Urban Forestry & Urban Greening 19 (2016) 35–46

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Modeling the optimal ecological security pattern for guiding the urban constructed land expansions

Yongxian Su[a], Xiuzhi Chen[b,*], Jishan Liao[c], Hongou Zhang[a], Changjian Wang[a], Yeyao Ye[a], Yang Wang[a]

[a] *Key Lab of Guangdong for Utilization of Remote Sensing and Geographical Information System, Guangdong Open Laboratory of Geospatial Information Technology and Application, Guangzhou Institute of Geography, Guangzhou, 510070, China*
[b] *Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou, 510650, China*
[c] *Department of Biological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA*

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 14 June 2016
Accepted 19 June 2016
Available online 7 July 2016

Keywords:
Ecological security pattern
Constructed land expansion
Ecology protection
Cost-distance analysis
Cask principle
GIS modeling

ABSTRACT

Rapid urbanization has induced numerous ecological and environmental issues seriously threatening the ecological security. The ecological security pattern (ESP), an effective way for protecting the ecological security, is becoming increasingly important in reconciling the rapid urbanization and ecology protection in urban planning practices. Based on the cost-distance analysis method, we constructed a three-rank (basic, moderate and strict-rank) composite ESP of Gaoming (Guangdong, China) aiming at protecting the survivals and habitat securities of rare vegetations, wild animals and human beings. The proposed composite ESP is established on five equal-weighted individual ESPs (namely Geology-ESP, Hydrology-ESP, Atmosphere-ESP, Biodiversity-ESP and Farmland-ESP) for geologic disasters prevention, flood prevention and drinking water protection, air pollution prevention, biodiversity conservation and farmland protection, respectively. Our results show that under the basic, moderate, and strict- rank ESPs, the integration and connectivity of the ecological components are constantly improved, but the connectivity between neighboring urban patches decline gradually. The moderate-rank ESP proves to be the optimal spatial pattern for balancing the conflicts between urban development and ecological protection. Notably, the ESP that considers the security of atmosphere and farmland securities, which protects the regional farmlands better and well balance the expansions of industrial and residual lands, proves to be much more reasonable.

1. Introduction

Rapid urbanization has taken place worldwide during the last decades, which resulted in an unprecedented scale and rate of urban expansions and led to fundamental changes in land use and landscape pattern around the globe, especially in developing countries (Deng et al., 2009; Weng, 2007; Su et al., 2012). This has induced serious ecological and environmental issues (eg. deforestation, farmland loss, gas and water pollution) threatening the security of human beings, animals and plants (Yue et al., 2003; Elmqvist et al., 2008; Grimm et al., 2008; Tan and Abdul Hamid, 2014; Wu et al., 2014).

The ideology of ecological security is therefore raised for evaluating the basic structure and function of ecosystem whether being threatened by the urban expansions and economic developments (Solovjova, 1999; Kullenberg, 2002; Ma et al., 2004; Gong et al., 2009; Eckersley, 2005). It was firstly proposed by the federal government of the United States (Ezeonu and Ezeonu, 2000). Till now, the definition and emphasis of ecological security has been given different concepts by numerous scholars (Table 1). Among them, the ecological security is commonly defined as a kind of state that the structure and function of ecosystem are integrated, healthy and stable enough to safeguard the habitats of species and human beings, to protect the migrations of wild animals, to provide sufficient eco-services for supporting the human living and socio-economic activities (Guo, 2001; Li and Xu, 2010; Zhou and Shen, 2003).

The ecological security pattern (ESP) is therefore proposed as a new powerful tool to protect the ecological security of regional

---

* Corresponding author at: South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China.
E-mail addresses: suyongxian@gdas.ac.cn (Y. Su), chenxz@scbg.ac.cn (X. Chen).

http://dx.doi.org/10.1016/j.ufug.2016.06.013
1618-8667/

Table 1
The definitions of ecological security in previous studies.

Reference	Definitions
Xiao et al. (2002)	Ecological security, including the natural, economic and social security, means the well protection of basic livelihood, the health of human life, and the ability of acclimatizing to the environment are free from threat (International Institute for Application System Analysis, 1989).
Ezeonu and Ezeonu (2000)	Ecological security refers to the states that the health and integrity of the Earth's ecosystem are well conserved, protected and restored (United States Government, 1990).
Pirages (1996)	Ecological security refers to the balances between human needs and environment affordability for sustainable development, the harmonies between human beings, wild species and micro-organisms.
Guo (2001)	Ecological security can be regarded as the status that the structure of the landscape is integrated and the function is stable to provide enough eco-services to support the development of the socio-economic system and further to maintain the human sustainable development.
Xiao et al. (2002)	Ecological security refers to the security of nature and semi-nature ecosystem, that is, the reflection of the ecosystem integrity and health, including ecological system and environment security
Chen (2002)	Ecological security means that the regional, national and global ecologies and environments of human habitats are free from stressing, damaging and even destroying. It is a state that ecosystem is healthy for sustainable development.
Zhou and Shen (2003)	Ecological security means that, in certain space-time scope, the natural, artificial and compound ecosystems maintain their basic ecological structure and the functions for supporting the sustainable social and economic activities of human beings.

Table 2
The definitions of ecological security pattern in previous studies.

Reference	Definitions
Yu (1996)	The spatial security pattern is comprised of both the strategic portions and positions of the landscape with critical significance in safeguarding and controlling certain ecological processes.
Ma et al. (2004)	The spatial security pattern is a regional-scale spatial pattern that can well protect the structure and function of ecosystem and control the regional ecological and environmental problems.
Waldheim (2006)	The ecological security pattern is comprised the non-hierarchical, flexible, and strategic elements that are essential for urban designing.
Tzoulas et al. (2007)	The ecological security pattern is a conceptual spatial pattern of green space that could protect the ecosystem health and human health.
Kattel et al. (2013)	The ecological security pattern is an ecology framework to interact ecosystems with land use, architecture and urban design, under which the green areas, roads, wetlands, 'habitat islands' and urban architecture all benefit from combining different types of urban landscapes.

ecosystem (Su et al., 2013; Berkes and Folke, 1998; Haeuber and Ringold, 1998; Devuyst et al., 2001; Ehrlich, 2002; Tzoulas et al., 2007). Several studies investigated the ESP and give similar definitions (Table 2) (Costanza, 1997; Schaeffer et al., 1998; Xiao et al., 2002; Yang and Lu, 2002). It is widely defined as the spatial pattern comprising the vital ecological components, patches and corridors of the ecosystem with critical significance in controlling the basic ecological processes (such as species migration, disaster diffusion, urban expansion etc.), protecting the structures and functions of ecosystem, and controlling the regional ecological and environmental problems (Yu, 1996; Ma et al., 2004). The most commonly used method for constructing the ESP is the GIS-based modeling approach developed by Yu (1995) based on cost-distance spatial analysis method (see method). The GIS-based modeling approach has been used for numbers of urban planning applications in the eastern, northern and southern China (Yu, 1998; Yu et al., 2005; Chen et al., 2008; Li et al., 2010; Su et al., 2012; Solovjova, 1999; Kullenberg, 2002; Ma et al., 2004; Gong et al., 2009).

Till now, ESP is becoming increasingly important in reconciling the rapid urbanization and ecology protection in urban planning practices and is attracting global attentions (Solovjova, 1999; Gong et al., 2009; Fu et al., 2010; Li et al., 2010). However, what kinds of ecological components, patches and corridors of the ecosystem should be included in ESP still remain inconsistent and need standardized by further studies (Zhao et al., 2006; Gong et al., 2009; Li et al., 2010). In general, all the vital components related to nature conservation, economic and social growth, human wellbeing and adaptive abilities with respect to ecological security should be considered in ESP (Xiao et al., 2002; Chang et al., 2011). But most previous studies mainly focused on the ecological securities in three aspects, i.e. geology, hydrology, and biodiversity, to construct the ESP. Other considerable ecological and environmental issues, i.e. air pollution and farmland degradation, caused by the urbanizations were failed to be included in most ESPs (Yu, 1995; Tzoulas et al., 2007; Li et al., 2010).

