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ANÁLISE DE INDICADORES GEOAMBIENTAIS DE SUSTENTABILIDADE NA AMAZONIA PARAENSE, BRASIL

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ABSTRACT

The recent urban expansion in the Amazonian state of Pará has deepened the effects of climate change, while also imposing social and environmental challenges resulting from inadequate land use planning policies. Furthermore, an integrated assessment of the impacts of human activities and government actions in the region remains limited, mainly due to the scarcity of research based on geoenvironmental sustainability indicators (GEIs). Thus, this study aims to assess the GEIs in the municipality of Barcarena, state of Pará, from 2000 to 2010 with the purpose of identifying the main environmental and socioeconomic effects, as well as offering subsidies for territorial planning and the formulation of public policies oriented towards sustainable development. Therefore, data from the Brazilian Institute of Geography and Statistics (IBGE) were used, which have been associated with geoprocessing techniques to evaluate indicators related to water supply, sewage treatment, and solid waste management. Its adopted timeframe results from the unavailability of updated microdata from the 2022 Demographic Census at the time of research. Results indicate important advances in promoting environmental sustainability in Barcarena. However, its inequalities and areas with precarious infrastructure persist, especially in the most peripheral districts and those far from the urban center where vulnerabilities are most evident. In this context, this research contributes to monitoring the goals of the 2030 Agenda and assisting the achievement of the Sustainable Development Goals in Amazonian territories deeply marked by historical trajectories of vulnerability and intense socio-environmental transformations.

Keywords: Environmental Management; Sustainable Development; Agenda 2030.

RESUMO

A recente expansão urbana na Amazônia Paraense tem aprofundado os efeitos das mudanças climáticas, ao mesmo tempo em que impõe desafios sociais e ambientais decorrentes da inadequação das políticas de ordenamento territorial. Além disso, na região, permanecem limitadas as avaliações integradas dos impactos das atividades humanas e das ações governamentais, especialmente pela escassez de investigações baseadas em indicadores geoambientais de sustentabilidade (IGAS). Assim, o presente estudo busca analisar os IGAS no município de Barcarena, estado do Pará, de 2000 a 2010 com o propósito de identificar os principais efeitos ambientais e socioeconômicos, assim como oferecer subsídios para o planejamento territorial e a formulação de políticas públicas orientadas ao desenvolvimento sustentável. Dessa forma, foram utilizados dados do Instituto Brasileiro de Geografia e Estatística (IBGE), associados às técnicas de geoprocessamento, para avaliar indicadores relativos ao abastecimento de água, tratamento de esgoto e gestão de resíduos sólidos. A delimitação temporal adotada resulta da indisponibilidade de microdados atualizados do Censo Demográfico de 2022 até o momento da pesquisa. Resultados apontam avanços importantes na promoção da sustentabilidade ambiental em Barcarena. Entretanto, ainda há desigualdades internas e zonas com infraestrutura precária, sobretudo nos distritos mais periféricos e afastados do centro urbano, onde fragilidades são mais evidentes. Nesse contexto, a presente investigação contribui para o monitoramento das metas da Agenda 2030 e fortalece a articulação dos Objetivos de Desenvolvimento Sustentável em territórios amazônicos profundamente marcados por trajetórias históricas de vulnerabilidade e intensas transformações socioambientais.

Palavras-chave: Gestão Ambiental. Desenvolvimento Sustentável. Agenda 2030.

INTRODUTION

An intensification of the effects of climate change, coupled with a disorderly advance of urbanization, has caused profound transformations in socio-environmental dynamics, exerting direct repercussions on the planning and management of regional development (Feil; Schreiber, 2017). In the Amazon, conflicts between economic expansion, environmental conservation and social justice are becoming increasingly evident, since the region is home to ecosystems especially vulnerable to human intervention. Understanding and addressing such conflicts, as pointed out by Ribeiro et al. (2024), requires an integration of ecological, social and spatial aspects, especially in territories where historical inequalities impose the need for sensitive approaches to local diversity.

The municipality of Barcarena, located in the metropolitan mesoregion of Belém, Pará, is a clear example of this scenario. In this context, the presence of large industrial enterprises, associated with population growth, coexists with precarious urban infrastructure and sanitation services, which in turn increases impacts on natural systems (Piratoba et al., 2017). This reality reflects in the degradation of forest areas, the contamination of water resources, and the exposure of vulnerable communities to imminent health risks.

Barcarena's insertion into global production chains through the port of Vila do Conde, the Tucuruí hydroelectric plant and the Albrás-Alunorte industrial complex further accentuates socio-environmental pressures (Carmo; Costa, 2016). Among the most significant effects are the compromise of water quality by industrial effluents, in addition to negative impacts on biodiversity and public health (Paz et al., 2011). The situation is aggravated by accelerated urban expansion, which leads to the loss of vegetation cover and lowering the resilience capacity of ecosystems (Ribeiro et al., 2024).

Given these complex dynamics, there must be analyses capable of capturing the transformations underway and guiding public intervention strategies based on principles of sustainability and equity. In this sense, Geoenvironmental Sustainability Indicators (GEIs) emerge as a highly relevant analytical tool, as they enable an integrated assessment of interactions between society and the environment, revealing patterns of use of natural resources and levels of impact on ecosystems.

