Environ Earth Sci (2011) 62:69–76
DOI 10.1007/s12665-010-0498-2

ORIGINAL ARTICLE

Using the radial basis function network model to assess rocky desertification in northwest Guangxi, China

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Received: 23 April 2009 / Accepted: 11 February 2010 / Published online: 6 March 2010

Abstract Karst rocky desertification is a progressive process of land degradation in karst regions in which soil is severely, or completely, eroded. This process may be caused by natural factors, such as geological structure, and population pressure leading to poor ecosystem health and lagging economic development. Karst rocky desertification is therefore a significant obstacle to sustainable development in southwest China. We applied a radial basis function network model to assess the risk of karst rocky desertification in northwest Guangxi, a typical karst region located in southwest China. Factors known to influence karst rocky desertification were evaluated using remote sensing and geographic information systems techniques to classify the 23 counties in the study area from low to extreme risk of karst rocky desertification. Counties with extreme or strong karst rocky desertification risk (43.48%, nearly half of the study area) were clustered in the north, central and southeast portions of the study area. Counties with low karst rocky desertification (30.43%) were located in the west, northeast and southwest of the study area. The spatial distribution of karst rocky desertification was moderately correlated to population density.

Keywords Radial basis function network (RBFN) · Karst rocky desertification · Northwest Guangxi, China · Remote sensing (RS) · Geographic information systems (GIS)

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Introduction

Karst areas characterized by soluble limestone bedrock and thin soils are some of the most fragile regions of the world (Parise and Gunn 2007; Parise et al. 2008). Soils in karst areas are slow to form, in fact, it has been estimated that 250,000–850,000 years are needed to form a 1-m depth soil in the karst region of Guangxi (Yuan and Cai 1988). Karst rocky desertification is a progressive process of land degradation where soil is seriously or thoroughly eroded (Yuan 1993; Xiong 2002; Wu and Zhang 2007). Effects of karst rocky desertification include widespread exposed bedrock, declining land productivity, and evolution of desert-like landscape. Southwest China boasts one of the largest continuous karst-dominated regions (620,000 km^2) in the world, with about 22.3% of the region currently undergoing karst rocky desertification (Su 2002). With a population of more than 1 million, this region is one of the poorest areas in China, facing problems of environmental degradation and lagging economic development (Cai 1996). An assessment of karst rocky desertification is useful to policy makers and stakeholders as an educational tool and as an aid in the development of regional policies addressing the issue (Huang and Cai 2005, 2006).

Both academic and government researchers in China have focused on karst rocky desertification. Several studies have assessed the spatial distribution of karst rocky desertification at a variety of scales using Landsat TM images (Wang et al. 2003; Xiong 2002; Yan and Li 2008) while others have focused on the effects of karst rocky desertification on the ecological environment (Long et al. 2005; Zhang et al. 2007). Still other studies have assessed evaluation methods (Huang and Cai 2005; Cao et al. 2008) and measures of recovery (Liang et al. 2007; Zhang et al. 2008). Currently, visual interpretation of remotely sensed images accompanied by field verification is the main identification method for karst rocky desertification studies (Huang and Cai 2005). Though the current method is direct and simple, it is time consuming and highly dependent on expert knowledge. A fast and efficient method to evaluate karst rocky desertification is needed.

A radial basis function network (RBFN) is a neural network approached by viewing the design as a curve-fitting (approximation) problem in high dimensional space (Park and Sandberg 1991). The design of an RBFN in its most basic form consists of three separate layers. The input layer is the set of source nodes. The second layer is a hidden layer, whose activation function is determined by a self-organizing rule. The output layer gives the response of the network to the activation patterns applied to the input layer. RBFN is capable of modeling any nonlinear function using a single hidden layer, and it is commonly employed in problems of classification (Haykin 1994). RBFN has several advantages over other methods. First, RBFN is capable of approximating nonlinear mappings effectively. Second, the training time of RBFN is quite short compared to other neural network approaches such as the multi-layer perception (Haykin 1994). Third, RBFN generally has a higher classification accuracy (5–10%) than that of the back propagation algorithm (Moody and Darken 1989). Fourth, RBFN can successfully identify regions of sample data in an unknown class using a nonmonotonic transfer function based on the Gaussian density function (Moody and Darken 1989). Finally, RBFN performs better than conventional kernel classifiers (Fidêncio et al. 2008; Nicos et al. 1998). These properties make it attractive for many applications.

