An eco-city evaluation method based on spatial analysis technology: A case study of Jiangsu Province, China

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ABSTRACT

An eco-city is an eco-sustainable, balanced and intensive human settlement, and the method selected to evaluate an eco-city is an important determinant of the accuracy of the evaluation. We present a new eco-city evaluation method comprising an ecological vulnerability evaluation index system and an economic, social and environmental evaluation index system based on land use, economic development, social progress and environmental protection using spatial analysis technology (remote sensing (RS) and geographic information system (GIS)). We constructed an ecological vulnerability evaluation index system using a pressure-state-response (PSR) model and the analytic hierarchy process (AHP) based on an ecological suitability index, landscape pattern index and land resource utilization degree index and comprehensively evaluated the ecological vulnerability condition using principal component analysis (PCA) and an expert scoring method. We established an economic, social and environmental evaluation index system using factor analysis. These index systems are associated with the GIS and the AHP, and Jiangsu Province was used as an example to verify the applicability and efficiency of the evaluation method. The results show the following. (1) The ecological vulnerability of Jiangsu is relatively low but unevenly distributed. The regions with slight, light and medium vulnerabilities comprised 79.49% of the total area. (2) Thirteen cities were divided into economic advantages type (Suzhou), environmental advantages type (Nanjing, Wuxi, Yangzhou, Zhenjiang and Taizhou), social security advantages type (Changzhou, Xuzhou and Nantong) and general type (Lianyungang, Huai'an, Yancheng and Suqian). (3) The overall condition of the eco-cities was classified as middle or upper and was unevenly distributed. The eco-cities were divided into four categories and there was a gradually decreasing trend from southeast to northwest, resulting in a gradient from southern Jiangsu to middle Jiangsu and northern Jiangsu. Every city should be constructed on the basis of its weak points to achieve healthy and optimum development. The results indicated that the method is an efficient and practical process, which differs from existing methods, and makes extensive use of spatial information technology and can be widely applied to evaluate eco-cities.

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1. Introduction

The concept of the eco-city was first proposed in the “Man and Biosphere (MAB)” program launched by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1971 (Wu et al.), and its prototypes are the garden city concept devised by utopian socialist R. Owen in 1820 and the garden city theory proposed by British architect Howard (1898). Since then, domestic and foreign scholars have conducted extensive research on the significance of the eco-city. Summarizing their views (Yanitsky, 1987;

Register, 1987; Huang and Yang, 2001; Mou, 2009; Krasny and Tidball, 2012), eco-cities are eco-sustainable, balanced, intensive human settlements; the development of the economy, society and nature are coordinated in an eco-city; material, energy, and information are used efficiently; technology, culture, and the landscape are fully integrated; residents are healthy and the full potential of humans and nature is achieved.

The eco-city is an essential model to achieve sustainable development, and the assessment of an eco-city forms the quantitative basis of eco-city planning, construction, and management effectiveness. Different evaluation methods produce different significance of evaluation results, after studying the evaluation methods used by scholars worldwide, we found that eco-city evaluation mainly adopts two types of index system framework:

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One is the structure–function–coordinated degree index system, which considers that the eco-city should be the ecosystem with reasonable structure, efficient function, coordinated ecological relationship, and the structure, function and coordinated degree are generally taken as the primary indicators. Song et al. (1999) established the structure–function–coordinated degree index system, evaluating the ecological level of five coastal cities with the weighted index method, and the evaluation results were basically consistent with the actual situation, but the fine detail was greatly reduced by using the administrative divisions as the evaluation unit. Li (2003) established such an index system and evaluated the eco-city level of Zhangjiagang, Suzhou Jiangsu using PCA, and although the evaluation effect was good, there was only qualitative and not quantitative analysis in the evaluation process. Liu and Yang (2011) analyzed the structure and function of urban systems and established an ecological network based mainly on industry, agriculture, tertiary industry, and transportation subsystems and effectively assessed the eco-city level of Beijing with the analysis tools based on a life-cycle network, but it did not consider the spatial association of different regions. The other system is the economy–society–environment index system, which uses the development of a compound ecosystem as the core and considers economic, social and environmental systems to have the relationship of coordinated development and mutual restriction, usually using economic development, social progress and environmental protection as its primary indicators, and this index system framework has been widely used at home and abroad. Hu and Huang (2006) established an eco-city multi-level fuzzy comprehensive evaluation model and evaluation support system based on the social, economic and environmental index system, which was a type of effective method to evaluate the eco-city, but lacked the support of spatial analysis technology, the analysis of the evaluation results were not intuitive or in-depth enough. Li and Yu (2011) combined index systems developed by domestic and international authoritative organizations and domestic ministries and commissions and constructed a set of evaluation index systems based on five perspectives, i.e., resource-saving, environmentally friendly, economic-sustainability, social harmony and innovation-leading, using comprehensive selection methods, expert discussion, the Delphi method and case studies, and although the indicators were relatively comprehensive, it ignored the ecological factors. The findings of Wang et al. (2015) also showed that the existing

economic–social–environmental index system cannot effectively evaluate the development level of the eco-city, and the ecological factors were urgently required.