According to Kazak et al. (2017), IGAS couple variables associated with water quality and availability, waste management, land use and energy use, thus offering an overview of environmental conditions and development models in certain geographic contexts. Its analytical structure contributes to environmental monitoring in territorial analyses, in addition to favoring the improvement of regional planning and the strengthening of local institutional capacities.

Furthermore, IGAS aids to address territorial inequalities, help mitigate climate vulnerabilities, and strengthen environmental planning practices. In municipalities such as Barcarena, characterized by intense exploitation of natural resources and ongoing structural deficiencies, such analytical instruments provide essential support for devising public decisions encompassing ecological boundaries in alignment with socio-territorial singularities. In this context, the link between IGAS and the Sustainable Development Goals (SDGs) of the 2030 Agenda increases their relevance in devising local agendas guided by sustainability.

Thus, this research is based on the following guiding question: how can IGAS support territorial planning and guide public policies aimed at socio-environmental sustainability in contexts marked by structural inequalities, as it is the case of the municipality of Barcarena-PA? Based on this question, the GEIs of the municipality are assed within the period ranging between 2000 and 2010. The choice of this timeframe is due to the availability of systematized and comparable data at the time the research was

being conducted, since results from the 2022 Demographic Census had not yet been fully released, which hindered the addition of more up-to-date information.

THEORETICAL PERSPECTIVES ON SUSTAINABILITY AND PLANNING

Discussions about the Legal Amazon region regarding sustainability and territorial planning take on peculiar detours, since its socio-environmental complexity and occupation trajectory require integrated approaches considering its ecological, cultural and economic diversity. Thus, GEIs are regarded as relevant instruments for the analysis of local and regional dynamics, contributing to diagnose patterns of use of natural resources and identify socio-environmental vulnerabilities with the view of developing public policies aimed at reducing inequalities and turn to more sustainable development models.

GEOENVIRONMENTAL SUSTAINABILITY INDICATORS: CONCEPTS AND APPLICATIONS

The concept of sustainability, though widely disseminated, remains polysemic and subject to ongoing theoretical debates (Pombo; Jacobi, 2024). Broadly, it denotes development that meets present needs without compromising future generations, as defined in the Brundtland Report (CMMAD, 1987). However, this framework lacks tools for territorial application, making sustainability indicators essential for bridging technical-scientific knowledge and public action.

In this context, IGAS stand out by integrating environmental, social, and spatial data in territorial analyses. Veiga (2009) emphasizes their capacity to accurately express the interrelations between ecological systems and human actions, enabling continuous assessments of environmental quality. Kazak et al. (2017) further note their particular applicability at the regional scale, encompassing variables such as water availability and quality, waste management, land use, pollutant emissions, and access to urban infrastructure.

Beyond monitoring environmental degradation, IGAS provide an empirical foundation for territorial planning. Soligo (2012) highlights that integrated indicators clarify the relationships between anthropic pressures and ecosystem carrying capacity, supporting planning across multiple scales. In this regard, the Sustainability Barometer (Prescott-Allen, 1995) is notable for articulating ecological and social indicators, facilitating the identification of disparities and critical areas in the Amazon, thereby informing public policy.

SUSTAINABLE DEVELOPMENT IN THE LEGAL AMAZON REGION: CHALLENGES AND CONFLICTS

The Legal Amazon, consisting of nine states and approximately 60% of the Brazilian territory, is one of the greatest challenges to consolidate strategies aimed at sustainable development. Despite having a significant share of global biodiversity, the region copes with intense social inequalities, structural deficiencies in sanitation services and occupation processes often characterized by territorial disorganization (Brites Figueiredo et al., 2024).

Public policies historically directed at the Amazon have prioritized economic integration through intensive natural resource exploitation, often neglecting local socio-environmental specificities (Becker, 2005). Programs such as the National Integration Plan (PIN) and, more recently, the Sustainable Amazon Plan (PAS) have proposed distinct development models, yet yielded ambiguous outcomes in terms of social inclusion and environmental preservation. As Bunker (1985) contends, resource extraction in frontier economies tends to generate immediate gains, with benefits accruing to external regions, thereby perpetuating environmental degradation and persistent social inequalities.

In recent years, however, several authors have advocated a shift in development strategies concerning the studied region, which are marked by local production arrangements, valorization of traditional knowledge, biotechnology, bioeconomy and environmental fairness (Nobre; Nobre, 2019; Ribeiro et al., 2024). Such perspectives require the development of diagnostic bases capable of understanding ongoing territorial dynamics, as well as the environmental and social impacts arising from urbanization and industrialization processes.

In this scenario, the use of GEIs in the context of the Amazon emerges as a promising alternative by offering support to develop regional public policies based on empirical data and methodologies able to be replicated. As highlighted by Silva Júnior et al. (2023), the development of indicators adjusted to local realities constitutes an indispensable condition for guiding public interventions capable of simultaneously addressing ecological preservation and social demands, thus promoting more equitable and sustainable forms of development.

ENVIRONMENTAL ASSESSMENT AND LAND USE PLANNING

The relationship between environmental assessment and land use planning is central to the formulation of public policies oriented toward sustainability. Environmental assessment involves systematizing and analyzing information on the natural and anthropic components of a territory to identify pressures, vulnerabilities, and potential (Gonçalves, 2001). Land use planning, in turn, entails coordinated actions to organize spatial use in alignment with the social, economic, and environmental objectives established by a given society.

