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Regional Eco-Security Assessment Based on the Perspective of Complex System Science: A Case Study of Chongming in China

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ABSTRACT

The objective of this study is to evaluate eco-security of Chongming in China and identify eco-security grades of the relevant subareas. In addition, the study aims to put forward the framework for a regional eco-security assessment system that is suitable for the analysis and evaluation of a man–land complex ecosystem. From the perspective of complex system science, this study puts forward the ANP-PRS-SENCE framework for a regional eco-security assessment. Based on the framework, a compressive assessment index system and a spatial variation assessment index system for Chongming's eco-security were established. Additionally, the eco-security threshold of Chongming was determined through the approach of system dynamics simulation. The assessment results show that in recent years the comprehensive score of eco-security has been on a gradual rise. With respect to the second-grade indices, the ecological risk and ecological protection indices are still relatively low. Therefore, in order to reduce the ecological risk, ecological construction needs to be strengthened and management measures need to be improved. The spatial variation assessment of eco-security shows that although the eco-security levels of most subareas remain between 0.3 and 0.6, regional variations are still quite obvious.

Key Words: eco-security, complex system, assessment, Chongming.

INTRODUCTION

With the high-speed development of society and economy, regional and global environmental problems have been exacerbating, including environmental pollution, forest degradation, water and soil loss, land desertification, acid rain production, and biodiversity reduction. These crises seriously threaten the living environment of

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human beings and the sustainable development of society and economy. As a result, meaningful responses have become an urgent social demand in order to guarantee eco-security (Barnthouse 1992; Boughton *et al.* 1999; Xiao *et al.* 2002; Qing *et al.* 2007).

Although it has been approximately 20 years since the concept of eco-security was introduced, no consensus has been reached on a unified and universally acceptable definition of the term (Zhao *et al.* 2006). This is partly because of the variety and complexity of the concept and partly because of the lack of detailed studies on the issue. At present, there exist broad-sense and narrow-sense concepts of eco-security. The broad-sense concept includes natural, economic, and social eco-security. The narrow sense concept covers the security of ecosystems influenced by nature and humans (Xiao *et al.* 2002). Both concepts focus on the interactions between economic and ecological environment, and base eco-security on the presence of a sound ecosystem, on sustainable exploitation of natural resources, and on the harmony between humans and nature.

Eco-security assessment is the basis of eco-security management and construction, and is an important issue in eco-security research and the object of regional eco-security assessment is a complex system including many subsystems and elements.

A complex system is the basic scientific object of study in complex science, and it is applicable to such fields as biology, chemistry, physics, economics, and management. An open complex giant system includes four types of typical systems: the geographic and eco-environmental system; the socioeconomic system; the human system; and the human brain system. They all share the common feature of being related to the phenomenon of life. Man as the system element plays a dual role, namely, smart behavior and value orientation. Meanwhile, complex system theory is the frontier of system science. The object of the regional ecosystem includes the above-mentioned geographical and eco-environment system and socioeconomic system.

The rapid development of a global ocean economy and the vulnerability of island ecosystems combine to determine the seriousness of island eco-security issues. The study of island eco-security is of great significance within a regional sustainable development paradigm. With Chongming in China as an example, this study adopts the method of complex system science to analyze and solve some issues on regional eco-security assessment, such as the establishment of an assessment indictor system and the identification of crucial security threshold of indictors. In addition, a regional eco-security assessment of Chongming is also carried out. The results will provide a basis for the management of Chongming's eco-security and also a reference guide for the region's future sustainable development. On the basis of system science and the methods and theories of previous studies, this study aims to put forward a framework of a regional eco-security assessment system that is suitable for the analysis and evaluation of the man-land complex ecosystem.

METHODOLOGY

Study Area

The Chongming islands comprise Chongming Island, Changxing Island, and Hengsha Island. Its land area is 1411 km^2. It is situated in the north subtropical region, where the climate is mild and humid. With an average annual temperature of 15°C, sunlight and rainfall are plentiful and each of the four seasons is distinct.

Chongming Island is located in the central point of the West Pacific Bank on the Chinese coast, at the estuary of the Yangtze River. It is the largest river alluvial island and the third largest of China's islands. The location is between 121°09′30″ to 121°54′00″E and 31°27′00″ to 31°51′15″N and it covers an area of 1267 km^2. The island has flat land and is free from any mountain or hill. It is relatively higher in the northwest and middle parts and lower in the southwest and eastern parts. The elevation of more than 90% of land is between 3.21 m and 4.20 m. To the southeast of Chongming Island lie Changxing Island and Hengsha Island. Changxing takes the shape of belt, with an area of 88 km^2. Hengsha is encircled by rivers on three sides and by sea on the other. The average altitude is 2.8 m and total area 56 km^2. Over a long period of time, due to the barrier of transportation, the economy of Chongming developed at a relatively slow pace, lagging behind other regions in Shanghai.

The Chongming islands are an important strategic place for the sustainable development of Shanghai in the 21st century. In 2004, the State Council officially approved the comprehensive planning of urban development in Shanghai and further made explicit the objectives of developing Chongming as the "Comprehensive ecological island." Doing so presents new opportunities and challenges for the development of Chongming. In recent years, with rapid economic development of the Yangtze River Delta, acceleration of the regional urbanization process, and exploitation and opening of Chongming, stability and biodiversity of ecosystem in the Chongming islands and biodiversity have been greatly affected. It is therefore of both theoretical and practical significance to conduct systematic eco-security research.

The Framework of the Eco-security Assessment Indictor System

In the process of constructing the eco-security assessment index system (EAIS) for the Chongming islands, the analysis of new process (ANP), the society-economy-nature complex ecosystem theory (SENCE) and the pressure-state-response model (PRS) are used to establish systematic structure and choose indiators.

