Mg.ha<sup>1</sup>.ano<sup>1</sup>); K = soil erodibility factor (MJ/ha.mm/h); L = slope length factor, (m); S = Slope degree factor, (%); C = Use and management factor (dimensionless); P = Conservationist practice factor (dimensionless).

#### 2.4.1. Factor R (Erosivity by rains)

In order to determine the annual rainfall erosivity, annual average precipitation data of the 28 rainfall stations contained in Paragominas were used for the period from 2000 to 2018. **Fig. 2** shows the monthly average rainfall erosivity using the formula used in Amazon:

(3)

$$EI_{monthly} = 42,307 (Pm^2/Pa) + 42,77$$

Where: Pm = monthly precipitation and; Pa = annual precipitation average.

The average annual rainfall erosivity is obtained by the sum of the monthly erosivity average of each season. The map was generated in the ArcGis environment, by inserting the table (dbase format) with spatial distribution of the stations (UTM coordinates of the stations) and their respective values of calculated erosivity. The interpolation of the values representing the spatial variation of erosivity was done through the ArcGis Spline tool.

#### 2.4.2. Factor K (Soil Erodibility)

The evaluation of soil erodibility was obtained from IBGE Geoscience Center (Brazilian Institute of Geography and Statistics) in scale 1:5000.000, based on the new Brazilian System of Soil Classification (EMBRAPA, 1999). The soil classes were grouped, generating a map of soil types, where the value of K was associated for each type.

#### 2.4.3. Factor LS (Topographic factor)

In this factor the length of slope L represents the distance between the point which originates the surface flow to the point where the slope decreases enough for sediment deposition to occur. The slope gradient (S) refers to slope variation in slope intervals, these two parameters (LS) are represented as a single topographic factor, defined as the rate of soil loss per unit area of a standard plot of 22.13 m in length and 9% of slope (Wischmeier and Smith, 1978). Calculated by means of the following steps:

$$F = \frac{\sin\beta/0.0896}{3(\sin\beta)^{0.8}+0.56} \quad m = \frac{F}{(1+F)} \quad L \left( \frac{\lambda}{22.13} \right)^m$$

$$S_{(i,j)} = \begin{cases} 10,8 \sin \beta (i, j) + 0,03 & \tan \beta (i, j) < 0,09 \\ 16,8 \sin \beta (i, j) + 0,5 & \tan \beta (i, j) > 0,09 \end{cases}$$

In factor L the  $\lambda$  is the slope length, m the slope length exponent and  $\beta$  the slope angle. The slope length is defined as the horizontal distance from which originates the surface flow to the point where the deposition begins or where the flow flows into a channel, and at factor S the angle  $\beta$  is taken as the mean angle of all sub -redes in the steepest direction (**Fig. 4**).

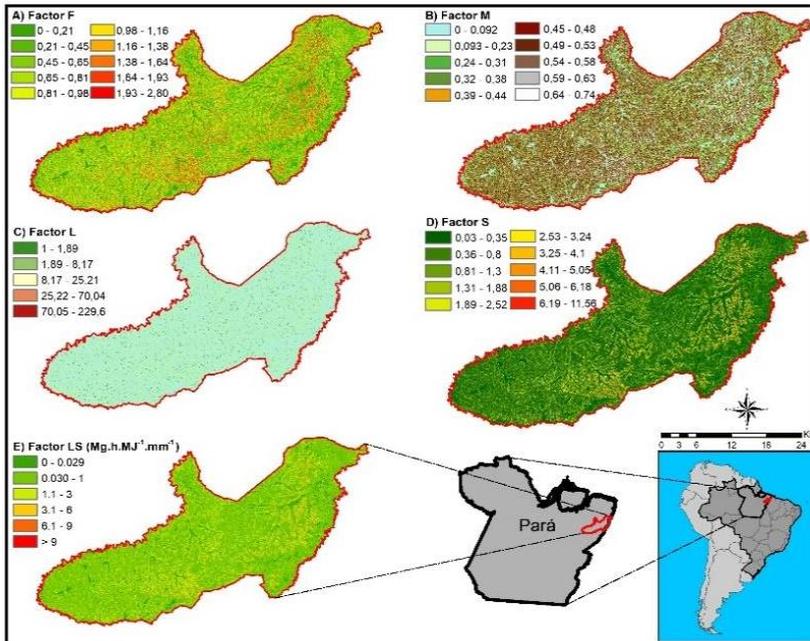


Fig. 4. Erosivity factors for the L.S calculation (source: authors).

#### 2.4.4. Factor C (Use/soil management) and P (Conservationists practices)

Factor C is the expected relationship between the soil loss of a cultivated land under given conditions and the corresponding losses of a land kept continuously uncovered and cultivated (Bertoni, 2005). While the factor P is the relationship between losses in soils with a given conservationist practice and those where the crop is planted in the slope direction. A factor P of 0.01 was considered for areas with primary, secondary and urban vegetation, 0.09 for agriculture, 0.45 for pasture, 1 for deforestation and 0 for water. To elaborate the map of factor C, it was necessary to classify the satellite image for soil use and to assign C and P values for each type of use (Donzelli *et al.*, 1992), then convert to a raster format, where  $CP = C.P$  and CP factor specializations were obtained from the numerical reclassification of the vegetation cover and land use maps (Table 1) for the year 2017.