In Brazil, territorial planning gained normative support through the enactment of the 1988 Constitution and the establishment of legal frameworks, such as the City Statute (Law No. 10,257/2001). However, its implementation faces obstacles related to institutional barriers, lack of integrated data and limitations between different scales. Such vulnerabilities are particularly heightened in areas of the Legal Amazon, where dispersed occupations and discontinuities in the provision of public services predominate.

In this context, GEIs can play a structuring role by enabling an integrated assessment of the territory and assisting decisions regarding urban expansion, the allocation of infrastructure, and the conservation of areas of environmental interest. As highlighted by Robati and Rezaei (2022), indicators adjusted to an urban-peripheral context allow assessing the efficiency of environmental and territorial management policies, in addition to contributing both to the development of master plans and the review of ecological-economic zoning.

PUBLIC POLICIES AND REGIONAL SUSTAINABILITY

In addition to technical assessment, the development of sustainable public policies requires ongoing social participation and recognition of multiple Amazonian territorialities. As highlighted by Sachs (2004), it is a complex process comprising ecological, economic, social, cultural and political-institutional dimensions, which also require interdisciplinary approaches and sensitive methodologies to the diversity of knowledge, in which social participation is affirmed as an indispensable component to produce legitimate and sustainable solutions.

In this context, environmental governance directly depends on strengthening local analysis, planning, and monitoring capabilities. As argued by Ribeiro et al. (2024), the adoption of integrated indicators, such as GEIs, contributes to enhance local institutions, thus promoting the development of a political culture oriented towards sustainability. These indicators produce evidence on socio-environmental inequalities and unsustainable patterns of using natural resources, assuming a strategic role in reformulating public policies.

In the Amazon, recent initiatives demonstrate the potential of indicator systems to support intergovernmental agreements, foster international cooperation, and promote sustainable territorial development. Notable among these are the Climate Observatory and MapBiomas, which have facilitated the generation and dissemination of qualified data, enhanced civil society participation, and strengthened public managers' responsiveness to complex environmental challenges. In this context, consolidating participatory and informed decision-making is essential for advancing public policies that integrate environmental preservation, social justice, and sustainable development in the region.

MATERIAL AND METHODS

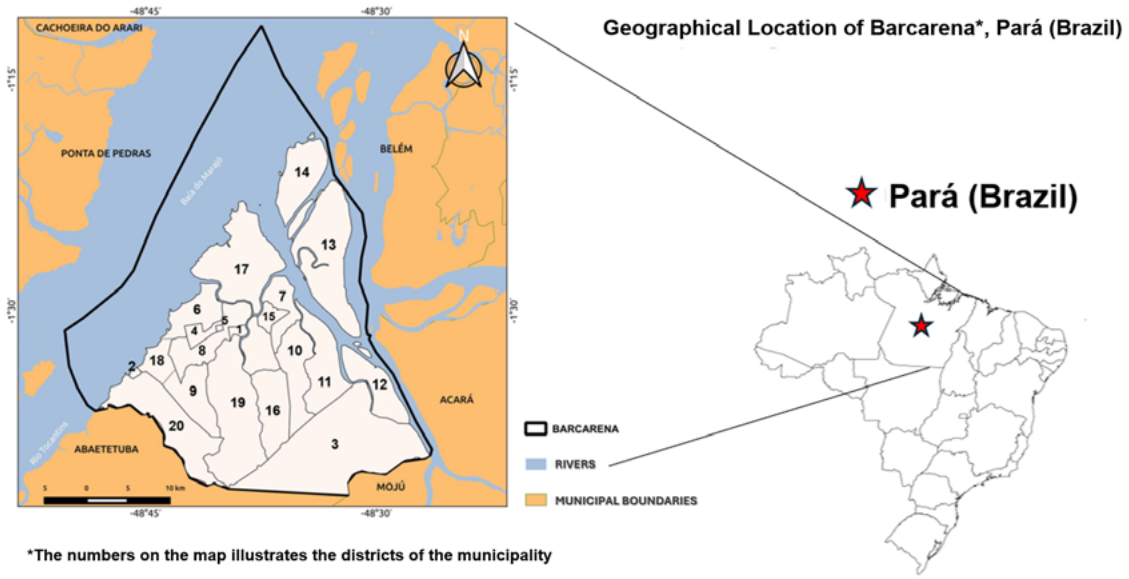
This assessment adopts a mixed methodological approach combining secondary data from the Brazilian Institute of Geography and Statistics (IBGE), thematic maps produced by the TerraClass Project and geoprocessing techniques. The set of procedures employed enables an integrated assessment of environmental and socioeconomic conditions of the area under investigation. The choice of Barcarena as an empirical site is explained by its strategic position in the Amazon context, once it is marked by intense productive activities, ecological vulnerabilities and social inequalities, thus constituting an exemplary site of contradictions and potentialities inherent to development in bordering areas.

STUDY LOCATION

The municipality of Barcarena is located in the Northern region of Brazil at latitudes between 1° 34' 18.6" S and 1° 35' 22.58" S and longitudes between 48° 42' 56.08" W and 48° 46' 11.74" W, and average altitude of 9 meters above sea level (Figure 1). According to data from the Brazilian Institute of Geography and Statistics (IBGE, 2024), its population consists of 126,650 inhabitants residing in an area of 1,310.4 km², whose population density is approximately 96.6 inhabitants per km².

