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Environmental risk factors of leishmaniasis in Bahia State, Brazil using NASA Earth observation satellites

Fatores de risco ambientais para leishmanioses no estado da Bahia, Brasil, utilizando satélites da NASA de observação da Terra

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ABSTRACT

NASA's Earth Observing Satellites (EOS) were used to calculate three vegetation indices, extract precipitation and elevation data, and then evaluate their applicability for assessing risk of visceral leishmaniasis (VL) and cutaneous leishmaniasis (CL) in Bahia State, Brazil. Regression models showed that either form of leishmaniasis can be predicted by NDVI, NDMI, NDWI data products and TRMM) precipitation data (R^2= 0.370; p<0.001). Elevation was not significantly associated with the distribution of either VL or CL. In areas of high annual precipitation, CL was 3.6 times more likely to occur than VL. For vegetative moisture (NDMI), CL was 2.11 times more likely to occur than VL. Odds of CL occurrence increased to 5.5 times when vegetation (NDVI) and 13.5 times when liquid water content of vegetation canopies (NDWI) was considered. Areas at risk of CL and VL were mapped based on the selected explanatory variables. Accuracy of models were assessed using area under the receiver operating characteristic curve (AUC=0.72). We propose that statewide scale risk models based on use of EOS products will be a useful tool at 1 km^2 spatial resolution to enable health workers to identify and target high risk areas to prevent transmission of leishmaniasis.

Keywords. earth observing satellites, leishmaniasis, vegetation index, risk assessment.

RESUMO

Os satélites de observação da Terra (SOT) da NASA foram usados para calcular três índices de vegetação, extrair dados de precipitação e elevação e avaliar sua aplicabilidade para identificar o risco para leishmaniose visceral (LV) e leishmaniose tegumentar (LT) no Estado da Bahia, Brasil. Modelos de regressão mostraram que ambas as formas de leishmaniose podem ser preditas pelos NDVI, NDMI, NDWI e precipitação TRMM (R^2 = 0,370; p<0,001). A elevação não foi significativamente associada à distribuição de LV ou LT. Em áreas de alta precipitação anual, a LT foi 3,6 vezes mais provável de ocorrer do que a LV. Para a umidade vegetativa (NDMI), a LT apresentou 2,11 maior probabilidade de ocorrer do que a LV. As chances de ocorrência de LT aumentaram para 5,5 vezes em relação com a vegetação (NDVI) e 13,5 vezes quando o conteúdo de água líquida dos dosséis da vegetação (NDWI) foi considerado. Áreas em risco de LT e LV foram mapeadas com base nas variáveis explicativas selecionadas. A precisão dos modelos foi avaliada usando a área sob curva característica de operação do receptor (Curva COR=0,72). Propusemos que os modelos de risco em escala estadual baseados no uso de produtos SOT são uma ferramenta útil na resolução espacial de 1 km^2 por permitir que profissionais de saúde identifiquem e direcionem áreas de alto risco para evitar a transmissão da leishmaniose.

Palavras-chave. Satélites de observação da Terra, leishmanioses, índices de vegetação, avaliação de risco.

INTRODUCTION

The use of satellite remote sensing technology has shown promise for assessing the risk of vector-borne diseases at multiple spatial scales. Although remote sensing products do not identify the vectors themselves, they can be used to characterize the environment in which the vectors thrive. Earth observing satellite measurements of environmental conditions have distinct advantages over ground measurements because they can be collected repeatedly, automatically, and they are considerably faster to obtain over broad synoptic coverage areas. For the present study, NASA satellite data were used to generate three different vegetation indices and to extract precipitation and elevation information that was then correlated with incidence of leishmaniasis in Bahia State, Brazil.

In Latin America, the risk of cutaneous leishmaniasis (CL) or visceral leishmaniasis (VL) has been associated with proximity to woodlands, elevation, and temperature[1]. Annual rainfall is an important predictive variable for the prevalence and annual incidence of VL[2] the distribution of the vector, and presence of reservoir hosts by affecting the vegetation, the diurnal temperature range, and the relative humidity of a given area.

