Mapping of Environmental Fragility in Agricultural Expansion Areas in Matopiba, Piauí, Brazil

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ABSTRACT
The need to identify and map the fragility of environments is extremely important for environmental planning and quantification of changes caused by human activities in the various ecosystems. With agricultural expansion, the conversion of natural vegetation cover is increasingly intense, causing loss of biodiversity and increasing damage to ecosystems. Thus, the objective was to quantify and map the temporal evolution of Matopiba's environmental fragility, verifying the impacts of agricultural expansion on vulnerability to degradation. This study addresses the Matopiba area located in the state of Piauí, which has transitional vegetation between the Cerrado and Caatinga biomes. For the space-time assessment of natural vulnerability, maps of geomorphology, geology, pedology, climate, vegetation and land cover were superimposed, assigning risk scores, based on the methodology of Crepani et al. (2001). Over the years, there has been an increase in areas classified as high and very high vulnerability, which are directly related to agricultural expansion, inversely related to the presence of native vegetation. Thus, environmental policies must be implemented in order to use conservationist practices that aim to mitigate the effects of agricultural expansion on the fragility of the soil and the preservation of biodiversity and local natural resources.

Keywords: environmental vulnerability, land degradation, deforestation, land use and land cover

Mapeamento da Fragilidade Ambiental em Áreas de Expansão Agrícola no Matopiba, Piauí, Brasil

RESUMO
A necessidade de identificar e mapear a fragilidade dos ambientes é de extrema importância para o planejamento ambiental e quantificação das alterações causadas pelas atividades humanas nos diversos ecossistemas. Com a expansão agrícola, a conversão da cobertura vegetal natural é cada vez mais intensa, causando perda da biodiversidade e aumentando os danos aos ecossistemas. Assim, objetivou-se quantificar e mapear a evolução temporal da fragilidade ambiental do Matopiba, verificando os impactos da expansão agrícola na vulnerabilidade à degradação. Este estudo aborda a área de Matopiba localizada no estado do Piauí, que possui vegetação de transição entre os biomas Cerrado e Caatinga. Para a avaliação espaço-temporal da vulnerabilidade natural, foi realizada uma superposição de mapas de geomorfologia, geologia, pedologia, clima, vegetação e cobertura do solo, atribuindo notas de risco, com base na metodologia de Crepani et al (2001). Ao longo dos anos, houve aumento das áreas classificadas com vulnerabilidade alta e muito alta, que estão diretamente relacionadas à expansão agrícola, inversamente relacionadas à presença de vegetação nativa. Assim, políticas ambientais devem ser implementadas de forma a utilizar práticas conservacionistas que visem mitigar os efeitos da expansão agrícola na fragilidade dos solos e na preservação da biodiversidade e dos recursos naturais locais.

Palavras-chave: vulnerabilidade ambiental, degradação da terra, desmatamento, uso e cobertura da terra
Introdução

The intensification of agricultural activities has raised serious concerns about potential environmental impacts, such as the deforestation of native forests to make way for crops such as: soybeans, corn, cotton, which have been causing significant losses in biodiversity, considerably increasing greenhouse gas emissions. greenhouse effect (GHG), soil erosion, contamination of water resources, impacts on climate regulation and air quality (Roriz et al., 2017; Fernandes et al., 2021; Hu et al., 2021). This process makes areas more vulnerable to degradation (Tomasella et al., 2018).

The Matopiba region, which encompasses the states of Maranhão, Tocantins, Piauí and Bahia, is part of the so-called “arc of deforestation” and becomes a dynamic center of land conversion in the Brazilian scenario, accounting for 0.63% of the total area, equivalent to 4,677 km², it records worrying trends of degradation (Vieira et al., 2021). The unsustainable management of natural resources has favored drastic transformations in the ecosystem, whether through human interventions, the expansion of agricultural activity or even forest fires, damaging the soil biota. Santos et al. (2021) expanded the complexity of the situation by identifying production risks associated with soil physical properties, including texture, compaction, porosity, water storage, and stability.

According to the Annual Report on Deforestation in Brazil (Mapbiomas, 2020), around 430,000 hectares of native vegetation were deforested in the Cerrado biome in 2020, of which 1,444 hectares were protected areas. In addition, the same report highlights that among all Brazilian biomes, the highest rate of deforestation (ha day⁻¹) in 2020 was recorded in the municipality of Baixa Grande do Ribeiro (PI), a region belonging to Matopiba, where it was verified. removal on average of 89 ha day⁻¹.

Over the past 40 years, approximately 50% of the natural vegetation of the Cerrado biome has been removed for the establishment of livestock, soy, sugarcane, and eucalyptus, and mining and charcoal production areas (Pita and Vega 2017). Ferreira et al. (2013) show through deforestation projections that from 2002 to 2050 the Matopiba region will lose about 40,000 km² of its native vegetation, making room for human activities that tend to increase the region’s fragility (Tomasella et al. 2018).

Therefore, the hypothesis in this work is the correlation between the agricultural expansion of MATOPIBA and the worsening of environmental fragility. And, given this scenario, promote the use of geotechnological tools to analyze natural and anthropogenic modifications in a spatio-temporal manner of potential and emerging vulnerability.