To date, only one study has applied RBFN to karst rocky desertification (Huang and Cai 2005), however, study results were not validated. In this study, RBFN will be used to assess karst rocky desertification in northwest Guangxi, China and the efficiency of the model, when applied to a typical karst region, will be assessed.

Study area

Northwest Guangxi is located in southwest China at approximately 104°29′–109°09′E, 23°41′–25°37′N (Fig. 1). It has an area of about 71,992 km^2, encompassing 23 counties with a population of 7.55 million. This region has a subtropical wet monsoon climate with an average annual temperature of 20°C and precipitation of 1,000–1,600 mm, most of which falls during the summer months. Vegetation cover is largely shrub, subtropical evergreen forests, and grassland over elevations ranging from 100 to 2,000 m above sea level.

This area is dominated by a full suite of karst landforms, including poljes, cockpits, towers and dolines (sinkholes). According to the Ministry of Land Resource, China, in 2005, Guangxi was home to 25.3% of China's karst rocky desertification impacted land. Nearly 10% of Guanxi's total land area is impacted by karst rocky desertification.

The primary land use\land cover (LULC) classes of the study area vary from agricultural fields (such as rice, corn, soybeans, wheat, rape oil seed, oats, barley and sweet potatoes) in the more populated areas to secondary forests in remote areas. Agricultural land is very limited because the high relief associated with mountains and karst topography leaves little flat land available for agricultural uses. The best arable lands are found in karst valleys or closed depressions, where major settlements are also situated and consequently friction arises between conflicting demands for agricultural development and ecosystem conservation.

Data and methods

Data

Variables selection

The choice of variables used to measure the risk of karst rocky desertification was founded on results of previous research (Li and Wang 2004; Xiong 2002): percentage of area with severe soil erosion, per-capita cropland area (ha person^{-1}), percentage of forest cover, average annual rainfall (mm), percentage of land with slope angle >25°, percentage of cropland with slope angle ≥25°, and index of average relief degree of land surface (RDLS).

Data acquisition

A digital elevation model (DEM), satellite imagery (Landsat TM) and socio-economic datasets were downloaded from the Data-sharing Network of Earth System Science in China (http://www.geodata.cn). The grid format DEM and soil

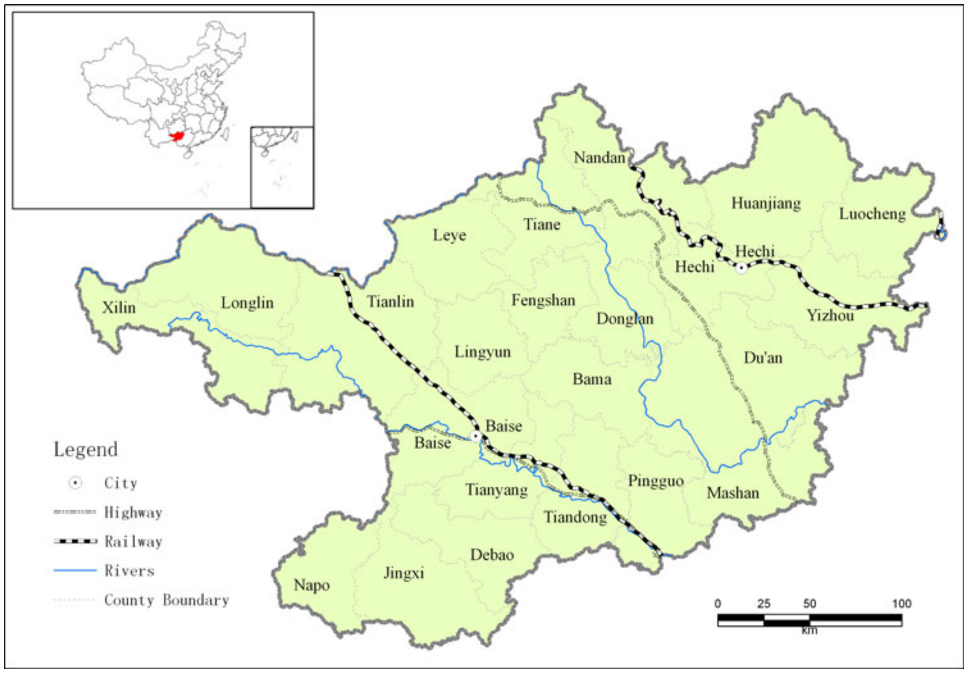

Fig. 1 The study area is located in southwest China. Baise and Hechi are the two largest towns in this area

