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An integrated sustainable development approach to modeling the eco-environmental effects from urbanization

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ABSTRACT

Urbanization induces detrimental effects on the eco-environment that are beginning to be extensively described. However, the adoption of suitable indicators and reliable methods still requires attention to provide a basis for a more accurate understanding of eco-environmental effects from urbanization. The aggregated index system representing the coupling relationships between urbanization and eco-environment was introduced and an integrated sustainable development approach (ISD) to simulate and evaluate the integrative effects was developed in this paper. The ISD consists of modules of the coupling relationship assessments, systematic analysis of potential eco-environmental changes, and sustainability evaluation. An interpretative structural modeling (ISM) and grey relative technique (GRT) are used to analyze the systematical structure and assess the coupling relationships. A system dynamics model (SD) and artificial neural network (ANN) are used to simulate the potential environmental changes and compare the sustainability, respectively. An application study of Jiangsu province in China was performed, where the general eco-environmental integrity is under significant urbanization pressure. The potential eco-environmental scenarios from 2010 to 2015 under natural, populated, economic, spatial and social urbanization patterns were simulated and analyzed. The result reveals that the urbanization sustainability may be met on condition that either populated urbanization or social urbanization pattern is adopted in Jiangsu province, China. The aggregated indexes and ISD may help local authorities better understand and address the complex coupling relationship, and develop improved regional environmental management strategies that better balance urbanization and eco-environmental conservation.

1. Introduction

Rapid urbanization in many countries worldwide has become a major concern because of its detrimental effects on the environment (Jaeger et al., 2010). However, considerable variability surrounds the general eco-environmental integrity with urbanization so that equivalent levels of urbanization can be associated with a wide range of eco-environmental indicator scores (Wang et al., 2004; Scipioni et al., 2009). For example, slopes and thresholds of urbanization effects differ among urban areas and countryside (Walton et al., 2007). Anthropogenic development due to urbanization is also another regional impact on ecosystem structure and function (Miltner et al., 2004). Land use and land cover (LULC) change associated with urban development is considered one of the most disturbing processes because it causes dramatic changes in the natural energy and material cycles of ecosystems and influences mesoscale weather patterns, local climate conditions, biodiversity, and water resources (McDonnell and Pickett, 1990; Alberti, 2005; Kalnay and Cai, 2003). Several studies have described changes in composition and structure of ecological communities associated with urban land use (Posa and Sodhi, 2006; Sadler et al., 2006). Recent studies indicate the eco-environmental indicators can include the increase of greenhouse gas concentration in the atmosphere (Karl and Trenberth, 2003), the degradation of air and loss of farmland, forests (Squires, 2002), and distinct biotas (Grimm et al., 2000; Vitousek et al., 1997). Nevertheless, a more accurate understanding of eco-environmental effects from urbanization is a challenging task as its measuring is rather complex without a set of suitable indicators. Such complexity is unlikely to be captured by any single model (Allan, 2004; Booth et al., 2004; Walton et al., 2007).

Over the past years, studies the eco-environmental effects induced by urbanization were mainly conducted within watershed and ecological fragile areas (Wang et al., 2004; Xian et al.,

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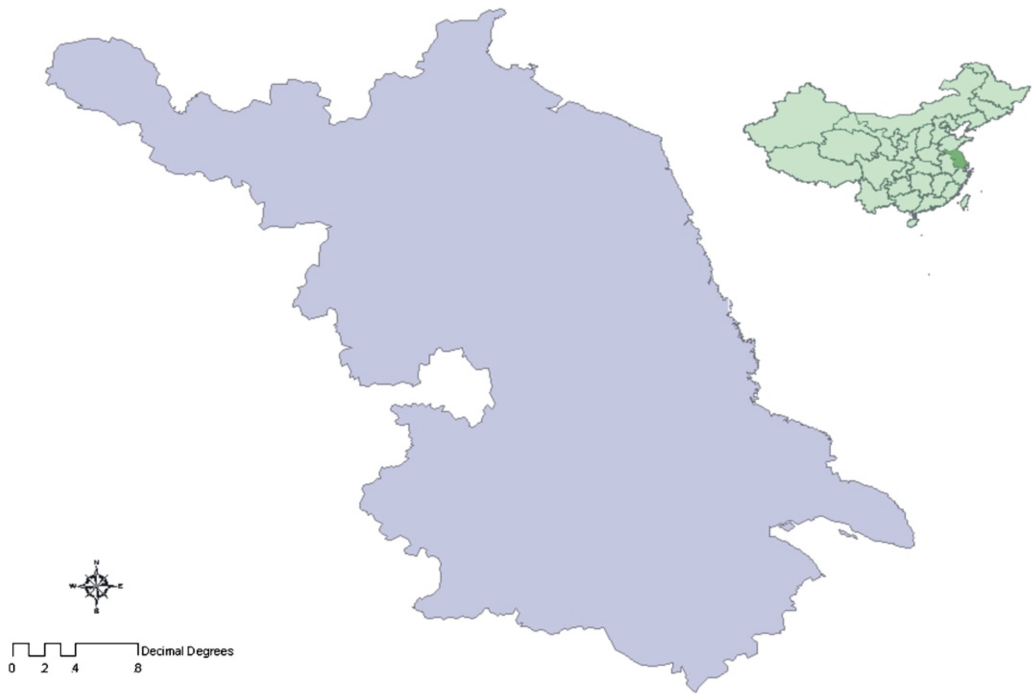

Fig. 1. Location of Jiangxi province in China.

2007), focusing on urban area and metropolitan areas (Svoray et al., 2005; Walton et al., 2007; Weber and Puissant, 2003). A number of approaches were applied in a regional environment management, urban suitability assessment, environmental changes forecasting with urban sprawl, including system-dynamics modeling, scenario analysis, input–output design, land-transformation simulation, CA model and neural networks prediction (Fischer and Sun, 2001; Pijanowski et al., 2002; Yu and Ng, 2007; Tang et al., 2005; Liu et al., 2007; Li and Kuo, 2008), and some ecological evaluation including NPP, ecological footprints, energy flow and energy model (Odum and Elisabeth, 2000; Rees, 1997; Bjorklund et al., 1999; Imhoff et al., 2004). However, urban ecology has focused principally on biological surveys of habitat typologies, and multi-ecological studies in the inner city (Gilbert, 1989). Most studies about eco-environmental effects resulted form urbanization showed considerable interests in the urban sprawl and its relationship with the eco-environment, and pay much more attention to its ecological aspects, yet there is still a lack of consensus not only on the conceptual framework, but also the approach favored. As a result, the existing measures of urbanization sustainability suffer from a confusing variety of differing and sometimes contradictory.

