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High-resolution remote sensing-based spatial modeling for the prediction of potential risk areas of schistosomiasis in the Dongting Lake area, China

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ABSTRACT

The geographical distribution of snail (i.e., the intermediate host of schistosomiasis) is consistent with that of endemic areas. The suitable snail habitus requires necessary environmental conditions for snail population. The high-resolution remote sensing provides an important tool for the spatio-temporal analysis of disease monitoring and prediction. This study conducted a typical schistosomiasis epidemic area in the marshland and lake regions along the Yangtze River, Yueyang City, Hunan Province of China. And three types of environmental factors, i.e., NDVI, soil moisture, and shortest distance to water body, associated with the geographical distribution of snail population, were extracted from the high-resolution remoting sensing data. The predicted distribution of snail habitus from the high-resolution environmental factors were compared with the data of annual program of snail survey. The results have shown that the application of high-resolution remote sensing can improve the accuracy of the modeled and predicted the potential risk areas of schistosomiasis, and may become an important tool for the ongoing national schistosomiasis control program.

1. Introduction

Schistosomiasis, caused by *Schistosoma japonicum*, is one of the widespread zoonotic diseases that continues to be a severe risk to public health in the People's Republic of China (PR China)(Ross et al., 2001; Xianyi et al., 2005). After six decades of endeavors with the national control programs, remarkable progress could be achieved at the beginning of the early 21 st century (Chitsulo et al., 2000; Utzinger et al., 2005). Among the 12 endemic provinces, five have interrupted the transmission process while seven others, namely, Hunan, Hubei, Jiangxi, Anhui, Jiangsu, Sichuan, and Yunnan have attained the transmission control stage(Li-Juan et al., 2017). However, due to the extensive habitat of the intermediate snail host and frequent human and livestock activities, the risk of schistosomiasis persists, especially in the swamps and lakes of the Yangtze River basin in Hunan, Hubei, Anhui, Jiangxi, and Jiangsu provinces (Li et al., 2000; Cao et al., 2017; Li et al., 2009).

Transmission of schistosomiasis is usually associated with multiple biological and climatic factors, including soil, hydrology, and vegetation, which influence the biological and ecological characteristics of host snail(Mas-Coma et al., 2009; Izah and Angaye, 2016; Li et al., 2016). These factors can be extracted by using remote sensing technologies, and can deepen our understanding of environmental drivers in relation to the spatial and temporal distribution(Li et al., 2016; Trouve et al., 2005). Consequently, research on the factors influencing spatial distribution is of great significance for the investigation of snail habitats, transmission risk surveillance, and schistosomiasis assessment (Spear et al., 2004). The normalized difference vegetation index (NDVI) is the most popular tool used to rebuild maps(Pettorelli et al., 2005). NDVI maps have been constructed using unsupervised classification method in the swamp and lake region(Zhang et al., 2003a); the results reflected the distribution of snail habitats and the potential diffusion areas. Landsat TM image was used to identify potential snail host habitats; NDVI and tasseled-cap transformation features were extracted from the image. In the marshlands of the Poyang Lake, a high correlation coefficient of 95% was found between healthy vegetation and snail habitats (Guo et al., 2002). The NDVI and earth surface maximum temperature (T_{max}) satellite data were combined to build an

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environmental risk model for schistosomiasis; their relationships with *Schistosoma mansoni* and infection rates were analyzed (Malone, 2005). However, due to limitation in resolution, only one or two factors were used to analyze the potential transmission risk in these studies, and accuracy, reliability, and consistency of prediction could not be improved further.

Recently, high-resolution remote sensing, which can greatly improve the accuracy of distinguishing between the types of ground objects, and express the spatial structure, surface texture features, and spectral information of ground objects more clearly, has been widely used in spatio-temporal analysis of disease monitoring and prediction (Gu et al., 2017; Soucy et al., 2018; Dash et al., 2017). However, there is a lack of usage of high-resolution in research related to snail host breeding environment and schistosomiasis transmission risk evaluation. In the present study, we used high-resolution remote sensing imaging to extract the ecological elements in the endemic area of schistosomiasis around Dongting Lake, and modeled and predicted the potential risk areas of schistosomiasis.

