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ORIGINAL PAPER

Assessing land ecological security in Shanghai (China) based on catastrophe theory

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Abstract Given the important role of land ecosystem in social-economic progress at regional, national, and international scale and concurrent degradation of land ecosystems under rapid urbanization, a systematic diagnosis of land ecological security (eco-security) for sustainable development is needed. A catastrophe model for land ecological security assessment was developed in order to overcome the disadvantages in subjectivity and complexity of the currently used assessment methods. The catastrophe assessment index system was divided into hierarchical subsystems under the pressure-state-response framework. The catastrophe model integrated multiple assessment indices of land eco-security according to the inherent contradictions and relative importance of indices without calculating weights. Specifically, membership degree of higher level index was calculated based on the membership degrees of lower level indices that were subjective to suitable model, such as cusp, fold, swallowtail and butterfly model. This model was applied to evaluate the state of land eco-security in Shanghai. Mann–Kendall's test was utilized to characterize its temporal trend between 1999 and 2008. Significant downward trend was identified for land eco-security, in terms of pressure sub-index, state sub-index, response sub-index and synthetic index. All these implied that land ecosystem conditions were not optimistic for Shanghai and such situation should draw the attention of policy makers. The calculation procedure presented in this paper does not require a high level of technical expertise to determine the membership degree, making it simple and operational. Being applicable to similar land ecosystems, the catastrophe model is thus believed to provide an alternative approach to land eco-security assessment.

Keywords Land ecological security · Catastrophe theory · Multi-attribute assessment · Temporal analysis · Mutation analysis · Pressure-state-response

1 Introduction

Land, the main resource governing world ecosystem productivity and primary source of the energy and mass that compose our food and fiber, serves as the most important interaction between humans and other biological communities (Darwin et al. 1996). The service values and functions of land ecosystem play a driving role in social advancement and economic progress at regional, national and even international scale. Meanwhile, recent changes in both climate and social factors related to agriculture intensification, population growth, urban sprawl, and industrial concentration have transformed traditional land ecosystem life cycle, which further impeded human sustainable development, cannot be ignored. There is enough evidence now that land ecosystems of many regions have become highly stressed and dysfunctional due to the continuous, excessive exploitation and utilization of land resources (Wessels et al. 2004; García et al. 2008; Su et al. 2010a; Salvati and Bajocco 2011). In this regard, there is considerable need for methods and indicators to diagnose the state of land ecosystem for prompting ecological restoration, management and regulation, among which the land ecological security (eco-security) assessment based on an analogy with the threat to survival is a necessary procedure.

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“Security”, a concept that is old in abstract terms, but whose application to real world problems is recent, in particular with regard to ecological topic, is the key focus of many politicians and scientists (Westing 1989; Mische 1998; Schreurs and Pirages 1998; Mark 2006; Honson and Marvin 2009). Eco-security is a major paradigm for promoting the sustainability and, when applied to land ecosystem, is also a foundational concept for developing new ways of assessing and managing land resources. Land ecological assessment is a process of decision making that takes into account the full suite of socio-economic, institutional, and ecological processes that mitigate and prevent the degradation and destruction of regional land ecosystems and is based on the data available to know how long the ecosystem can work regularly. Such assessment can be used to monitor trends in condition over time, provide an early warning of land resource degradation, and recommend appropriate countermeasures for sustainable exploitation and protection of land resources (Su et al. 2010b). Consequently, the evaluation of regional land eco-security is commonly applied home and broad (Schreurs and Pirages 1998; Zhao et al. 2006; Gao et al. 2007; Su et al. 2010b).

Although considerable attention has been given from the scientific community and policy-makers to evaluate the security of land ecosystem, most related studies often have disadvantages in subjectivity and complexity associated with the weight determination procedure. The assessment of land eco-security was conducted mainly through the use of proxy indicators. These indicators were usually aggregated into a composite index of land eco-security by weight determination procedures like analytic hierarchy process (AHP) or fuzzy AHP. The indices aggregation procedure is a continuous process of optimization, the transition of the equilibrium state from instability to stability. However, the weight determination procedure of AHP or fuzzy AHP, is treaded as a discontinuous process, given that the importance of the indicators is divided into certain grades. Consequently, such methods are often criticized for its inability to avoid subjectivity and to incorporate adequately the inherent uncertainty.

