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Spatial fine-resolution model of malaria risk for the Colombian Pacific region

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Abstract

OBJECTIVE To categorise and map, at high resolution, the risk of malaria incidence in the Pacific region, the main malaria-endemic region of Colombia.

METHODS The relationship between the environmental variables Normalized Difference Vegetation Index Normalized Difference Water Index, Topographic Wetness Index, precipitation and temperature with the observed Annual Parasitic Index was evaluated using a generalised linear model. An incidence risk map at a resolution of 1 km^2 was constructed and projected to the entire endemic region. Associations of malaria risk categories with both presence records and co-occurrence of the three main malaria vectors were determined.

RESULTS A significant correlation was found for the incidence of malaria with precipitation and Normalized Difference Vegetation Index (R^2 = 0.98, $P < 0.05$), whereas there was no significant correlation with the remaining environmental and topographic variables. Moderate- to high-risk areas were located mainly in central Chocó Department along the San Juan and Atrato rivers and in areas west of the Cauca River and Pacific lowlands of the Andes Mountains. There was a statistically significant relationship for the presence of the two main vectors *Anopheles darlingi* and *Anopheles nuneztovari* with the high malaria risk category. Furthermore, malaria risk was directly proportional to the number of co-occurring vector species.

CONCLUSIONS The map obtained provides useful information on the risk of malaria in particular places of the Colombian Pacific region. The data can be used by public entities to optimise the allocation of economic resources for vector control interventions and surveillance.

keywords malaria, incidence, risk, *Anopheles*, environmental variables, Colombia

Sustainable Development Goals (SDGs): SDG 3 (good health and well-being), SDG 15 (life on land)

Introduction

In Colombia, malaria is an important problem of public health and the country ranks third in the number of cases in Latin America with 61,339 cases reported in 2018 [1]. Currently, the Pacific (PAC) region is the most important endemic area of the country registering more than 52% of the total cases in 2018 [2]. Historically in Colombia, *Plasmodium vivax* has been the main circulating species in humans, except during the period 2015-2018 when *Plasmodium falciparum* predominated [1]; although in PAC both parasite species exist, *P. falciparum* has always prevailed [2]. Furthermore, in this region the three main Colombian malaria vectors have been found naturally infected with *Plasmodium* spp.; *Anopheles* (*Nyssorhynchus*) *albimanus* Wiedemann 1820 was detected with *P. falciparum* and *P. vivax* [3]; *Anopheles* (*Nys.*) *nuneztovari* Gabaldon 1940 with *Plasmodium* sp. [4]; and *P. vivax* [5] and *Anopheles* (*Nys.*) *darlingi* Root 1923 with *P. falciparum* [6]. Information on vector parasite infection is relevant as an indicator of transmission risk [3,7].

In Colombia, in 2018, the estimated malaria risk was 7.49 cases per 1,000 population based on the number of cases diagnosed by thick blood smear (90.1 %) and rapid tests (9.4 %) [2]. However, cases are vastly underreported [8–10]. Considering that factors related to the triad host, parasite and vector play an important role in the risk of infection [11], an ecoepidemiological characterisation of malaria using malaria risk maps is proposed. Generating such maps involves variables strongly associated with the disease, including environmental, topographic and anthropic [12]. Among the variables showing a stronger correlation with malaria risk are precipitation and temperature [13], vegetation [14], humidity [15], deforestation [16], land use and cover [17], altitude [18] and human population density, terrain elevations and proximity to *Anopheles* habitats [19]. The construction of risk maps is achieved by the use of geographic information systems – GIS, satellite images at different spatio-temporal scales and the application of statistical models that may include the generalised linear model-GLM [19,20], multicriteria decision analysis [21,22] and Bayesian logistic regression [23,24].

