

# Predicting the spatial distribution of *Biomphalaria straminea*, a potential intermediate host for *Schistosoma mansoni*, in China

Mohamed R. Habib,<sup>1,2</sup> Yun-Hai Guo,<sup>2</sup> Shan Lv,<sup>2</sup> Wen-Biao Gu,<sup>2</sup> Xiao-Heng Li,<sup>3</sup> Xiao-Nong Zhou<sup>2</sup>

<sup>1</sup>Medical Malacology Laboratory, Theodor Bilharz Research Institute, Giza, Egypt;

<sup>2</sup>National Institute of Parasitic Diseases, Chinese Center for Diseases Control and Prevention, Shanghai; <sup>3</sup>Shenzhen Center for Disease Control and Prevention, Shenzhen, China

## Abstract

Schistosomiasis is one of the most prevalent parasitic diseases impacting human health in the tropics and sub-tropics. The geographic distribution of *Schistosoma mansoni*, the most widespread species, includes areas in Africa, the Middle East, South America and the Caribbean. Snails of the genus *Biomphalaria* act as intermediate host for *S. mansoni*. *Biomphalaria straminea* is not indigenous in China but was accidentally introduced to Hong Kong from South America and has spread to other habitats in the southern parts of the country. This species is known for its great dispersal capacity that highlights the importance of the snail as a potential host for *S. mansoni* in China. In

this connection, although no such infection has been recorded in the field so far, the continuous expansion of China's projects in endemic areas of Africa and import of the infection via returning workers or visitors deserve attention. The purpose of this study was to map and predict the spatial distribution of *B. straminea* in China. Snail occurrence data were assembled and investigated using MaxEnt software, along with climatic and environmental variables to produce a predictive risk map. Of the environmental variables tested, the precipitation of warmest quarter was the most contribution factor for snail's spatial distribution. Risk areas were found in southeastern China and it is expected that they will guide policies and control programmes to potential areas area of snail abundance and used for spatial targeting of control interventions for this invasive species.

Correspondence: Xiao-Nong Zhou, National Institute of Parasitic Diseases, Chinese Center for Disease Control and Prevention, 207 Rui Jin Er Road, Shanghai 200025, China.

Tel: +86-21-64738058 - Fax: +86-21-64332670.

E-mail: zhouxn1@chinacdc.cn

Key words: *Biomphalaria straminea*; *Schistosoma mansoni*; MaxEnt; Risk map; China.

Acknowledgments: this work was supported by the National Key Research and Development Program of China (2016YFC1202001), and research fund for the prevention and control of technical reserves, National Institute of Parasitic Diseases, Chinese Center for Disease Control and Prevention (CB-1603). Mohamed R. Habib was supported by a post-doctoral programme from the Ministry of Science and Technology of China and National Center for International Research on Tropical Diseases (Shanghai, China).

Received for publication: 21 January 2016.

Revision received: 15 September 2016.

Accepted for publication: 16 October 2016.

©Copyright M.R. Habib *et al.*, 2016

Licensee PAGEPress, Italy

Geospatial Health 2016; 11:453

doi:10.4081/gh.2016.453

This article is distributed under the terms of the Creative Commons Attribution Noncommercial License (CC BY-NC 4.0) which permits any non-commercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

## Introduction

Invasive species have been the focus for many studies in diverse fields such as biology, agriculture, transportation, and economics (Carlton, 1996; Higgins *et al.*, 1999; Kareiva, 1996; Meyerson and Mooney, 2007; Williamson, 1999). Man-derived ecological modification, land reclamation, and movement to new areas resulted in introductions of species to novel landscapes (Peterson, 2003). It is difficult to identify the key factor for successful invasion and colonization that can be employed for a predictive understanding of which species represent potential invaders (Perrins *et al.*, 1993; Peterson, 2003). Instead some climate factors are used to predict the behaviour of invasions based on the concept of ecological niches as a constraint to the distributional potential of species (Grinnell, 1924). Species can only establish populations in areas that meet the ecological requirements found in native areas of these species.

The study of invasive *Biomphalaria* species acquires an additional importance due to their potential role as intermediate hosts for *Schistosoma mansoni* that impact human health in tropical and subtropical countries (Basch, 1976; Mandahl-Barth, 1957; Morgan *et al.*, 2001). While factors such as dispersion by floods, plants, aquarium fish shipment, and aquatic birds' migration are linked to the widespread distribution of this intermediate host, other environmental factors regulate their abundance and establishment in new areas. Although these snails can tolerate variations in physical, chemical and biological parameters in the environment where they live (Kloos *et al.*, 2001; Utzinger *et al.*, 1997; Woolhouse, 1992), there is a threshold limit for this tolerance. Several biotic and abiotic factors in the environment control *Biomphalaria* abundance and distribution (Brown, 1994;

Rollinson, 2011). Nevertheless, some species of *Biomphalaria* have proven successful in occupying new ecological niches that in turn led to schistosomiasis expansion, even to non-endemic areas (Sturrock, 1973; Yousif *et al.*, 1996; Lardans and Dissous, 1998; Pointier *et al.*, 2005a; Teodoro *et al.*, 2010).

*Biomphalaria straminea* is highly invasive, apparently due to its association with aquatic plants trade (Pointier *et al.*, 2005b). It is an important intermediate host for *S. mansoni* transmission in South America especially Brazil (Paraense and Corrêa, 1989; Melo *et al.*, 2006; Fernandez and Thiengo, 2010). Reports of natural infection of this snail species with *S. mansoni* were recorded from different parts of Brazil (Malek, 1985; Fernandez and Thiengo, 2010; Galvão *et al.*, 2010; Barboza *et al.*, 2012). Although it is less important for *S. mansoni* transmission in areas where its distribution overlaps with *B. glabrata* (Carvalho, 1992), it has been implicated in disease transmission in some Brazilian states, *i.e.* in Fordlandia in the state of Para (Machado and Martins, 1951) and Goiania in the state of Goiás (Cunha, 1967). In addition, its importance in schistosomiasis transmission is linked to its wide distribution in almost all water basins in Brazil especially in the Northeast, south of Bahia and in the northeastern part of the state of Minas Gerais (PAHO, 1968; Paraense *et al.*, 1986). This wide distribution can be attributed to the fact that *B. straminea* has a high capacity to resist periods of drought (Barbosa and Barbosa, 1994). The ability of this snail species to occupy and replace other *Biomphalaria* species following its introduction proves that it is not only an invasive and competitive species, but also a good colonizer of natural environments (Michelson and Dubois, 1979; Barbosa *et al.*, 2014).

In China, the snail was introduced to Hong Kong in 1974 (Meier-Brook, 1974) and subsequently dispersed to different water habitats in Guangdong Province in southern China (Gao *et al.*, 2013; Wang *et al.*, 2013; Attwood *et al.*, 2015). The presence of this species in China and its potential expansion is important from a public health perspective as a potential transmitter of *Schistosoma mansoni* to mainland China where is only the endemic area for *S. japonica* (Collins *et al.*, 2012; Zhou *et al.*, 2016a). Yet, to date no studies have described the potential distribution of this snail in China.