erosion data have a pixel size of 100 m. Ten scenes of TM images (7 bands, orbits 125-42, 125-43, 125-44, 126-42, 126-43, 126-44, 127-42, 127-43, 127-44 and 128-43) were used. Precipitation records from 97 weather stations were downloaded from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). All data were year 2000 data with the exception of the Landsat imagery (2004).

Data preprocessing

ARCGIS 9.0 (Environment Systems Research Institute) and ERDAS IMAGINE 9.0 (Leica) were used to finish data preparation and the RBFN model was run in Matlab 7.0 (The MathWorks).

Precipitation and socio-economic data were interpolated using the spatial analysis tool in ARCGIS 9.0. Forest coverage and LULC were extracted from Landsat TM images with ERDAS IMAGINE 9.0 using the Normalized Difference Vegetation Index (NDVI) and supervised classification, respectively. Slope data were extracted from the DEM using ArcGIS 9.0. Agricultural land with a slope $\geq 25°$ was identified using overlaid LULC and slope layers. Relief degree of land surface (RDLS) was calculated using raster functions in ARCGIS 9.0. All data were projected or reprojected to the same projection (Albers Conical Equal Area projection, Krasovsky Spheroid) and resampled to a 100 × 100 m pixel spacing. The zoning statistic function in ArcGIS 9.0 was used to calculate the percentage data (i.e., percentage of land with slope $\geq 25°$ and percentage of land with severe soil erosion) for each county. Both the average annual rainfall and per-capita crop land data were standardized using:

$$x' = (x - x_{\min})/(x_{\max} - x_{\min}) \tag{1}$$

where x is the pixel value of the data layer, $x_{\min}$ is the minimal value of the data layer, $x_{\max}$ is the maximum value of the data layer.

Desertification evaluation

Structure of RBFN

RBFN was applied to classify the risk of karst rocky desertification by approximating the dataset distribution using a linear combination of Green's functions (Haykin 1994; Moody and Darken 1989; Park and Sandberg 1991; Fidêncio et al. 2008; Nicos et al. 1998).

$$F(x) = \sum_{i=1}^{N} w_i G(\| x - x_i \|) \tag{2}$$

where G is Green's function and x is its center.

The Green's functions were defined as multivariate Gaussian functions characterized by a mean vector x_j and common variance σ^2, as:

$$G(\| x - x_i \|) = e^{-\frac{\|x - x_i\|}{2\delta_j^2}} \tag{3}$$

and

$$F(x) = \sum_{i=1}^{N} w_i e^{-\frac{\|x - x_i\|}{2\delta_j^2}} \tag{4}$$

where each equation consists of a linear superposition of multivariate Gaussian basis functions (probability bells) with centers x_j, located at the data points and widths δ_j^2.

The initial number of nodes is set at two. The first node is assigned a Gaussian function centered on the center of data set, determined by

$$x_{\text{av}} = \sum_{i=1}^{N} \frac{x_i}{N} \tag{5}$$

and the second node is assigned a Gaussian function centered on the point determined by vector x_p maximizing the function

$$P(x) = \int_S Q(x)\mathrm{d}S \tag{6}$$

where

$$Q(x) = \begin{cases} 1, & \text{if} \quad x \in D \\ 0, & \text{if} \quad x \notin D \end{cases} \tag{7}$$

The variance of Gaussian functions is assumed to be constant and equal to

$$\delta = r \frac{\sum_{i=1}^{N} \prod_{j=1}^{m} \left(x_i^{(j)} - \bar{x}^{(j)}\right)}{\prod_{j=1}^{m} \sqrt{\sum_{i=1}^{N} \left(x_i^{(j)} - \bar{x}^{(j)}\right)^2}} \tag{8}$$

where m is the number of dimensions (number of nodes in the hidden layer), $\bar{x}^{(j)}$ is the mean value for dimension j and r is an arbitrary ratio defining the total number of Gaussian functions.