According to Figure 1, Barcarena is composed of the following districts: Headquarters (1), Murucupi (2), Guajarauna (3), Vila Itupanema (4), Vila dos Cabanos (5), Laranjal Neighborhood (6), Cafezal (7), Jupariquara (8), São Vicente (9), Guajará do Icaraú (10), São Mateus Island (11), Arapari Island (12), Onças Island (13), Arapiranga (14), Vila São Francisco (15), CDI (16), Trambioca Island (17), Industrial District (18), Nova Santarém (19) and Castanhalzinho (20). Each of them has distinct characteristics and contributes to the socioeconomic and environmental diversity of the region.

Figure 1 | Barcarena and geographical distribution of its districts, territorial configuration and geographical extent of the study area



Source: The authors (2024)

According to the Köppen-Geiger climate classification, the region has a rainy tropical climate of the Afi type, with an average annual rainfall of around 2500 mm throughout the year (Silva Júnior et al., 2023). Its predominant vegetation is tropical forest, in addition to dense forests in higher areas, floodplain vegetation in floodplain areas and secondary forests. (Ribeiro *et al*., 2013).

The region geology encompasses the sedimentary basin of the mouth of the Amazon River characterized by the Barreiras Group, which is composed of sandstones, claystones and conglomerates formed in unstable coastal and marine environments, in addition to more recent and unconsolidated sediments (Rossetti et al., 1989). Among its predominant soils, the dystrophic Yellow Latosol, the Hydromorphic Podzol and the Lateritic Concretionary stand out with expressive variations in texture. (Cohen et al., 2007).

According to the Pará Economic Development Company (Condec, 2024), Barcarena plays a relevant role as an industrial hub in the state, with emphasis on the processing and export of kaolin, alumina, aluminum, and cables for power supply. The municipality is also home to the largest harbour in Pará, the Harbour of Vila do Conde, which is considered strategic for mining, metallurgical and port activities in the region (Paz et al., 2011). Although the local economy is rooted in agriculture and artisanal fishing, a process of diversification has been observed, which expands to tourism and industrial sectors, such as petrochemical and fertilizer production industries, boosting economic growth for both the municipality and the state of Pará.

METHODOLOGY

This research was carried out coupling a bibliographic search with the use of specific formulas to calculate indicators related to water supply, sanitation and waste disposal. The development of GEIs was based on Prescott-Allen's Barometer of Sustainability (1995), i.e. a method integrating assessments of ecosystems and human systems into a single assessment tool. According to Robati and Rezaei (2022), it allows selecting indicators adjusted to the context being analyzed, thus offering a clear and adaptable representation of progress towards sustainability.

FIELD RESEARCH

A map of Barcarena was created using georeferenced data provided by IBGE (2010). The census sectors were selected and grouped into districts using vector data from the TerraClass Project and the QGIS 2.18 software according to the territorial specificities of the municipality under analysis (Figure 1). The TerraClass Project, developed by the Amazon Regional Center (CRA), aims to qualify deforestation in the Brazilian Legal Amazon and provide support for understanding the forms of land use and land cover in the region. Its database is composed of deforestation areas mapped and published by the PRODES Project, which has been monitoring the Brazilian Amazon Rainforest through satellite images since 1988, under the coordination of the National Institute for Space Research (INPE). (Almeida et al., 2016).

Data were arranged and classified using the natural breaks algorithm adapted from Chen et al. (2013) with the aim of reducing the internal variance of classes and easing the visualization of the spatial distribution of variables.

IBGE census data on the years 2000 and 2010 have been systematized in tables so as to allow temporal comparisons and enable an analysis of the evolution of geoenvironmental sustainability indicators in Barcarena. This timeframe was selected based on the availability of information sorted by census sectors, once it is an essential requirement for using the adopted methodology. Although such selection does not represent the most current scenario, it is the most recent set of data systematized on a scale compatible with the proposed approach, thus ensuring consistency and comparability between the districts under analysis.

Once the 2022 Census was done, new analytical possibilities could be explored, although a complete release of microdata is still underway, which impedes its immediate use. Thus, the alternative of using data from 2000 and 2010 remains the most appropriate for assessments requiring spatial detail. Such timeframe enables to outline an evolutionary panorama of local sustainability and supports future regional planning strategies.

The variables assessed include: permanent private households (V002); those with water supply from the general network (V012); supply via well or spring on the property (V013); rainwater stored in a cistern (V014); other water supply methods (V015); households with an exclusive bathroom or

toilet (V016); sewage discharged into the general sewer or rainwater network (V017); septic tank disposal (V018); rudimentary cesspit (V019); ditch disposal (V020); dumping into rivers, lakes, or the sea (V021); other drainage types (V022); waste collection (V035); collection by cleaning services (V036); collection via service dumpsters (V037); waste incinerated on the property (V038); buried on the property (V039); disposed of on vacant land or public areas (V040); dumped into rivers, lakes, or the sea (V041); and other waste disposal methods (V042).

CALCULATION OF GEIS

The GEIs calculation was performed based on the following procedures:

Step 1: Calculation of Each Individual Indicador

Specific equations were devised in order to calculate each individual sustainability indicator in each district for each component (water, sewage and waste).

Water supply (Eq. 1):

$$Water\ Indicator = \frac{(AGERAL + APOCO - AOUTRA)}{TP} \quad \text{Eq. 1}$$

Where: AGERAL: Water supplied by the municipality's general water supply network; APOCO: Water supplied by artesian well; AOUTRA: Other forms of water supply; TP: Total number of properties.