Although malacological surveys based on manual snail collection are simple and straightforward, they are time-consuming and logistically challenging. A possible alternative way to overcome these challenges is to determine factors that regulate the snail abundance, and use this information to predict its presence in un-surveyed areas (Kristensen *et al.*, 2001; Stensgaard *et al.*, 2006). Suitable and better models for the distribution and transmission of schistosomiasis can be obtained by integrating the essential biology of the parasite, the intermediate snail host and the definitive human host (Stensgaard *et al.*, 2013). Many studies have demonstrated the relation between environmental and climatic factors and the distribution of *Biomphalaria* species and prevalence of *S. mansoni* (Woolhouse and Chandiwana, 1989; Bavia *et al.*, 1999; Brooker and Michael, 2000; Kristensen *et al.*, 2001; Malone *et al.*, 2001; Raso *et al.*, 2005; Simoonga *et al.*, 2009; Malone and Bergquist, 2012). Many of these factors are easy to incorporate in a geographical information system (GIS) for the analysis of species suitable habitats and providing estimates of the potential spread of that species (Haltuch *et al.*, 2000; Elith *et al.*, 2006). In addition, data on climate and environment, such as land surface temperature and vegetation indices can easily be obtained from various earth orbiting satellites, and represents a rapid way to develop spatial models of snail distribution (Stensgaard *et al.*, 2005). Prediction maps developed by spatial technologies and species distribution models (SDMs) provide adequate understanding of the potential distribution of various species. Such maps are useful in the management of invasive species (Peterson, 2003; Peterson and

Shaw, 2003).

Different spatial modelling techniques have been used to model *Biomphalaria* distribution such as maximum entropy (MaxEnt) (Scholte *et al.*, 2012; Stensgaard *et al.*, 2013; Pedersen *et al.*, 2014), genetic algorithm for rule-set prediction (GARP) (Stensgaard *et al.*, 2006), and geostatic indicator Kriging (Guimarães *et al.*, 2009). There are also non-regression models such as the Bayesian geostatistical approach for modelling *Biomphalaria spp.*, distribution (Raso *et al.*, 2005; Vouatsou *et al.*, 2009; Standley *et al.*, 2012; Schur *et al.*, 2013). The data employed in the present study are presence-only data for *B. straminea* in China. These data were used to produce predictive risk maps of the spatial distribution of this potential intermediate host snail using MaxEnt modelling approach using environmental and climatic proxies, obtained from remote sensing (RS) and climate databases, as constraints for the snail distribution. The MaxEnt model is well suited to make predictions from presence only-data, and has been shown to outperform other species distribution modelling software, especially when sample sizes are low (Elith *et al.*, 2006; Phillips *et al.*, 2006; Phillips and Dudík, 2008; Stensgaard *et al.*, 2013). Occurrence-based approaches statistically link spatial data to species distribution records (Elith *et al.*, 2010). The generated maps are useful for the targeting this invasive and potential schistosomiasis snail host for control interventions. The main purpose of this study is to link the distribution of a species to environmental and/or climatic factors to create a prediction map, in order to understand the distribution pattern of the invasive species *Biomphalaria* in China. (Elith *et al.*, 2006; Zhou *et al.*, 2016b).

## Materials and Methods

### Study area and malacological surveys

Shenzhen City, located in southern China, lies between longitudes 113°.46 and 114°.37E and latitudes 22°.27 and 22°.52N. Shenzhen was selected to build our initial training MaxEnt model because *Biomphalaria* snails are well established in many water systems of the city. In addition, Shenzhen is adjoining Hong Kong in which the first introduction of *B. straminea* was reported and followed by subsequent dispersal (Meire-Brook, 1974; Attwood *et al.*, 2015). The malacological surveys were conducted during 2015 in many freshwater habitats throughout urban and rural areas of Shenzhen city to map the distribution of *B. straminea* (Figure 1). Sampling was quantified, with two collectors investigating 100 m length of the water body for 30 minutes and collecting all *Biomphalaria* found. The snail dip-net with long handle was used for snail collection. Samplings were carried out at different water levels and at least ten dip-nets were taken from each water body. Each location was georeferenced with a handheld geographical positioning systems (GPS) device (Garmin GPSMap 60CS, Garmin Ltd., Kansas City, MO, USA) and the coordinates were recorded. Collected snails were transferred to the laboratory and identified using integrated morphological and molecular approach (Paraense, 1961; Paraense, 1975; Attwood *et al.*, 2015).

### Environmental layers

Environmental data were obtained from different freely accessible remote sensing data sources, as summarised in Table 1. Briefly, climatic data were obtained from Worldclim global dataset (available from: <http://www.worldclim.org>; Hijmans *et al.*, 2005). These data provide interpolated monthly climatic information from weather stations averaged over a 50-year period (from 1950 to 2000) at the 1-km spatial res-

olution. The altitude variable was derived from the Hydro-K data set of the United States Geological Survey (USGS) at the same spatial resolution. The bioclimatic variables were selected based on their perceived biological relevance for intermediate host snail distributions (Appleton and Eriksson, 1984; Stensgaard *et al.*, 2013). Also, temperature of the warmest and coldest quarter was included due to the sensitivity of *Biomphalaria* snails to temperature changes (Appleton, 1977; Pflüger, 1981).