#### 2.5. Conservation management and Practices

In order to evaluate the activities developed in Paragominas, a mapping was carried out on the land use, a classification carried out by the TerraClass Project, then developed and executed by the Regional Center of the Amazon (CRA). The data base of this project are the mapped deforested areas published by the PRODES Project - Monitoring of the Amazon Forest by Satellite. TerraClass analyzes the possible causes of tree cutting considering the following classes: annual agriculture; unobserved area; urban area; mining; occupation mosaic; pasture with soil exposed; clean pasture; dirty grass; regeneration with grass; reforestation; secondary vegetation; forest and not forest. This mapping counts a series of 10 years analysis of use and coverage (2004, 2008, 2010, 2012 and 2014), and to evaluate the current situation an unsupervised classification was performed in an image from 2017, described in Table 6.

In order to analyze the use and coverage of the soil obtained by the classifications carried out by satellite images, we also used the data base of the IBGE Automatic Recovery System - SIDRA. This system has an economic historical series of data since 1974, in this component we analyzed only the years of 2004, 2008, 2010, 2012, 2014 and 2017. Another important practice developed in Paragominas is mining and to evaluate this component, it was used data from the National Department of Mineral Production (DNPM), available through the Geographic Information System of Mining – SIGMINE.

### **3. RESULTS AND DISCUSSIONS**

After analysis, for the entire area of Paragominas municipality, a map with values of vulnerability to soil erosion was obtained for each following category: geology, slope, pedology, vegetation and climate. Then, a general map of vulnerability to soil erosion and estimates of soil loss was created, according to the method of ecodynamics proposed by Tricart (1977) and adapted by Crepani *et al.*, (2001), and by RUSLE.

#### **3.1. Analysis of the vulnerability based on the ecodynamic concept**

##### **3.1.1. Geology attribute**

The basic information of geology is the cohesion degree of integrated rocks from the ecodynamics (Tricart, 1977). It means that in the most cohesive rocks the processes of weathering and pedogenic formation prevailed, while the less cohesive rocks are more susceptible to erosive processes. It is considered that in rocks with little cohesion erosive processes can prevail, while in very cohesive rocks the processes of weathering and soil formation must prevail (Crepani *et al.*, 2001). For this attribute, it was identified that only 1% (212 km<sup>2</sup>) of the municipality area has low vulnerability to erosion, with rocks of granite, granodiorite, gneiss and schist, with value between 1.1 to 1.3 these rocks are more weather resistant (Gomes, 2000), since the igneous rocks are more resistant to temperature rises.

Paragominas municipality presents ca. 61% (11,874 km<sup>2</sup>) of its territory in the moderate-high attribute class (value 2.5) with sedimentary rocks of the sandstone, argillite, and silt types. This material can be composed from angular grains to sub-rounded enveloped by clay matrix of infiltration (Frostick, 1984), which can lead to greater erosive process. In 38% (7,397 km<sup>2</sup>) of the municipality area there is a high vulnerability to soil erosion (value 3). These sediments have smaller interfluves (of higher-intensity dissection), for this reason receive vulnerability value higher for the geology attribute (Crepani, *et al.*, 2001) (**Fig. 5 A**).

##### **3.1.2. Declivity attribute**

Declivity is the relief slope regarding the horizon that has a direct relation with transformation speed from potential to kinetic energy. Thus, the higher the slope the faster the potential energy of rainwater becomes kinetic energy and higher the water masses velocity and their transport capacity, responsible for relief erosion (Watson & Lafflen, 1986). With respect to this attribute, it was verified that 46% (8,954 km<sup>2</sup>) of the municipality has declivity lower than 2% (value 1). In 34% (6,618 km<sup>2</sup>) of the municipality the slope is between 2% and 6%, with low-moderate vulnerability (value 1.5). The regions presenting a slope between 6% and 20% represent 13% (2,530 km<sup>2</sup>) of Paragominas, moderate vulnerability value. Lang *et al.*, (1984) observed that zones with 9% of slope presented greater erosion between furrows of a topsoil compared to an area of 3% slope.

Paragominas is located in the morphostructural domain of plateaus in non-folded sedimentary sequences (IBGE, 1996), characterized by flattened structural surfaces, with average altitude around 200 m. For this reason, only 5% (973 km<sup>2</sup>) of the municipality has a slope between 20% and 50% (moderate-high vulnerability), so regions having a slope higher than 50% (high vulnerability) correspond to only 2% (289 km<sup>2</sup>) of the total area (**Fig. 5 B**).