Analysis of net process (ANP)

Systematic analysis of hierarchical process (AHP) is a commonly used method to solve the assessment issues of a complex system and has been widely adopted in the construction of the eco-security assessment system (Zhao *et al.* 2006; Zuo *et al.* 2002; Wang 2006; Zhou and Wang 2005; Xie and Li 2004; He *et al.* 2006). The basic assumption of AHP is that there is a hierarchical structure within which every sub-system is independent of each other. However, in the actual research concerning complex systems and in the decomposition of the overall layer, the internal elements at each level are often interdependent. The low-level element sometimes dominates the high-level element. In consequence, the AHP model becomes powerless. In order to meet this need, Thomas (2004) proposed a more complex net process, namely, the existence of both a hierarchical structure and an inter-dominant structure with internal cycles. It is these characteristics that enable analysis of net process (ANP) to be an effective tool in dealing with many complex issues. The process is shown in Figure 1.

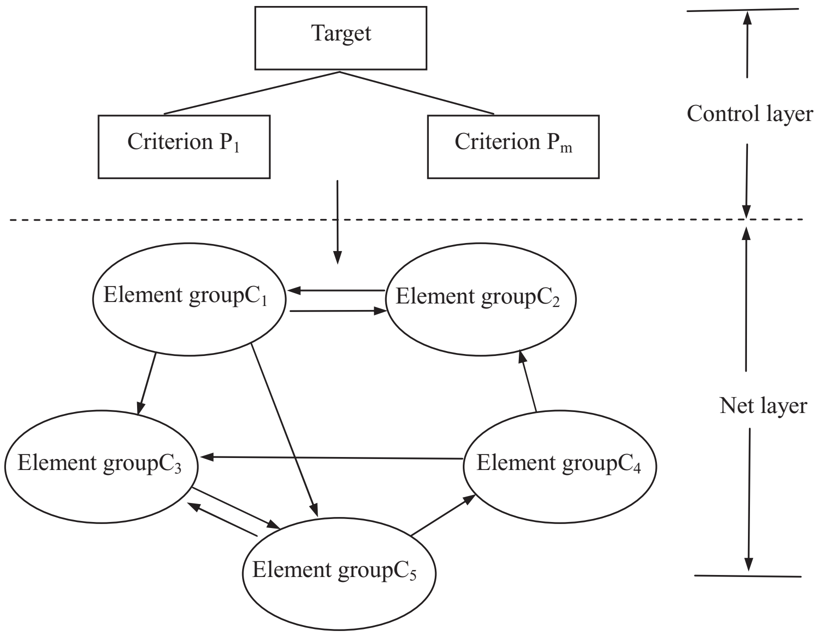

Figure 1. Analysis of net process (ANP).

Society–economy–nature complex ecosystem theory (SENCE)

The theory of ecosystem was first proposed by the British biologist A.G. Tansley in 1935 and was further developed by L. Lindeman in 1942. It has since been universally accepted. The term *ecosystem* refers to the combined physical and biological components of an environment. An ecosystem is generally an area within the natural environment in which physical (abiotic) factors of the environment function together along with interdependent (biotic) organisms, within the same habitat (Wikipedia 2010).

In discussing a human-centered ecosystem of agriculture, forestry, animal husbandry, and urban ecological systems, the concept and the intension of the ecosystem have been extended. Ma and Wang (1984) put forward the complex ecosystem of "society–economy–nature," which captures the complexity of the development of ecosystem theory. The social–economic–natural complex ecosystem consists of the three sub-systems of nature, society, and economy through synergy in a particular region. It is a symbiotic system with humans and nature interdependent in a particular region through synergy.

Pressure–state–response (PSR)

The "pressure–state–response" model (PSR) was proposed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (Qian *et al.* 2001). The "pressure-state-response (PSR)" conceptual framework (Figure 2) stresses the logical relationship of the cause, effect, and measure of a particular problem (Zhao *et al.* 2006). Therefore, it can

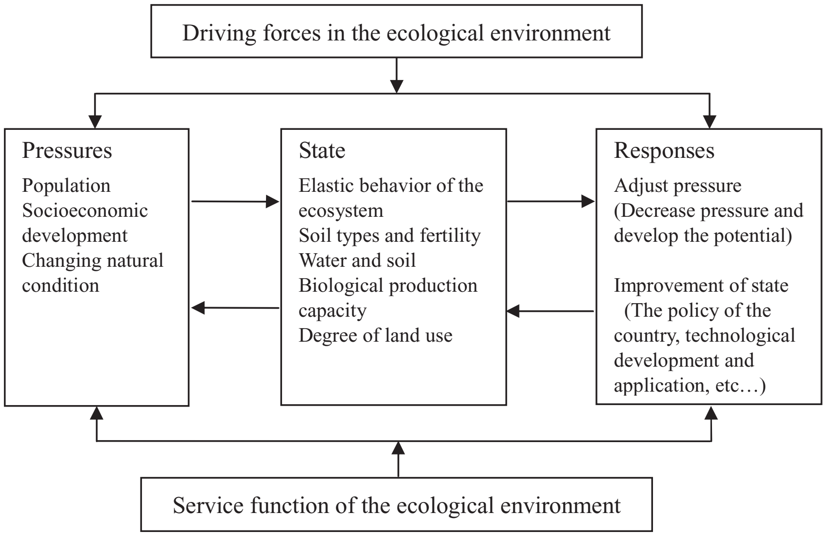

Figure 2. Framework of pressure-state-response model (PSR) (Zhao *et al*. 2006).

achieve a better result when used to carry out a composite assessment of system development and evolutionary process. Quite a number of researchers have adopted the framework as the mechanism of eco-security evaluation and carried on quite a lot of studies on regional eco-security assessment (Peng and Wen 2004; Wang *et al.* 2007; Jia *et al.* 2006; He *et al.* 2006). This study will use the PSR as the conceptual framework of the assessment indictor system.

Framework of Eco-security Assessment Indictor System

A regional ecosystem is a social–economic–natural complex system, which is dynamic and open. The overall framework of an indictor system of regional ecosystem assessment is ANP-PSR- SENCE (Figure 3).

1. The pressure–state–response (PRS) model was chosen as the theoretical framework. It mainly includes ecological risk (pressure), ecological health (state), and ecological protection (response) as a theoretical basis of top layer index design in constructing a comprehensive index of the criterion layer.
2. ANP (analysis of net process) is employed to establish the control and network layers for the EAIS.
3. According to society–economy–nature complex ecosystem (SENCE) theory, the specific indicator system is chosen in terms of society, economy, and nature. There exists a network relationship between an indicator in the network layer and an index in the higher layer.

