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RISK OF AGROCHEMICAL CONTAMINATION IN A HYDROGRAPHIC BASIN IN THE MATOPIBA REGION IN BRAZIL

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ABSTRACT

The intensive use of agrochemicals has been associated with global human health problems and environmental contamination. Brazil is the world's largest agrochemical consumer, and this position highlights the growth of agribusiness in the MATOPIBA region (Maranhão, Tocantins, Piauí, and Bahia states). The use of agrochemicals is recurrent in local agricultural practices. However, there is little information on the environmental impacts and risks of contamination regarding river basins in this region. Thus, this study aimed to evaluate the risk of contamination by agrochemicals in the basin area of the Açailândia River in Maranhão. From the multicriteria evaluation, environmental information plans were used to determine the trend of water behavior, infiltration, and runoff, along with agrochemical transportation. The joint evaluation of this information was used to generate the final map of the areas of contamination risk posed by agrochemicals in the region. The hydrographic basin presented high anthropization, with an increase of approximately 27% in land use and occupation by crops in the period from 1984 to 2018. The area of 1087.62 km², corresponding to 35.9% of the basin area, presented a *high* and *extremely high* risk of contamination.

Palavras-chave:
Planejamento ambiental
Análise multicritério
Sistema de informação geográfica
Agronegócio

RISCO DE CONTAMINAÇÃO POR AGROQUÍMICOS EM UMA BACIA HIDROGRÁFICA NA REGIÃO DO MATOPIBA, BRAZIL

RESUMO

O uso intensivo de agroquímicos tem sido associado a problemas globais de saúde humana e contaminação ambiental. O Brasil é o maior consumidor mundial de agroquímicos e esta posição destaca o crescimento do agronegócio na região do MATOPIBA (Maranhão, Tocantins, Piauí e Bahia). O uso de agroquímicos é recorrente nas práticas agrícolas locais. Entretanto, há poucas informações sobre os impactos ambientais e riscos de contaminação de bacias hidrográficas nesta região. Assim, este estudo visou avaliar o risco de contaminação por agroquímicos na área da bacia do rio Açailândia, no Maranhão. A partir de uma avaliação multicritério, foram utilizados planos de informação ambiental para determinar a tendência do comportamento da água, infiltração e escoamento superficial, juntamente com o transporte de agroquímicos. A avaliação conjunta destas informações foi utilizada para gerar o mapa final das áreas de risco de contaminação por agroquímicos na região. A bacia hidrográfica apresentou alta antropização, com um aumento de aproximadamente 27% no uso e ocupação do solo por culturas no período de 1984 a 2018. A área de 1087,62 km², correspondente a 35,9% da área da bacia, apresentou alto e extremamente alto riscos de contaminação.

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INTRODUCTION

Contamination by agrochemicals worldwide represents potential damage to fauna, flora, and human health. Once present in the ecosystem, agrochemicals can reach and damage the metabolism of living organisms, unbalancing the environmental synergy of the entire region close to its application (BRITTO *et al*., 2015). Above all, they may represent an environmental risk for adjacent bodies of water (SOLIS *et al*., 2019).

In Brazil, agrochemical consumption increases every year. Between 2000 and 2014, the national consumption of active agrochemical ingredients per hectare increased by 109% (IBGE, 2017). The increase in the number of new registrations granted to agrochemicals points to an accelerated continuation of this trend (IPEA, 2020), leading the country to become the largest consumer of agrochemicals in the world, according to data from the Union of Products of the National Agricultural Defense Industry1 (SINDAG, 2012). In 2017, 593,944.95 t of active ingredients were marketed in Brazil (IBAMA,2018), drawing attention to the implications of environmental exposure to these compounds in the long term. In 2020, 493 new chemical compounds were released, 19 more than in 2019. According to the National Health Surveillance Agency (ANVISA), of these products, 25 were considered moderately to extremely toxic to human health, and 251 were very or highly dangerous to the environment (MATIAS *et al*., 2021).

The environment and human health suffer from the results of the wide use of these chemicals, which mostly have toxic properties that can cause biodiversity loss, soil, air, and water resource contamination, damaging fauna and flora, producing harmful effects on health and acting against sustainability (SOUZA *et al*., 2020; MATIAS *et al*., 2021).

The basin of the Açailândia River (HBAR2) in the state of Maranhão arouses interest in the study due to its importance for water supply in the region of Açailândia, the eighth largest population in the state and nearby communities, encompassing extensive areas of agricultural and silvicultural projects (IBGE, 2018). HBAR is located in the MATOPIBA region, an extensive agricultural area encompassing the states of Maranhão, Tocantins, Piauí, and Bahia, one of the few basins in that region that is part of the Amazonian domain. In this sense, understanding the impacts on the risk of environmental contamination by agrochemicals and the dynamics of changes in the land use of HBAR is fundamental for planning actions aimed at the sustainable development of the region.

In order to evaluate the environmental contamination by agrochemicals, a number of alternatives have been investigated (NEVES *et al*., 1998; GOMES *et al*., 2002; BRITTO *et al*., 2015; QUEIROZ *et al*., 2018), such as the development of risk maps for pesticide contamination in a river basin in Piauí (FRANÇA *et al*., 2016a), which is an important tool for planning the rational use of these products. In this aspect, geotechnologies such as Remote Sensing (RS) and Geographic Information Systems (GIS) have already proved to be effective for this procedure (FRANÇA *et al*., 2016a). This is because such technologies have operational advantages, such as data availability on free platforms, relative ease of image manipulation, high spatial data processing power, and quality of obtained results. Multicriteria modeling is widely used to study scenarios with multiple landscape factors involved. GIS-MCDA can be defined as the process of transforming and combining various geographic spatial data for the purpose of obtaining new information on the studied object (DOMAZETOVIĆ *et al*., 2019; MORANDI *et al*., 2020). The method is based on the contextualization and structuring of a problem, followed by analysis in a GIS environment and the formulation of the most appropriate decision for the reality of the area under study (ALMEIDA *et al*., 2020; FRANÇA *et al*., 2020).