Catastrophe theory (CT), a mathematical model proposed by Thom (1975), studies systems that, under particular conditions, show sudden changes in the steady equilibrium state as a consequence of small changes in the value of certain input parameters (Schreiber et al. 1997). Due to its dialectic characteristics and advantages as a simple mathematical construct with clear physical meaning, the catastrophe theory has recently found home in multiple discontinuity non-mechanically studies (Weidlich and Huebner 2008; Barunik and Vosvrda 2009; Wang et al. 2011). We argue that the change of land eco-security state can be considered as a particular catastrophic behavior, a small and gradual change in the steady equilibrium state of a sub-system can rapidly cause the whole system to reach the crush state. Following such idea, this paper aims to propose a catastrophe model for land eco-security assessment with a case study in Shanghai, China. Specifically, our objectives are to: (1) develop a catastrophe model for land eco-security assessment and apply the model to the case study of Shanghai; (2) determine the main influential factors and temporal trends of land eco-security levels in this region; (3) demonstrate how to evaluate land eco-security levels at administrative scale; and (4) provide a frame of reference for policy makers to promote the protection of land resources as well as to advance sustainable development in the region.

For reader’s convenience, we first briefly introduce the catastrophe theory used in the paper. Then, we apply this theory to the detailed study of a catastrophe assessment model, to show how the assessment is designed and performed. Described by the equilibrium surface, the CT-based evaluation method does not determine weights using absolute numbers. Instead, it aggregates all the indicators when continuous process is optimized and the system reaches a steady equilibrium state, overcoming the disadvantages in subjectivity and uncertainty.

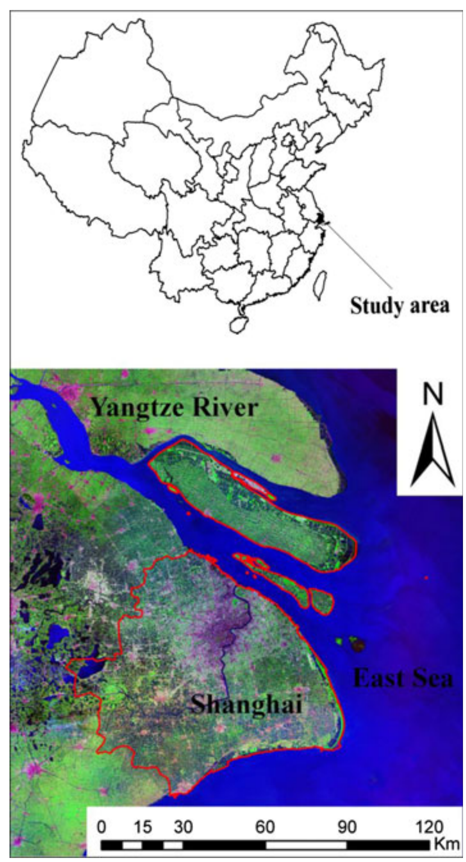

Fig. 1 Location of Shanghai, China

2 Study area

Shanghai is a metropolis in eastern China and a direct-administrated municipality by the State Council of China. Located in the middle part of the coast of mainland China, it sits at the mouth of the Yangtze River (Fig. 1) and has a population of 20.3 million. Apart from a few hills in the southwestern corner, the vast majority of Shanghai's land area is flat, with an average elevation of 4 m. This region has a humid subtropical climate and experiences four distinct seasons. The city is also susceptible to typhoons, making the land ecosystems fragile. In addition, land ecosystems in the region have sustained increasing development pressures and degradation due to rapid population growth, extensive urbanization and excessive tourism activity in recent past. If the highly stressed condition of land ecosystems in the region continues to worsen, it will become a major impediment to regional social-economic development.

3 Method

3.1 Catastrophe theory

Catastrophe theory was proposed in an attempt to rationally account for the phenomenon of discontinuous change in behaviors (outputs) resulting from continuous change in parameters (inputs) in a given system. In this section, we present a brief discussion of the basic assumptions and results of catastrophe theory in a form useful for applications. For details, see Woodstock and Poston (1974).

Let f: $R^k \times R^n \rightarrow R$ be a smooth (infinitely differentiable) function representing a dynamical system M in the sense that R^k is the space of input variables (controls, parameters) while R^n represents the space of output variables (responses, behaviors). The fundamental assumption is that M attempts to locally minimize f. Given any such function f, if we fix the point $c \varepsilon R^k$, we obtain a local potential function f_c: $R^n \rightarrow R$. Therefore, f_c can be expressed as follows:

$$V = V(x, u) \tag{1}$$

where V is the potential function; x and u represents response and control variables, respectively.

According to catastrophe theory (Zeeman 1976), the critical points of the potential function f_c form an equilibrium surface. The equation of the surface is obtained by calculating the first derivative of f_c, $f'_c(x) = 0$ and the singularities are obtained by calculating the second derivative of f_c, $f''_c(x) = 0$. Bifurcation set of the catastrophe system is obtained by eliminating x between $f'_c(x) = 0$ and $f''_c(x) = 0$. A normalization formula is derived by decomposing bifurcation set. The values of x and all control variables in the normalization formula range between 0 and 1. These variables are called "catastrophe progression". The catastrophe progression of each control variable can be obtained from the initial membership function, using recursive algorithm subject to the normalization formula. Suppose response variable is one dimension, catastrophe models can be classified into four categories according to the dimension of control variables. Summary descriptions of these models are given in Table 1.

