

**GEOSPATIAL ANALYSIS OF MALARIA VECTOR RECEPTIVITY IN A LOW-ENDEMIC AREA OF THE BRAZILIAN AMAZON: A TERRITORY-BASED APPROACH TO SURVEILLANCE**

**ANÁLISE GEOESPACIAL DA RECEPTIVIDADE AO VETOR DA MALÁRIA EM UMA ÁREA DE BAIXA ENDEMICIDADE DA AMAZÔNIA BRASILEIRA: UMA ABORDAGEM TERRITORIAL PARA A VIGILÂNCIA**

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**ABSTRACT**

Malaria remains a significant public health challenge in Brazil, particularly in regions with environmental conditions that favor vector proliferation. Although transmission is concentrated in the Amazon, historically vulnerable areas outside this region, such as parts of Maranhão, still present ecological and epidemiological characteristics that warrant attention. This study aimed to demonstrate how geospatial modeling based on environmental and geomorphological variables can help identify areas with higher malaria receptivity in low-incidence settings. Using the Analytic Hierarchy Process (AHP), environmental layers were weighted to create a composite index reflecting the relative influence of each factor on malaria receptivity. By integrating multiple layers of information through this structured decision-making approach, the proposed model supports entomological surveillance and land-use planning for disease control. The findings highlight the value of territorial approaches for understanding vector ecology and anticipating risks in favorable environments. Autocorrelation analyses, including Global Moran's I and Cross Moran's I, confirmed significant associations between the receptivity index and malaria incidence, supporting the ecological consistency of the model. Even without current cases, favorable environmental conditions may sustain receptivity and pose a potential threat for malaria reintroduction.

**Keywords:** Malaria. Health Geography. Health surveillance. Spatial epidemiology. Vector ecology.

**RESUMO**

A malária permanece como um importante problema de saúde pública no Brasil, especialmente em áreas com condições ambientais favoráveis à proliferação vetorial. Embora a transmissão esteja concentrada na Amazônia, regiões historicamente vulneráveis fora dessa área, como partes do Maranhão, ainda apresentam características ecológicas e epidemiológicas que demandam atenção. Este estudo teve como objetivo demonstrar como a modelagem geoespacial baseada em variáveis ambientais e geomorfológicas pode auxiliar na identificação de áreas com maior receptividade à malária em cenários de baixa endemicidade. Utilizando o Processo de Hierarquia Analítica, as camadas ambientais foram ponderadas para gerar um índice composto que reflete a influência relativa de cada fator sobre a receptividade à malária. A integração dessas múltiplas camadas de informação subsidia a vigilância entomológica e o planejamento territorial para o controle da doença. Os resultados destacam o valor das abordagens territoriais para compreender a ecologia vetorial e antecipar riscos em ambientes favoráveis. Análises de autocorrelação, incluindo os índices de Moran Global e Cruzado, confirmaram associações significativas entre o índice de receptividade e a incidência da malária, reforçando a consistência ecológica do modelo. Mesmo sem casos atuais, condições ambientais favoráveis podem sustentar a receptividade e representar ameaça potencial de reintrodução da doença.

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**Palavras-chave:** Malária. Geografia da Saúde. Vigilância em saúde. Epidemiologia espacial. Ecologia de vetores.

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## INTRODUCTION

In many tropical countries, malaria remains a leading cause of morbidity and mortality, with approximately 2.2 billion cases and 12.7 million deaths reported between 2000 to 2023 (WHO, 2024). In Brazil, over 99% of cases are concentrated in the Amazon region, where transmission is favored by climatic, and environmental conditions favor transmission. Additionally, sociocultural, economic, and political factors, as well as the quality of healthcare services, also influence the incidence (BRASIL, 2011; BRASIL, 2022a; Lopes et al., 2013; Tadei et al., 1998, 1988).

The Amazonian state of Maranhão historically had a high malaria prevalence throughout the 20th century (Lopes et al., 2013). However, there has been a systematic reduction in the number of cases since 2000, following the implementation of the Intensified Malaria Control Program in the Amazon (PIACM), and then the National Malaria Control Program in 2003. In the subsequent years, a gradual decline in cases and parasitic incidence was observed in the state, indicating a trend toward maintaining low transmission levels despite minor fluctuations (Oliveira-Pereira; Rebêlo, 2000; Silva et al., 2009, 2016).

The primary malaria vector species in Brazil belong to the genus *Anopheles*, mainly within the subgenera *Nyssorhynchus* and *Kerteszia*. In the Amazon region, *Anopheles darlingi* (*Nyssorhynchus*) is the most epidemiologically significant species due to its widespread distribution, high vectorial capacity and anthropophilic behavior. Deforestation, human migration, and occupational exposure in mining and agriculture contribute to maintaining endemic transmission, making effective control challenging (Carlos et al., 2019; Oliveira-Ferreira et al., 2010; Taui; Daniel-Ribeiro, 1998).

The World Health Organization (WHO) recommends malaria risk stratification, which enhances understanding of territorial variations in transmission and supports tailoring interventions to local contexts, in line with the global elimination strategy (Bhatt et al., 2015; WHO, 2017). Risk stratification requires accurate definition of risk, incorporating factors such as vector and parasite density, which vary over time and space. Malaria risk is characterized by the intersection of receptive and vulnerable areas (WHO, 2021). This operational definition enables a stratification approach in which malaria prevalence data are integrated with vector suitability information using Geographic Information Systems (GIS), allowing regions to be classified into distinct risk zones (Alimi et al., 2016). The WHO further emphasizes monitoring both direct and indirect determinants of transmission in regions where the disease has already been eliminated (WHO, 2017, 2021).

Malaria foci are classified as active, residual non-active, or cleared. Maranhão is in the process of malaria elimination, but some active foci still exist in some areas. Preventing disease reintroduction requires strong surveillance and assessment of receptivity, ensuring effective and sustainable control. Mapping and identifying potential *Anopheles* spp. larval habitats are critical for vector control and for transitioning these areas of Maranhão from active to residual non-active foci (Chanda et al., 2013; Dambach et al., 2009). Therefore, GIS-based surveillance tools are recommended for epidemiological and entomological monitoring (WHO, 2017, 2021, 2025).