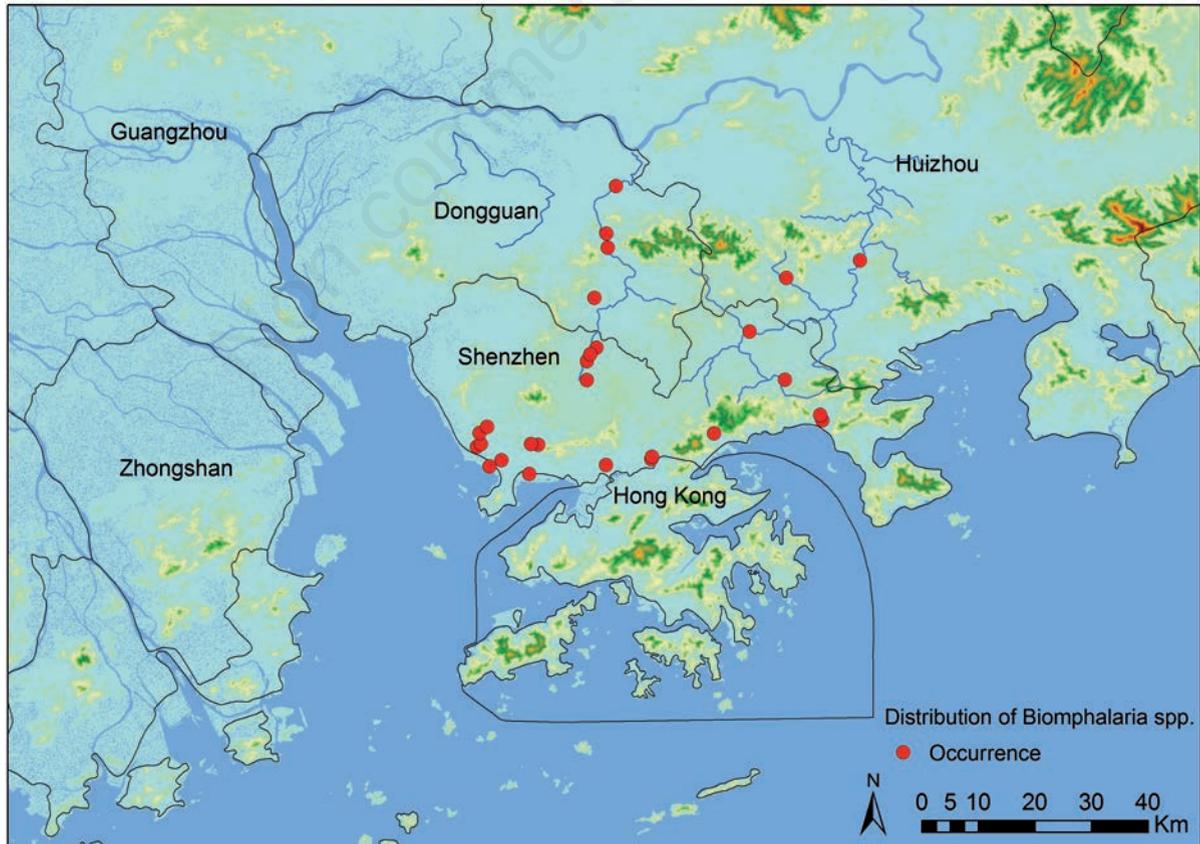
### Model implementation

Distribution modelling was implemented using the MaxEnt approach that is efficient in modelling the potential distributions of species using presence-only datasets (Elith *et al.*, 2011). MaxEnt model estimates niches by finding the distribution of probabilities closest to uniform (maximum entropy), constrained by known observations (i.e. environmental and/or climatic variables) (Phillips *et al.*, 2006). The training model for *B. straminea* distribution in China was built in MaxEnt software version 3.3.3k (<https://www.cs.princeton.edu/~schapire/maxent/>) using 27 GPS coordinates for *Biomphalaria* occurrences representing data from the current study, data from the National Institute of Parasitic Diseases (NIPD), Chinese Center for Disease Control and Prevention (CDC), and previously published data (Attwood *et al.*, 2015). Occurrence data were divided into training data, the 75% of occurrence point data that was used for model prediction and test data, the 25% of occurrence point data that was used for model validation (Phillips *et al.*, 2006). The model was evaluated using a threshold-independent index to calculate the area under the receiver operating

**Table 1. Environmental and climatic variables used in the regression analysis model to predict the occurrence of *Biomphalaria straminea* in China.**

Data type	Source
Altitude variable at the 1-km resolution	Hydro-K data set (USGS)
BIO1 (annual mean temperature)	Worldclim Global Climate ( <a href="http://www.worldclim.org/">http://www.worldclim.org/</a> )
BIO2 (mean diurnal range)	
BIO3 (isothermality)	
BIO4 (temperature seasonality)	
BIO5 (max. temperature of warmest month)	
BIO6 (min. temperature of coldest month)	
BIO7 (temperature annual range)	
BIO8 (mean temperature of wettest quarter)	
BIO9 (mean temperature of driest quarter)	
BIO10 (mean temperature of warmest quarter)	
BIO11 (mean temperature of coldest quarter)	
BIO12 (annual precipitation)	
BIO13 (precipitation of wettest month)	
BIO14 (precipitation of driest month)	
BIO15 (precipitation seasonality)	
BIO16 (precipitation of wettest quarter)	
BIO17 (precipitation of driest quarter)	
BIO18 (precipitation of warmest quarter)	
BIO19 (precipitation of coldest quarter)	

USGS, United States Geological Survey (<https://www.usgs.gov/>).



**Figure 1. A map showing the locations of *Biomphalaria straminea* abundance in China.**

characteristic (ROC) curves (AUC), which measures the accuracy of predictive distribution models (Lobo *et al.*, 2008). AUC values near one indicate high predictive performance of the model, while values smaller than 0.5 indicate low model predictive ability (Phillips *et al.*, 2006; Peterson *et al.*, 2008; Phillips and Dudík, 2008). Visualization display was carried out in ArcGIS version 10.1 (ESRI; Redlands, CA, USA). The final models were plotted with a 1-km spatial resolution. The probability of snail presence was expressed as a map layer of habitat suitability on a scale of 0-0.9 for non-suitable and suitable habitat, respectively.

## Results

### Snails habitats

In Shenzhen, the *Biomphalaria* habitats were mostly located in urban areas and it included areas of fishing and agricultural activities. The habitats were standing water bodies such as reservoirs, streams, and rivers (Figure 1). Most of locations were typical habitats for snails and all were positive for the presence of *Biomphalaria* with variable population densities. *B. straminea* was collected mostly from lentic sites (flooded furrows and ponds) than from lotic sites (streams and rivers).

### Distribution model

Based on occurrence data for *B. straminea*, we generated a distribution map for the potential areas of snail occurrence in China (Figure 2). The map shows the suitable areas for snail presence. Jackknife

analysis (<http://www.physics.utah.edu/~detar/phys6730/handouts/jackknife/jackknife/>) of variables, response curves and percent contributions of variable to the model indicated that, among the environmental and climatic variables used, precipitation of warmest quarter showed the highest contribution to the predictive model (Figure 3).

A full description for the estimates of relative contributions of each environmental variable is presented in Table 2. Percent of contribution was estimated by adding the increase in regularized gain to the contribution of the corresponding variable, or subtracted from it if the change to the absolute value of lambda is negative and randomly permute the values of each environmental variable on training presence and background. The model was re-evaluated on the permuted data, and the resulting AUC is shown in the table, normalized to percentages. While factors such as temperature seasonality, precipitation of driest month, altitude, and mean temperature of wettest quarter were also effective contributors to the model, others such as precipitation seasonality, precipitation of coldest quarter, precipitation of wettest quarter, mean temperature of driest quarter, annual mean temperature, and minimum temperature of coldest month had no contribution to the spatial distribution model.

The possible habitats for *B. straminea* are coded in colours from light green to darker red, representing fewer to greater models. The models suggest that there is a high relative probability of presence, indicating that new, yet un-occupied areas could be suitable habitats for *B. straminea* exist outside the sampled areas; these are mainly distributed in the south of China including Shenzhen and its surrounding areas in Guangdong province, south of Guangxi, and Fujian provinces as well as area outside China such as the North of Taiwan. The logistic threshold