It is worth highlighting the importance of Geographic Information Systems (GIS), widely used in analyzing and quantifying levels of fragility. By employing analytical techniques that consider spatial and temporal factors together with environmental susceptibility, it makes it possible to interpret changes in intensive land use (Ferreira; Silva, 2020; Takikawa, Silva and Lourenço, 2021, Moura Neto et al., 2022; Moura Neto et al., 2023).

Therefore, understanding the aspects that encompass the landscape of land use and occupation are based on physical, social and environmental characteristics, thus providing subsidies for land use management, allowing the definition of guidelines and actions to be taken to mitigate environmental degradation. This understanding takes into account factors: geological, pedological, geomorphological, climatic, phytogeographic and land use and occupation (Teixeira et al., 2021).

According to Teixeira et al. (2021) and Macedo et al. (2021) assessing the susceptibility of environmental compartments to degradation is of fundamental importance, as it makes it possible to verify the incidence of impacts arising from human interventions (emerging fragility) or even through natural processes (potential fragility).

França; Piuza; and Ross (2017), when comparing maps of potential and emerging environmental fragility in Gilbués/PI, showed that the municipality had 26% of areas prone to environmental degradation arising from natural processes, with its vulnerability levels considered high and extremely high. . Inserting land use and occupation factors linked to changes resulting from human activities, the emerging fragility tends to increase considerably.

In this context, the objective was to quantify and map the temporal evolution of Matopiba's environmental fragility, verifying the
impacts of agricultural expansion on vulnerability to degradation.

**Material e métodos**

Matopiba comprises 337 municipalities in the states of Maranhão (MA) - 33%, Tocantins (TO) - 38%, Piauí (PI) - 11%, and Bahia (BA) - 18%, considered the last agricultural frontier in Brazil, corresponding to an extension of 734,752 km² (Ibge, 2020), and its predominance in the domains of the Cerrado biome (665,400 km²) (Brasil, 2015), but with fragments of the Caatinga and Amazon. The Region is located in an area with transitional vegetation between the Cerrado and Caatinga biomes (Figure 1):

![MATOPIBA REGION](image)

**Figura 1.** Spatial location of the region under study. Elaboration: Authors, 2021.

The region's natural resources have suffered from agricultural expansion, especially in terms of grain production, such as soy, corn, and cotton, and this has caused major economic and social transformations in southern Piauí (Pereira; Porcionato; Castro, 2018).

According to Medeiros, Cavalcanti, and Duarte (2020), the Köppen model (1928, 1931) presented climatic variability for the state of Piauí, and it was possible to verify three climatic categories, of the “Aw” types (hot and humid, with summer rains) located in the West, South, and part of the central region of the State. The type of climate “Bsh” (semi-arid) predominates in almost all semi-arid areas of Piauí and isolated areas in the central region. The type of climate “As” (hot and humid with summer/autumn rains) predominates in the East and Northeast of the state and in an isolated range in the central region. Regarding rainfall, the southern region of Piauí has an average annual rainfall of 159 mm, concentrated in the period from October to March, with an average annual temperature of 27 °C (Figure 2).
Figure 2. Monthly climatological temporal distribution of rainfall and air temperature. Elaboration: Adapted from INMET (2021).

Figure 3. Data acquisition steps.

For a spatiotemporal assessment of the natural vulnerability to soil loss in the Piauí strip that makes up Matopiba for a period of 25 years (1995 – 2020), an overlay of thematic maps was performed, with degradation risk scores being assigned to each criteria: soil, geology, vegetation, land use and occupation, climate and Geomorphology, so that vulnerability maps were obtained for each component using QGIS Software 3.8.3 (Qgis development team 2019). The components were obtained on different platforms, as described in the data acquisition steps in Figure 3, below:

The methodology used in this work was based on Crepani et al. (2001), whose application consists of presenting a range of values that indicate the vulnerability of the ecosystem to degradation, including classes of high vulnerability (values close to 1.0), passing through intermediate situations (values around 2.0) and situations of high vulnerability (values close to 3.0) and receives value assignments according to Table 1. Methodological details can be seen in Crepani et al. (2001). Geomorphology, so that vulnerability maps were obtained for each component using QGIS Software 3.8.3 (Qgis development team 2019). The components were obtained on different platforms, as described in the data acquisition steps in Figure 3, below:

Table 1. Vulnerability classes.

<table>
<thead>
<tr>
<th>Vulnerability scale</th>
<th>Degree of vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 – 1.3</td>
<td>Stable</td>
</tr>
<tr>
<td>1.4 – 1.7</td>
<td>Moderately stable</td>
</tr>
<tr>
<td>1.8 – 2.2</td>
<td>Fairly stable/vulnerable</td>
</tr>
<tr>
<td>2.3 – 2.6</td>
<td>Moderately vulnerable</td>
</tr>
<tr>
<td>2.7 – 3.0</td>
<td>Vulnerable</td>
</tr>
</tbody>
</table>

Source: Crepani et al. 2001.
the Shuttle Radar Topography Mission (SRTM), available on the National Aeronautics and Space Administration (NASA) website with a spatial resolution of 30 m. Then, the MDE’s spurious depressions were filled in, to avoid errors that could harm or interfere with the analysis of the results (Guimarães et al. 2017).

Subsequently, it was possible to map the degree of carving of the valleys, considering the relative amplitude of the relief, which according to Guerra (1993) represents the difference between the highest and lowest points, considered at a relative level per sample area, which his relationship with the deepening of drainage, being defined as vertical dissection (DV).