In Latin America, few studies have attempted to categorise and map malaria risk. One of them used environmental and anthropic variables to design a malaria risk map for Buenaventura municipality in the Colombian Pacific region and showed that 89% of the cases corresponded to areas with moderate/high malaria risk [25]. Later, risk maps for Colombia and surrounding areas [26], and for northern South America [22] were produced based on expert opinion of key environmental and population risk factors. These maps provided spatial representation of potential vector exposure and the areas of relative moderate to high risk, including those in the Colombian Pacific [22,26]. Although previous works document the efforts to map malaria risk/vector exposure in the Colombian Pacific, they were constructed at the municipality level, but the high topographic and environmental complexities of this region [27] suggest the need to develop risk maps at a finer spatial scale. Therefore, this work was conducted to categorise and map, at a fine spatial scale, the risk of malaria incidence in the currently main malaria-endemic region of Colombia, the Pacific region. In addition, the associations of risk categories with both, presence records and co-occurrence of the three main malaria vectors, were determined. The identification of specific areas under malaria risk in this endemic region will provide useful information for public health entities to efficiently direct surveillance and vector control interventions, and it will allow the optimisation of resources allocated for malaria control.

Materials and methods

Study area

The Colombian Pacific region is located in the west of the country and includes the departments of Chocó, Valle del Cauca, Cauca and Nariño, which comprise 179 municipalities (Figure 1). This region is one of the most biodiverse and rainiest areas of the planet with an annual precipitation above 9000 mm [27]. The climatic and environmental conditions, active parasite circulation and a population mostly composed of people of African descent [2], are aspects contributing to the high risk of malaria incidence in this region. Furthermore, the negative Duffy blood group frequently present in this ethnic group confers resistance to infection by *P. vivax,* increasing the risk of *P. falciparum* malaria [28].

Epidemiological data

Data on the number of malaria cases by the predominant parasite species *P. falciparum* and *P. vivax*, per municipality and for the years 2013-2015 were obtained from the national public notification system [29]. The annual parasitic index (API) was calculated per municipality considering the number of malaria cases (observed API = No. of cases × 1000/population at risk per year), and the three-year data were averaged using ArcGIS software (ESRI Corporation, Redlands, CA) [30]. The output was a raster layer with a 1 km^2 resolution, and the observed API value per pixel corresponded to the average of the municipality.

Environmental variables

Environmental and topographic variables were chosen after performing a literature review that indicated their relevance for the occurrence of both malaria and vectors [12,17,31]. These included the Normalized Difference Vegetation Index (NDVI), which determines how much near-infrared light is reflected compared to visible red and helps to evaluate vegetation conditions or to differentiate bare soil from grass or forest [32]; the Normalized Difference Water Index (NDWI) used for assessing the presence of moisture in vegetation cover; changes in NDWI values reflect either sufficient vegetation water content or water stress [33], and the Topographic Wetness Index (TWI), which predicts relative surface wetness; it is an indicator of places where water will tend to accumulate [34]. The variables were obtained from various databases (Table 1), processed in raster format of 1 km^2 resolution and filtered with a mask for the Pacific region. Boundary shapefiles (polygons of urban areas) were used, and a buffer of 400-metre radius from each urban centre was generated [35]. In addition, information on environmental layers was extracted from the mask of urban areas. A database was created that contained the information of an urban centre per municipality, based on the criterion of greater nocturnal luminosity [20].

Model risk map and data analysis

The analyses performed to obtain the risk map and validate the model were as previously described [20]. Briefly,