Construction of the second layer of the RBFN is carried out using a self-organizing algorithm with the following steps:

1. For each point of the data set D, calculate the output of the Gaussian functions for all hidden nodes

   $$y_i = e^{-\frac{\|x_j - c_i\|}{\delta^2}} \tag{9}$$

   where $i < n$ (number of nodes).
2. Identify the winner $y_w = \max\,(y_i)$, $i < n$.
3. If $y_w > \alpha T$, then change the position of the center of the winner using

   $$c_w^{(k+1)} = c_x^{(k)} + r\left(x_j - c_w^{(k)}\right) \tag{10}$$

   where α is an arbitrary ratio ($\alpha = 2.0$ in this case) and T is the threshold value ($T = 10^{-4}$).
4. If $y_w < T/\alpha$, then construct a new hidden node with center at the point x_j and variance equal to δ and increase the number of total hidden nodes n by 1.

The algorithm stops when there are no new hidden nodes after testing all points of data set D.

The risk of karst rocky desertification was determined by applying a threshold to the RBFN output.

Rocky desertification evaluation

Previous research has identified four types of rocky desertification (Li and Wang 2004; Xiong 2002): (I) slight karst rocky desertification, (II) medium karst rocky desertification, (III) strong karst rocky desertification, and (IV) extremely strong karst rocky desertification (Table 1).

The conceptual model for the study is outlined in Fig. 2. DEM, Landsat TM images, weather data, soil erosion data and socio-economic statistics were preprocessed (discussed in "Data preprocessing") with ARCGIS and ERDAS IMAGINE. Each variable was standardized to range from 0 to 1 (Fig. 3). Using the processed data at the county-level resolution, the RBFN model was constructed in Matlab and the karst rocky desertification risk was assessed for each county.

Model results validation

The risk assessment results were validated using field data collected in July and August 2008 (Table 2). Results from the RBFN had an overall accuracy of 82.02% and a Kappa coefficient of 75.34%, which indicates that results are satisfactory.

Results and discussion

Seven counties (Tian'e, Longlin, Xilin, Lingyun, Baise, Tianyang and Napo) were under slight risk for karst rocky desertification (Fig. 4); six counties (Huanjiang, Luocheng, Yizhou, Tianlin, Pingguo and Debao) were under medium karst rocky desertification; five counties including Nandan, Donglan, Fengshan, Du'an and Jingxi were under strong

Table 1 The characteristic of karst rocky desertification risk

	RDLS (%)	PSE (%)	PCC (ha person^{-1})	AFC (%)	AAR (mm)	PLS (%)	PLCS (%)
Slight	<0.1	<20	>0.06	>50	<1,060	<40	<15
Medium	0.1–0.15	20–30	0.05–0.06	35–50	1,060–1,200	40–50	15–20
Strong	0.15–0.2	30–40	0.04–0.05	20–35	1,200–1,300	50–60	20–25
Extreme	>0.2	>40	<0.04	<20	>1,300	>60	>25

RDLS relief degree of land surface, *PSE* percentage of area with severe soil erosion, *PCC* per-capita cropland, *AFC* average forest coverage, *AAR* average annual rainfall, *PLS* percentage of land with slope angle >25°, *PLCS* percentage of slope ≥25° crop land

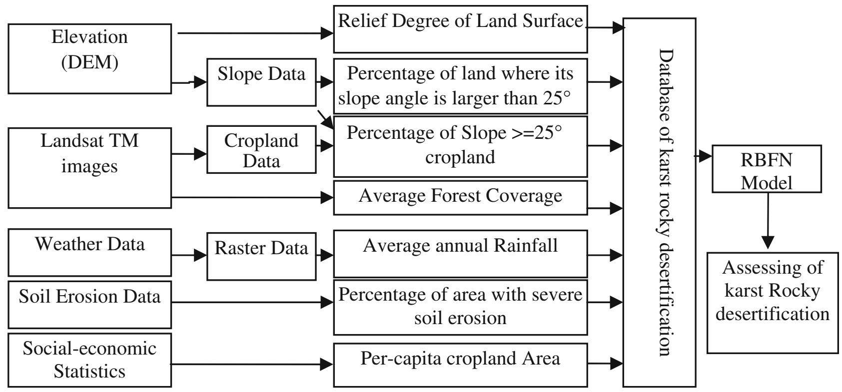

Fig. 2 Flow chart of karst rocky desertification risk assessment using RBFN model

