Evaluation of a linear spectral mixture model and vegetation indices (NDVI and EVI) in a study of schistosomiasis mansoni and *Biomphalaria glabrata* distribution in the state of Minas Gerais, Brazil

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This paper analyses the associations between Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) on the prevalence of schistosomiasis and the presence of Biomphalaria glabrata *in the state of Minas Gerais (MG), Brazil. Additionally, vegetation, soil and shade fraction images were created using a Linear Spectral Mixture Model (LSMM) from the blue, red and infrared channels of the Moderate Resolution Imaging Spectroradiometer spaceborne sensor and the relationship between these images and the prevalence of schistosomiasis and the presence of* B. glabrata *was analysed. First, we found a high correlation between the vegetation fraction image and EVI and second, a high correlation between soil fraction image and NDVI. The results also indicate that there was a positive correlation between prevalence and the vegetation fraction image (July 2002), a negative correlation between prevalence and the soil fraction image (July 2002) and a positive correlation between* B. glabrata *and the shade fraction image (July 2002). This paper demonstrates that the LSMM variables can be used as a substitute for the standard vegetation indices (EVI and NDVI) to determine and delimit risk areas for* B. glabrata *and schistosomiasis in MG, which can be used to improve the allocation of resources for disease control.*

Key words: schistosomiasis - geographical information system - linear spectral mixture model - *Biomphalaria glabrata* - epidemiology

Schistosomiasis mansoni is an endemic disease present in approximately 54 American and African countries (WHO 1985, Chitsulo et al. 2000). The etiological agent is the trematode *Schistosoma mansoni* (Sambon), which causes a variety of symptoms ranging from acute to chronic forms with predominantly intestinal manifestations. Severe forms of the disease may occur, such as splenomegaly, impairment of the central nervous system, fibro-obstruction in the liver and portal hypertension. Schistosomiasis treatment is simple due to readily available drugs that can be administered in a single oral dose (Katz et al. 1989). The disease has been primarily spreading from the outskirts of cities to urban centres and other regions of the country (Graeff-Teixeira et al. 1999). Schistosomiasis is primarily caused by a lack of basic sanitation in the peripheries of large urban centres where in natura sewage is directly released into drainage.

The intermediate hosts are molluscs of the *Biomphalaria* genus. Among the three intermediate hosts species of *S. mansoni* present in Brazil (*Biomphalaria glabrata*, *Biomphalaria tenagophila* and *Biomphalaria straminea*), *B. glabrata* is of the greatest significance due to its extensive geographic distribution, higher infection rates and higher effectiveness in the transmission of schistosomiasis. Indeed, the occurrence of *B. glabrata* has always been associated with the disease in endemic areas.

The extensive distribution of these intermediate hosts in Minas Gerais (MG), Brazil, results in the wide-ranging distribution of schistosomiasis, which is now commonly found in non-endemic areas (Katz & Carvalho 1983, Carvalho et al. 1988, 1989). The disease is known to be endemic in the regions north (zone of Médio São Francisco and Itacambira), oriental and central (zone of Alto Jequitinhonha, Oeste, Alto São Francisco and Metalúrgica). The highest infection rates are found in the north-eastern and eastern parts of MG, including Mucuri, Rio Doce and Zona da Mata (Pellon & Teixeira 1950, Katz et al. 1978, Carvalho et al. 1987, Lambertucci et al. 1987). In the endemic areas, high host concentrations cause a high prevalence of schistosomiasis, where high host concentrations are associated with other risk factors.

Environmental factors, such as vegetation, temperature, land use and drainage net, can affect the spread and prevalence of schistosomiasis. Here, environmental factors were characterised using satellite imagery and spatial

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analysis. Increasingly, research into the link between the disease, environmental conditions, geographical information systems and remote sensing data is being conducted and this paper may play an important role in schistosomiasis studies (Beck et al. 1997, 2000, Bavia et al. 2001).

Recently, Moderate Resolution Imaging Spectroradiometer (MODIS) satellites with sensors of high temporal resolution and moderated space resolution became operational.

Two vegetation indices (VI) based on MODIS data provide robust spectral measures of the amount of vegetation covering the land. The two indices provide spatial and temporal comparisons of global vegetation conditions that can be used to monitor changes in the Earth's terrestrial photosynthetic vegetation activity and to detect changes in phenology. Additionally, they allow a biophysical derivation of radiometric and structural vegetation parameters (Huete et al. 1999).