3.2 Development of a catastrophe model for land eco-security assessment

3.2.1 Indices selection

Su et al. (2010b) reported that the "Pressure-State-Response" framework was suitable for being the basis for defining indices to assess land ecological security, since it could reflect the balance between anthropogenic activities and land ecological carrying capacity. Besides, indices selection in this study was guided by the principles of integrity, simplicity, dynamic response, geographical accuracy, and data availability (Zhao et al. 2006), and the "three-step" method proposed by Su et al. (2010b).

Table 1 Summary description of catastrophe models

Category	Dimension of control variables	Potential function	Bifurcation set	Normalization formula
Fold model	1	$V(x) = x^3 + u_1 x$	$u_1 = -3x^2$	$X_{u_1} = \sqrt{u_1}$
Cusp model	2	$V(x) = x^4 + u_1 x^2 + u_2 x$	$u_1 = -6x^2, u_2 = 8x^3$	$X_{u_1} = \sqrt{u_1}, X_{u_2} = \sqrt[3]{u_2}$
Swallowtail model	3	$V(x) = \frac{1}{5}x^5 + \frac{1}{3}u_1 x^3 + \frac{1}{2}u_2 x^2 + u_3 x$	$u_1 = -6x^2, u_2 = 8x^3,$ $u_3 = -3x^4$	$X_{u_1} = \sqrt{u_1}, X_{u_2} = \sqrt[3]{u_2},$ $X_{u_3} = \sqrt[4]{u_3}$
Butterfly model	4	$V(x) = \frac{1}{6}x^6 + \frac{1}{4}u_1 x^4 + \frac{1}{3}u_2 x^3 + \frac{1}{2}u_3 x^2 + u_4 x$	$u_1 = -10x^2, u_2 = 20x^3,$ $u_3 = -15x^4, u_4 = 4x^5$	$X_{u_1} = \sqrt{u_1}, X_{u_2} = \sqrt[3]{u_2},$ $X_{u_3} = \sqrt[4]{u_3}, X_{u_4} = \sqrt[5]{u_4}$

Source: Woodstock and Poston (1974)

We referred to previous studies and the framework as well as the principles explained above to generate a set of assessment indices. Initially, a set of 60 indices was developed. Subsequently, we established a three-round Delphi Process (Linstone and Turoff 1975) from which 32 indices were selected that favored the consensus needed to validate our analysis. Experts with skills in the appropriate fields of study evaluated the set of 32 indices for relevance to our assessment. After performing principal component analysis to reduce data dimensionality, a total of 18 indices were generated.

3.2.2 Data source and standardization

Statistical data between 1999 and 2008, obtained from the Statistical Yearbook (Shanghai Bureau of Statistics 2000–2009), were used in this paper. Given the different dimension and distribution of indices, it was difficult to directly compare or operate among them. As a result, the original data of indices should be dimensionless by data standardization. In addition, indices can be either negative or positive correlated with land eco-security level. Positive correlation is highly advantageous to land eco-security. The higher the values of those indices are, the more secure the land ecosystem is. Conversely, negative correlation is disadvantageous to land eco-security. The higher the evaluation values of indices are, the more insecure the land ecosystem is. All the indices were standardized using the following equations:

$$x_i' = \frac{x_i - x_{i\min}}{x_{i\max} - x_{i\min}} \quad (2)$$

$$x_i' = 1 - \frac{x_i - x_{i\min}}{x_{i\max} - x_{i\min}} \quad (3)$$

where i is the index, x_i is the original value of i, $x_{i\max}$ and $x_{i\min}$ are respectively the maximum and the minimum value of i. Equation 2 is for positive indices and Eq. 3 is for negative indices.

3.2.3 Application of catastrophe theory

The catastrophe assessment index system can be divided into hierarchical sub-systems. If the index at higher level (response variable) contains two lower level indices (control variable), it can be assumed as a cusp system. The relative importance of these two control variables should be determined (u_1, important; u_2, less important), and control variable can then be obtained from the membership function, using recursive algorithm subject to the normalization formula. Similarly, when the index at higher level contains one, three or four lower level indices, it can be respectively calculated based on fold, swallowtail and butterfly membership function. The catastrophe assessment model for Shanghai was therefore developed following such approach.