The average interfluvial dimension is the size of the interfluves in a certain portion of the earth's surface, which, according to Guerra (1993), can be understood as “ripples that separate the valleys”, characterizing horizontal dissection (DH). And, by crossing the morphometric information, it was possible to calculate the relief dissection values as proposed by Crepani (2001), according to equation 1:

\[ G^o = DV + DH \]  

(1)

On what, \( G^o \) = degree of dissection vulnerability; \( DV \) = vertical dissection; \( DH \) = horizontal dissection.

Thus, taking these attributes into account, it was possible to assess the geomorphological vulnerability through the following morphometric parameters: relief dissection, altimetric amplitude, and slope, described in equation 2:

\[ G_e = \frac{G^o + A + D}{3} \]  

(2)

on what, \( G_e \) = Geomorphological vulnerability; \( G^o \) = degree of dissection vulnerability; \( A \) = Altimetric amplitude vulnerability; \( D \) = Slope vulnerability.

The altimetric amplitude parameters, degree of relief dissection, and slope were classified according to tables 2, 3, and 4, respectively:

Table 2. Vulnerability values for the degree of relief dissection.

<table>
<thead>
<tr>
<th>Degree of relief dissection (m)</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;5000</td>
<td>1.0</td>
</tr>
<tr>
<td>4750 - 5000</td>
<td>1.1</td>
</tr>
<tr>
<td>4500 – 4750</td>
<td>1.2</td>
</tr>
<tr>
<td>4250 – 4500</td>
<td>1.3</td>
</tr>
<tr>
<td>4000 – 4250</td>
<td>1.4</td>
</tr>
<tr>
<td>3750 – 4000</td>
<td>1.5</td>
</tr>
<tr>
<td>3500 – 3750</td>
<td>1.6</td>
</tr>
<tr>
<td>3250 – 3500</td>
<td>1.7</td>
</tr>
<tr>
<td>3000 – 3250</td>
<td>1.8</td>
</tr>
<tr>
<td>2750 – 3000</td>
<td>1.9</td>
</tr>
<tr>
<td>2500 – 2750</td>
<td>2.0</td>
</tr>
<tr>
<td>2250 – 2500</td>
<td>2.1</td>
</tr>
<tr>
<td>2000 – 2250</td>
<td>2.2</td>
</tr>
<tr>
<td>1750 – 2000</td>
<td>2.3</td>
</tr>
<tr>
<td>1500 – 1750</td>
<td>2.4</td>
</tr>
<tr>
<td>1250 – 1500</td>
<td>2.5</td>
</tr>
<tr>
<td>1000 – 1250</td>
<td>2.6</td>
</tr>
<tr>
<td>750 – 1000</td>
<td>2.7</td>
</tr>
<tr>
<td>500 – 750</td>
<td>2.8</td>
</tr>
<tr>
<td>250 – 500</td>
<td>2.9</td>
</tr>
<tr>
<td>&lt;250</td>
<td>3.0</td>
</tr>
</tbody>
</table>


### Table 3. Vulnerability values for altimetric amplitude.

<table>
<thead>
<tr>
<th>Altimetric amplitude (m)</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>1.0</td>
</tr>
<tr>
<td>20 – 29.5</td>
<td>1.1</td>
</tr>
<tr>
<td>29.5 – 39</td>
<td>1.2</td>
</tr>
<tr>
<td>39 – 48.5</td>
<td>1.3</td>
</tr>
<tr>
<td>48.5 – 58</td>
<td>1.4</td>
</tr>
<tr>
<td>58 – 67.5</td>
<td>1.5</td>
</tr>
<tr>
<td>67.5 – 77</td>
<td>1.6</td>
</tr>
<tr>
<td>77 – 84.5</td>
<td>1.7</td>
</tr>
<tr>
<td>84.5 – 94</td>
<td>1.8</td>
</tr>
<tr>
<td>94 – 103.5</td>
<td>1.9</td>
</tr>
<tr>
<td>103.5 – 113</td>
<td>2.0</td>
</tr>
<tr>
<td>113 – 122.5</td>
<td>2.1</td>
</tr>
<tr>
<td>122.5 – 132</td>
<td>2.2</td>
</tr>
<tr>
<td>132 – 141.5</td>
<td>2.3</td>
</tr>
<tr>
<td>141.5 – 151</td>
<td>2.4</td>
</tr>
<tr>
<td>151 – 160.5</td>
<td>2.5</td>
</tr>
<tr>
<td>160.5 – 170</td>
<td>2.6</td>
</tr>
<tr>
<td>170 – 179.5</td>
<td>2.7</td>
</tr>
<tr>
<td>179.5 – 189</td>
<td>2.8</td>
</tr>
<tr>
<td>189 - 200</td>
<td>2.9</td>
</tr>
<tr>
<td>&gt;200</td>
<td>3.0</td>
</tr>
</tbody>
</table>