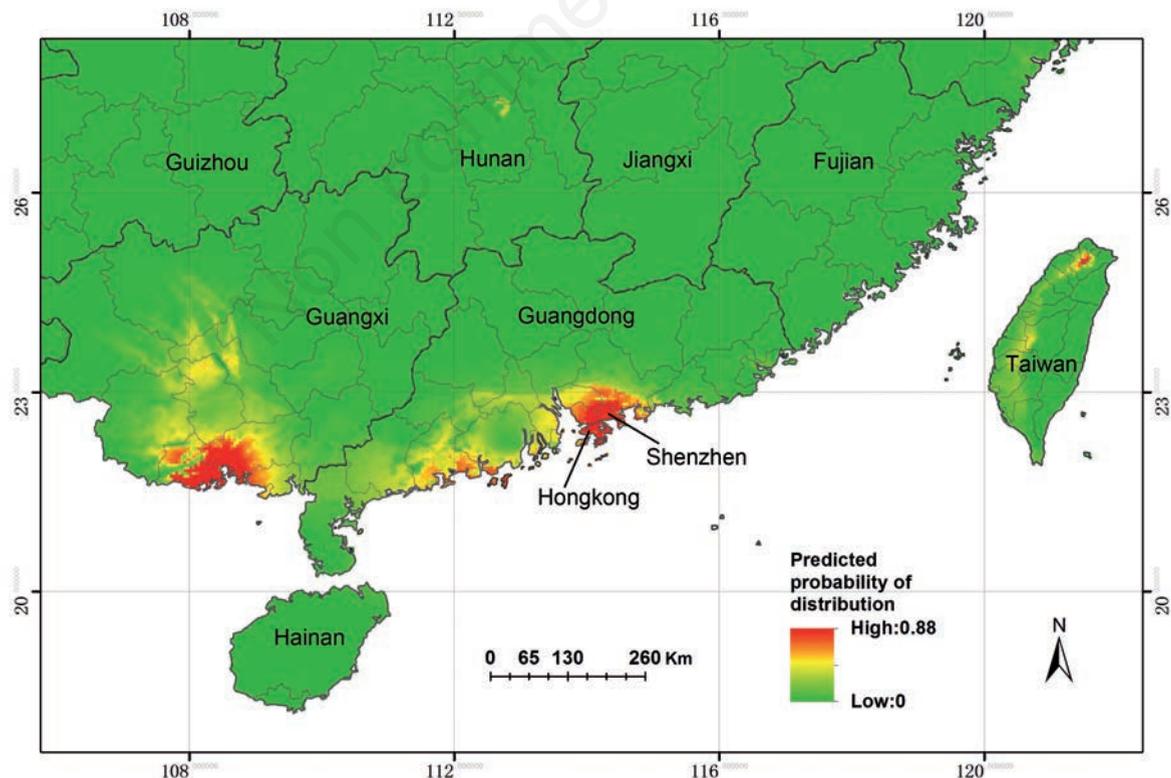


Figure 2. Predicted potential distribution for *Biomphalaria straminea* using all occurrence records and climatic and environmental variables. Dark red indicates a higher probability of occurrence, while green indicates a low probability of occurrence.

for the model ranged from 0.010 to 0.396 with an AUC value of 0.99, indicating a good model performance and high predictive ability.

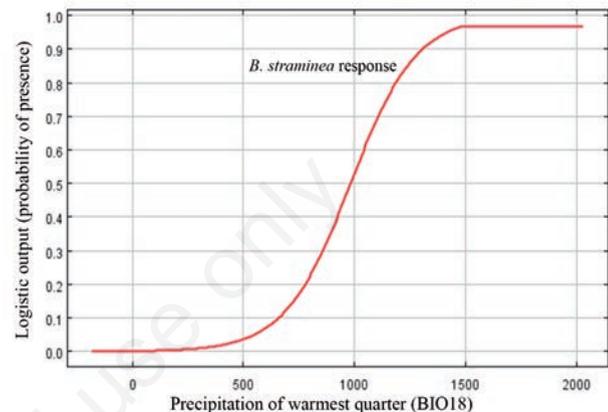
## Discussion

The present study represents the first predictive map for China with regard to the spatial distribution of *B. straminea*, an invasive species known for its potential ability to transmit *S. mansoni*. A MaxEnt modelling approach was employed to analyze a presence-only dataset for *B. straminea*. The model showed a gradient in suitability for *B. straminea* habitats across southern China ranging from areas of low to high suitability (Figure 2). The MaxEnt output represents the likelihood of natural habitat suitability - or the potential distribution; despite the fact that it does not give the realized distribution of snails in relation to climatic and environmental factors (used as covariates). Our models showed a high predictive accuracy with AUC value above 0.9, which is a best model-fit category (Phillips and Dudík, 2008).

Previous studies showed that SDMs such as MaxEnt are useful for the identification of environments that can sustain organisms outside their native areas (Phillips *et al.*, 2006). MaxEnt and other SDMs have been applied to study intermediate host distribution (Scholte *et al.*, 2012; Stensgaard *et al.*, 2013; Pedersen *et al.*, 2014). MaxEnt's principle for estimating the distribution of the species is through finding maximum entropy for distribution (the distribution closest to uniform) with the constraints that the expected value of each variable constraint matches its empirical average. The advantage of MaxEnt over other modelling techniques is that it can perform prediction using presence-only data even with few samples (Phillips *et al.*, 2004). When using presence-only in MaxEnt, the pixels of the study area define the space of MaxEnt probability distribution. The pixels of occurrence recorded constitute the sample points and the responsible features are climatic or other environmental variables (Phillips *et al.*, 2006). In our study, presence-only data describes the occurrences records of *B. straminea*. Although it is advantageous to have the absence data as well, sometimes it is difficult to find these data due to misidentification or inaccessibility at some water bodies. The advantage of using presence-absence data is that it gives valuable information about surveyed locations (enabling analyses of biases) and prevalence (Phillips *et al.*, 2009). However, sometimes absence data may introduce confounding information because of errors in identifying suitable habitats. Moreover, absence data may be misleading because the species or environment is not at equilibrium (Elith and Leathwick, 2009). SDMs assume that the target species is at equilibrium or close to equilibrium with current environmental conditions (the species has already occupied all suitable habitats and is absent from all unsuitable sites (Guisan and Thuiller, 2005). SDMs also assume that the species' ecological niche is stable in space and time, which mean that it occupied similar environmental conditions as in the native range (Guisan and Zimmermann, 2000). The distribution model could be misleading if the species is missing from locations where climate is actually suitable (areas which can support its establishment following introduction). As a result, spatial models will under-predict potential habitats (Václavík and Meentemeyer, 2012).

Climatic variables such as temperature and precipitation influence species distribution at both global and meso-scales. It is important therefore to carefully select the variables to use for modelling as this will likely influence the degree of model ability to predict presence areas outside the study area or with different environmental conditions (Tambo *et al.*, 2014). This study was capable to provide the precision

guideline for the management of invasive species (Peterson and Robins, 2003) and the determinants to predict the impact of climate change on their distribution (Thomas *et al.*, 2004). Climate changes tend to influence the spatial distribution of *Biomphalaria* with increasing suitable habitats for the snails in the future in addition to the current ones. In our model of prediction, precipitation of warmest quarter



**Figure 3.** Response curve of *Biomphalaria straminea* to the climatic variable, precipitation of warmest quarter.

**Table 2.** Estimates of relative contributions of the environmental variables to the MaxEnt distribution model of *Biomphalaria straminea*.