2. Materials and methods

2.1. Study area

This study was conducted in Yueyang City, Hunan Province of China, which is located beside Dongting Lake in the middle and lower reaches of Yangtze River. As shown in Fig. 1, the total area of Yueyang City is 15,020 km^2 with the population around 5.5 million. This area was a high schistosomiasis epidemic area in history, due to its ecological conditions suitable for the breeding of schistosomiasis host snail, especially in the marshland and lake regions along the Yangtze River.

2.2. Data collection

2.2.1. Annual snail survey program

The geographical distribution of host snail is consistent with that of schistosomiasis endemic areas. The suitable snail habitus requires necessary mild climate and abundant rainfall for snail population, i.e., annual average temperature of over 14℃ and an annual average precipitation of over 750 mm. In China, the program of snail survey is carried out annually, aiming for obtaining information about snail distribution and density as well as the environmental characteristics of habitats. In this study, the data of snail geographical distribution was collected from the local program of snail survey in Yueyang City in spring and autumn in 2017. The survey data contained the area of surveyed snail habitus, the number of live snails as well as the geographical location for survey sampling (i.e., latitude and longitude).

2.2.2. High-resolution remote sensing data for snail suitable habitus

Potential ecological predictors for schistosomiasis host snail distribution were identified from the existing literatures. The geographical distribution of snails in marshland and lake region is related to ecological factors, including elevation, soil types, rainfall patterns, proximity to human and livestock residential areas, and climate variables related to temperature and precipitation. The values of these ecological predictors were derived from the image data (Fig. 2).

The image data is two scenes remote sensing image of domestic high resolution satellite (simply as GF-1), with a spatial resolution of 2 m and multi-spectral data with resolution of 8 m, and the imaging date was April 14, 2015., These data were provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. The main processing consists of three steps, the first is pretreatment, and including both rectification and image fusion, the second is object oriented information extraction, including image segmentation and information extraction, the last step is removing the error elements under semantic constraints, in order to formulate these semantic constraints.

1) NDVI can distinguish vegetation from soil and water, and is often used for land classification. Its formula is as follows(Field et al., 1995; Los et al., 1994):

$$NDVI = \frac{NIR - R}{NIR + R}$$

where NIR and R are the remote sensing reflectance of near-infrared and red wave bands, and are the fourth and third bands of high-resolution images, respectively.