Entomological surveillance is particularly important for evaluating malaria receptivity in endemic and low transmission settings, especially in contexts characterized by marked spatial heterogeneity of transmission. (WHO, 2021). According to the WHO (2021), receptivity refers to the ecological and environmental conditions that allow the establishment and maintenance of malaria transmission. This definition is also consistent with the Brazilian Ministry of Health framework, which highlights the role of environmental and ecological conditions in sustaining vector presence and transmission potential (BRASIL, 2022b). However, recent advances expanded this concept to incorporate a spatial perspective, in which receptivity reflects the interaction between environmental suitability, vector dynamics, human population distribution, and health system performance (Yukich; Lindblade; Kolaczinski, 2022).

From this perspective, receptivity is inherently spatial, varying across territories according to local ecological conditions and human-environment interactions. Studies have demonstrated that malaria transmission is highly heterogeneous in space, with localized areas of higher receptivity associated with environmental and landscape characteristics, such as vegetation cover, proximity to water bodies, and land use patterns (Burkot et al., 2018; Walshe et al., 2024).

In this context, the integration of Geographic Information Systems (GIS), remote sensing, and spatial modeling has become essential for identifying and stratifying areas with different levels of receptivity, supporting targeted surveillance and intervention strategies (McMahon et al., 2021; Odhiambo et al., 2020).

Despite these advances, relatively few studies have focused on modeling receptivity as an operational component of territorial surveillance in regions undergoing malaria elimination. This gap is particularly relevant in Maranhão, where recent epidemiological evidence has demonstrated a substantial decline in autochthonous malaria alongside a growing predominance of imported cases, reinforcing the need for spatially explicit tools capable of identifying territories environmentally suitable for possible reintroduction (Oliveira-Neto et al., 2025).

Therefore, this study contributes to this field by proposing a spatial model of malaria receptivity in Maranhão, integrating environmental variables through the Analytic Hierarchy Process (AHP) (Saaty, 1977) within a GIS-based framework. This approach enables the identification of spatial patterns of receptivity and supports the development of more efficient, territorially oriented surveillance strategies (Albuquerque et al., 2018).

## METHODS

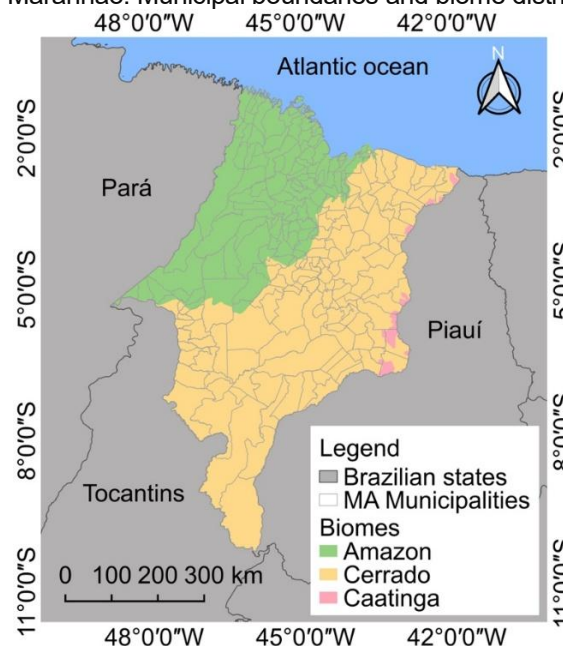
### Study area

Maranhão, located in northeastern Brazil, is the country's eighth-largest state and the second-largest in the Northeast, covering approximately area of 332,000 km<sup>2</sup>. It borders Piauí to the east, Tocantins to the south and southwest, Pará to the west, and the Atlantic Ocean to the north. With 6,775,152 inhabitants, it ranks as Brazil's 12th most populous state and has a Human Development Index (HDI) of 0.676 (IBGE, 2023a) (Figure 1).

Maranhão encompasses three distinct biomes, contributing to a high diversity of landscapes: the Cerrado (64%), features varied phytophysiognomies ranging from open fields to dense forests; the Amazon Rainforest (35%), featuring tall trees, seasonally flooded plains ("varzea" forests), and permanently flooded forests ("igapó"); and a small portion of the Caatinga biome (1%), characterized by shrubby vegetation with twisted branches, deep roots, and species such as cacti and bromeliads (Spinelli-Araújo et al., 2016).

Maranhão's climate is divided into three main climatic types: equatorial, characterized by a hot and humid climate due to Amazonian influence, with high rainfall throughout the year; humid tropical, predominant in most of the state, with a rainy season from January to June and a dry season from June to December; and semi-humid tropical, marked by a rainy period from March to October and a dry season from November to February, influenced by its proximity to the northeastern semi-arid region (Nimer, 1989; Nimer; Brandão, 1989).

Figure 1 – Maranhão: Municipal boundaries and biome distribution, 2025



Source: Prepared by the authors based on IBGE (2023b).

### Data source and analysis

The receptivity model was developed using secondary data sources. Geomorphology and vegetation cover data were extracted from the Environmental Information Database (BDIA), a web platform provided by the Brazilian Institute of Geography and Statistics (IBGE, 2023c). Precipitation and temperature data were obtained from the WorldClim platform (Fick; Hijmans, 2017).

Based on these sources, a comprehensive database was assembled to characterize the current environmental conditions in Maranhão. The study used four main data categories: geomorphology, precipitation, temperature, and vegetation (Figure 2). Model variables were adapted from the study by Albuquerque et al. (2018) and collectively referred to as larval habitat potential (Barve et al., 2011; WHO, 2021). Identifying and mapping water bodies, where multiple *Anopheles* spp. species could lay their eggs, is a key strategy for effective vector control, particularly in managing larval sources. All model variables in the proposed model are closely linked to the ideal conditions for larval habitats of *Anopheles* spp., particularly those belonging to the subgenus *Nyssorhynchus*.

