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Water Deficits and Socioeconomic Condition Related To the Epidemiology of Malaria in State Of Para, Amazon (2003–2011)

Douglas Gasparetto[a], Lucieta Guerreiro Martorano[b], Giselle Maria Rachid Viana[c], Cléa Carneiro Nazaré Bichara[d]

[a] *Geoprocessing Laboratory, Center for Natural Sciences and Technology, University of Para. Tv. Enéas Pinheiro, 2626, Marco, Belem – Para, Brazil.*
[b] *Embrapa Eastern Amazon, Trav. Dr. Enéas Pinheiro s/n, Marco, Belem – Para, Brazil.*
[c] *Section of Parasitology, Instituto Evandro Chagas, BR-316 km 7 s/n -Levilândia, Ananindeua – Para, Brazil.*
[d] *Department of Community Health, Center of Biological and Health Sciences, University of Para. Trav. Perebebuí, 2623, Marco, Belem – Para, Brazil.*
Corresponding Author: Lucieta Guerreiro Martorano

Abstract: *In this study, we performed a geomatic analysis of malaria's epidemiology in Para, Brazil (2003–2011), and compared the incidence of malaria to socioeconomic and climate variables. Our results indicate that malaria was mainly observed in three clusters, with higher incidences in Marajó Island, Tucuruí and Jacareacanga, which had a water deficit of 30–120 mm and an Human Development Index of <0.65m. In addition, malaria requires appropriate weather conditions for transmission. These findings may be used to help support decision making regarding public health and malaria control measures in the state of Para, Amazon.*

***Key words**: Malaria, Geomatics, Human Development Index, Water deficits.*

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I. Introduction

The Amazon has both national and global effects on society and nature. In this context, the Amazon is the largest rainforest on earth, harbors a large amount of biodiversity, and helps to stabilize the global climate. However, the predatory use of the Amazon's natural resources can threaten the present and future benefits that are provided by the Amazon. Therefore, it is important that the natural and local resources be carefully and conservatively used, as these actions can directly influence the health of human populations [1].

In this context, the relationship between society, human health, and nature has been extensively studied, and this knowledge has provided the foundation for examining the specific relationships between these factors [2]. In addition, studies of the relationship between epidemiology and environmental sustainability have been made viable by the temporal dimensions of these components, which help to form the basis for health information research [3, 4, 5, 6, 7, 8, 9, 10]. In this context, the use of images and geoprocessing techniques has facilitated analysis of the spatial distribution of specific diseases' prevalences and incidences.

Geomatics is a field of research that uses computing resources (e.g., hardware and software solutions) to perform focused spatial analyses of indexed geographical information, which can generate information regarding phenomena that occur in a given geographical area. These tools can integrate environmental, socioeconomic, and health data, and can be used to identify spatial patterns in the distributions of diseases and health conditions in human populations [11]. These tools can also incorporate historical data to identify patterns in the spatio-temporal distribution and trends for diseases and deaths in specific geographical areas [12, 13]. Therefore, the field of geomatics has allowed us to identify vulnerabilities and environmental conditions that facilitate the spread of diseases within geographical areas [14, 15].

The World Health Organization considers malaria to be a tropical parasitic disease with severe socioeconomic impacts and climate conditions [16]. In the Americas, 60% of the malaria cases occur in Brazil and 99% of malaria cases in Brazil occur in the Amazon Basin. In this area, deforestation, agricultural practices, gold mining, and unbalanced migratory movement are related to increases in both the diversity and abundance of *Anopheles* vectors. Furthermore, these factors also contribute to increases in the number of malaria case notifications, and although this disease has low lethality, its presence in the Amazon Basin is alarming. Moreover, changes in socioeconomic and/or climate variables can affect malaria transmission, and may be responsible for malaria outbreaks in Brazil. Furthermore, *Plasmodium falciparum* drug resistance has rapidly and critically spread in some areas, where bio-geographic barriers contribute to establishing genetic differentiation among parasites with limited dispersion. Therefore, this systematic study aimed to evaluate the spatial distribution of malaria cases in Para State, Brazil between 2003 and 2011, and to examine the correlation between this distribution and various socioeconomic and climatic variables.