2) Soil moisture was roughly estimated using the spectral

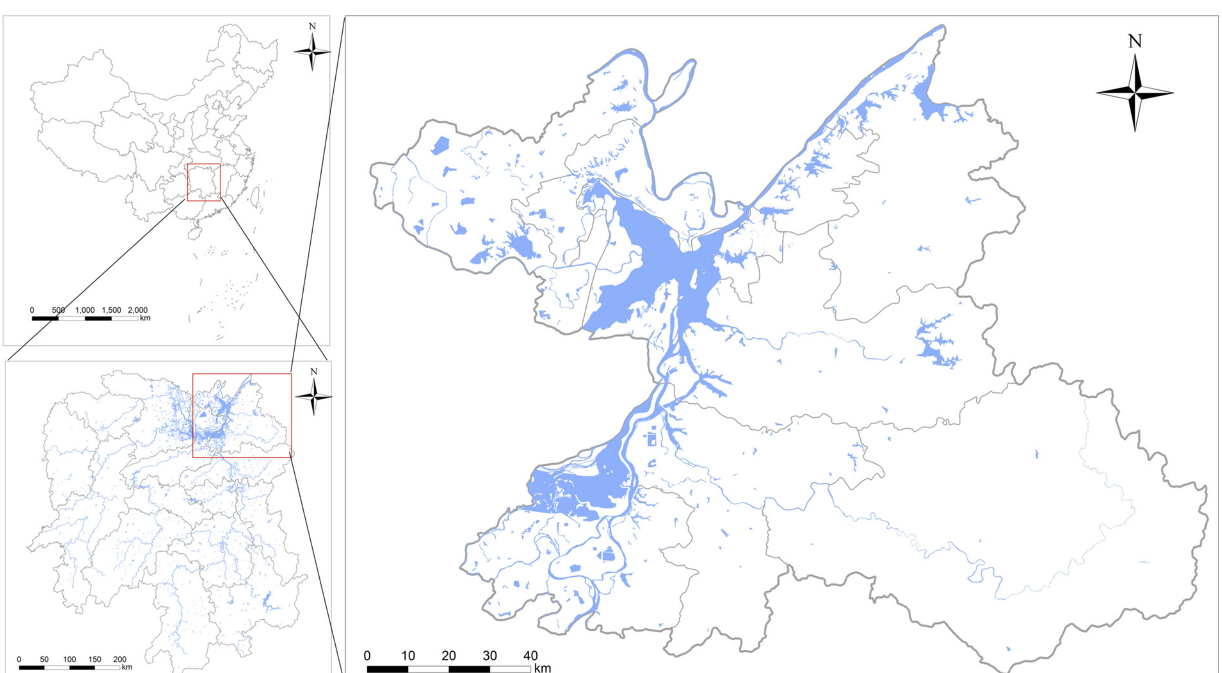

Fig. 1. The study area of Yueyang City, Hunan Province of China is a typical marshland area located beside Dongting Lake in the middle and lower reaches of Yangtze River.

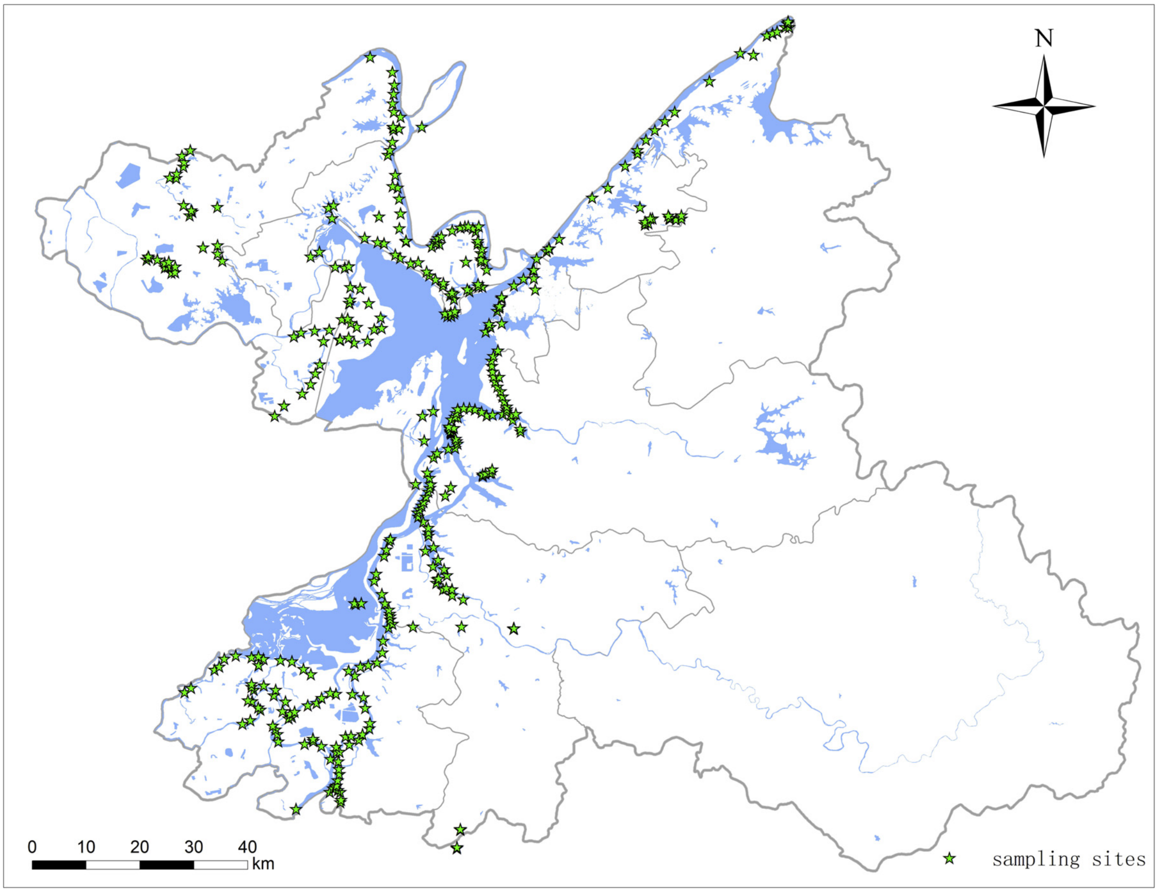

Fig. 2. The schistosomiasis epidemic areas of Yueyang City, Hunan Province: Spatial distribution map of snail habitats.