Data analysis employed the Analytic Hierarchy Process (AHP) (Saaty, 1977), which involves ranking and assigning weights to each model layer. Initially, the layers were categorized into classes based on frequency distribution (Table 1): geomorphology was classified into five altitude ranges (0–20 m, 20–100 m, 100–200 m, 200–400 m, > 400 m); precipitation was divided into five annual rainfall categories (0–79.5 mm, 80–130 mm, 131–180 mm, 181–210 mm, > 210 mm); mean monthly temperatures were grouped into five classes (22.0–23.0°C, 23.1–24.0°C, 24.1–25.0°C, 25.1–26.0°C, > 26.0°C); and vegetation was classified into natural vegetation cover and other land cover types. Weights were assigned based on the ecological relevance of each variable for malaria receptivity, considering previous GIS-based receptivity models, the environmental determinants of *Anopheles* spp. larval habitat suitability, and the specific landscape characteristics of Maranhão (Albuquerque et al., 2018; WHO, 2021).

Vegetation was assigned the highest weight (40%) because it represents a major structural component of the landscape, influencing shading, moisture retention, local hydrological dynamics, and the persistence of potential larval habitats. Previous studies have demonstrated that vegetation cover and landscape change are strongly associated with vector distribution and malaria transmission dynamics, particularly in tropical environments (Bonan, 2008; Chaves et al., 2021; Laporta et al., 2021; Arisco et al., 2024; Walshe et al., 2024). Geomorphology, temperature, and precipitation were each assigned a weight of 20%, as they act as macro-environmental determinants of receptivity. Geomorphology influences drainage patterns and water accumulation, while temperature and precipitation regulate climatic conditions necessary for vector development and survival (Machado, 2003; Gage et al., 2008).

To formalize the weighting process, a pairwise comparison matrix was constructed following the Analytic Hierarchy Process (AHP) (Saaty, 1977), in which vegetation was considered moderately more important than the other criteria, while geomorphology, temperature, and precipitation were considered equally important. Criterion weights were derived from the principal eigenvector of the matrix, resulting in weights of 0.40 for vegetation and 0.20 for geomorphology, temperature, and precipitation. Matrix consistency was evaluated using the Consistency Ratio (CR), adopting 0.10 as the threshold for acceptable consistency. The calculated CR was 0.00, indicating acceptable internal consistency of the weighting structure.

To further assess the robustness of the weighting structure, a formal sensitivity analysis was conducted using the original AHP scenario and four alternative weighting scenarios, with moderate variations in the weights assigned to vegetation and climatic variables, which represented the criteria with the greatest ecological uncertainty in the model. For each scenario, the multicriteria model was recalculated, and the resulting spatial distributions were compared through visual inspection and quantitative assessment of the area (km<sup>2</sup>) occupied by each receptivity class. This procedure was used to evaluate the influence of alternative weighting structures on both the spatial distribution and proportional extent of the receptivity classes.

Model processing was carried out using QGIS-LTR 3.34 Prizren, employing tools such as r.reclass from GRASS GIS to classify layers based on classification criteria and the raster calculator, which overlays multiple data layers on a common measurement scale and assigns weights to each layer according to its importance. These tools were used to construct the AHP model. Model validation was performed through an internal and indirect assessment of spatial coherence. The final receptivity map was compared with the spatial distribution of Annual Parasite Incidence (API) and with the municipal distribution of malaria cases from 2012 to 2022. Furthermore, Global Moran's I, Local Moran's I, and Cross Moran's I were applied to examine whether areas with higher receptivity were spatially associated with municipalities presenting higher malaria incidence. These procedures allowed an integrated internal validation of the spatial coherence of the model in relation to observed epidemiological patterns. The receptivity classification framework was based

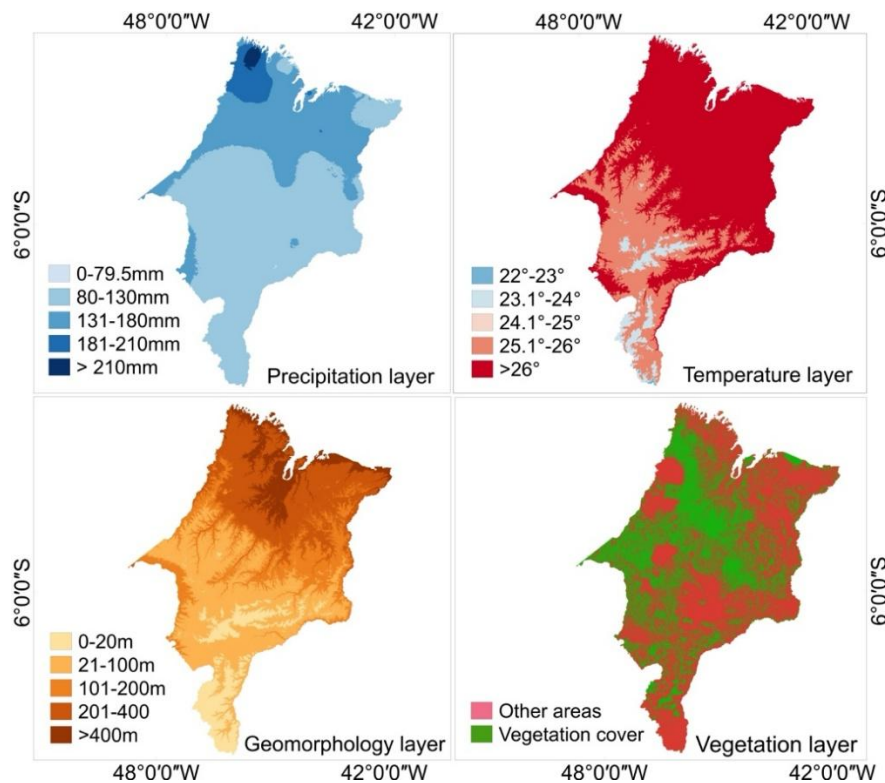
on the categories proposed by Albuquerque et al., 2018. The “layer properties” tool and the equal interval classification method were used to classify the five receptivity classes. After constructing the AHP model, we analyzed the distribution of receptivity classes across each municipality in Maranhão state, using data from the Brazilian Institute of Geography and Statistics (IBGE). Data processing was conducted in QGIS 3.34, using the R.report tool to calculate the total area occupied by each receptivity class. Maranhão has a total land area of 329,651 km<sup>2</sup>, while the modeled area was 328,045 km<sup>2</sup>, with minor discrepancies due to database limitations. Final proportions of land cover by receptivity class were calculated based on the total modeled area.