Therefore, this study aimed to identify and map the areas at risk of contamination by agrochemicals in the basin of the Açailândia River, Brazil, and to analyze the changes in soil use that have occurred in this basin in the last decades.

1 *Sindicato dos Produtos da Indústria Nacional de Defesa Agropecuária (Union of National Agricultural Defense Industry Products)*

2 *Bacia Hidrográfica do Rio Açailândia (Açailândia River Basin)*

MATERIAL AND METHODS

Study area

The study area comprises the Hydrographic basin of the Açailândia River (HBAR), southwest of the state of Maranhão, Brazil (Figure 1). According to the Köppen climate classification, the climate of the region is classified as Aw, characterized by a tropical climate with a dry winter season, with an average annual precipitation of 1,300 to 1,600 mm and an average annual temperature above 26ºC (ALVARES *et al*., 2013). The basin of the Açailândia River is located in the Amazon Rainforest, with Dense Ombrophylous Forest vegetation and fragments of Seasonal Semideciduous Forest represented by Deciduous plants (MMA, 2012).

HBAR brings together the municipalities of Açailândia and São Francisco do Brejão, which are predominantly based on pastures, temporary crops, and eucalyptus forestry (IBGE, 2018). In the MATOPIBA region, the study area has favorable edaphoclimatic conditions for expanding cultivated lands and implementing technological packages in agricultural and silvicultural production.

Information Plans (IP)

To prepare the pesticide contamination risk map, 34-year satellite images and environmental information plans were used to know the history of anthropization and intensity of land use, as well as the hydrological dynamics of the potential for infiltration and surface runoff. This is because water drag is an important factor in the movement of agrochemicals in the soil. The flowchart shown in Figure 2 summarizes the procedures used to perform this study. The methodological steps were performed on ArcGIS 10.3.1 software.

Land use Intensity

For the land use intensity, the condition of the natural vegetation was analyzed from the NDVI (Normalized Difference Vegetation Index) and the digital classification of the soil cover classes.

In this phase, Landsat 5 Thematic Mapper (TM) sensor, images were used for the years 1984, 1988,