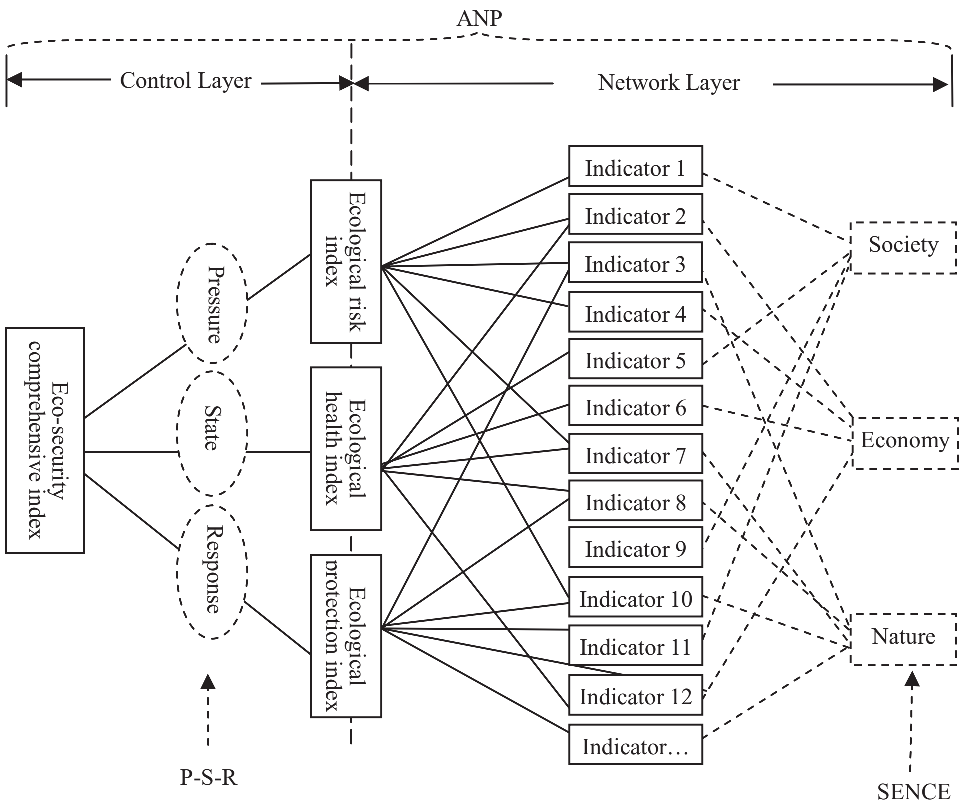

Figure 3. Framework of eco-security assessment index system (EAIS).

Indicator Selection and Weight

Conducting a temporal dynamic assessment and regional spatial variation analysis can reveal the evolutionary process of regional eco-security pattern, the characteristics of internal spatial variation. They are two important tasks in regional eco-security assessment.

The choice of specific indicators is made within the overall framework of the index system and the alternative set of indicators is established (Table 1). Further, through expert advice and discussions with the relevant government departments, the indicators are finally selected and a comprehensive assessment indicator system is constructed. In the meantime, in order to reveal the spatial variation of eco-security within the region, the indicators with a bigger difference are chosen and indicators similar to the current value are dropped out. Eventually the assessment system of spatial variation is formed (Table 2).

In this study, the method of AHP was employed to determine the weights (Table 2). The judgment matrices of criteria index and indicators showed consistency ratios were all less than 0.1.

Table 1. The eco-security assessment index system for the Chongming islands.

Target layer	Criteria layer	Indicator layer
A: Eco-security composite index	B1: Ecological risk	C1:Natural disaster Losses
		C2:Emission intensity of COD
		C3:Energy consumption of per unit of GDP
		C4:Water consumption per unit of GDP
		C5:Population density
		C6:Intensity of chemical fertilizer
		C7:Intensity of pesticide application
		C8:Risk of storm surges
		C9:Salt water intrusion Criticality
	B2: Ecological health	C10:Ratio of organic/green agricultural products
		C11:Ratio of the tertiary industry
		C12:Forest coverage ratio
		C13:Beach area ratio
		C14:Terrestrial water area ratio
		C15:GDP per capita
	B3: Ecological protection	C16:Ratio of infrastructure construction investment
		C17:Treatment rate of industrial pollution
		C18:Treatment rate of domestic pollution
		C19:Ratio of renewable energy sources
		C20:Number of hospital beds for a million people
		C21:Percentage of fixed phones for 100 households

Indicator Threshold

The indicator threshold value is a critical point of eco-security and a yardstick of comprehensive assessment of regional eco-security. The study will use the method of system dynamics model to determine the threshold of an indicator.

System dynamics model

Computer simulation is an important method in a complex system research. A system dynamics model can reflect an interactive relationship between the structure and function of a complex system and its dynamic behavior. It is applicable to complex socio-economical and eco-environmental issues where precision is not required. The representative work in this area, called *Limits to Growth* was published in the 1970s. At present, system dynamics has been widely applied to the field of

Table 2. Indicator selection and weight.

	Comprehensive assessment indicators		Spatial variation assessment indicators	
Indicator	Indicator	Weight	Indicator	Weight
C1	√	0.0927		
C2	√	0.0881		
C3	√	0.0686		
C4	√	0.0591		
C5			√	0.0572
C6			√	0.0469
C7			√	0.0433
C8			√	0.0757
C9			√	0.0854
C10	√	0.0736		
C11	√	0.0829	√	0.0900
C12	√	0.0863	√	0.0995
C13	√	0.0973		
C14	√	0.0627	√	0.1277
C15			√	0.0856
C16	√	0.0869		
C17	√	0.0786		
C18	√	0.0677		
C19	√	0.0554	√	0.1304
C20			√	0.0818
C21			√	0.0765

eco-environmental research (Saysel 2002; Ali *et al.* 2002; Guneralp 2003; Shi *et al.* 2007; Tang *et al.* 2005; Tuo *et al.* 2006; He *et al.* 2008; Xu *et al.* 2009).