Table 1 – Maranhão: AHP weighting scheme for environmental variables, 2025

Layer used	Influence in the model (%)	Classes/Categories	Model weight
Temperature (°C)	20	22.0-23.0	1
		23.1-24.0	2
		24.1-25.0	3
		25.1-26.0	4
		>26.0	5
Precipitation (mm)	20	0-79,5	1
		80-130	2
		131-180	3
		181-210	4
		>210	5
Geomorphology (m)	20	0-20	5
		21-100	4
		101-200	3
		201-400	2
Vegetation	40	Vegetation cover	2
		Other areas	1

Source: Prepared by the authors based on IBGE (2023c); WorldClim (2024).

Figure 2 – Maranhão: Environmental layers used in the AHP model (precipitation, temperature, geomorphology, and vegetation), 2025



Source: Prepared by the authors based on IBGE (2023c); WorldClim (2024).

### Statistical analysis

Moran's global index (I) was used to assess the spatial autocorrelation of API, determining whether municipalities with high or low API values cluster geographically (Moran, 1950). Local indicators of spatial association were calculated to identify local clusters and spatial outliers (Anselin, 1995). Bivariate spatial correlation analyses (Cross Moran's I) were performed to examine the spatial association between API and the proportion of each receptivity class (% of municipal area classified as "Very High", "High", "Medium", "Low", and "Very Low") in neighboring municipalities. Cross Moran's I was computed by correlating API values with the spatial lag of each receptivity variable, enabling the detection of spatial patterns linking incidence with environmental suitability (Wartenberg, 1985). Statistical significance was assessed using Monte Carlo permutation tests with 999 simulations applied to all Cross Moran's I analyses. Spatial weights matrices were constructed using first-order Queen contiguity and row-standardized weights. All analyses and graphical representations were conducted in RStudio (R Core Team, 2024) using the *spdep* and *ggplot2* packages (Bivand; Pebesma; Gómez-Rubio, 2013; Wickham, H., 2016). Spatial autocorrelation analyses were incorporated not only to assess the statistical dependence of malaria incidence across municipalities, but also to identify territorially relevant patterns for surveillance. Global Moran's I was used to evaluate whether malaria incidence exhibited overall spatial clustering, Local Moran's I to detect priority clusters and spatial outliers, and Cross Moran's I to examine whether municipalities with higher incidence were spatially associated with neighboring areas presenting higher proportions of receptive environments. Together, these analyses provide an operational basis for territorial surveillance by supporting the identification of priority areas for entomological monitoring, targeted control measures, and prevention of malaria re-establishment.

### RESULTS

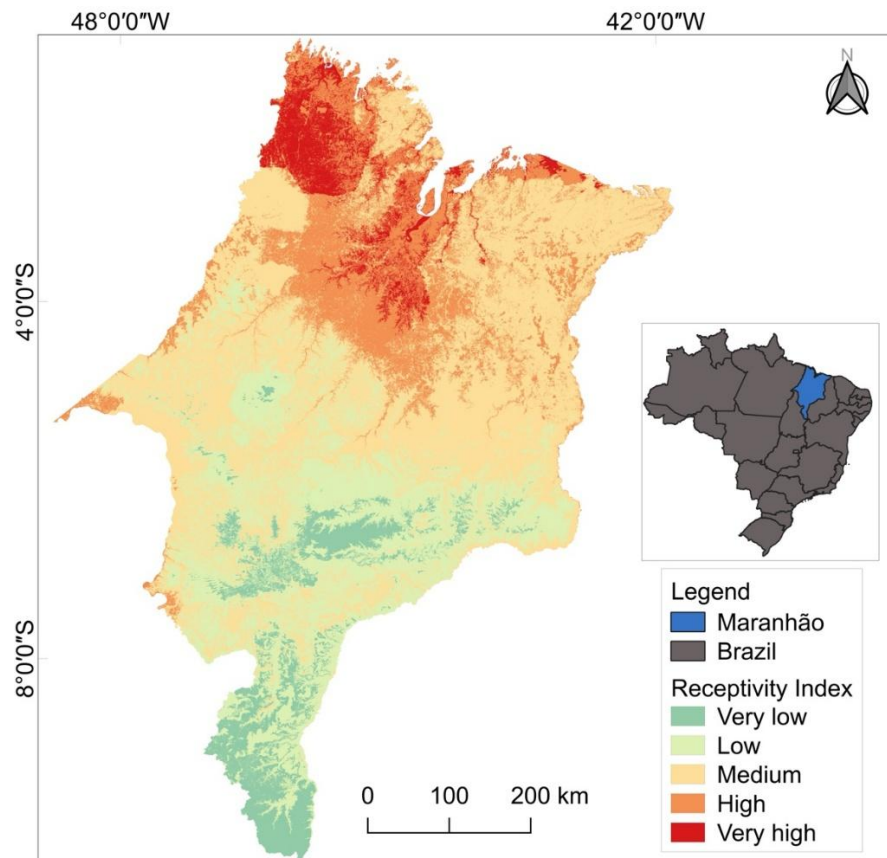
The territorial receptivity model identified five distinct classes of receptive areas for malaria transmission in the state of Maranhão: very low, low, medium, high, and very high. The "medium" class represented the largest portion of the state (147,728.25 km<sup>2</sup>, 44.81%), while the "very high" class, representing areas most suitable for *Anopheles* spp. larval habitats, particularly those associated with the subgenus *Nyssorhynchus*, accounted for only 5.30% of the state's territory (17,474.78 km<sup>2</sup>). This class is concentrated in areas with highly favorable environmental and climatic conditions for the presence of malaria vectors (Table 2, Figure 3).