Environmental variable	Percent contribution	Permutation importance
Precipitation of warmest quarter	72.3	23.8
Temperature seasonality	14.4	0
Precipitation of driest month	4	0
Altitude	4	0
Mean temperature of wettest quarter	2.6	67.1
Isothermality	0.9	8.3
Precipitation of wettest month	0.7	0.6
Mean temperature of coldest quarter	0.3	0
Mean temperature of warmest quarter	0.2	0
Precipitation of driest quarter	0.2	0
Annual precipitation	0.1	0
Mean diurnal range	0.1	0.1
Maximum temperature of warmest month	0.1	0
Temperature annual range	0.1	0
Precipitation seasonality	0	0.1
Precipitation of coldest quarter	0	0
Precipitation of wettest quarter	0	0
Mean temperature of driest quarter	0	0
Annual mean temperature	0	0
Minimum temperature of coldest month	0	0



was the most contributing climatic factor to the model. Environmental and climatic factors have a variable effect on *Biomphalaria* spatial distribution depending on the species and geographic areas of occurrence. Both temperature and precipitation were identified as important environmental factors governing the distribution of South American species of *Biomphalaria* (Scholte *et al.*, 2012). Also, Guimarães *et al.* (2013) showed that precipitation, minimum temperature, the estimated vegetation index (EVI) and sanitation were positively correlated with *B. glabratal* abundance and consistent with the adequate environmental conditions for the transmission of schistosomiasis. The authors concluded that, the regression models confirmed the importance of the use of environmental variables to characterize the snail habitat in the endemic area of the state of Minas Gerais in Brazil. Bavia *et al.* (2001) also showed that the distribution of schistosomiasis in Bahia, at municipalities level, is related to the vegetation index (NDVI) and temperature using low-resolution sensor data such as the advanced very high-resolution radiometer (AVHRR). Table 3 reviews some of the spatial technologies used to study the distribution of *B. straminea* in South America and the most contributing climatic or environmental factors to the distribution model.

In the case of African species *Biomphalaria*, most of the SDMs studies indicated that warmer climate is expected to minimize the range of snails distribution (Stensgaard *et al.*, 2013). NDVI and day temperatures values were also found to govern *B. Pfeifferi* and *B. sudanica* distribution and *S. mansoni* transmission in Uganda (Stensgaard *et al.*, 2005). Moreover, Pedersen *et al.* (2014) showed that temperature play an important role in *B. Pfeifferi* potential distribution in Zimbabwe and indicated that climate change may significantly alter the future spatial distribution of this snail species. Also, NDVI and maximum temperature were important factors determining the spatial distribution of *B. Pfeifferi* in Ethiopia (Malone *et al.*, 2001). Although SDMs based on the temporal climate have similar accuracy to realistic models (Hijmans and Graham, 2006), it is difficult to measure accuracy under future climate conditions. SDMs approaches do not include any physiological information about invasive species or their mode of spread and competition with local species. These approaches depend on empirical data

and can thus be judged as more trustworthy because correlation between climate and distribution does not necessarily imply a causal relationship between climate and distribution (Dormann, 2007). However, there is a high degree of correlation among environmental variables and the best predictors of species distribution may therefore be hidden and different from the ones governing species establishment. In the current study, for example, precipitation of warmest quarter was the most contributing environmental factor for *B. straminea* distribution model although this snail species is known as drought-resistant. There is thus a complication in the modelling of invasive species because they do not simply follow the factors regulating their abundance in their native range. Instead, they can undergo adaptive evolution to the new environmental condition in the newly invaded areas (Huey *et al.*, 2005; Colwell and Rangel, 2009).

A thorough understanding the biology of possible hosts of schistosomiasis is necessary for any control strategy. In this respect, the current study is a critical addition to the tools needed to efficiently manage surveillance, control the potential intermediate host, *B. straminea* and prevent schistosomiasis transmission to mainland China. Although there are no records for the implication of *B. straminea* in *S. mansoni* transmission in China so far, the current model of snail distribution merits further attention in view of the increased number of schistosomiasis *mansoni* infected Chinese returning from endemic areas in Africa, as well as the possibility of introduction of infected snails in a similar way to what resulted in the current colonization of *B. straminea* in southern China (Wang *et al.*, 2013). Moreover, the ability of *B. straminea* to tolerate hypertrophic conditions increases its potential for spread to organically polluted sites involving human activity. There is thus a clear risk for the establishment of *S. mansoni*-infected foci with functional transmission if the parasite were also introduced (Yipp, 1990). Spatial technologies have been extensively used to study vector distribution and parasite prevalence with relevance for medical and veterinary medicine, encouraging studies of the potential impact of climate change and revealing the spatial and climatic parameters which determine the distribution limits of diseases at various scales (Lobitz *et al.*, 2000; Tanser *et al.*, 2003; Rogers and Randolph, 2006; Malone and Bergquist,

**Table 3. Review of spatial techniques used to study the spatial distribution of *Biomphalaria straminea* in Brazil.**

Satellite sensor	Effective covariates	Procedure/technique	Reference
-	Population density and the duration of the annual dry period	GIS/intergraph MGE <sup>o</sup> a	Bavia <i>et al.</i> (1999)
AVHRR	NDVI; dT	GIS/SPRING <sup>#</sup> modular GIS software	Bavia <i>et al.</i> (2001)
-	Rainfall	Differential global positioning systems (DGPS) <sup>§</sup> and GIS software	Kloos <i>et al.</i> (2001)
MODIS; SRTM	TN <sub>s</sub> ; NDVI <sub>w</sub>	Multiple linear regression/GIS	Guimarães <i>et al.</i> (2008)
-	-	Geostatic indicator Kriging/SPRING (georeferenced information processing system)	Guimarães <i>et al.</i> (2009)
-	Rainfall	GPS/ArcGis 9.3 (ESRI software) <sup>^</sup>	Galvão <i>et al.</i> (2010)
-	Annual precipitation; temperature seasonality; temperature annual range	Maximum entropy/MaxEnt	Scholte <i>et al.</i> (2012)
-	-	GIS in ArcGIS 10.0 (ESRI software) <sup>^</sup>	Barbosa <i>et al.</i> (2013)
-	-	GIS/TerraView 4.1.0 <sup>§</sup>	Barbosa <i>et al.</i> (2014)

GIS, geographical information system; MGE, modular geographic environment; AVHRR, advanced very high resolution radiometer; NDVI, normalised difference vegetation index; dT, average diurnal temperature differences; MODIS, moderate resolution imaging spectroradiometer; SRTM, shuttle radar topography mission; TN<sub>s</sub>, summer minimum temperature; NDVI<sub>w</sub>, winter normalized difference vegetation index. <sup>o</sup><http://www.grs-gis.com/mgemga.html>; <sup>a</sup> a freeware GIS and remote sensing image processing system; <sup>#</sup><http://www.esri.com/news/arcuser/0103/differential1of2.html>; <sup>^</sup><http://www.esri.com/software/arcgis>; <sup>§</sup>[http://www.dpi.inpe.br/ter-view\\_eng/index.php](http://www.dpi.inpe.br/ter-view_eng/index.php)

2012). According to King *et al.* (2006), the next generation of schistosomiasis control will largely depend on using new monitoring tools and effective transmission containment including statistical ecological modelling that would include spatial technologies.

