



Modelling of the distribution of *Biomphalaria glabrata* and *Biomphalaria straminea* in the metropolitan region of Recife, Pernambuco, Brazil

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Abstract

The occurrence of schistosomiasis is directly linked to the presence of its snail intermediate host *Biomphalaria* spp. Knowledge of geographical distribution, habitats and behaviour of these snails in relation to the climate is essential for guiding measures for disease prevention and control. This study aims to model the distribution of *B. glabrata* and *B. straminea* in schistosomiasis non-endemic areas of the metropolitan region of Recife (MRR) based on environmental data and estimates of snail distributions in endemic and neighbouring areas. We applied Kriging with the aim of determining the spatial distribution of these two snail species and MaxEnt for modelling their ecological behaviour. Kriging showed that the North and the Centre of the MRR were generally either snail-free or contained only *B. straminea*, while both snail species could be found in the South. MaxEnt supported our observation that the northern and southern coastal regions were favoured by *B. glabrata* and diurnal mean temperature variation; July rainfall and November rainfall were the three variables favouring *Biomphalaria* breeding sites that contributed the most in the predictive model we developed. The study showed the location of areas suitable to *Biomphalaria* spp. and therefore

at potential risk, first for invasion of these snails and later for the development of new schistosomiasis-endemic areas. This information should be useful, not only to estimate expansion possibilities of this disease in the MRR, but also to point out the climatic variables that would contribute to this expansion, thereby allowing timely application of prevention and control measures.

Introduction

The snails that host schistosomiasis belong to class Gastropoda, family Planorbidae, genus *Biomphalaria*. In Brazil, eleven species and one subspecies of *Biomphalaria* (Preston, 1910) have been described: *B. glabrata*, *B. straminea*, *B. tenagophila*, *B. peregrina*, *B. schrammi*, *B. kuhniiana*, *B. intermediai*, *B. amazonica*, *B. oligoza*, *B. occidentalis*, *B. cousini* and *B. tenagophila guaibensis* but only the first three of these are found to be naturally infected with *Schistosoma mansoni* (Brazilian Ministry of Health, 2009, 2014). *B. glabrata* is the main intermediate host given its wide geographical distribution and the fact that it presents high levels of infection, while *B. straminea* is the most successful species given its capacity to adapt to climatic variations. *B. tenagophila* has epidemiological importance for transmission of *S. mansoni* in the states of the southern and south-eastern Brazil (Brazilian Ministry of Health, 2014). The genus *Biomphalaria* has existed since the Jurassic period (approximately 140 million years ago). It is directly influenced by the environment in which it lives and has developed a variety of survival strategies (Brazilian Ministry of Health, 2014). These snails' habitats consist exclusively of freshwater bodies with little water velocity (less than 30 cm/sec), such as rivers, streams, channels and flooded areas, preferably with little depth (Barbosa and Barbosa, 1994; Pieri and Favre, 2008). There are even reports of the existence of these snails in puddles, drains and flooded, vacant land (Barbosa *et al.*, 2001, 2004; Silva *et al.*, 2006; Souza *et al.*, 2008). The presence of vertical or floating vegetation contributes food and shelter and provides support for spawning, which is always done on when the snails are submerged (Brazilian Ministry of Health, 2014). Presence of schistosomiasis has been described in 18 of the states of Brazil, including the Federal District, and its occurrence is directly linked to the presence of *Biomphalaria* (Brazilian Ministry of Health, 2009). In the state of Pernambuco, *B. straminea* is endemic in the Zona da Mata region, with some records also on the coast of this state, while *B. glabrata* occurs in the coastal region (Barbosa *et al.*, 2010, 2014). Knowledge of these snails' habitats, behaviour in relation to climate change and geographical distribution is essential for guiding measures for prevention and control of schistosomiasis.

Geospatial techniques were first applied to studies on schistosomiasis in the Philippines and in the Caribbean (Cross and Bailey, 1984).

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Key words: Schistosomiasis; Biomphalaria; Geospatial techniques; Brazil.

Acknowledgments: to the staff of Schistosomiasis Laboratory of the Research Center Aggeu Magalhães-Fundação Oswaldo Cruz, FACEPE (Amparo Foundation Science and Technology of Pernambuco) and CAPES - Brazil Program Without Misery.