II. Materials And Methods

2.1 Ethical considerations and data types

No human biological materials were collected during this study, which only evaluated information that was derived from secondary data, public domain data, and geocoded patient data. Geocoding is a formal process for indexing descriptive information regarding the characteristics of spatial data, during which the codes are generated via geoprocessing and stored for future research, such as in eco-epidemiological studies. This data can include patients' epidemiological characteristics and their laboratory test results, which are organized and indexed in databases to ensure simple and efficient access to data. This process facilitates the analysis of the data according to spatial characteristics (proximity and size), and the subsequent statistical modeling of the relevant data in space [17].

2.2 Working area

In this study, we evaluated information from the state of Para, which is located between 02º 30'0'' north and 8° 0'0'' south latitude, 58º0'0'' and 46°0'0''W longitude. This state occupies an area of 1,248,042 km^2 in the north-central region of Brazil, has an equatorial climate, and includes 144 cities with an estimated 7,740,195 inhabitants. Para is the second largest state in Brazil, and is bordered by Suriname, the Amapa river, and the Atlantic Ocean to the north; Maranhão state to the east; Tocantins state to the southeast; Mato Grosso state to the south; Amazonas and Roraima states to the west; and Guyana to the northwest. Para state's main rivers are the Amazon, Tapajós, Xingu, Jari, Tocantins, and Para rivers, and its vegetation is predominantly mangrove coastal fields (in Marajó Island), savanna, or Amazon rain forest [18].

2.3 Databases

The Brazilian Institute of Geography and Statistics provided the cartographic data (1:250,000 scale) and the Human Development Index (HDI) data [18]. Meteorological data were provided by the National Institute of Meteorology. Precipitation data were provided by the National Water Agency and the Amazon Protection System. Epidemiological data were provided by the Ministry of Health's Health Information Systems (SIS) and the Information System for Epidemiological Surveillance of Malaria.

2.4 Debugging and statistical analysis

Redundant, incomplete, and unnecessary attributes that were derived from the SIS databases were debugged using Tabwin 32 software, which was provided by the Ministry of Health. To assess whether the malaria incidences exhibited any associations with climate conditions, we overlaid the infection data on maps of the annual water deficit, which was calculated based on an assumption of 300 mm ground water capacity [19]. Based on these maps, the total quarterly (3-month) rainfall was recorded for periods with water deficiency in the areas that were found to have high incidences of malaria. Next, we evaluated the association between the total quarterly rainfall for periods of water deficiency and the incidence of malaria, using SigmaPlot software 12.3. In addition, we examined the quarterly temperature range to evaluate for the number of positive responses and the thermal conditions in the areas of with higher malaria incidences. Once these calculations were completed (to provide descriptive historical series for the study period), data was then expressed in the form of thematic maps, describing the various characteristics for the period of 2003 to 2011.

In the study areas, we used SIS data (2003–2011) to calculate the risk of contracting malaria, according to the Annual Parasite Index (API), which is classified as a high (an IPA of ≥50), medium (an IPA of 10–49.9), or low (an IPA of 0.1–9.9) risk of transmission [20]. This analysis required us to calculate the estimated population for each year during study, and to then calculate the IPA, as shown in Equation 1.

$$IPA = \frac{NEP}{P} * 1000 \tag{1}$$

In Equation 1, IPA is defined as the annual number of parasite cases per 1,000 persons (‰), NEP is defined as the number of positive malaria tests during the period, and P is defined as the total population during the period. The median and interquartile range values were then used to create boxplots for the annual IPA, which were then used to identify changes in IPA and the years in which an elevated IPA was observed. The joins techniques (join and joinSpatial) in the ArcGIS 10 software were used for processing and spatial evaluation of the interrelationships between the debugged eco-epidemiologic and cartographic data.