Based on the GIS-based modeling approach (Yu, 1995), we comprehensively take into account the ecological securities of the geology, hydrology, atmosphere, biodiversity and farmland, and construct the composite ESP by integrating five individual ESPs (Fig. 1), i.e., ESPs for geologic disasters prevention (Geology-ESP), flood prevention and drinking water protection (Hydrology-ESP), air pollution prevention (Atmosphere-ESP), biodiversity conservation (Biodiversity-ESP), and farmland protection (Farmland-ESP), respectively. Among the five individual ESPs, the Geology-ESP is defined as the spatial region containing the geological hazard regions as well as the potential geological hazard areas for preventing human beings from geological hazards. The Hydrology-ESP for protecting the drinking waters and preventing human beings from the flood disasters is comprised of the vital watershed regions, lakes and rivers of drinking water sources and the places where tend to be flooded. The Atmosphere-ESP is the spatial pattern preventing the ecological sources susceptible to air pollution from being damaged by the air pollutants. The Biodiversity-ESP is comprised of the key habitats of wild species and migration corridors of wild animals, while the Agriculture-ESP mainly contains the high-quality farmland and certain buffer regions. Moreover, each individual ESP has three ranks: basic rank, moderate rank and strict rank. The basic-rank ESP is only comprised of the core ecological components, patches and corridors (68% of the total), while the moderate and strict-rank ESPs are the spatial patterns that 95% and 99% of the ecological components, patches and corridors are well protected, respectively.

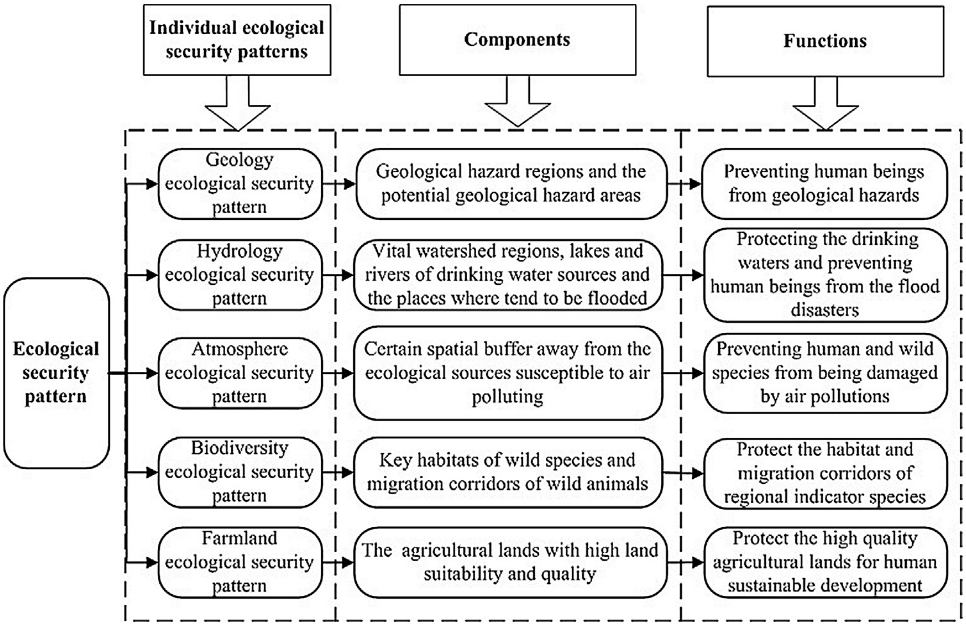

Fig. 1. Contents of the campsite ecological security pattern and components and functions of the five individual ecological security patterns.

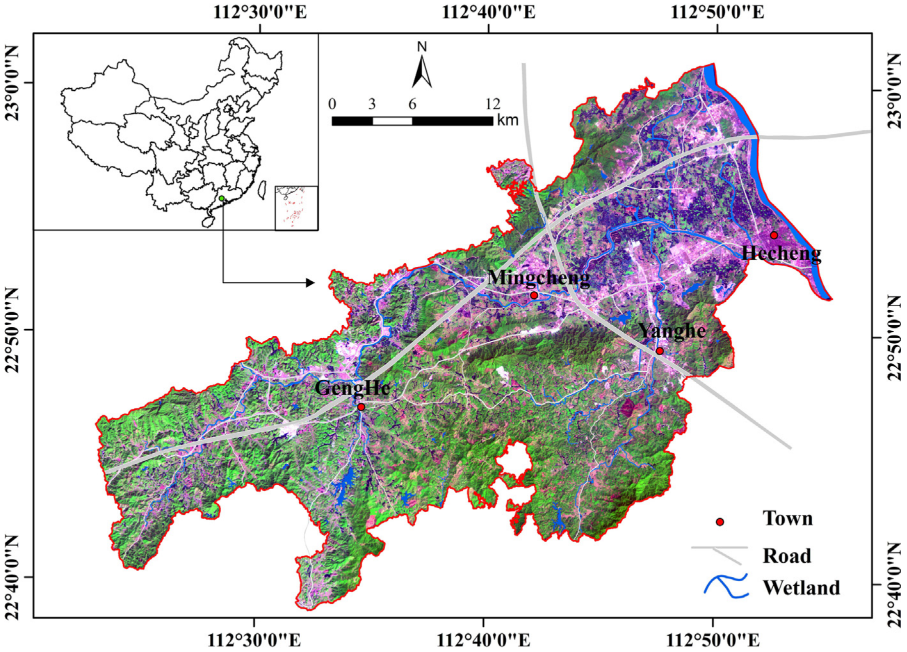

Fig. 2. Gaoming of Guangdong province, Southern China.

2. Study area

Gaoming city is located in the central of Guangdong province, south China (Fig. 2), close to the Xijiang River, a tributary of the Pearl River. Due to the dense river networks and dense vegetation coverage, there are various species of wild animals and plants with high biodiversity. With the rapid urbanization and economic development, lots of forests and farmlands are occupied by the constructed lands, which can be directly reflected by the land use/cover changes between 1996 and 2010 (Fig. 3 and Table 3). The factories (.i.e., textiles, paper making, agriculture product and food handling, black metal smelting and crude processing industries) also discharge lots of atmospheric and water pollutants, which bring great detrimental effects on vegetations, wild species and human beings (Tan, 2011). The sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter with particle size below 10 μm (PM_{10}) are the three main atmospheric pollutants, among which the SO_2 is the most

Table 3
Changes of land cover/use between 1996 and 2010.

Land types	Area in 1996(km^2)	Area in 2010 (km^2)	Changes (km^2)
Farmland	156.83	118.14	−38.69
Forest	540.97	529.85	−11.12
Grassland	20.51	6.88	−13.63
River/lake	116.52	142.75	26.23
Wetland	2.21	1.90	−0.31
Construction land	78.52	101.65	23.13
Other land	24.08	38.46	14.38

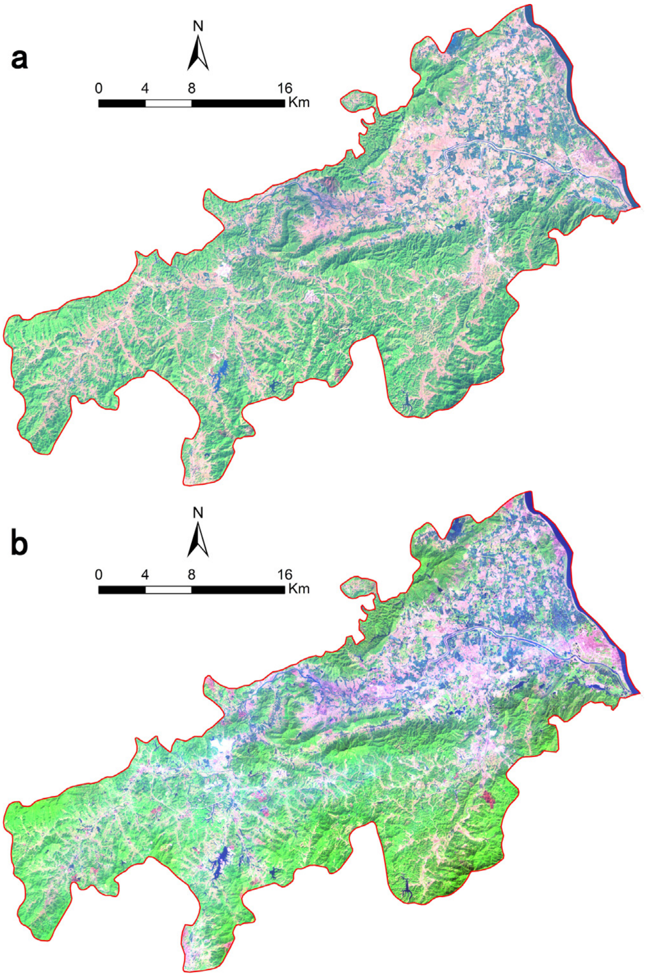

Fig. 3. Land cover/use changes between 1996 and 2010. (a) Landsat TM imagery in 1996; (b) Landsat TM imagery in 2010.

serious (Ruan, 2014). In addition, the low northeastern plains are frequently flooded due the Xijiang River and high density of river networks when rainstorm occurs. Hence, it is desirable to construct the ESP for protecting the life and habitat securities of both human and animals in Gaoming city.