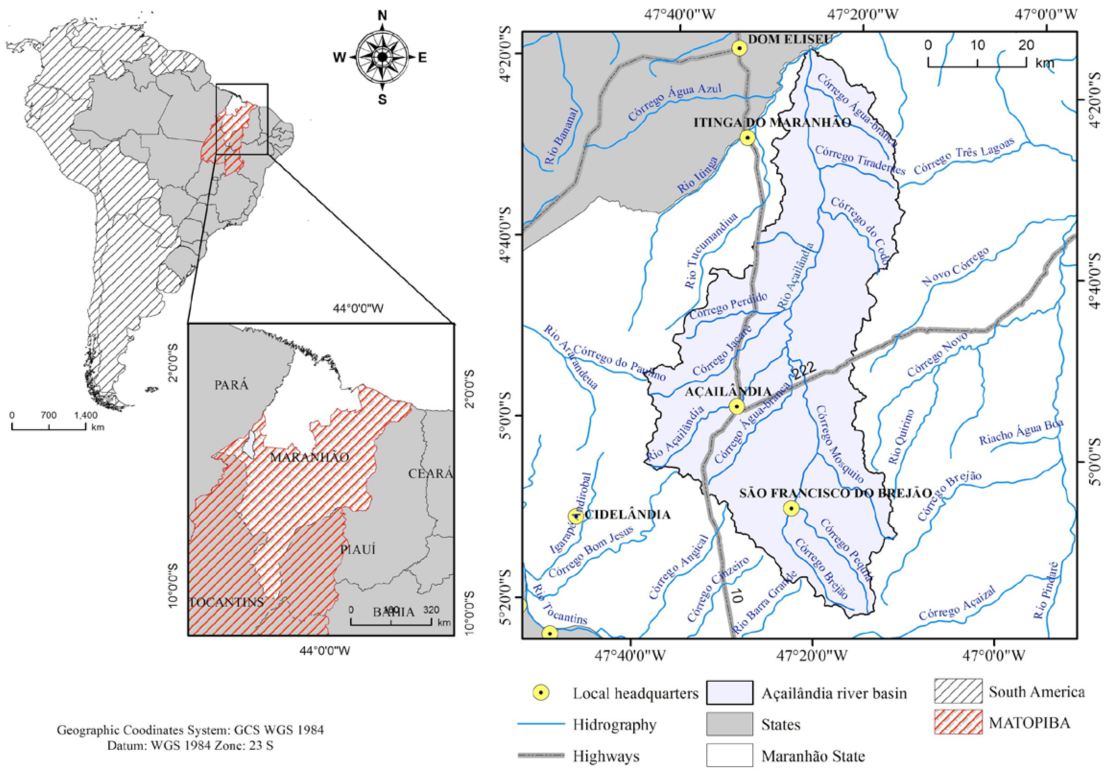


Figure 1. Localization map of the basin of the Açailandia River

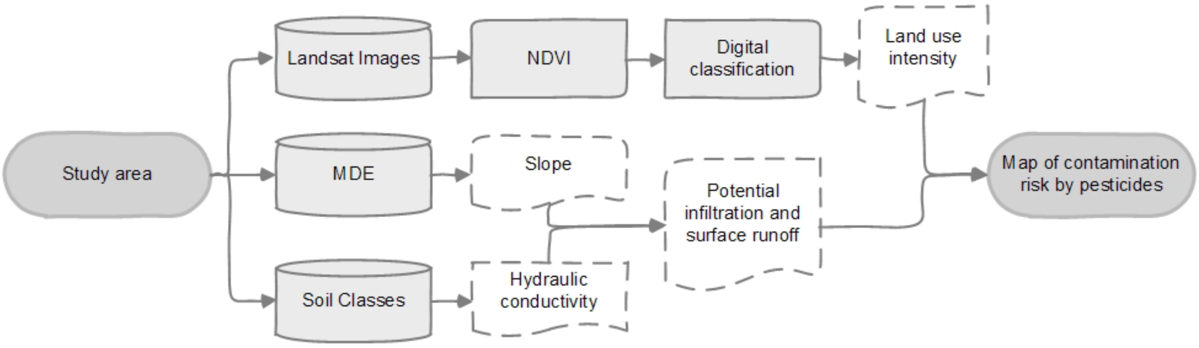


Figure 2. Methodological steps. Adapted from Neves et al. (1998). Legend: MDE - Digital Elevation Model; NDVI - Normalized Difference Vegetation Index

1994, 1999, 2003, and 2008, and in the Landsat 8 Operational Land Imager (OLI) sensor, they were used for the years 2014 and 2018, obtained from the United States Geological Survey (USGS) (USGS, 2022). In the images' selection and acquisition, the seasons and years with less cloud interference were prioritized, and for that, the period between July 1 and August 31 was established to acquire the images.

The NDVI was determined from the map calculator (*Raster calculator* tool), considering the standard calculation of the red (RED) and infrared (NIR) bands (Equação 1).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

The digital classification of the images was performed on the NDVI image by the supervised method of the Maxver algorithm. Two types of soil occupation were established: natural vegetation and anthropic areas based on the Land Coverage and Use Classification System (SCUT3) (IBGE, 2013).

To verify the thematic accuracy of the classification, the Kappa indexes (COHEN, 1960), Global Accuracy (THOMLINSON *et al*., 1999), and the User Accuracy and Producer Accuracy coefficients (CONGALTON, 1991) were applied to validate the classification. To represent the field, images from the digital platform Google Earth Professional version 7.3 were used from the periods corresponding to each classified year, the points of which were randomly distributed within the basin. The Kappa index's result was compared with that proposed by Landis and Koch (1977).

3 *Sistema de Classificação da Cobertura e do Uso da Terra (Land Cover and Land Use Classification System)*

Multicriteria Analysis

After the classification step, the overlap of the classified images was performed through Multicriteria Analysis (MCA), which produceda land-use intensity map with the overlay of the areas (native and cultivated) over the years. The *raster calculator* function was used to obtain the overlap analysis, based on an arithmetic operation to associate the variables studied and generate the map of risk areas. Thus, the most anthropogenic areas of HBAR were obtained in the evaluated period, assuming the greater probability of traces of agrochemicals in these areas, given the potential of these compounds to stay in the environmental compartments.

Potential infiltration and surface runoff

The topographic base of the Digital Elevation Model (DEM), SRTM (Shuttle Radar Topographic Mission), provided free of charge by the United States Geological Survey (USGS, 2021) (https://earthexplorer.usgs.gov/), with a spatial resolution of 30 meters, was used to determine the slope of the terrain. This slope was classified as: low (flat relief with slopes of 0 to 3%), mild (smooth undulating relief with slopes between 3 and 8%), and high (undulating relief with slopes above 8%) (EMBRAPA, 1979).

According to the classification of Gomes *et al*. (2002), the hydraulic conductivity was established qualitatively. In this classification, the hydraulic conductivity of the main types of Brazilian soil, at a high categorical level, is determined as a function of the dominant texture, dominant structure, aggregate stability, and depth of the A + B horizons as a risk assessment subsidy method of pesticide contamination. The vector information related to the soil classes of the region was obtained from the public data of the survey of Soils of Brazil (Scale: 1:5,000,000) of Embrapa Solos (SANTOS *et al*., 2011) in agreement with the Brazilian Soil Classification System (SIBCS4) (DOS SANTOS, 2018).

Then, a third information plane with a generic classification of the infiltration potential and surface runoff based on a matrix relationship from the intersection of the slope and hydraulic conductivity planes was also obtained according to the methodology by Gomes *et al.* (2002) (Tabela 1).

Table 1. Potential infiltration and surface runoff according to the methodology of Gomes *et al*. (2002)

Infiltration potencial			
Hydraulic conductivity	**Slope**		
	Low	Medium	High
Low	Medium	Low	Low
Medium	High	Medium	Low
High	High	High	Medium
Surface runoff potential			
Hydraulic conductivity	**Slope**		
	Low	Medium	High
Low	Medium	High	High
Medium	Low	Medium	High
High	Low	Low	Medium

Agrochemicals

To corroborate the results presented, a survey of information on agrochemicals and their environmental hazard classes was carried out in each state belonging to MATOPIBA, with the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA5) between 2009 and 2017.

Contamination risk map

The last step of this study consisted of the multicriteria analysis of the information plans of soil use intensity and their potential for infiltration and surface runoff. The multicriteria approach can add several landscape characteristics to the analysis, with applications already proven in the forest sector (VALENTE *et al.*, 2017).

In this way, the areas of simultaneous occurrence of conditions that potentiate the chances of contamination by agrochemicals were identified. This allowed them to be classified for the presented risk as follows: (I) Low, (II) Slightly low, (III) Medium, (IV) High, and (V) Extremely high.

Table 2 presents the matrix relationship used to classify the degree of risk of contamination by agrochemicals due to infiltration and surface runoff potential. It is critical to highlight the inverse relationship between infiltration and surface runoff as greater soil infiltration capacity is closely related to the lower water runoff and latter areas and sandy soils.