Received for publication: 2 June 2016.
Revision received: 12 September 2016
Accepted for publication: 18 October 2016.

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Licensee PAGEPress, Italy
Geospatial Health 2016; 11:490
doi:10.4081/gh.2016.490

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In Brazil, use of geographical information systems (GIS) in relation to schistosomiasis occurred initially in Bahia (Bavia *et al.*, 1999). They constructed maps showing environmental characteristics, prevalence of *S. mansoni* and its snail host in order to study the spatial and temporal dynamics of the infection thereby providing an indication of the environmental factors that influence the distribution of schistosomiasis. Geostatistical techniques such as Kriging (Isaaks and Srivastava, 1989) and MaxEnt (Elith *et al.*, 2011) were initially applied in the field of mining and assessment of mineral resources, and later for studies of plant and animal ecology.

Kriging is a spatial estimation technique that can be used to build probabilistic models for values not sampled, allowing inferences from observed values (Felgueiras, 1999; Shad *et al.*, 2009). Indicator Kriging for categorical data takes into consideration the uncertainties associated with the data and methods involved in modelling, thus enabling creation of maps of snails spatial distributions along with the corresponding uncertainties (Felgueiras, 1999). MaxEnt is a maximum entropy approach to species distribution that allows estimation and modelling of species distribution based on environmental characteristics (Phillips *et al.*, 2004). This means that places with similar climatic and other environmental characteristics are likely to present biomes suitable to the same plants and animals (in this case snails). Biomes are distinct from habitats because any biome can comprise a variety of habitats.

Since the beginning of this century, several authors have started to use these techniques also towards advancing human health (Campos *et al.*, 2002; Fortes *et al.*, 2004; Lourenço and Landim, 2005; Castro and Singer, 2007; Cardim *et al.*, 2013; Samy *et al.*, 2014). In particular, these techniques have been used to model diseases such as schistosomiasis in studies developed by Guimarães *et al.* (2009, 2010, 2012) to estimate the spatial distribution of *Biomphalaria* snails in the state of Minas Gerais. Furthermore, Scholte *et al.* (2012) used modelling based on environmental characteristics with this aim in the whole country. These studies are based on data from the literature and the authors pointed out that there is a need for new studies using primary, georeferenced data derived from malacological surveys.

The present study had the aim of modelling the distribution of *B. glabrata* and *B. straminea* in non endemic areas of the metropolitan region of Recife (MRR), Pernambuco based on estimates of the distribution of the species in neighbouring areas and environmental data.

Materials and Methods

Study area

The study was carried out in MRR that is characterized by a tropical humid climate or pseudo-tropical climate according to the Koppen classification (Alvares *et al.*, 2013), with rain well distributed throughout the year but with the months May to July the wettest and October to December the driest. The average annual temperature of the area is 24°C, ranging from 18 to 32°C (CPRH, 2003a).

The hydrography of the area is made up of coastal and transcoastal rivers. The coastal river begins and flow into the coastal zone is in general perennial, although small in size, play an important role in maintaining ecosystems and communities. The transcoastal begins in the region Agreste of Pernambucano, where they present a temporary basis, becoming perennial to penetrate the Forest Zone, have wide scope and large number of tributaries and flow into the coastal zone (CPRH, 2003b).

The geological structure of the MRR consists of tertiary, quaternary and recent deposits (marine terraces and mangrove deposits). In the East, the coastal plain forms a geological relief of sedimentary origin with variable width and an altitude from 0 to 10 m. This includes features, such as beaches, salt marshes (marine terraces), mangroves (marsh or muddy formations), temporarily and permanently flooded river floodplains and terraces bordering the terminal course of rivers. In the West, the coastal plain ends with hills and mountains that rise up to 400 m (CPRH, 2003a, 2003b).

The vegetation consists of remnants of the Atlantic Forest that covered the area up to the colonial times, but which has now been replaced by agriculture with sugarcane and coconut as the main produce. Implementation of allotments and logging for firewood added to the destruction of the forests. The land along the coastal strip is subject to constant tidal forces of the sea, which favours mangrove vegetation, which remains relatively conserved (CPRH, 2003a, 2003b).