Interpolation for the calculated IPA and water stress was performed using the "inverse of distance" statistical model, which is based on spatial dependence, and assumes that two close points will be highly correlated. For example, weather and climate in one location are affected by the same atmospheric conditions, which are attributed a greater weight than those at more distant points. Therefore, this model consists of multiplying the sample values by the inverse of their respective distances from the reference point's interpolation values [21]. In the present study, we used this model to evaluate water stress (water deficiency relative to an assumed soil water capacity of 300 mm), IPA, HDI, and the years that exhibited the greatest variation in IPA. The results were expressed in the form of thematic maps for the study period.

III. Results

We observed that the incidence of malaria was consistently below 80,000 during periods of high rain. However, between May and August, we observed sharp increases in the incidence of malaria and water deficits (Figure 1).

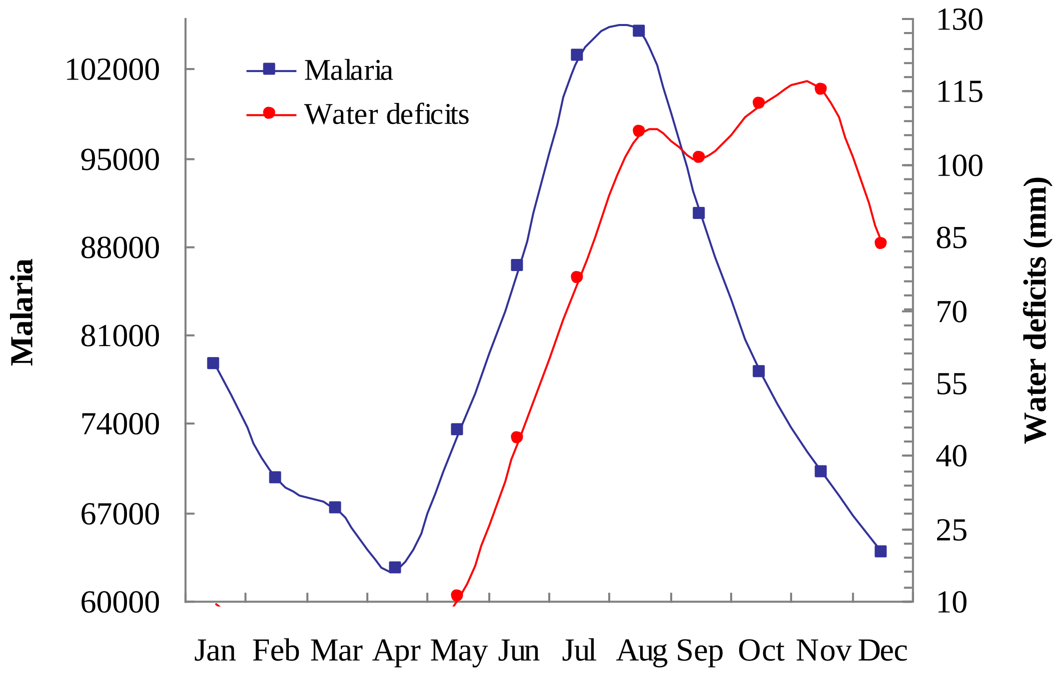

Figure 1. The incidence of malaria and water deficits according to month.

The increased water deficits coincided with the 43% increase in the incidence of malaria (from 73,409 in May to 104,414 cases in August). Between August and December, we observed water deficits of 85–115 mm. Between January and April we did not observe any water deficits, although we did observe a decrease in the incidence of malaria, which reached its lowest rate in April. These evidences indicate that the number of malaria cases increase exponentially after periods will 300 mm of rainfall, which provides favorable conditions for proliferation, breeding, oviposition, and egg hatching. Further analysis revealed a high correlation between these factors, which was described by a sigmoidal function. Thus, even in periods of low rainfall, there are still rainfall effects on the incidence of malaria. Therefore, it is possible to estimate the incidence of higher rates of malaria, as shown in Equation 2, with approximately 93% accuracy.

$$PIA = \frac{261402.3}{\langle 1 + Exp(-(\frac{Ptm - 518.3)}{64.4}))\rangle} \qquad (2)$$

In Equation 2, PIA is defined as the Positivity Index of Average, and Ptm is the precipitation in three months (July to September).