The model structure and feedback relationship are established according to the theory of complex ecological system and the regional eco-environmental characteristics of Chongming. The system is made up of the economic, population, resource, environment and ecological sub-systems. In order to reflect the major problems and the internal cause-effect relations of Chongming's eco-security, in establishing the system flowchart, 71 parameters are finalized that play a core role in affecting Chongming's eco-security. The model is built through the use of specialized software Vensim_PLE and the major data originate from the Chongming Statistical and Shanghai Statistical Yearbooks. The flow chart is shown in Figure 4.

All together there are 69 equations in the model, including 16 in the economic sub-system, 4 in the population subsystem, 15 in the environment subsystem, 22 in the resources subsystem, and 12 in the ecological subsystem. The major equations are listed in the following:

$$\text{GDP1} = \text{INTEG (IGDP1, 16.84)}$$
$$\text{GDP3} = \text{INTEG (IGDP3, 45.78)}$$
$$\text{GDP2} = \text{INTEG (IGDP2, 60.16)}$$
$$\text{NGDP} = \text{GDP-NDL-IPOE-IRE}$$

Table 3. The constant parameters and the variable coefficient of the system model.

Parameter/ coefficient	Value	Parameter/ coefficient	Value	Parameter/ coefficient	Value	Parameter/ coefficient	Value
RG1	0.0188	UQLP	328.49	QPE	0.0005	QWE	0.0007
RG2	0.17118	UQIP	8.2071	UQIGW	10.8544	QEE	0.0006
RG3	0.1348	RIPD	0.8300	UWCL	9.8695	TE	0.0100
RBEI	0.1800	RGFP	0.2770	UECL	250.466	RSA	0.2500
QNP	0.0001	RLPD	0.0200	UQGE	1074.25	TF	1887.4
TE	192263	UQFM	30	UQWM	60	AI	1411
RB	0.0600	RWAL	0.1000	RF	0.18	—	—

$$
\begin{aligned}
\mathrm{PG} &= \mathrm{RPI} * \mathrm{TP}\\
\mathrm{TP} &= \mathrm{INTEG}\ (\mathrm{PG},\ 69.71)\\
\mathrm{NIP} &= \mathrm{IPE} * (1\text{-}\mathrm{TPIP})\\
\mathrm{NDP} &= \mathrm{DPE} * (1\text{-}\mathrm{TRPD})\\
\mathrm{AP} &= \mathrm{PPA} * \mathrm{GDP1}\\
\mathrm{IRE} &= \mathrm{CIWE} * \mathrm{FWG} + \mathrm{CIEE} * \mathrm{EG}\\
\mathrm{AWR} &= \mathrm{WRT} * (1\text{-}\mathrm{PSI})\\
\mathrm{MNE} &= \mathrm{PCPF} * \mathrm{FA} + \mathrm{PCPW} * \mathrm{WA}\\
\mathrm{EWD} &= \mathrm{FA} * \mathrm{CFWR} + \mathrm{CWWR} * \mathrm{WA}
\end{aligned}
$$

The setting of constant parameters in the system model is based on the statistics of 2007, and the variable coefficients are determined through experience and expert advice. They are shown in Table 3.

Relative error and linear regression are used to test the result derived from the operation of the SD model. With the two variables GDP and gross population as an example, the check result (Table 4) shows that the relative error of their simulation results and historic results from 2001 to 2007 do not exceed 0.1 and therefore is quite ideal; in the meantime, we used the software Origin Pro 7.5 to check the linear

Table 4. Historic test of GDP and population.

	GDP (10^8RMB)			Population (10^4 people)		
Year	Historical value	Simulation value	Relative error	Historical value	Simulation value	Relative error
2000	54	53.9937	−0.08572	65.37	65.37	—
2001	57.83	60.3977	−0.04440	64.72	65.7459	−0.01585
2002	62.48	67.7125	−0.08375	64.01	66.1247	−0.03303
2003	70.07	76.0767	−0.08572	63.54	66.5066	−0.04668
2004	85.31	85.6503	−0.00399	63.26	66.8922	−0.05741
2005	95.72	96.6188	−0.00939	70.12	67.2819	0.04047
2006	108.26	109.1966	−0.00865	69.98	67.6766	0.03291
2007	122.79	123.6321	−0.00686	69.71	68.0770	0.02342