reflectance characteristics of the soil and covering vegetation, and a Kauth-Thomas (K–T) transformation was performed using(Baig et al., 2014; Liu et al., 2015):

$$Y = R^{T}X$$

where X is a matrix composed of multi-spectral data, each being a vector consisting of a band of pixels; Y is a K–T transformed data matrix; R is a unit orthogonal matrix of K–T transform, its formula given below:

$$R = \begin{bmatrix} 0.326 & 0.509 & 0.560 & 0.567 \\ -0.311 & -0.356 & -0.325 & 0.819 \\ -0.612 & -0.312 & -0.325 & 0.819 \\ -0.650 & 0.719 & -0.243 & -0.031 \end{bmatrix}$$

3) The shortest distance of the observation point from the nearest water body has a great impact on snail habitat. The method as follow:

- Classification of land features and identification of water pixels;
- Setting the minimum distance for storage of non-aqueous pixels in the range of N pixels from the center of the water body boundary (for instance, the boundary with the land) centered on the left and right. N was set to 320 in the current study.
- After the water cell traversal was over, all the values in the distance matrix that were greater than a set upper limit were equal to the upper limit.

When extracting the distance between a point of interest and water body; for example, when extracting the nearest distance to 100 points of scattered 100 pixels. In this way, centered on a point of interest, the circle spreads to the periphery until the water pixel is found. This distance would be the closest from the water to the pixel.

2.3. Spatial modeling by multiple regression method

Multiple regression analysis refers to a statistical analysis method in which one variable is regarded as the dependent variable and one or more other variables are regarded as independent variables, and quantitative relations of linear or nonlinear mathematical models between Multiple variables are established and sample data are used for Analysis We used the method to find the relationship between snail distribution measurement points and the extraction of environmental quantum parameters.

In order to understand the quantitative relationship between the information of environmental factors and distribution of snails, with the support of ArcGIS (Environmental Research Systems Institute, Redlands, CA, USA) software, vector maps of snail distribution points on the ground were overlaid on the extracted relevant environmental factors, and the pixels of each snail distribution measurement point were collected. The corresponding values, as attributes of the environmental factors on snail distribution measurement points, were used for further analysis.

Based on the environmental factors, the actual ground snail distribution points were established. Applying spatial regression analysis, the distribution of snail breeding ground was used as a dependent variable, whereas NDVI, soil moisture, and closest distance from water body were used as independent variables. Multiple stepwise regression analysis was used to obtain a predictive model for the distribution of snail breeding grounds.

