Ocean & Coastal Management 120 (2016) 39–48

Contents lists available at ScienceDirect

Ocean & Coastal Management

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

Prediction analysis model of integrated carrying capacity using set pair analysis

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ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form
12 November 2015
Accepted 15 November 2015
Available online 11 December 2015

Keywords:
Integrated carrying capacity
Set pair analysis
Prediction analysis
Entergy method
Principal component

ABSTRACT

As a comprehensive capacity of nature, society and humans, integrated carrying capacity (ICC) is the driving force of regional socioeconomic development. Only when an ecosystem is under-loaded can socioeconomic development be sustainable. ICC is an accumulative total value of each indicator's carrying capacity, which reflects a static status. The ICC prediction analysis is one prerequisite to making economic development plans. In this paper, a dynamic prediction model is developed by using the model of set pair analysis (SPA) to predict the growth tendency of ICC. The model is tested in a case comprising eight coastal cities in Yangtze. (1) The average error rate of this prediction model is merely 0.38%, and the lowest error rate is 0.01%. The SPA model is better to predict ICC tendencies. (2) According to the national development plan, the eight cities' ICC is predicted in 2015. (3) The prediction model is a multiple method that can contain all indicators of ICC. This model can estimate the maximal carrying capacity of a natural ecosystem to make the most suitable economic development policy. The socioeconomic development must comply with the under-loaded capacity to maintain sustainable development.

1. Introduction

The theory of carrying capacity (CC) was first proposed in the field of mechanics (Malthus, 1798). Since this theory was first introduced to the research field of ecosystems, ecological accommodation, resources, and environmental issues have been investigated gradually (Bishop and Crawford, 1997; Hadwen and Palmer, 1922; Lane, 2010; Leopold, 1941; Perry and Schweigert, 2008; Zacarias et al., 2011). The ecosystem of our world is a compound system of nature, society and humans. Given the complexity of the ecosystem, each subsystem's contribution to the entire ecosystem should be combined. The integrated carrying capacity (ICC) represents the integrated capacity of the natural resources in a given period and space that is able to support long-term sustainable regional development (Ye and Wei, 2012).

With the theory of multi-indicator frames, a variety of methods have been developed to calculate the carrying capacity, especially in terms of ecological footprint, comprehensive index evaluation, system dynamic model, and artificial neural network (Fu and Li, 2008; Gao, 2011; Liu et al., 2012; Yang, 2009). In the early 1990s, William (1990) proposed the ecological footprint concept and the calculation method for assessing the biologically productive land and marine area required to produce the resources a population consumes and absorb the corresponding waste. Slesser (1990) presented a new method to evaluate resource and environmental CC by using the model of evolution of capital creation option (ECCO), which aimed to analyze the relationships among humans, resources, the environment and development. In China, Zhang et al. (2011) compared the differences between assessing methods using fuzzy mathematics and system dynamics based on time series analysis, linear analysis and regression analysis to predict the carrying capacity tendencies. Gao (2011) constructed a system dynamic model of the water resource and the population to predict the carrying capacity evolution in three different scenarios of water resources by using the Vensim software program.

The socioeconomic development of coastal areas is especially

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http://dx.doi.org/10.1016/j.ocecoaman.2015.11.011
0964-5691/

rapid in countries around the world. With overexploitation of natural resources and deterioration of the ecological environment, the stability of the ecosystem is declining quickly. The prerequisite of economic development is an under-loaded natural ecosystem. The prediction analysis of ICC is an effective way to judge between under-loaded and up-loaded, which determines whether an economic development plan will be accelerated or decelerated.

Existing research has mainly focused on the static status of carrying capacity. The conclusion merely reflects the influence of socioeconomic development on the ecological environment. Moreover, the study method must comply with some restrictions. Certain randomness and fuzziness indicators are often valued based on artificial experience. Such research cannot represent the capacity of a natural ecosystem to support social development. In ICC research, the prediction is just intended to analyze the tendency of specific indicators. Because nature is a complicated and integrated ecosystem, we should include the indicators of all ecosystems to predict ICC. In this paper, a dynamic model is proposed to predict the tendency of ICC and thus provide a meaningful reference for socioeconomic development plans.