A drawback of the MODIS sensor data is the relatively low spatial resolution. The Linear Spectral Mixture Model (LSMM) can be used (Cross et al. 1991) to overcome this restriction. This model estimates proportions of determined objects of interest inside a pixel. The "pure" terrestrial coverage for the set of classes of interest is identified and their spectra are used to define the "endmember signatures". All other pixels are assigned proportions of these endmembers (Cross et al. 1991, Quarmby et al. 1992). Each pixel spectral response is considered a linear mixture of the pure pixel (endmember) spectral signatures.

Efforts to predict the prevalence of schistosomiasis using Geographic Information System (GIS) were first attempted in the Philippines and the Caribbean by Cross et al. (1984). In Brazil, the first studies were performed in the state of Bahia and attempted to correlate the disease distribution with Normalized Difference Vegetation Index (NDVI), diurnal temperature difference and the length of the annual dry period (Bavia et al. 2001). Other studies in Brazil using GIS were conducted in Pernambuco (Barbosa et al. 2004) and MG (Carvalho et al. 2005, Freitas et al. 2006, Guimarães et al. 2006, 2008, 2009, Martins 2008).

The aim of this paper is to use images created using LSMM from MODIS radiometric data to analyse the correlation with schistosomiasis prevalence and *B. glabrata* presence in MG and compare these results to analyses using NDVI and Enhanced Vegetation Index (EVI) channels.

MATERIALS AND METHODS

MODIS - The MODIS instrument is operating on both the Terra and Aqua spacecraft. It has a viewing swath width of 2,330 km and views the entire surface of the Earth every 1-2 days. Its detectors measure 36 spectral bands between 0.405-14.385 µm and it acquires data at three spatial resolutions - 250 m, 500 m and 1,000 m. Data products derived from MODIS observations describe features of the land, oceans and the atmosphere that can be used for studies of processes and trends on local to global scales (Justice et al. 1998).

The MODIS MOD13 product, which was used in this study, comprises the blue, red, near infrared (NIR) and the middle infrared bands (the radiometric set of channels), as well as the VIs. The VI products contain two indices, the NDVI and a new EVI, which has improved sensitivity to differences in vegetation from sparse to dense vegetation conditions (Justice et al. 1998). The MOD13 product is delivered as a set of image compositions produced globally with 1 km, 500 m and 250 m resolution in a 16-day period (Huete et al. 1999).

The NDVI reduces noise and some uncertainty associated with instrument characteristics and cloud shade effects, but the disadvantages include nonlinearity and scaling problems, signal saturation at high leaf biomass and sensitivity to exposed soil backgrounds (Running et al. 1994, Justice et al. 1998). The NDVI can be calculated using the formula:

$$NDVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R}$$

where ρ_{NIR} = reflectance from NIR and ρ_R = reflectance from red.

The EVI offers improved sensitivity in high biomass regions and improved vegetation monitoring (Justice et al. 1998, Weier & Herring 2004). The EVI is defined:

$$EVI = G^* \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + C_1 * \rho_R - C_2 * \rho_B + L}$$

where ρ_{NIR} = reflectance from NIR, ρ_R = reflectance from red, ρ_B = reflectance from blue, G is the gain factor, L is a canopy background adjustment term and C_1 and C_2 weigh the use of the blue channel in aerosol correction of the red channel. The coefficients used have been usually applied to Landsat TM: L = 1, C_1 = 6, C_2 = 7.5 and G = 2.5 (Justice et al. 1998).

LSMM - The LSMM is an image processing algorithm that generates images with the proportion of each endmember (vegetation, soil and shade) inside a pixel. The proportion values must be nonnegative and they also must add to unity (Shimabukuro & Smith 1991). In this case, the pixel response in any given spectral band is assumed to be a linear combination of the responses of each individual component. For any individual pixel, the linear model can be written as:

$$r_i = \sum_{j=1}^{n} (a_{ij} x_j) + e_i \quad i = 1, ..., p$$

where r_i represents the pixel's mean spectral reflectance in the ith spectral band, a_{ij} is the spectral reflectance of the $_j$th component in the $_i$th spectral band, x_j is the proportion of the $_j$th component within the pixel, n is the number of components, e_i is the residual for the $_i$th spectral band and p is the number of spectral bands. The proportions x_j are subjected to two constraints:

$$\Sigma x_j = 1 \text{ and } x_j \geq 0 \text{ for all components}$$

The least squares technique can then be applied to estimate the component proportions x_j (Shimabukuro & Smith 1991).