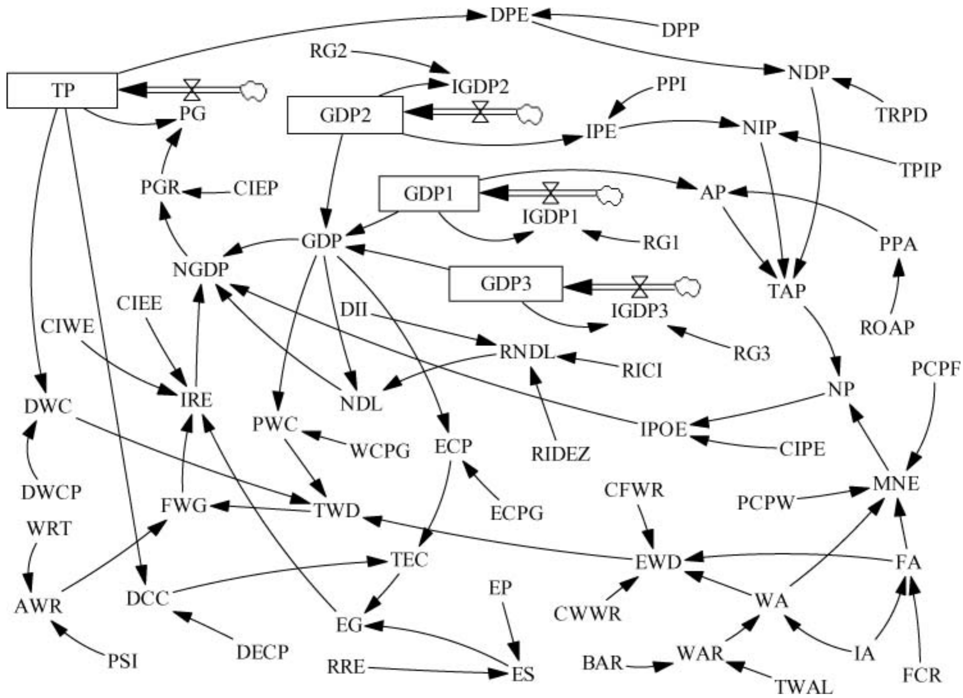

Figure 4. Flow chart of system dynamics model of Chongminmg complex ecosystem... Notes: GDP: Gross domestic product; GDP1: Gross domestic product of primary industry; GDP2: Gross domestic product secondary industry; GDP3: Gross domestic product of tertiary industry; NGDP: Net GDP; IRE: Impact of resources on the economy; IGDP1: 1Increase of GDP 1; RG1: Rate of increase of GDP 1; IGDP2 Increase of GDP 2; RG2: Rate of increase of GDP 2; IGDP3: Increase of GDP 3; RG3: Rate of increase of GDP 3; RICI: Ratio of infrastructure construction investment; NDL: Natural disasters Losses; RNDL: Rate of natural disasters losses; DII: Disaster intensity index; IRDEZ: Intact rate of disaster-preventing ecological function zones; CIPE: Coefficient of impact of pollution on the economy; PG: Population growth; PGR: Population growth rate; TP: Total population; CIEP: Coefficient of impact of economy on the population; DPP: Domestic pollution Per capita; PPA: Pollutants per unit of agriculture output; AP The amount of agricultural pollution; IPOE: Impact of pollution on the economy; NP: Net amount of pollution; TAP Total amount of pollutants; PPI: Pollutants per unit output of industry; TRIP: Treatment rate of industrial pollution; IPE: Industrial pollution emissions; NIP: Net amount of industrial pollution; NDP: Net amount of domestic pollution; TRDP: Treatment rate of domestic pollution; DPE: Domestic pollution emissions; ROAP: Ratio of Organic/green agricultural products; CIPE: Coefficient of impact of pollution on the economy; ECPG: Energy consumption of per unit of GDP; PSI: Proportion of salt water intrusion area; RRE: Ratio of renewable energy sources; WCPG: Water consumption per unit of GDP; TEC: Total energy consumption;

Figure 4. (Continued) ECP: Energy consumed in the production; DCC: Domestic energy consumption; AWR: The amount of available water resources; WRT: The amount of water resources in theory; FWG: Fresh Water gap; TWD: Total water demand; PWC: Production water consumption; DWC: Domestic Water consumption; DWCP: Domestic water consumption Per capita; DECP: Domestic Energy consumption per capita; ES: Energy supply; EG: Energy gap; EWD: Ecological water demand; CFWR: Coefficient of Forest ecological water requirement; CWWR: Coefficient of Wetland ecological water requirement; EP: Energy production; CIEE: Coefficient of the impact of energy on economy; CIWE: Coefficient of the impact of water resources on economy; IRE: Impact of resources on the economy; MNE: Metabolism of natural ecosystems; PCPF Pollutant carrying capacity per unit of forest land; PCPW: Pollutant carrying capacity per unit of wetland; IA: Island Area; FCR: Forest coverage ratio; FA: Forest area; WA: Wetland area; WAR: Wetland area ratio; BAR: Beach area ratio; TWAR: Terrestrial water area ratio.

regression, and the results are as follows:

GDP	$R = 0.99624$, $SD = 2.27797$, $P < 0.0001$
Gross population	$R = 0.71797$, $SD = 0.71169$, $P = 0.04489$

The fitting modulus (R) of historical and simulation result is relatively high and diversity Probability (P) is relatively low. Therefore, synthesizing the two methods, the two variables pass the test. The historic check of other variables is similar to this and they pass the historic test.

Determination of indicator threshold

Since the construction of Chongming's ecological island was proposed, a lot of planning and research has been done, such as the planning of the Eleventh Five-Year Development of Chongming (Program I) in 2006, Construction Planning of Chongming County (Program II) in 2007, Research of index system of Chongming ecological island (Program III) in 2008, among others. These studies have played a positive role in the development of Chongming in recent years. This study will use the system model to simulate the Chongming development trends under the above-mentioned three programs and the program of the status quo (no planning). The values of the simulation variables are shown in Table 5.

The threshold of eco-security indicator in the Chongming islands is determined based on system simulation and comparison of the three scenarios in compliance with the principle of the sustainable socio-economic development and ecological environment (Table 6).

In this model, the variable "net GDP," refers to GDP minus the losses from natural disasters, the impact of resources and environment on the economy (*i.e.*, capital consumption of resources and the environment); the loss of net GDP refers to the level of ecological risks under the specified socioeconomic development model and ecological environment. It is in inverse proportion to eco-security.

Table 5. The parameter values of the system simulation programs.

Program	GDP	GDP1	GDP2	GDP3	WCPG	ECPG	TRIP	ROAP	TRDP	RRE	RICI	IRDEZ	WAR	FCR
Status quo trend	13.34	1.88	17.11	13.46	145	1074.25	8.21	27.70	12	1	18	60	17	18
Program I	9.44	8.32	9.27	10.03	100	447.60	3.5	50	23.34	5	30	90	17	25
Program II	13.52	10.79	11.76	16.11	100	550.89	3.93	60	80	5	30	90	19	30
Program III	12	10.86	11.82	12.61	120*	859.40	4.10	35*	17.51*	—	25*	75	17	24

*The values are derived on the basis of statistical estimates; other values are index values of the programs.

Table 6. Indicator threshold of comprehensive assessment and standardization results of status value.

Indicator	Threshold Lower limit	Threshold Upper limit	Status value	Standardization results
C1	6	5.4	9.00	0.67
C2	3.5	3.18	8.21	0.43
C3	447.6	402.84	1074.25	0.42
C4	100	90	10.85	0.60
C10	65	71.5	27.70	0.43
C11	60	66	37.00	0.62
C12	35	38.5	18.00	0.51
C13	11.36	12.5	6.00	0.53
C14	11	12.1	10.00	0.91
C16	30	33	18.00	0.6
C17	100	110	83.00	0.83
C18	80	88	12.00	0.15
C19	5	5.5	1.00	0.20

The unit of indicators of C1, C2, and C3 are kg/10^8 yuan, kilowatt-hour/10^8 yuan and 108 ton/10^8 yuan, respectively; the other indicators unite are percent (%).