3. Methods

3.1. *Technical route for developing the ESP*

Fig. 4 is the technical route for developing the proposed ESP of Gaoming city. Firstly, we selected the ecological sources need protection (i.e. natural reservations, wetlands, forest park and farmlands) and critical areas for keeping away (geological hazard regions and areas susceptible to air pollution). Next, we modeled the resistance coefficient maps for simulating the ecological processes of geological hazard, flooding, stress of ecological sources by air pollution, animal migration and farmland degradation based on the cost-distance analysis method (see Section 3.3). Then, we indentified five spatial patterns that comprised of vital ecological components, patches, corridors and certain buffers, and extracted the regions of the three ranks (basic, moderate, and strict) for each spatial pattern, respectively (see Section 3.2), and then constructed the five individual ESPs (Geology-ESP, Hydrology-ESP, Atmosphere-ESP, Biodiversity-ESP and Farmland-ESP). Finally, we overlaid all the individual ESPs and obtain the composite three-rank ESP of Gaoming city.

3.2. *Criteria for classifying the three-rank composite ESP*

Yu (1995) described the relationship curves between the areas of protected patches and corresponding accessibilities of different species. Decrease the areas of some types of lands (for example, protected nature reserves) beyond certain threshold may lead to increase in the cumulative resistance for species (for example, birds) to overcome for migration. An increase in the areas of protected lands beyond certain threshold may result in low accessibilities for wild species. These thresholds can be used as the criteria for classifying three-rank composite ESPs. Here, the empirical values of 68%, 95% and 99% of the ecological components, patch and corridors are set as the corresponding thresholds for classifying the composite ESP of Gaoming city into three ranks: the basic, moderate and strict-rank ones, respectively.

3.3. *Cost-distance analysis method*

The cost-distance analysis is to determine the least costly path to reach a source for each cell location. It firstly calculates the weighted distances for all the possible paths from each cell to the target source location by calculating the sum of the expansion resistance coefficient values of all the pixels in each path and generates the cost map. Then, the shortest weighted distance (or accumulated travel cost) is determined from each cell to the nearest source location (http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/understanding-cost-distance-analysis.htm). Till now, the cost-distance analysis method has been

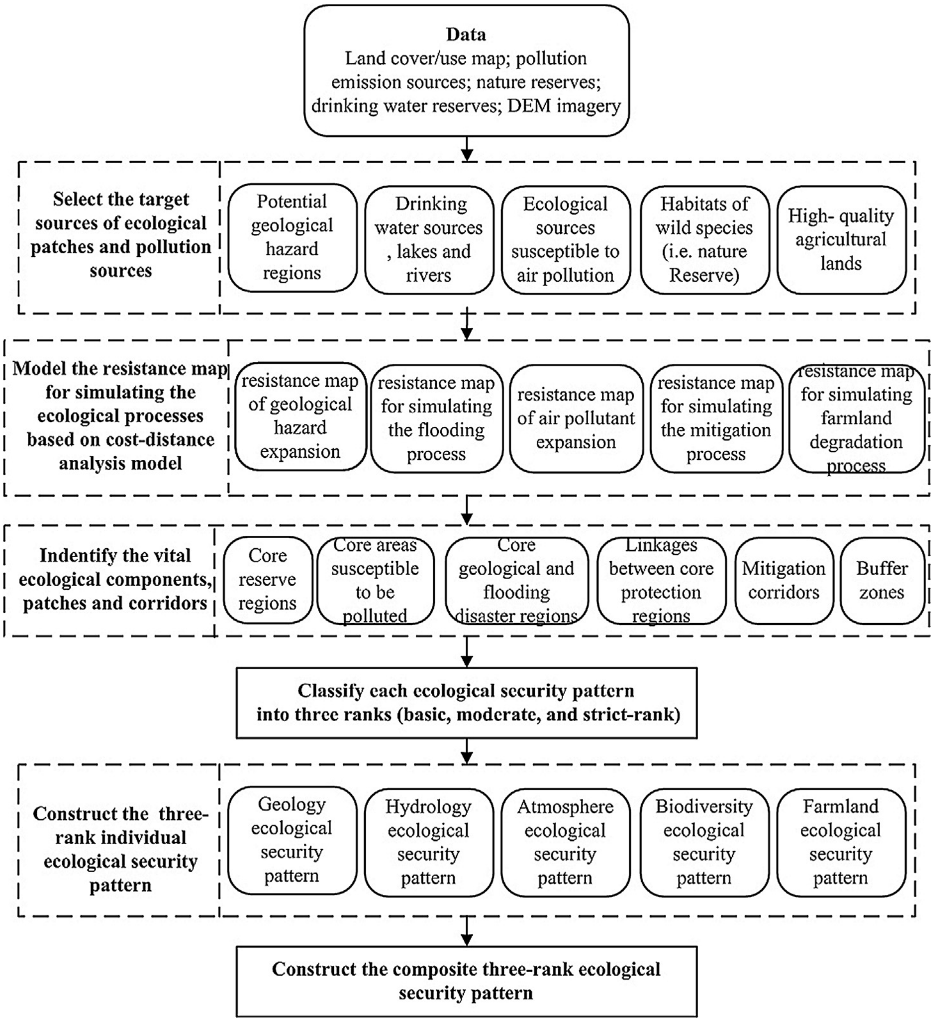

Fig. 4. Technical route for constructing the three-level ecological security pattern.

widely used in site selection (Jobe and White, 2009), landscape and land use change simulation (Yeh and Li, 1998, Richard and Armstrong, 2010), and also in modeling the process of gene flow (Zhu et al., 2010; Coulon et al., 2004), animal migration (Janin et al., 2009; Verbeylen et al., 2003; Graham, 2001; O'Brien et al., 2006) and disaster expansion (Bono and Gutierrez, 2001; Li et al., 2010; Imamura et al., 2012; Post et al., 2009).

Currently, the value of the resistance coefficient for each cell are usually set empirically by most studies(Adriaensen et al., 2003; Spear and Balkenhol, 2010; Verbeylen et al., 2003; Driezen et al., 2007; Walker et al., 2007; Chardon et al., 2003). To sum up, the resistance coefficient value is mainly related to the certain important land surface characteristics (i.e. hydrogeology, land use types, soil properties, slope, elevation and aspect etc.) that influence the vital ecological processes (Yu, 1995). The cumulative resistance coefficient value of one possible route has been taken as an indication of relative accessibility of the cell to the sources. There are numbers of routes from the sources to the cell and the minimal cumulative resistance is regarded as the optimal ecological process (migration, expansion, and degeration etc.) from the ecological sources to other places (Yu, 1995).

3.4. Cask principle

The Cask Principle is similar to the Peter Principle (Peter and Hull, 1969). The Peter Principle states that in a hierarchy every employee tends to rise to his level of incompetence, but in time every post tends to be occupied by an employee who is incompetent to carry out its duties. Work is accomplished by those employees who have not yet reached their level of incompetence. The Cask Principle is a native version in China that illustrates the same ideas like Peter Principle. It means that the capacity of a cask is decided by the shortest piece of boards that compose the cask. That is to say no matter how high the cask is, it is the shortest board of the cask, not the longest one, determines how much water the cask can hold. In this paper, the composite ESP is also determined by the minimum individual ESP but not the maximum one.