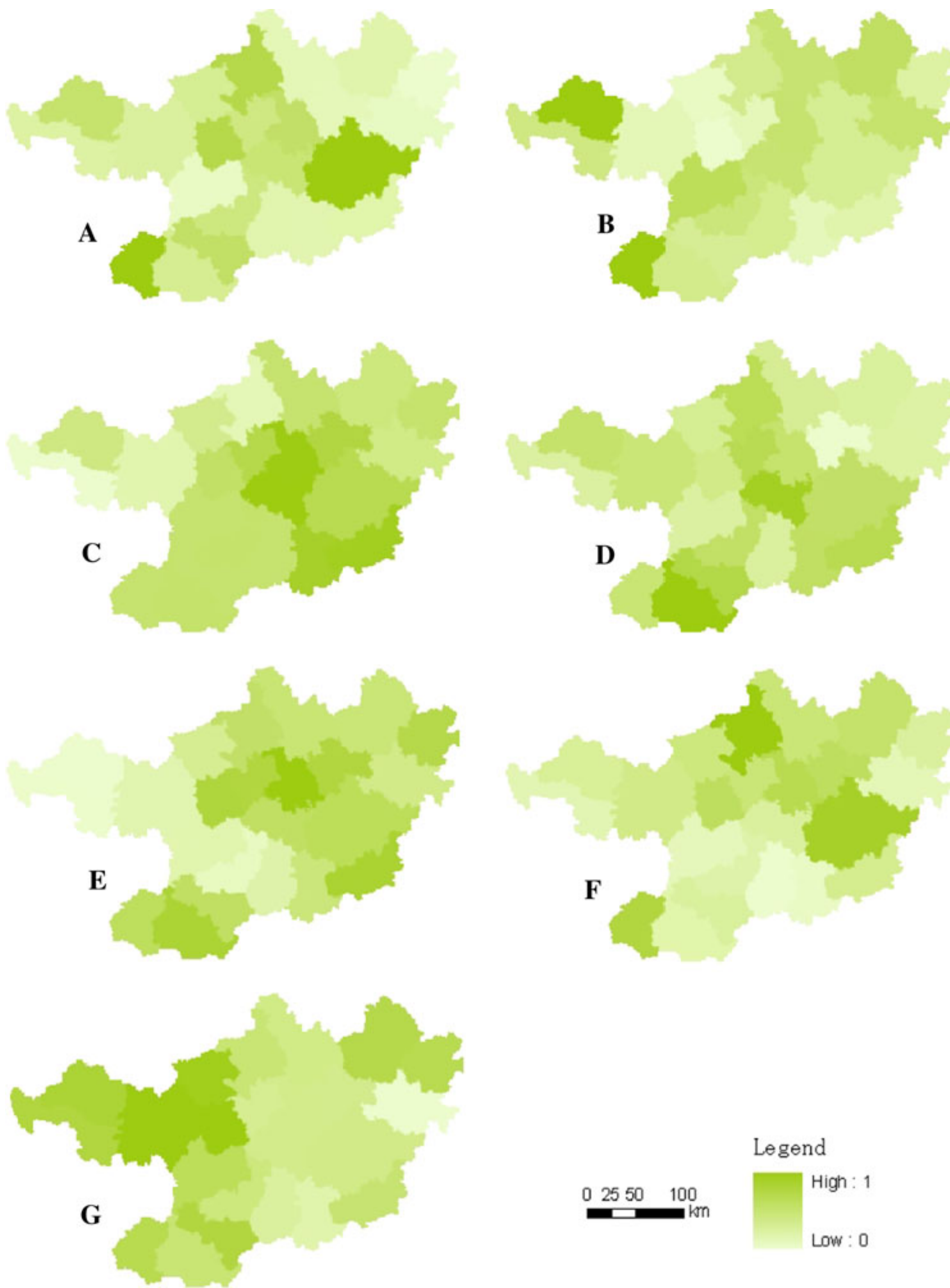

Fig. 3 Standardized values for various variables of karst rocky desertification evaluation in northwest Guangxi, China, standardized value ranges from 0 to 1, where different colors indicate various standardized values; the darker the color, the higher the value. **a** Percentage of slope ≥25° cropland, **b** percentage of area with severe soil erosion, **c** 1/(per-capita cropland area), **d** 1/(percentage forest coverage), **e** average annual rainfall, **f** percentage of land with slope angle >25°, and **g** relief degree of land surface (RDLS)