Most of these methods selected specific evaluation indicators from the economy, society and nature and qualitatively or semi-quantitatively evaluate eco-city levels, but rarely consider urban ecological factors (land use, terrain, climate, etc.) or spatial correlations or in-depth analysis of the evaluation results.

We present a new evaluation method for eco-cities comprising an ecological vulnerability evaluation index system and an economic, social and environmental evaluation index system using land use, economic development, social progress and environmental protection based on RS and GIS technology. Jiangsu Province was used as an example to verify the applicability and efficiency of this new evaluation method. The results indicate that the method is an efficient, practical and widely applicable process.

2. Methods

2.1. Eco-city evaluation process

The eco-city evaluation index system includes an ecological vulnerability assessment index system and an economic, social and environmental evaluation index system; these index systems are associated with AHP and GIS technology. We built the ecological vulnerability assessment index system using RS and GIS technology combined with a PSR model, the AHP and PCA. We constructed the economic, social and environmental evaluation index system using factor analysis and an expert scoring method to determine the weight of each evaluation index to comprehensively evaluate an eco-city. The combination of the ecological vulnerability assessment and the economic, social and environmental evaluation provides a powerful exploration of eco-city evaluation. The eco-city evaluation technology roadmap is presented in Fig. 1.

2.2. Ecological vulnerability assessment index system

Currently, ecological vulnerability research mainly concentrated in the evaluation of ecosystem variety, sensitivity, potential impacts and adaptability. The method of building an ecological vulnerability assessment index system combining the AHP, factor

Fig. 1. The eco-city evaluation technology roadmap.

Table 1
Ecological vulnerability evaluation index system.

Target layer	Criterion layer	Evaluation index layer	Index layer
Ecological vulnerability	Pressure	Ecological suitability index	Soil erosion sensitivity index Soil desertification sensitivity index
	State	Landscape pattern index	Landscape unit plaques density Landscape evenness index
	Response	Land resources utilization degree index	Land utilization degree composite index

Table 2
Sensitivity classification of ecological suitability.

Index	Slight sensitivity	Light sensitivity	Medium sensitivity	Heavy sensitivity	Extreme sensitivity
R	<250	250–300	300–350	350–400	>400
LS	0–20	20–50	50–100	100–300	>300
C	Water, herbs, swamp, rice paddies	Broad-leaved forest, coniferous forest, grass, bush forest	Shrub grassland, double cropping crop	Desert, once cropping crop	No vegetation
I	>0.65	0.5–0.65	0.2–0.5	0.05–0.2	<0.05
W	<16	16–20	20–24	24–28	>28
VC	>0.7	0.5–0.7	0.3–0.5	0.1–0.3	<0.1
Value	1	3	5	7	9

analysis and fuzzy comprehensive evaluation with landscape ecology methods (Mortberg et al., 2007) and 3S technology has been widely used in ecological vulnerability studies of wetlands, cities, rivers and other areas (Liao et al., 2013). We constructed an ecological vulnerability evaluation system using the AHP, PCA and PSR model.

2.2.1. Evaluation model

The PSR framework was initially proposed by the Organization for Economic Cooperation and Development (OECD) to evaluate the world environmental situation (Adriaanse, 1993). The basic idea was that human activities exert pressure on the environment and natural resources. Consequently, this changes the environmental quality and quantity of natural resources, and society responds to these changes through policies, decisions or management measures of the environment, economy and land use to reduce pressure on the environment and maintain environmental health. The PSR model answers three basic questions, i.e., “What happened? Why did it happen? And What do we do?” The PSR framework of ecological vulnerability is presented in Fig. 2.

2.2.2. Evaluation index

We established the ecological vulnerability evaluation index system based on land use using the PSR model, AHP and PCA. The index system includes a target layer, a criterion layer, an evaluation index layer and an index layer (Table 1). The target layer is ecological vulnerability; the criterion layer P-S-R corresponds to the evaluation index layer of the ecological suitability index, landscape pattern index and land resources utilization degree

index, respectively. The index layer includes the soil erosion sensitivity index and soil desertification sensitivity index, landscape unit plaques density and landscape evenness index, and land utilization composite degree index. We assigned weights to the various indicators using an expert scoring method.