3.2.4 Score transformation

The synthetic values of catastrophe assessment are generally high and the differences are not obvious (Poston and Ian 1978). These can be attributed to the fact that catastrophe progression is calculated based on the normalization formula (Shi et al. 2003). Therefore, it is difficult to determine the actual secure level directly using the results obtained by catastrophe assessment. Usually, the synthetic values of multi-attribute assessment are divided into five grades using equality distribution function (Xiong et al. 2007). The land eco-security level accordingly can be divided into five grades: 0.2 (very insecure), 0.4 (insecure), 0.6 (middle), 0.8 (secure) and 1.0 (very secure). The problem is how to find a way to transform the results obtained by catastrophe assessment into the ordinary-used synthetic values. The method for score transformation used in this paper is described as follows: Suppose the relative membership degree for all indices equals n, then the relative membership degree for higher level indices should also equal n. Consequently, the synthetic membership degree can be obtained by applying suitable catastrophe model. By virtual of this method, the catastrophe progression value for each secure grade was calculated (Table 2).

3.2.5 Method demonstration

This section is provided additionally to show this method in terms of a simple example using the 2004 data of study area (Table 3).

Table 2 Corresponding values between assessment results of catastrophe model and ordinary-used values at different secure level

Secure level	Relative membership degree obtained by catastrophe model				Corresponding ordinary-used values
	Pressure	State	Response	Synthetic	
Very secure	>0.971	>0.969	>0.961	>0.988	>0.8
Secure	0.971–0.935	0.969–0.930	0.961–0.913	0.988–0.973	0.8–0.6
Middle	0.935–0.887	0.930–0.879	0.913–0.849	0.973–0.953	0.6–0.4
Insecure	0.887–0.813	0.879–0.800	0.849–0.753	0.953–0.920	0.4–0.2
Very insecure	<0.813	<0.800	<0.753	<0.920	<0.2

Table 3 Statistical data of 2004 used in land eco-security assessment for Shanghai (China)

Indices	No.	Original data	Standardized data
Natural population growth rate (%)	C1	−1.16	0.338
Length of highways (km)	C2	1.26	0.692
Non-agriculture population proportion (%)	C3	81.16	0.509
Number of tourists per year (10,000 persons)	C4	1.45	0.504
Intension of chemical fertilizer application (kg/hm^2)	C5	2320.60	1.000
Intension of agricultural film application (kg/hm^2)	C6	731.48	0.822
Load of industrial wastewater (10,000 ton/km^2)	C7	30.50	0.748
Load of industrial solid wastes (10,000 ton/km^2)	C8	0.29	0.472
Grain yield per capita (kg/ha)	C9	78.59	0.941
Effectively irrigated land proportion (%)	C10	88.93	0.829
Total output per hectare (RMB Yuan)	C11	27032.64	0.414
Farmland area per person (ha)	C12	0.02	0.553
Forest cover rate (%)	C13	17.10	0.000
Green area per capita (m^2)	C14	10.11	0.281
Natural protection zones proportion (%)	C15	11.80	0.070
Scientific research people proportion (%)	C16	1.60	0.445
Industrial solid wastes utilized proportion (%)	C17	97.19	0.123
Industrial wastewater up to the discharge standards proportion (%)	C18	96.30	0.179

(1) Calculating membership degree for items variables (B) with corresponding indices (C) as control variables

Butterfly model for B1

$$x_{B1} = (\sqrt{x_{c1}} + \sqrt[3]{x_{c2}} + \sqrt[4]{x_{c3}} + \sqrt[5]{x_{c4}})/4 = \left(\sqrt{0.338} + \sqrt[3]{0.692} + \sqrt[4]{0.509} + \sqrt[5]{0.504}\right)/4 = 0.795$$

Butterfly model for B2

$$x_{B2} = (\sqrt{x_{c5}} + \sqrt[3]{x_{c6}} + \sqrt[4]{x_{c7}} + \sqrt[5]{x_{c8}})/4 = \left(\sqrt{1.000} + \sqrt[3]{0.822} + \sqrt[4]{0.748} + \sqrt[5]{0.472}\right)/4 = 0.932$$

Swallowtail model for B3

$$x_{B3} = (\sqrt{x_{c9}} + \sqrt[3]{x_{c10}} + \sqrt[4]{x_{c11}})/3 = \left(\sqrt{0.941} + \sqrt[3]{0.829} + \sqrt[4]{0.414}\right)/3 = 0.904$$

Butterfly model for B4

$$x_{B4} = (\sqrt{x_{c12}} + \sqrt[3]{x_{c13}} + \sqrt[4]{x_{c14}} + \sqrt[5]{x_{15}})/4 = \left(\sqrt{0.553} + \sqrt[3]{0.000} + \sqrt[4]{0.281} + \sqrt[5]{0.070}\right)/4 = 0.292$$

Swallowtail model for B5

$$x_{B5} = (\sqrt{x_{C16}} + \sqrt[3]{x_{C17}} + \sqrt[4]{x_{C18}})/3 = \left(\sqrt{0.455} + \sqrt[3]{0.123} + \sqrt[4]{0.179}\right)/3 = 0.605$$