When we assessed the annual incidence of malaria, the highest incidence was observed in 2005, although there was a very wide distribution in the IPA, as indicated by the low median values and wide IQRs

(Figure 2). These findings indicate that many cities have an average IPA, while only a few have an extremely high IPA. We also observed that certain areas in Para state exhibited a high concentration of malaria cases, and that significant variability was observed in 2005, 2009, 2010, and 2011. Furthermore, when we constructed the spatial distribution maps, we observed that malaria was highly concentrated in three major clusters (Figures 3–5): Marajó Island, around the Tucurui dam, and in Jacareacanga (in southwestern Para). During all years, the greatest concentration of malaria cases coincided with water deficits of 30–150 mm.

During the study period, the State of Para had the highest rates of malaria in 2005, 2010, and 2011. However, a decrease in the annual IPA was observed between 2005 and 2008, although a subsequent increase was observed in 2009 (Figure 2).

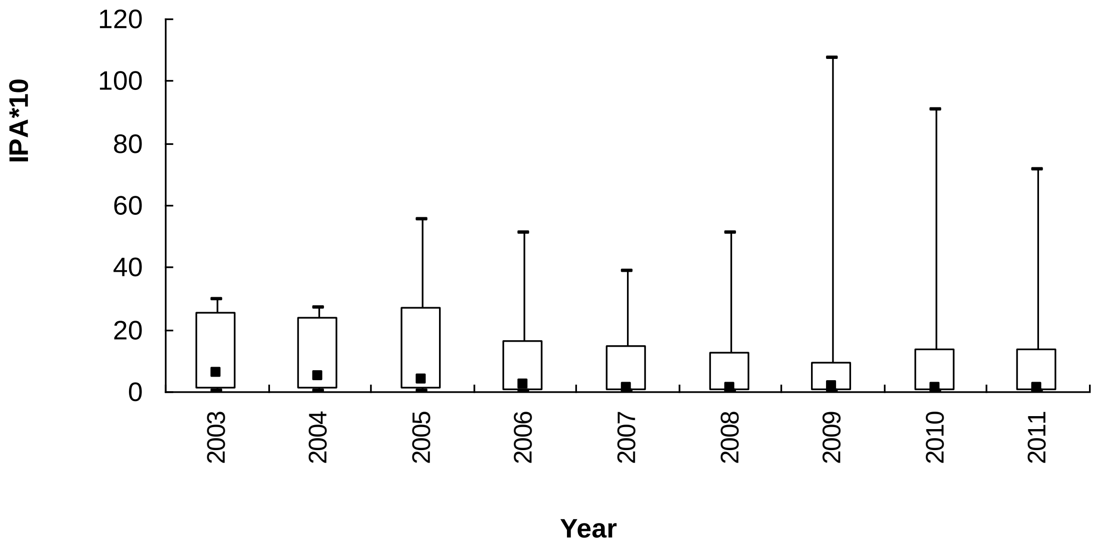

Figure 2. Box plot of the Annual Parasite Index.

Similar patterns for the incidence of malaria were observed in 2005 (a period of strong El Niño in the Amazon) (Figure 3) and 2009 (a period of strong La Niña in the Amazon), although the absolute values were lower in 2009 (Figure 4), except in the northern region, where malaria was mainly concentrated around Anajás. In this context, the El Niño Southern Oscillation (ENSO) describes changes in sea surface temperatures in the Pacific Ocean (El Niño) and in atmospheric pressure across the Pacific basin (Southern Oscillation).

These changes in precipitation, temperature, and hurricane activity all contribute to the effect of El Niño on human health. Furthermore, there is evidence that El Niño is associated with an increase in the burden of natural disasters in some regions. Therefore, seasonal forecasting methods and information can be used to improve the use of health resources, such as forecasting the onset and progression of El Niño, which can provide sufficient time to create appropriate responses for the subsequently increased incidence of malaria.