### **3.1.3. Soil attribute**

Approximately 79% (15,337 km<sup>2</sup>) of Paragominas soil area are composed of latosols, which are mineral soils, deep, well-drained, with B horizon latosolic, usually cohesive, quite hard when dry, mainly in the AB and BA horizons (Rodrigues *et al.*, 1991; Embrapa, 1999). Therefore, there are more stable soils and resistant soils to erosive processes with value 1 of vulnerability. Only 2% (389 km<sup>2</sup>) of its territory has argisol soils (vulnerability value 2), since their soils are moderately stable in relation to erosive processes. This type of soil has a different textural gradient between A and B horizons, this can lead to soil loss by difficulty in infiltration, Schaefer *et al.*, (2002), in their study identified nutrients losses by erosion on simulated rainfall conditions, with different surface coverages on argisol soils.

The vulnerable soil erosion (vulnerability value 3) of the municipality corresponded to the regions with Gleysol and Plintosol representing 2% and 17% (3,698 km<sup>2</sup>), respectively (**Fig. 5 C**). The plintosols, for example, are mineral soils formed through water percolation restriction. These soils are poorly drained with excessive plinization (Rodrigues, 2003), while gleysol is characterized by high gley status of soils, which results in a reduced moisture regime whereby soil waterlogging for a long period during the year (Embrapa, 1999).

### **3.1.4. Vegetation attribute (Soil use)**

The composition and structure of the vegetation are important components in soil losses analyzes (Gomes, 2000). Deforestation is one of the anthropogenic actions that changes the forest structure and speeds up processes of soil erosion. According to the PRODES project, up to 2017 the accumulated deforestation in Paragominas reached ca. 45% (8,744 km<sup>2</sup>) of its territory. These areas have been converted to others land uses, and were intended for livestock raising and crop production, mostly grain cultivation, with practices characterized by monoculture, intense mechanization and agrochemical inputs (Alves, *et al.*, 2014). After processing the satellite imagery, 9% (1,752 km<sup>2</sup>) of the municipality was identified in the high vulnerability category presenting sparse vegetation or exposed soil (**Fig. 5 D**)

The most stable Paragominas areas correspond to about 76% (14,793 km<sup>2</sup>) of the municipality, which is occupied by ombrophilous forest with altered primary and secondary vegetation under advanced successional stage, thus, low potential for vulnerability to soil erosion. In this advanced stage of succession, there is a greater production of litter (Pezatto & Wisniewski, 2006; Barbosa & Faria, 2006) that may favour soil protection, since it is the main form of nutrient return to the soil and moisture retention (Espig *et al.*, 2009).

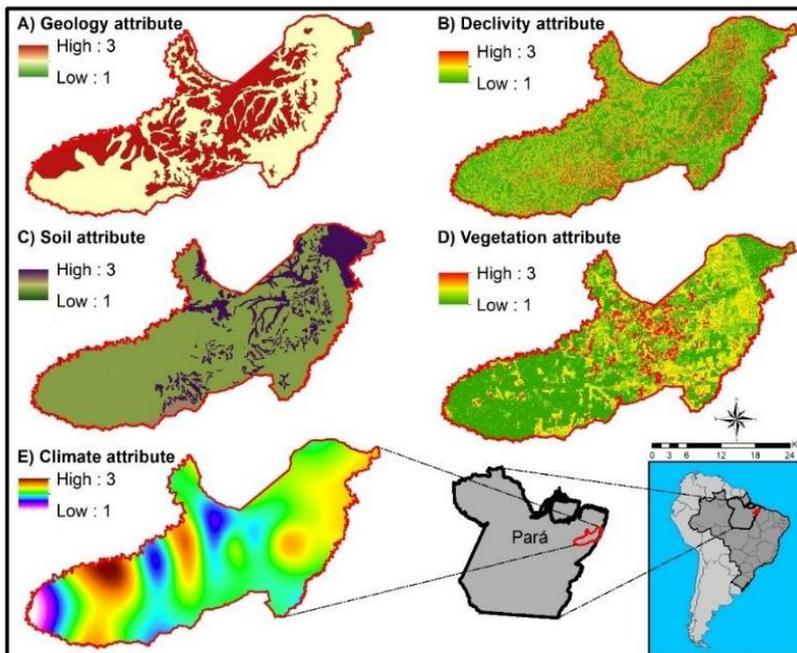
### **3.1.5. Climate attribute**

The potential capacity of rainfall to accelerate the process of soil erosion is related to the precipitation intensity in a region (Bertoni & Lombardi Neto, 2008; Guerra, Silva & Botelho, 2009). The climate in humid equatorial Amazon is very favourable to the vegetal production benefiting the forest protection, acting as a huge thermostat avoiding extremes

of temperature (Schmidt, 1947), and by means of rainfall and temperature the climate controls the weathering of a region (Mota, *et al.*, 2009). The erosion process caused by rainfall (Santos, *et al.*, 2010) is the result of soil particles surface disaggregation, due to the energy of the drop's impact and by the surface runoff force. The detachment and transport of sediments promotes soil losses by floods (Bertol *et al.*, 2007; Bertoni & Lombardi Neto, 2012).