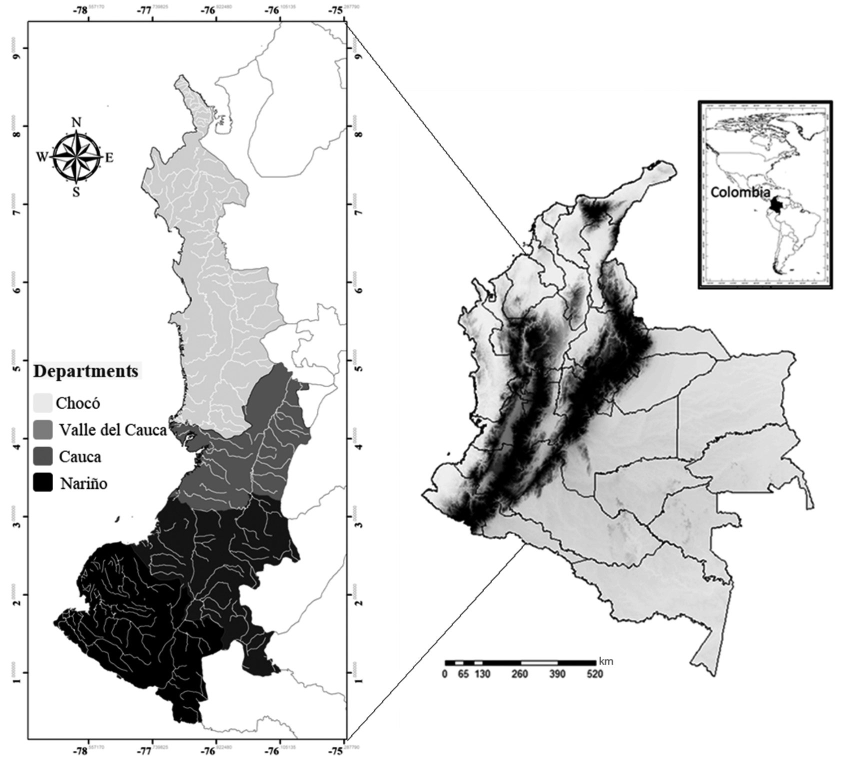

Figure 1 The malaria-endemic Pacific region (left) in relation to the Colombian map (right). The rectangle in the right upper corner shows the location of Colombia in South America.

the association between observed API and environmental variables was evaluated using the GLM; then, an estimated API map with a 1 km^2 resolution was constructed using the most explicative variables, precipitation and NDVI, in ENVI Software v.5.3. Based on the model previously proposed by Altamiranda et al. [20], the values for the variables in the GLM were included in the following function:

$$\text{Log (API)} = \text{intercept} + \text{coef.Var1} + \text{coef.Var2}$$

where Var1 and Var2 are the environmental variables that most influenced the model.

The model was validated with a linear regression analysis that assessed the relationship between observed and estimated API. The obtained map was reclassified into four risk categories (very low, low, moderate and high) by dividing the estimated API values into four classes using quartiles of incidence data. Finally, the associations of risk categories with both presence records and co-occurrence of the three main malaria vectors *An. darlingi*, *An. nuneztovari* and *An. albimanus* were determined. Records on malaria vectors were from the collections for this study and obtained from the literature [3,6,7,36,37].

Results

Malaria epidemiological data for the Pacific region or the observed API showed that Novita municipality in Chocó department presented the highest number of new cases during the period 2013-2015 with an average API of 142.8, whereas Pasto in Nariño department showed the lowest API, 0.003. Based on GLM results, the following model was defined as follows: Log (API) = 5.7502 – 37.3362 (NDVI raster data) + 0.008 (precipitation raster data). Then, the inverse equation was applied to all pixels of the area of interest to generate a malaria risk map: API = exp (5.7502) x exp [(37.3362) (NDVI raster data)] x exp [(0.008) (precipitation raster data)]. The GLM revealed that the environmental variables related to malaria incidence (observed API) were precipitation and the NDVI (with a statistically significant correlation $R^2 = 0.98$, $P < 0.05$) (Table 2). The linear regression analysis showed a statistically significant relationship

Table 1 Environmental and topographic variables used to determine the risk of malaria in the endemic Pacific region of Colombia

Environmental/ Topographic variable	Source	Spatial resolution
Annual precipitation	WorldClim	1 km
Annual mean temperature	WorldClim	1 km
Normalized difference vegetation index (NDVI)	Moderate Resolution Imaging Spectroradiometer (MODIS)	1 km
Normalized difference water index (NDWI)	Moderate Resolution Imaging Spectroradiometer (MODIS)	1 km
Topographic wetness index (TWI)	Calculated from Shuttle Radar Topography Mission Digital Elevation Data	1 km

between the observed and estimated API ($R^2 = 0.86588$, $P < 0.05$) (Figure 2).

The map constructed with the observed API showed that the departments Chocó and Nariño had the highest malaria incidence values (Figure 3a). However, the model for the estimated API, based on the incidence explanatory variables precipitation and NDVI, allowed to categorise malaria risk at a finer spatial resolution. In the Pacific region, 69 of all 179 municipalities had areas at moderate to high malaria risk (Figure 3b). They encompassed the banks of the San Juan and Atrato Rivers in Chocó department and municipalities west of the Cauca River along the lowlands of the western and central branches of the Andean Mountains, in Valle del Cauca department. The areas of low risk were located mainly northeast of Valle del Cauca and in the middle of Cauca and Nariño departments (Figure 3b).