Application of the LSMM to the MODIS radiometric images - The vegetation, soil and shade components (end-members) were extracted from MODIS images. Fig. 1 depicts the spectral answer of the vegetation component (green) in areas of ciliary's woods, the shade component (blue) in the area corresponding to a dam and the soil component (red) in areas of exposed soil in (i) the summer period (from 17 January 2002-1 February 2002) and (ii) the winter period (from 28 July 2002-12 August 2002).

Schistosomiasis prevalence and presence of B. glabrata - Schistosomiasis prevalence data were gathered from the Brazilian Health National Foundation and the Health Secretariat of Minas Gerais Annual Reports. Information on the presence of *Biomphalaria* was obtained from Souza et al. (2001) and from the Helminthiasis Laboratory and Medical Malacology of the Rene Rachou Research Institute-Fiocruz (MG) (Carvalho et al. 2008).

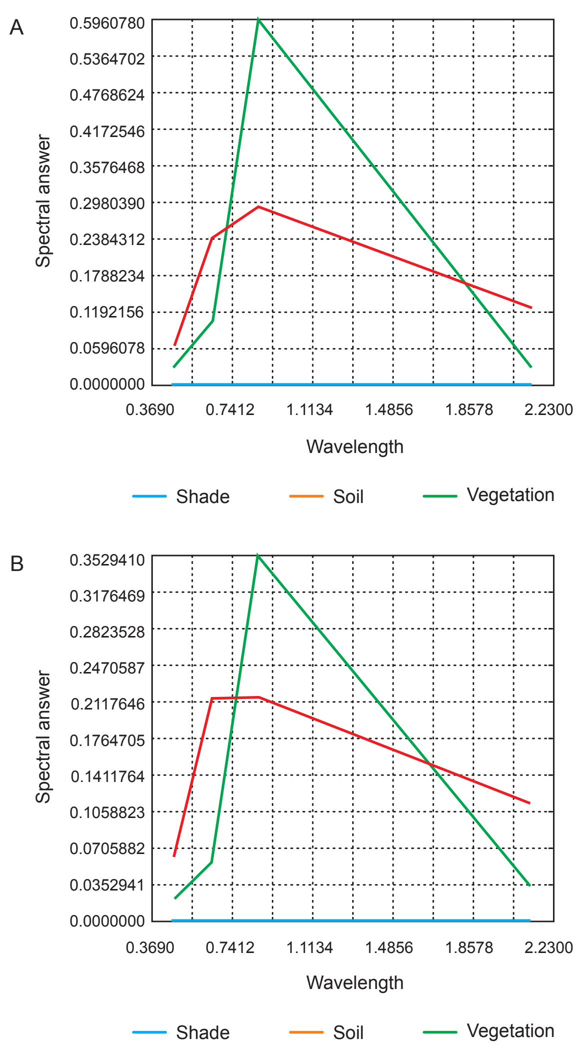

Fig. 1: spectral answer of the shade (blue), soil (red) and vegetation (green) components. Extracted of the Moderate Resolution Imaging Spectroradiometer images: A: summer; B: winter.

There were 853 points (pixels) in MG selected to correspond to the mass centre of each municipality, as depicted in Fig. 2A. The correlation between fraction images and the VIs was analysed at these 853 points in two seasons (January and July 2002) to determine the extent to which they are linearly related and then represent the same information.

Additionally, 96 municipalities from MG were studied, where information for these municipalities on schistosomiasis prevalence and the presence of *B. glabrata* was available, as depicted in Fig. 2B. Because these data were available at the municipality level, the averages were extracted by considering the pixels inside area of each municipality for all of the shade, soil and vegetation fraction images.

RESULTS

The soil, vegetation and shade fraction images were generated using the soil, vegetation and shade components, respectively, of each pixel from the spectral answer in MODIS' several bands.