Rainfall directly influences erosion processes, and in Paragominas the pluviometric intensity average (mm/moth) is smaller than 1 mm during the dry season (June to November) and more than 1,000 mm in the rainy season (December to May). As a consequence, the entire municipality has value 2 - 2.4 moderate (52%; 10,044 km<sup>2</sup>), to high-moderate 2.5 - 2.7 value (39%; 7,591 km<sup>2</sup>) vulnerability to soil erosion for the climate attribute (**Fig. 5 E**).

Only 1.5% (311 km<sup>2</sup>) of the municipality has a value of 1.7-1.9 vulnerability considered medium-low and another 8% (1,557 km<sup>2</sup>) considered to be a high vulnerability potential to soil erosion (2.8 - 3 vulnerability value). As the dry and rainy period in the municipality are well defined they do not cause a significant impact on soils covered by vegetation. The rainfall of a given region is considered a risk factor due to the production of sediments per unit of drainage area which raises with the increase of the drainage area, the larger the river basins, the greater the possibility of possible erosions (Oakes *et al.*, 2012).



**Fig. 5.** Map of attributes responsible for vulnerability to soil erosion (*source: authors*).

## 3.2. Estimation of soil loss according to (RUSLE)

### 3.2.1. Factor R (Erosivity of rains)

Soil erosivity of this factor involves the disintegration of soil particles, transported and deposited by rainfall and surface runoff of water on the soil (Crepani, 2004). The values of

this factor for the 28 rainfall stations vary from 5,621 to 17,540 MJ.mm/ha.h, with an average of 13,500 MJ.mm/ha.h, standard deviation of 1,630 MJ.mm/ha.h. Paragominas has a very heterogeneous R-factor, however, the highest and lowest values of erosivity estimation indices are found in the southeast of the municipality, which are well-vegetated zones (**Fig. 6 A**). According to Da Silva (2004), the highest values for the R-factor were found in the Amazon region, in that study the strong class of erosivity are between 7,000 to 9,800 MJ.mm/ha.he very strong are higher than 9800. In Paragominas only 1.7 % (325 km<sup>2</sup>) in the strong category and 97.1% (18,892 km<sup>2</sup>) in the very strong class.

### **3.2.2. Factor K (Soil erodibility)**

This factor is related to the soil and understanding its characteristics and properties is primordial, since its composition can affect the velocity of infiltration, water storage capacity, permeability, transport by rain, runoff, splash, dispersion and abrasion (De Lima, 2010). The soils most likely to undergo laminar erosion are in a small part of the northeast of the municipality and in the administrative limits (rivers boundaries) present in the soils Argisols (2%, 389 km<sup>2</sup>) and Gleysol (2%, 389 km<sup>2</sup>) a small part of the municipality, most of the municipality is Latosol type (79%, 15,377 km<sup>2</sup>) and has a low factor K (**Fig. 6 B**).

### **3.2.3. Factor LS (Topographic factor)**

Considered as one of the factors of high relevance, the factor has a strong influence (Wischmeier & Smith, 1978), because the volume of the floods is directly related to the degree of slope of the terrain, however in the municipality of Paragominas there is not a high degree of slope. **Fig. 6 C** shows the distribution of the factor LS, the lowest LS value was between 0 - 0.029 t h Mh<sup>-1</sup> mm<sup>-1</sup> corresponding to 8% (1,677 km<sup>2</sup>) of the municipality, while the higher value that was above 9 t h Mh<sup>-1</sup> mm<sup>-1</sup>, represents only 0.03% (7 km<sup>2</sup>) of Paragominas. The majority of Paragominas (80%, 15,539 km<sup>2</sup>) is between 0 to 1 t h Mh<sup>-1</sup> mm<sup>-1</sup>, with an average of 0.2 t h Mh<sup>-1</sup> mm<sup>-1</sup> and a standard deviation of 0.9 t h Mh<sup>-1</sup> mm<sup>-1</sup>.

### **3.2.4. Factor C (use/soil management) and P (conservationist practices)**

Brazil loses per year tons of soil from the surface layers, which are dragged into the streams, rivers, lakes and lowlands, resulting in an increase in bed volume and a decrease in the soil covered by vegetation (Dlamini *et al.*, 2011; Podwojewski *et al.*, 2011). When spatializing the factor CP values with soil types, it was observed that the lowest values are found in the latosols, Dystrophic Argilubic Pintossol, and Gleysol soils, while the Petroferric Eutrophic have a higher CP value. Values range from 0 to 1, with an average of 0.12 and a deviation of 0.21. Paragominas has an area of 71% (13,749 km<sup>2</sup>) with a CP factor between 0 - 0.086, where the primary and secondary vegetation is located, between 0.087 - 0.047 only 6% (1,076 km<sup>2</sup>) is found in cattle ranching regions and in 24% (4,640 km<sup>2</sup>) of Paragominas found a CP factor greater than 0.048 zones under agricultural cultivation (**Fig. 6 D**).