(2) Calculating membership degree for element variables (A) with corresponding items (B) as control variables

Cusp model for A1

$$x_{A1} = (\sqrt{x_{B1}} + \sqrt[3]{x_{B2}})/2 = \left(\sqrt{0.795} + \sqrt[3]{0.932}\right)/2 = 0.934$$

Cusp model for A2

$$x_{A2} = (\sqrt{x_{B3}} + \sqrt[3]{x_{B4}})/2 = \left(\sqrt{0.904} + \sqrt[3]{0.292}\right)/2 = 0.807$$

Fold model for A3

$$x_{A3} = \sqrt{x_{B5}} = \sqrt{0.605} = 0.778$$

(3) Calculating membership degree for synthetic land eco-security of Shanghai

Swallowtail model for A

$$x_A = (\sqrt{x_{A1}} + \sqrt[3]{x_{A2}} + \sqrt[4]{x_{A3}})/3 = \left(\sqrt{0.934} + \sqrt[3]{0.807} + \sqrt[4]{0.778}\right)/3 = 0.946$$

(4) Relating results with Table 2, the synthetic land eco-security is graded as "insecure".

3.3 Temporal trend analysis and mutation analysis

The Mann–Kendall's test (Mann 1945) was used to account for the temporal trend of land eco-security. The Kendall's test is a robust, nonparametric procedure for randomness against trend. It is not intended for exploring the hypothesis that a change has occurred at some prespecified time (as a result of known human action for example), but rather for detecting monotonic trend or change (gradual or sudden) during some interval of time (Cun and Vilagines 1997). Besides, it works without requiring normality or linearity, and is therefore widely used for trend detection (Zhang et al. 2010). The basic requirement of Mann–Kendall's test is that the number of observed measurements is no less than ten (Su et al. 2011). The procedure is described as follows:

Let $x_1, x_2, \ldots x_n$ represents n data points where x_j is the data point at time j. Then the Mann–Kendall statistic (S_k) is expressed by Eq. 4.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sign}(x_j - x_k), \quad k = 2, 3, 4 \ldots n \tag{4}$$

where $\operatorname{sign}(x_j - x_k) = \begin{matrix} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{matrix}$

Compute statistic UF_k using following equation:

$$UF_k = \frac{[S_k - E(S_k)]}{[Var(S_k)]^{1/2}}, \quad (k = 1, 2, 3 \ldots n) \tag{5}$$

where $UF_1 = 0$, $E(S_k)$ and $Var(S_k)$ are respectively the mean and variance of S_k.

Compute the probability and decide on a probability level of significance (95% in this paper). The trend is assumed as downward if UF_k is negative and the computed probability is greater than the level of significance. The trend is regarded as upward if UF_k is positive and the computed probability is greater than the level of significance. If the computed probability is less than the level of significance, there is no trend.

When Mann–Kendall's test is used for mutation analysis, we can apply the above procedure to the reverse sequence of x_n and calculate statistic UB_k, where $UB_k = -UF_k$, $k = n, n-1, \ldots, 1$; $UB_1 = 0$. Then the cross-point between curve UF_k and curve UB_k is assumed as mutation point.

4 Results

Catastrophe model for land eco-security assessment in Shanghai is shown in Fig. 2. Land eco-security assessment indices and transformed standards are respectively given in Tables 2 and 4. By using the model mentioned above, as well as statistical data between 1999 and 2008, we estimated land eco-security states (Fig. 3). In addition, the temporal trend of land eco-security (synthetic index) values was evaluated using Mann–Kendall's test (Fig. 4d). Similarly, temporal trends of pressure (Fig. 4a), state (Fig. 4b) and response (Fig. 4c) were also calculated.

As displayed in Fig. 4a (pressure), the security membership degree presented a parabola-shaped curve. The values of security membership degree gradually increased first, reached peak at 2003 and then decreased. Mann–Kendall's test was applied to visualize the evolution law of security membership degree from apparent irregularity. Figure 4a exhibited that security membership degree generally showed downward trend, signifying the excessive and intensified pressure sustained by the land ecosystem of Shanghai. In addition, 2007 was identified as mutation point by Mann–Kendall's test, denoting that the secure state of pressure was worsened after 2007. From Fig. 3, it