The objective of this study is to investigate the eco-environmental effects from urbanization and to forecast the ecosystem quality and environmental conditions of Jiangsu province in China in the future. The aggregated indexes and ISD may help local authorities better understand and address the complex coupling relationship, and develop an improved regional environmental management strategy that better balance urbanization and eco-environmental conservation.

2. Materials and methods

2.1. Study area

Jiangsu province is located in the east part of China and extends from 30.45′N to 35.07′N and 116.22′E to 121.55′E. It covers an area totaling 1.03×10^4 km^2, of which 69% is plain (see Fig. 1). As a one of the most developed provinces in the economy of China, Jiangsu province is presently undergoing rapid urbanization process, companying industrialization and significant socio-economic adjustments. Associated with rapid economic development and urban sprawl, the amount of arable land in Jiangsu province sharply decreased and the persistent reduction of arable land has become an important challenge to restrict the urbanization sustainability. Correspondingly, the eco-environmental impacts posed by urbanization are also prominent in Jiangsu province.

2.2. Data sources

The investigated data and statistical data are taken as the main data sources. The statistical data of eco-environmental indicators are originally from the past Land & Resource Bulletin and Water Conservancy Annals of Jiangsu province. The socio-economic data of each administrative area are obtained in the statistical yearbooks of Jiangxi province from 1999 to 2009.

2.3. Methods

2.3.1. Index system

As urbanization undertakes a large-scale transition and centralization process of resources, industries and population in a certain area, the notable result is that it will break the traditional agriculture-oriented structure and results in the concentration of population and industry and the expansion of urban land. Urbanization may actualize the rational and intensive utilization of resources, but it may reversely cause a environmental deterioration and ecological degradation as well. It is safe to say that a subsystem of urbanization is set up in a greater eco-environmental system. Objectively, there are all sorts of contradictions and intimidations between urbanization and the eco-environment. On the one hand, the urbanization with a resource shortage background will suffer from the intimidations of resources and environment and the intimidations will destroy the surrounding environment to various extents during its development process. On the other hand, the fragile eco-environment will restrict the development of cities, block the urbanization process and may even cause the

Table 1
Index system of coupling system.

Subsystem	Functional group	Index set	Indicators
Urbanization (32)	Populated urbanization (7)	Total size (2)	Total number of urban population (X1), Total number of non-agricultural population (X2)
		Population structure (3)	Percentage of urban population (X3), Percentage of non-agricultural population (X4), Percentage of non-agricultural industry employed persons (X5), Proportion of tertiary industry employed persons to total employed persons (X6)
		Population growth (2)	Growth rate of urban population (X7), Growth rate of non-agricultural population (X8)
	Economic urbanization (10)	Economic amount (3)	Per capita GDP (X9), Output of Per unit built up areas (X10), Per capita non-agricultural output (X11)
		Economic structure (3)	Proportion of industrial output to industrial & agricultural output (X12), Proportion of heavy industry output to total industry output (X13), Proportion of value-added of tertiary industry to GDP (X14)
		Economic growth (2)	Annual growth rate of per capita GDP (X15), Annual growth rate of value-added of tertiary industry (X16)
		Economic efficiency (2)	Productivity of total industry employed persons (X17), Per capital Value-added of tertiary industry (X18)
	Social urbanization (11)	Living quality (5)	Per capita annual disposable income of urban residents (X19), Per capita total retail sales of consumer goods (X20), Total floor space of urban households (X21), Number of doctors per ten hundred persons (X22), Per capita number of standard vehicles (X23)
		Infrastructure (4)	Transportation network density (X24), Per capita area of roads (X25), Number of phone per hundred persons (X26), Rate of population with access to tap water (X27)
		Science, technology and culture (2)	Number of college enrollment per ten thousand persons (X28), Number of technical personnel per ten thousand persons (X29)
	Spatial urbanization (4)	Urban quantity (1)	Total number of cities (X30)
		Urban scale (2)	Percentage of built-up areas in the total land area (X31)
		Urban density (1)	Urban population density (X32)
Eco-environment (26)	Eco-environmental endowment (11)	Resource and energy endowment (5)	Per capita total amount of water resources (Y1), Per capita land areas (Y2), Per capita area of cultivated land (Y3), Per capita total of energy resources (Y4), Abundant degree of mineral resources (Y5)
		Ecological condition (6)	Per capita total plant products (Y6), Per capita total grain output (Y7), Per capita public green land areas (Y8), proportion of nature reserve areas to total land area (Y9), Coverage rate of green land in built-up areas (Y10), Coverage rate of forests (Y11)
	Eco-environmental press (10)	Per cap pollution discharge (4)	Per capita volume of industrial waste water discharge (Y12), Per capita volume of industrial waste air emission (Y13), Per capita volume of industrial solid waste produced (Y14), Per capita volume of consumption waste water discharge (Y15)
		Ecological degradation (3)	Percentage of water and land loss (Y16), frequency of natural calamities (Y17), Per capita economic loss led by environmental pollution (Y18)
	Eco-environmental management (5)	Environmental disposal (3)	Percentage of industrial waste water meeting discharge standards (Y19), Percentage of industrial waste gas meeting discharge standards (Y20), Ratio of industrial solid wastes utilized (Y21)
		Environmental investment (1)	Proportion of investment of industrial pollution treatment to GNP (Y22)
		Technological ability (4)	Efficient index of energy utility (Y23), volume of industrial waste water discharge per ten thousand Yuan (Y24), volume of industrial waste air emission per ten thousand Yuan (Y25), volume of industrial solid waste produced per ten thousand Yuan (Y26)

ruin of cities after the eco-environmental subsystem has been destroyed. Thus, the coupling relationship between urbanization and eco-environment can be address as a press-state-response (PSR) framework (Liu et al., 2005), and the system that is composed of urbanization subsystem and eco-environment subsystem can be defined as a coupling system, in which to coordinate the coupling relationship is elementary to realize a sustainable urbanization management (Tanguay et al., 2010). Obviously, the coupling degree that indicates the magnitude of interaction between the two subsystems can be calculated. According to the conceptual framework and implication of the coupling system, an aggregated index system can be introduced to evaluate urbanization process and its eco-environmental effects. Given these objectives, the following general selection criterion has been adopted: (1) choose the most cited indicators; (2) cover the components of urbanization sustainability and the pertinent predetermined categories and (3) choose the simplest indicators to facilitate data collection, understanding and dissemination (Table 1).

2.3.2. Integrated SD-based analysis system (ISD)

As a sustainable urbanization management is a multi-component and multidisciplinary process that requires more than a single method for a successful result, an integrated SD-based analysis system (ISD) is developed in this study. The ISD consists of modules of the coupling relationship assessments, systematic analysis of potential eco-environmental changes, and sustainability evaluation. An interpretative structural modeling (ISM) and a grey relative technique (GRT) are used to analyze the systematical structure and assess the coupling relationships. A system dynamics model (SD) and artificial neural network (ANN) are used to simulate the potential environmental changes and compare the sustainability situations, respectively. The procedure can be shown in Fig. 2.