Table 2 – Maranhão: Distribution of malaria receptivity classes, 2025

Receptivity class	Coverage area (km <sup>2</sup> )	Coverage area (%)
Very low	24,658.86	7.48
Low	80,168.28	24.32
Medium	147,728.25	44.81
High	58,015.35	17.60
Very high	17,474.78	5.30
No data	1,605.48	0.49
Total	329,651.00	100

Source: Prepared by the authors, 2024.

Figure 3 – Maranhão: Spatial distribution of receptivity to *Anopheles* spp. larval habitats, 2025



Source: Prepared by the authors based on IBGE (2023b); WorldClim (2024).

Maranhão has 217 municipalities, of which 95 contain regions classified as “very high” receptivity. Five municipalities together account for 18.32% of the total area in this category. Governador Nunes Freire (1,037.13 km<sup>2</sup> / 849.58 km<sup>2</sup>, 81.92% of its territory) and Santa Luzia do Paruá (1,010.48 km<sup>2</sup> / 836.06 km<sup>2</sup>, 82.74% of its territory) have the largest absolute areas of “very high” receptivity. Conversely, the municipalities with the highest territorial proportion in this category are Maranhãozinho (86.43%), Presidente Médici (85.88%), and Junco do Maranhão (84.70%). All are located in the northwestern region, with a combined estimated population of 71,038.

Additionally, the “very high” and “high” receptivity areas were predominantly concentrated within the Amazon biome, with smaller isolated occurrences in the Cerrado biome. In other regions, there is a direct correlation with vegetation cover: both within and outside the Amazon, the most receptive areas follow this pattern, reinforcing the central role of vegetation cover as a structuring environmental determinant of receptivity in the model. A detailed table containing the distribution of receptivity classes and biomes by municipality was generated (Supplementary Material; interested readers may contact the authors to obtain the underlying data). To validate the receptivity model, results were compared with parasite incidence data from Maranhão between 2012 and 2022 (Figure 4).

Visual comparison indicated strong spatial correspondence, demonstrating similarities between the modeled areas and observed data. Regions with the highest parasite incidence overlapped with the “very high” and “high” receptivity classes, while areas with low or no reported incidence aligned with lower receptivity classes in the model. The eight municipalities with the highest malaria cases in the analyzed period are located in high and very high receptivity areas: Alcântara (958 cases), Amapá do Maranhão (790), Boa Vista do Gurupi (643), Cândido Mendes (1,697), Centro Novo do Maranhão (2,109), Monção (608), Santa Helena (1,270), and Turiaçu (1,034). Regarding parasite incidence, five municipalities with the highest average incidence rates were located in the northwestern region with the largest extent of “very high” receptivity areas in the model. These municipalities include Amapá do Maranhão (3.63 cases/1,000 inhabitants), Cândido Mendes (1.99/1,000 inhabitants), Presidente Sarney (1.44/1,000 inhabitants), Turiaçu (1.12/1,000 inhabitants), and Turilândia (1.19/1,000 inhabitants). By

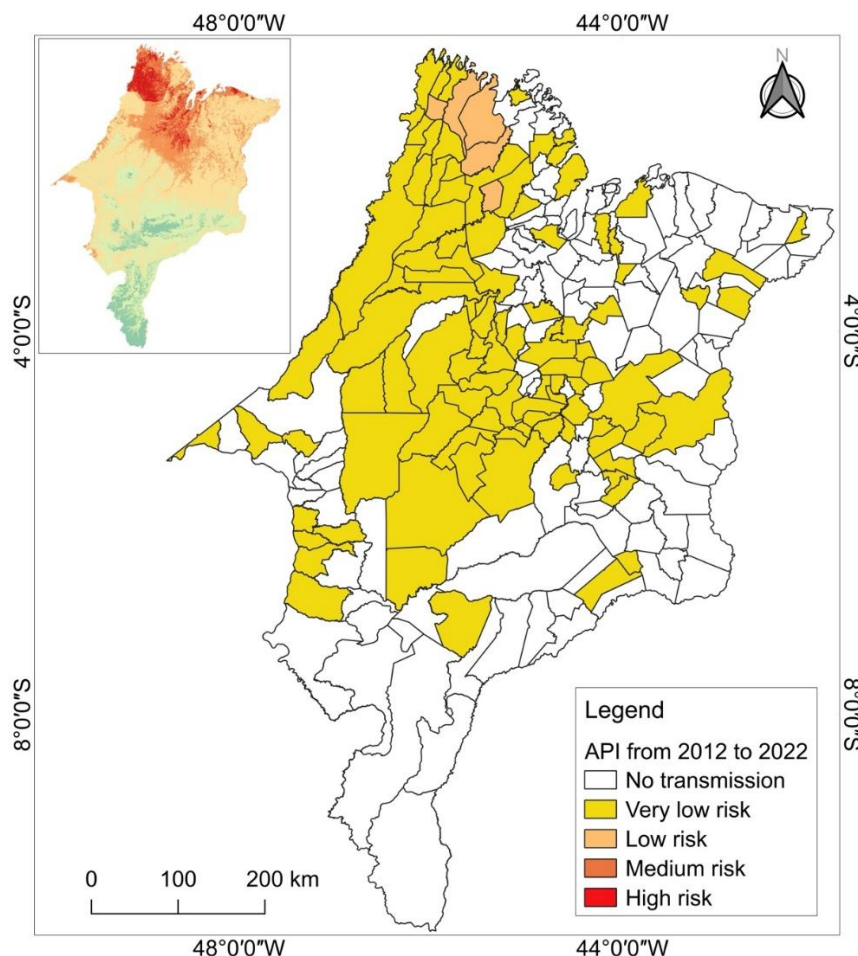
contrast, areas classified as “very low” receptivity were concentrated in the southern part of the state, where no malaria transmission occurred during the analyzed period. Notable municipalities in this category include Alto Parnaíba, Balsas, Loreto, Riachão, Sambaíba, São Félix de Balsas, and Tasso Fragoso. These areas belong to the Cerrado biome, characterized by low vegetation cover, reduced precipitation, lower average temperatures, and higher altitudes.