When the lower limit of the standard threshold values is placed within the model for simulation, through the observation of the value of "GDP minus net GDP," the verification result is shown in Table 7. As can be seen from Table 3, the values of "GDP minus net GDP" are all negative from years 2009 to 2016, which means that socio-economic development does not result in a deficit of resources and the environment. From 2017 to 2020, the values of "GDP minus net GDP" begin to be positive, but their verification values (in terms of percentage) are low (less than 0.1) and it has little impact on the eco-security. The security levels can be guaranteed through

Table 7. The verification result of threshold of eco-security.

Year	GDP	Net GDP	GDP–net GDP	Verification value
2009	146.513	222.939	−76.427	−0.522
2010	160.346	230.698	−70.352	−0.439
2011	175.706	239.357	−63.651	−0.362
2012	192.783	249.033	−56.250	−0.291
2013	211.789	259.855	−48.066	−0.227
2014	232.967	271.972	−39.005	−0.167
2015	256.591	285.552	−28.961	−0.113
2016	282.973	300.786	−17.813	−0.063
2017	312.466	317.891	−5.425	−0.017
2018	345.469	337.114	8.355	0.024
2019	382.437	358.734	23.703	0.062
2020	423.887	383.071	40.816	0.096

small-scale external input. Overall, the verification results are appropriate and it can be said that the threshold values can exhibit the main features of Chongming before 2020.

Eco-security Assessment Process

Because the assessment indicators have different units and the calculation methods differ, standardization of all indicators is required. According to the aim of comprehensive eco-security assessment, the indicators are compared with their criteria (*i.e.*, the threshold value) to standardize the data. For some indicators, the higher, the better. For other indicators, the lower, the better. Equation (1) is for the former case:

$$x_{ij} < s_{j,}\ z_{ij} = \frac{x_{ij}}{s_{ij}}\ (i = 1, 2, 3, \ldots n; j = 1, 2, 3, \ldots m); \quad x_{ij} \geq s_{j,} z_{ij} = 1 \tag{1}$$

Eq. (2), the latter case:

$$x_{ij} > s_{j,}\ z_{ij} = \frac{s_{ij}}{x_{ij}}\ (i = 1, 2, 3, \ldots n; j = 1, 2, 3, \ldots m); \quad x_{ij} \leq s_{j,} z_{ij} = 1 \tag{2}$$

where, x_{ij} is the current value of various indicators, s_{ij} is the standard value of the indicator, namely, the threshold value of the indicator, n is the number of evaluated regions, m is the number of assessment indicators.

Regional eco-security spatial variation is to make a horizontal comparison of the security levels of all the assessment units. Therefore, the method of differential standardization is adopted in order to standardize the data. The standardization formula of the indicators with positive effect (the higher the better) is Eq. (3):

$$\mathrm{Z}_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

The standardization formula of the indicators with negative effect (the lower the better) is Eq. (4):

$$\mathrm{Z}_i = 1 - \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{4}$$

where, x_i is the original value of an indicator, $x_{\min}$ is the minimum of an indicator, $x_{\max}$ is the maximum of an indicator, Z_i is the standardized value of an indicator.

The calculation of the eco-security composite indicator is made on the basis of comprehensive assessment model and the weighted sum model. The calculation formula is Eq. (5):

$$U = \sum_{i=1}^{n} w_i z_i \tag{5}$$

where, U is the comprehensive value of the indicator; Z_i is the standardization value of the indicator i; W_i is the weight co-efficient of the indicator i; n is the number of indicators.

The composite index grading method is adopted to determine the degree of regional eco-security. So in the study, the ecological system security index is divided into five grades, according to which ecological assessment is carried out to determine whether the region is in a safe condition. These rankings are as follows: I (a very high level of eco-security, with composite index of $\geq$0.9), II (a high level of eco-security, with composite index of 0.75–0.90), III (a middle level of eco-security, with composite index of 0.50–0.75), IV (a low level of eco-security, with composite index of 0.20–0.50), and V (a very low level of eco-security, with composite index $\leq$0.20).

RESULTS AND DISCUSSION

Results of Comprehensive Assessment

By using the aforementioned method to conduct a comprehensive assessment of eco-security, the assessment results of Chongming's eco-security in recent years can be obtained (Table 8).

The comprehensive assessment of Chongming's eco-security can be summarized as follows:

First, it can be seen from the result of a current eco-security assessment of Chongming that the eco-security of Chongming remains at Grade III (in 2008). The basic situation shows that Chongming is in the middle sensitive area. In this case, with the completion of the bridge project, the impact of economic and social pressure on eco-security will be a great challenge to Chongming in the near future.

Second, a comparison of the results of the comprehensive eco-security assessment between 2002 and 2008 shows that the comprehensive score of eco-security has been on the rise in recent years. The increasing reinforcement of eco-environment protection and building in policies and management enables the overall composite index to increase in recent years.

Third, in secondary composite index scores, the ecological health index is relatively higher while that of ecological risk and ecological protection is relatively lower. The latter are the main factors that constrain the comprehensive level of eco-security. It follows that under current circumstances to strengthen ecological construction, improve management and protection measures, and reduce the impact of ecological risks on the whole ecosystem of Chongming are ways to improve the grade of the comprehensive index of eco-security.

Result of Spatial Variation Assessment

In this study, eco-security of the 29 subareas in this area were evaluated and classified. According to the 2008 data, the spatial variation assessment result of the eco-security in Chongming can be obtained (Figure 5). Generally speaking, the grade of eco-security level at most subareas is not high and most remain at the middle or lower level and spatial variation are quite obvious.

At the same time, by analyzing the grading results of eco-security of the subareas (Figure 6), the distribution characteristics in the sub-domains are as follows.

Table 8. Valuation result of eco-security of Chongming from 2002 to 2008.