2.3.2.1. ISM and GRT-based assessment on coupling relationships. The selection of critical variables is a fundamental step in the sustainable urbanization management (Allan, 2004). It can be defined as the identification of the most appropriate assessment for future

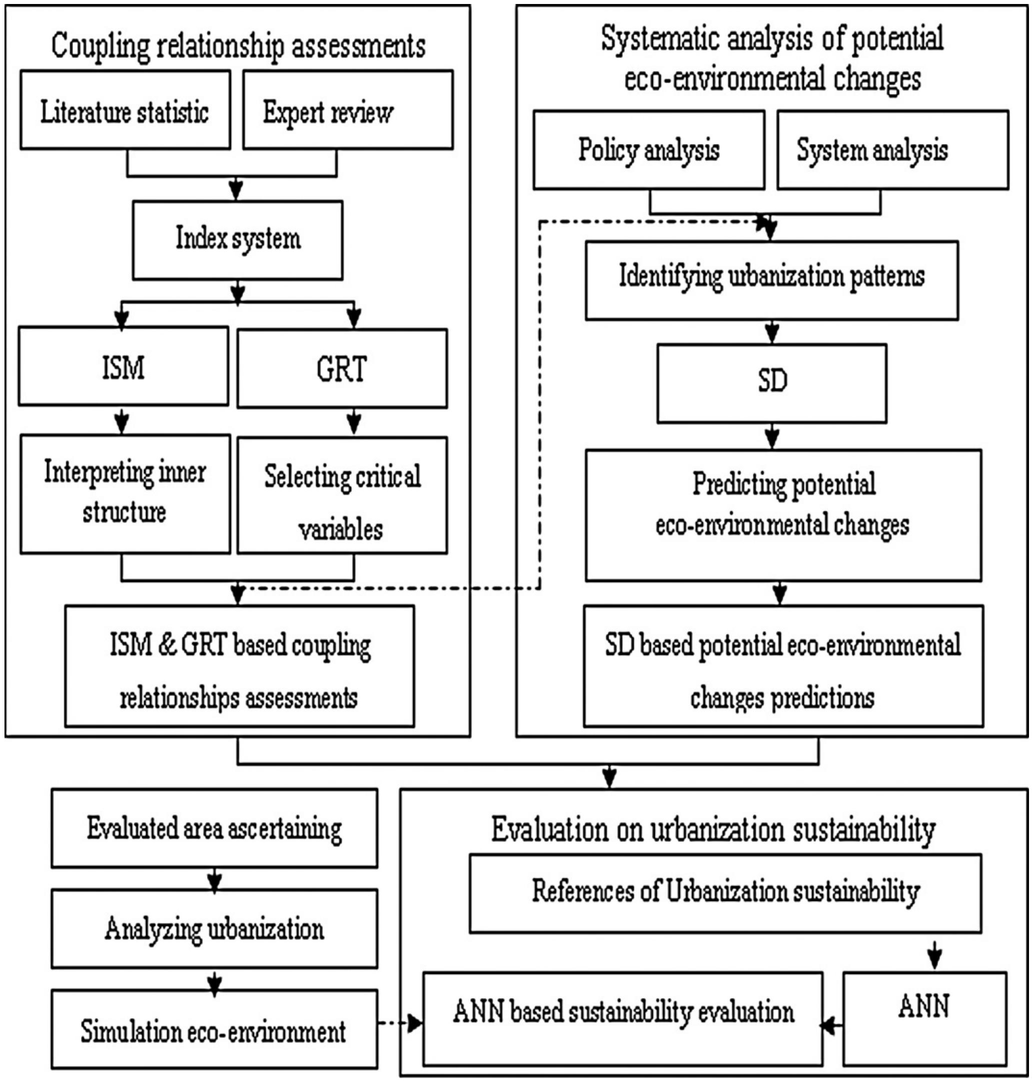

Fig. 2. General framework of the ISD.

harmonious urbanization sustainability management (Wang et al., 2004). The coupling relationship assessments have been developed from qualitative calculation and expert knowledge under a variety of situations. In addition, because the suitability of any assessment not only depends on the demands on the specific region, but also relates to the coupling situation of the evaluated system, the assessments of the coupling relationship can be obtained by structural analysis and systematical decomposition. Obviously, the coupling relationship assessments become a multi-criteria decision-making problem. To reveal the coupling relationships, an interpretative structural modeling (ISM) is principally used to analyze the systematical structure. With the attainable matrixes calculated, the 58 primary indicators have been selected by ISM model from Table 1, where the coupling system can be divided into four hierarchies and eight subsystems.

To further discover the coupling magnitudes for the two subsystems of urbanization and the eco-environment, the coupling degrees were applied. According to the grey relational coefficients of urbanization and eco-environment, the coupling degrees can be calculated and can be expressed as follows:

$$C(t) = \frac{1}{n \times m}\sum_{i=1}^{n}\sum_{j=1}^{m} r_{ij}(t) \tag{1}$$

where n and m are the numbers of the indices of urbanization and the eco-environment respectively and r_{ij} is the grey relational coefficient. To calculate the grey relational degree r_{ij}, the first step must calculate the grey relational coefficient between main-array and sub-array. The grey relational coefficient is defined as (Xu, 2002):

$$r_{ij}(k) = \frac{\min_j \min_k \left|x_i(k) - x_j(k)\right| + \xi \max_j \max_k \left|x_i(k) - x_j(k)\right|}{\left|x_i(k) - x_j(k)\right| + \xi \max_j \max_k \left|x_i(k) - x_j(k)\right|} \tag{2}$$

where $r_{ij}(k)$ is the grey relational coefficient of the main-array and sub-array at time k; $x_i(k)$ is the main-array; $x_j(k)$ is the sub-array and ξ the differentiation coefficient, which is used to increase the most prominent differences between two arrays. Generally, the value is assumed to be 0.5. The second step is to calculate the grey relational degree between the main-array and sub-array. It is defined as:

$$r_{ij} = \frac{1}{n}\sum_{k=1}^{n} r(x_i(k), x_j(k)) \tag{3}$$

where r_{ij} is the grey relational degree of sub-array j and main-array i; n is the length of the arrays. The third step is to set up the matrix of the grey relative degrees.

$$\Gamma = (r_{ij}) = \begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{vmatrix} \tag{4}$$

In the grey relational matrix Γ, it can be seen that the i sub-array prior to the j sub-array according to the main-array, if the j row meets the following condition:

$$r_{li} \succ r_{lj}, \quad l = 1, 2, \cdots, n;\ i \neq j \tag{5}$$

In the matrix Γ, if Ω is taken as the level set, when r_{ij} meets the following condition, the critical variables can be selected by the condition function.

$$\Omega = \left\{ r_{ij} \geq \sigma | \quad l = 1, 2, \cdots, n;\ i = 1, 2, \cdots n \right\} \tag{6}$$

where σ is constant and generally ranges from 0.5 to 1.0.