3.5. Landscape metrics method

The most commonly used measurements to characterize the connections of the landscapes are the connection index (*CI*) and splitting index (*SI*) (Blüthgen et al., 2006). *CI* is defined as the proportion of the actually observed interactions to all possible interactions. The splitting index (*SI*) is defined as the number of patches one gets when dividing the total region into parts of equal size (Jaeger, 2000). The formula of *CI and SI* are shown as Eqs. (1) and (2).

$$CI = \frac{I}{r \times c} \tag{1}$$

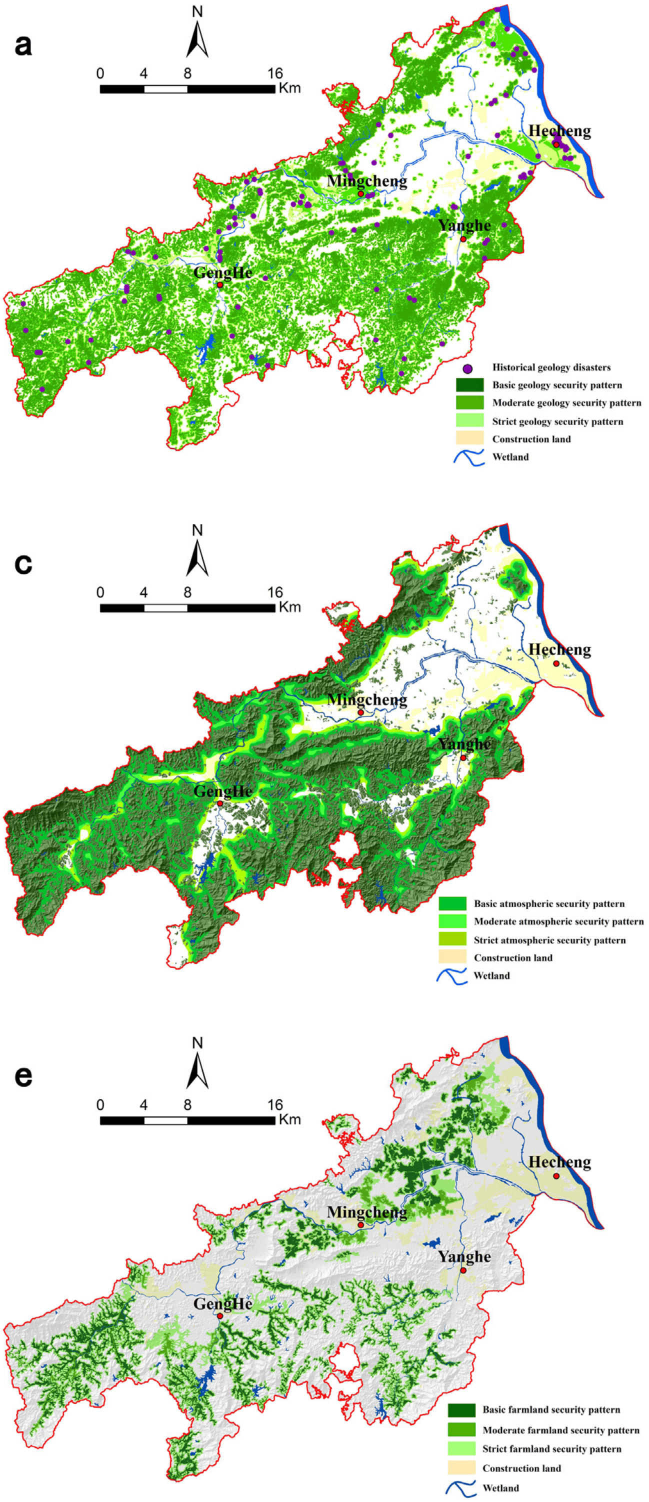

Fig. 5. Five individual ecological security patterns. (a) Geology-ESP for geologic disasters prevention; (b) Hydrology-ESP for flood prevention and drinking water protection; (c) Atmosphere-ESP for air pollution prevention; (d) Biodiversity-ESP for biodiversity conservation; (e) Farmland-ESP for farmland protection.

where r and c means the row number (e.g., plant species) and column number (e.g., pollinators), respectively; I means the total number of non-zero elements in the matrix.

$$SI = \frac{A_t^2}{\sum_{n=1}^{n} A_i^2} \tag{2}$$

where n means the number of patches; A_i means the size of the i patches ($i = 1, 2 \ldots, n$); A_t means the total area of the region.

4. Construction of the ecological security patterns

4.1. Individual ecological security patterns

4.1.1. Ecological security pattern for geologic disasters prevention (Geology-ESP)

The major types of geological disasters encountered in Gaoming are collapse, landslide and surface subsidence. Collapse and

Table 4
Weights and resistance coefficients for different susceptibilities of the impact factors of geological hazards.

Type of geological hazard	Factors	Value assignment rules for different susceptibility degrees				Contribution Weight
		1000	100	10	1	
Land collapse and landslide disasters	Type of rock and soil	Rock group of bedded carbonate	Layered rock, slate, phyllite group	Layered elastic rock group	Sandy soil, clay, sludge soil, group of massive and intrusive rocks	0.3
	Topography and landscape	Elevation > 200 m Waviness > 200 m Slope $\geq 30^\circ$	Elevation 100 m–200 m; Waviness 50 m–100 m; Slope 15°–30°	Elevation 50 m–100 m; Waviness 10 m–50 m; Slope 5°–15°	Elevation < 50 m Waviness < 10 m; Slope < 5°	0.2
	Vegetation coverage	NDVI < 0.2	$0.3 > \text{NDVI} \geq 0.2$	$0.5 > \text{NDVI} \geq 0.3$	NDVI > 0.5	0.15
	Conditions of human engineering activities	Urban, industrial, road lands	Residential and hydraulic construction lands	Paddy and dried fields, as well as other agricultural lands	Woodlands, grasslands, rivers	0.35
Surface deformation disasters	Degree of Karst development	Strongly developed Karst, with development zone >10 m	Moderately developed Karst, with a development zone ranging from 5 m–10 m	Weakly developed Karst, with a development zone ranging from 3 m–5 m	Undeveloped Karst, with a development zone <3 m	0.25
	Quaternary cover thickness	Sandy or soft soil layers with a thickness of <10 m	Double or multiple sandy layers with thicknesses ranging from 10 m–20 m	Malleable clay with a thickness of 20 m–30 m	Bed rock or hard plastic land with a thickness >30 m	0.2
	Topography and landscape	Low-lying areas close to ground water	Plain, valley, low-level land	Gentle Piedmont slope, mid- and high-level land	Table, high-level lands	0.3
	Conditions of human engineering activities	Strong human engineering activities	Stronger human engineering activities	Generally strong human engineering activities	Weak human engineering activities	0.25

landslide are caused by the shift of rock and soil, whereas surface subsidence is related to ground deformation. After analyzing 122 historical geological disasters in Gaoming, we found that the shift of rock and soil is mainly determined by elevation, slope, type of rock and soil, vegetation cover, surface undulation, and human engineering activities. Ground deformation disasters are closely related to the degree of karst development, land features, land form, groundwater conditions, thickness of quaternary coverage, and human engineering activities. For these potential impact factors, we empirically classified them into four types and set four different resistance coefficient values (1, 10, 100, and 1000) for each type according to its susceptibility degree that might cause geological hazards and also empirically set different weights to the corresponding four influencing factors of the collapse, landslide and surface subsidence geological disasters (Table 4). After that, we used the cost-distance method to analyze the land susceptibility for geological disasters and mapped the potential areas that might encounter geological hazards. Finally, we extracted the three-rank Geology-ESP (namely, the basic, moderate and strict rank Geology-ESPs), respectively (Fig. 5a).

4.1.2. Ecological security pattern for flood prevention and drinking water protection (Hydrology-ESP)

Flood disaster always takes place when the rainfall exceeds the storage capacity of wetlands. The areas around the river junctions, connections of lakes to rivers and low-lying areas mostly tend to be flooded. Here, we firstly identified the river junctions based on the river network map of Gaoming. Using the cost-distance analysis method, we further simulated the flow backward in the Xijiang River and modeled the potential submergence areas of Gaoming caused by floods that encountered per 10, 20 and 50 years, respectively according to the digital elevation map of Gaoming. The flooded regions under 10-, 20- and 50-year floods were classified as the basic, moderate and strict-rank Hydrology-ESPs, respectively (Fig. 5b). In addition, the conservation areas of drinking water along the rivers were also included in the proposed water security patterns.

4.1.3. Ecological security pattern for air pollution prevention (Atmosphere-ESP)

Air condition is another critical factor for influencing the regional ecological security. Fresh air is mainly produced by vegetation, which releases oxygen, absorbs carbon dioxide, cools and humidifies the atmosphere, reduces noise and removes air pollutants (Chen et al., 2012). But when the pollutant concentrations exceed the vegetation's recycling ability, the ecological functions of vegetation would be weakened or damaged. The SO_2 is the most serious atmospheric pollutants in Gaoming city (Tan, 2011; Ruan, 2014), while the main pioneer species of Gaoming is mason pine, which is significantly sensitive to SO_2 (Shaw et al., 1992). The mason pine will be impacted slightly, severely and damaged within 4 h when the concentration reaches 0.66, 1.31 and 3.39 mg/m^3, respectively (Liu and Li, 1990). Here, we calculated the potential smallest distance between vegetation and pollution sources by considering the speed, direction, and frequency of wind and other climate conditions using the method given in the National Environmental Protection Bureau of National Environmental Protection Bureau, 1991 Eq. (3). The SO_2 concentrations at the edge of the vegetation patch were set as 0.66, 1.31, and 3.39 mg/m^3, respectively for the basic, moderate and strict-rank ESPs (Fig. 5c).

$$\overline{C} = \sqrt{2/\pi} \times \left[(n \times f \times Q)/2\pi\mu x\sigma_z\right] \times \exp\left(-h_e^2/2\sigma_z^2\right) \tag{3}$$

Table 5
Resistance coefficients of wild animal migrations for different land types.