Table 2. Risk of environmental contamination due to the land use intensity and potential infiltration and surface runoff

Contamination risk by agrochemical			
Land use intensity	**Potential infiltration**		
	Low	Medium	High
No use	Low (I)	Low (I)	Slightly low (II)
Low	Low (I)	Slightly low (II)	Medium (III)
Medium	Slightly low (II)	Medium (III)	High (IV)
High	Medium (III)	High (IV)	Extremely high (V)

At the end of this stage, a map of areas at risk of contamination by agrochemicals was developed, identifying critical areas that deserve greater attention regarding the agrochemicals used.

4 *Sistema Brasileiro de Classificação de Solos (Brazilian Soil Classification System)*

5 *Instituto Brasileiro de Meio Ambiente e dos Recursos Naturais Renováveis (Brazilian Institute of Environment and Renewable Natural Resources)*

RESULTS AND DISCUSSION

Land use classification

The results of the soil cover classification (Figure 3) show a strong process of the anthropization of the basin of the Açailândia River as early as 1984, with 48.0% of anthropized areas. During the analyzed period, 27.8% of these areas increased, corresponding to 420 km², reaching 60% of the basin (1,935.4 km²) in 2018. Figure 4 shows the difference in NDVI for the main years of evaluation (initial year: 1984 and final year: 2018). In addition to the numbers presented in the graph in Figure 3, it is possible to visually verify an evident increase in anthropized areas and a reduction in areas with natural vegetation.

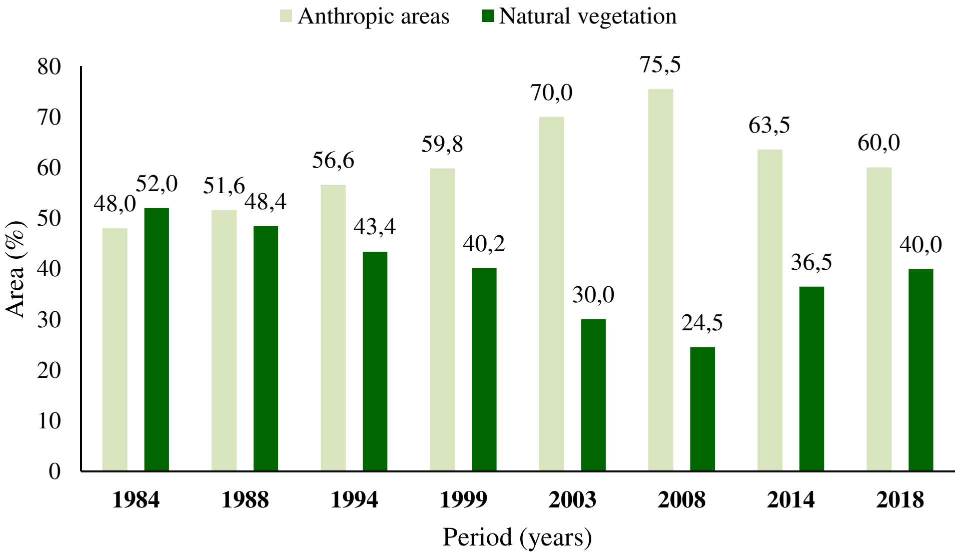


Figure 3. Dynamics of anthropic use and natural soil cover in the Açailândia river basin

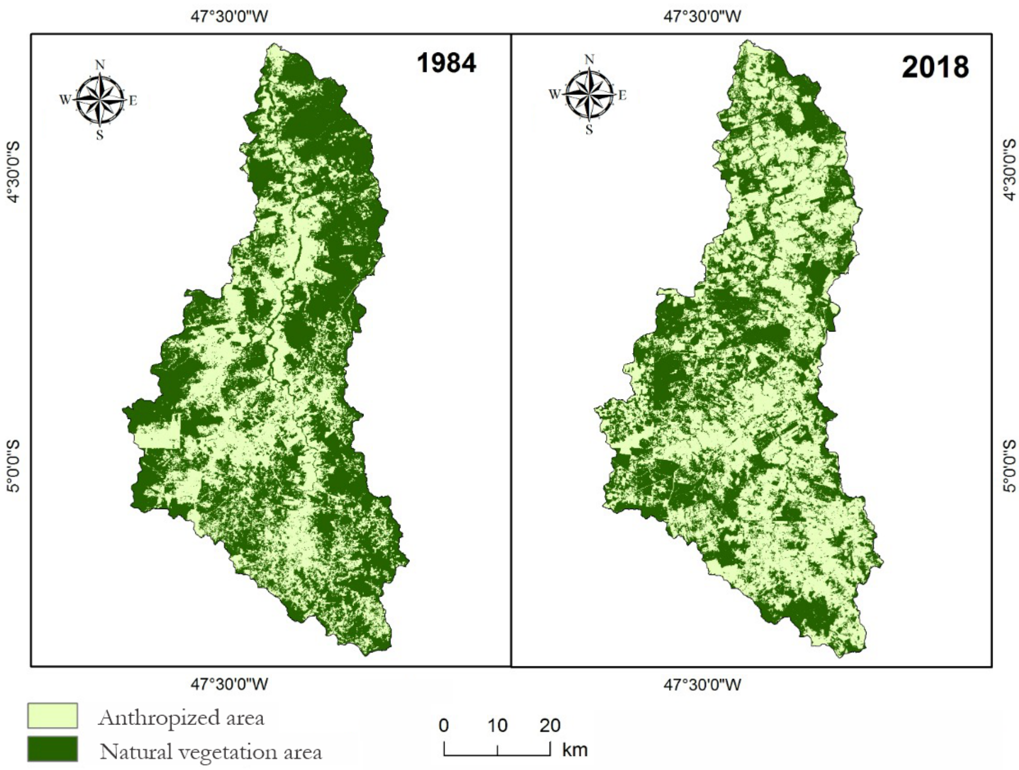


Figure 4. Temporal evolution of the change in the natural vegetation cover of the HBAR

The expressive anthropogenic activity evidenced in the HBAR as early as 1984 may have had a direct influence on the implementation process of large road and railroad projects in Maranhão, especially from the Grande Carajás Program (Decree of Law, No. 1,813, dated November 24, 1980) (BRASIL, 1980) granted in 1980 as a stimulus to the industrialization of municipalities in the state. The construction of the Carajás Railroad and the Norte-Sul Railroad boosted logging and demographic density in the region, modifying the landscape. From 2003 onwards, there was a greater discrepancy between the classes evaluated. According to the IBGE (2018), with data available from 2003 for the municipality of Açailândia, there was a high in agricultural production, emphasizing annual crops such as corn and beans, increased logging, increased livestock, and increased eucalyptus forestry.