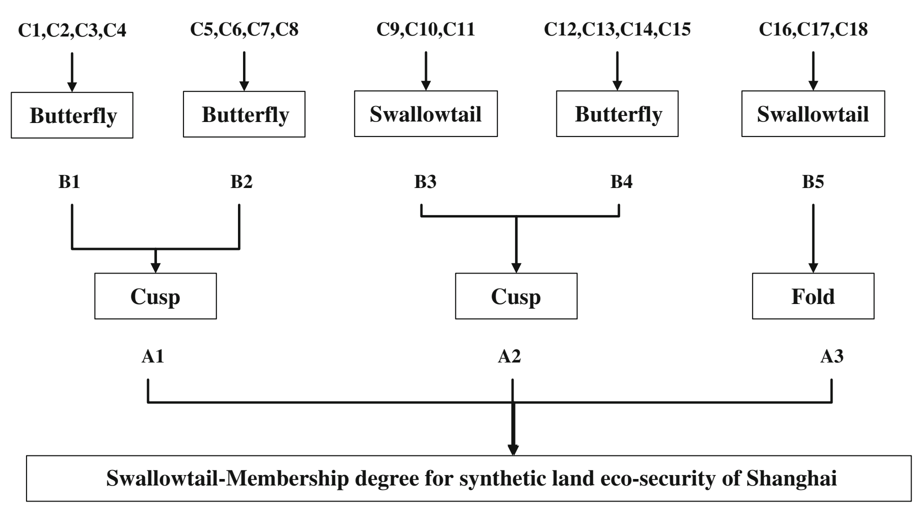

Fig. 2 Catastrophe model for land eco-security assessment of Shanghai (China)

Table 4 Land ecological security framework, items, and indices for Shanghai (China)

Element	No.	Items	No.	Indices	No.
Pressure	A1	Social-economic	B1	Natural population growth rate (%)	C1
				Length of highways (km)	C2
				Non-agriculture population proportion (%)	C3
				Number of tourists per year (10,000 persons)	C4
		Natural	B2	Intension of chemical fertilizer application (kg/hm^2)	C5
				Intension of agricultural film application (kg/hm^2)	C6
				Load of industrial wastewater (10,000 ton/km^2)	C7
				Load of industrial solid wastes (10,000 ton/km^2)	C8
State	A2	Land quality	B3	Grain yield per capita (kg/ha)	C9
				Effectively irrigated land proportion (%)	C10
				Total output per hectare (RMB Yuan)	C11
		Land use	B4	Farmland area per person (ha)	C12
				Forest cover rate (%)	C13
				Green area per capita (m^2)	C14
				Natural protection zones proportion (%)	C15
Response	A3	Improvement	B5	Scientific research people proportion (%)	C16
				Industrial solid wastes utilized proportion (%)	C17
				Industrial wastewater up to the discharge standards proportion (%)	C18

Note: hm^2 = hectometer (100 m^2), or 1 ha (10,000 m^2)

Data source: Statistical Yearbook (Shanghai Bureau of Statistics 2000–2009)

can be seen that the land eco-security level for pressure was evaluated as secure in 2002 and 2003, but became very insecure in 2007 and 2008. Rapid urbanization accompanied by population growth in recent decades was an important cause for the current land ecological problems being experienced in Shanghai. Where high population density and wealth come together, demands for public infrastructure (e.g. roads, water facilities, and utilities), housing, industrial and commercial uses increase and upcoming construction projects start to appear as "rural sprawl" (Mann 2009). Statistical data evidenced that urbanization greatly stimulated the upscaling and expansion of road systems in Shanghai, with the length of highways increased from 4,231 km in 1999 to 15,844 km in 2008, an increase of 3.7 times. The modern urban landscapes of Shanghai have attracted flows of people into the city, which exerted great pressure on land ecosystems. In addition, overuse of chemical fertilizers, pesticides, and plastic films in the croplands led to land pollution and also contributed to degradation of land ecosystems in Shanghai.

Similar to pressure, security membership degree for state also presented downward trend and the mutation point was detected in 2007 (Fig. 4b). Figure 3 revealed that land security level, with regard to state index, generally remained insecure across the period between 1999 and 2008. More specifically, land eco-security was considered as very insecure in 2007 and 2008. Experience in other parts of the world suggests that intensive urbanization will necessitate the transfer of significant areas of land to the secondary and tertiary sectors (Chan and Shimou 1999). In many cases, farmland has to be given up for development purposes and therefore a large amount of high-quality farmland was converted to build-ups (Long et al. 2009; Su et al. 2010a). This is exactly the case in Shanghai. During the 10 years, per capita farmland, per capita crop yield and effectively irrigated land proportion all exhibited decline tendencies, posing considerable threat to regional food security. The concentration of factories with low treatment efficiency of waste gas, water and other wastes also contributed to the insecure state. According to the statistics, load of industrial wastewater increased from 319,800 ton/km^2 in 1999 to 356,400 ton/km^2 in 2008. The case with industrial solid wastes was more serious, load of which doubled during the study period. All these phenomena indicate that the ecological service function of land ecosystem in Shanghai has been deteriorating rapidly. If no appropriate measures are adopted timely, the land ecosystem would continue to degrade, possibly beyond the point of recovery.