2.2.3. Index calculation

2.2.3.1. Ecological suitability index. Ecological suitability indicators include the soil erosion sensitivity index and soil desertification sensitivity index obtained from the specific grading standards “Interim regulations of ecological function zoning techniques” Annex C, prepared by the Chinese Academy of Sciences and issued by the State Environmental Protection Administration (China Academy of Sciences, 2003). However, the grading standard does not objectively reflect the true status of the study area; therefore, the grading standard was modified according to the true status. A single factor sensitivity evaluation was conducted initially and then a comprehensive sensitivity was evaluated using spatial overlay analysis. The sensitivity classification is presented in Table 2.

(1) *Soil erosion sensitivity index.* The purpose of this index is to identify regions that are susceptible to soil erosion and to evaluate the sensitivity level of soil erosion to human activity. Based on the Universal Soil Loss Equation (USLE) (Renard et al., 1997) combined with GIS technology and accounting for rainfall, topography and vegetation factors, we selected the rainfall erosivity (R), slope and aspect (LS) and land cover (C) as the evaluation indicators.

The rainfall erosivity indicates the potential ability of rainfall to cause soil erosion. The existing rainfall erosivity models for this region include the rainfall-intensity model, the kinetic energy-intensity model, and a simple rainfall model (Li et al., 2010). We calculated rainfall erosivity based on a simple formula using the R-value for China's southern region, proposed by Zhou et al. (1995). We used the ArcGIS10.0 (ESRI Inc.) raster calculator to obtain an R-value distribution, which was reclassified to obtain an R-grade distribution according to the classification criteria.

$$R = \sum_{i=1}^{12} (0.3046P_i - 2.6398) \quad (1)$$

in which R is the annual rainfall erosivity (J cm/(hm² h)) and P_i is the average monthly rainfall of 1–12 months (mm).

Topographic relief was selected as a soil erosion assessment indicator. We extracted regional topographic relief data using a 5 km × 5 km moving window analysis (Liu et al., 2001) on digital

Fig. 2. The PSR framework of ecological vulnerability.
Modified from Pieri et al. (1995).

Table 3
The weights of ecological suitability evaluation factors.

Soil erosion sensitivity	Weight (%)	Soil desertification sensitivity	Weight (%)
R	30.4	I	35.0
LS	36.5	W	35.0
C	33.1	VC	30.0

elevation model (DEM) data through the focal function in ArcGIS, we reclassified the data to obtain a topographic relief distribution map.

We reclassified the current land use map to generate a land cover classification map in accordance with the classification standards.

(2) *Soil desertification sensitivity index*. This index represents the potential extent of land desertification caused by human activities (Liu et al., 2002a,b). The moisture index (I), wind index (W) and vegetation cover (VC) were selected as the evaluation indicators.

Moisture, which is the reciprocal of dryness, can objectively reflect the water and heat balance of a region and relates directly to rainfall and temperature. Dryness was calculated using the method of Zhang Baokun. Regions with temperature $\geq 10^{\circ}\text{C}$ were identified from the monthly average temperature raster data using Band Math of ENVI 4.7 (RSI Inc.), then the product operation with number of days per month was performed to generate the $\geq 10^{\circ}\text{C}$ cumulative monthly temperature; the results were superimposed to obtain the $\geq 10^{\circ}\text{C}$ cumulative annual temperature.

$$K = \frac{0.16 \times \sum t}{r} \quad (2)$$

in which K is the dryness; $\sum t$ is $\geq 10^{\circ}\text{C}$ cumulative annual temperature, r is the corresponding total precipitation.

The wind index was determined as the number of days with wind speed greater than 6 m/s in winter and spring (December to May) (Zhang et al., 2001). We calculated the average number of gale days by counting the daily average wind speed from the stations in the study area and performed Kriging interpolation on average gale days at each station to generate a distribution of gale days.

Vegetation cover is an important factor affecting desertification sensitivity. Soil desertification does not occur in water, snow or in areas with high vegetation cover, whereas bare ground and sparse vegetation increase the likelihood of desertification. We used NDVI to estimate vegetation cover, and a vegetation cover index map was obtained in accordance with classification standards. Water bodies were classified as insensitive factors.

$$C = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (3)$$

in which C is the vegetation cover; $NDVI$ is the vegetation index; $NDVI_{\min}$, $NDVI_{\max}$ are the minimum and maximum $NDVI$ values, respectively.