The results presented in Figures 3 and 4 corroborate the findings of Castro and Santos (2016), who studied the changes in land use between 1988 and 2008 in the sub-basin of the Água Branca stream, a tributary of the Açailândia River. Changes occurred in the soil cover marked by the accelerated deforestation expansion where the main occupations evidenced were agriculture, urban expansion, and silvicultural activities, especially the eucalyptus crop.

A decrease was also observed in the anthropization class between 2008 and 2018 (Figure 3). On the other hand, there was an increase in soybean plantation areas from 2012 in the region of Açailândia (IBGE, 2018). Thus, the areas destined for agricultural plantations in this period may be derived from the use of already anthropized areas and not from the conversion of new areas. In addition, existing silvicultural activity in the area may have overestimated areas of natural vegetation due to the high NDVI value of planted forests, similar to native forests.

The increase in anthropogenic areas, potentially converted into areas for agribusiness, follows the pattern of increased production in the MATOPIBA region. The region showed significant growth in soybean production during a time series from 1990 to 2015, rising from 260,624 t in 1990 to 10,758,927 t in 2015, an increase of 4,028% in 25 years (ARAÚJO *et al*., 2019).

However, changes in the landscape may be associated with the fragmentation of natural areas and habitat loss, which may interfere with the conservation of species biodiversity (CORDEIRO *et al*., 2015; SAEKI *et al*., 2018), carbon stocks, soil loss (ISLAM *et al*., 2017; LAM *et al*., 2018; ROLO *et al*., 2018), seed survival, recruitment of individuals (BROCARDO *et al*., 2018), the diversity of pollinating agents (MORATO & CAMPOS, 2000), and the occurrence of diseases in the population (SCINACHI *et al*., 2017), among other impacts.

The application of the Kappa, Global Accuracy, and user and producer accuracy showed that the classification of the images provided satisfactory results (Table 3).

The classification performed in this work for the Kappa index can be considered excellent (LANDIS & KOCH, 1977). The Global Accuracy, which represents the accuracy of the entire mapping, presented values above 0.80 agreement. According to Thomlinson *et al*. (1999), the general evaluation of the classification should aim at 85% accuracy,

Table 3. Digital classification validation indices

Year	Kappa	Global Accuracy	User Accuracy		Producer Accuracy	
			Natural vegetation	Anthropic areas	Natural vegetation	Anthropic areas
1984	0.84	0.86	0.86	0.86	0.83	0.89
1988	0.86	0.88	0.95	0.83	0.79	0.96
1994	0.92	0.92	0.92	0.92	0.92	0.92
1999	0.89	0.90	0.88	0.92	0.91	0.89
2003	0.86	0.90	0.84	0.94	0.91	0.91
2008	0.84	0.88	0.80	0.93	0.89	0.88
2014	0.81	0.86	0.83	0.88	0.89	0.90
2018	0.84	0.86	1.00	0.78	0.72	1.00

with no accuracy lower than 70%.

The Class of Natural Vegetation in Producer Accuracy of 2018, with 0.72, was the one with the lowest index, representing an error of omission for this class and this year of about 28%. The difficulty in distinguishing native vegetation from anthropic areas may have occurred due to the similarity between the spectral signatures of forests and cultivated areas, especially silvicultural plantations, whose planted areas are gaining more and more space in the region. However, in general, accuracy values ranged from 0.7 to 1 (Table 2). Thus, it is understood that individual classes have been satisfactorily established.

Information Plans (IP)

Figure 5 shows the main information plans used to generate the risk map of contamination.

The Land-use intensity map was generated from the results of the algebraic combination of land use for each year evaluated (Figure 5-A), where it is possible to verify the high proportion of areas with high intensity of use, accounting for 47.70% of the basin, with 1,538.20 km², followed by average intensity, with 29.90%, corresponding to 965.00 km². With this, historical use of most of the areas in the basin of the Açailândia River was demonstrated.

Most of the HBAR area presented low (0 to 3%) and mild slopes (3 to 8%), corresponding to 42.43% (1,287.75 km²) and 40.44% (1,227.34 km²), respectively, of its total area (Figure 4-B). Such slopes are considered ideal for the operation of machinery and tools used in agricultural practices, a scenario apt to the intense mechanization of the productive processes. An area of 519.56 km² (17.12%) of the basin has a slope classified as high, limiting the use of mechanized agricultural practices.

The anthropic areas' expansion occurs mainly on oxisol spots. This is compatible with the dynamics of occupation of the traditional agricultural activities in the region by the favorable physical characteristics of this class of soils for cultivation and mechanization practices, as observed in visual analysis between the maps of land-use intensity (Figure 5-A) and soil classes (Figure 5-C). França *et al*. (2016b) pointed out a hydrographic basin of the MATOPIBA region with a high agricultural productivity rate, which, due to the local biophysical characteristics, presented 55.15% of its area with very high agricultural aptitude.