Figs 3 and 4 present the VIs (NDVI and EVI) and the fraction images from each season (January and July 2002) for MG. As apparent in Fig. 3, the highest values (bright pixels) have a similar pattern in the vegetation

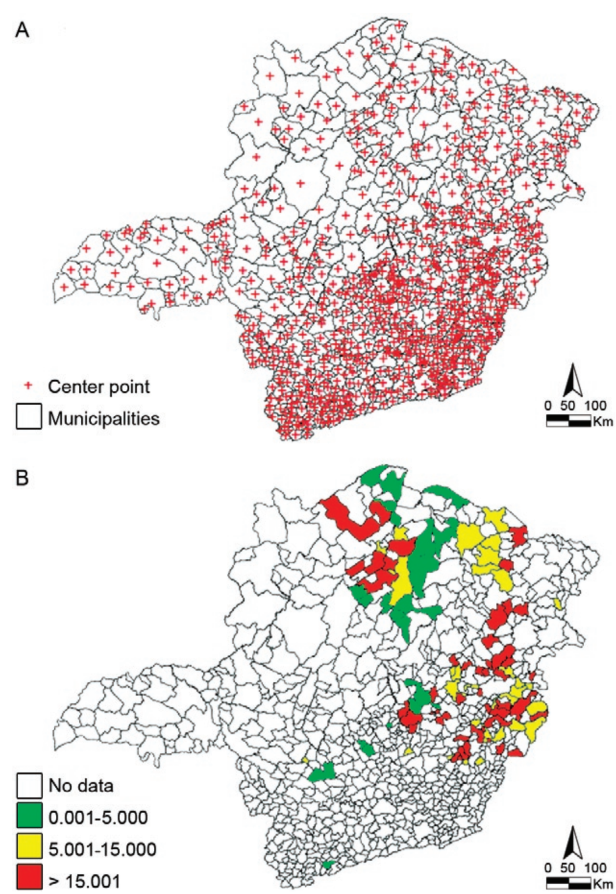

Fig. 2A: the state of Minas Gerais with the points selected through the municipalities' center point; B: sets: 96 municipalities.