### Table 4. Vulnerability values for terrain slope.

<table>
<thead>
<tr>
<th>Slope (degrees)</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2.0 – 3.3</td>
<td>1.1</td>
</tr>
<tr>
<td>3.3 – 4.6</td>
<td>1.2</td>
</tr>
<tr>
<td>4.6 – 5.9</td>
<td>1.3</td>
</tr>
<tr>
<td>5.9 – 7.3</td>
<td>1.4</td>
</tr>
<tr>
<td>7.3 – 8.6</td>
<td>1.5</td>
</tr>
<tr>
<td>8.6 – 9.9</td>
<td>1.6</td>
</tr>
<tr>
<td>9.9 – 11.2</td>
<td>1.7</td>
</tr>
<tr>
<td>11.2 – 12.5</td>
<td>1.8</td>
</tr>
<tr>
<td>12.5 – 13.8</td>
<td>1.9</td>
</tr>
<tr>
<td>13.8 – 15.2</td>
<td>2.0</td>
</tr>
<tr>
<td>15.2 – 16.5</td>
<td>2.1</td>
</tr>
<tr>
<td>16.5 – 17.8</td>
<td>2.2</td>
</tr>
<tr>
<td>17.8 – 19.1</td>
<td>2.3</td>
</tr>
<tr>
<td>19.1 – 20.4</td>
<td>2.4</td>
</tr>
<tr>
<td>20.4 – 21.7</td>
<td>2.5</td>
</tr>
<tr>
<td>21.7 – 23</td>
<td>2.6</td>
</tr>
<tr>
<td>23 – 24.4</td>
<td>2.7</td>
</tr>
<tr>
<td>24.4 – 25.7</td>
<td>2.8</td>
</tr>
<tr>
<td>25.7 – 27</td>
<td>2.9</td>
</tr>
<tr>
<td>&gt;27</td>
<td>3.0</td>
</tr>
</tbody>
</table>

The vulnerability parameters regarding the soil criterion were evaluated according to the values established in table 5:

**Table 5. Values assigned to ground units.**

<table>
<thead>
<tr>
<th>Soils</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz Sands</td>
<td>3.0</td>
</tr>
<tr>
<td>Yellow Oxisol</td>
<td>1.0</td>
</tr>
<tr>
<td>Red-Yellow Podzolic</td>
<td>2.0</td>
</tr>
<tr>
<td>Strophic Red-Yellow Podzolic</td>
<td>2.0</td>
</tr>
<tr>
<td>Solonetz-Solodized</td>
<td>2.0</td>
</tr>
<tr>
<td>Alluvial soils</td>
<td>3.0</td>
</tr>
<tr>
<td>Lithic soils</td>
<td>3.0</td>
</tr>
</tbody>
</table>


The geological factors and vegetation were also studied, and their parameters were determined according to the lithotype and vegetation mapping units, presented in tables 6 and 7, respectively.

**Table 6. Values assigned to lithotype geology units.**

<table>
<thead>
<tr>
<th>Geology</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Migmatite, Orthogneiss, Paragneiss</td>
<td>1.3</td>
</tr>
<tr>
<td>Orthogneiss</td>
<td>1.3</td>
</tr>
<tr>
<td>Sandstone, Siltite, Shale</td>
<td>2.4</td>
</tr>
<tr>
<td>Sandstone, Shale, Claystone, Siltite</td>
<td>2.4</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.4</td>
</tr>
<tr>
<td>Siltite, Shale, Sandstone</td>
<td>2.7</td>
</tr>
<tr>
<td>Shale, Sandstone, Siltite</td>
<td>2.8</td>
</tr>
<tr>
<td>Schist, Philito</td>
<td>2.0</td>
</tr>
<tr>
<td>Metabasito</td>
<td>2.0</td>
</tr>
<tr>
<td>Debris-Laterite Deposits, Laterite</td>
<td>3.0</td>
</tr>
<tr>
<td>Sand deposits, Gravel deposits, Clay deposits</td>
<td>3.0</td>
</tr>
<tr>
<td>Agglomerate, Laterite, Sand deposits, Clay deposits</td>
<td>3.0</td>
</tr>
<tr>
<td>Gneissic Granodiorite</td>
<td>1.2</td>
</tr>
<tr>
<td>Granodiorite, Granite</td>
<td>1.2</td>
</tr>
<tr>
<td>Sand deposits, gravel deposits</td>
<td>3.0</td>
</tr>
<tr>
<td>Sandstone, Sandy Siltite, Shale, Orthoconglomerate</td>
<td>2.4</td>
</tr>
<tr>
<td>Shale, Sandstone, Conglomerate, Siltite</td>
<td>2.8</td>
</tr>
<tr>
<td>Conglomeratic sandstone, Pelitic rock, Sandstone</td>
<td>2.4</td>
</tr>
</tbody>
</table>


**Table 7. Values assigned to vegetation units.**

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact (Ecotone and Enclave)</td>
<td>2.1</td>
</tr>
<tr>
<td>Deciduous Seasonal Forest</td>
<td>2.2</td>
</tr>
<tr>
<td>Seasonal Semideciduous Forest</td>
<td>1.6</td>
</tr>
<tr>
<td>Savanna</td>
<td>2.1</td>
</tr>
<tr>
<td>Savanna-Steppe</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 8. Values assigned to land use and land cover units.