The presence of spatial patterns in API was assessed using Global Moran’s Index ( $I = 0.3269$ ,  $p < 0.001$ ), indicating the presence of a spatial structure in the data. This suggests that malaria distribution is not random but follows a well-defined geographic pattern, with adjacent municipalities exhibiting similar API levels. Local Moran’s Index analysis identified high-incidence areas “hotspots” and low-incidence areas “coldspots” (Figure 7), showing that certain municipalities have significantly higher API levels than their neighbors, while others exhibit reduced incidence.

Furthermore, bivariate spatial correlation analyses (Cross Moran’s I) revealed distinct associations between API and environmental receptivity classes in neighboring municipalities. The strongest positive spatial correlation occurred in the “Very High” receptivity class (Cross Moran’s  $I = +0.401$ ,  $p < 0.001$ ), indicating that higher malaria incidence tends to occur adjacent to municipalities with highly receptive environments for transmission. A weaker positive correlation was observed for the “High” class ( $I = +0.1299$ ,  $p < 0.001$ ).

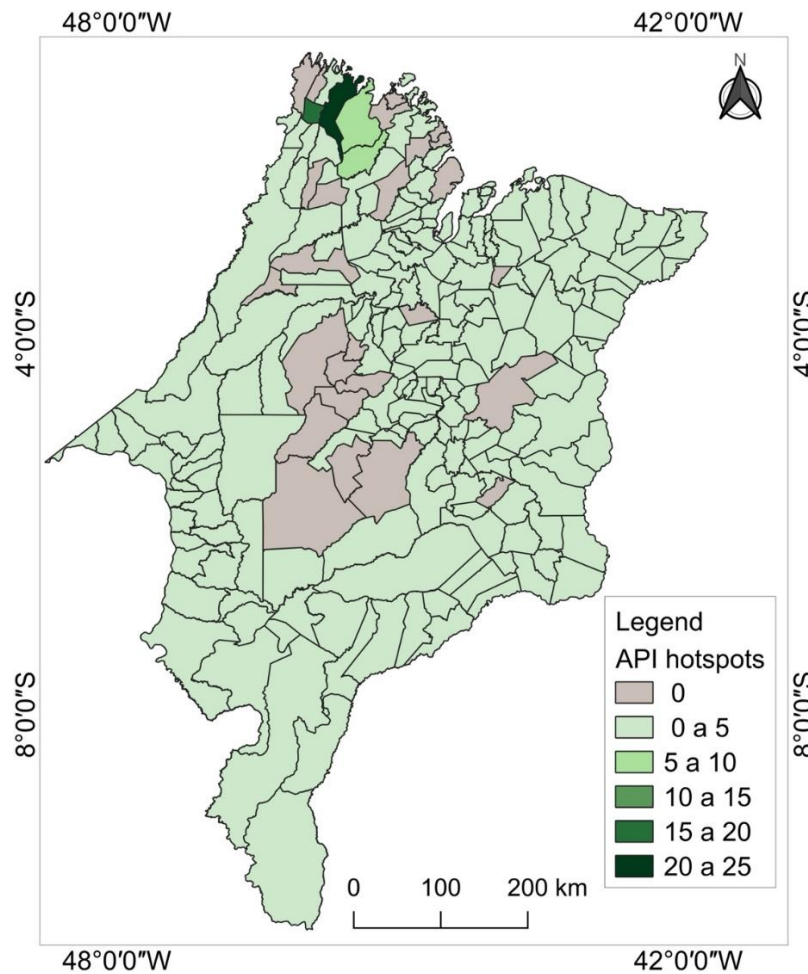
Conversely, negative correlations were found for the “Medium” ( $I = -0.2196$ ,  $p < 0.001$ ), “Low” ( $I = -0.1308$ ,  $p < 0.001$ ), and “Very Low” ( $I = -0.0902$ ,  $p < 0.001$ ) receptivity classes, suggesting that areas of lower environmental suitability are generally located further from the main transmission clusters. These findings reinforce the ecological validity of the receptivity model and highlight the importance of integrating spatial environmental data into malaria surveillance strategies.

Figure 4 – Maranhão: Spatial correspondence between receptivity and Annual Parasite Incidence (API), 2012–2022 (inset map showing receptivity model), 2025



Source: Prepared by the authors based on IBGE (2023b); WorldClim (2024).

Figure 5 – Maranhão: API hotspots identified by Local Moran's I, 2025



Source: Prepared by the authors based on IBGE (2023b); WorldClim (2024).

Overall, the spatial distribution of malaria receptivity in Maranhão reveals a clearly heterogeneous pattern, with higher receptivity concentrated in the northwestern region, particularly within the Amazon biome, where environmental conditions favor the persistence of larval habitats. In contrast, lower receptivity predominates in the southern portion of the state, associated with the Cerrado biome and less favorable environmental conditions for vector development. The spatial clustering of high receptivity areas and their strong association with higher malaria incidence highlight the existence of well-defined territorial risk zones. These findings indicate that malaria receptivity is spatially structured and driven by environmental and climatic factors, reinforcing the importance of incorporating territorial analysis into surveillance strategies and identifying priority areas for targeted interventions.

## DISCUSSION

The malaria receptivity index used in this study effectively stratified the state of Maranhão into five different areas based on the potential presence of *Anopheles* spp. larval habitats, particularly those associated with the subgenus *Nyssorhynchus*, which includes the primary malaria vectors in Brazil. Receptivity, defined as the likelihood of an area supporting *Anopheles* spp. larval habitats, ranged from “very low” to “very high”. The WHO recently replaced the term “breeding sites” with “larval habitats” to better reflect the ecological niche concept and species’ tolerance to specific abiotic conditions (Barve et al., 2011; WHO, 2021). The “medium” receptivity class dominated the model, covering nearly half of Maranhão’s total area (44.81%).