Land cover	Resistance coefficients
Woodland	0
Water	10
Shrubbery	10
Garden and grassland	30
Paddy field	100
Dried field	300
Construction land[a]	400
Highway	500

[a] In this study, construction land does not include highways.

where $\bar{C}$ represents the concentration of pollutants that spread from emission sources, in mg/m^3; n denotes the number of wind directions, which is 16 in this study; and f indicates the proportion of all wind directions at a certain period. $f_{\mathrm{N}} = 4.1 f_{\mathrm{NNE}} = 2.3 f_{\mathrm{NE}} = 8.9 f_{\mathrm{ENE}} = 2.3 f_{\mathrm{E}} = 6.0 f_{\mathrm{ESE}} = 4.3 f_{\mathrm{SE}} = 10.9 f_{\mathrm{SSE}} = 4.5 f_{\mathrm{S}} = 9.8 f_{\mathrm{SSW}} = 2.5 f_{\mathrm{SW}} = 7.2 f_{\mathrm{WSW}} = 1.5 f_{\mathrm{W}} = 5.1 f_{\mathrm{WNW}} = 1.9 f_{\mathrm{NW}} = 11.7$, and$f_{\mathrm{NNW}} = 5.6$. Q corresponds to the emission intensity of the pollution source at continuous and permanent points. In Gaoming, this value is 4006.94 mg/s according to the amount of industrial waste gas SO_2.μ represents average wind speed. In Gaoming, the annual μ is 2.1 m/s based on meteorological data. h_e denotes the effective height of point source, which is 5 m as per factory height. The industry in this area has a low frame source. σ_z indicates the mean values of vertical dispersion parameters in m; it is calculated using the diffusion equation developed by Briggs (1973) as follows: $\sigma_z = 0.14x(1 + 3 \times 10^{-4}x)^{(-1/2)}$, x corresponds to the horizontal distance of a pollution source from a point in space (in m). Specifically, it refers to the distance between the pollution source and the edge of the green patch. The neutral atmosphere is assumed to be stable in all seasons according to meteorological data in Gaoming.

Industrial pollution also significantly threatens the security of human beings and animals. When SO_2 concentration ranges from 10 mg/L to 15 mg/L, the movement of human respiratory ciliary is inhibited (mucosal secretion). When the concentration reaches 20 mg/L, it will cause coughing. When the concentration reaches 100 mg/L, the bronchus and lung tissues are heavily damaged. These values of SO_2 concentrations were considered as the thresholds to control the distance between the pollution sources and human settlements, which were used to restrict the expansions of urban regions (see section 5).

4.1.4. *Ecological security pattern for biodiversity conservation (Biodiversity-ESP)*

The Biodiversity-ESP is for protecting the security of both endangered animals and plants. During the past decades, the high-quality native forests in Gaoming, which are the primary habitats of wild animals (such as the pangolin, wild civet and boar, etc) and rare plants (such as the Alsophila spinulosa, Aquilaria sinensis and Angiopteris etc.), are shrinking gradually as a result of human activities such as logging and urbanization etc. At present, these native forests are mainly distributed mainly in west, south, center, and north high-altitude mountain areas, which were chosen as the vital ecological patches for constructing the Biodiversity-ESP of Gaoming. In addition, certain important vegetation zones in west, south, center, and north high-altitude mountain regions were also selected as the essential ecological corridors for protecting the migrations of wild animal species.

In this paper, we empirically set different expansion resistance coefficients according to the different land use types (Table 5) and then used cost-distance analysis method to construct the three-rank Biodiversity-ESPs (Fig. 5d), namely, the basic-rank Biodiversity-ESP (i.e., protect the basic habitats of wild animals and plants), moderate-rank Biodiversity-ESP (i.e., maintain connectivity between these basic habitats), and strict-rank Biodiversity-ESP (i.e., protect both the current habitats, migration paths and potential expanding spaces for wild animals and plants).

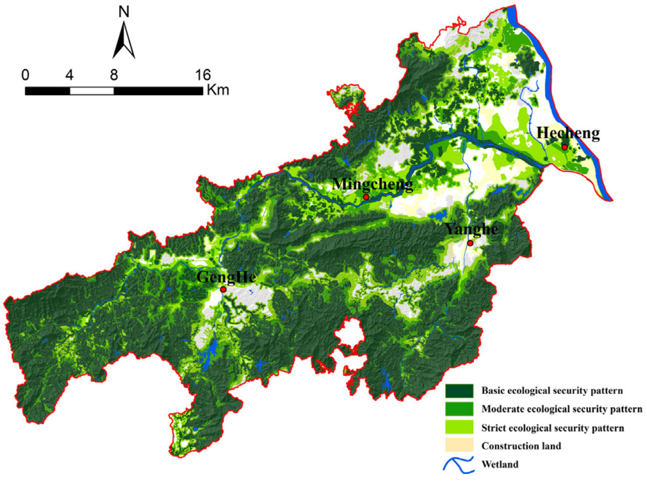

Fig. 6. Composite ecological security pattern of Gaoming.

4.1.5. *Ecological security pattern for farmland protection (Farmland-ESP)*

Farmlands, which are fundamental to guarantee providing sufficient food for the survival of human beings and animals, should be granted as the same importance as natural reservations and wetlands etc. In this paper, the primary farmlands were selected as the ecological sources from the National Basic Farmland Inventory, which were investigated and selected by the Second Land Class Survey of China (2009). Then, we evaluated the land suitability for the farmlands in Gaoming by considering the soil type, lithology type, slope and underground water level (Table 6). Higher land susceptibility means the lower possibility to be expanded. In other words, the expansion resistance coefficient decreases with the increase of land susceptibilities. Hence, we empirically set the resistance coefficient values according to the susceptibilities of different land types. Finally, the three-rank Farmland-ESP (Fig. 5e) (namely, basic, moderate and strict) was modeled by simulating three buffer zones around the ecological sources (farmlands) according to the resistance coefficient values using the cost-distance analysis method.

4.2. *Composite ecological security pattern*

Based on “the Cask Principle” (see method), we constructed the composite ESP of Gaoming (Fig. 6) by equally overlaying the above five individual ESPs, namely, Geology-ESP, Hydrology-ESP, Atmosphere-ESP, Biodiversity-ESP and Farmland-ESP, respectively. The composite ESP also contains three ranks: the basic-rank, moderate-rank and strict-rank ESPs. The vital ecological components, patches and corridors of the ecosystem are mainly contained in the basic-rank ESP, where are the top priority areas for protection. Urban developments and economic activities must be prohibited or restricted in these regions. Any human disturbances in the basic-rank ESP would bring significant damage to the ecosystems. The moderate-rank ESP is a transition zone between the basic-rank ESP and strict-rank ESP. Less-intense human activities generating slight influences on the ecosystems can be conducted in these regions, but high-intense ones must be avoided. Under the strict-rank ESP, human activities have few negative impacts on the ecosystem

Table 6
Farmland suitability and resistance coefficient evaluation criterion.

Factors	Farmland suitability evaluation criterion	Suitability value	Resistance coefficients
Soil types	Red tide soil	9	1
	hydragric paddy soil	7	10
	page red soil	5	100
	bast red soil	3	500
	gley paddy soil	1	1000
Nature of rock and soil	Sandy soil, clay, sludge soils such as multi-layer soils	9	1
	layered elastic rock	7	10
	sandy soil, clay double-layer soil	5	100
	bedded carbonate rock, layered rock, slate, phyllite rock	3	500
	massive and intrusive blocks of rock	1	1000
Ground water level	Plain, valley, low-level land	9	1
	low-lying area	7	10
	gentle piedmont slope, mid- and high-level table land	5	100
	Terrace, hills	3	500
	Mountain area	1	1000
Slope	<=2°	9	1
	2–6°	7	10
	6–15°	5	100
	15–25°	3	500
	>25°	1	1000
Land use status	Paddy and dry fields	9	1
	Other	1	1000

Table 7
Resistance coefficients of constructed land expansions under different restriction patterns.