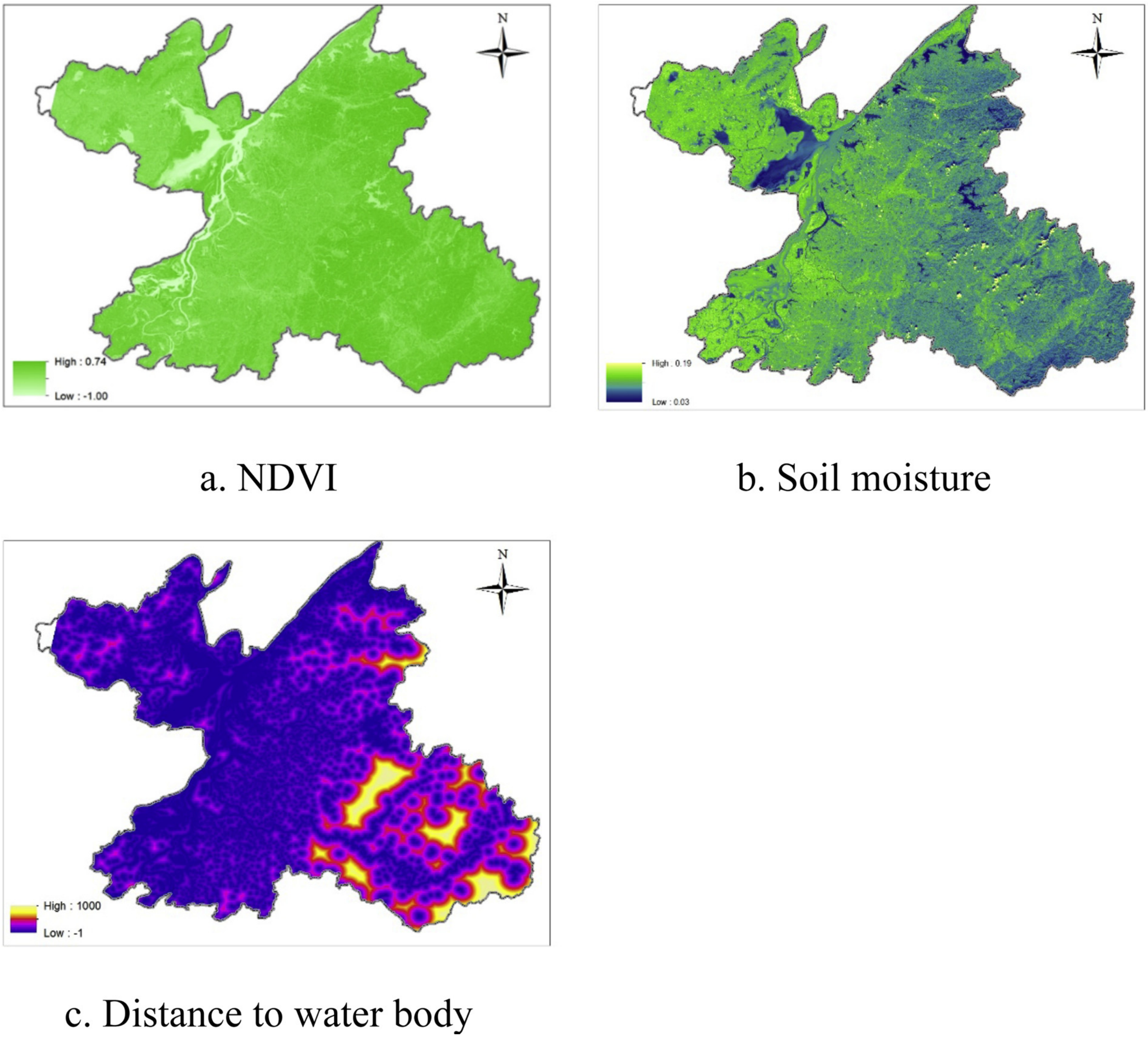

Fig. 3. Extraction of ecological or environmental factors based on remote sensing image inversion.

3. Results

3.1. Geographical distribution of host snail

Based on the latitude and longitude of the actual measurement points on the ground as per GPS, along with the WGS84 coordinate system setting of the actual measurement point, a spatial distribution map of the investigated points was made and overlaid on the surrounding area of the Dongting Lake in the experimental area of the ArcGIS platform. The snail investigation point is presented as a blue square. Selecting the high-resolution image data of Dongting Lake, a total of 125 ground snail distribution sites were actually identified, and the area of each site was measured to be 0.1 m^2.

3.2. Environmental factors for predicting snail distribution

Following the previous methods, environmental factors that affected snail distribution were extracted from remote sensing images; the results are shown in Fig. 3.

The NDVI analysis shows the index to be suitable for Oncomelania breeding environment when ranging from 0.5 to 0.6, which is different from the uniform distribution of natural environment. Analysis of soil moisture indicated that the index suitable for Oncomelania breeding environment was approximately -0.025–-0.015. Analysis of the shortest distance from water bodies shows that the area with high snail density is basically located within 500 m from the water body. Distance of the nearest water body and snail density are inversely proportional. When the distance from the water body is greater than 500 m, the measured snail density decreases significantly; when it is more than 1000 m, snail density is very low.

3.3. Correlation relationship for snail distribution with environmental factors

Considering the distribution level of snail breeding ground as the dependent variable (indicated by Y) and NDVI, soil moisture, and the shortest distance between the observation point and water body as the independent variables, multi-variate stepwise regression analysis was conducted. A predictive model for the snail breeding ground was established as follows:

$$Y = -7.278 - 14.995 * NDVI * NIR - 0.0015453 * DISTANCE - 45.011 * BRIGHT$$

where NDVI is the normalized vegetation index, NIR is the remote sensing reflectance of the high-resolution image near-infrared, DISTANCE is the shortest distance between the observation point and water