2.3.2.2. SD-based prediction on potential eco-environmental changes. A sustainable urbanization management must consider a wide variety of factors, such as population increases, economic development, social improvement and demand for natural resources, as well as environmental changes and ecological endowments. All of these factors are dynamic, and thus sustainable urbanization management models must not only consider these factors simultaneously, but forecast any potential changes in these factors.

The coupling system in Jiangsu province can be divided into four logical subsystems in this study: population, economy, eco-environment and urbanization subsystem. The relationships among these subsystems are a complexity. The increasing population and urbanization will undoubtedly result in more demand for urban areas and urban residential areas. The expansion of industry and the adjustment of economic structure will also lead to increases in demand for industrial and commercial output, civil engineering, financial services and sports. Arable land will reduced due to urban sprawl. All of these changes will potentially lead to more pollutants discharged. The demand for environmental conservation and terrestrial ecosystems is a dominant reason so that green land and forest areas should be increased (Liu et al., 2005).

2.3.2.3. ANN-based evaluation on sustainability. As the above PSR implied, the coupling relationship between urbanization and eco-environment represents complex, non-linear behaviors so that the sustainable urbanization management can confront many uncertainty and has to undertake more complex intrigues. To much synthetically and directly evaluate the sustainability, an artificial neural network (ANN) is introduced because it offer more advantages over conventional modeling techniques, which include the ability to handle large amounts of noisy data from dynamic and nonlinear systems, especially where the underlying physical relationships are not fully understood (Kingston, 2006). Here, a specific approach used in ANN is the BP network, which has shown significant results in modeling nonlinear functions (Tang et al., 2005). The BP network can be formulated as follows:

$$\begin{cases} a_{1i} = f_1\left(\displaystyle\sum_{j=1}^{r} w_{1ij}p_j + b_{1i}\right) \ (i = 1, 2, \cdots, s_1) \\ a_{2k} = f_2\left(\displaystyle\sum_{i=1}^{s_1} w_{2ki}a_{1i} + b_{2k}\right) \ (k = 1, 2, \cdots, s_2) \\ f_1 = \dfrac{1}{1 + e^{-p}},\ f_2 = wa_1 + b_2 \\ E(W, B) = \dfrac{1}{2}\displaystyle\sum_{K=1}^{S_2}(t_k - a_{2k})^2 \\ f(X^{(k+1)}) = \min f(X^{(k)} + \eta^{(k)}S(X^{(k)})) \\ X^{(k+1)} = X^{(k)} + \eta^{(k)}S(X^{(k)}) \end{cases} \tag{7}$$

where p_j, a_{1j} are input values of input layer and hidden layer respectively; w_{1ij}, w_{2ki} are weights used to compute the hidden and output layers; b_{1i}, b_{2k} are threshold values of input layer and hidden layer; t_k, a_{2k} are output value and predictive value; $E(W, B)$ is the vector of predictive errors; k is the training epoch; $\eta^{(k)}$ denotes the learning rate.

3. Results

3.1. Coupling relationship assessments

3.1.1. Variables selection

To identify available variables are very important for further urbanization sustainability evaluation. After literature reviews and discussions with researchers and local experts in 2009, the critical indicators for urbanization suitability assessment in Jiangsu province were selected from Table 1 that included natural and ecological endowments, socio-economic conditions and urbanization factors. The GRT was used to calculate the grey relational coefficients of the main-array and sub-array in 2009. According to $\Omega = \left\{ r_{ij} \geq 0.65 | l = 1, 2, \cdots, 29;\ i = 1, 2, \cdots 29 \right\}$, the 16 critical variables are selected as following: proportion of industrial output to industry and agriculture output (X12, 0.741), percentage of non-agricultural industry employed persons (X5, 0.6985), proportion of value-added of tertiary industry to GDP (X14, 0.6960), total floor space of urban households (X21, 0.6861), number of doctors per ten hundred persons (X22, 0.6811), percentage of built-up areas in the total land area (X31, 0.6614), per capita GDP (X9, 0.661), percentage of urban population (X3, 0.6515), percentage of industrial waste water meeting discharge standards (Y19, 0.7520), coverage rate of green land in built-up areas (Y10, 0.7340), per capita volume of industrial waste air emission (Y13, 0.7171), Ratio of industrial solid wastes utilized (Y21, 0.7163), volume of industrial waste water discharge per ten thousand Yuan (Y24, 0.6991), coverage rate of forests (Y11, 0.6924), per capita public green land areas (Y8, 0.6888), volume of industrial waste air emission per ten thousand Yuan (Y25, 0.6605), which not only relate to the four aspects of urbanization, such as population, economy, society and space, but also can reflect the eco-environmental changes such as pollution discharge, forest, green land and so on.

3.1.2. Coupling degrees variation

According to the model of coupling degrees, the coupling degrees in Jiangsu during 1990–2009 are calculated (Fig. 3). As illustrated in Fig. 3, the coupled degrees range form 0.64 to 0.74, and

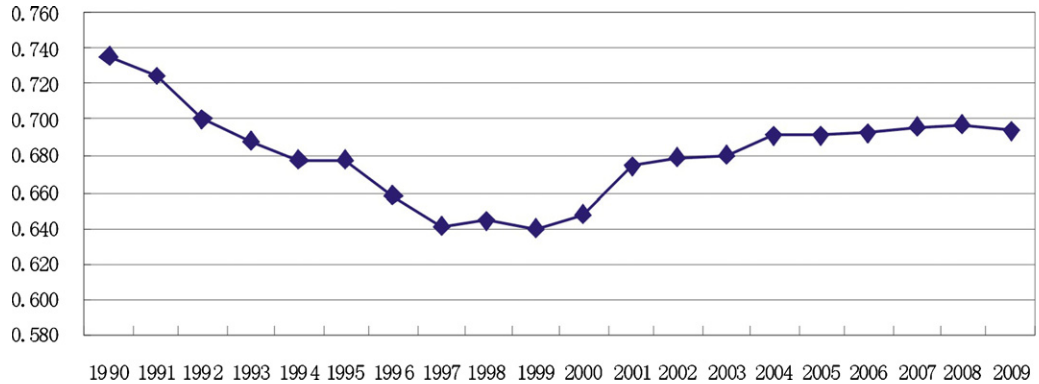

Fig. 3. Variation of the coupling degrees.