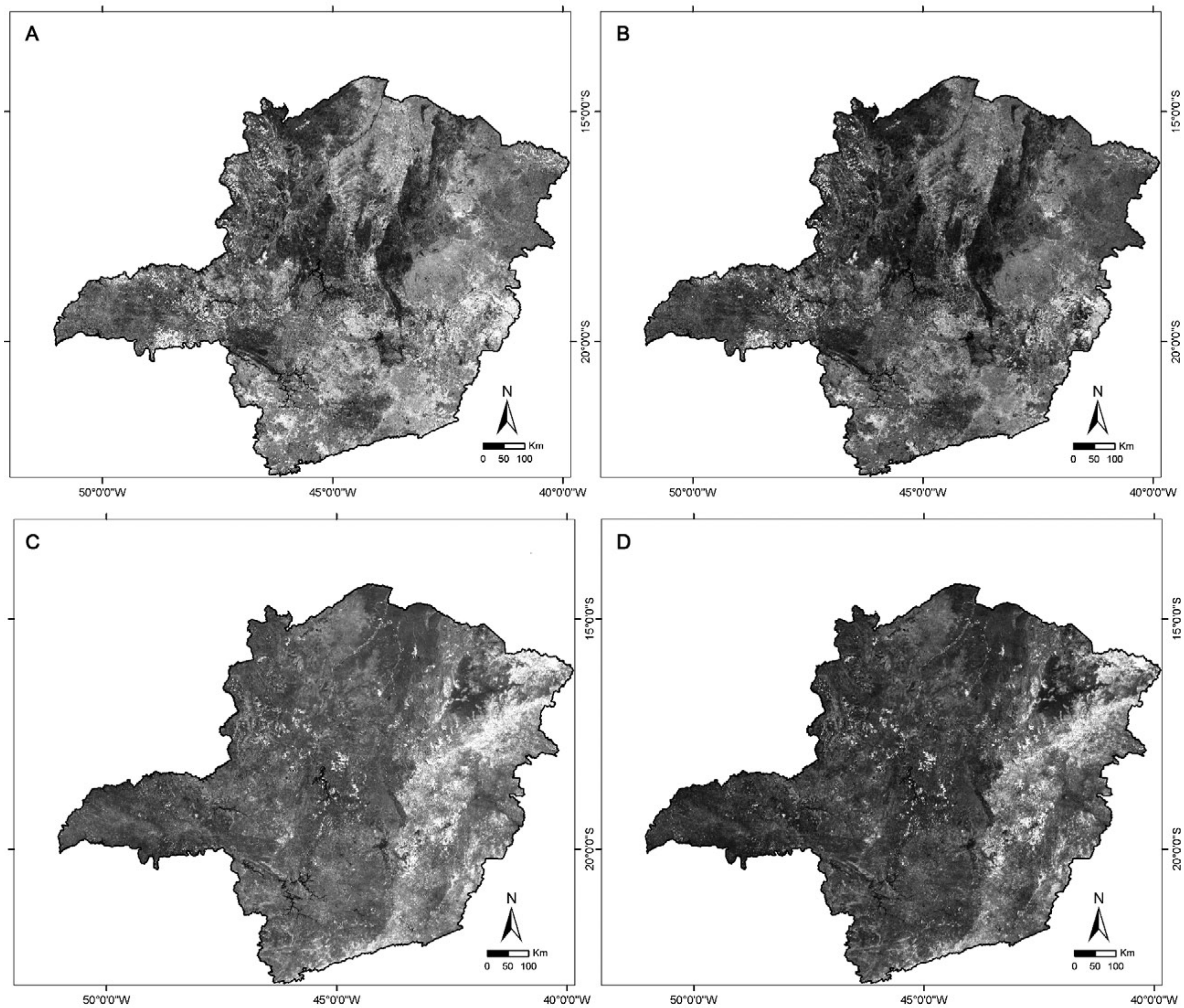

Fig. 3: similar behavior in the Enhanced Vegetation Index (EVI) (A) and in vegetation fraction image (B) of January/2002 and EVI (C) and in vegetation fraction image (D) of July/2002.

fraction image and in EVI. In Fig. 4, NDVI depicts a similar pattern, however negatively related, with the soil fraction image.

Table I depicts correlations between the VIs and the vegetation, soil and shade fraction images for the two periods (January and July). There was a high correlation between the vegetation fraction image and the EVI (0.90 and 0.96 in the January and July images, respectively) and between the soil fraction image and the NDVI (-0.86 and -0.88 in January and July, respectively).

These results demonstrate that the atmosphere and soil components influenced the NDVI results mainly in the rainy season when the effect of soil between scarcely vegetated areas was greater. Additionally, both the vegetation fraction image and the EVI were more correlated with the NDVI in the July image (0.85 and 0.91, respectively) than the January image (0.65 and 0.63, respectively). This is likely due to the fact that rain is nearly absent in July and the vegetation is dry, which consequently minimises the effect of the soil component in the NDVI.

Correlations were higher in July than January for all the variables except the shade fraction image, which had higher correlations with January variables (Table I). This may be because the rainy season is in January, at which time there is more shade from the trees.

The Table II shows the correlation values between the prevalence of schistosomiasis, the presence of *B. glabrata* and the soil, vegetation and shade fraction images from MODIS data in January and July 2002.

Correlations that are significant at the 5% are highlighted in bold. There is not a significant correlation to the fraction images of the rainy season (January 2002) as much as to the prevalence as to the existence of *B. glabrata*. On the other hand, the prevalence is positively correlated with the vegetation fraction in July 2002 but negatively correlated with the soil fraction. This indicates that the prevalence was associated with the type of vegetation because in the dry season there is better differentiation between the biomes (e.g., forest, *cerrado* and *caatinga*). Prevalence was negatively correlated with soil