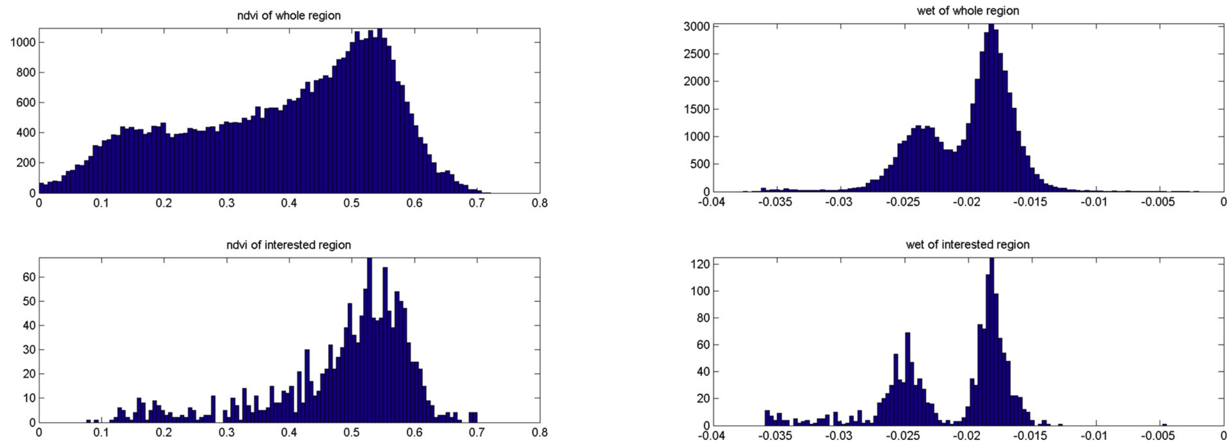

Fig. 4. The verification results of NDVI and soil moisture.

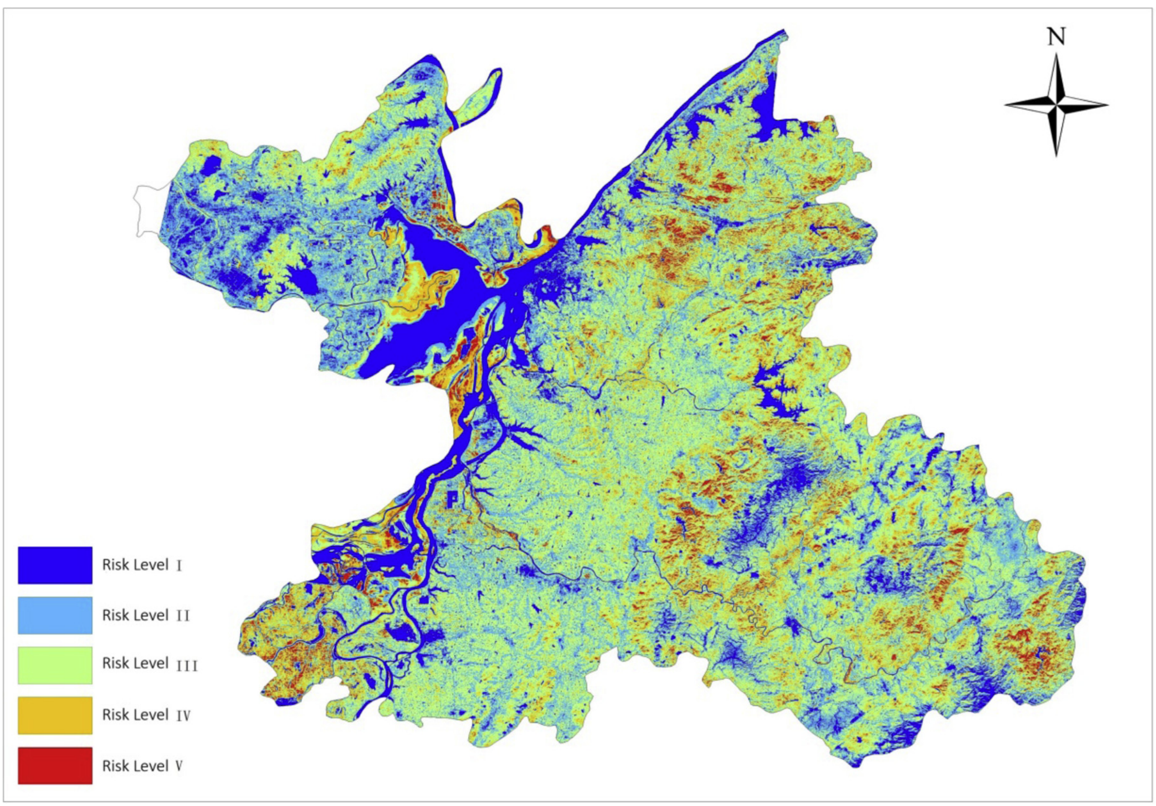

Fig. 5. Grade map of snail breeding inversion in Yueyang City, Hunan Province.

body, and BRIGHT is the brightness value of the skullcap transform. For the prediction and identification of snail breeding area, distribution of the snail breeding ground was estimated.