the coupling curve exhibits a U-shaped, indicating that a sustainable urbanization process during 1990–1999 and an unsustainable urbanization process after 2000. Since 1990s, attributing to an opportunity on "the Yangtze River Delta Development", the sate government of Jiangsu province rethought the special urbanization pattern when the resident worked in cities without leaving their settlements, and reestablished a regional integration strategy, when a healthy and ecological city became a primary developing goal for urbanization. Meanwhile, because of a gradually improved environmental awareness and some key projects invested into Jiangsu province in "The Eighth and Ninth Five Year Planning of China", with more and more environmental protection infrastructures supplied, some eco-environment indicators such as per capita public green land areas, coverage rate of green land in built-up areas, coverage rate of forests gradually increased, therefore the coupling degrees significantly declined. On the other hand, the second phase was from 2000 to 2009, when the coupling degrees increased. "The City and Town Planning of Jiangsu province (2001–2020)" was authorized by the China central government in 2000, and to develop the three metropolitan areas of Nanjing, Su-Xi-Chang and Xuzhou in Jiangsu province was a new urbanization strategy over the next several years. The bottleneck of resources and energy emerged by rapid urban sprawl, where the urban population dramatically increased and the pollutants discharged from the production and living were the menaces on the urbanization sustainability. As a result, the eco-environmental pressure induced by per cap pollution discharge and ecological degradation became more serious.

3.2. Scenarios for potential eco-environmental changes

3.2.1. Parameters calculation and verification analysis

3.2.1.1. Systemic parameters calculation. To use the integrated systematical models, some parameters have to be calculated in advance. Based on the previous studies mentioned (Fang and Yu, 1999; Tang et al., 2000), the relative importance methods are applied to calculate the parameters. (1) The parameters were calculate by arithmetic average method with the historical statistical data, including average birth rate (0.00908), average death rate (0.00679), coverage rate of green land in built-up areas (0.375), coefficient of environmental investment (0.1), coefficient of primary industrial investment (0.032), coefficient of secondary industrial investment (0.479), coefficient of tertiary industrial investment (0.489). (2) The coefficients of some policy factors were estimated by trend extrapolation, such as population planning index (0.85), growth coefficient of value-added of primary industry (0.03266), growth coefficient of value-added of secondary industry (0.14786), growth coefficient of value-added of tertiary industry (0.13108), growth coefficient of percentage of urban population (0.04087), growth coefficient of built-up areas (0.15233), growth coefficient of floor space of urban households (0.06085), growth coefficient of scientific and technological level (0.023), growth coefficient of educational level (0.37406), growth coefficient of medical & healthy level (0.01) and so on. (3) The coefficients of some key factors are define by the table functions, such as pollution discharges index, food provision index, congestion index, scientific-technological development index, medical and healthy development index, educational development index. (4) The proportions of the structural factors are estimated by regression analysis, including percentage of non-agricultural industry employed persons, proportion of secondary industry employed persons to total employed persons, proportion of culture, scientific-technology, education and health expenditure to government expenditure, coefficient of social production investment.

3.2.1.2. Verification analysis. The developed ISD model is verified using the data of 2001–2009. The 16 critical variables are examined and the result shows the relative errors range from −4.5% to 9.2%, indicating the SD model is reliable and can be simulated.

3.2.2. Scenarios simulation

A SD model is constructed for the study area, containing 312 parameters and formulations. The scenarios that were used to test the model are based on a benchmark (natural urbanization) and four aspects of urbanization from Table 1, which are population growth oriented mode (populated urbanization), economic growth oriented mode (economic urbanization), social development oriented mode (social urbanization) and spatial expansion oriented mode (spatial urbanization). Five scenarios were predicted for the period 2010–2015 based on the system dynamics model described above. Scenario I predicts eco-environmental effects changes under the present developmental mode, while scenario II–V considers impacts of local policies on urbanization, and modification of economic structure and technological coefficients. A comparative assessment of the five scenarios was conducted based on the criteria of per capita GDP, percentage of urban population, percentage of built-up areas in the total land area, total floor space of urban households, coverage rate of green land in built-up areas, coverage rate of forests, per capita public green land areas and per capita volume of industrial waste air emission selected from the above16 critical variables, and the results are shown in Table 2.

3.2.2.1. Natural urbanization (I). Under scenario I, GDP, urban population, built-up areas increases respectively at its annual average rate of 12.1%, 6.19% and 7.5% during 1999–2009, and proportion of culture, scientific-technology, education and health expenditure to government expenditure will be kept at 0.02. The expansion of the urban area in scenario I will result in a rapid increase in eco-

Table 2
Results of scenarios simulated.

Variables	2009	2010					2015				
		I	II	III	IV	V	I	II	III	IV	V
X3 (%)	54.30	54.39	54.98	56.23	54.60	54.23	58.70	59.03	60.14	58.83	58.63
X5 (%)	63.70	54.17	58.36	64.42	57.73	64.17	66.20	64.12	67.12	64.11	66.23
X9 (Yuan)	11152	11192	13802	11875	11192	10429	16323	20734	17457	16307	15136
X12 (%)	94.35	94.68	95.12	94.76	94.48	94.52	95.84	96.47	95.89	95.83	95.82
X14 (%)	42.42	42.75	42.67	42.65	42.45	42.76	44.87	45.23	45.12	44.78	44.89
X21 (m^2)	32.41	32.71	32.48	32.13	32.66	32.73	39.03	39.03	38.78	39.10	38.89
X22 (Person)	17.81	17.90	17.64	17.92	17.59	18.23	18.29	18.32	18.21	18.89	18.54
X31 (%)	3.45	3.99	4.09	3.81	4.31	3.94	4.57	4.68	4.25	4.94	4.50
Y8 (m^2)	12.85	13.35	13.45	13.29	14.49	13.35	15.37	15.21	15.28	16.21	15.40
Y10 (%)	45.60	45.61	45.73	45.35	46.01	45.54	46.28	46.39	45.93	46.64	46.22
Y11 (%)	10.12	10.17	10.18	10.17	17.17	10.17	10.43	10.42	10.40	10.39	10.45
Y13 (m^3)	3.21	3.47	3.54	3.49	3.48	3.46	4.75	4.82	4.79	4.81	4.65
Y19 (%)	98.75	98.80	98.79	98.92	98.65	98.80	98.91	98.82	98.87	98.76	99.20
Y21 (%)	99.20	99.20	99.10	99.17	99.14	99.20	99.24	99.22	99.31	99.25	99.30
Y24 (t)	12.34	12.09	13.24	12.89	12.12	12.09	10.90	10.98	10.96	10.92	10.89
Y25 (m^3)	0.93	0.92	0.89	0.93	0.93	0.92	0.87	0.84	0.86	0.87	0.87

nomic amount, urban population and built-up areas. By 2015, per capita GDP will reach RMB 16323 Yuan (1990 fixed price), which meet the low economic development target of Jiangsu long-term planning, but does not meet the high economic development target set by Jiangsu province government of China (Zhang et al., 1997). The percentage of urban population will respectively reach 54.39% and 58.70% in 2010 and 2015, meeting the urbanizing target of Jiangsu long-term planning ahead, which leads to the percentage of built-up areas in the total land area will be 4.57% by 2015. Meanwhile, the rapid urbanization can induce a rapid growth in pollutant discharges and an ecological degradation. By 2015, the per capita volume of industrial waste air emission will reach 4.75 m^3, and the coverage rate of forests and per capita public green land areas will be only 10.43% and 15.37 m^2, which does not meet the ecological target of Jiangsu long-term planning.