In the classification of land use and cover, the expressive classes were primary vegetation 47% (9,228 km<sup>2</sup>), secondary vegetation 22,9% (4,463 km<sup>2</sup>) and pasture 21,8% (4,252 km<sup>2</sup>) respectively, however the latter (pasture) has a higher CP value, followed by deforestation (1.7%, 337 km<sup>2</sup>) and agriculture (5.6% 1.086 km<sup>2</sup>). The data of intense agricultural production (Schlesinger, 2010) indicate that areas under crop production are increasingly overused around the world, exhausting soils capacity and making them less resilient and more vulnerable to erosion (Mazzali, 2000).

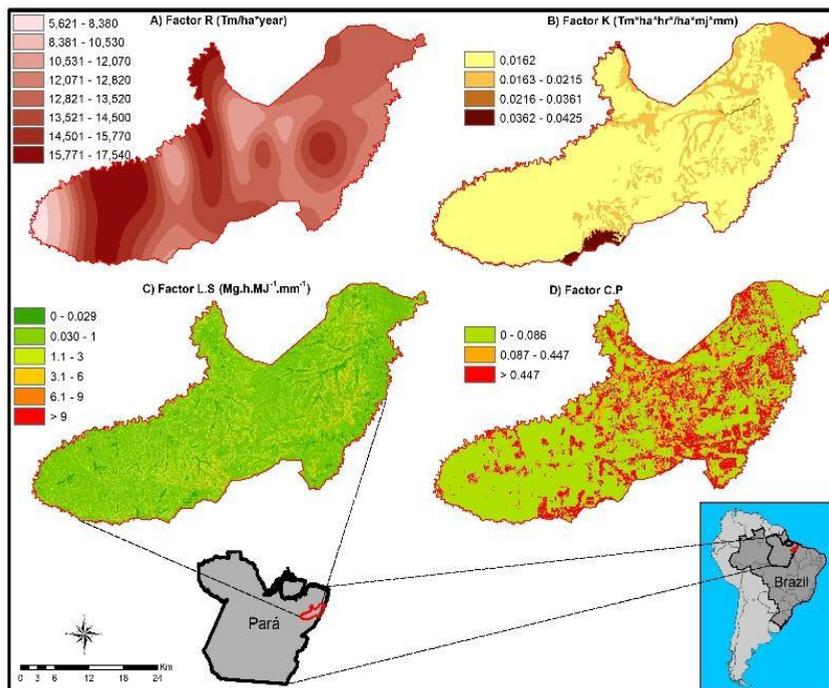


Fig. 6. Erosion estimation calculated by the RUSLE method (source: authors).

### 3.3. Soil loss estimation and vulnerability (Ecodynamic concept and RUSLE method)

These methods are widely applied in Brazil, allowing quantification and regionalization of the area with the highest risk of soil erosion. Paragominas presents ca. 77% (15,064 km<sup>2</sup>) of its territory with low-moderate (t ha<sup>-1</sup> year<sup>-1</sup>) degree of soil loss calculated by the RUSLE method, not so different from the method based on the ecodynamic concept, which was 60% (11,485 km<sup>2</sup>) with low and low-moderate degree of erosion of vulnerability to soil erosion (1 - 1.8 value). Similar situation was found for areas with high soil loss, with high soil loss, which represented only 3% (642 km<sup>2</sup>) degree of erosion according to RUSLE and 2.7% (584 km<sup>2</sup>) according to the ecodynamic concept, (Table 8, Fig. 7). This erosion can cause flow of superficial layers carrying organic matter, nutrients and seeds, resulting in high production costs (Parker *et al.*, 1995).

In almost all variables analyzed in the two methods with respect to their potential of soil erosivity the values are similar. Soil and slope attribute, for example, obtained 79% (15,377 km<sup>2</sup>) and 80% (15,572 km<sup>2</sup>) respectively of the municipality with low vulnerability value and erosivity estimation. Similar situation was noted for the low vulnerability degree for the vegetation attribute (soil use and cover), the result of erosivity value was 76% (14,793 km<sup>2</sup>) for the ecodynamic concept and 71% (13,820 km<sup>2</sup>) for calculation of RUSLE (CP). The only exception was in relation to the climate and factor R attribute, in both methods the rainfall data are used to generate the index vulnerability and erosion estimation, only 1.5% (292 km<sup>2</sup>) and 1.3 (253 km<sup>2</sup>) of Paragominas is considered as low vulnerability grade, according to the ecodynamic concept and RUSLE respectively. Consequently, for this factor, vulnerability values and erosion estimation were more significant throughout the municipality.

Table 8.

Estimates of loss and vulnerability to soil erosion in Paragominas.