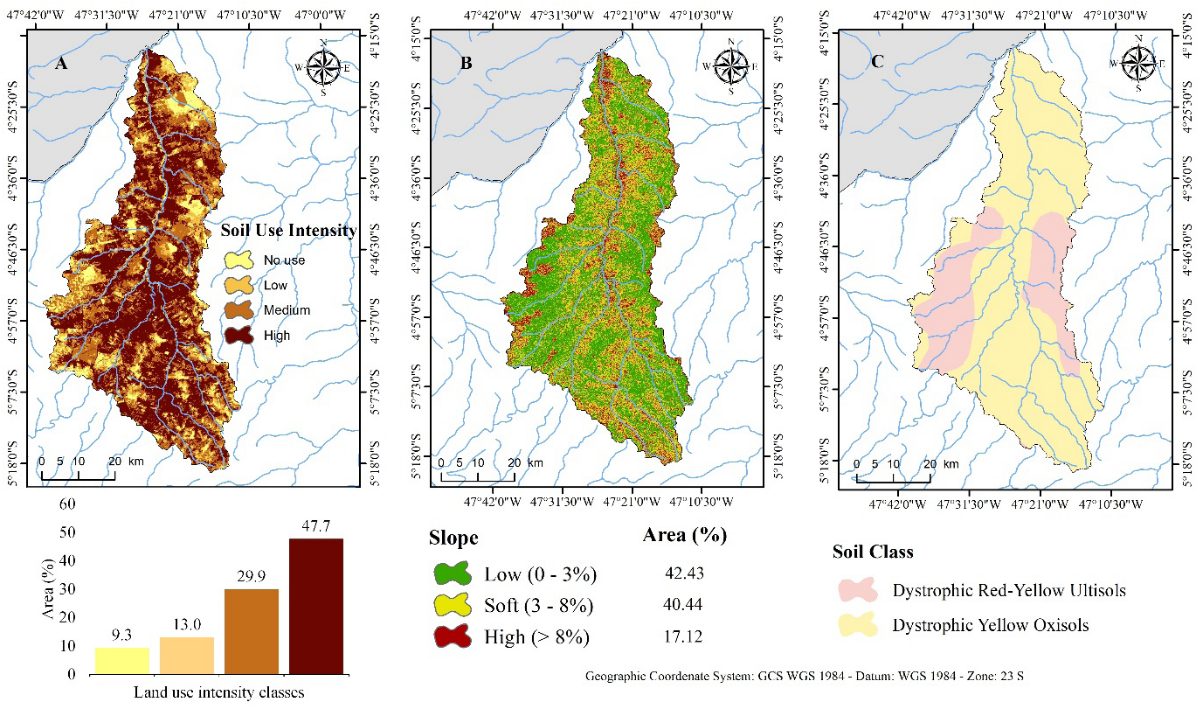


Figure 5. Environmental information plans. **A**) A map of land-use intensity and the percentage of each class. **B**) HBAR slope map, with the percentage of each class. **C**) Soils classes at a high categorical level, found in HBAR

The chemical properties of soils, especially clay and organic matter, facilitate the adsorption of agrochemicals and restrict their desorption, increasing the retention of these compounds in the soil, while the mobility of products is higher in sandy soils (SHAHEEN *et al*., 2017). However, the mentioned work showed that organic matter has greater potential to bind the chemical particles to the soil, such that even in samples of clay soils, the adsorption was smaller than the lower the organic matter content.

Based on this approach, it is understood that river basins under more sandy soil conditions are more subject to the leaching of these chemicals. Moreover, soils deficient in organic matter, as frequently occurs with ultisols and oxisols found in the study area of this work, may present greater agrochemical mobility. In addition to the good drainage, natural characteristics of these soils, the low slope of the terrain of the study area, percolation and subsurface, and underground flow are favored, increasing the chances of contamination of water bodies and groundwater.

Higher agrochemical adsorption to soil clay can also be related to the accumulation of these contaminants in the soil profile due to their time of environmental permanence. The chemical, physical, and biological mechanisms of soil are complex, and there are gaps in the dynamics of their behavior with agrochemicals. Thus, it is generally necessary to collect field material and perform tests to obtain precise statements on the adhesion and transport of agrochemicals in the edaphic compartments. Overall, it is noted that the lower the adsorption levels of an active ingredient in the soil, the greater the ecotoxicological effects that reduce the biodegradation by microorganisms. In this way, the possibility of products descending deeper into the soil profile and becoming unavailable for direct degradation increases (DE SOUZA *et al*., 2017).

Contamination risk map

According to the criteria adopted by Gomes *et al*. (2002) for the qualitative generalization of the hydraulic conductivity of the soils for the basin under study, the hydraulic conductivity was classified as average, making the classification of the infiltration and flow potential possible. The combination of the intensity of use and the potential for infiltration and runoff generated the risk of contamination by agrochemicals (Figure 6).