(3) *Comprehensive sensitivity evaluation*. We determined the weights of the soil erosion and desertification sensitivity indicators using PCA in Matlab 2013a (MathWorks Inc.) (Table 3); a weighted

summation was used to calculate the soil erosion and desertification sensitivity indices. The formula used was

$$SS(DS) = \sum_{i=1}^3 C_i W_i \quad (4)$$

in which SS is the soil erosion sensitivity index; DS is the soil desertification sensitivity index; C_i is the sensitivity level value of indicator i ; W_i is the weight of indicator i .

2.2.3.2. Landscape spatial pattern index. The main indicators of the landscape spatial pattern are the landscape unit plaques density (PD) and landscape evenness index (SHEI). A grid analysis was performed using ArcGIS 10.0, in which the study area was divided into a $1000\text{ m} \times 1000\text{ m}$ grid. Then, the number of plaques in each grid was obtained and the area ratio of the different land use types in each grid cell was counted using overlay and statistical analysis. The PD and SHEI were calculated and associated with the grid to generate a PD and SHEI indicator map. The formula used to calculate PD is

$$PD = \frac{N}{A} \quad (5)$$

in which PD is the landscape unit patch density; N is the number of plaques in each grid; A is the area of each landscape unit.

The formula used to calculate the SHEI is

$$SHEI = \frac{-\sum_{i=1}^T p(i) \ln(p(i))}{\ln(T)} \quad (6)$$

in which $SHEI$ is the landscape evenness index; $p(i)$ is the area ratio of land use type i in the landscape unit; T is the total number of land use types.

2.2.3.3. Land resource utilization degree index. This index reflects the level of land use (Wang et al., 2002). Liu et al. (2002a,b) proposed land use degree grading standards (Table 4). We generated a land resource utilization degree map using ArcGIS 10.0 and the grid analysis and land use degree calculation method.

The formula used to calculate the degree of land resource utilization is

$$La = 100 \times \sum_{i=1}^n A_i \times C_i \quad (7)$$

in which La is the land resource utilization degree index; A_i is the land use degree grading index of level i ; C_i is the area ratio of the land use degree grading of level i .

2.3. Economic, social and environmental evaluation index system

2.3.1. Evaluation index

According to the true status and results of previous studies in this area, the objectivity, representativeness, data availability, economic development, social progress and environmental protection were established as senior grade indicators of the economic, social and environmental evaluation index system. Additionally, each indicator comprised numerous second-grade indicators. The specific indicators are listed in Table 5.

Table 4
Land use types classification table.

Type	Unused land level	Forest, grass, water level	Agricultural land level	Urban settlements land level
Land use type	The land unused and difficult to use	Forest, grass, water	Farmland, garden, artificial turf	Urban, settlement, industrial land, transportation land
Grading index	1	2	3	4

Table 5
Economic, social and environmental evaluation index system.

Senior grade indicator	Second grade indicator
Economic development	Per capita GDP growth (%)
	Per capita income (yuan/person)
	Per capita disposable income (yuan)
	The added value of tertiary industry to GDP (%)
	Per unit comprehensive energy consumption to GDP (tce/ten thousand yuan)
	Per unit water consumption to GDP (m ³ /ten thousand)
	High-tech industry output to GDP (%)
	Fixed asset investment to GDP (%)
Social progress	Urban population rate (%)
	Registered urban unemployment rate (%)
	Bed number per thousand people (beds/thousand)
	Public bus and trolleybus per thousand people (unit)
Environmental protection	Natural population growth rate (‰)
	Crop planting area per capita (ha/person)
	Water resources per capita (m ³ /person)
	Green coverage rate (%)
	Industrial wastewater discharge compliance rate (%)
	Green area per capita (m ² /person)
	Removal amount of sulfur dioxide per capita (tons/person)

2.3.2. Index calculation

The economic, social and environmental conditions of the study area were analyzed using SPSS 19.0 (SPSS Inc.). We collected specific data to quantify the condition of the eco-city by factor analysis, i.e., a linear combination of few potential factors were used to represent many indicators. (1) The sample data were standardized to eliminate the effects introduced by different dimensions; (2) the suitability of the factor analysis method to analyze the data was determined using KMO and the Bartlett sphericity test; (3) four common factors, i.e., the economic development (F1), natural environment (F2), social security (F3) and social structure (F4), and the factor loading matrix were determined; (4) the factor score model was constructed according to the factor loading matrix: $F = 0.642F_1 + 0.173F_2 + 0.112F_3 + 0.073F_4$, in which F is the economic, social and environmental score; (5) the economic, social and environmental score of the cities was calculated; (6) the score of each city was associated with the location.