RUSLE method				Ecodynamic model method			
Loss of soil (t ha <sup>-1</sup> year <sup>-1</sup> )	Degree of erosion	Municipal area		vulnerability values	Degree of erosion	Municipal area	
		Km <sup>2</sup>	%			Km <sup>2</sup>	%
0-10	low-moderate	15,064	77.4	1-1,5	low	4,672	24.3
10.1-50	moderate	2,093	10.8	1,6-1,8	low-moderate	6,813	35.4
50.1-150	high-moderate	1,665	8.6	1,9-2,1	moderate	5,256	26.9
151.1-200	high	218	1.1	2,2-2,4	high-moderate	2,141	10.7
>200	very high	424	2.2	2,5-3	high	584	2.7
-	-	19,465	100	-	-	19,465	100

Source: Elaborated by the author.

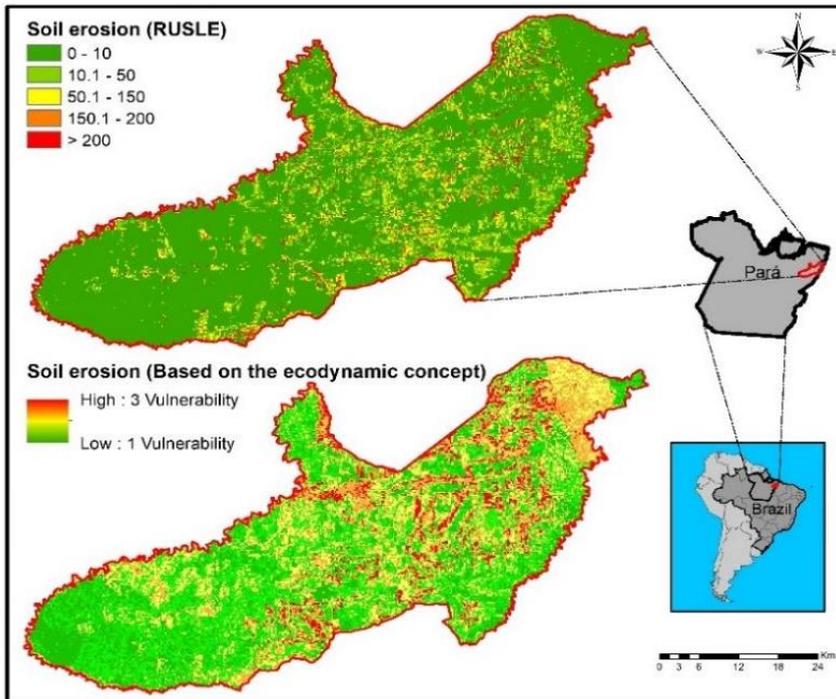


Fig. 7. Soil erosion soil calculated by the method based on the ecodynamic concept and RUSLE (source: authors).

### 3.4. Management and Soil conservation

The conservation practices aim to control soil and water losses in areas with agricultural activities, for example, without altering the productive capacity of the soil. Thus, it is important to adapt the soil conservation to the occupation of the area according to its capacity of use, so that the management practices can favor the erosion control, improving the water infiltration capacity in the soil, reducing the surface runoff that leads to the formation of aggregates and minimizing then the impact of rain drops.

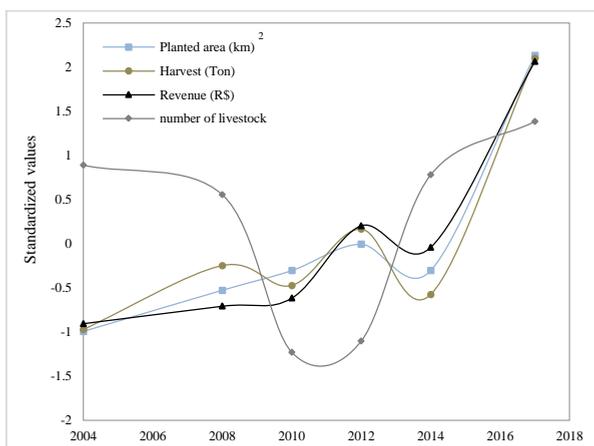
The conservation processes can be mechanical, edaphic and vegetative, depending on the cropping system. However, for a good result it is necessary to apply them

simultaneously, since each one develops a function and solves a part of the problem. The mechanical practices use artificial structures for the conduction or interception of surface runoff, while edaphic practices are related to the cropping system, controlling erosion and contributing to better soil fertility. On the other hand, the vegetative activities combat erosion based on the protection of the soil against the action of precipitation using the vegetation. For this reason, the maintenance of the adequate vegetation coverage in the soil is one of the basic principles for conservation, a process that is hampered by deforestation.

Paragominas was born in the troubled development process of the Brazilian Amazon, which was encouraged by the government in order to develop the region economically (Mahar, 1979). With around 50 years it owns already ca. 45% (8,773.3 km<sup>2</sup>) from its territory deforested and converted into other uses (INPE/Prodes, 2018). Over the years these deforested areas have been converted into other uses and the municipality is currently characterized mainly by agriculture, logging and mining extraction (especially bauxite).