## Conclusions

The results presented here show that there may be potential for *B. straminea* to disperse further in China as the model here indicates large suitable habitats in areas around its current distribution. The results also confirm the important role played by climatic factors in regulating freshwater snail distributions and indicate the usefulness of WorldClim databases in SDMs. Although the predictive map obtained by MaxEnt seems efficient in analysing and predicting presence-only data for understanding geographical and ecological distributions of this snail species, comparisons with other SDMs are also needed. The obtained risk map for *B. straminea* distribution in China can be used to inform proper public health strategies, guiding fieldwork in places with higher occurrence probability of the new invasion of a potential intermediate host species for *S. mansoni* in China. The map might be used as predictor for potential *S. mansoni* distribution in case of any accidental introduction of the parasite to areas harbouring this snail. Since the presence of the intermediate host snails of *S. mansoni* is a proxy for the disease distribution, the risk map can guide spatial targeting of control interventions.

## References

- Appleton C, 1977. The influence of temperature on the life-cycle and distribution of *Biomphalaria pfeifferi* (Krauss, 1948) in South-Eastern Africa. *Int J Parasitol* 7:335-45.
- Appleton C, Eriksson IM, 1984. The influence of fluctuating above-optimal temperature regimes on the fecundity of *Biomphalaria pfeifferi* (Mollusca: Planorbidae). *T Roy Soc Trop Med Hyg* 78:49-54.
- Attwood SW, Huo GN, Qiu JW, 2015. Update on the distribution and phylogenetics of *Biomphalaria* (Gastropoda: Planorbidae) populations in Guangdong Province, China. *Acta Trop* 141:258-70.
- Barbosa CS, Barbosa VS, Melo FLd, Melo MSBd, Bezerra L, Campos JV, Rodrigues BX, Nascimento WCd, Gomes ES, Leal-Neto O, 2013. Autochthonous cases of schistosomiasis in children in Recife, Northeastern Brazil. *Rev Saúde Pública* 47:684-90.
- Barbosa CS, Barbosa VS, Nascimento WC, Pieri OS, Araújo KC, 2014. Study of the snail intermediate hosts for *Schistosoma mansoni* on Itamaracá Island in northeast Brazil: spatial displacement of *Biomphalaria glabrata* by *Biomphalaria straminea*. *Geospat Health* 8:345-51.
- Barbosa FS, Barbosa CS, 1994. The bioecology of snail vectors for schistosomiasis in Brazil. *Cad Saúde Pública* 10:200-9.
- Barboza DM, Zhang C, Santos NC, Silva MMBL, Rollemberg CVV, de Amorim FJR, Ueta MT, de Melo CM, de Almeida JAP, Jeraldo VdLS, 2012. *Biomphalaria* species distribution and its effect on human *Schistosoma mansoni* infection in an irrigated area used for rice cultivation in northeast Brazil. *Geospat Health* 6:103-9.
- Basch PF, 1976. Intermediate host specificity in *Schistosoma mansoni*. *Exp Parasitol* 39:150-69.
- Bavia M, Malone J, Hale L, Dantas A, Marroni L, Reis R, 2001. Use of thermal and vegetation index data from earth observing satellites to evaluate the risk of schistosomiasis in Bahia, Brazil. *Acta Trop* 79:79-85.
- Bavia ME, Hale LF, Malone JB, Braud DH, Shane SM, 1999. Geographic information systems and the environmental risk of schistosomiasis in Bahia, Brazil. *Am J Trop Med Hyg* 60:566-72.
- Brooker S, Michael E, 2000. The potential of geographical information systems and remote sensing in the epidemiology and control of human helminth infections. *Adv Parasitol* 47:245-88.
- Brown D, 1994. Freshwater snails of Africa and their medical importance. Taylor and Francis, London, UK.
- Carlton JT, 1996. Biological invasions and cryptogenic species. *Ecology* 77:1653-5.
- Carvalho OdS, 1992. Intermediate hosts of *Schistosoma mansoni* in Brazil. *Mem I Oswaldo Cruz* 87:307-9.
- Collins C, Xu J, Tang S, 2012. Schistosomiasis control and the health system in P.R. China. *Infect Dis Poverty* 1:8.
- Colwell RK, Rangel TF, 2009. Hutchinson's duality: the once and future niche. *P Natl Acad Sci USA* 106:19651-8.
- Cunha NA, 1967. [Primeiros focos de esquistossomose mansônica em Goiânia, Estado de Goiás, Brasil]. [Article in Brazilian]. *Rev I Med Trop S Paulo* 9:357-8.
- Dormann CF, 2007. Effects of incorporating spatial autocorrelation into the analysis of species distribution data. *Global Ecol Biogeograph* 16:129-38.
- Elith J, Graham CH, Anderson RP, Dudik M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, Leathwick JR, Lehmann A, Li J, Lohmann LG, Loiselle BA, Manion G, Moritz C, Nakamura M, Nakazawa Y, Overton JMcC, Peterson AT, Phillips SJ, Richardson KS, Scachetti-Pereira R, Schapire RE, Soberón J, Williams S, Wisz MS, Zimmermann NE, 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* 29:129-51.
- Elith J, Kearney M, Phillips S, 2010. The art of modelling range shifting species. *Methods Ecol Evol* 1:330-42.
- Elith J, Leathwick JR, 2009. Species distribution models: ecological explanation and prediction across space and time. *Annu Rev Ecol Syst* 40:677.
- Elith J, Phillips SJ, Hastie T, Dudik M, Chee YE, Yates CJ, 2011. A statistical explanation of MaxEnt for ecologists. *Divers Distrib* 17:43-57.
- Fernandez MA, Thiengo SC, 2010. Susceptibility of *Biomphalaria straminea* from Peixe Angical dam, Tocantins, Brazil to infection with three strains of *Schistosoma mansoni*. *Mem I Oswaldo Cruz* 105:488-91.
- Galvão AF, Favre TC, Guimarães RJ, Pereira AP, Zani LC, Felipe KT, Domingues ALC, Carvalho OS, Barbosa CS, Pieri OS, 2010. Spatial distribution of *Schistosoma mansoni* infection before and after chemotherapy with two praziquantel doses in a community of Pernambuco, Brazil. *Mem I Oswaldo Cruz* 105:555-62.
- Gao S, Li X, Huang S, Xie X, Mei S, Ruan C, Huang D, 2013. Primary investigation of distribution and ecological environment of *Biomphalaria straminea* in Dasha and Guanlan Rivers in Shenzhen areas. *Chin Trop Med* 13:313-7.
- Grinnell J, 1924. Geography and evolution. *Ecology* 5:225-9.
- Guimarães RJ, Freitas CC, Dutra LV, Felgueiras CA, Moura AC, Amaral RS, Drummond SC, Scholte RG, Oliveira G, Carvalho OS, 2009. Spatial distribution of *Biomphalaria* mollusks at São Francisco River Basin, Minas Gerais, Brazil, using geostatistical procedures. *Acta Trop* 109:181-6.
- Guimarães RJ, Freitas CC, Dutra LV, Moura AC, Amaral RS, Drummond SC, Scholte RG, Carvalho OS, 2008. Schistosomiasis risk estimation in Minas Gerais state, Brazil, using environmental data and