2.4. Index standardization and the determination of the weights

Because of having several indicators and the division between the units, it was necessary to standardize the indicators before analyzing the data to eliminate the effects caused by different dimensions and to ensure the analysis was accurate. We standardized the indicators between [0–1]; the standardized formulas used are as follows:

$$P_i = \frac{E_i - E_{\min}}{E_{\max} - E_{\min}} \quad (8)$$

Table 6
The index weights of the eco-city assessment system.

Target layer	Weight	Evaluation index layer	Weight	Index layer	Weight	Total weight
Ecological vulnerability	0.7	Ecological suitability index	0.3	Soil erosion sensitivity index	0.4	0.12
				Soil desertification sensitivity index	0.6	0.18
		Landscape pattern index	0.2	Landscape unit plaques density	0.7	0.14
				Landscape evenness index	0.3	0.06
Economy society and environment	0.3	Land resources utilization degree index	0.2	Land utilization degree composite index	0.2	0.2
		Economy society and environment	0.3	Economy society and environment	0.3	0.3

$$P_j = 1 - \frac{E_i - E_{\min}}{E_{\max} - E_{\min}} \quad (9)$$

in which P_i is the normalized value of a participating indicator (positive) in pixel i ; P_j is the normalized value of a participating indicator (negative) in pixel j ; E_i is the property value of a participating indicator in pixel i ; $E_{\min}$ and $E_{\max}$ denote the minimum and maximum property values of a participating indicator, respectively (Wang et al., 2007). The economic, social and environmental index and the composite land utilization degree index belong to the positive indicators, whereas the soil erosion sensitivity index, soil desertification sensitivity index, landscape unit plaques density, and landscape evenness are negative indicators (Qiao et al., 2013). We calculated the weight of each evaluation indicator using an expert scoring method after standardization (Table 6).

2.5. Eco-city evaluation

The weighted sum of each evaluation indicator was used to comprehensively evaluate the eco-city; the formula is $EC = \alpha \cdot SS + \beta \cdot DS + \gamma \cdot PD + \omega \cdot SHEI + \varphi \cdot La + \varepsilon \cdot ESE$, in which EC is the eco-city index, SS is the soil erosion sensitivity index, DS is the soil desertification sensitivity index, PD is the landscape unit plaques density, $SHEI$ is the landscape evenness index, La is the land utilization degree composite index, ESE is the economic, social and environmental index, and $\alpha, \beta, \gamma, \omega, \varphi, \varepsilon$ are weights.

The ecological condition was divided into excellent (0.53–0.87), good (0.42–0.53), medium (0.33–0.42), and general (0.11–0.33) grades using natural breaks. This type of classification method identifies the demarcation point using the Jenk optimization method (Li et al., 2009) and therefore minimizes the sum of the internal variance of all conditions.

3. Case

3.1. Study area

The study area is Jiangsu Province (30°45′ to 35°20′ North; 116°18′ to 121°57′ East), in the center of the eastern coast of mainland China, downstream on the Yangtze River. The Yellow Sea is to the East, and Shanghai and Zhejiang are Southeast of the study area, which is bordered by Anhui to the West and Shandong to the North. There are 13 provincial cities, and the capital is Nanjing. The land area covers 102,600 km² and has a climate that transitions from temperate to subtropical. The terrain is mainly flat with an elevation of 50 m or less. Low mountains and uplands, which are concentrated in the southwest region of the province, account for 14.3% of the total area. There are many rivers and lakes, and the annual rainfall runoff ranges from 150–400 mm. The population is approximately 78.66 million, and the Yangtze River Delta city groups include Shanghai and Zhejiang. The comprehensive economic strength of this region is at the forefront of the country. In recent years, Jiangsu has effectively promoted the construction of an “ecological province” and has built the largest “eco-city group”

Fig. 3. Land use map of Jiangsu Province.

in the country. The land use map of Jiangsu Province is shown in Fig. 3.