Regarding the association between vector presence and malaria risk categories, a significant statistical relationship was found for the presence of *An. darlingi* ($X^2 = 21.022$, $P = 0.0002$) and *An. nuneztovari* ($X^2 = 12.932$, $P = 0.0059$) with the high-risk category; and for *An. albimanus* with the low malaria risk category ($X^2 = 13.62$, $P = 0.004$) (Figure 4). Furthermore, analysis of the number of co-occurring species and risk category revealed that the presence of a single species is related to low risk, while co-occurrence of two or more species increases the risk from moderate to high ($X^2 = 88.008$, $P < 0.005$) (Figure 5).

Discussion

We constructed a malaria risk map for the Pacific region that allows the definition of areas at moderate to high risk and established relationships between the presence and co-occurrence of the Colombian main vectors with the high malaria risk category. Among the few studies conducted in the Pacific region to map malaria risk, this is the first to produce a high-resolution risk map for the entire region. Our main findings are, statistically significant environmental variables for malaria risk are NDVI and precipitation; high to moderate-risk areas are primarily distributed along important rivers and low lands of the Andean mountains, the main Colombian malaria vectors *An. darlingi* and *An. nuneztovari* are positively related to high-risk areas; and that the co-occurrence of two or more vector species increases malaria risk.

The environmental variables precipitation and NDVI explained malaria risk in Pacific region; these variables were also important predictors of malaria risk in Nigeria, Africa, Mozambique and India [23,38–40]. It is well known that these conditions directly affect the presence and abundance of malaria vectors [23]. The NDVI index estimates the quantity and quality of vegetation [41]; thus, the finding that NDVI influenced the presence of high-risk areas in the Pacific region may be explained by the nature of its territory, with 80% of rural areas

Table 2 Relationship between the observed API with environmental and topographic variables, as defined by a generalised linear model

	Estimate	SE	*z* value	*P* value
Intercept	1.001e + 01	1.002e + 01	0.999	0.31782
NDVI	-5.051e + 01	1.919e + 01	−2.632	0.00848**
NDWI	6.638e + 00	4.520e + 00	1.469	0.14190
TWI	2.587e-04	5.05e-04	0.470	0.63844
Precipitation	1.002e-02	3.971e-03	2.523	0.01164*
Temperature	1.610e-01	3.999e-01	0.403	0.68718

SE, standard error.
* $P < 0.05$; ** $P < 0.01$.

characterised by natural forest of hygrophilic type [27,42]. Similarly, in a previous study conducted in a rural settlement of the Brazilian Amazon, malaria risk was associated with open areas having high NDVI [43]. Regarding the variable precipitation, the Colombian Pacific is a region with one of the highest rainfall levels in the world [27]. It is known that intense rains generate water bodies that having the appropriate conditions may serve as larval habitats for *Anopheles* species to propagate [44]. In this regard, in the Pacific region, the presence of *An. nuneztovari* has been related to transition periods from the dry to rainy season [6], and vector presence and abundance are risk factors for malaria transmission [45].

In this study, high-risk areas were primarily distributed along important rivers and low lands of the Andes Mountains. This may be related to the formation of

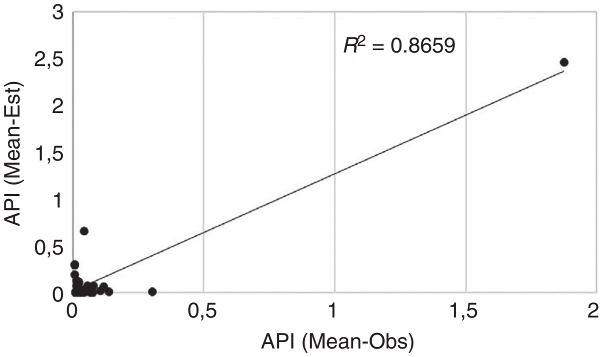

Figure 2 Linear regression analysis between the observed and estimated API. A statistically significant relationship was found (R^2 = 0.86588, P < 0.05).