<table>
<thead>
<tr>
<th>Use and coverage</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Formation</td>
<td>1</td>
</tr>
<tr>
<td>Savannah Formation</td>
<td>2.2</td>
</tr>
<tr>
<td>Country Formation</td>
<td>2.3</td>
</tr>
<tr>
<td>Pasture</td>
<td>2</td>
</tr>
<tr>
<td>Annual Culture</td>
<td>3</td>
</tr>
<tr>
<td>Perennial Culture</td>
<td>2.5</td>
</tr>
<tr>
<td>Urbanization</td>
<td>3</td>
</tr>
<tr>
<td>Exposed Soil</td>
<td>3</td>
</tr>
<tr>
<td>Rocky Outcrop</td>
<td>3</td>
</tr>
<tr>
<td>Mining</td>
<td>3</td>
</tr>
<tr>
<td>Water</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Source: MapBiomas, 2019.

The degree of vulnerability regarding land use and land cover was verified based on the values assigned in Table 8.

The climate variable was determined from the survey of historical data relating to rainfall collected by meteorological stations, within and near the study area, obtained from the National Institute of Meteorology (Inmet, 2021).

The rainfall intensity was calculated from the accumulated annual precipitation and the number of rainy days, converted into months (divided by 30) for a period from 1995 to 2020, as shown in Equation 3 (Crepani et al., 2001):

\[ IP = \frac{\text{Annual rainfall}}{\text{Number of days with rain}/30} \]  

(3)

After quantifying the rainfall intensity at each station, these data were spatialized by the Inverse Distance to Power (IDW) method and reclassified according to Table 9, by QGIS Software 3.8.3 (Qgis development team 2019).

So, from the values of rainfall intensity, the vulnerability of landscapes to soil loss can be verified, as the greater the rainfall, the greater the erosivity, and how this factor is directly related to morphodynamic processes (Crepani; Medeiros; Palmeira, 2004).

Table 9. Values assigned to rainfall intensity.

<table>
<thead>
<tr>
<th>Rainfall intensity (mm/month)</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50</td>
<td>1.0</td>
</tr>
<tr>
<td>50 – 75</td>
<td>1.1</td>
</tr>
<tr>
<td>75 – 100</td>
<td>1.2</td>
</tr>
<tr>
<td>100 – 125</td>
<td>1.3</td>
</tr>
<tr>
<td>125 – 150</td>
<td>1.4</td>
</tr>
<tr>
<td>150 – 175</td>
<td>1.5</td>
</tr>
<tr>
<td>175 – 200</td>
<td>1.6</td>
</tr>
<tr>
<td>200 – 225</td>
<td>1.7</td>
</tr>
<tr>
<td>225 – 250</td>
<td>1.8</td>
</tr>
<tr>
<td>250 – 275</td>
<td>1.9</td>
</tr>
<tr>
<td>275 – 300</td>
<td>2.0</td>
</tr>
<tr>
<td>300 – 325</td>
<td>2.1</td>
</tr>
<tr>
<td>325 – 350</td>
<td>2.2</td>
</tr>
<tr>
<td>350 – 375</td>
<td>2.3</td>
</tr>
<tr>
<td>375 – 400</td>
<td>2.4</td>
</tr>
<tr>
<td>400 – 425</td>
<td>2.5</td>
</tr>
<tr>
<td>425 – 450</td>
<td>2.6</td>
</tr>
<tr>
<td>450 – 475</td>
<td>2.7</td>
</tr>
<tr>
<td>475 – 500</td>
<td>2.8</td>
</tr>
<tr>
<td>500 – 525</td>
<td>2.9</td>
</tr>
<tr>
<td>&gt;525</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Source: Crepani et al. 2001.
After analyzing each component, it was possible to verify the degree of vulnerability based on the proposal by Crepani et al. (2001), having as answer the arithmetic mean of the individual values of each component, expressed in Equation 4:

\[
V = \frac{G + R + S + V_e + C}{5}
\]

On what, \(V\) = potential vulnerability; \(G\) = geological vulnerability; \(Ge\) = geomorphological vulnerability; \(S\) = pedological vulnerability; \(Ve\) = vulnerability to the vegetation theme; \(C\) = vulnerability to the climate theme.

After obtaining potential fragility, an average was made between this variable and soil use and coverage, characterizing emergency fragility. This variable includes, in addition to natural characteristics, the degrees of protection of different types of use and vegetation cover on the environment. With fragility quantified for each use and coverage, a linear regression was carried out between the corresponding fragile area and the area associated with the type of use and coverage, using the R software (R CORE TEAM, 2021).

**Resultados e discussão**

The vegetation in the region (Figure 3) is mainly composed of areas of savanna formation (Savanna and Steppe Savanna). This type of vegetation covers areas of Caatinga and Cerrado that have high temperatures and low water availability (Ivanov et al., 2022). This vegetation cover is associated with the 2.1 vulnerability index, being considered moderately vulnerable (Figure 4). Transition areas (ecotone), which are also significantly present in this portion of Piauí of Seasonal Deciduous and Semideciduous Forest, have the same classification (medium vulnerable), except for the semideciduous formation, which is considered moderately stable.

![Figure 4. Spatial distribution of natural vegetation in the region under study. Source: Adapted from IBGE (2021).](image)

The vegetation typology is the result of factors inherent to the plant biodiversity present in the area, such as density, leaf architecture, diversity and richness of species, and plant height. These features directly affect terrain coverage. In this sense, the presence of vegetation, especially dense vegetation, is a protective factor for the soil against morphogenetic processes that are mainly related to erosion (Fernandes et al., 2022; Rua et al., 2023).