3.2. Data sources

The research data included land use, social progress, economic development and environmental protection data, which included mainly the following. (1) Meteorological data: the 2010 raster

data of the country's average monthly rainfall and temperature, obtained from the Chinese Academy of Environmental Science Data Center Resources with a 1000-m resolution grid, were masked to obtain related data of the study area; the 2010 daily average wind speed data of thirteen stations in the study area from the Chinese Meteorological Data Sharing Service network (<http://cdc.cma.gov.cn/home.do>). (2) Image data: MOD13A2 NDVI image data of the study area in 2010 with a 1000-m resolution, derived from geospatial data cloud network (<http://www.gscloud.cn/>). (3) Statistics: 2010 economic, social and environmental data of the study area from the "2011 Jiangsu Statistical Yearbook" and the China Economic Information Network database (<http://db.cei.gov.cn/page/Login.aspx>). (4) Additional information: the DEM of the study area with a resolution of 500 m, the 2010 land use distribution raster of the study area with a 100-m resolution and the related vector map from the Chinese Academy of Environmental Science Data Center Resources. The study area was divided into arable land, woodland, grassland, water, mining and rural residential land, and unused land with six types of senior-grade classifications and 25 types of second-grade classifications. The Krasovsky 1940 Albers projection was used for all spatial data, and the raster data were 1-km grid data.

3.3. Results and analysis

(1) Distribution maps. The distribution maps of all indicators are as follows: the distribution of soil erosion sensitivity indicators, i.e., the rainfall erosivity, topographic relief and land cover are shown in Fig. 4; the distribution of soil desertification sensitivity indicators, i.e., the moisture, number of gale days and vegetation cover, are shown in Fig. 5; the distribution of

Fig. 4. Soil erosion sensitive indicators grade distribution map.

Fig. 5. Soil desertification sensitive indicators grade distribution map.

Fig. 6. Landscape space pattern indicators grade distribution map.

Fig. 7. Land resource utilization degree index grade distribution map.

Fig. 8. Ecological vulnerability grade distribution map.

landscape space pattern indicators, i.e., the landscape unit plaques density and landscape evenness index, are shown in Fig. 6; land resource utilization degree index, ecological vulnerability, economic, social and environmental evaluation index and the eco-city distribution are shown in Figs. 7–10, respectively; the proportions of ecological vulnerability of each condition and the economic, social and environmental scores for each city are shown in Tables 7 and 8, respectively.

- (2) Ecological vulnerability level. The ecological vulnerability level of Jiangsu is fairly low but unevenly distributed (Fig. 8). The regions with slight, light and medium vulnerabilities comprise 79.49% of the total area. The ecological vulnerabilities of Suzhou, Nanjing, and Xuzhou are relatively lower, and the ecological vulnerabilities of Wuxi, Nantong, Yancheng and Lianyungang are higher, which has a great relationship with local resources and the environment, governmental policy, and historical and cultural factors. Different cities should formulate corresponding policies and measures to reduce the ecological vulnerability according to the true condition of the city.

- (3) Results of economic, social and environmental city category. Thirteen cities were divided into four categories based on the economic, social and environmental aspects:

- (1) Economic advantage: Suzhou. Suzhou's economic development score was considerably higher compared with other cities, and its natural environmental score was relatively high. This is because Suzhou is in the Yangtze River Delta

area, which is a superior geographical position; the Huning railway and Huning speedway link the East and West, the Jinghang Canal runs North and South, and Suzhou is adjacent to Shanghai, the largest modern city in China.

Fig. 9. Economy society and environment index grade distribution map.

Fig. 10. Eco-city grade distribution map.

Moreover, Suzhou is a famous tourist city, containing more than 60 gardens and 34 important specially preserved historical monuments. However, there is a slight shortage in social security; therefore, Suzhou should focus on solving problems in this region. First, the government should improve the social security system, and second, the government should provide more jobs and skills training for laid-off workers to reduce unemployment.

- (2) Environmental advantage: includes Nanjing, Wuxi, Yangzhou, Zhenjiang and Taizhou. The natural environmental score for these cities was extremely high,

especially for Nanjing, with a score of 2.91 (Table 8), which was considerably higher than the other cities. Nanjing is the capital of Jiangsu Province, the ancient capital of the six dynasties, and has been voted as one of the best cities to live. These types of cities can extensively develop the tourism industry to promote the development of the economy by relying on their own environmental advantages and then create a balanced and stable social environment through economic development.