A growing number of studies have demonstrated that the El Niño cycle is associated with changes in the risk of diseases that are transmitted by mosquitoes, such as malaria, dengue, and other arboviruses. Malaria transmission is particularly sensitive to climate variations, and populations lack protective immunity in areas with unstable malaria. Therefore, serious epidemics may occur when weather conditions make transmission possible [16].

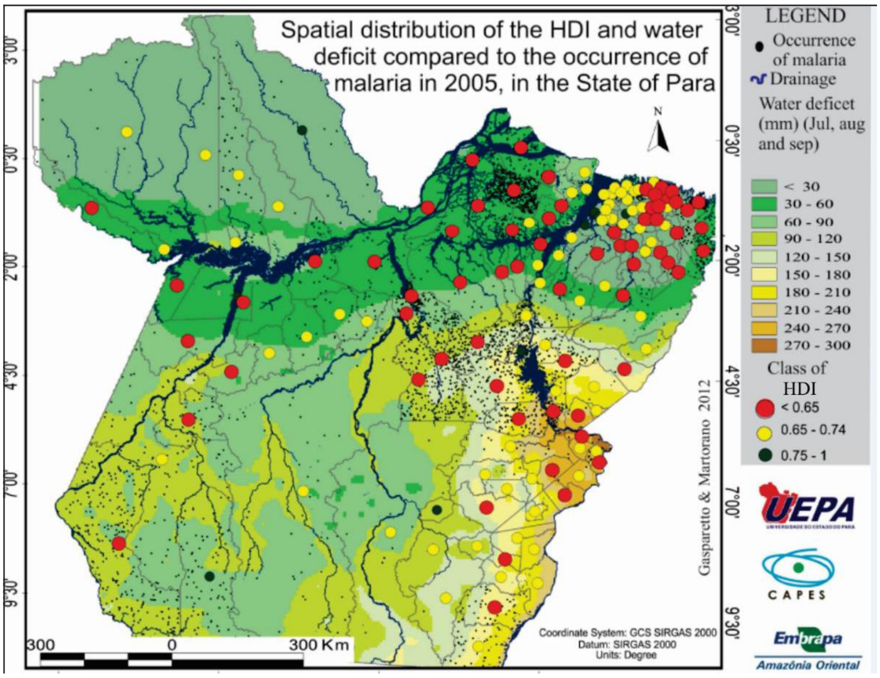

Figure 3. Spatial distribution of the Human Development Index (HDI), water deficits, and the incidence of malaria in the state of Para during 2005.

In 2009, malaria was strong concentrated in Marajó, which coincided with water deficits of 30–60 mm, and around the Tucurui dam and Jacareacanga, which coincided with water deficits of 90–120 mm (Figure 4). The spatial concentration of malaria was mainly in cities with an HDI of <0.65.