Table 2 The error matrix of karst rocky desertification assessment using a RBFN model

	Karst rocky desertification				Total
	Slight	Medium	Strong	Extreme	
Slight	37	33	0	0	70
Medium	0	76	0	0	76
Strong	0	0	46	0	46
Extreme	0	0	8	28	36
Total	37	109	54	28	228

karst rocky desertification and five (Leye, Hechi, Bama, Mashan and Tiandong) were under extremely strong karst rocky desertification. Overall, 43.48% of the counties were under extremely strong and strong karst rocky desertification while only 30.43% counties were classified under slight karst rocky desertification, indicating that karst rocky desertification in northwest Guangxi, China is a serious concern.

Population density and area of cropland are two factors that have been shown to influence the spatial distribution of karst rocky desertification (Long et al. 2005; Liang et al. 2007). Extremely strong and strong karst rocky desertification is found mainly in the north, middle and southeast, where population density is highest (180 person km^{-2}), while slight and medium rocky desertification is more prevalent in the west and northeast, where population density is low (40 person km^{-2}). There is a moderate correlation between the spatial distribution of karst rocky desertification and that of population density in most regions ($r = -0.488$, $P < 0.05$). The most serious occurrences of karst rocky desertification coincide with areas of high population density.

A second factor influencing karst rocky desertification is the area of cropland. In the karst-dominated counties of Guangxi, China, the per-capita cultivated land is 0.06 ha, 70% of which consists of cropland with high slope angles. Twenty percent of the high slope angle cropland has slopes >25° and more than 50% of the cropland has medium or low productivity. The average grain yield (2,265 kg ha^{-1}) is about one quarter of the national average (9,285 kg ha^{-1}). Under pressures of population growth, limited arable land and low soil productivity, locals turn to forests, shrubs and grasslands, converting them to croplands for subsistence. Such activities promote soil erosion and rocky desertification, and as a result, the region falls into a poverty, population growth and land-degradation (PPL) cycle, wherein low agricultural productivity associated with the fragile environment causes poverty leading to overexploitation. This, in turn, causes land degradation and further stresses the environment (Huang and Cai 2005).

Stages of karst rocky desertification are found coincident with specific geographic conditions (Table 1). For example, land with a slight risk of karst rocky desertification is associated with high forest coverage, high per-capita cropland, low percentage of severe soil erosion and little cropland with slopes >25°. In contrast, extreme karst rocky desertification is associated with low forest coverage, low per-capita cropland, a high percentage of severe soil erosion, a high percentage of cropland with slope >25°, and a high index of RDLS.

The relationship between topography and karst rocky desertification is well established (Li and Wang 2004). Generally speaking, the risk of karst rocky desertification is mild in areas of low relief and its distribution is sporadic. In rugged and fragmented areas, karst rocky desertification is more common. In fragile karst ecosystems, where thin