Thus, high vegetation densities imply areas with greater stability and less vulnerability, as observed in the typology of Seasonal Semideciduous Forest, which, as they do not present leaf loss as significant as the deciduous forest, has greater stability (vulnerability = 1.6),...
Vegetation with more open density characteristics, such as savannas, have moderate vulnerability due to the moderate ground cover provided by this forest formation.

The pedological formation of the region is composed of Litholic Soils and Yellow Latosols, mostly, however, it presents Quartz Sands, Red-

Yellow Podzolic, Strophic Red-Yellow Podzolic, Solonetz-Solodized and Alluvial Soils (Figure 5), whose indexes Vulnerability can be seen in Figure 4. The predominant soils have vulnerability classified as stable for Oxisol areas and Vulnerable for Litholic Soils (Figure 4; Table 1)

Figure 5. Spatial distribution of soil classes in the region under study. Source: Adapted from IBGE (2021).

The fragility of soils is given by their erodibility, that is, the soil's ability to resist erosion (Crepani et al., 2001). According to the same authors, this physical characteristic comes from its mineralogical composition, particle size, and chemical and physical conditions, thus, they are determinants in the natural tendency of these pedological formations to suffer erosion.

Oxisols are considered stable soils, with low vulnerability in terms of soil loss, as a result of having characteristics such as good development, high porosity, high depth, and advanced degree of weathering (Matias et al., 2009). On the other hand, Litholic Soils and Quartz Sands are soils considered young and undeveloped, are characterized by presenting a small evolution in their profiles and by not having a B horizon. These soils, as they do not have a well-established structure, present a high degree of fragility (Crepani et al., 2001).

Considering the geological formation, the region has a diversity, such as a migmatite, orthogneiss, paragneiss, orthogneiss, sandstone, siltstone, shale, claystone, siltstone shale, metabasite phyllite, debris-laterite deposits, laterite, sand deposits, gravel deposits, clay deposits, agglomerate, gneissic granodiorite, granodiorite, granite, sandy siltite, orthoconglomerate, pelitic rock, according to the classification shown in Figure 4.

However, there is a predominance of areas of Sandstone, Shale, Claystone, Siltite (Figure 6) and, from the geological lithotype units, lower stability can be observed (vulnerability = 2.4), provided by sedimentary rocks, and that the predominant geological formation of the area is classified as moderately vulnerable (Figure 4; Table 1).
Figure 6. Spatial distribution of geological formations in the region under study. Source: Adapted from IBGE (2021).

According to (Schiavo et al., 2010), sedimentary rocks have a low degree of weathering and originate soils with a texture that varies from medium to sandy. According to Crepani et al. 2001, the weathering process of rocks can occur by chemical decomposition or mechanical disintegration, thus, in addition to the chemical composition of the minerals that make up the rocks, other factors such as particle size, selection, maturity, diagenesis, and lithification must be taken into account so that a certain order of resistance can be established from sedimentary rocks to weathering and erosion.

The relief is mostly poorly dissected (smooth wavy and flat), with a slope of 0 to 6% (flat) and 6 to 12% (smooth wavy), providing a very low to a low degree of vulnerability in some regions (Figure 7). On the other hand, it is possible to observe areas classified as mountainous and rugged, which can be classified with high to very high vulnerability (Figure 5; Table 1).

Figure 7. Spatial distribution of the slope of the region under study. Source: Adapted from USGS (2021).

The altimetric amplitude of the relief is associated with the deepening of the dissection, being considered an indication of the potential energy available for the “runoff”. In this sense, the greater the altimetric amplitude, the greater the potential energy. However, the study area showed...
mostly amplitude ranging from 1.0 to 91.5 (Figure 8), indicating situations of stability to moderately stable as the natural landscape units. According to Yang et al. (2018), the magnitude of the relief is an important factor in the geomorphological description, topographical type, areas susceptible to erosion, and assessment of geological risks and environmental quality. According to Matias; Lupinacci; Nunes (2020), in environments under the imperative of a hot and humid climate, the water discharge resulting from precipitation acts in the sculpting of the relief in a prominent way, serving as a driving force for triggering erosive processes. In this sense, the dynamics of linear erosion processes are associated, among other factors, with the inherent potential of the concentrated flow of surface runoff, and, consequently, with the relief of the location. Thus, topographic forms condition surface runoff, determining flow concentration routes, as preferential lines for the formation and growth of incisions in the terrain. Therefore, in areas characterized by strong susceptibility to erosion, the forms of land use and occupation can strongly contribute to the dynamization of erosion processes.

Figure 8. Altimetric range of the region under study. Source: Adapted from USGS (2021).

The intensity of drainage dissection can be obtained from measurements, performed on topographic maps or satellite images, of the amplitude of interfluves (distance between drainage channels), dissection is less in flat areas usually with low drainage density (Crepani et al., 2001).

Drainage speed indicates the degree of development of the drainage system, that is, it provides an indication of the drainage efficiency of a given location, showing whether the water flow speed is greater or lesser (Souza; Silva, 2022).