Sewage treatment (Eq. 2):

$$Sewage\ Indicator = \frac{(3 \cdot ESG\_GERAL + 2 \cdot ESG\_FOSS - ESG\_RUD - 2 \cdot ESG\_OUT)}{TP} \quad \text{Eq. 2}$$

Where: ESG_GERAL: Sewage dumped through the municipality's general sewer network; ESG_FOSS: Sewage dumped into a cesspit; ESG_RUD: Sewage dumped into a rudimentary cesspit; ESG_OUT: Sewage dumped through other forms; TP: Total number of properties.

Waste disposal (Eq. 3):

$$Waste\ Indicator = \frac{(3 \cdot RES\_COL - 3 \cdot RES\_TERR - 2 \cdot RES\_OUT)}{TP} \quad \text{Eq. 3}$$

Where: RES_COL: Collected waste; RES_TERR: Waste dumped onto plots of land; RES_OUT: Other disposal methods; TP: Total number of properties.

Step 2: Classification of Sustainability Levels

The sustainability levels adopted herein are in accordance with the Prescott-Allen Barometer of Sustainability (1995), which organizes data on a scale of 0 to 1 (Table 1). Lower values indicate a greater degree of unsustainability, while higher values reflect more sustainable conditions. Such classification allows an integrated assessment of environmental and social aspects of the districts under analysis, thus facilitating a comparison between different periods and areas.

Table 1 | Sustainability levels, according to the Prescott-Allen barometer of sustainability (1995)

LEVEL OF SUSTAINABILITY	ESTIMATED RANGE
Unsustainable	0 – 0.25
Potentially Unsustainable	0.26 – 0.50
Intermediate	0.51 – 0.70
Potentially Sustainable	0.71 – 0.85
Sustainable	0.86 - 1

Fonte: The authors (2024)

Step 3: Classification of Districts

After determining each individual indicator, districts were classified according to values obtained by taking into account the sustainability levels shown in Table 1. Maps of each level were prepared in order to present each indicator individually (water, sewage and waste) for each district.

Step 4: Calculation of each Geoenvironmental Sustainability Indicator (Eq. 4)

The weighted average formula of each individual indicator (water, sewage and waste) was used to calculate the Geoenvironmental Sustainability Indicator:

$$IGAS = \frac{\Sigma\, Individual\ Indicator}{n} \qquad \text{Eq. 4}$$

Where n = 3, is the number of indicators (water, sewage and waste).

RESULTS AND DISCUSSION

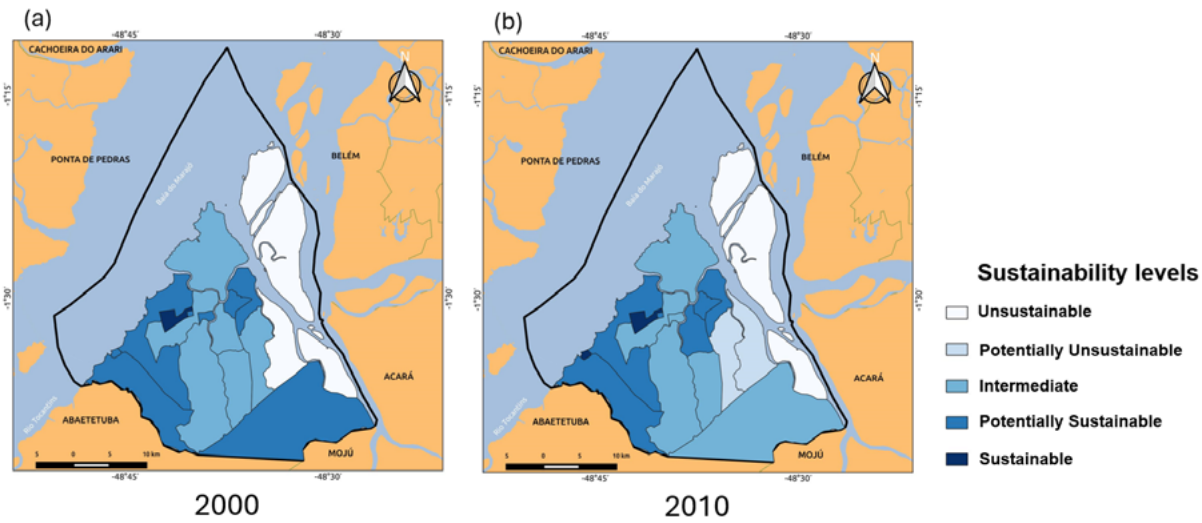
The results of GEIs are going to be presented as follows by covering aspects related to water supply, sewage treatment and solid waste management in the districts of the municipality of Barcarena, Pará.

INDIVIDUAL SUSTAINABILITY INDICATORS CLASSIFIED BY DISTRICT

According to the Barometer of Sustainability methodology, an assessment of indicators allowed an integrated analysis of ecological and human conditions regarding sustainable development in the region. Figure 2 shows the evolution of the level of water resource sustainability in Barcarena, Pará, from 2000 to 2010.

An analysis of maps shown reveals significant changes in the sustainability of water resources over the decade under consideration. In 2000 (Figure 2a), a significant area of the municipality was classified as “Unsustainable” or “Potentially Unsustainable”, highlighting significant flaws in water resource management and supply infrastructure. Areas classified as unsustainable were scattered throughout its territory, revealing an uneven distribution of water supply services.