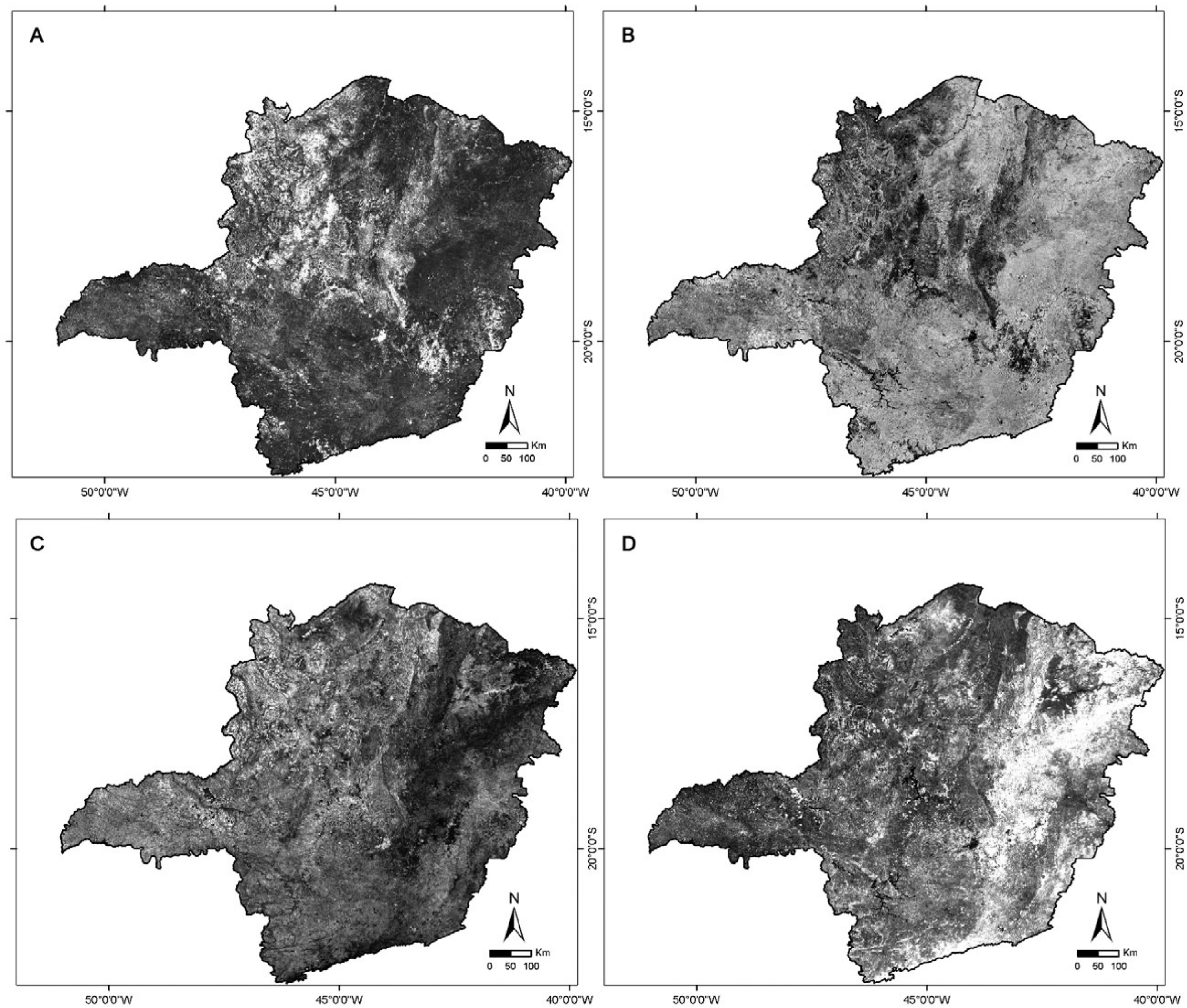

Fig. 4: similar behavior, however inverse, in the soil fraction image (A) and in Normalized Difference Vegetation Index (NDVI) (B) of January/2002 and the soil fraction image (C) and in NDVI (D) of July/2002.

TABLE I

Correlations between the vegetation indices and the vegetation, soil and shade fraction images for the January/2002 [summer (s)] and July/2002 [winter (w)] dates