3.4. Modeling validation

Based on geographical distribution of host snail from annual survey data and predictive environmental factors from high resolution remoting sensing data, a multivariate stepwise regression model was developed and used to represent the correlation relationships between environmental impact factors with the snail distribution. In order to validate the accuracy of the developed spatial modeling for predicting snail distribution, such a snail survey dataset will be used for comparing the predicted snail distribution with the actual surveyed distribution. Specifically, the 125 survey snail habitus sites were split into two subsets, one was for spatial modeling, the other was for validation. In our study, we utilize the modeling-testing validation method by randomly collecting 15% of the survey snail distribution habitus as the validation subset and then repeat such a process for 20 iterations. The accuracy for the developed spatial modeling is around 87.64%.

4. Discussion

The application of remote sensing technology to monitor the distribution of snail is mainly based on the extraction of relevant environmental factors that can be used as surrogate indicators to establish a predictive model of Oncomelania snail distribution (Feng et al., 2016; Walz, 2015). Low or medium-resolution remote sensing images were considered earlier in the remote sensing inversion of snail breeding areas(Zhou et al., 2002; Zhang et al., 2005, 2003b). The resolution ratio, however, was so limited that it was difficult to identify some environmental factors affecting the distribution of snail breeding areas, resulting in erroneous inversion images(Yang et al., 2005).

In this study, we constructed a model and preliminarily explored the use of high-resolution remote sensing data to analyze the geographical distribution of snail in the epidemic region of schistosomiasis. High-resolution remote sensing images have greatly enhanced the resolution and accuracy of ground objects, and express the spatial structure, surface texture features, and abundant spectral information from ground objects more clearly(Yu et al., 2006; Valero et al., 2010; Sun et al., 2012). It has helped the researchers in obtaining more information about the ground structure, shape, and texture (Meinel and Neubert, 2004).

Based on the data of snail annual survey by combining with the ecological or environmental factors extracted from high-resolution remote sensing images, risk level of the distribution of snail breeding areas could be measured through high-resolution remote sensing images, which could distinguish between snail breeding and non-breeding areas. Based on the key spatio-temporal factors affecting the spread of schistosomiasis, combined with environmental factors and spatio-temporal characteristics of schistosomiasis, as well as the parameters obtained from remote sensing spectroscopy, we carried out spatial analysis and correlation research, to establish correlation techniques and mapping relationships between the spectral characteristics of high-resolution remote sensing image and information of schistosomiasis epidemic and propagation element (Fig. 4 and Fig. 5).

We applied the environmental parameters, related to the epidemic and transmission of schistosomiasis, to study the influence of natural environmental factors on the spread of schistosomiasis. High-resolution remote sensing images were used to extract environmental indicators, such as normalized vegetation index, soil moisture, and distance from the snail points to water sources, based on which, a model was established relating the snail breeding areas with environmental factors. The model can be used to monitor the distribution of snails. Due to data limitations, we only selected one high-resolution remote sensing image and the snail survey data of April 2015 in this study. In addition, several environmental factors such as vegetation index, soil moisture, and distance of the nearest water source, which could affect the habitat of snails, were considered. The remaining factors were not included in the construction of this model. Follow-up work will include additional factors for further improvements.

5. Conclusion

In summary, this study conducted a typical schistosomiasis epidemic area in the marshland and lake regions along the Yangtze River, Yueyang City, Hunan Province of China. And three types of environmental factors associated with the geographical distribution of snail were extracted from the high-resolution remoting sensing data. The predicted distribution of snail habitus from the high-resolution environmental factors were compared with the data of annual program of snail survey. The results have shown that the application of high-resolution remote sensing can improve the accuracy of the modeled and predicted the potential risk areas of schistosomiasis, and may become an important tool for the ongoing national schistosomiasis control program.

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Declaration of Competing Interest

All the authors have no competing interests.

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