Figure 2 | Evolution of the level of water sustainability in Barcarena (2000- 2010)



Fonte: The authors (2024)

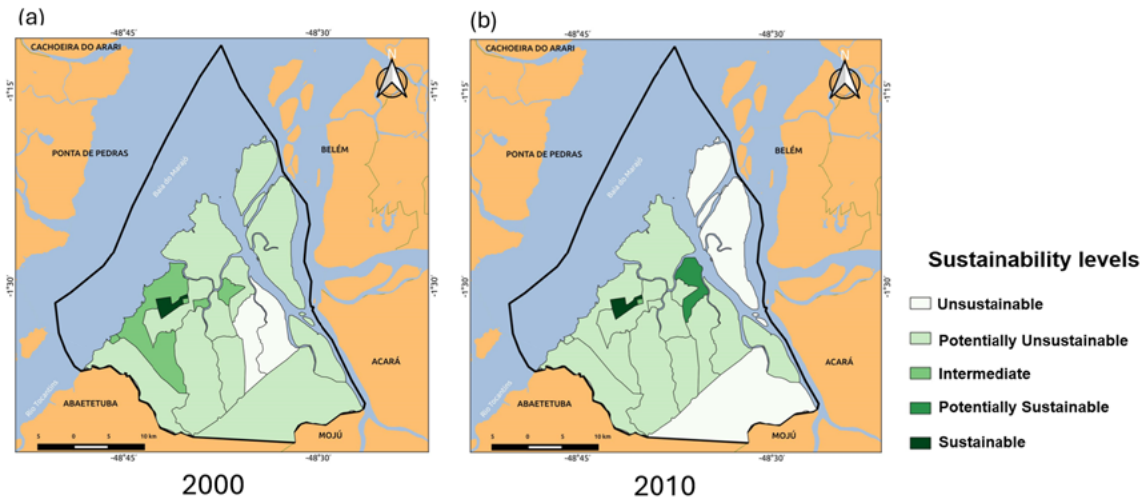
The 2010 map (Figure 2b) indicates that areas previously classified as unsustainable are now classified as “Intermediate”, “Potentially Sustainable” or “Sustainable”, demonstrating advances in public policies and interventions aimed at improving water supply and basic sanitation infrastructure.

There was an expansion of areas classified as “Potentially Sustainable” and “Sustainable”, resulting from investments that have increased access to drinking water and contributed to improving the quality of life of the local population. As shown in Figure 2b, the territories classified as sustainable have become more extensive, encompassing a large area of the municipality and suggesting a more efficient and reasonable water resources management. However, despite the progress achieved, areas remain at intermediate or potentially unsustainable levels, revealing that the path to consolidating full sustainability still requires continuous efforts and strategies aimed at overcoming the remaining challenges.

Figure 3 shows the evolution of the sustainability level of sewage treatment in Barcarena, Pará, between 2000 and 2010.

The 2000 map (Figure 3a) indicates that most of the territory was classified as ‘Unsustainable’ or ‘Potentially Unsustainable’, with few areas in satisfactory condition. By contrast, the 2010 panorama (Figure 3b) reveals a notable shift, with expanded areas classified as ‘Intermediate’ and ‘Potentially Sustainable’. This evolution reflects improvements in sewage treatment driven by public policies and infrastructure investments. The trajectory is favorable, enhancing both population quality of life and local ecosystem preservation—key elements for advancing toward a sustainability-based development model.

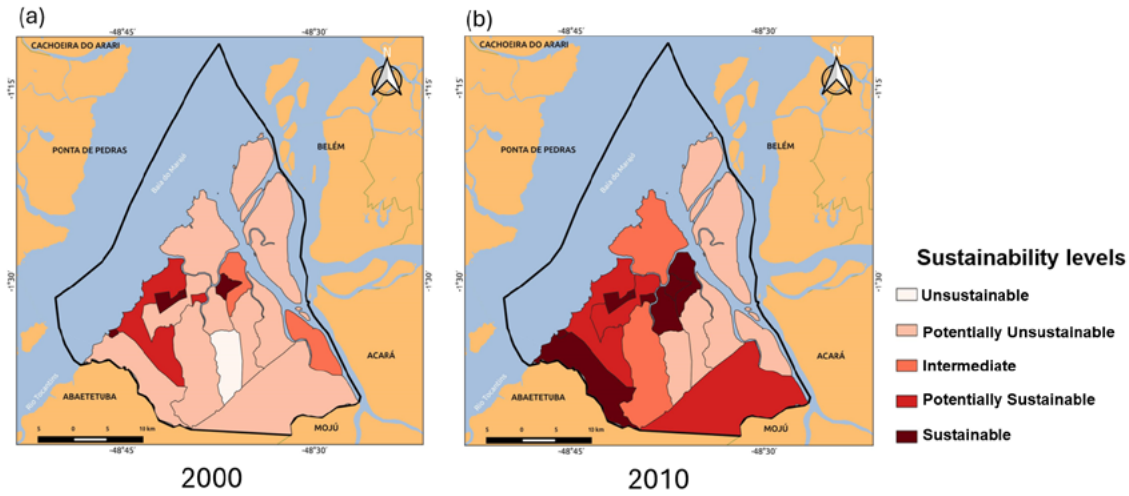
Figure 3 | Evolution of the level of sewage treatment in Barcarena (2000- 2010)



Fonte: The authors (2024)

Figure 4 shows the evolution of the sustainability level in waste management in Barcarena, Pará, between 2000 and 2010.