2. Materials and methods

2.1. Integrated carrying capacity

Based on the indicator model of driving forces–pressure–state–response–control (Xu and Ye, 2008), the index system of carrying capacity contains three categories: pressure, status and response. Given the environmental and economic conditions of a study area, the index system contains nine first-class indicators and eleven second-class indicators (Table 1). According to the availability of data, this system can be further refined to a third class. The indicator system is presented in Table 1 and is applicable to integrated carrying capacity evaluation of coastal cities in the Yangtze River Delta (Wei et al., 2014).

The state–space method is an effective and quantitative method to describe and evaluate an ecosystem's carrying capacity (Mao and Yu, 2001; Wang and Zou, 2007). The state–space method is a Euclidean geometry space state that is constructed by a three-dimensional axis. In the ecosystem, the three-dimensional axis contains human–society economy, regional resources and environment (Fig. 1). The formula to calculate ICC is as follows:

$$RCC = \sqrt{\sum_{i=1}^{n} \omega_i x_i^2} \tag{1}$$

where x_i is the indicator's normalization value, ω_i is the indicator's weight, and n is the total number of indicators.

2.2. Set pair analysis (SPA)

2.2.1. Theory of SPA

In nature, one object must be associated with others, which is defined as association degree. Zhao (1989) proposed a method of set pair analysis (SPA) by using an uncertainty system analysis theory, also known as connection mathematics. Based on the theory of identical–discrepancy–contrary (IDC), this method solves the certainty or uncertainty problem by using quantitative analysis. The SPA method has been applied in evaluation, management, prediction, decision-making and planning (Qiu et al., 2007; Yao et al., 2010; Zhang et al., 2003).

The ICC reflects the capacity of a natural ecosystem to support socioeconomic development. Base on the multiple index system, ICC is composed of indicator values. There is an association relationship between ICC and indicators, which is a stationary degree. Considering the object as a set, the pair relationship provides a quantitative description of identity, discrepancy and contrary of two sets. This model is used to analyze the set pair and its association degree.

In the theory of SPA, the identity and contrary are easily determined, but the discrepancy is uncertain. By using the mathematical method, the association degree can be calculated. Let A and B be two sets, and let N be the total number of element characteristics in the sets. Assuming that S is the total number of identical characteristics, F is the total number of contrary characteristics and P is the total number of discrepancy characteristics, we have $N = S + P + F$. The association degree is obtained by using the following formula:

$$\mu = \frac{S}{N} + \frac{P}{N} + \frac{F}{N} = a + bi + cj \tag{2}$$

where μ is the association degree, $S/N\,(a)$ is the identical degree of A and B, $P/N\,(b)$ is the discrepancy, $F/N\,(c)$ is the contrary degree, i is the coefficient of discrepancy ($i \in [-1, 1]$), and j is the coefficient of contrary ($j = -1$). Meanwhile, $a,b,c > 0$, $a + b + c = 1$. The formula can be improved:

$$\mu' = a + bi \tag{3}$$

$$\mu' = a + cj \tag{4}$$

$$\mu' = bi + cj \tag{5}$$

2.2.2. Prediction model

With the association degree between ICC and indicators, the ICC tendency is represented by the indicator's growth rate. Let A be the study target, the classification set of A be $B = \{B_1, B_2, \ldots, B_m\}$, and the

Table 1
The ICC assessment indicator system of Yangtze coastal.

First-class indicator	Second-class indicator
coastal environment pressure	pollution and energy consumption
coastal development intensity	coastal line utilization intensity
coastal available resource	available space resource
	available biology resource
marine environmental quality status	ocean environmental quality
coastal population density	population density
coastal economic development level	regional economic development level
coastal ecological assets	coastal ecosystem service value
scientific and technological support conditions	science and technology innovation ability
society support conditions	external contribution ability
	infrastructure and protection