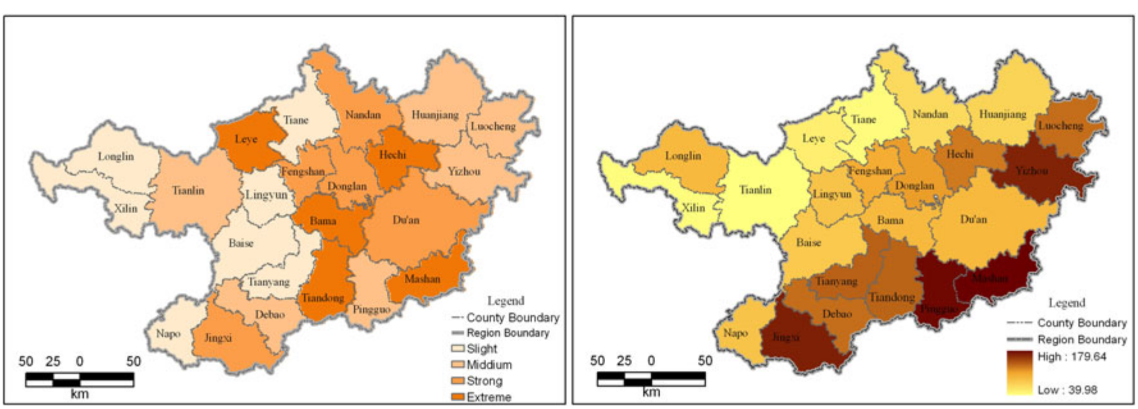

Fig. 4 Distribution of karst rocky desertification hazardous and population density in northwest Guangxi, China in 2000. *Left* Distribution of karst rocky desertification risk, where different color degree means the different risk of rocky desertification; the darker the color, the higher the risk. *Right* Population density, where different color degrees represent different values of population density; darker the color, the higher population density

soils are intensively eroded and deforested, severe karst rocky desertification exists.

Results from this study are in good agreement with other research (Yang 2003; Hu et al. 2005; Hu et al. 2008; Yang et al. 2008a). Yang (2003) detected rocky desertification in the middle, southwest and peak-cluster depression of Guangxi, including the counties of Pingguo, Du'an, Mashan, Bama, Donglan, Fengshan, Debao, and some peak-cluster depressions of Jingxi, Napo, Mashan, Du'an. Hu et al. (2005, 2008) and Yang et al. (2008a) found that areas of rocky desertification occur mainly in west Guangxi, and 66.67% of the karst rocky desertification impacted areas are located in Baise and Hechi. Spatial distributions of karst rocky desertification in northwest Guangxi from this research are similar when compared to those of Yang (2003), Hu et al. (2005), Hu et al. (2008) and Yang et al. (2008a). In addition, field verification and a random sample check verified the classification accuracy of the RBFN model to be 82.02%. Therefore, the application of the RBFN model in assessing karst rocky desertification produces comparatively reliable results.

Conclusions

This paper used a RBFN model along with remote sensing and GIS techniques to classify types of karst rocky desertification in northwest Guangxi, China and to assess changes in spatial distribution from 1990 to 2005. Variables used in this model include climatological, geological, and land use data such as percentage of area with severe soil erosion, per-capita cropland area (ha person^{-1}), percentage of forest cover, average annual rainfall (mm), percentage of land with slope angle $>25°$, percentage of cropland with slope angle $\geq 25°$, and index of average relief degree of land surface (RDLS). Karst rocky desertification in a county was categorized into four degrees: slight, medium, strong and extremely strong. Validation of RBFN model indicates satisfactory model performance in classifying the degree of karst rocky desertification. An overall classification accuracy of 82.02% indicates that RBFN can be a reliable method for rocky desertification assessment. Results of the classification show that northwest Guangxi has undergone serious karst rocky desertification: 43.48% of the counties are under strong and extremely strong karst rocky desertification and 30.43% counties are at low risk of karst rocky desertification. Regarding the spatial distribution of karst rocky desertification, strong and extremely strong karst rocky desertification areas are located in the north, middle and southeast of the study region, while the slight or moderate karst rocky desertification risk areas are located in the west. The spatial distribution of risk of karst rocky desertification is closely related to the population density and area of cropland in this region, with high population density areas coinciding with strong and extremely strong rocky desertification risk, and low population density areas coinciding with slight rocky desertification risk. The results agree well with other studies (Yang 2003; Hu et al. 2005; Hu et al. 2008; Yang et al. 2008b).

Acknowledgments This study was supported by the Chinese Academy of Sciences Action Plan for the Development of Western China (No. KZCX2-XB2-08), National Fundamental Scientific Research Development Plan (No. 2006CB403208), and National Key Technology Research and Development Program of China (2009BADC6B008, 2006BAC01A10). We thank Wei Fu, Wei Zhang, QingQing Yang, FeiDe Fan, RongRong Yu and Teng Feng for their help in field validation. Finally, we would like to thank the anonymous reviewers who helped to improve the quality of this paper.

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