As for response, security level was evaluated as very secure and secure in the initial 2 years. However, insecure and very insecure level was identified for the following years (Fig. 4c). Results of the Mann–Kendall's test demonstrated downward trend of security membership degree for response, which was indicative of the unsatisfactory efforts of the city in promoting land ecosystem protection. It is true that Shanghai has invested in a number of environmental

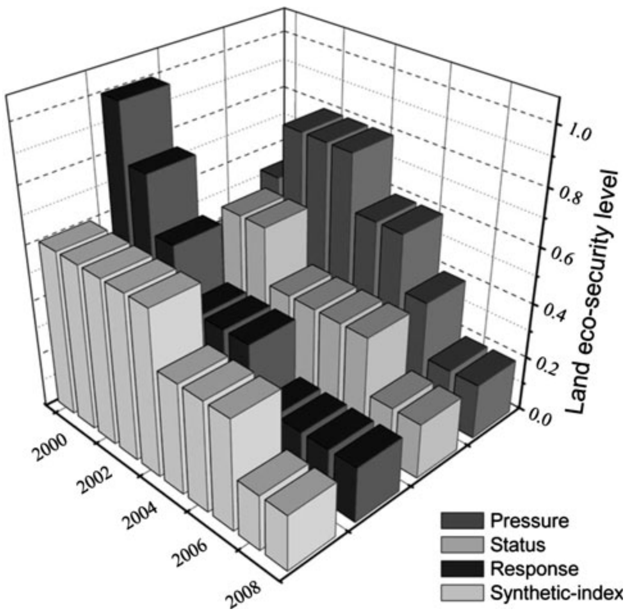

Fig. 3 Temporal changes of land eco-security level for Shanghai between 1999 and 2008. The value for land eco-security from 0.2 to 1.0 respectively represents very insecure, insecure, middle, secure and very secure

protection projects and the proportion of scientific research persons has been keeping increasing. However, the industrial pollution issues have not been effectively tackled. Performance evaluation on local officials is mainly associated with economic growth. Environmental protection is not listed as one of the criteria except if serious environmental disasters are made public and raise concern (Wang et al. 2008). Industries are the major sector of local labor market and also the major financial source for local government (Wang et al. 2008). Most officers often ignore such industrial activities. Though pollution levy systems have been introduced in this city, they fail to play an effective role since the levy is too low to give polluters incentives to reduce their emissions. This is similar for water pollution fees that are small relative to the marginal costs of pollution control (Sinkule and Ortolano 1995). We suspect all these led to the declined land eco-security level.

Among the 10 years, the synthetic land eco-security was evaluated as middle in initial 5 years, insecure in the interval 3 years, and very insecure in the last 2 years (Fig. 3). Downward trend of security membership degree for synthetic index was identified and 2005 was regarded as mutation point by Mann–Kendall's test (Fig. 4d). These results implied that land ecosystem conditions were not optimistic for Shanghai and such situation should draw the attention of policy makers and public as well.

5 Discussion and conclusions

Composition and distribution of the systems components are the two main aspects that represent structure of land ecosystems. Most of the earlier studies concentrated on