Restriction pattern	Factor		Range	Resistance coefficients
Non-restriction conditions	Main roads (buffer areas)	0–10 m	10	
		10–20 m	20	
		⋮	⋮	
		190–200 m	200	
	Main water bodies		500 m	500
	Current construction lands	0–100 m	10	
		100–200 m	20	
		⋮	⋮	
		1900–2000 m	200	
	Slope	<5°	0	
		5–10°	25	
		10–25°	100	
		>25°	500	
Three-rank ecological security pattern	Urban land expansion	Basic-rank ecological security pattern		1000
		Moderate-rank ecological security pattern		100
		Strict-rank ecological security pattern		10
		Restricted by industrial lands under the atmosphere security pattern	0–50 m	1000
			50–100 m	100
			100–150 m	10
	Industrial land expansion	Basic-rank ecological security pattern		1000
		Moderate-rank ecological security pattern		100
		Strict-rank ecological security pattern		10
		Restricted by urban lands under the atmosphere security pattern	0–500 m	1000
			500–1000 m	100
			1000–1500 m	10

5. Simulation of constructed land expansions

Constructed lands are mainly comprised of two types: urban lands and industrial lands. Industries always produce air pollutants, which bring detrimental impacts to human beings. The expansions of industrial lands should be restricted not threatening the current urban regions. That is to say, constructed land expansions are not only restricted by the ESPs, but also self-limited by the inter-controlling between urban lands and industrial lands. Besides the three-rank ESPs, this paper also constructed the atmosphere security pattern for current urban regions of Gaoming using the cost-distance analysis method. To simulate the constructed land expansions of Gaoming, we firstly simulated the regions that tend to be dispersed by the air pollutants surrounding the air pollution sources. Then, we overlaid these regions with the three-rank composite ESPs and modeled the constructed land expansions under the restrictions of both the simulated air-polluted areas and the three-rank composite ESPs, respectively. After that, we similarly modeled the industry land expansions under the restrictions of both the simulated constructed lands and the three-rank composite ESPs, respectively. Finally, we overlaid the simulated constructed lands and industry lands and obtained the potential lands for future urban expansions under basic-rank (Fig. 7b), moderate-rank (Fig. 7c) and strict-rank (Fig. 7d) ESPs, respectively. For comparison, the constructed land expansions with no restrict from the ESP was

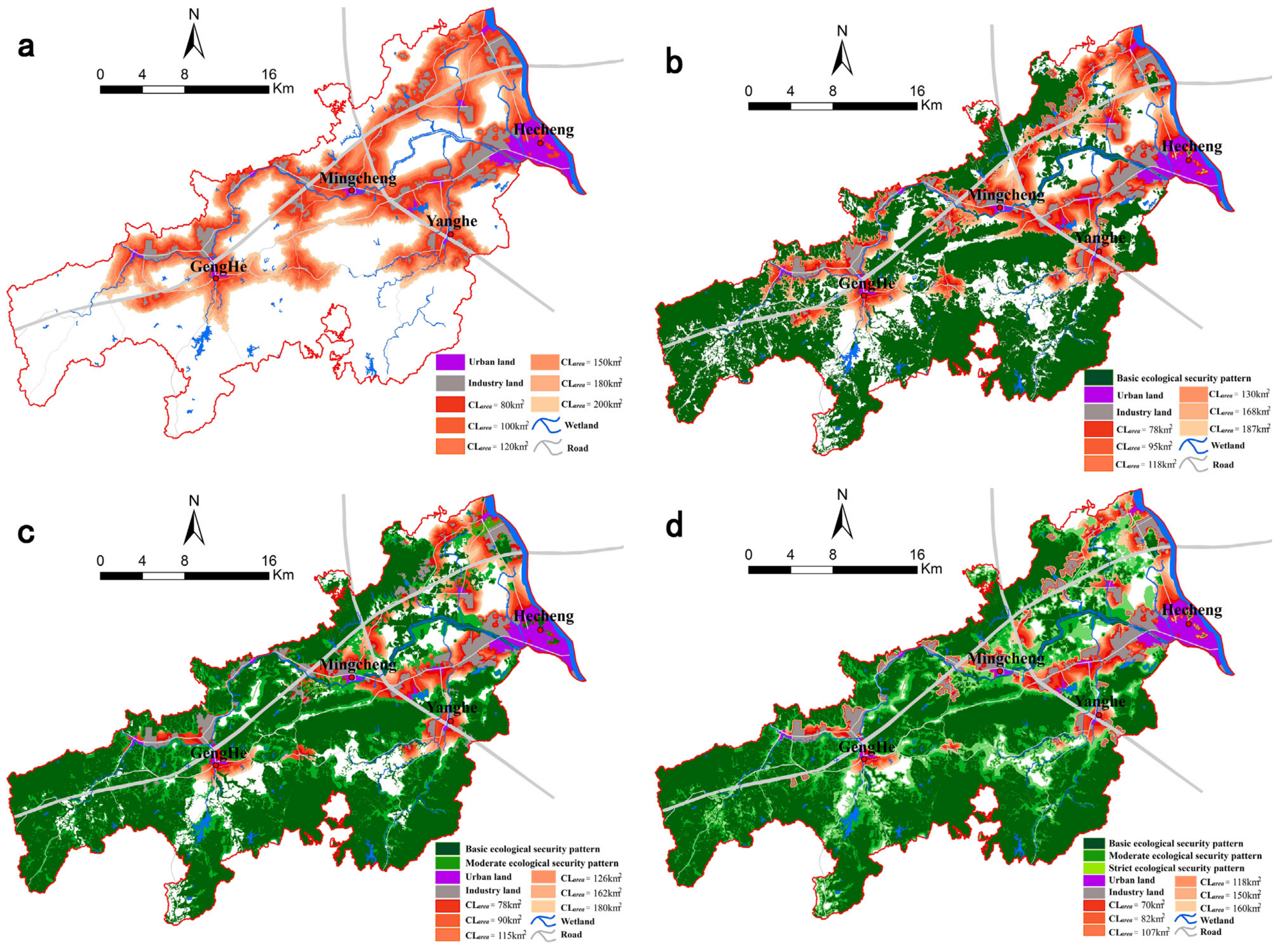

Fig. 7. Simulation of constructed land expansions. (a) under non-restriction condition; (b) under the basic-rank ESP; (c) under the moderate-rank ESP; (d) under the strict-rank ESP.

Table 8
The connectivity index of the ecological components and splitting index and expansion modes of the constructed lands under different restriction patterns.

Restriction pattern	Connectivity index of ecological patches	Splitting index of construction patches	Expansion mode
Basic-rank ESP	48.89	1.16	Spread
Moderate-rank ESP	67.91	8.50	Clustered
Strict-rank ESP	71.61	14.29	Disperse

also modeled (Fig. 7a). Impact factors and corresponding resistance coefficients are listed in Table 7.

Under the non-restriction condition (Fig. 7a), important farmlands and forests are occupied by the constructed lands, which expand continually and mainly along the traffic routes. The connectivity between vital ecological sources is cut off, which might bring serious negative impacts on wild animals and severely damage the ecological service functions of forests and farmlands. Under the basic-rank ESP (Fig. 7b, Table 8), the patches of constructed lands are contiguously clustered ($SI = 1.16$) and the connections among protected ecological components are still poor ($CI = 48.89$). Contrarily, under the strict-rank ecological security pattern (Fig. 7d), all the ecological components were well connected ($CI = 71.61$) and get the best protection. But the constructed lands are separated by all kinds of ecological lands and become much more scattered ($SI = 14.29$), which makes it difficult for urban developments. Compared with the basic- and strict-rank ESPs, both the ecological components and urban patches are well connected and moderately distributed ($CI = 67.91$; $SI = 8.50$). It suggests that the vital ecological regions are not only well protected under the moderate-rank ESP but also guides the constructed land to expand orderly. The moderate-rank ESP proves to be the most suitable ESP in reconciling the rapid urbanization and ecology protection (Fig. 7c). Overall, the constructed land expansions are healthier and more organized under the restrictions of ESPs than those under non-restriction condition, while the moderate-rank ESP proves to be the optimal one for guiding the constructed land expansions than the basic-rank and strict-rank ESPs.

It is worth mentioning that this paper firstly considers the Atmosphere-ESP and Farmland-ESP to restrict the constructed land expansions, which were not mentioned in most previous studies. Compared with constructed land expansions under non-restriction condition (Fig. 8a), the farmlands are well protected under the proposed moderate-rank ESP (Fig. 8b). In addition, industrial lands and urban lands under the proposed moderate-rank ESP are also notably separated from each other (Fig. 8d), rather than mixed together under non-restriction condition (Fig. 8c). Therefore, it is more reasonable to consider the influencing factors of atmosphere and farmland for developing the composite ESP.