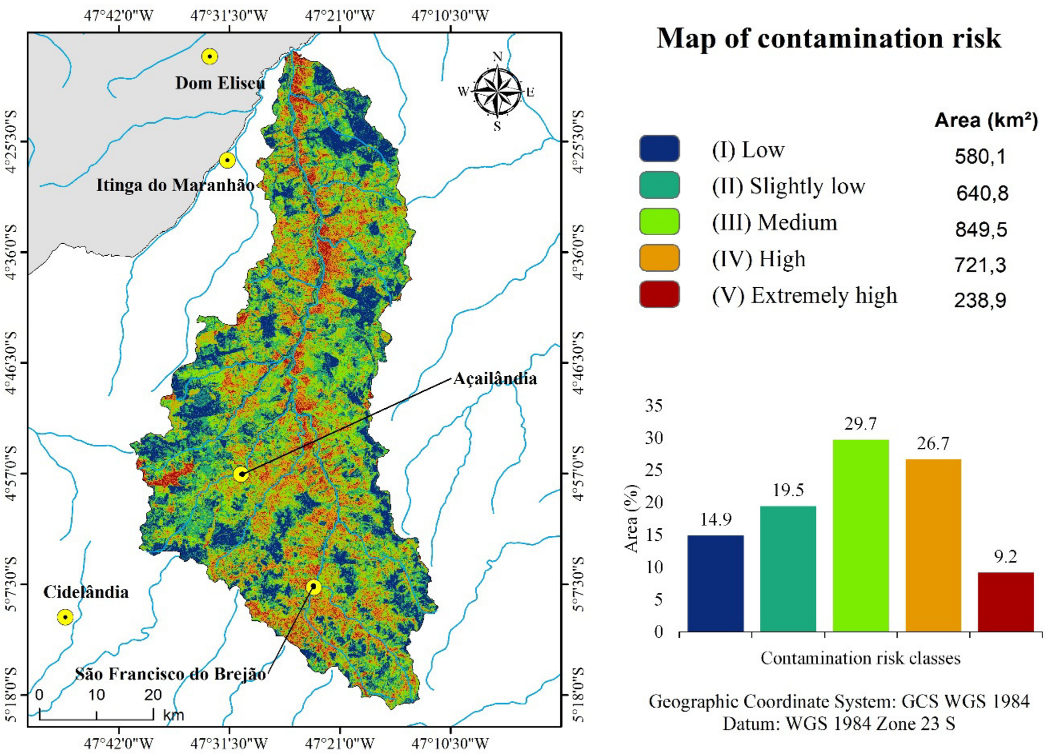


Figure 6. Contamination risk map by agrochemicals. Each contamination risk class is presented on the map with its respective area in km² and in percentage

The areas with a high and extremely high risk of contamination by agrochemicals correspond to 1,087.62 km² (35.90%). This means that more than one-third of the basin area simultaneously has factors contributing to increasing the likelihood of contamination by agrochemicals, especially regarding soil compartments and water resources. In addition to the areas indicated as high and extremely high contamination risks, characterized by a direct relationship with agricultural and silvicultural activities over the years, agrochemicals can also be leached into the other tributaries and sub-tributaries of the Açailândia River.

In the final map, it is possible to observe that class V (*extremely high*) is distributed along the hydrographic basin, especially with evident proximity to areas of lower relief in the basin close to watercourses, especially around the main river (Açailândia River) and its tributaries. This finding highlights the need for close attention to these sites, which may eventually present soil contamination problems and especially hydrography. Despite representing a smaller proportion of areas equivalent to 9.20% of the basin or 238.90 km² of the total area, the extremely high contamination risk class is associated with these sites of high environmental sensitivity since the association is direct with the local hydrography. This may affect flora, fauna, and populations dependent on the water consumption in the hydrographic basin. Concerning class I, *low risk* of contamination, these areas are predominantly associated with flatter relief sites.

It is important to emphasize that the areas indicated as susceptible to contamination may be contaminated. In the final map, these classes indicate only areas of intense exploration and agricultural use, indicating that agrochemicals can accumulate in the soil or leach into water sources. Although it is impossible to show the actual contamination of surface and subsurface waters and the soil/ecosystem, it is possible to provide a basis for defining the places with the greatest potential for contamination risk.

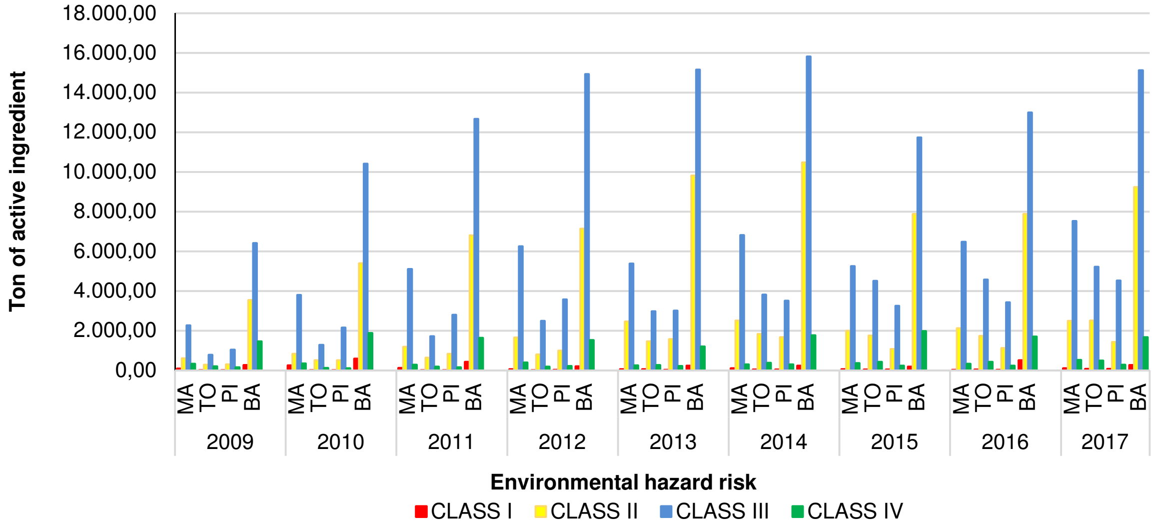
Regarding the environmental assessment of agrochemicals and their components, the classification of potential environmental hazard (PPA) is IBAMA's responsibility, item II of Article 7 of Decree No. 4,074/02 (Tabela 4). According to the environmental hazard classes, figure 7 presents a time series of the most sold agrochemicals by the state of MATOPIBA.

Table 4. Classification of potential environmental hazards of agrochemicals

Classes	Definition
Class I	Highly hazardous to the environment
Class II	Very hazardous to the environment
Class III	Dangerous to the environment
Class IV	Not dangerous to the environment

It was verified that the states of Bahia and Maranhão present the highest sales of active ingredients (AI) of agrochemicals in the classes *very dangerous* (II) and *dangerous* (III) to the environment (Figure 7). Glyphosate and its salts are the leaders in the group of the 10 I, the most sold and used in the region of MATOPIBA, besides being classified in class III (IBAMA, 2018). There was a lack of information on mesoregion or microregion sales and the geographic application of agrochemicals. Consequently, there is a certain obstacle in scientific investigations directed to the real contamination of the agrochemical. However, such data provides an idea of the potential risk of contamination of the environment due to the consumption scale.