- GIS techniques. *Acta Trop* 108:234-41.
- Guimarães RJ, Freitas CC, Oliveira G, Dutra LV, Carvalho OS, 2013. Multiple regression for the schistosomiasis positivity index estimates in the Minas Gerais State-Brazil at small communities and cities levels. INTECH Open Access Publisher, Rijeka, Croatia.
- Guisan A, Thuiller W, 2005. Predicting species distribution: offering more than simple habitat models. *Ecol Lett* 8:993-1009.
- Guisan A, Zimmermann NE, 2000. Predictive habitat distribution models in ecology. *Ecol Modell* 135:147-86.
- Haltuch MA, Berkman PA, Garton DW, 2000. Geographic information system (GIS) analysis of ecosystem invasion: exotic mussels in Lake Erie. *Limnol Oceanogr* 45:1778-87.
- Higgins SI, Richardson DM, Cowling RM, Trinder Smith TH, 1999. Predicting the landscape scale distribution of alien plants and their threat to plant diversity. *Conserv Biol* 13:303-13.
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A, 2005. Very high resolution interpolated climate surfaces for global land areas. *Int J Climatol* 25:1965-78.
- Hijmans RJ, Graham CH, 2006. The ability of climate envelope models to predict the effect of climate change on species distributions. *Global Change Biol* 12:2272-81.
- Huey RB, Gilchrist GW, Hendry AP, 2005. Using invasive species to study evolution. *Species invasions: insights. Ecol Evol Biogeogr* 1:139-64.
- Kareiva P, 1996. Developing a predictive ecology for non-indigenous species and ecological invasions. *Ecology* 77:1651.
- King CH, Sturrock RF, Kariuki HC, Hamburger J, 2006. Transmission control for schistosomiasis – why it matters now. *Trend Parasitol* 22:575-82.
- Kloos H, Souza Cd, Gazzinelli A, Soares Filho BS, Temba PdC, Bethony J, Page K, Grzywacz C, Lewis F, Minchella D, 2001. The distribution of *Biomphalaria* spp. in different habitats in relation to physical, biological, water contact and cognitive factors in a rural area in Minas Gerais, Brazil. *Mem I Oswaldo Cruz* 96:57-66.
- Kristensen T, Malone J, McCarroll J, 2001. Use of satellite remote sensing and geographic information systems to model the distribution and abundance of snail intermediate hosts in Africa: a preliminary model for *Biomphalaria pfeifferi* in Ethiopia. *Acta Trop* 79:73-8.
- Lardans V, Dissous C, 1998. Snail control strategies for reduction of schistosomiasis transmission. *Parasitol Today* 14:413-7.
- Lobitz B, Beck L, Huq A, Wood B, Fuchs G, Faruque A, Colwell R, 2000. Climate and infectious disease: use of remote sensing for detection of *Vibrio cholerae* by indirect measurement. *P Natl Acad Sci USA* 97:1438-43.
- Lobo JM, Jiménez Valverde A, Real R, 2008. AUC: a misleading measure of the performance of predictive distribution models. *Global Ecol Biogeogr* 17:145-51.
- Machado W, Martins C, 1951. [Um foco autóctone de Schistosomose no Pará]. [Article in Brazilian]. *Hospital* 39:289-90.
- Malek EA, 1985. Snail hosts of schistosomiasis and other snail-transmitted diseases in tropical America: a manual. Pan American Health Organization, Regional Office of the World Health Organization, Washington, DC, USA.
- Malone J, Yilma J, McCarroll J, Erko B, Mukaratirwa S, Zhou X, 2001. Satellite climatology and the environmental risk of *Schistosoma mansoni* in Ethiopia and east Africa. *Acta Trop* 79:59-72.
- Malone JB, Bergquist NR, 2012. Mapping and modelling neglected tropical diseases and poverty in Latin America and the Caribbean. *Geospat Health* 6:1-5.
- Mandahl-Barth G, 1957. Intermediate hosts of *Schistosoma*: African *Biomphalaria* and *Bulinus*: 2. *B World Health Organ* 17:1.
- Meier-Brook C, 1974. A snail intermediate host of *Schistosoma mansoni* introduced into Hong Kong. *B World Health Organ* 51:661.
- Melo FL, do Vale Gomes AL, Barbosa CS, Werkhauser RP, Abath FG, 2006. Development of molecular approaches for the identification of transmission sites of schistosomiasis. *T Roy Soc Trop Med Hyg* 100:1049-55.
- Meyerson LA, Mooney HA, 2007. Invasive alien species in an era of globalization. *Front Ecol Environ* 5:199-208.
- Michelson E, Dubois L, 1979. Competitive interaction between two snail hosts of *Schistosoma mansoni*: laboratory studies on *Biomphalaria glabrata* and *B. straminea*. *Rev I Med Trop São Paulo* 21:246.
- Morgan J, Dejong R, Snyder S, Mkoji G, Loker E, 2001. *Schistosoma mansoni* and *Biomphalaria*: past history and future trends. *Parasitology* 123:211-28.
- PAHO, 1968. A guide for the identification of the snail intermediate hosts of schistosomiasis in the Americas. Pan American Health Organization, Regional Office of the World Health Organization, Washington, DC, USA.
- Paraense W, 1975. *Biomphalaria orbigny* sp. n. from Argentina (Gastropoda: Basommatophora: Planorbidae). *Rev Brasil Biol* 35:211-22.
- Paraense W, Reis F, Faria I, Katz N, 1986. [Distribuição dos caramujos no Brasil. Modernos conhecimentos sobre esquistossomose mansônica]. [Book in Brazilian]. Biblioteca da Academia Mineira de Medicina, Belo Horizonte, Brazil.
- Paraense WL, 1961. The nomenclature of Brazilian planorbids. II. *Australorbis tenagophilus* (Orbigny, 1835). *Rev Bras Biol* 21:343.
- Paraense W, Corrêa LR, 1989. A potential vector of *Schistosoma mansoni* in Uruguay. *Mem I Oswaldo Cruz* 84:281-8.
- Pedersen UB, Midzi N, Mduluza T, Soko W, Stensgaard A-S, Vennervald BJ, Mukaratirwa S, Kristensen TK, 2014. Modelling spatial distribution of snails transmitting parasitic worms with importance to human and animal health and analysis of distributional changes in relation to climate. *Geospat Health* 8:335-51.
- Perrins J, Fitter A, Williamson M, 1993. Population biology and rates of invasion of three introduced Impatiens species in the British Isles. *J Biogeogr* 33:44.
- Peterson AT, 2003. Predicting the geography of species' invasions via ecological niche modeling. *Quart Rev Biol* 78:419-33.
- Peterson AT, Pape M, Soberón J, 2008. Rethinking receiver operating characteristic analysis applications in ecological niche modeling. *Ecol Model* 213:63-72.
- Peterson AT, Robins CR, 2003. Using ecological niche modeling to predict barred owl invasions with implications for spotted owl conservation. *Conserv Biol* 17:1161-5.
- Peterson AT, Shaw J, 2003. Lutzomyia vectors for cutaneous leishmaniasis in Southern Brazil: ecological niche models, predicted geographic distributions, and climate change effects. *Int J Parasitol* 33:919-31.
- Pflüger W, 1981. Experimental epidemiology of schistosomiasis. *Z Parasit* 66:221-9.
- Phillips SJ, Anderson RP, Schapire RE, 2006. Maximum entropy modeling of species geographic distributions. *Ecol Model* 190:231-59.
- Phillips SJ, Dudík M, 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 31:161-75.
- Phillips SJ, Dudík M, Elith J, Graham CH, Lehmann A, Leathwick J, Ferrier S, 2009. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecol Appl* 19:181-97.