Spatial analysis

To model the spatial distribution of the intermediate snail host of schistosomiasis, the following two geospatial techniques were applied: Kriging, with the aim of estimate what species of *Biomphalaria* (with focus on quantity and proximity) would be most likely based on information from neighbouring areas; and MaxEnt for estimate and modelling of the distribution of the species of snails based on ecological behaviour.

Kriging

To estimate the distribution of *Biomphalaria*, geolocation data for the localities distributed across the 14 municipalities of the MRR were used. We used categorical Kriging to take into account uncertainties associated with the data and methods involved in the models, thus enabling creation of random fields equiprobable. The conditions for the positive localities were that *B. glabrata* only, *B. straminea* only or *B. glabrata* + *B. straminea* were present, while areas where there were no snails were considered negative. For the municipalities for which there was no information regarding the geolocation of *Biomphalaria*, the attributes (presence or absence of snails) were distributed across the six hydrographic basins of Pernambuco that were present within the study area, in accordance with the methodology suggested by Guimarães *et al.* (2009). This methodology consists of distribute a point sequence along the drainage network when there isn't a geolocation of breeding places.

A total of 290 points were used in the categorical Kriging according to indication. Variogram models that are used to characterization of spatial correlation through creation of experimental semivariograms were fitted for each class of *Biomphalaria*, through exploratory analysis, using the geostatistical procedures of SPRING software (Câmara *et al.*, 1996). These procedures involve the creation of user-interactive semivariograms, which were adjusted using theoretical mathematical models (spherical, exponential, Gaussian or potency models). After fitting the models, their appropriateness in relation to the theoretical models was verified according to Camargo (1997). Following this, categorical Kriging procedures were applied as indicated. The snail spatial distribution maps, with a spatial resolution of 100 m, along with their corresponding uncertainties, which can vary from 0 to 1, were constructed using ArcGis 10 (<http://www.esri.com/software/arcgis/>), based on estimated functions.

MaxEnt

We used MaxEnt (<https://www.cs.princeton.edu/~schapire/maxent/>)



to estimate and model the distribution of *Biomphalaria* spp. snails based on environmental variables; 67 climate data were used. The 19 monthly, bioclimatic variables (<http://www.worldclim.org/bioclim>) were obtained from Worldclim Global Climate (<http://www.worldclim.org/>), which provides monthly climatic information interpolated from meteorological stations over a 50-year period (1950-2000) with 1-km spatial resolution (Table 1). We applied MaxEnt with 441 georeferenced points to estimate the occurrence of species of the schistosomiasis intermediate host snails *B. glabrata* and *B. straminea*. The models produced were implemented through the MaxEnt software, the configurations used were: random teste percentage of 30% and 10 replications to enable a better data representation. The other resources were selected automatically. The performance of the model was ascertained using the area under the curve (AUC) of the receiver operating characteristic (ROC) curve, which measures the exactness of the predictive distribution models. The final models were plotted at a spatial resolution of 1 km using the ArcGIS software.

Table 1. Worldclim global climate variables.

Variable	Code
Annual mean temperature	Bio 01
Mean diurnal range	Bio 02
Isothermality	Bio 03
Temperature seasonality	Bio 04
Maximum temperature of the warmest month	Bio 05
Minimum temperature of the coldest month	Bio 06
Annual temperature range	Bio 07
Mean temperature of the wettest quarter	Bio 08
Mean temperature of the driest quarter	Bio 09
Mean temperature of the warmest quarter	Bio 10
Mean temperature of the coldest quarter	Bio 11
Annual precipitation	Bio 12
Precipitation of the wettest month	Bio 13
Precipitation of the driest month	Bio 14
Precipitation seasonality	Bio 15
Precipitation of the wettest quarter	Bio 16
Precipitation of the driest quarter	Bio 17
Precipitation of the warmest quarter	Bio 18
Precipitation of the coldest quarter	Bio 19