Other studies investigating the number of agrochemicals used in the HBAR region may be important for understanding local environmental issues. The deforestation progress in the whole MATOPIBA region can also lead to an increase in agrochemical commercialization and consumption. Matricardi *et al*. (2018) found that simulated scenarios for this region indicate an increase of 10.30, 15.30, and 15.90 million hectares of native vegetation deforestation between 2011 and 2050,



Source: IBAMA, 2018

Figure 7. Sale of agrochemicals for environmental hazard category between the years 2011 and 2017. MA - Maranhão; TO - Tocantins; PI – Piauí; and BA - Bahia

assuming the optimistic, tending, and pessimistic scenarios, respectively, thus reinforcing the attention from the viewpoint of the environmental conservation of the natural resources in this region.

Among the potential solutions to problems associated with pesticide contamination is adopting Integrated Pest Management (IPM) programs by farmers in the region. This could represent an alternative to the scenario mentioned above since it would decrease the need and quantity of products used. It can thus reduce the exposure of rural workers and the environment to these products and, overall, favor the production of healthier foods.

Recommendations for land use and agrochemicals

Based on the final contamination risk by the agrochemicals map (Figure 5), we propose some conservationist and land-use practices that are most appropriate to ensure safe conditions in the use of agrochemicals, environmental conservation, and sustainable development (Table 5). Land use and management directly influence the magnitude of possible environmental impacts. For all categories, precision agriculture is a highly recommended strategy for the sustainable development of these regions.

These land-use recommendations, agrochemical applications, and environmental conservation are indicated from a regional perspective, and each conjuncture in real instances requires specific attention. Environmental damage is directly linked to the site's environmental fragility when it receives contamination, an inherent property of a given ecosystem. In general, an ecosystem has a certain risk of environmental damage according to its degree of exposure to any disturbances, in this case, agricultural practices and how agrochemicals are used. Therefore, relating ecosystems to disturbances and anthropic actions that act on them can provide useful and fundamental assessments in the design of environmental zoning and management of the use of chemical pesticides. This approach is closely related to the assessment of environmental impacts.

The results of this study can be incorporated into decision-making processes for creating legislation at the state level seeking to avoid the contamination of ecosystems and human populations with agrochemicals. We recommend future risk studies that indicate the priority agrochemicals and consider their environmental dynamics and toxicity to help an adequate understanding and prediction of the risks associated with such compounds.

Table 5. Degrees of contamination risk by agrochemicals and recommendations/proposals for conservation, management, and sustainable use of land

Risk of contamination	Degree of damage to the ecosystem	Recommendations
Low	Low Environmental Impact *(Higher degree of resistance to environmental damage)*	**(1)** Lands more suitable for anthropic land use and rational use of agrochemicals.
		(2) It is essential to use conservationist practices in anthropic land use activities and agrochemical application practices
Slightly Low	Slightly low environmental impact *(Some factors reduce the ecosystem's resistance to the stress caused)*	**(3)** Land suitable for anthropic land use and rational use of agrochemicals
		(4) Maintenance of conservation practices of anthropic activities of land use and agrochemical application practices
Medium	Medium environmental impact *(State of attention to the local ecosystem due to the transition from stable to unstable with potentially aggravating environmental damage)*	**(5)** Lands suitable for anthropic land use and rational use of agrochemicals but which demand attention due to the medium risk of contamination
		(6) It is necessary to use conservation practices in anthropic land-use activities, especially in the application of agrochemicals.
High	High environmental impacts *(Ecosystem highly susceptible to stress and serious environmental damage)*	**(7)** It is recommended that these areas be framed for possible future land-use changes.
		(8) Maximum attention to the proximity to watercourses and development of practices to protect water sources
		(9) Rigorous use of conservationist practices in anthropic land-use activities, especially in the application of agrochemicals.
Extremely High	Serious environmental impacts *(Extremely susceptible ecosystem with potentially irreversible damage)*	**(10)** Frequent hydrogeological studies are essential for the diagnosis of groundwater quality.
		(10) Priority areas for the destination of remediation practices or phytoremediation of potentially contaminated soils
		(11) High precision in using conservation practices in anthropic activities of land use and application of agrochemicals
		(12) If possible, and depending on each case, these are priority areas for land-use change.

CONCLUSIONS

- Açailandia River basin presented high anthropization, with an increase of approximately 27.00% in land use and occupation by crops from 1984 to 2018. The area of 1,087.62 km², corresponding to 35.90% of the basin, presented a high and extremely high risk of contamination. Areas adjacent to the main watercourse presented a higher risk.
- Although it is not possible to show real contamination of the Açailândia River basin by agrochemicals, the risk map presented in this study provides a tool to define the sites with the highest potential for contamination risk, serving as a fundamental subsidy for conservation and management strategies of land use.
- The results of this research highlight the need to revise the agricultural and silvicultural practice models in the MATOPIBA region. It also aims to develop accurate water quality assessments and other potentially contaminable sources and resources for validating the risk estimates of contamination here suggested.
- The methodology presented in this paper can be adapted to other world ecoregions and different types of plant crops.

AUTHORSHIP CONTRIBUTION STATEMENT

FERRAZ, F.T.: Conceptualization, Formal Analysis, Methodology, Software, Writing – original draft; **FRANÇA, L.C.J.:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing; **AGUIAR JÚNIOR, A.L.:** Conceptualization, Writing – review & editing; **LIMA, T.P.:** Conceptualization, Writing – review & editing; **ACERBI JÚNIOR, F.W.:** Project administration, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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