- Phillips SJ, Dudík M, Schapire RE, 2004. A maximum entropy approach to species distribution modelling. Proceedings of the 21st International Conference on Machine Learning, Banff, Canada, 2004.
- Pointier J, David P, Jarne P, 2005a. Biological invasions: the case of planorbid snails. *J Helminthol* 79:249-56.
- Pointier J-P, DeJong R, Tchuente LT, Kristensen T, Loker E, 2005b. A neotropical snail host of *Schistosoma mansoni* introduced into Africa and consequences for the schistosomiasis transmission: *Biomphalaria tenagophila* in Kinshasa (Democratic Republic of Congo). *Acta Trop* 93:191-9.
- Raso G, Matthys B, N'goran E, Tanner M, Vounatsou P, Utzinger J, 2005. Spatial risk prediction and mapping of *Schistosoma mansoni* infections among schoolchildren living in western Côte d'Ivoire. *Parasitology* 131:97-108.
- Rogers D, Randolph S, 2006. Climate change and vector-borne diseases. *Adv Parasitol* 62:345-81.
- Rollinson D, 2011. *Biomphalaria*: natural history, ecology and schistosome transmission. *Biomphalaria* snails and larval trematodes. Springer, Amsterdam, The Netherlands.
- Scholte RG, Carvalho OS, Malone JB, Utzinger J, Vounatsou P, 2012. Spatial distribution of *Biomphalaria* spp., the intermediate host snails of *Schistosoma mansoni*, in Brazil. *Geospat Health* 6:95-101.
- Schur N, Hürlimann E, Stensgaard A-S, Chimfwembe K, Mushingi G, Simoonga C, Kabatereine NB, Kristensen TK, Utzinger J, Vounatsou P, 2013. Spatially explicit *Schistosoma* infection risk in eastern Africa using Bayesian geostatistical modelling. *Acta Trop* 128:365-77.
- Simoonga C, Utzinger J, Brooker S, Vounatsou P, Appleton C, Stensgaard A-S, Olsen A, Kristensen TK, 2009. Remote sensing, geographical information system and spatial analysis for schistosomiasis epidemiology and ecology in Africa. *Parasitology* 136:1683-93.
- Standley CJ, Vounatsou P, Gosoni L, Jørgensen A, Adriko M, Lwambo NJ, Lange CN, Kabatereine NB, Stothard JR, 2012. The distribution of *Biomphalaria* (Gastropoda: Planorbidae) in Lake Victoria with ecological and spatial predictions using Bayesian modelling. *Hydrobiologia* 683:249-64.
- Stensgaard A, Jørgensen A, Kabatereine N, Malone J, Kristensen T, 2005. Modeling the distribution of *Schistosoma mansoni* and host snails in Uganda using satellite sensor data and geographical information systems. *Parassitologia* 47:115.
- Stensgaard A-S, Jørgensen A, Kabatereine NB, Rahbek C, Kristensen TK, 2006. Modeling freshwater snail habitat suitability and areas of potential snail-borne disease transmission in Uganda. *Geospat Health* 1:93-104.
- Stensgaard A-S, Utzinger J, Vounatsou P, Hürlimann E, Schur N, Saarnak CF, Simoonga C, Mubita P, Kabatereine NB, Tchuente L-AT, 2013. Large-scale determinants of intestinal schistosomiasis and intermediate host snail distribution across Africa: does climate matter? *Acta Trop* 128:378-90.
- Sturrock R, 1973. Field studies on the transmission of *Schistosoma mansoni* and on the bionomics of its intermediate host, *Biomphalaria glabrata*, on St. Lucia, West Indies. *Int J Parasitol* 3:175-94.
- Tambo E, Ai L, Zhou X, Chen JH, Hu W, Bergquist R, Guo JG, Utzinger J, Tanner M, Zhou XN, 2014. Surveillance-response systems: the key to elimination of tropical diseases. *Infect Dis Poverty* 3:17.
- Tanser FC, Sharp B, Le Sueur D, 2003. Potential effect of climate change on malaria transmission in Africa. *Lancet* 362:1792-8.
- Teodoro TM, Janotti-Passos LK, dos Santos Carvalho O, Caldeira RL, 2010. Occurrence of *Biomphalaria cousini* (Mollusca: Gastropoda) in Brazil and its susceptibility to *Schistosoma mansoni* (Platyhelminths: Trematoda). *Mol Phylog Evol* 57:144-51.
- Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BF, De Siqueira MF, Grainger A, Hannah L, 2004. Extinction risk from climate change. *Nature* 427:145-8.
- Utzinger J, Mayombana C, Mez K, Tanner M, 1997. Evaluation of chemical and physical-morphological factors as potential determinants of *Biomphalaria pfeifferi* (Krauss, 1848) distribution. *Mem I Oswaldo Cruz* 92:323-8.
- Václavík T, Meentemeyer RK, 2012. Equilibrium or not? Modelling potential distribution of invasive species in different stages of invasion. *Divers Distrib* 18:73-83.
- Vounatsou P, Raso G, Tanner M, N'goran E, Utzinger J, 2009. Bayesian geostatistical modelling for mapping schistosomiasis transmission. *Parasitology* 136:1695-705.
- Wang W, Liang YS, Hong QB, Dai JR, 2013. African schistosomiasis in mainland China: risk of transmission and countermeasures to tackle the risk. *Parasite Vector* 6:249.
- Williamson M, 1999. Invasions. *Ecography* 22:5-12.
- Woolhouse M, 1992. Population biology of the freshwater snail *Biomphalaria pfeifferi* in the Zimbabwe. *J Appl Ecol* 29:687-94.
- Woolhouse M, Chandiwana S, 1989. Spatial and temporal heterogeneity in the population dynamics of *Bulinus globosus* and *Biomphalaria pfeifferi* and in the epidemiology of their infection with schistosomes. *Parasitology* 98:21-34.
- Yipp MW, 1990. Distribution of the schistosome vector snail, *Biomphalaria straminea* (Pulmonata: Planorbidae) in Hong Kong. *J Moll Stud* 56:47-55.
- Yousif F, Haroun N, Ibrahim A, El-Bardicy S, 1996. *Biomphalaria glabrata*: a new threat for schistosomiasis transmission in Egypt. *J Egypt Soc Parasitol* 26:191-205.
- Zhou X, Yap P, Tanner M, Bergquist R, Utzinger J, Zhou XN, 2016a. Surveillance and response systems for elimination of tropical diseases: summary of a thematic series in infectious diseases of poverty. *Infect Dis Poverty* 5:49.
- Zhou YB, Liang S, Chen Y, Jiang QW, 2016b. The three gorges dam: does it accelerate or delay the progress towards eliminating transmission of schistosomiasis in China? *Infect Dis Poverty* 5:63.