NASA EOS provides a potentially useful tool to identify favorable environmental conditions for the transmission of leishmaniasis in Bahia, Brazil[3]. The capability of identifying and monitoring risk areas using remote sensing allows for the efficient use of available resources to prevent leishmaniasis transmission by providing fast and affordable identification of areas in need of targeted control practices. The objective of this study was to investigate the usefulness of data products from NASA Earth Observing Systems (EOS) and their applicability in surveillance and response systems for leishmaniasis in Bahia, Brazil.

MATERIAL AND METHODS

Study Area

Bahia state occupies an area of 567,295 Km^2 on the northeastern Atlantic coast of Brazil with a tropical, semi-arid climate and average temperatures between 19.2 to 26.6 °C. Bahia is composed of 417 municipalities and has a population of 14.5 million[4]. The study period for this project included data collected at five-year intervals, 2001, 2006, and 2011. All twelve months were included in each study year so that wet and dry season patterns could be analyzed. The five-year intervals within the study period were chosen, rather than each year, so that any climatic/environmental effects could be analyzed over the past decade.

Data Acquisition

Leishmaniasis data was provided by the Bahia State Secretary of Health and Surveillance (SESAB) (Secretaria de Saúde do Estado de Bahia, 2012). It included VL and CL cases per municipality per month for the study period. Data products from the MODIS sensor were downloaded from the USGS Global Visualization Viewer (Glovis http://glovis.usgs.gov/). The temporal resolution of the product was 8-days and the spatial resolution of the imagery was 250 meters[5]. The Tropical Rainfall Measuring Mission (TRMM) product used for this study was obtained through the NASA Goddard Space Flight Center's release Giovanni (TRMM Online Visualization and Analysis System - TOVAS) (http://disc.sci.gsfc.nasa.gov/gesNews/version_7_tmpa-rt). This product uses a combination of the monthly multi-satellite product and rain gauge data to estimate monthly rainfall (Huffman, 2007; Liu et al., 2012). Shuttle Radar Topography Mission (SRTM) data were downloaded from the DIVA-GIS web site as a digital elevation model product for Brazil (http://www.diva-gis.org).

Data Processing

After imagery processing, three environmental vegetation indices were calculated as follows (**Figure 1**):

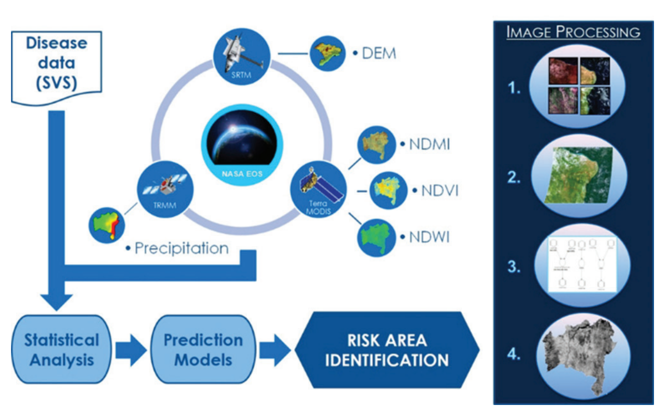

Figure 1. Schematic of Data Processing and Analysis. Areas at risk of CL and VL were mapped using the probability of having either CL or

VL, considering elevation (SRTM), precipitation (TRMM), moisture (NDMI), vegetation (NDVI) and water content of vegetation (NDWI). The multiple stepwise regression model developed showed that the occurrence of both VL and CL was influenced by NDMI, NDVI, NDWI and precipitation (R^2= 0.370; p<0.001). The accuracy of VL and CL prediction models were assessed using the area under the receiver operating characteristic curve (AUC=0.72)

1) *Normalized Difference Vegetation Index* (*NDVI*): using the near infrared band (0.86μm) and the visible red band (0.66μm) to determine changes in greenness on the earth's surface based on the density of green chlorophyll in vegetation[6].