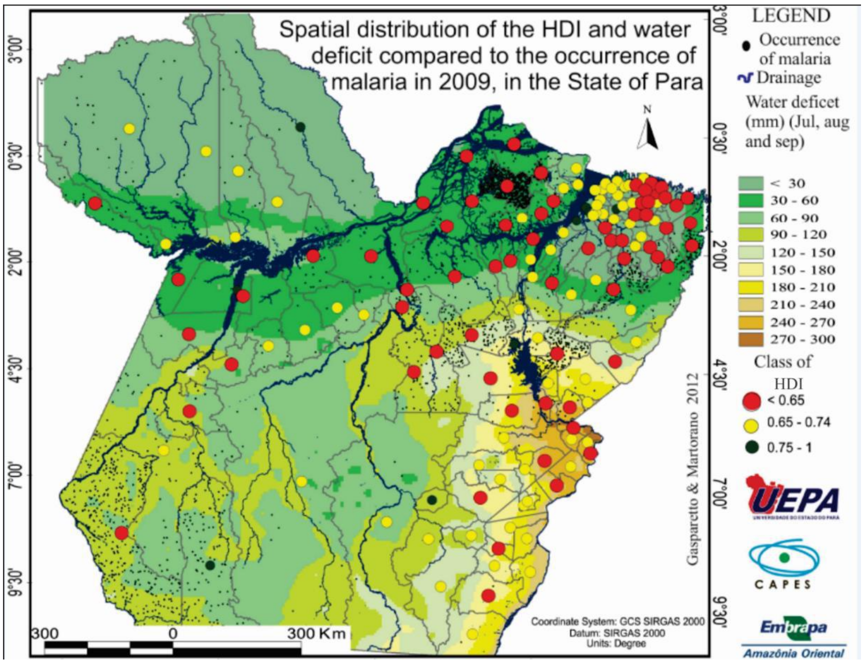

Figure 4. Spatial distribution of the Human Development Index (HDI), water deficits, and the incidence of malaria in the state of Para during 2009.

In 2011, a shift in the main concentration of malaria was observed, as it had spread to cities that are located south of Anajás (Figure 5).

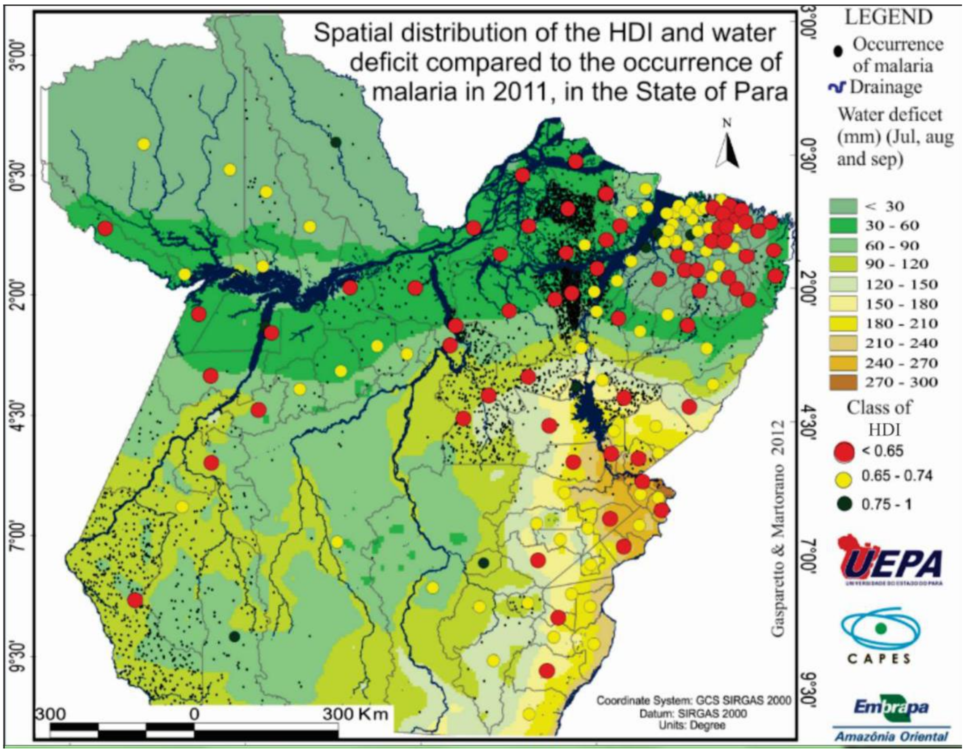

Figure 5. Spatial distribution of the Human Development Index (HDI), water deficits, and the incidence of malaria in the state of Para during 2011.

IV. Discussion

Our findings appear to confirm the fact that the transmission of malaria via the *Anopheles* vector requires favorable environmental conditions, and highlight the influence of heat, humidity, and abundant vegetation in modifying the vector's biological cycle. For example, the vector migrates with increasing temperatures, and this poses a threat to human health [22]. Another important factor appears to be lack of water in the soil, because increasing water deficit (beginning in May) was mirrored by an increase in the incidence of malaria. Interestingly, we observed that periods of extreme water stress coincided with the lowest incidence rates, which may be related to the fact that these conditions result in the reduction or destruction of the vector's breeding grounds (both natural and artificial) [23]. We also observed that the greatest increase in the incidence of malaria was observed during periods with a water deficiency of 30–120 mm. Thus, it appears that the state of Para has favorable conditions for the proliferation of malaria, and that these conditions occur throughout the state [24].