Figure 4 | Evolution of sustainability in waste management in Barcarena (2000- 2010)



Fonte: The authors (2024)

In 2000 (Figure 4a), most areas of the municipality were classified as “Unsustainable” or “Potentially Unsustainable”, and few areas reached an “Intermediate” level. In contrast, the 2010 map (Figure 4b) reveals significant progress, as several areas have reached “Intermediate”, “Potentially Sustainable” and “Sustainable” levels. Such progress indicates improvements in waste management, as well as reflecting progress in solid waste management policies and greater investment in infrastructure for adequate waste collection and disposal in the municipality.

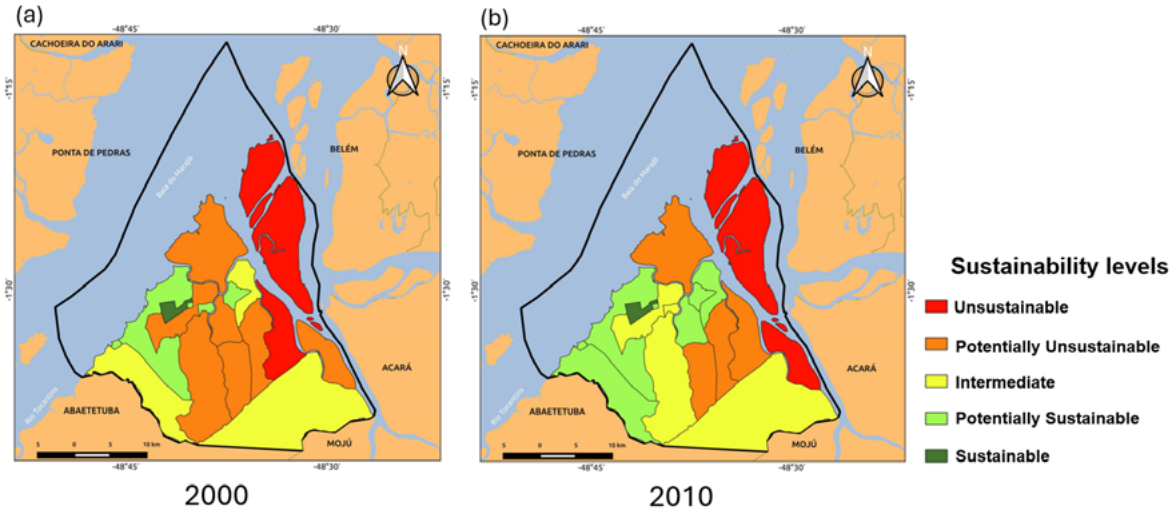
The maps in Figures 2, 3 and 4 show the effects of public policies and investments in infrastructure, which have led to improvements in sustainability indicators in the municipality. Although some progress was actually achieved, there are still areas requiring undivided attention to reach more appropriate sustainability levels.

The obtained results emphasize the importance of integrated environmental management, as well as the need for developing public policies aimed at ensuring long-term sustainable development, in addition to simultaneously promoting improvements in the quality of life of the local population and preservation of natural resources.

GEOENVIRONMENTAL SUSTAINABILITY INDICATORS OF EACH DISTRICT OF BARCARENA

The weighted average equation of each individual indicator (water, sewage and waste) was used to calculate the GEIs. Figure 5 shows the evolution of the GEIs in Barcarena, Pará, between 2000 and 2010.

Figure 5 | Evolution of GEIs in Barcarena (2000-2010)



Fonte: The authors (2024)

According to Figure 5a, a large are of the municipality was classified as “Unsustainable” or “Potentially Unsustainable”, but few areas reached “Intermediate” or higher levels in 2000. In 2010 (Figure 5b), an improvement in sustainability indicators became evident, as several areas progressed to the “Intermediate”, “Potentially Sustainable” and “Sustainable” categories. Such evolution indicates an advance in public policies, greater environmental awareness and investments in infrastructure and environmental management. However, there are still areas at alarming levels, pointing out that there must be greater efforts to promote sustainability throughout the region.

By analyzing the 19 districts of Barcarena in 2010 (Figure 5b), it is observed that 36.8% of the municipality is classified as potentially unsustainable, indicating a need for significant interventions. Additionally, 26.3% of the areas fall into the intermediate category, reflecting moderate sustainability that still requires improvement. Potentially sustainable areas account for 21.1% of the municipality, suggesting generally good environmental conditions but with room for further progress

Only 10.5% of the areas are classified as sustainable, indicating an excellent state of sustainability. Conversely, 5.3% of the territory is considered unsustainable, highlighting critical regions that demand immediate environmental recovery actions. This distribution underscores the diversity of sustainability conditions within Barcarena and emphasizes the need for environmental management strategies tailored to the specific characteristics of each area.

GEIS IN BARCARENA–PA: ADVANCEMENTS, LIMITATIONS AND PERSPECTIVES

The results of this study reveal advancements in Barcarena's environmental performance between 2000 and 2010, indicated by an improvement of indicators concerning water supply, sewage treatment and solid waste management. These observed advances reflect efforts linked to the expansion of urban and environmental infrastructure, although they were made unevenly among districts composing the municipality.