2) *Normalized Difference Moisture Index* (*NDMI*): a moisture index that measures the amount of moisture by sensing characteristic differences between the very reflective near infrared band (0.86μm) and the water absorbed short-wavelength infrared band (1.64μm). This index highlights areas of healthy green vegetation with high moisture content and disturbed areas of vegetation with low moisture content using values also ranging from +1 and -1[7,8].

3) *The Normalized Difference Water Index* (*NDWI*) detects liquid water content in vegetation. Using the near-infrared band (0.86μm) and a particular short-wave infrared band (1.24μm), NDWI measures vegetative liquid water in the canopy[9].

TRMM accumulated rainfall totals were derived for each month during the years 2001, 2006, and 2011, for the area encompassing the state of Bahia. The data were interpolated using an ordinary exponential kriging technique in ArcGIS 10.1 to create a raster file displaying the rainfall distribution across the study area.

Data Analysis

Pearson's correlation and logistic regression were used to analyze the variables that most influenced the occurrence of VL and CL in the state. Analysis of variance (ANOVA) was used to identify significant differences over time. The probability of occurrence of VL and CL was calculated, and the accuracy of the prediction model was assessed using the area under the receiver operating characteristic curve (ROC). Statistical analyses were performed using SPSS© version 18.0 (SPSS Inc., Chicago, 2009) and SAS© version 9.1.3 (SAS Institute Inc., Cary, 2004).

RESULTS

In the years 2001, 2006 and 2011, SESAB recorded a total of 12,456 cases of leishmaniasis of which 10,782 were for CL of this disease and 1,674 were for VL. VL was reported in approximately 59% of the municipalities in Bahia State, while CL was present in approximately 70% of the municipalities. VL was concentrated in the north and central region of the state while CL was mainly concentrated along the coast and only sparsely occurred in the southern part of the state (**Figure 2**).

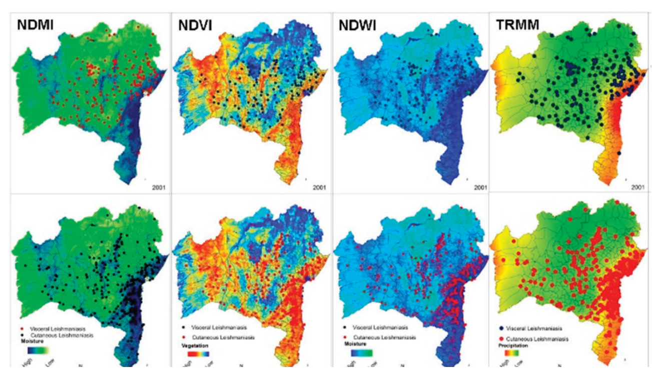

Figure 2. Maps represent annual averages for vegetation indices (NDMI, NDVI and NDWI), annual precipitation derived from TRMM, and cutaneous and visceral leishmaniasis case incidence from 417 municipalities in Bahia state. The maps show areas ranging from highest to lowest values of vegetation indices derived from MODIS imagery. Each map represents an annual composite for moisture content, vegetation abundance and water content of vegetation in Bahia State and disease incidence data for visceral leishmaniasis (VL) (black circles) or cutaneous leishmaniasis (CL) (red circles). The annual precipitation map was derived from TRMM. A risk map of CL and VL in Bahia state was later calculated by the probability of incidence of CL or VL based on significantly associated environmental features using Maxent software

A significant difference between the number of cases reported each year was observed (p= 0.0201). It was also observed a peak in the number of cases of both CL and VL in January, February and March in all three years studied (p=0. 0158).

The mean NDMI was 0.084 (SEM±0.004). The mean NDVI was 0.561 (SEM±0.004) and the NDWI mean of -0.064 (SEM±0.001). No significant oscillation between months, years and mean values of the three indices was observed, which suggests the potential of some transmission throughout the year.

Pearson's correlation indicated that both forms of disease increased when NDMI (r=0.23; $p<0.001$), NDVI (r=0.17; $p<0.001$), NDWI (r=0.25; $p<0.001$), and precipitation (r=0.21; $p<0.001$) were greatest. June and December were the wettest months in all three years studied, with the highest precipitation observed between 200 and 276 mm/month ($p<0.05$). An inverse relationship of elevation and VL and CL cases was observed, with leishmaniasis decreasing as elevation increased.