	EVIs	NDVIs	VEGs	SOILs	SHADs	EVIw	NDVIw	VEGw	SOILw	SHADw
EVIs	-	0.63	0.90	-0.40	-0.36	0.18	0.16	0.17	-0.07	-0.10
NDVIs	0.63	-	0.65	-0.85	0.41	0.29	0.33	0.27	-0.26	0.05
VEGs	0.90	0.65	-	-0.50	-0.34	0.18	0.14	0.19	-0.05	-0.15
SOILs	-0.40	-0.85	-0.50	-	-0.53	-0.24	-0.27	-0.24	0.30	-0.14
SHADs	-0.36	0.41	-0.34	-0.53	-	0.15	0.25	0.12	-0.25	0.20
EVIw	0.18	0.29	0.18	-0.24	0.15	-	0.91	0.96	-0.71	-0.12
NDVIw	0.16	0.33	0.14	-0.27	0.25	0.91	-	0.85	-0.88	0.25
VEGw	0.17	0.27	0.19	-0.24	0.12	0.96	0.85	-	-0.71	-0.17
SOILw	-0.07	-0.26	-0.05	0.30	-0.25	-0.71	-0.88	-0.71	-	-0.57
SHADw	-0.10	0.05	-0.15	-0.14	0.20	-0.12	0.25	-0.17	-0.57	-

EVI: Enhanced Vegetation Index; NDVI: Normalized Difference Vegetation Index; SHAD: shade fraction image; SOIL: soil fraction image; VEG: vegetation fraction image.

TABLE II

Correlation of variables

Variables	Prevalence	*Biomphalaria glabrata*
Shade[a]	-0.10	-0.07
Soil[a]	0.01	0.17
Vegetation[a]	0.11	-0.11
Shade[b]	-0.10	**0.30**
Soil[b]	**-0.38**	-0.12
Vegetation[b]	**0.50**	-0.05

a: 17 January 2002; *b*: 28 July 2002.

fraction, including areas of exposed soil. The shade fraction in July 2002 was positively correlated with the presence of *B. glabrata,* indicating that the mollusc inhabits areas with different forms of relief. Shade fraction can indicate water retention in the soil and in areas with the presence of water bodies (e.g., river, lakes and lagoons).

DISCUSSION

The vegetation fraction image of the LSMM was highly correlated with the EVI, while the soil fraction image was highly correlated with the NDVI for both dates. EVI minimizes the atmospheric and soil influences, as reported by Justice et al. (1998) and Weier and Herring (2004). Our results indicate that the vegetation fraction image of the LSMM also minimizes the influences of the atmosphere and soil, which makes these images more accurate than the NDVI in the changing of type of vegetation (biome).

This study also found that the variables were not highly correlated between the dry and rainy season, which demonstrates that variables from both seasons can be used in multiple regression analysis. Our results show that the variables from the LSMM in the dry season were significantly correlated with the prevalence of the disease and the presence of the mollusc. This may be due to the fact that higher concentrations of snails occur in the dry season, which increases disease transmission due to the decrease in rain and volume of water bodies and people searching for water bodies to minimize the warmth, either for drinking, bathing or entertainment. This information reiterates the importance of conducting studies on water bodies and snail presence.

The results show that variables from the LSMM can be used in place of the EVI and NDVI to determine and delimit risk areas for the presence of *B. glabrata* and for the occurrence of schistosomiasis in MG. This information can be used to improve the allocation of resources in disease control.

The fraction images of the LSMM presented in this paper have been used in the following papers:

Freitas et al. (2006), Guimarães et al. (2008) and Martins (2008) used the vegetation, soil and shade fraction images to estimate schistosomiasis prevalence in regression models. However, only Martins (2008) obtained a model with vegetation fraction image during the dry season.

Martins-Bedé et al. (2010) presented the decision tree approach to model and classify infection risk. In this approach, the main tree was compared to three sub-trees and two sub-trees with the shade fraction image from the dry season (ShadeW) were very similar to the main tree, which did not have the variable ShadeW.

Additionally, Martins-Bedé et al. (2009) proposed the application of a similarity-based fuzzy case-based reasoning approach to classify the prevalence of schistosomiasis in MG using fraction images.

We observed that fraction images were highly useful in the study of schistosomiasis. The fraction images obtained in the dry and rainy seasons can characterise the environment, such as the type of biome (Affonso 2003, Ferreira 2003), geomorphology (Sousa 1998), hydrography (Hansen et al. 2008) and land cover change (Adams et al. 1995), which are important factors for predictive models.

The use of MODIS images from other dates and places is recommended in order to verify if there is a high correlation between fraction images, VIs and the prevalence of schistosomiasis and the occurrence of *Biomphalaria*.

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