In 2005, Para state exhibited the highest incidence of malaria in the study period, and this increase may be related to the strong effects of El Niño, as the effects of La Niña and El Niño modulated the weather and climate conditions in the Amazon Basin during the period from 2004 to 2006. In addition, it is also worth noting the phenomenon of *P. falciparum* resistance to chloroquine (a drug that is used to treat *P. falciparum* malaria) did not emerge until 2005 in Brazil. Furthermore, the impact of ENSO over South American precipitation is exerted through perturbation of the Walker circulation over Amazonia and through anomalous Rossby wave propagation from eastern Pacific towards southeastern South America [25, 26]. Moreover, during 2005 (strong ENSO in Amazon), malaria was common throughout the state of Para, although it was mainly concentrated in the northeast and southwest regions of the state (e.g., Anajás city) and around the Tucurui dam (Figure 3). However, for the four years with the greatest IPA variability, we observed that the spatial concentration of malaria was mainly in cities with an HDI of <0.65, although spatial concentrations were also observed in Cametá and Itaituba (an HDI of 0.65–0.74) and near the Tucurui dam (an HDI of >0.75). Unfortunately, vector control measures in many areas have failed, or their resources are too limited to maintain adequate control of vector-borne diseases, such as malaria. Therefore, the association of the ENSO cycle with the incidence of malaria may facilitate climate forecasting to provide seasonal and semi-annual predictions to help mitigate future epidemics.

We also observed that Para state had favorable conditions for the spread of malaria, which resulted in 948,142 reported cases during the period of the study. However, it is believed that the true incidence is greater than the reported incidence, given the possibility of underreporting in locations where monitoring is difficult. Interestingly, it is possible that the sporadic changes in the incidences of malaria may indicate that the anti-malarial drugs had become less effective during the study period, as the number of patients with strong symptoms increased by approximately 20%. Another important factor might be the effect of climate changes in Para state during the study period [16].

Another important factor was the improvement of malaria reporting systems, as the SIVEP malaria reporting system was implemented in 2003, which is more efficient than the previous SISMAL system. In addition, during 2010 and 2011, the reported incidence of malaria may have been influenced by the response capacity of health systems, surveillance and control programs, and early diagnosis and treatment. Furthermore, the Political Economy of Public Health 2010 may have influenced the incidence of malaria, due to healthcare changes, as the IPA during this period was relatively high (≥ 50), according to national statistics [16]. Therefore, using our sigmoidal model, we believe that we can predict the periods and locations in which an increased incidence of malaria is expected. Using this information, it may be possible to effectively deploy prevention and control teams, and to develop effective public policies to control malaria infection in those areas.

Barbier and Sawyer [1] have highlighted the influence of rainfall on the dynamics of malaria infection. Similarly, we found that increased incidences of malaria were co-located with geographic areas that had temperatures that were >10°C above the national average, which indicates that the vector can become particularly established in Para state, which has high temperatures and humid conditions. Our findings also indicate that there are clusters in which the malaria cases were concentrated during all years throughout the study period [27]. In the years that we analyzed, epidemiological clusters of malaria were pronounced in areas that experienced changes in climate and socioeconomic variables [28], For example, our findings indicate that malaria has a strongly relationship with human-related environmental changes. In this context, the construction of roads, agricultural projects, settlements, extraction plants, and logging can all cause profound environmental changes, disrupt the local ecological balance, and possibly cause the epidemiological changes that we observed.