The multiple stepwise regression model developed showed that the occurrence of both VL and CL was influenced by NDMI, NDVI, NDWI and precipitation ($R^2= 0.370$; $p<0.001$). In areas with high precipitation, CL was 3.6 times more likely to occur than VL. When considering vegetative moisture (NDMI), CL was 2.11 times more likely to occur than VL. The odds of CL occurrence increased 5.5 times when vegetation (NDVI) and increased 13.5 times as compared to VL when liquid water content of vegetation canopies (NDWI) was considered.

Areas at risk of CL and VL were mapped using the probability of having either CL or VL, considering elevation, precipitation, moisture (NDMI), vegetation (NDVI) and water content of vegetation (NDWI) (**Figure 2**). It was observed that for CL, coastal areas are at higher risk, but there was also high risk at a specific area on the northwest region of the state. For VL, areas at higher risk included the north and southwest regions of the state. Although specific areas for occurrence of one or the other form of the disease were identified, both forms of leishmaniasis can overlap, and, even within a municipality, the risk levels may differ. The accuracy of VL and CL prediction models were assessed using the area under the receiver operating characteristic curve (AUC=0.72).

DISCUSSION

Bahia State is affected by both the cutaneous and visceral forms of leishmaniasis (**Figure 2**). Cutaneous leishmaniasis is widespread in Bahia with existence of foci of infection in all geographic regions (SUVISA, 2013). For VL, areas of occurrence in Bahia are expanding, especially in the semi-arid areas of the north and west regions of the state. Occurrence of VL in these areas has been associated with the implementation of agricultural projects[10]. Increasing incidence in municipalities in the east region of the state, especially north of the state capital Salvador, has been attributed to a progressive increase in human population density. Bahia State had more municipalities with reported cases of CL than VL and an increase of both forms of the disease in the state has been observed, especially towards the west region; this has been proposed to be a consequence of environmental changes associated with the development of soybean and rice production[10].

The climate in Bahia state is tropical with stable and elevated temperatures throughout the year and two distinct wet seasons. A tropical climate is predominant in the coastal areas, while in the interior areas, which occupy most of the land area, the climate is predominantly semi-arid. The wet season for the coastal area is from April to July, but rainfall is observed throughout the year. In the semi-arid region, the annual rainfall never exceeds 24 mm and the dry season is from April to October. In the semi-arid northeast region, where most records of both CL and VL are reported, dry and rainy seasons are clearly defined and there is evidence that vector density is low during the dry season and increases after the end of the rainy season (December–April), reaching its highest density level around May. These observations support reports of peak numbers of Leishmaniasis cases in the months of January, February and March when an increase in vector density favors transmission[11].

NDMI - The NDMI gives an indication of the wetness of the land surface. It detects the different content of humidity from the landscape elements, especially soil, rocks and vegetation. This index is also a good indicator of dryness[5]. High NDMI values indicate the existence of greater soil surface moisture and low values indicate low soil surface moisture content. The mean NDMI observed in the present study indicates dry soils are prevalent in areas in the interior classified as a semi-arid environment. By contrast, high moisture is observed throughout the coast where a tropical climate predominates. NDMI has been proven reliable in measuring moisture from soil, vegetation and even predicting surface temperatures[5]. Soil moisture plays a significant role in leishmaniasis incidence[12]. Vegetated areas have a greater abundance of sand flies than exclusively urban environments[13]. The impact of moisture and small water bodies as a source of moisture in the environment on the occurrence of VL indicates that NDMI is useful for identifying areas that provide suitable conditions for vector development[12].

NDVI – NDVI has been widely used for environmental studies on parasites as a remote sensing surrogate of precipitation and surface hydrologic regime Areas of recent interaction between population growth and NDVI in urban areas have been shown to be risk factors for VL in Piaui State, Brazil, and demonstrated the impact of recent, rapid occupation of periurban areas on risk of VL[14]. Population growth in an area that is already urbanized has a much smaller impact on VL incidence than the same level of growth in an area with heavy vegetation cover; NDVI can thus be a useful tool in identifying pockets of dense or scarce vegetation coverage. Vegetation in endemic areas provide shelter sites for sand flies as well carbohydrates, which is the main energy source for sand flies.