3.2.2.2. Economic urbanization (II). Given a more rapid economic growth, an economic growth oriented mode (economic urbanization) can be simulated. In contrast, the coefficient of social production investment and coefficient of secondary industrial investment are increased by 0.4 and 0.6 under scenario II, respectively. Thus, manufacture, trade and commerce will become the main economically important industries. Usually, the situation of industrial development determines the level of economic development and employment in an area, which in turn drives the process of urbanization. As a result, economic urbanization will lead to the most rapid increase in economic amount, and by 2015 the per capita GDP will reach RMB 20734 Yuan. In addition, rapid economic growth of urbanization process will also result in a fairly rapid increases in urban population, built-up areas and floor space of urban households, in which percentage of urban population, percentage of built-up areas in the total land area and total floor space of urban households can reach 59.03%, 4.68% and 39.03m^2, but the environmental and ecological deterioration will be the most serious because of a mount of pollutant discharges. By 2015 the per capita volume of industrial waste air emission will reach 4.82 m^3, and the coverage rate of forests and per capita public green land areas will be only 10.42% and 15.21 m^2. The rapid economic urbanization will lead to the worst environmental and ecological sustainability.

3.2.2.3. Populated urbanization (III). In comparison, given the average growth rate of urban population increased by 1.7‰ under scenario III, a populated urbanization can be simulated. In view of the rapid structural shift in employment activities and the increase in migration of rural people, a rapid increase in both economic amount and urban population can be induced, in which per capita GDP and percentage of urban population will be RMB 17457 Yuan and 60.14% by 2015 and both are higher than those in scenario I. Obviously, the growth rate of urban population will be the most rapid, which can in advance meet the urbanizing target of Jiangsu long-term planning than that in other patterns. However, on the one hand, because populated urbanization lead to land-use efficiency improved, urban expansion are different from those in scenario I, which percentage of built-up areas in the total land area will be only 4.25%, but the total floor space of urban households only reach 18.21 m^2; on the other hand, populated urbanization will induce fairly environmental and ecological restriction, and by 2015 the simulated per capita volume of industrial waste air emission will reach 4.79 m^3 and the coverage rate of forests and per capita public green land areas will be only 10.40% and 15.28 m^2.

3.2.2.4. Spatial urbanization (IV). The spatial urbanization is a scenario that attempts to accelerate urbanization process by expanding urban areas. Given the average growth rate of built-up areas being 7% under scenario IV, a spatial urbanization can be simulated. As a result, the most rapid expansion of the urban area will result in a slower growth in economic amount in which per capita GDP will be only RMB 16307Yuan by 2015, but lead to a more rapid increase in built-up areas, floor space of urban households and green land areas, and by 2015 the percentage of built-up areas in the total land area, total floor space of urban households and per capita public green land areas will reach 4.94%, 39.10 m^2 and 16.21 m^2, respectively. However, the rapid spatial urbanization will lead a rigid environmental deterioration pollution and ecological degradation, which is similar to that in scenario I. By 2015, the per capita volume of industrial waste air emission will reach 4.81 m^3, and the coverage rate of forests will be only 10.39%.

3.2.2.5. Social urbanization (V). Given a more rapid socialization process, such as urban culture, science and technology, medical treatment and health, etc., a social development oriented mode (social urbanization) can be simulated. In contrast, the proportion of culture, scientific-technology, education and health expenditure to government expenditure and the coefficient of tertiary industrial investment are increased by 0.05 and 0.5 under scenario V, respectively. Because the industrialization stage has not completely gone through in Jiangsu of China, the more investment on the social activities will imply the less stimulation on the industrialization. The simulated results show that social urbanization will result in the slowest increases in economic amount, urban population and built-up areas, and by 2015 per capita GDP, percentage of urban population and percentage of built-up areas in the total land

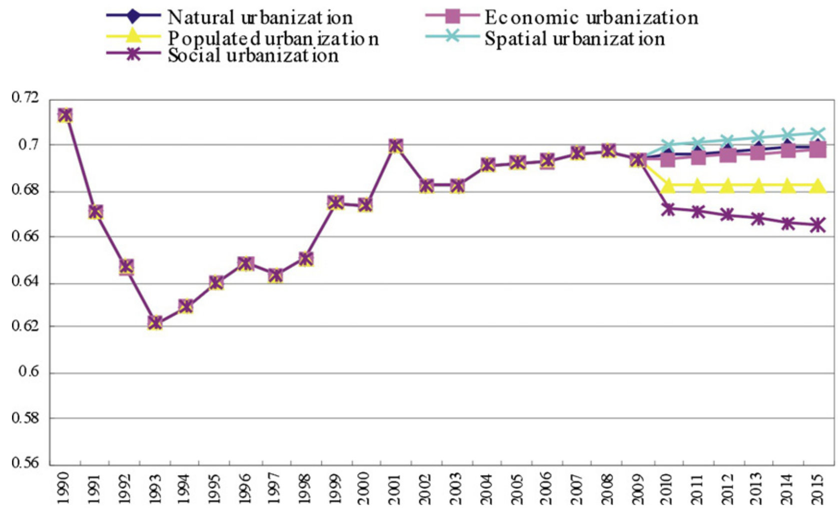

Fig. 4. Result compared by five urbanization sustainability.

area will only reach RMB 15136 Yuan, 58.63% and 4.50%, in which per capita GDP and percentage of urban population do not meet the economic and urbanizing target of Jiangsu long-term planning. However, the rapid social urbanization will lead a least environmental impact and ecological degradation, and by 2015 the per capita volume of industrial waste air emission will only be 4.65 m^3, while the per capita public green land areas and coverage rate of forests will be over 15.40% and 10.44%.