In the classification analyzed in this study for the period from 2004 to 2017 we noticed that between 65% and 70% of Paragominas is covered by primary vegetation altered and secondary vegetation. In the last year (2017), for example, about 47% (9,110 km<sup>2</sup>) of the Paragominas territory was covered by altered primary vegetation, 23% (4,406 km<sup>2</sup>) by secondary vegetation and 5.5% (1,074 km<sup>2</sup>) correspond to agricultural activity (**Table 9**).

The values in mapped area were not so different from the agricultural areas available in the SIDRA system. However, when we analyzed the standardized agricultural production data of planted area, harvested tone and revenue, we noticed that in 2008 there was an increase in the cultivated area and in the quantity of harvested product, despite the decrease in revenue. The Worst scenario was identified in the year 2010, when crop area and revenue decreased while acreage increased. In 2012, it was the year of the best agricultural performance, according to SIDRA data, since there was a small increase in the area produced, with an increase in the area collected and a better performance of the income, during the same period the production of head of cattle was one of the worst. Another atypical event was in 2014, in that year, production and harvest decreased, but revenue grew (**Fig. 8**). The trend of inverse proportionality between agricultural and livestock production was also noticed, that is, when there is a decrease in livestock production, agricultural production rises, evidenced from 2008.



**Fig. 8.** Planted area, harvest and revenue of the agriculture data and number of livestock (source: authors).

Table 9.

**Land use classification (TerraClass of 2004 to 2014 and sentinel-2 of 2017)**

Class	TerraClass (km <sup>2</sup> )					Unsupervised Classification (km <sup>2</sup> )
	2004	2008	2010	2012	2014	2017
Annual Agriculture	172	449	683	835	1,019	1,074
Unobserved area	1275	2,378	264	1,702	859	-
Urban area	15	23	29	31	38	39
Deforestation	1,029	55	64	16	10	333
Forest	11,180	10,757	10,645	10,602	10,490	9,110
Hydrography	26	50	50	50	26	45
Mining	-	7	18	31	-	69
Occupation mosaic	27	23	12	7	44	24
Non-Forest	7	7	7	7	7	-
Others	16	5	34	8	4	166
Pasture with exposed soil	-	-	0	0	-	-
Clean pasture	2,871	2,775	2,678	2,569	3,148	-
Dirty pasture	540	712	418	334	441	4,199
Reforestation	-	-	134	252	208	-
Regeneration with pasture	707	224	1,005	281	405	-
Secondary vegetation	1,601	2,002	3,423	2,741	2,767	4,406
Total	19,465	19,465	19,465	19,465	19,465	19,465

Source: Elaborated by the authors.

Paragominas was one of the Amazon municipalities with higher rate of illegal logging for many years. According to Imazon (Institute of Man and the Environment of the Amazon), during the period from 2007 to 2012, ca. 74% (960 km<sup>2</sup>) of the municipality's logging was carried out without authorization, in all that years of monitoring the logging without permission was higher than the authorized one (Fig. 9). When analyzing the official data of wood production in m<sup>3</sup> and revenue of SIDRA/PEVS - Production of Plant Extraction and Silviculture, we noticed that there is a significant difference between the production of wood in m<sup>3</sup> in relation to the generated revenue. In the period from 2008 to 2012 the revenue increased, while the harvest decreased, that difference is quite evident when comparing the area of logging monitored by Imazon with the data of harvest and revenue in 2008, that year the logging in the municipality was 80% (601 km<sup>2</sup>) of the total (749 km<sup>2</sup>), and the data of the PEVS also show an overestimation of the revenue in relation to production (Fig. 10), this can be explained by the illegality in the sector.

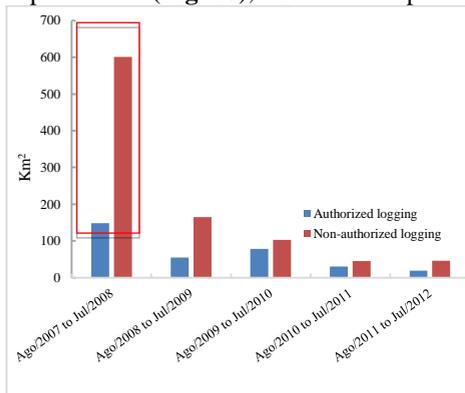


Fig. 9. Logging monitoring (Imazon).

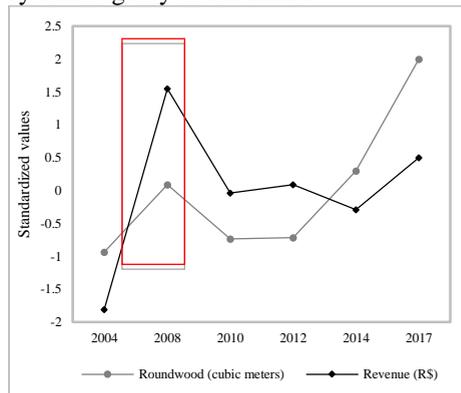


Fig. 10. Logging data (PEVS).