6. Conclusions

This study constructs a composite three-rank (basic, moderate and straict) ESP of Gaoming city based on five individual

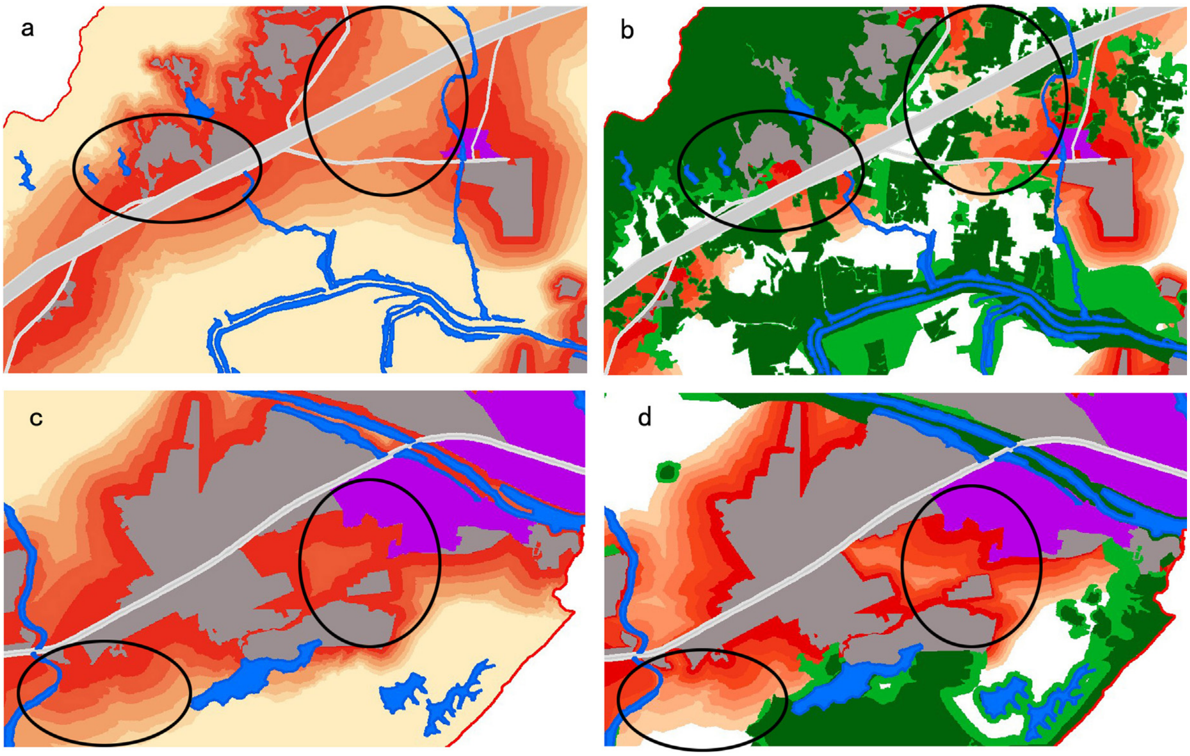

Fig. 8. Comparison of the constructed land expansions under the moderate-rank ESP with those under non-restriction condition. (a) Simulation of constructed land expansions in site 1 under non-restriction condition; (b) Simulation of constructed land expansions in site 1 under moderate-rank ESP; (c) Simulation of constructed land expansions in site 2 under non-restriction condition; (d) Simulation of constructed land expansions in site 2 under moderate-rank ESP.

ESPs (Geology-ESP, Hydrology, Atmosphere-ESP, Biology-ESP and Farmland-ESP). Without the constraint of ESP, farmlands, forests and other important ecological areas are always severely affected, damaged or occupied, while under the three-rank (basic, moderate and strict) ESPs, the integration and connectivity of the ecological components are better protected. By comparison, the moderate-rank ESP proves to be the best spatial pattern for resolving the conflicts between urban development and ecological protection. Compared with previous studies, the atmosphere and farmland security are firstly considered as the vital aspects to construct the composite ESP. Results demonstrate that the proposed ESP of Gaoming is significantly improved by taking into consideration of the atmosphere and farmland factors.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Grant No. 41401055, 31500357, 41430529, 41401164), the Natural Science Foundation of Guangdong Province, China (Grant No. 2014A030310233, 2015A030313809, 2015A030313811), the Science and Technology Plan Fund of Guangdong Province, China (Grant NO. 2014A020216028), the Science and Technology Plan Fund of Guangzhou City, China (Grant NO. 201510010240, 201610010134), the Water Resource Science and Technology Innovation Program of Guangdong Province (Grant NO. 2016-16, 2015-14), the Scientific Platform and Innovation Capability Construction Program of GDAS (2016GDASPT-0210) and the High-level Leading Talent Introduction Program of GDAS (2016GDASRC-0101).

The authors also like to thank the editor and the anonymous reviewers for their thorough review and constructive comments.

References

Adriaensen, F., Chardon, J.P., De Blust, G., et al., 2003. The application of 'least-cost'modelling as a functional landscape model. Landsc. Urban Plann. 64 (4), 233–247.

Berkes, F., Folke, C., 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge.

Blüthgen, N., Menzel, F., Blüthgen, N., 2006. Measuring specialization in species interaction networks. BMC Ecol. 6 (9), 1–12.

Briggs, G.A., 1973. Diffusion estimates for small emissions. U. S. Natl. Oceanic Atmos. Admin., 1973.

Chang, H., Li, F., Li, Z., Wang, R., Wang, Y., 2011. Urban landscape pattern design from the viewpoint of networks: a case study of Changzhou city in Southeast China. Ecol. Complex. 8 (1), 51–59.

Chardon, J.P., Adriaensen, F., Matthysen, E., 2003. Incorporating landscape elements into a connectivity measure: a case study for the Speckled wood butterfly (Pararge aegeria L.). Landsc. Ecol. 18 (6), 561–573.

Chen, Y., Li, X., Su, W., Li, Y., 2008. Simulating the optimal land-use pattern in the farming-pastoral transitional zone of Northern China Computers. Environ. Urban Syst. 32 (5), 407–414.

Chen, X., Su, Y., Li, D., Huang, G., Chen, W., Chen, S., 2012. Study on the cooling effects of urban parks on surrounding environments using Landsat TM data: a case study in Guangzhou, southern China. Int. J. Remote Sens. 33 (18), 5889–5914.

Chen, G.J., 2002. On ecological security. Chongqing Environ. Sci. 24 (3), 1–18, in Chinese.

Costanza, R., 1997. The value of the word's ecosystem services and natural capital. Nature 287, 253–260.

Coulon, A., Cosson, J.F., Angibault, J.M., et al., 2004. Landscape connectivity influences gene flow in a roe deer population inhabiting a fragmented landscape: an individual–based approach. Mol. Ecol. 13 (9), 2841–2850.

Deng, J.S., Wang, K., Hong, Y., Qi, J.G., 2009. Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization. Landscape Urban Plann. 92 (3), 187–198.

Devuyst, D., Hens, L., De Lannoy, W., 2001. How Green Is the City?—Sustainability Assessment and the Management of Urban Environments. Columbia University Press, New York.

Driezen, K., Adriaensen, F., Rondinini, C., et al., 2007. Evaluating least-cost model predictions with empirical dispersal data: a case-study using radiotracking data of hedgehogs (Erinaceus europaeus). Ecol. Modell. 209 (2), 314–322.

Eckersley, R., 2005. Ecological security dilemmas. N. Environ. Agendas II.

Ehrlich, P.R., 2002. Human natures, nature conservation, and environmental ethics. Bioscience 52, 31–43.

Elmqvist, T., Alfsen, C., Colding, J., 2008. Urban systems. In: Jorgensen, S.E., Fath, B.D. (Eds.), Ecosystems, Vol. 5 of Encyclopedia of Ecology. Elsevier, Oxford, pp. 3665–3672.

Ezeonu, I.C., Ezeonu, F.C., 2000. The environment and global security. Environmentalist 20, 41–48.

Fu, B., Li, S., Yu, X., Yang, P., Yu, G., Feng, R., Zhuang, X., 2010. Chinese ecosystem research network: progress and perspectives. Ecol. Complex. 7 (2), 225–233.