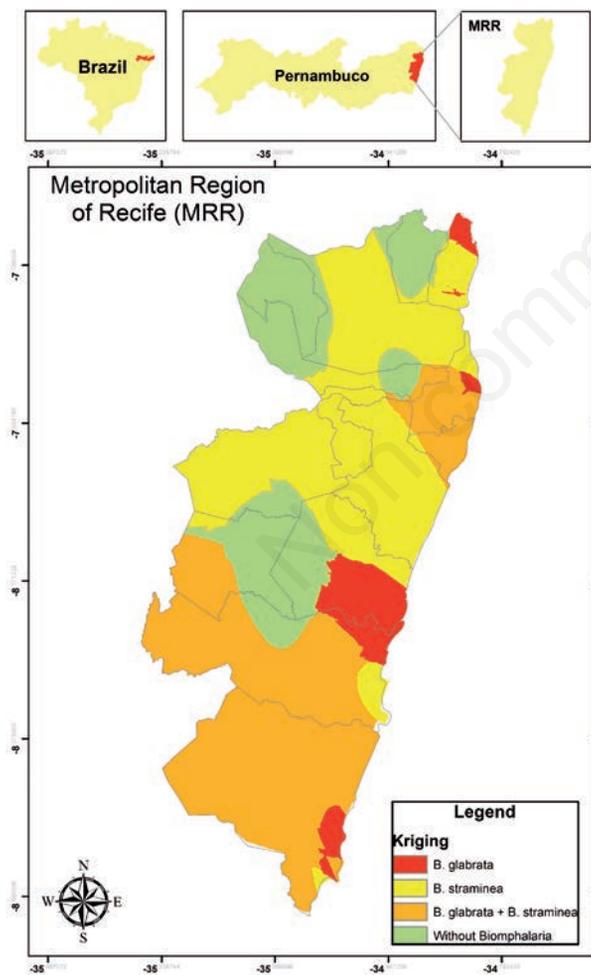


Figure 1. Spatial distribution of *Biomphalaria* in the metropolitan region of Recife obtained by Kriging.

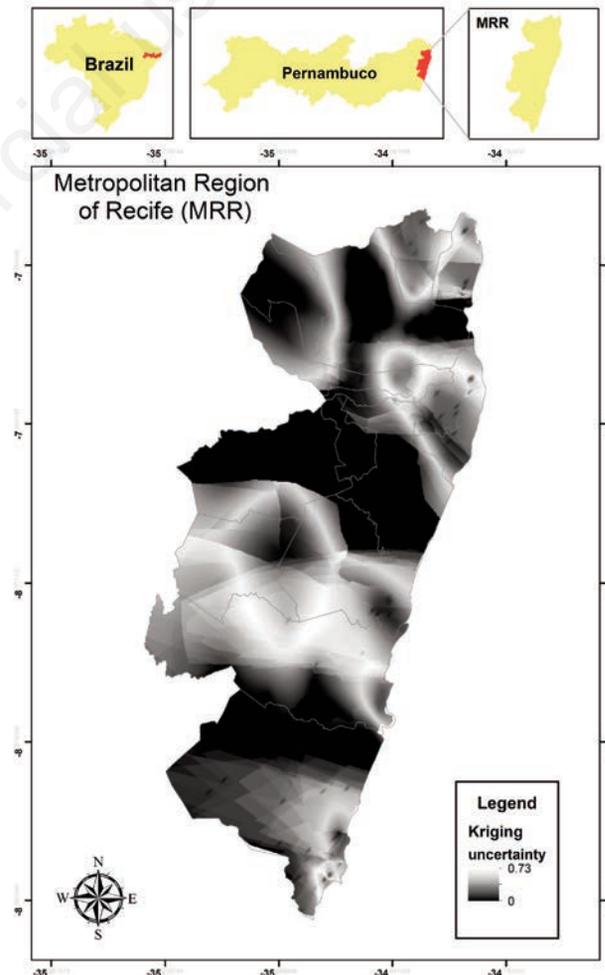


Figure 2. Demonstration of the area of uncertainty regarding the spatial distribution of *Biomphalaria* in the metropolitan region of Recife obtained by Kriging.



Results

Figure 1 shows the result of applying categorical Kriging in MRR. It demonstrates that either *B. straminea* alone or complete absence of snails predominate in the North and Centre of the MRR, both *B. glabrata* and *B. straminea* coexist in the South. Figure 2 shows the 0.73 uncertainty map of the modelling. The uncertainties were higher in the transition areas between the two species.