- (3) Social security advantage: includes Changzhou, Xuzhou and Nantong. The social security scores of these cities were high, and the natural environmental scores were lower. Among these cities, Changzhou has the greatest economic strength. Nantong and Xuzhou, the two northern cities, are rich in resources; however, most are non-renewable, making it necessary to use limited resources legitimately and implement effective protection methods. Additionally, traditional energy-intensive production methods should be changed. We can use the economic advantages of Changzhou to strengthen ecological and environmental construction, which includes increasing city greening and improving the condition of lakes.
- (4) General type: includes Lianyungang, Huaian, Yancheng and Suqian. The economic and natural environmental scores of these cities were low. Each city should correctly manage the relationship between economic development and environmental protection and should establish an economic development model based on low energy consumption, low pollution, and low emissions and must not blindly pursue economic development and ignore environmental protection.
- (4) Eco-city distribution trend. There was a gradually decreasing trend in the condition of the eco-cities from southeast to

Table 7
Ecological vulnerability proportions of each level.

City	Slight vulnerability (%)	Light vulnerability (%)	Medium vulnerability (%)	Heavy vulnerability (%)
Nanjing	19.91	32.88	34.05	13.16
Wuxi	25.89	22.45	32.61	19.05
Xuzhou	13.98	38.36	34.69	12.97
Changzhou	13.41	27.25	39.42	19.92
Suzhou	28.15	26.16	30.11	15.58
Nantong	1.17	20.33	54.97	23.53
Lianyungang	6.74	29.32	43.75	20.19
Huaian	17.89	29.26	29.48	23.37
Yancheng	2.66	18.32	43.75	35.27
Yangzhou	12.4	27.85	47.11	12.64
Zhenjiang	13.85	20.54	40.49	25.12
Taizhou	5.44	31	48.7	14.86
Suqian	14.85	30.78	35.97	18.4

Table 8
Economic, social and environmental scores.

City	F_1	F_2	F_3	F_4	F	Ranking
Nanjing	-0.376	2.91	0.210	0.383	0.315	4
Wuxi	1.074	0.604	0.359	-0.021	0.832	2
Xuzhou	-0.651	-0.374	0.981	-1.019	-0.447	10
Changzhou	0.673	-0.402	1.260	-0.367	0.477	3
Suzhou	2.658	0.414	-0.884	0.896	1.600	1
Nantong	-0.084	-0.743	0.629	-0.875	-0.176	7
Lianyungang	-0.773	-0.468	0.251	1.378	-0.448	11
Huaian	-0.654	-0.948	1.291	1.678	-0.317	8
Yancheng	-0.718	-0.516	-1.415	-0.007	-0.709	12
Yangzhou	-0.159	0.254	0.172	-1.249	0.130	6
Zhenjiang	0.126	0.660	0.024	-0.012	0.197	5
Taizhou	-0.033	0.472	-1.126	-1.517	-0.340	9
Suqian	-1.083	-0.096	-1.752	0.732	-0.854	13

Table 9

The overall grade ratio of the eco-city.

Eco-city level	Number of cells	Ratio (%)
Excellent	10,457	10.7
Good	25,131	25.7
Medium	37,518	38.4
General	24,563	25.2

Table 10

The grade ratio of each eco-city.

City	Excellent (%)	Good (%)	Medium (%)	General (%)
Nanjing	9.85	75.23	13.7	1.22
Wuxi	51.34	47.06	1.6	0
Xuzhou	0	19.91	61.73	18.36
Changzhou	11.57	76.19	12.24	0
Suzhou	94.99	4.97	0.04	0
Nantong	0.03	11.32	70.36	18.29
Lianyungang	0	15.49	59.26	25.25
Huaian	0.01	25.36	52.3	22.33
Yancheng	0	2.26	20.78	76.96
Yangzhou	1.33	54.92	41.38	2.37
Zhenjiang	2.91	64.44	31.01	1.64
Taizhou	0.18	14.83	71.37	13.62
Suqian	0	4	38.67	57.33

northwest. It represented a gradient from southern Jiangsu to middle Jiangsu and northern Jiangsu. Southern Jiangsu had the best ecological conditions, followed by middle Jiangsu and northern Jiangsu. This ecological gradient was driven mainly by differences in the level of economic development, conditions of regional natural resources, history and culture, and the coordinated development of the economy, society and environment (Qi, 2010). From a macro perspective, the overall eco-city condition of Jiangsu Province is at a middle or upper level (Table 9). The region with an excellent ecological level occupied 10.7% of the total area, the good level occupied 25.7%, the medium level occupied the greatest area (38.4%) and the general level occupied 25.2% of the total area. From a micro perspective, the ecological conditions of the cities in Jiangsu Province are unbalanced; the Suzhou eco-city condition is the best, followed by Wuxi and Changzhou, whereas Suqian is the worst (Table 10). The eco-cities were divided into four categories (Table 9 and Fig. 10); the first class comprised Suzhou; the second class comprised Wuxi, Changzhou, Nanjing, Zhenjiang and Yangzhou; the third class comprised Taizhou, Nantong and Xuzhou and the fourth class comprised Huaian, Yancheng, Suqian and Lianyungang. Each eco-city should be constructed because of its weak points to achieve healthy and optimum development.