This pattern like reflects seasonal variation in water availability across both the Cerrado and Amazon. However, malaria transmission is more intense in the Amazon due to a combination of favorable ecological factors, such as the presence of *An. darlingi* (subgenus *Nyssorhynchus*), a highly efficient vector, extensive vegetation cover, and long-lasting floods that create persistent and ecologically

suitable larval habitats with clean water, organic matter, and the necessary balance for the development of the vector's immature stages (Arisco et al., 2024; Carlos et al., 2019; Rocha et al., 2020). In contrast, although the Cerrado also experiences seasonal flooding and temporary water collections, rapid evaporation, lower density of efficient vectors, and suboptimal breeding conditions, such as water stability and sufficient organic matter, along with the absence of a sustained transmission cycle, significantly limit the incidence of the disease (Rocha-Adorno et al., 2022).

Previous studies reported the presence of *An. darlingi* in different regions of the state of Maranhão, including Buriticupu in the western region, and São José de Ribamar in the northern region (metropolitan region of São Luís), where the vector exhibited high abundance, anthropophilic behavior, and *Plasmodium* spp. positivity (Barros et al., 2020; Rebêlo et al., 2007). Conversely, the Amazon biome remains malaria-endemic due to the high presence of *An. darlingi*, stable larval habitats formed by persistent water bodies, and increased human exposure to fragmented landscapes, particularly in deforested areas (Chaves et al., 2021; Laporta et al., 2021). Additionally, the seasonal water cycle in the Amazon sustains favorable transmission conditions over time, reinforcing the persistence of the disease (Wolfarth-Couto; Silva; Filizola, 2019).

The “very high” receptivity areas were characterized by elevated temperatures and precipitation levels, primarily in densely forested regions, particularly in the Amazon biome. The *Anopheles* spp. larval habitat model incorporated a forest component, representing the Amazon rainforest, which covers a significant portion of Maranhão's territory within the Legal Amazon region. The Amazon's environmental characteristics provide diverse and favorable conditions for malaria transmission, such as temperature, humidity, and vegetation, which sustain large mosquito populations year-round with minimal seasonal variation compared to other regions (Da Silva-Nunes, 2010).

Forest regions have a greater capacity to retain rainwater (Machado, 2003). Groundwater is gradually released into rivers to maintain permanent water bodies in the region. Furthermore, tropical forests influence local climate conditions (Bonan, 2008), while stable climate patterns near forest fragments provide optimal conditions for larval development and larval habitats formation. The northwestern region of Maranhão showed the highest concentration of “very high” receptivity areas, especially in the Amazonian floodplains. These include the dissected surface of Santa Luzia do Paruá and the sub-coastal surface of Bacabal, covering the Baixada Maranhense and Baixada do Turiaçu, regions with sedimentary basins containing numerous continental water bodies.

This study highlights how detailed spatial analyses improves understanding of vector distribution and ecology. Despite declining malaria incidence, these areas retain considerable transmission potential (BRASIL, 2022a; Deane, 1986; Hochman; Mello; Santos, 2002; Silva et al., 2009, 2016). In addition to the visual correspondence between receptivity classes and parasite incidence, bivariate spatial correlation analyses (Cross Moran's I) confirmed this association, showing that higher malaria incidence often occurs near municipalities with larger proportions of “Very High” and “High” receptivity areas. This spatial dependency underscores the role of environmental suitability in sustaining localized transmission clusters. Similar patterns have been reported in other low-incidence settings, where detailed spatial modeling effectively identified persistent hotspots of vector-borne disease transmission (Chaves et al., 2021; Walshe et al., 2024). These findings emphasize the importance of incorporating quantitative spatial correlation measures when validating ecological models of malaria receptivity.

In the early 2000s, this region was among the most affected by malaria in Maranhão (Silva et al., 2009), suggesting that suitable vector habitats and the risk of transmission may persist. The north and northeast regions also contained “high” receptivity areas, including the coastal plains and parts of the coastal plateaus. In these areas, the primary malaria vector is *Anopheles aquasalis*, a species adapted to coastal regions and previously documented in the literature (Ribeiro et al., 2005; Xavier; Rebêlo, 1999). Several municipalities may show a high probability of hosting extensive *Anopheles* spp. larval habitats. Eight municipalities with “very high” receptivity reported over 100 confirmed autochthonous cases between 2012 and 2022, demonstrating the model's potential for guiding surveillance efforts: Cândido Mendes (377 cases), Turiaçu (358 cases), Santa Helena (284 cases), Amapá do Maranhão (265 cases), Turilândia (241 cases), Presidente Sarney (168 cases), Governador Nunes Freire (145 cases), Centro Novo do Maranhão (132 cases), all these municipalities belong to the Amazon biome (BRASIL, 2024).

The (WHO, 2021) recommends continuous entomological surveillance in such areas to monitor environmental dynamics and prevent malaria outbreaks caused by imported, introduced, or reintroduced cases. Additionally, imported malaria cases were detected in 13 municipalities with a high proportion of “very high” receptivity areas, according to the model developed. Eight municipalities among them

reported over 150 imported cases: Santa Helena (398), Turilândia (347), Turiaçu (344), Cândido Mendes (298), Centro Novo do Maranhão (217), Santa Luzia do Paruá (211), Amapá do Maranhão (199), Governador Nunes Freire (196) (BRASIL, 2024).

According to our model, these municipalities are among the most receptive in Maranhão. This finding has significant epidemiological implications: high receptivity combined with vulnerability to imported cases may create conditions for outbreaks or disease reintroduction. Cohen et al. (2012) identified 75 malaria reintroduction events in 61 countries, highlighting that malaria resurgence often occurs in previously endemic areas that remain receptive after transmission has been interrupted. Cohen's study found that the primary cause of malaria resurgence (68/75 events, 91%) was the discontinuation of control programs, often due to funding disruptions. Malaria resurgence is also associated with imported infections, and/or recurrent *Plasmodium vivax* infections in highly receptive areas (Karunasena et al., 2019; Ranjbar et al., 2016; Sturrock et al., 2015; Wang et al., 2015).