Gong, J.Z., Liu, Y.S., Xia, B.C., Zhao, G.W., 2009. Urban ecological security assessment and forecasting, based on a cellular automata model: a case study of Guangzhou, China. Ecol. Modell. 220, 3612–3620.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., et al., 2008. Global change and the ecology of cities. Science 319, 756–760.

Graham, C.H., 2001. Factors influencing movement patterns of keel-billed toucans in a fragmented Tropical Landscape in Southern Mexico. Conserv. Biol. 6, 1789–1798.

Guo, Z.W., 2001. To build the early warning and maintaining system of national ecological security. Science and Technology Review 1, 54–56, in Chinese.

Haeuber, R., Ringold, P., 1998. Ecology, the social sciences, and environmental policy. J. Appl. Ecol. 8, 330–331.

Imamura, F., Muhari, A., Mas, E., et al., 2012. Tsunami disaster mitigation by integrating comprehensive countermeasures in Padang City, Indonesia. J. Disaster Res. 7 (1), 48–64.

Jaeger, J.A., 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landsc. Ecol. 15 (2), 115–130.

Janin, A., Léna, J.P., Ray, N., et al., 2009. Assessing landscape connectivity with calibrated costédistance modelling: predicting common toad distribution in a context of spreading agriculture. J. Appl. Ecol. 46 (4), 833–841.

Jobe, R.T., White, P.S., 2009. A new cost-distance model for human accessibility and an evaluation of accessibility bias in permanent vegetation plots in Great Smoky Mountains National Park, USA. J. Veg. Sci. 20 (6), 1099–1109.

Kattel, G.R., Elkadi, H., Meikle, H., 2013. Developing a complementary framework for urban ecology. Urban For. Urban Greening 12 (4), 498–508.

Kullenberg, G., 2002. Regional co-development and security: a comprehensive approach. Ocean Coastal Manag. 45 (11–12), 761–776.

Li, Z.X., Xu, L.Y., 2010. Evaluation indicators for urban ecological security based on ecological network analysis. Procedia Environ. Sci. 2, 1393–1399.

Li, Y., Sun, X., Zhu, X., Cao, H., 2010. An early warning method of landscape ecological security in rapid urbanizing coastal areas and its application in Xiamen, China. Ecol. Modell. 221 (19), 2251–2260.

Liu, H.T., Li, Y.C., 1990. Atmosphere SO_2 pollution and decline of masson pine (Pinus mssoniana) forest in Nanshan, Chongqing. Acta Ecol. Sin. 10 (4), 305–311.

Ma, K.M., Fu, B.J., Li, X.Y., 2004. The regional pattern for ecological security (RPES): the concept and theoretical basis. Acta Ecol. Sin. 24 (4), 761–768, in Chinese.

1991. National environmental protection bureau, chinese research academy of environmental sciences. In: City Air Pollution Control Methods Manual. Environmental Science Press, Beijing, China.

O'Brien, D., Manseau, M., Fall, A., et al., 2006. Testing the importance of spatial configuration of winter habitat for woodland caribou: an application of graph theory. Biol. Conser. 130 (1), 70–83.

Peter, L.J., Hull, R., 1969. The Peter Principle: Why Things Always Go Wrong. William Morrow & Co. Inc, New York.

Pirages, D., 1996. Ecological security: micro-threats to human well-being. In: International Studies Association Annual Meeting, San Diego CA (April).

Post, J., Wegscheider, S., Mück, M., et al., 2009. Assessment of human immediate response capability related to tsunami threats in Indonesia at a sub-national scale. Nat. Hazards Earth Syst. Sci. 9 (4), 1075–1086.

Richard, Y., Armstrong, D.P., 2010. Cost distance modelling of landscape connectivity and gap-crossing ability using radio-tracking data. J. Appl. Ecol. 47 (3), 603–610.

Ruan, J.W., 2014. Analysis of change of ambient air pollutants in Gaoming district of Foshan city. Environ. Monit. China 30 (6), 90–92 (in Chiness).

Schaeffer, D.J., Henricks, E.E., Kerster, H.W., 1998. Ecosystem health: measuring ecosystem health. Environ. Manag. 2, 397–402.

Shaw, P.J.A., Dighton, J., Poskitt, J., McLeod, A.R., 1992. The effects of sulphur dioxide and ozone on the mycorrhizas of Scots pine and Norway spruce in a field fumigation system. Mycol. Res. 96 (9), 785–791.

Solovjova, N.V., 1999. Synthesis of ecosystemic and ecoscreening modelling in solving problems of ecological safety. Ecol. Modell. 124, 1–10.

Spear, S.F., Balkenhol, N., FORTIN, M.J., et al., 2010. Use of resistance surfaces for landscape genetic studies: considerations for parameterization and analysis. Mol. Ecol. 19 (17), 3576–3591.

Su, S., Xiao, R., Jiang, Z., Zhang, Y., 2012. Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. Appl. Geogr. 34, 295–305.

Su, Y.X., Zhang, H.O., Chen, X.Z., Huang, G.Q., Ye, Y.Y., Wu, Q.T., Huang, N.S., Kuang, Y.Q., 2013. The ecological security patterns and construction land expansion simulation in Gaoming. Acta Ecol. Sin. 33 (5), 1524–1534.

Tan, P.Y., bin Abdul Hamid, A.R., 2014. Urban ecological research in Singapore and its relevance to the advancement of urban ecology and sustainability. Landsc. Urban Plann. 125, 271–289.

Tan, Y.H., 2011. Research on Planning of Main Pollutant Cap Control in Gaoming Distriet of Foshan During the Twelfth Five-Year Master's Thesis. Jinan University.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. Landsc. Urban Plann. 81 (3), 167–178.

Verbeylen, G., De Bruyn, L., Adriaensen, F., et al., 2003. Does matrix resistance influence Red squirrel (Sciurus vulgaris L: 1758) distribution in an urban landscape? Landsc. Ecol. 18 (8), 791–805.

Waldheim, C., 2006. In: Waldheim (Ed.), The Landscape Urbanism Reader. Princeton Architectural Press, New York.

Walker, R.S., Novaro, A.J., Branch, L.C., 2007. Functonal connectivity defined through cost-distance and genetic analyses: a case study for the rock-dwelling mountain vizcacha (Lagidium viscacia) in Patagonia, Argentina. Landsc. Ecol. 22 (9), 1303–1314.

Weng, Y., 2007. Spatiotemporal changes of landscape pattern in response to urbanization. Landsc. Urban Plann. 81, 341–353.

Wu, J., Xiang, W.N., Zhao, J., 2014. Urban ecology in China: historical developments and future directions. Landsc. Urban Plann. 125, 222–233.

Xiao, D.N., Chen, W.B., Guo, F.L., 2002. On the basic concepts and contents of ecological security. Chin. J. Appl. Ecol. 13, 354–358 (in Chinese).

Yang, J.P., Lu, J.B., 2002. The System Analysis of Ecological Security. Chemicals Industry Press, Beijing, China.

Yeh, A.G., Li, X., 1998. Sustainable land development model for rapid growth areas using GIS. Int. J. Geographic. Infor. Sci. 12 (2), 169–189.

Yu, K., Li, D., Liu, H., Cheng, J., 2005. Growth pattern of Taizhou city based on ecological infrastructure: a negative approach physical urban planning. City Plann. Rev. 9, 76–80.

Yu, K., 1995. Ecological security patterns in landscapes and GIS application. Geogr. Info. Sci. 1 (2), 88–102.

Yu, K., 1996. Security patterns and surface model in landscape ecological planning. Landsc. Urban Plann. 36 (1), 1–17.

Yu, K., 1998. Landscape ecological security patterns in biological conservation. Acta Ecol. Sin. 19 (1), 8–15.

Yue, T.X., Liu, J.Y., Jørgensen, S.E., Ye, Q.H., 2003. Landscape change detection of the newly created wetland in Yellow River Delta. Ecol. Modell. 164 (1), 21–31.

Zhao, Y.Z., Zou, X.Y., Cheng, H., Jia, H.K., Wu, Y.Q., Wang, G.Y., Gao, S.Y., 2006. Assessing the ecological security of the Tibetan plateau: methodology and a case study for Lhaze County. J. Environ. Manage. 80 (2), 120–131.

Zhou, C.X., Shen, W.S., 2003. Research progress of ecological security. Rural Eco-Environ. 19 (1), 56–59 (in Chinese).

Zhu, L., Zhan, X., Meng, T., et al., 2010. Landscape features influence gene flow as measured by cost-distance and genetic analyses: a case study for giant pandas in the Daxiangling and Xiaoxiangling Mountains. BMC Genetics 11 (1), 1.