Figures 3 and 4 show the MaxEnt results regarding the most likely areas for occurrences of *B. glabrata* and *B. straminea* in the MRR. The northern and southern coastal regions showed the greatest receptiveness for the former snail species, while the central area was favoured by the latter. The diurnal mean temperature suited both snail species equally well, while the variables particularly favourable for *B. glabrata* and which contributed most to the predictive model were the diurnal mean temperature, July rainfall and November rainfall, while in the case of *B. straminea* it was November rainfall. With an AUC of 0.999, the predictive capacity of the models was high.

Discussion

Knowledge of the density, dynamic population and distribution of *Biomphalaria* snails is an important tool for planning schistosomiasis control programs in the areas where these snails occur. In the present study, the use of categorical Kriging according to indication made it possible to ascertain the spatial distribution of *Biomphalaria* in the MRR based on the distribution of the two different species. One type of neighbourhood was clearly favoured by both species, while *B. straminea* was found alone in another. It has been pointed out that competitive exclusion influences the distribution of the species since the 1970s, *i.e.* *B. straminea* showing dominance due to the biological characteristics of this species, such as high reproductive rate, invasiveness and relatively ease in adaptation to new environments (Barbosa *et al.*, 2014). This has allowed its establishment in new locations, bringing with it the possible endemicity of schistosomiasis, *e.g.* in the forest zone of Pernambuco where this species is now common (Barbosa *et al.*, 2006). The replacement process of *B. glabrata* by *B.*

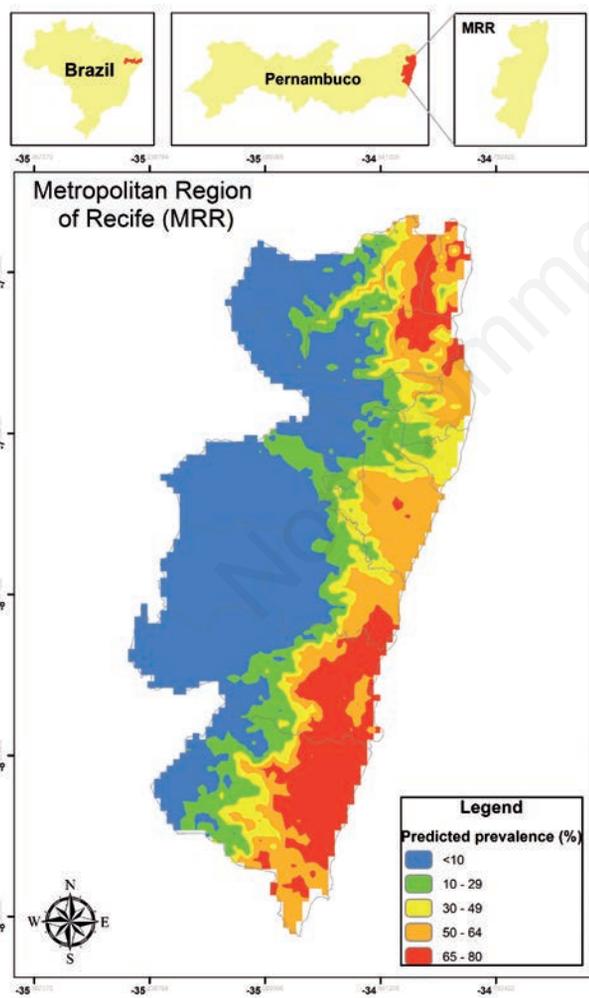


Figure 3. Spatial distribution of *Biomphalaria glabrata* in the metropolitan region of Recife obtained by MaxEnt.