4. Discussion

We provide a new method of improving the existing eco-city evaluation system. In current evaluation index system, the selection of the environmental indicators almost focuses on the biological and resource environments (Xue et al., 2008; Zhang et al., 2010) while always ignoring the relevant contents of the ecological environment, which caused the index system to rarely imply ecological environment factors. Our method adds to the ecological vulnerability index, supplementing the existing evaluation index system by selecting elements such as climate, topography, land use indicators, etc., that are closely related to the city's ecological development, and the method effectively makes up for the deficiency of ecological factors.

(1) Spatial correlation. The existing eco-city evaluation methods generally used the purely statistical softwares such as SPSS

software to evaluate eco-city level, which cannot convey the spatial dimensions. This method considers the spatial correlation of topographic, climate and landscape pattern factors among different regions, evaluating the eco-city level in the spatial level by GIS spatial analysis software.

- (2) Evaluation of fineness. Existing eco-city assessment normally uses the administrative districts as evaluation units, which have irregular shapes, large areas, and uneven arrangements, taking Jiangsu Province as an example, the smallest area, Changzhou City, is approximately 4300 km², and the largest area is approximately 14,500 km². This cannot meet the fine scale requirements of the evaluation results. This method uses the raster grid as the evaluation unit, and unit size is determined by the resolution of the data source (1 km² in this paper), the fine scale of which is much better than most of other methods.
- (3) Visual qualitative and quantitative analysis. The current eco-city evaluation results are usually the eco-city score, ranking, grading and the corresponding measures required, which are only qualitative or semi-quantitative analyses, and mostly exist in form of text, tables, or other forms. This method displays the results with more intuitive figures. With the aid of spatial analysis techniques (e.g., spatial statistical analysis, spatial autocorrelation analysis, etc.), the further quantitative statistics and qualitative analysis of evaluation results can be obtained, for example, considering area and proportion of each eco-city grade, further analyzing the spatial autocorrelation of eco-city level and so on, which may lay the theoretical foundation for the government to grasp the eco-city spatial distribution and to formulate the corresponding countermeasures more accurately.
- (4) Index weight assignment of flexibility. The method determines the weights according to an expert scoring method, and the actual situation of the study area influences the scoring results significantly, so the index weights can flexibly change according to the experts' experience and the local economic and social environment. For example, although the western regions of China are in the core area of the Eurasian Economic Belt and have rich resources and energy, the ecological environment is extremely fragile and seriously hinders the sustainable development of the economy and society, also leads to a decrease in ecological levels of the west and even the entire country. The ecological vulnerability may be given greater weight in the expert scoring process because its impacts are relatively more significant than the economic and social environmental factors. In this paper, the level of economy, society and culture in Jiangsu Province is well developed, and the quality of its ecological environment is of great significance to sustainably develop the city, therefore, the ecological vulnerability index was given a higher weight, which was 0.7 in this paper, and the weight of economic social and environmental indicators was 0.3.
- (5) Method of extensibility. It maybe impossible for an evaluation index system framework to cover every indicator, and this is also true with this method. It should be improved with different study areas and the development of the society. The good extensibility of the system is convenient for the further improvement, for example, the economic, social and environmental index system can be divided into economic, social, environmental, political and cultural indicators (Wang and Liang, 2011), or social, natural, environmental and economic indicators, according to the requirements (Zhou and Qiao, 2010) to reflect the situation of eco-city development more objectively. Foreign ecological indicators concentrate more on low carbon city models, and it is perhaps appropriate to add CO₂ and NO₂ emissions, buildings, transportation, power plants, population and other indicators to the eco-city evaluation process.

5. Conclusion

We present a new eco-city evaluation method based on spatial analysis technology. The eco-city evaluation index system contains the ecological vulnerability evaluation index system and the economic, social and environmental evaluation index system, which is constructed from land use, economic development, social progress and environmental protection perspectives. Based on the index system, we evaluate the eco-city level of Jiangsu Province, China, the eco-level of which was overall in medium to high. So far, we assess the condition of an eco-city combining the ecological vulnerability and economic, social and environmental indicators firstly. The results indicated that the method is an efficient, practical process, which differs from existing methods and can be widely applied to evaluate eco-cities.

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