3.3. Sustainability evaluation

3.3.1. Network training and testing

The BP network cannot directly be applied for the original data set; otherwise, the errors will not meet the simulated requirements. Thus, the values of the 16 variables selected have to be normalized to a range of 0–1 before they are applied. The samples from 1990 to 2000 are employed to train BP network, and the samples during 2001–2009 are tested. The BP network only includes three neurons in the hidden layer, so less than six-step training on the errors. From the trained results, the average relative error between and actual values and simulated values is only 0.94%, sufficiently meeting accuracy evaluation demand.

3.3.2. Sustainability comparison

To take the simulated data by SD as a baseline, the urbanization sustainability are simply forecast and compared by BP network, and numerical simulated results are depicted in Fig. 4. As is shown in Fig. 4, it can be clearly demonstrated the five urbanization patterns at the same time period will result in different eco-environmental effects. (1) Under natural urbanization, economic urbanization and spatial urbanization, the coupling degrees will gradually increase, indicating the urbanization sustainability in Jiangsu province will become very worse. In particular, the eco-environmental effects induced by spatial urbanization are the worst because the average value of coupling degrees is the largest one, and its increases are also the most rapid one. (2) Under the social urbanization, the average value of coupling degrees will be the lowest one, and its increases are the slowest one, indicating to implement the policy by advancing urban socialization progress can effectively alleviate the negative eco-environmental effects, and help promote urbanization sustainability. (3) The coupling degrees will slightly change under populated urbanization, and the average value will be at around 0.68. Obviously, the populated urbanization not only can maintain the present coupling condition in Jiangsu province, but also will promote the rapid urbanization process. Therefore, under certain conditions, it should be a worthy strategy to be recommended.

4. Discussions and conclusions

4.1. Discussions

In most previous studies, only urban ecology assessment or urban environment evaluation were tackled in the sustainable urbanization management process, which cannot reflect the long-term eco-environmental changes in different driving oriented urbanization patterns or the integrative eco-environmental effects induced by urbanization on a regional environment management. The developed ISD model addresses this problem by integrating the coupling relationship assessments, forecasting of potential eco-environmental changes, and sustainability evaluation into a general framework. Integrated, systematic complex, and dynamic characteristics are involved in the proposed ISD model. In addition, previous studies of sustainable urbanization management focused mainly on metropolitan areas or ecological fragile areas such as watersheds and semi-arid region, and there are no such studies on developed areas at a mesoscale. The dual goals of urbanization and eco-ecological conservation need to be satisfied in the urbanization sustainability management process, especially for the cities experiencing rapid urbanization in Jiangsu province, China.

The selection of index system is essential for the coupling relationship assessments. Compared with the criteria used for urban sustainability management, including urban climate, hydrology, producers of carbon dioxide, biodiversity, etc., those of developed areas at a mesoscale are clearly different. The 16 critical variables in this study are associated with the special goals of urbanization sustainability management for socio-economic and eco-environmental requirements. Meanwhile, the systematic and complex characteristics of the coupling systems make system analysis be an essential tool for supporting the sustainable urbanization management. In the integrated model, the joint application of ISM and GRT is an available approach for studying the coupling relationship assessments, and this approach is successfully applied in the study. The SD is a basic tool to successfully forecast the potential eco-environmental changes and ANN is a useful tool for integrating information, and evaluating urbanization sustainability. However, the evaluation of the results from this model is constrained by the nature of the problem being investigated. This is because the model is assigned a spatial decision and a spatial allocation that cannot yet be implemented, although the integrated model has been used for a number of simulations. Obviously, the forecasting of eco-environmental changes and its spatial allocation based on GIS to integrate information and to assist in decision-making, is more useful for urbanization sustainability management in the future.

4.2. Conclusions

The harmonious management of urbanization and eco-environment in Jiangsu province is a dynamic, rather than a static process. The coupling relationship is affected by many factors, such as population, economic structure, policy, ecological conservation goals and environmental conditions. Therefore, systemic analysis and dynamic modeling of the coupling system are essential for the future urbanization sustainability. Four subsystems are considered in this study, and potential eco-environmental changes are modeled by SD from 2010 to 2015. According to the results, under the natural urbanization, per capita GDP and percentage of urban population will individually reach RMB 16323 Yuan (1990 fixed price) and 58.70% by 2015, and the percentages of built-up areas in the total land will be 4.57%. Local eco-environmental conditions can be worse because of the increases in pollutant discharges and built-up areas. Obviously, the simulated eco-environmental changes under the other urbanization patterns can be compared. To identify sustainable urbanization patterns, a BP network is also designed to compare the suitability. The forecast results show that the advantages and disadvantages are significant for the five urbanization patterns. Firstly, economic growth will be the most rapid but the eco-environmental pollution pressure will be the worst under economic urbanization; Secondly, although populated urbanization can meet the urbanizing target of Jiangsu long-term planning as soon as possible and effectively promote economic growth, the eco-environmental pollution pressure will be more heavy and urban infrastructure will not well develop; Thirdly, spatial urbanization can availably meet the goal of urban sprawl and urban infrastructure improvement, but the pattern will excessively occupy the available lands so as to lead to rapid environmental deterioration and ecological degradation; Finally, social urbanization can not only rapidly promote urban socialization process, but also effectively protects eco-environment condition, but the economic growth may be rarely slowest.

On one hand, it has generally been agreed that a combination of a pull factor of cities and a push factor of villages promotes the process of industrialization and urbanization, which in turn drives the development of rural areas (Long et al., 2009). The urbanization process of Jiangsu province in China had often been perceived as a “unique case” because of its peculiar pattern of rapid industrialization without a parallel growth of the urban population (Shen and Ma, 2005). The experiences of Jiangsu’s urbanization indicate that industrialization is a necessary precondition to urbanization, which in turn leads to the rapid economic urbanization. Meanwhile, a significant economic growth and population aggregations in the population urbanization pattern can be induced because of the rapid structural shift in employment activities and the increase in migration of rural people. However, the social urbanization will slow down the population urbanization process, resulting from the less investment on the potential industrialization. On the other hand, as urbanization undertakes a large-scale transition and centralization process of resources, industries and population in a certain area, the notable result is that it will break the traditional agriculture-oriented structure and results in the concentration of population and industry and the expansion of urban land. Urbanization may actualize the rational and intensive utilization of resources, but it may reversely cause an environmental deterioration and ecological degradation as well. The compared results for will be useful for policy decision making on Jiangxi’s urbanization strategy and eco-environmental conservation.