NDWI - NDWI values exhibit a quicker response to drought conditions than NDVI[5]. This index was associated with increased probability of having VL or CL in the state. Although little utilized thus far in studying diseases, NDWI can be a useful tool in the public health sphere by either identifying water bodies or a considerable quantity of water in vegetation and isolated water bodies[15]. Since NDWI is also a good indicator for drought, it is important to note that droughts have been shown to favor the development of epidemics in Latin American countries. Prolonged droughts in semi-arid north-eastern Brazil have provoked rural-urban migration of subsistence farmers, and a re-emergence of VL. Such outbreaks could be the result of human migration due to drought, environmental degradation or economic reasons and may lead to the spread of diseases in unexpected ways, and new breeding sites for vectors. The vector of VL in Bahia, *Lu. longipalpis*, has been often found inside residences during drought periods[3]. Prolonged drought periods can impact vector density and contribute to a gradual increase in the potential risk of some related epidemiologic factors, such as waning population immunity and increase in the susceptible population in the endemic areas[10]. According to Wilson and Sader[16], NDWI and NDMI are theoretically similar to each other for detection of spatial variation of surface wetness. However, NDWI performed better than other indices in identifying wetland surface water in Bihar, India and detected more pixels with water and water features in the Sahara-Sahel transition zone[2].

TRMM *Precipitation* - Precipitation is an important risk factor for CL and VL, and each form of disease, and their respective vectors, have unique environmental suitability requirements related to moisture. Precipitation plays an indirect role in the incidence of leishmaniasis by providing a suitable habitat for vector development in terms of humidity.

SRTM - Topographic influences, especially in landscapes where major altitude relief occurs, is of particular importance in predicting disease risk. Elevation by itself may not represent a crucial factor in the incidence of leishmaniasis but may influence other factors such as distance to water bodies, low vegetation, soil rich in organic matter, which are basic requirements for development and maintenance of the sand fly vectors. Bhunia et al[2] observed that altitude had a relatively strong influence on the distribution of Phlebotomus vectors in India where Kala-azar incidence is concentrated at low altitudes with fewer cases in the highlands. These results indicate that a higher incidence should be expected at low elevation as was found to be the case in Bahia State. The results of the current study in Bahia State agreed with studies by Bavia[3] in which an inverse relationship between leishmaniasis and altitude was observed. Elnaiem et al[17], observed that although the elevation did not correlate with VL incidence in Sudan in their preliminary analysis, it appeared as an important variable when used in multivariate analysis indicating that in the final analysis, elevation integrates the effects of many other factors, including distance from rivers. Such results are in agreement with other authors regarding the requirements and environmental preferences of vectors of *Leishmania* parasites. However, it is necessary to take into consideration the differences between different geographic areas as well as sand fly species.

CONCLUSION

The present study indicated that risk models based on use of environmental data generated from NASA EOS can be used to identify and specifically target interventions in areas for control of transmission of leishmaniasis. Knowledge of the timing of the transmission cycle and associated environmental features is important so that intervention measures, such as insecticide spraying, can be directed to areas at risk. The cutaneous form of leishmaniasis was more sensitive to environmental factors and NDWI was the index that best depicted occurrence of both forms of leishmaniasis in Bahia. NASA EOS data products can be an effective tool in identifying the environmental features that influence CL and VL distribution and abundance in Bahia State, Brazil as part of operational surveillance and response systems for control and elimination of neglected tropical diseases. Results of comparisons of classical NDVI measurements calculated by NIR and red wavelengths of the electromagnetic spectrum with more recent NDMI and NDWI indices calculated from the NIR and SWIR wavelengths, suggest further studies are needed to better define the usefulness of NDMI and NDWI as compared to NDVI on suitability of the environment for leishmania and other vector-borne diseases.

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