In this study, the areas with the highest malaria incidences coincided with the areas that were mapped by Health Surveillance National System, which identified 19 critical municipalities (Afuá, Altamira, Anajás, Anapú, Bagre, Breves, Cametá, Curralinho, Goianésia of Para, Ipixuna do Para, Itaituba, Jacareacanga, Mojú, Novo Progresso, Oeiras do Para, Pacajá, Paragominas, Portel and Tucuruí). These municipalities contributed approximately 80% of the reported malaria cases in 2010, with 12 municipalities exhibiting an IPA of >50 cases/1,000 inhabitants. Furthermore, we observed clusters of these cases in three major areas: in the center of Marajó Island, surrounding the Tucuruí hydroelectric dam, and in the municipality of Jacareacanga and neighboring municipalities. Several authors have related the onset of infection with human activity and the environment, such as road construction, agricultural projects, settlements, vegetal and/or mineral extraction, and logging, which create profound environmental changes by disrupting the ecological balance. Therefore, the dynamic changes that we observed in the various clusters may be related to dynamic changes in these activities [1].

The Marajó Island cluster was mainly centered in the city of Anajás, which has had the largest number of malaria cases in the State of Para over the last five years. According to the criteria that were established by the National Program for Prevention and Control of Malaria, Surveillance Secretariat of Health of the Ministry of Health, Anajás is classified as high-risk for having an IPA of 50 cases/1,000 inhabitants [20]. Furthermore, it has been estimated that approximately 90% of federal funding (approximately \$115,000 US dollars) during 2008 for surveillance and control of diseases and health problems was spent on controlling malaria in Anajás.

In the municipality of Jacareacanga and the neighboring region, we found that the increase in malaria cases was related to the process of occupation and land use, with simultaneous changes in agricultural colonization and livestock activities, mining, the creation of urban centers, and the movement of people into these areas [1]. However, it is possible that other factors can create changes in the incidence of malaria over time, despite the initial attention that is drawn to the effects of urban development, such as deforestation.

Although there are areas with low levels of malaria in the Amazon, with relative stable transmission, recently occupied regions exhibited increasing numbers of malaria cases, such as the Tucuruí region in Para State. In this area, the malaria cluster around the Tucuruí hydroelectric is likely related to the use and occupation of land, migration, urban sprawl, and especially the creation of reservoirs [29].

When we evaluated the spatial distribution of HDI, we observed different malaria profiles [3], although the malaria clusters (which responded to variable water stresses) were predominantly observed in areas with an HDI of <0.65. This finding reinforces the concept that socioeconomic variables can affect the incidence of malaria in Para state. Interestingly, during 2010 and 2011, 34,000 bed nets that contained long-lasting insecticide were distributed in various municipalities. However, our findings indicate that this method was not effective in controlling the incidence of malaria, as there was an increased incidence of malaria during the years when the bed nets were distributed. Therefore, new public policies must be developed to prevent the spread of malaria. Thus, our study (and future studies that use a similar design) provides data that can be used to support decision making regarding public health and malaria-control measures in the state of Para. Furthermore, this information could be used in systematic monitoring for indicators regarding the risk of malaria, which is largely affected by human settlement and various related environmental factors [30, 31].

These eco-epidemiological scenarios can be used to qualitatively and quantitatively examine the relationship between environmental variables (e.g., vegetation, drainage, and climate), socioeconomic variables (e.g., rural and urban population distribution, economic productivity, demographics, and dwelling types), and epidemiological variables (e.g., the incidence and prevalence of infectious and contagious diseases) [32]. Although changes in these factors can occur over different periods in specific geographical areas, eco-epidemiological analyses can be used to systematically evaluate the risks and effects that are associated with changes in these factors. For example, these studies have previously been used to evaluate the effects of environmental changes on the risk of malaria infection [29]. Therefore, these processes can be used to establish scenarios to systematically evaluate and understand the effects of eco-epidemiological changes, and to facilitate regional decision-making, especially regarding the allocation of financial resources to the most critical areas.

V. Conclusions

Our results revealed that, among the 948,142 registered cases of malaria in Para state between 2003 and 2011, the cases were most commonly reported between July and September (31%). In addition, we found that these cases were grouped in clusters in the southwest region of the state, in the center of the island Marajo, and around Lake Tucurui. Furthermore, the incidence of malaria had a very low annual correlation, which indicates spatial heterogeneity, with the irregular cluster distribution patterns being influenced by rainfall, especially during the drought period.

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