Spatially referenced entomological data have proven valuable for characterizing malaria receptivity heterogeneity in elimination settings to prevent future outbreaks. However, entomological surveillance remains logistically challenging in low-transmission areas because capturing significant mosquito populations is difficult, and the interest of managers in carrying out surveillance actions in scenarios of low or no transmission (Albuquerque et al., 2018; Burkot et al., 2018; Chen et al., 2017). By integrating environmental and epidemiological data, this study offers spatial insights that could guide malaria surveillance efforts in Maranhão. Environmental parameters generally change slowly over time (Herrera et al., 2012); however, this model assigned greater weight to vegetation cover a highly dynamic variable strongly associated with malaria risk. Unlike previous studies focused on municipal-level risk mapping, we aimed to highlight risk distribution beyond political boundaries in our study (Da Silva-Nunes et al., 2012; Herrera et al., 2012).

The proposed model incorporated environmental variables related to receptivity for *Anopheles* spp. (subgenus *Nyssorhynchus*), the main malaria vectors in the Amazon region, but did not include the *Kerteszia* subgenus, (such as *Anopheles cruzii* and *Anopheles bellator*), which is strongly associated with the Atlantic Forest and relies on epiphytic bromeliads as larval habitats, requiring environmental indicators different from those used in this model (Medeiros-Sousa et al., 2019). *An. darlingi*, in contrast, adapts to locations transformed by human action, using artificial habitats such as fish farming tanks and water reservoirs in degraded areas containing organic matter and vegetation in clean water (Prussing et al., 2019).

Earlier research relied on aggregated municipal data, potentially masking spatial transmission patterns (Da Silva-Nunes et al., 2012; Herrera et al., 2012). In contrast, this study incorporated environmental and climatic variations, geomorphological layers, and associations between vectors and transmission, as recommended by previous studies (Albuquerque et al., 2018; Fuller et al., 2014; Patz; Olson, 2006). The results demonstrate that environmental modeling can strengthen epidemiological surveillance systems and improve malaria control strategies. By integrating environmental and geomorphological variables, the approach may allow for more targeted and effective interventions. Spatial correlation analyses complement visual and descriptive comparison and represents an important step for the ecological validation of the model.

From a public health and territorial planning perspective, the proposed receptivity model provides an operational tool to support malaria elimination strategies in Maranhão (WHO, 2017; BRASIL, 2022b). By identifying spatially explicit areas with higher environmental suitability for vector presence, the model allows health authorities to prioritize municipalities and regions for intensified entomological surveillance, even in the absence of current transmission (Albuquerque et al., 2018; Walshe et al., 2024). This is particularly relevant in low-incidence or pre-elimination settings, where the risk of reintroduction is closely associated with the persistence of receptive environments (Sturrock et al., 2015; Ranjbar et al., 2016). Recent epidemiological evidence from Maranhão further contextualizes this scenario, indicating a marked decline in autochthonous malaria alongside the progressive predominance of imported cases, which characterizes the state as a low-endemicity setting vulnerable to re-establishment (Oliveira-Neto et al., 2025).

The spatial clustering of high and very high receptivity areas, especially in the northwestern portion of the state, indicates priority zones where targeted vector control, environmental monitoring, and active case detection should be strengthened (Chanda et al., 2013; Rocha et al., 2020). In contrast, areas with low receptivity may require less intensive surveillance strategies, allowing for more efficient allocation of limited public health resources (WHO, 2021).

Furthermore, integrating receptivity mapping with epidemiological surveillance systems can enhance early warning capacity and support proactive interventions, contributing to the prevention of malaria re-establishment (WHO, 2025; Cohen et al., 2012). In this operational context, the increasing role of imported malaria in Maranhão reinforces the value of this integration as an early warning strategy to identify territories at greater risk of re-establishment (Oliveira-Neto et al., 2025). In this broader framework, the incorporation of geospatial tools into routine surveillance practices represents a strategic approach aligned with current recommendations for malaria elimination and territorial health planning (Alimi et al., 2016; Fuller et al., 2014).

The consistent and statistically significant associations observed through cross Moran's I further support the applicability of the proposed approach in other low-incidence settings, where understanding the spatial relationship between environmental suitability and malaria transmission is critical. Future improvements should include external validation tests, alternative weighting strategies for environmental variables, and comparisons with independent datasets to improve the model's predictive capacity.

This study has some limitations that should be considered when interpreting the results. Methodologically, although the AHP weighting process was supported by literature and demonstrated internal consistency, no formal sensitivity analysis was conducted to assess the influence of alternative weighting scenarios on model outputs. From an environmental perspective, the model relies on environmental proxies and does not incorporate primary entomological field data, which may limit its ability to capture fine-scale variations in vector abundance and behavior. In addition, the use of secondary data sources, including climate and environmental datasets, may introduce uncertainties related to spatial resolution and temporal variability, while potential underreporting or inconsistencies in malaria case data may affect the observed epidemiological patterns used for comparison. Despite these limitations, the model provides a consistent representation of spatial receptivity patterns and contributes to a better understanding of malaria risk in low-transmission settings.

## CONCLUSION

In this study, we demonstrated how spatial modeling based on environmental and geomorphological variables can help identify areas with higher malaria receptivity in low-incidence regions. By integrating multiple layers of information, the model provides a valuable tool for guiding entomological surveillance strategies and land-use planning aimed at disease control. The results highlight the value of territorial and spatial approaches for understanding vector ecology and anticipating risks in environmentally favorable areas. The observed spatial association between receptivity and malaria incidence supports the model's reliability and ecological consistency. From the perspective of medical geography, these findings reinforce the role of territory as both an analytical and operational dimension for health surveillance. Thus, even in the absence of autochthonous cases, the presence of suitable environmental conditions may represent a risk for malaria reintroduction. Models such as this can strengthen proactive surveillance and support more efficient and targeted public health policies.

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