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References

Alberti, M., 2005. The effects of urban patterns on ecosystem function. International Regional Science Review 28 (2), 168–192.
Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35 (2), 257–284.
Bjorklund, J., Limburg, K.E., Rydberg, T., 1999. Impact of production intensity on the ability of the agricultural landscape to generate ecosystem services: an example from Sweden. Ecological Economics 29 (2), 269–291.
Booth, D.B., Karr, J.R., Schauman, S., Konrad, C.P., Morley, S.A., Larson, M.G., et al., 2004. Reviving urban streams: land use, hydrology, biology, and human behavior. Journal of American Water Resources Association 40 (5), 1351–1364.
Fang, C.L., Yu, D.L., 1999. Study on optimal-control experiment of the resources development and corresponding development between economy and eco-environment in the Qiadam basin. Acta Ecologica Sinica 19 (6), 767–774 (in Chinese).
Fischer, G., Sun, L.X., 2001. Model based analysis of future land-use development in China. Agricultural Ecosystem and Environment 85 (1–3), 163–176.
Gilbert, O.L., 1989. The ecology of urban habitats. Chapman and Hall, New York.
Grimm, N.B., Grove, J.M., Pickett, S.T.A., Redman, C.L., 2000. Integrated approaches to long-term studies of urban ecological systems. BioScience 50 (7), 571–584.
Imhoff, M.L., Bounoua, L., DeFries, R., Lawrence, W.T., Stutzer, D., Tucker, C.J., et al., 2004. The consequences of urban land transformation on net primary productivity in the United States. Remote Sensing of Environment 89 (4), 434–443.
Jaeger, J.A.G., Bertiller, R., Schwick, C., Kienast, F., 2010. Suitability criteria for measures of urban sprawl. Ecological Indicators 10 (2), 397–406.
Kalnay, E., Cai, M., 2003. Impact of urbanization and land-use change on climate. Nature 423 (6939), 528–531.
Karl, T.R., Trenberth, K.E., 2003. Modern global climate change. Science 302 (5651), 1719–1723.
Kingston, G.B., 2006. Bayesian artificial neural networks in water resources engineering. Thesis Ph.D. The University of Adelaide.
Liu, Y.B., Li, R.D., Li, C.H., 2005. Scenarios simulation of coupling system between urbanization and eco-environment in Jiangsu province based on system dynamics model. Chinese Geographical Science 15 (3), 219–226 [in Chinese].
Liu, Y., Lv, X.J., Qin, X.S., Guo, H.C., Yua, Y.J., Wanga, J.F., et al., 2007. An integrated GIS-based analysis system for land-use management of lake areas in urban fringe. Landscape and Urban Planning 82 (4), 233–246.
Li, S.T., Kuo, S.C., 2008. Knowledge discovery in financial investment for forecasting and trading strategy through wavelet-based SOM networks. Expert Systems with Applications 34, 935–951.
Long, H.L., Zou, J., Liu, Y.S., 2009. Differentiation of rural development driven by industrialization and urbanization in eastern coastal China. Habitat International 33 (4), 454–462.
McDonnell, M.J., Pickett, S.T.A., 1990. Ecosystem structure and function along urban rural gradients—an unexploited opportunity for ecology. Ecology 71 (4), 1232–1237.
Miltner, R., White, D., Yoder, C.O., 2004. The biotic integrity of streams in urban and suburbanizing landscapes. Landscape and Urban Planning 69 (1), 87–100.
Odum, H.T., Elisabeth, C., 2000. Modeling for All Scales: An Introduction to System. Simulation. Academic Press, San Diego.
Pijanowski, B.C., Brown, D.G., Shellito, B.A., Manik, G.A., 2002. Using neural networks and GIS to forecast land use changes: a land transformation model. Computer, Environment and Urban System 26 (6), 553–575.
Posa, M.R.C., Sodhi, N.S., 2006. Effects of anthropogenic land use on forest birds and butterflies in Subic Bay, Philippines. Biological Conservation 129, 256–270.
Rees, W.E., 1997. Urban ecosystems: the human dimension. Urban Ecosystem 1 (1), 63–75.
Sadler, J.P., Small, E.C., Fiszpan, H., Telfer, M.G., Niemela, J., 2006. Investigating environmental variation and landscape characteristics of an urban–rural gra-

dient using woodland carabid assemblages. Journal of Biogeography 33 (1), 1126–1138.

Scipioni, A., Mazzi, A., Mason, M., Manzardo, A., 2009. The Dashboard of sustainability to measure the local urban sustainable development: the case study of Padua Municipality. Ecological Indicators 9 (2), 364–380.

Shen, X.P., Ma, L.J.C., 2005. Privatization of rural industry and de facto urbanization from below in southern Jiangsu, China. Geoforum 36 (6), 761–777.

Squires, G.D., 2002. Urban sprawl and the uneven development of metropolitan America. In: Gregory, D. (Ed.), Urban Sprawl: Causes, Consequences and Policy Responses. Urban Institute Press, Washington, DC, pp. 1–22.

Svoray, T., Bar, P., Bannet, T., 2005. Urban land-use allocation in a Mediterranean ecotone: habitat heterogeneity model incorporated in a GIS using a multi-criteria mechanism. Landscape and Urban Planning 72 (4), 337–351.

Tang, Z., Engel, B.A., Pijanowski, B.C., Lim, K.J., 2005. Forecasting land use change and its environmental impact at a watershed scale. Journal of Environmental Management 76 (1), 35–45.

Tang, W.J., Gao, L., Wu, G., Li, X.Y., 2000. Simulation and adjustment of system dynamics on sustainable development in the mining area. Acta Ecologica Sinica 20 (1), 20–27 (in Chinese).

Tanguay, G.A., Rajaonson, J., Lefebvre, J.F., Lanoie, P., 2010. Measuring the sustainability of cities: an analysis of the use of local indicators. Ecological Indicators 10 (2), 407–418.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth's ecosystems. Science 277 (5235), 494–499.

Walton, B.M., Salling, M., Wyles, J., Wolin, J., 2007. Biological integrity in urban streams: toward resolving multiple dimensions of urbanization. Landscape and Urban Planning 79 (1), 110–123.

Wang, X.H., Yu, S., Huang, G.H., 2004. Land allocation based on integrated GIS-optimization modeling at a watershed level. Landscape and Urban Planning 66 (2), 61–74.

Weber, C., Puissant, A., 2003. Urbanization pressure and modeling of urban growth: example of the Tunis Metropolitan Area. Remote Sensing of Environment 86 (3), 341–352.

Xian, G., Crane, M., Su, J., 2007. An analysis of urban development and its environmental impact on the Tampa Bay watershed. Journal of Environmental Management 85 (4), 965–976.

Xu, J.H., 2002. Mathematics in Modem Geography. Higher Education Press, Beijing (in Chinese).

Yu, X.J., Ng, C.N., 2007. Spatial and temporal dynamics of urban sprawl along two urban–rural transects: a case study of Guangzhou, China. Landscape and Urban Planning 79 (1), 96–109.

Zhang, F., Yuan, F., Chen, J.Q., 1997. Development Strategies of Jiangsu during 1996–2020. Jiangsu People Press, Nanjing (in Chinese).