Nevertheless, an assessment of indicators reveals structural flaws and a significant gap in the production and provision of environmental data, which compromise the management of natural resources and hinder urban planning. Moreover, there is a recurring flexibilization of its Master Plan, often affected by private interests, which favors a disorderly expansion of the territory and heightens socio-environmental vulnerabilities. Occurrences such as the red mud spill (Liberal, 2018), soot rains and accidents involving kaolin waste (Steinbrenner et al., 2020) reveal the weakness of control mechanisms and highlight the need for more preventive and responsive environmental policies.

Among the GEIs under assessment, water supply showed the most significant improvement within the analyzed period, with further areas classified as sustainable or potentially sustainable. The observed trend indicates that there were public and private investments aimed at the expansion of water supply infrastructure, contributing, though partially, to mitigate historical deficiencies regarding access to drinking water. Considering the territory as a whole, the analysis highlights that there still is an uneven distribution of services, given that areas remained at intermediate or unsustainable levels, especially in urban peripheries and in more distant districts from industrial centers.

Although sewage treatment and solid waste management have also achieved improvements within the analyzed period, such advances remain limited in view of the magnitude of challenges. Large areas still lack adequate sanitation coverage, in addition to precarious infrastructure and the absence of regular waste collection and disposal services. As pointed out by Carmo and Costa (2016), such inequality highlights structural flaws in urban and environmental management, resulting from a constant prioritization of economically privileged areas instead of the most vulnerable territories. Such reasoning increases intra-urban inequalities even further, prevents the universalization of the right to proper sanitation services and overloads local ecosystems.

Furthermore, an asymmetric distribution of investments coupled with the lack of territorial planning integrating environmental equity and social inclusion compromises the effectiveness of public policies implemented in the municipality. The analyzed indicators reveal a governance structure that, although it has promoted local advances, it was unable to disrupt the traditional urbanization patterns, nor reduce asymmetries in access to environmental goods and services.

The reoccurrence of areas marked by unsustainable situations highlights the urgency of redistributive policies, in addition to the need to consolidate participatory planning strategies and continuous monitoring instruments capable of combining technical rigor with ethical commitment in view of structural inequalities in Barcarena's territory. Furthermore, a lack of integrated planning and intersectoral coordination hinders the construction of a development model based on sustainability principles, while decisions influenced by immediate results intensify the degradation of ecosystems, deepen social inequalities and compromise socio-environmental resilience.

In this context, public policies prioritizing environmental education, social participation and collaborative territorial governance constitute promising alternatives for transforming the current model (Ferreira et al., 2024). The authors state that an adoption of these practices can assist in more equitable and sustainable development paths capable of coupling the preservation of Amazonian ecosystems with an improvement in the living conditions of local populations. Thus, it is understood that strengthening participatory decision-making processes associated with transparency in public management and the use of monitoring instruments contributes to ensure the effectiveness of implemented policies.

In this scenario, the GEIs are relevant tools for assessing intra-urban inequalities and formulating public policies aimed at balancing economic growth, social justice and environmental preservation. Although it is based on data from the 2000 and 2010 censuses, its results provide a consistent analytical groundwork for future comparisons and improvements, especially in Amazonian contexts. With a full release of the 2022 Census microdata will enable novel possibilities of analyses, in addition to allowing an update of indicators and further in-depth pieces of research.

In response to the central question of this research, it is found that GEIs offer relevant support to territorial planning and the development of public policies in contexts marked by structural inequalities. In the case of Barcarena, their application highlighted uneven patterns of access to infrastructure and allowed determining critical areas and strengthening the connection between technical information, environmental equity and public management.

Although positive transformations have been observed during the analyzed period, numerous challenges are still found in the studied scenario. Consolidating lasting public policies guided by fair territorial planning, responsible environmental management and educational practices focused on sustainability is a fundamental step towards promoting better living conditions for the population, in addition to ensuring the protection of the Amazon ecosystems whose integrity is vital for present and future generations.

FINAL CONSIDERATIONS

The study analyzed geoenvironmental sustainability indicators in Barcarena (PA) between 2000 and 2010 with the aim of identifying environmental and socioeconomic impacts in the Amazonian region of Pará. Its results reveal progress in water supply, sewage treatment and solid waste management. Despite such improvements, there are still areas classified as intermediate or potentially unsustainable, thence revealing the need for immediate action in order to increase environmental fairness and reduce inequalities in the territory.

From a practical standpoint, the analysis emphasizes the relevance of monitoring through GEIs, in addition to highlighting the importance of public policies regarding territorial planning. Furthermore, there is technical support aimed at strengthening urban planning in Barcarena, in addition to contributions made to discussions on sustainability in bordering regions concerning environmental and socioeconomic factors. It also highlights the importance of strategies concerning the municipality's internal inequalities, with the aim of improving the population's quality of life and preserving local ecosystems.

Among the study limitations, the reliance on census data from 2000 and 2010 should be highlighted, since microdata from the 2022 Census were not yet fully available, thus restricting an update of the analysis and its spatial detailing. Future research should incorporate novel data in order to allow a more in-depth analysis of indicators, in addition to an identification of recent trends. Comparative studies on other municipalities in the Legal Amazon are also suggested to better understand sustainable strategies able to be adapted to different regional scenarios.

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