	2008	2007	2006	2005	2004	2003	2002
Ecological risk index	0.53	0.5	0.48	0.45	0.42	0.39	0.38
Ecological health index	0.58	0.55	0.53	0.5	0.52	0.51	0.49
Ecological protection index	0.48	0.37	0.34	0.29	0.26	0.24	0.22
Composite index	0.539	0.469	0.446	0.410	0.400	0.381	0.364

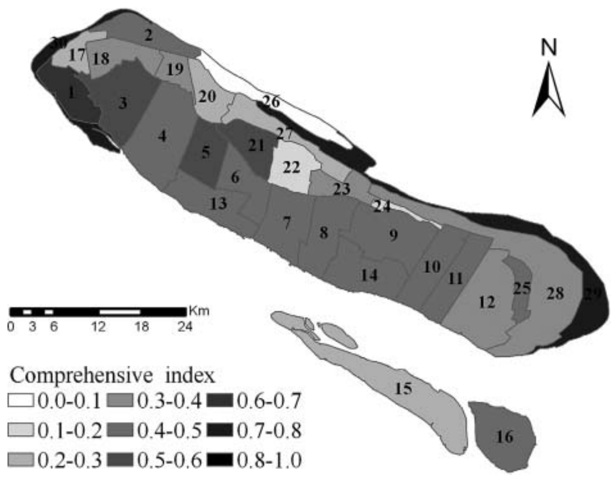

Figure 5. The result of spatial variations assessment. Notes: 1. Luhua 2. Xinxiang 3. Sanxing 4. Miaozhen 5. Zhenxi 6. Jianshe 7. Xinhe 8. Shuxin 9. Gangyan 10. Xianghua 11. Zhongxing 12. Chenjia 13. Chengqiao 14. Baozhen 15. Changxing 16. Hengsha 17. Yunjin Farm 18. Xinhai Farm 19. Hongxing Farm 20. Changzheng Farm 21. Dongfeng Farm 22. Changjiang Farm 23. Qianjin Farm 24. Fumin Farm 25. Qianshao Farm 26. Yonglong-Xinlong 27. Breeding ground 28. Dongtan 29. Dongtan natural reserve Figure 2: The result of space distribution of eco-security.

First, the composite index values of most subareas remain at the middle level. In the five grades of eco-security, no subarea arrives at the first level ($U \geq 0.90$) and only Dongtan natural reserve is at the second level ($0.90 > U \geq 0.75$). The third level includes 16 subareas, such as Luhua, Gangxi, and Shanxing and so on. The fourth level includes nine subareas, such as Chenjia, Qianjin, and Xinhai Farm and so on. The fifth level includes three subareas, namely Changjiang Farm, Fumin Farm, and Yonglong-Xinlong. Therefore, as far as regional eco-security is concerned, the majority of subareas remain at or below the middle level, and the proportion of low-score subareas is high. That means the comprehensive levels of eco-security remain to be improved.

Second, it can be seen that the distribution of the scores of the subareas within their respective range is relatively even and relatively high, with 11 between 0.6 and

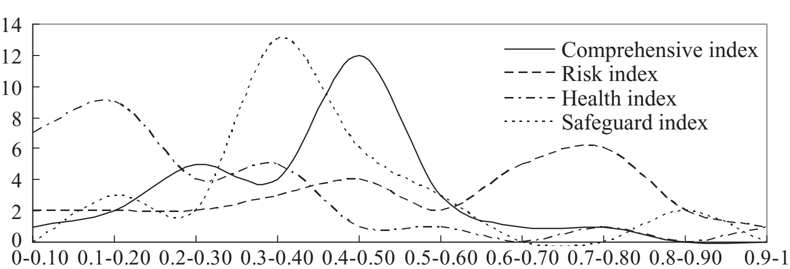

Figure 6. The distribution of eco-security grade of area cells.

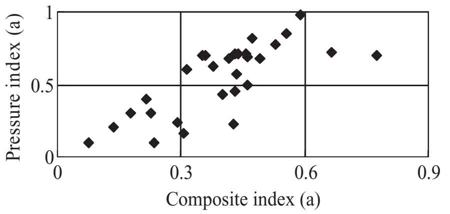

Figure 7. Sensitivity analysis of spatial variations assessment. (a) The primitive result of spatial variations assessment. (b) The assessment result with changing the weights. With the horizontal axis standing for the composite evaluation scores and the vertical axis for the ecological risk index scores.

0.8. The subareas with a high score are those areas with backward socioeconomy and a low level of natural disasters while the subareas with a low score are those with an advanced socio-economy and a high level of natural disasters. That is in line with the actual situation and the law of development. Therefore, in the process of strengthening the capacity of disaster prevention and mitigation, to make changes and innovations about the economic developmental model of Chongming and to replace the traditional economic development state for ecology-prioritized industries with a high added value are two steps essential if the scores of risk index are to improve.

Third, the scores of health index are low, with the subareas below 0.50 accounting for nearly 90%. The major reason is that the proportion of natural ecosystems (forests and wetlands) is low. Although the overall forest-covered area and wetland area in Chongming is larger than that in other regions of Shanghai, the distribution is concentrated in a small number of subareas. For example, the forest land is at Luhua township (58%), and beaches are concentrated at Dongtan. The two regions are the very areas with high scores. Besides, the overall irrational socioeconomic structure is also one of the reasons for the low scores.

Fourth, most of the ecological protection indices are below the middle, between 0.3 and 0.6. In relative terms, the scores of Chengqiao and Baozhen are higher. It is worth noting that Changxing Island achieves the lowest score in ecological protection index, and such a low response index is a worrisome trend considering its position as an equipment island.

Sensitivity Analysis

The uncertainties of a comprehensive evaluation system mainly come from weights and index scores. The index scores of this evaluation system are based on the actual measured data and the Statistical Yearbook. Therefore, given that uncertainty is introduced during the weighting process by AHP (Ni *et al.* 2006; Sun *et al.* 2010), the sensitivity analyses are conducted by changing the weights and investigating the effect on the result. With the spatial variation evaluation as an example, it is assumed that all index weights are equal, namely, 1/12. Shown in Figure 7 are the evaluation results for 29 subareas before and after the weight change, with the horizontal axis standing for the composite evaluation scores and the vertical axis for the ecological risk index scores (the choice is arbitrary and other alternatives do not affect the test result). It can be seen that weight changes do not greatly affect the overall evaluation results and that the scores of subareas exhibit little distributional change in the coordinate. The composite indices of 29 subareas vary with ±6.839% on average and the ecological risk indices vary with ±0.647% on average, while the weights of the twelve indicators vary with ±1114.25% on average. The variation range of overall evaluation scores is quite small, which demonstrates the reliability of the assessment approach.