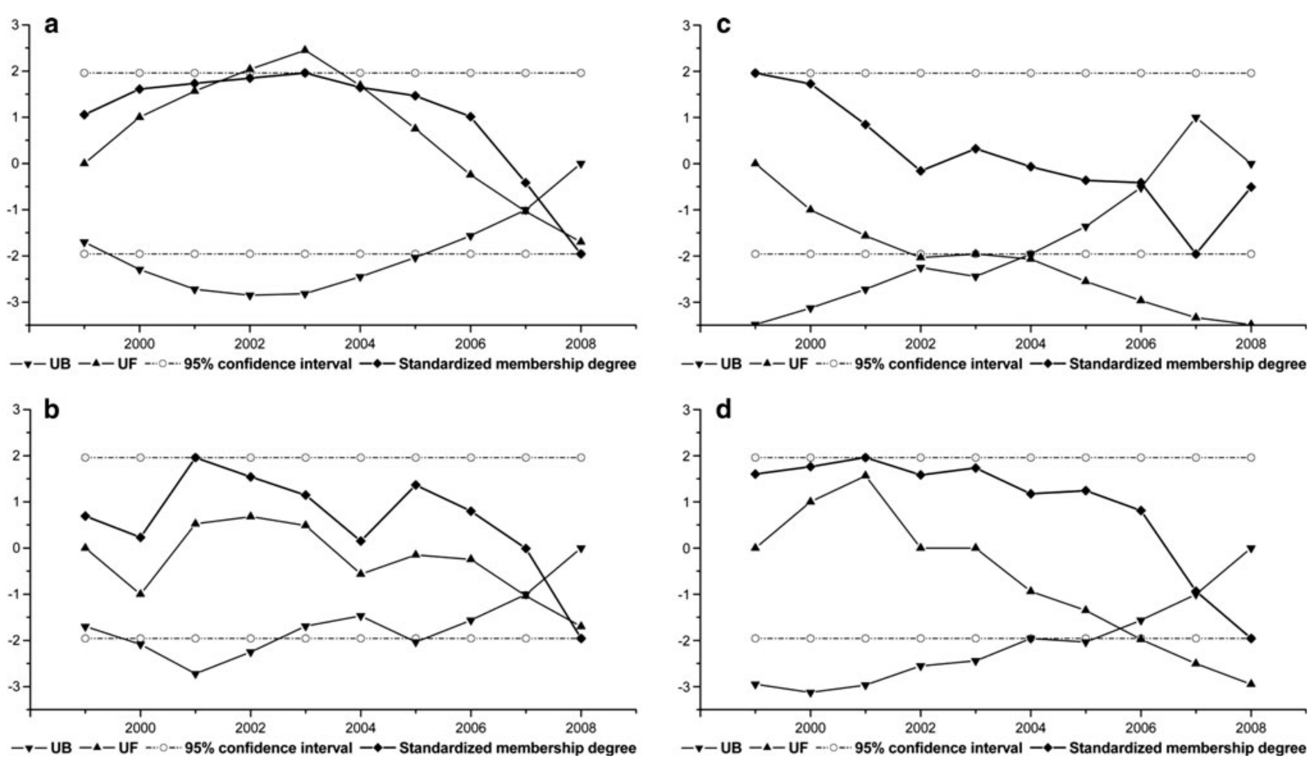

Fig. 4 Temporal trend explored by Mann–Kendall's test for **a** pressure, **b** state, **c** response and **d** synthetic index

structural characterization of individual components using indicators like production, soil conditions or NDVI. Vadrevu et al. (2008) pointed that system structure cannot be summarized as a simple sum of the structure of the individual parts. Employing the catastrophe model, however, this study integrated them in a hierarchical framework. The catastrophe model used multiple assessment indices of land eco-security according to the inherent contradictions and relative importance of indices. In this method, the indices aggregation procedure is considered as a continuous process of optimization, the goal of which is to obtain the steady equilibrium state. Consequently, the dependency of state variables on control variables is determined by the catastrophe fuzzy membership functions, rather than weights assigned by the users, thus reducing subjectivity and uncertainty. The whole calculation does not require a high level of technical expertise to determine the membership degree, making the calculation procedures simple and operational. Further, the data requirements for our study were low, since all the data were publicly available. Local governments worldwide are rapidly developing geographic information systems to establish data bases and make them available to the scientific community (Vadrevu et al. 2008).

Our study goal for the land eco-security assessment was to develop a means of quantifying the state of land ecosystems over time. Land ecosystems of Shanghai generally remained under the middle grade of eco-security across the 10 years between 1999 and 2008. During the 10 years, land ecosystems have sustained intensified pressure, presented worsened secure state and received reduced positive responses from human society. These led to the significant decline in the synthetic land eco-security. All the results, broadening our understanding of the past changes over time and factors that lead to the present state, can be used to predict and manage land ecosystems with considerable utility. It should be mentioned that this assessment mainly relied on the available data set and the eco-security, whether secure or insecure, was thus a relative concept. Though it lacks of absolute sense, this study allows us to know clearly the changes of land ecosystem conditions and assists officers and citizen in resolving the issues regarding regional land eco-security improvements. Therefore, the land eco-security index should be useful for policy makers and land managers to take measures that strengthen land ecosystem protection and promote its ecological reconstruction.

Despite considerable effort to define and describe land eco-security, a precise and practical method to quantify it has not previously been attempted. It has been acknowledged that assessment of land eco-security relies on the effective aggregation of multi-attribute data. We have demonstrated that such challenges can be overcome using catastrophe model. Results of catastrophe model can be further analyzed using time series analysis to estimate, map, and examine temporal variations of land eco-security. This capability could help design sustainable urban land ecosystems. Although this model offers new insights into land eco-security assessment, this study also has several limitations. First, CT-based assessment relies on the relative importance of indices and such process can not completely avoid human subjectivity. Second, this study used the whole administrative region as the unit of analysis, the city's internal spatial variations and land eco-system change cannot be analyzed in details. With the advancement in geo-information technology, evaluation and accuracy assessment can be enhanced to strengthen intra-level research efforts in the future. Last, we used the same indices for the 10 years in order to obtain comparable results. Then, the serial linked relationships in time dimension between three separate aspects can not be reflected in the pressure-state-response modeling procedure. Further study should include analysis of the inherent consistency of the data set, the sensitivity of the model, the application of the models at different spatial scales, etc.

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