Another quite significant activity mapped out in this study was mining. This activity has existed for a long time, but in the past, it did not require sophisticated technological processes. Before the areas were mined with a semi-mechanized extraction system, today they present a complex set of large equipment. One of the ores with a lot of potential in the Amazon is bauxite, which produces aluminum, which is used in various segments, such as: packaging, transportation, civil construction, electricity, consumer goods, machinery and equipment and others. It is important to point out that mining activity significantly improves the economy of a region, but also causes great degradation, since it unbalances the environment in huge extension of land and changes the soil components (Reis, 1999).

Paragominas has one of the greater enterprises of mineral activity of the state. According to DNPM (2018), the municipality presents 43% (8,308 km<sup>2</sup>) of its territory under mining process, with large majority (39%, 3,246 km<sup>2</sup>) having a research permit, 27% (2,318 km<sup>2</sup>) with a request of mining and 25% (2,070 km<sup>2</sup>) in concession (Fig. 11 A). Regarding the ore class, bauxite represents ca. 72% (5,998 km<sup>2</sup>) of the total in mining processes classified by DNPM (Fig. 11 B). As for the use of the extracted minerals (53%, 4,425 km<sup>2</sup>) there is no information about the use, for the metallurgy activities are destined 25% (2,035 km<sup>2</sup>) and about 1,726 km<sup>2</sup> (21%) of area is destined for extraction of ore for industry (Fig. 11 C).

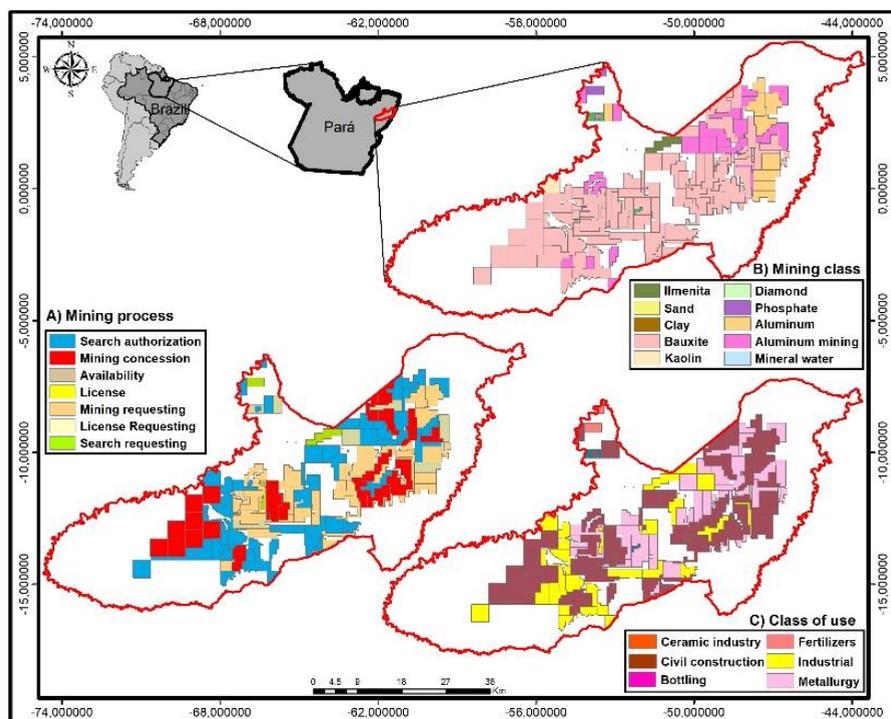


Fig. 11. DNPM mining data (source: authors).

#### 4. CONCLUSION

The attributes analyzed in the two methods presented in their majority low and intermediate vulnerability estimation and potential of soils loss, it requires attention to avoid such regions to become areas with high potential for erosion vulnerability in the future. For the two analyzed methods (Ecodynamic concept and RUSLE) only 3% of Paragominas had a high potential of erosivity. The identification of regions with vulnerability to soil erosion potential is efficient to assist decision making and territorial management, in order to answer important environmental questions, determine low operating costs, plan activities in management practices and environmental conservation of the municipality.

Monitoring erosion over large area extensions is a costly process, so geoprocessing becomes a useful tool for estimating soil loss. The multicriteria analysis using GIS tools (Geographic Information System) were extremely important in this study, because they mapped and estimated the vulnerability potential to soil erosion for the Paragominas municipality, however there are not many studies on the subject in the Amazon region, therefore it is necessary further researches with field analysis in the region to corroborate the results. Soil erosivity is a natural process, however, inadequate human actions regarding soil use generate irreversible environmental degradation. The intense erosion process, for example, leads to soil impoverishment and pollution of water networks, causing economic, social and environmental problems on a scale from local to the global. Thus, the results of this study reveal the need for greater attention in the areas of greater environmental risk.

Good data collection and analysis of rainfall, topographic information, land cover and management system lead to significant results to be obtained from areas susceptible to degrading erosive processes. The studies associated with soil erosion are fundamental, both for agricultural conservation practices, as to subsidize the planning environmental, in which economic practices must be calculated under conservationist principles.

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