CONCLUSION

Island ecosystems exhibit such typical features as vulnerability of the ecological environment, instability of the system, relative geographical independence and limited resources, and high incidence of natural disasters. Therefore, against the backdrop of rapid development of the global marine economy, the issue of island eco-security appears urgent and island eco-security research is of great significance to regional sustainable development. With the completion of the tunnel and bridge project, the eco-environment and resources of Chongming are faced with tremendous pressure, and, accordingly, the eco-security assessment is of great value to the sustainable development of Chongming.

Because the regional ecological system is a typical complex system, this study proposes the ANP-PRS-SENCE framework of regional eco-security assessment by using the method and theory of complex systems combined with a PSR model. Meanwhile, the eco-security threshold value of Chongming is determined based on the system dynamics modeling and simulation. It provides a fresh perspective on regional eco-security assessment and indicator threshold value.

The results of Chongming's eco-security assessment show that due to the implementation of eco-security protection measures, the composite index has been on the gradual rise in recent years. However, the overall level of eco-security remains at the third level. Therefore, in order to reduce ecological risk, ecological construction needs to be strengthened and management and protection measures need to be improved. They are the principal methods to improve the grade of eco-security comprehensive index. Meanwhile, due to the differences in regional ecological environment, the spatial distribution of Chongming's eco-security is appreciable. In the process of eco-security management, the differences in regional economy, population, natural disasters, and ecosystem types should all be taken into account so as to establish appropriate and effective corresponding measures and programs.

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REFERENCES

Ali K, Saysel YB, and Orban YJ. 2002. Environmental sustainability in an agricultural development project: A system dynamics approach. J Environ Manage 64:247–60

Barnthouse LW. 1992. The role of models in ecological risk assessment: A 1990's perspective. Environ Toxicol Chem 11:1751–60

Boughton DA, Smith ER, and O' Neill RV. 1999. Regional vulnerability: A conceptual framework. Ecosystem Health 5:312–22

Güneralp B and Barlas Y. 2003. Dynamic modelling of a shadow freshwater lake for ecological and economic sustainability. Ecological Modelling 167(1–2):115–38

He Y, You WH, and Wu J. 2006. Ecological security assessment of water environment in Shanghai. Chinese J Water Conservation 22(6):18–27

Jia YH, Zhao J, Nan ZR, *et al.* 2006. The application of entropy-right method to the study of eco-security evaluation of grassland: a case study at the eco-security evaluation of grassland to pastoral area of Gansu. Chinese J Ecology 25(8):1003–8

Ma SJ and Wang RS. 1984. Complex ecosystem of society, economy and nature. Acta Ecologica Sinica 4(1):1–9

Ni JR, Liu RZ, Wai OW, *et al.* 2006. Rapid zonation of abrupt mass movement hazard: Part I. General principles. Geomorphology 80(3–4):214–25

Peng Yi and Wen CH. 2004. A study of the forewarning index system for eco-security in vulnerable agricultural regions: the case of the upper reaches of the Pearl River. J Guizhou College of Finance and Econ 113(6):6–9

Qian HB, Xue YS, and Tian YJ. 2001. An overview of land resources rational use and assessment. China Land Sci 15:4–19

Qing HG, Wang RH, Ren ZY, *et al.* 2007. Regional eco-security assessment based on long periods of ecological footprint analysis. Resources, Conservation and Recycling 51:24–41

Saysel AK, Barlas Y, and Yenigun O. 2002. Long term sustainability in an agricultural development project: a system dynamics approach. Journal of Environmental Management 64:247–60

Shi HH, Gao M, Ding DW, *et al.* 2007. Advance of systemic dynamic complexities and its application in marine ecology research. Marine Environ Sci 26(6):594–600

Sun LY, Ni JR, and Alistair GL. 2010. Rapid assessment of sustainability in mainland China. J Environ Manage 91:1021–31

Tang J, She XY, and Lin NF. 2005. A study on system dynamics model in eco-environment planning for Da'an of Jilin Province. Acta Ecologica Sinica 25(5):1178–83

Thomas LS. 2004. Decision making-the analytic hierarchy and network processes (AHP/ANP). J Systems Sci Systems Engineer 13(1):1–35

Tuo XS, Chen XP, and Xue B. 2006. System dynamic simulation model of water-land resources carrying capacity in Minqin County. J Arid Land Resources Environ 20(6):78–83

Wang HM. 2006. National system of ecological security and strategic studies. PhD thesis, Northwestern Polytechnical University, 11–2

Wang MQ, Wang JD, and Liu JS. 2007. Research on urban eco-security assessment: a case study of Changchun. J Arid Land Resources Environ 21(3):72–6

Wikipedia. 2010. Ecosystem. http://en.wikipedia.org/wiki/Ecosystem

Xiao DN, Chen WB, and Guo FL. 2002. On the basic concepts and contents of eco-security. Chinese J App Ecol 13:354–8

Xie HL and Li B. 2004. A study on indices system and assessment criterion of eco-security for city. J Beijing Normal University (Natural Science) 40(5):705–10

Xu JP, Li XF, and Wu DS. 2009. Optimizing circular economy planning and risk analysis using system dynamics. Hum Ecol Risk Assess 15(2):316–31

Zhao YZ, Zou XY, Cheng H, *et al.* 2006. Assessing the eco-security of the Tibetan plateau: Methodology and a case study for Lhaze County. J Environ Manage 80:120–31

Zhou WH and Wang RS. 2005. Methodology assessment of urban eco-security-A case study of Beijing. Chinese J Ecol 24(7):848–52

Zuo W, Wang Q, and Wang WJ. 2002. Study on regional eco-security assessment index and standard. Geography and Territorial Res 19(1):67–71