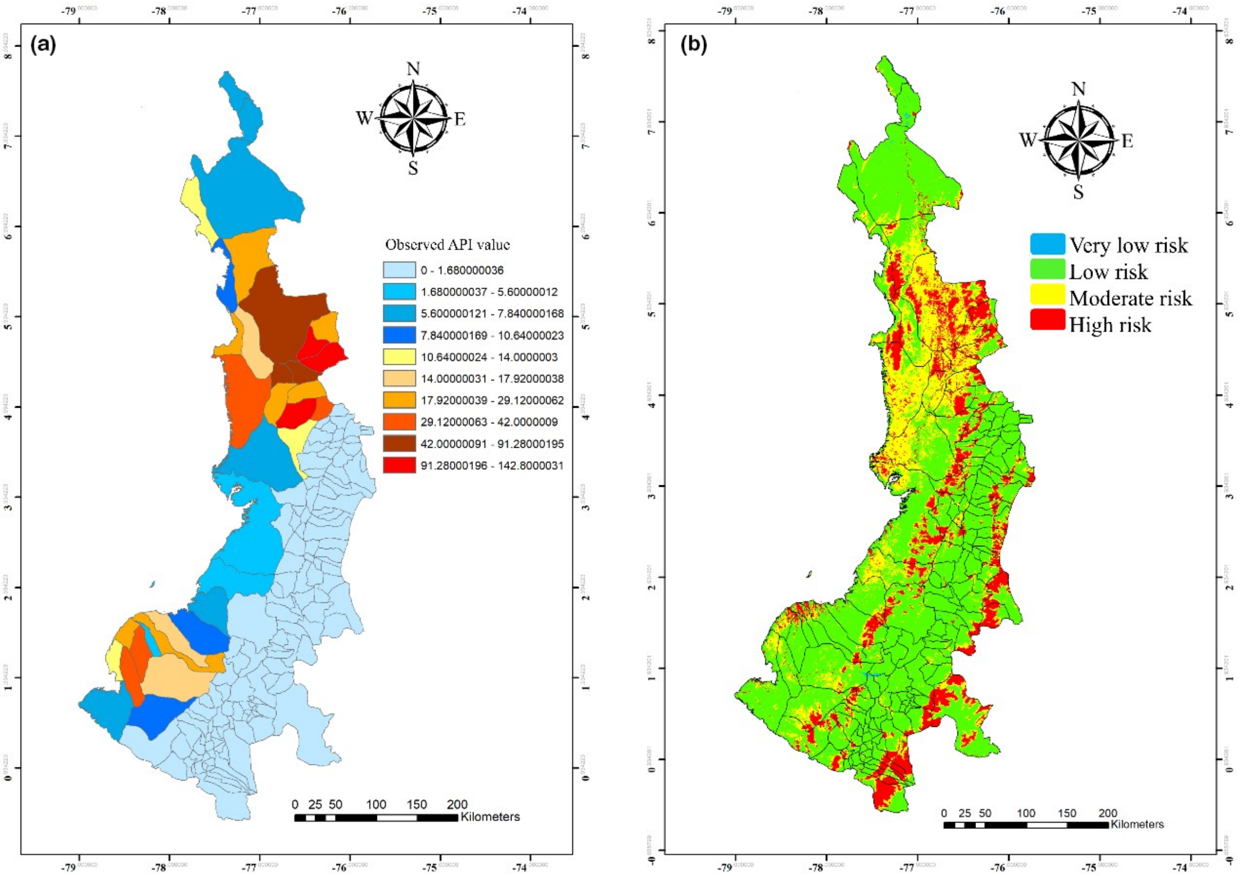

Figure 3 (a) Annual Parasitic Index (observed API) by municipality of the Pacific Region of Colombia. (b) Risk map of malaria incidence derived from a general linear model (estimated API); the coloured squares represent risk categories. [Colour figure can be viewed at wileyonlinelibrary.com]