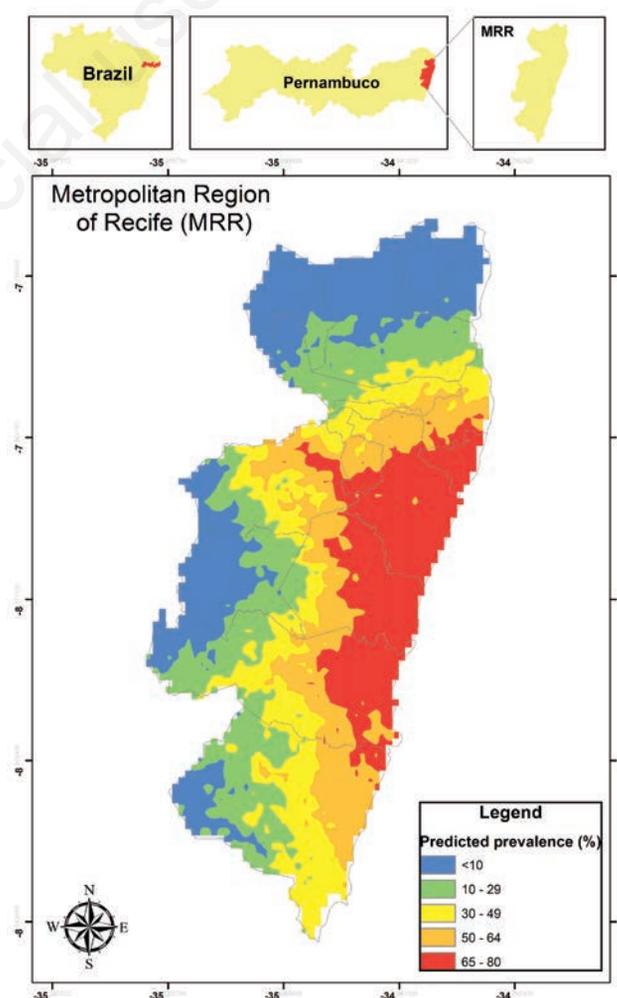


Figure 4. Spatial distribution of *Biomphalaria straminea* in the metropolitan region of Recife obtained by MaxEnt.



straminea in the MRR was reported by Barbosa *et al.* in 2014. The uncertainty found in this study was very similar to that seen by Guimarães *et al.* in 2012. These authors reported a mean of 0.23 in estimates with greater certainty (100% in the São Francisco River Basin) and 0.33 in estimates with lower certainty (67% in the Paraíba do Sul River Basin), which supports the view that transitions and uncertainties will be greater in areas in which several species occur simultaneously. When modelling the distribution of *Biomphalaria* based on environmental characteristics, temperature and rainfall were the characteristics that contributed the most, which was also observed by Scholte *et al.* (2012). Fluctuation of environmental temperatures and precipitation has a direct effect on the density of the snail populations studied. The hot season is most favourable for snail reproduction as it increases the microflora, which serves as an important nutritional source, while aquatic plants provide adequate dissolved oxygen and surface where the snails can crawl and deposit their egg masses (Malek, 1958). Increase in temperature also stimulates the release of cercariae (Lutz, 1919; Rey, 2008) with the optimum temperature for snail development is between 20 and 26°C (Barbosa and Barbosa, 1994), but temperatures from 18 to 41°C can be tolerated (Brazil, 2008). Rainfall influences the formation and expansion of snail breeding sites/foci (Barbosa and Barbosa, 1994). In the rainy season (May to August), *Biomphalaria* spp. populations decrease due to flooding, but there is accelerated snail growth and production of new individuals leading to repopulation of breeding sites, which mainly occurs at the end of the rainy season (September to December), when increasing the number of stagnant water (Paraense, 1972; Grisolia and Freitas, 1985; Juberg *et al.*, 1987). Despite being basically harmful, established snail populations may flush out snails leading to the formation of new habitats (WHO, 1957).

Our models presented high predictive accuracy given that AUC values >0.75 should be considered excellent according to Phillips *et al.* (2006). Snail distribution and consequently also cases of schistosomiasis could be modelled from the environmental and climatic characteristics and therefore the maps of the distribution of *Biomphalaria* obtained can be used as predictors for the distribution of *S. mansoni*. Since schistosomiasis is a disease with distribution determined by the structural and contextual components of the environment, geoprocessing should be a powerful tool for unravelling the causal factors and analyzing the risk of occurrence of this disease in space and time (Guimarães *et al.*, 2010).

Conclusions

This study showed areas of potential occurrence of *Biomphalaria* spp. snails. This facilitates the estimation of schistosomiasis in MRR by pointing out the variables that contribute to the expansion of this disease, allowing the application of effective measures to its prevention and control.

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