The degree of relief dissection or interfluval dimension allows for a morphodynamic assessment of the landscape and the recognition of different patterns of surface roughness (Bertolini; Deodoro, 2018). From the analysis of the interfluval dimension, it was possible to observe that the area corresponding to the region of Piauí in Matopiba has low interfluval values and, consequently, greater dissection intensity, indicating a high degree of vulnerability (Figure 9), which according to Crepani et al. (2001) the lower the value attributed to the interfluval dimension, the greater the degree of dissection of a given relief unit.
From the spatialization of rainfall intensity (Figure 10), it can be observed that between 1995 and 2005 the indices ranged from 215 mm to 405 mm, being classified as moderately stable (vulnerability = 1.7) to moderately vulnerable (vulnerability = 2.5). While between 2010 and 2020 there was a greater variation, from 26 mm being included in the stable vulnerability degree (1.0) to 405 mm considered moderately vulnerable (2.5).

The rainfall intensity is configured as a relevant parameter in the analysis of vulnerability and environmental fragility, as it influences soil losses due to water erosion (Almeida et al., 2012). Because rainfall in the tropical region is considered a meteorological component with high spatio-temporal variability, areas marked by climate extremes are more susceptible to the negative impacts promoted by intense rains (Amorim et al., 2020; Gomes et al., 2021b). In this sense, analyzing the vulnerability of natural and anthropic environments becomes essential for better planning and environmental

management. In general, one way to determine environmental fragility is through integrated analysis, allowing the assessment of the potential and susceptibilities of landscape elements.

Therefore, monitoring deforestation processes and conservation practices, as well as adequate soil management, are essential practices to reduce the chances of soil loss and degradation processes occurring. Thus, aiming to prevent not only economic losses in extreme years, but in some cases reduce the risk of social losses that erosion can cause (Gomes et al., 2021a). Therefore, conservation measures such as slowing down deforestation should be a priority for maintaining soil health, as it would contribute to mitigating the pronounced anthropogenic effects associated with high-intensity climate extremes, preventing possible cases of erosion in the future (Gomes et al., 2021b).

The portion of Matopiba belonging to the state of Piauí has, naturally, environmental fragility ranging from medium to high, that is, the region, due to its integrated natural characteristics of geomorphology, geology, natural vegetation cover, soils and climatic conditions, is predisposed to suffer degradation (Figure 11).

Figure 11. Spatial distribution of the temporal evolution of the potential for fragility to degradation in the region under study.
Source: own.

It is noted that about natural factors in the region (Figure 10), between 1995 and 2005, there is a predominance of fragility classified as high. Over the years, there has been an increase in areas that have low fragility. This situation may be related to the variation in rainfall intensity, given that this factor has a more variable nature compared to the others, as shown in Figure 8, the years 2010 to 2020 have lower intensity, which can cause a decrease in potential frailty. A reduction in total rainfall in the state of Piauí was identified by Fernandes et al. (2020), studying climate data in the state, which can cause a reduction in rainfall intensity.

Souza et al. (2020) mapped the potential environmental fragility in the municipality of Inconfidentes/MG, using both the slope variable (FAPd) and the relief dissection index (FAPidr), and found that the FAPd had a representation of 71% of the municipality, having medium degree of vulnerability, which corresponds to more than 100 km², while the very weak and weak areas make up

a total of 25% of the Municipality, equivalent to 38 km², and only 3% have a strong degree of vulnerability.

Also, according to the authors, FAPidr presented a much larger area, 89% of the municipality, and correspond to a medium degree of vulnerability, which represents 133,542 km². On the other hand, the area that presents potential fragility with the moderate relief dissection index is much larger than that of FAPd, corresponding to 13 km² of the area and 9% of the municipal territory.

The potential fragility, that is, the predisposition that the area has naturally to degradation, can be affected by changing the balance of the landscape by human activities, in this sense, the concept of emergency fragility arises. This is the result of the combination of potential fragility with the variable of land use and vegetation cover (Santos; Marchioro 2020).

Currently, the region has mostly natural forest areas, with savanna and grassland formation in most of the area. However, about land use, there is the presence of agricultural activities (temporary and perennial crops) and pasture (Figure 12).

![Figure 12. Spatial distribution of vegetation cover and land use in the region under study. Source: Adapted from MapBiomas (2021).](image)

As shown in Figure 12, the region has expressive areas dedicated to monoculture and this, as it is an important reference in Brazilian agricultural production, is in growing expansion. In figure 13, it is possible to verify the historical expansion of agriculture in the region, as well as the deforestation of areas of natural vegetation.

![Figure 13. Temporal evolution of areas of forest formation, agriculture and soybean monoculture in the region under study.](image)

In Figure 1, the clear removal of forest formation for the introduction of agriculture can be seen. Between 1985 and 2019, 938,022 hectares of native forest were deforested, corresponding to the deforestation of approximately 13% of the region's forest formation. At the same time, areas destined for agriculture grew by 13,926% over the same years, covering a current area of approximately 962,973 hectares, most of which (83%) were destined for soy production.

It is noteworthy that the contribution of agricultural production in the region to the development of Brazilian agribusiness is evident, in addition to the generation of jobs and income for the local population and the growth of industry and commerce (Araújo et al. 2019).

However, the degradation caused in the Cerrado by this activity has carried out relevant changes in the biome, resulting in excessive deforestation, soil compaction, erosion, siltation of rivers, groundwater contamination, and loss of biodiversity, causing an imbalance in the ecosystem (Santos et al., 2021).