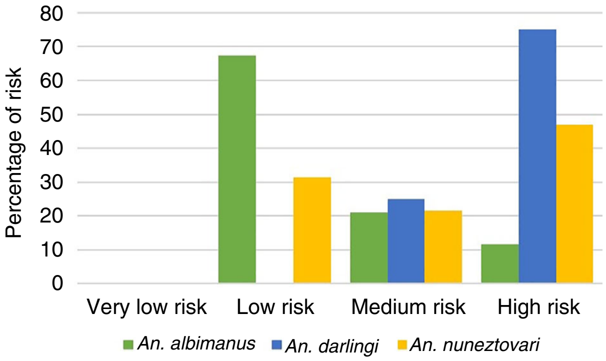

Figure 4 Relationship among risk categories of malaria incidence and the presence of the main malaria vectors in the Pacific region of Colombia. In the Y axis, the percentage of risk represent the percentage of records falling on a specific risk category. [Colour figure can be viewed at wileyonlinelibrary.com]

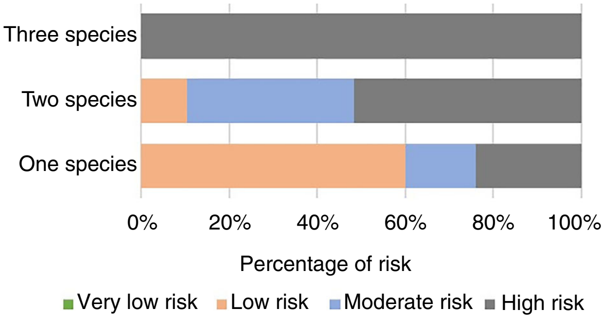

Figure 5 Co-occurrence of vector species (*Anopheles darlingi*, *Anopheles nuneztovari* and *Anopheles albimanus*) in relation to risk categories of malaria incidence in the Pacific region. [Colour figure can be viewed at wileyonlinelibrary.com]

larval habitats generated by river overflow and the ability of the soil to retain water [44,46]. Similarly, high-risk areas along stretches of rivers in the Amazon basin in Brazil and Peru [22] and in northern Colombia [26] were related to wetlands and riverine areas. Furthermore, in a malaria risk map produced for northwestern Colombia, high-risk areas were located southeast of the epidemic region and the low-risk areas were mapped in zones distant from wetlands of the main rivers, which is consistent with the lower probability of larval habitat formation and mosquito development in these areas [20]. These data agree with a pattern of disease dynamics where humans conducting activities by the rivers, such as open pit mining, are at greater risk of infection [17,46]; an increasing phenomenon in endemic localities of the Pacific region [47].

We hypothesise that the positive relationship between *An. darlingi* and *An. nuneztovari* with the category of high malaria risk is related to the ability of these vector species to adapt to disturbed environments; particularly, those caused by land use changes and socio-economic activities that generate larval habitats favourable to the proliferation of mosquito populations [6,48]. In the Pacific region, presence and abundance of *An. nuneztovari* and *An. darlingi* have been related to forest cover transitions [48], small-scale cultivated areas, livestock [5,7] and fishing [45,49]. All of these are the result of activities of inhabitants of this region [42]. Other well-known causes of altered environments that increase malaria risk are deforestation [6,50] and mining [7], which take place in various malaria-endemic areas of Colombia, including the Pacific region. It is documented that the Colombian armed conflict increased illegal open pit mining [51,52] and deforestation for the establishment of illicit crops [53].

Co-occurrence of two or more vector species increases malaria risk in the Colombian Pacific region. This confirms the findings of previous studies in northwestern Colombia, where the presence of two of the three main malaria vector species was positively related to moderate and high-risk categories of malaria incidence [20]; also, in northwestern and west Colombia, the number of malaria vector species was positively associated with the API [54]. Considering that *An. nuneztovari*, *An. darlingi* and *An. albimanus* are major malaria vectors and have been detected naturally infected with *Plasmodium* spp. in the Pacific region [3,6,37], their co-occurrence may increase human-vector contact, and as a consequence, there is a higher risk of contracting malaria.

Overall, our results indicate that at municipality level, malaria risk is heterogeneous and various categories of disease risk may be present. This observation is relevant for the implementation of directed vector control interventions specifically focused on high to moderate-risk areas as it will allow optimising outcomes and use of resources for vector monitoring and control. Our model could be used as a foundation for the design of an early alert system for disease prevention and surveillance.

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