The conversion of native vegetation in extensive deforested areas for monoculture, in addition to contributing to climate change, provides changes in the dynamics between the vegetation and the atmosphere, including the modification in the surface radiation and energy balance, and, consequently in the surface temperature, air humidity, evapotranspiration, albedo, and gas exchange processes, due to the constant modification of the leaf architecture of the vegetation (Roriz et al., 2017). In addition to leaving the surface uncovered or with insufficient coverage, enabling the action of erosive mechanisms with greater intensity, allowing the degradation of the soil surface.

In this context, when analyzing emergency fragility, it is observed in its spatial characterization, available in Figure 14, the evident relationship of this variable with the expansion of agricultural areas.

![Figure 14. Spatial distribution of the temporal evolution of emergency fragility to degradation in the region under study. Source: own.](image)

In 1995 and 2000 it appears that most of the region has emergency fragility classified as average, which correspond to 65 and 67% of the total area, respectively (Table 10). Over the years, the establishment and expansion of areas with colors ranging from red to orange can be observed.
indicating the introduction of areas of high and very high vulnerability.

Table 10. Areas of vulnerability to degradation classes (%) in Matopiba.

<table>
<thead>
<tr>
<th>Year</th>
<th>Very Low</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>0.1</td>
<td>4.4</td>
<td>65.3</td>
<td>29.9</td>
<td>0.3</td>
</tr>
<tr>
<td>2000</td>
<td>0.1</td>
<td>4.5</td>
<td>66.7</td>
<td>28.4</td>
<td>0.3</td>
</tr>
<tr>
<td>2005</td>
<td>0.1</td>
<td>4.5</td>
<td>63.0</td>
<td>32.0</td>
<td>0.4</td>
</tr>
<tr>
<td>2010</td>
<td>0.3</td>
<td>4.3</td>
<td>63.2</td>
<td>31.9</td>
<td>0.3</td>
</tr>
<tr>
<td>2015</td>
<td>1.2</td>
<td>3.2</td>
<td>63.7</td>
<td>31.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2020</td>
<td>1.0</td>
<td>3.6</td>
<td>61.0</td>
<td>33.9</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Source: own.

The appearance of areas with this level of vulnerability is associated with the expansion of agriculture, a type of land use that has vulnerability level 3 (Figure 4) and that predisposes the soil to degradation processes with greater intensity than other types of use. As shown in Table 2, areas of high and very high fragility increased by 4 and 0.3%, corresponding to 323,527 and 21,737 hectares, between 1995 and 2020, respectively. As it is constantly expanding, as shown by the Annual Report on Deforestation in Brazil (Mapbiomas, 2020), in 2020 Piauí reached the highest rate of deforestation for conversion to agriculture in Brazil, thus highlighting the importance of adequate environmental planning, aiming at soil conservation and biodiversity present in the region's biome.

Agricultural expansion areas in Matopiba are directly related to the configuration of a very high vulnerability and inversely related to the presence of native vegetation (Figure 15). Thus, the importance of environmental and natural resource management in this portion of Piauí is highlighted since disorderly deforestation intensifies the fragility of soils.

![Figure 15. Linear regression between agricultural area (km²) and emergency areas vulnerable to degradation (km²) in the region under study. Source: own.](image)

It is worth mentioning that deforestation and the use of non-conservationist management of agricultural soils have numerous impacts on the environment, including reduced biodiversity, soil degradation, siltation of watercourses, among others (Cuiabano et al., 2017). In this sense, the resulting emergency fragility is reinforced, especially in areas with mountainous and rugged relief, as is the case in the region analyzed in this study, in addition to identifying high vulnerability in areas with both more unstable and sandy soils such as soils, lithologic, how much of deeper and more stable soils such as oxisols. Roriz et al. (2017) when studying the impacts of agricultural expansion in the Matopiba region on the surface radiation balance, emphasize that changes in natural vegetation in Piauí are promoting a decrease in energy availability and an increase in surface temperature, thus ensuring an alteration of surface energy fluxes and an alteration in ecosystem dynamics. The identification of highly susceptible areas in Matopiba was also carried out by Vieira et al. (2021), where they found about 4700 km² of areas under strong signs of degradation, occurring mainly in areas destined for pastures.

As already emphasized, unsustainable practices related to agricultural and commercial development in the region, such as inadequate soil management, replacement of forest by monoculture and anthropogenic activities, is increasing vulnerable areas to soil degradation, predisposing the region to social and environmental impacts and economical. In this sense, with the growing and eminent agricultural expansion of Matopiba, it is necessary to adopt conservation practices such as the use of the direct planting system, crop rotation, crop-livestock-
forest integration systems, among others, in addition to inspection environment aiming at the preservation of permanent preservation and environmental protection areas, so that the environmental impacts caused by this development can be mitigated.

Conclusions

Agriculture in Matopiba has been growing and developing in recent years. This has led to an intensification of changes in land use and occupation, demanding an increase in soil vulnerability and causing environmental degradation in the area, mainly due to the removal of areas of native vegetation to expand the cultivation of monocultures, such as soybeans and corn. Thus, environmental policies for the conservation of native vegetation areas and monitoring of environmental damage caused by the expansion of crops or other human activities occurring in the region must be implemented to use practices designed to mitigate the effects of human activities on fragility of soils and the preservation of biodiversity and local natural resources, contributing to the conservation of the local environment and the quality of life of the local population.

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