ARTICLE IN PRESS

Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Evaluation on island ecological vulnerability and its spatial heterogeneity

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ARTICLE INFO

Keywords:
Island ecosystem
Island ecological vulnerability (IEV)
Spatial heterogeneity
Sensitivity analysis
Different scales
The southern islands of Miaodao Archipelago

ABSTRACT

The evaluation on island ecological vulnerability (IEV) can help reveal the comprehensive characteristics of the island ecosystem and provide reference for controlling human activities on islands. An IEV evaluation model which reflects the land–sea dual features, natural and anthropogenic attributes, and spatial heterogeneity of the island ecosystem was established, and the southern islands of Miaodao Archipelago in North China were taken as the study area. The IEV, its spatial heterogeneity, and its sensitivities to the evaluation elements were analyzed. Results indicated that the IEV was in status of mild vulnerability in the archipelago scale, and population pressure, ecosystem productivity, environmental quality, landscape pattern, and economic development were the sensitive elements. The IEV showed significant spatial heterogeneities both in land and surrounding waters sub-ecosystems. Construction scale control, optimization of development allocation, improvement of exploitation methods, and reasonable ecological construction are important measures to control the IEV.

1. Introduction

Island is not only the storage pool of important ecological functions and the living carrier of human beings, but is also the platform of ocean conservation and exploitation (Jupiter et al., 2014; Chi et al., 2015a). In recent years, the increasing human activities on islands, such as urban construction, tourism, aquaculture, and shipping, have profoundly affected the island ecosystem, threatened island biodiversity, decreased the ecosystem productivity, deteriorated the environmental quality, and changed the landscape pattern (Dahlin et al., 2014; Benitez-Capistros et al., 2014; Chi et al., 2015b; Chi et al., 2016). Thus, the island ecosystem and its vulnerability have aroused a significant concern. The island ecosystem is a special ecosystem that includes the land and surrounding waters sub-ecosystems, which are composed of interacting natural and anthropogenic factors (Shi et al., 2009; Chi et al., 2015a). Island ecological vulnerability (IEV) is the vulnerability to damage and the difficulty of restoration under unique conditions and various disturbances, and long-term, heterogeneity and controllability are the typical features of IEV (Chi et al., 2015a). Ecological vulnerability and ecological sensitivity are similar and both originated from the concept of ecotone (Dow, 1992). Ecotone emphasizes the regional particularity. Meanwhile, ecological sensitivity focuses on the features of susceptibility to damage. In comparison, ecological vulnerability contains more connotations, which can reflect not only the features of land–sea interface, resources shortage, independence, and completeness, but also the degradation and restoration of the island ecosystem. Therefore, conducting evaluation on IEV, which helps reveal the comprehensive characteristics of the island ecosystem and provide reference for controlling human activities and protecting the island ecosystem, is of a great significance.

The land–sea dual features of the island ecosystem should be the first consideration in the comprehensive evaluation of IEV. Land sub-ecosystem has the common characteristics of a continental ecosystem and is similar with the mainland in terms of biological community and habitat (Lagerström et al., 2013; Nogué et al., 2013), yet has the uniqueness of limited area and isolated space (Chi et al., 2015a). Surrounding waters sub-ecosystem has the common characteristics of a marine ecosystem, but shows significant spatial heterogeneity because of the separation effect of islands (Shen et al., 2016). These two sub-ecosystems have marked differences and close interrelations; therefore, balancing the unity and difference of their vulnerabilities is an important issue. Second, the island ecosystem simultaneously possesses natural and anthropogenic attributes and is now a natural–anthropogenic complex ecosystem because of the increasing island exploitation activities, especially in China (Ma and Wang, 1984). Thus, natural and anthropogenic factors and their relationships should be given thorough

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http://dx.doi.org/10.1016/j.marpolbul.2017.08.028
Received 19 December 2016; Received in revised form 8 August 2017; Accepted 13 August 2017
0025-326X/

Please cite this article as: Chi, Y., Marine Pollution Bulletin (2017), http://dx.doi.org/10.1016/j.marpolbul.2017.08.028

consideration when evaluating IEV. In addition, islands are commonly clustered in the form of an archipelago, and all islands in an archipelago are related and interact with each other to form a unity. Meanwhile, significant differences exist in the basic features of the islands in an archipelago, such as areas, mutual distances, and terrain conditions (Vogiatzakis et al., 2008).

Moreover, heterogeneous human activities, which account for the significant spatial heterogeneity of IEV, have been increasing. Many scholars conducted researches on the island ecosystem and its vulnerability to study their variation characteristics under the background of climate change and sea level rise or facing natural disturbances, such as typhoon, sea water intrusion, and biological invasion (Yamano, 2008; Baumberger et al., 2012; Morgan and Werner, 2014; Taramelli et al., 2015). The economic vulnerability of island countries was also given attention in several studies (Te'o, 2007; McGillivray et al., 2010; Guillaumont, 2010). However, these studies mostly considered vulnerability as the inherent feature of the island ecosystem and paid less attention to the vulnerability caused by human activities (Bonati, 2014). These studies have certain significances for island conservation, but lack applicability in regions with intensified human activities, especially in China, where the marine economy has been developing rapidly and island exploitation and conservation are now ascending. Meanwhile, current studies are unable to adequately reflect the land–sea dual features of the island ecosystem and their spatial heterogeneity. Therefore, the studies could not comprehensively reveal the IEV and its spatial characteristics.

An IEV evaluation model, which reflects the land–sea dual features, natural and anthropogenic attributes, and their spatial heterogeneities, was established in this paper. The southern islands of Miaodao Archipelago in North China were taken as an example, and the IEV and its spatial heterogeneity were clarified to provide a basis for maintaining the island ecosystem and a new method for the evaluation of the island ecosystem.

2. Materials and methods

2.1. IEV evaluation model establishment

2.1.1. Index system

The index system of the IEV model was established based on "exposure–sensitivity–adaptability" framework (Wan et al., 2006; IPCC, 2007; Zhang et al., 2013), and the "objective–element–index layers" structure was adopted. The index system consisted of 1 objective, 3 sub-objectives, 10 elements, and 18 indices. The objective layer took the IEV as the objective, including three sub-objectives: exposure (E), sensitivity (S), and adaptability (A). The elements were selected based on the comprehensive consideration of natural and anthropogenic factors. Indices were selected according to the land–sea dual features and their spatial heterogeneity (Table 1).

2.1.2. Index calculation

2.1.2.1. Exploitation intensity (B2). Exploitation intensity includes two indices: land exploitation intensity (C2) and surrounding waters exploitation intensity (C3). Specific calculation methods and evaluation standards are shown in Table 2 (State Oceanic Administration PRC, 2015b).

LA was calculated using the formula below:

$$LA = \sum_{i=1}^{n} LA_i \times LR_i \tag{1}$$

where LA_i is the area of land use type *i* and LR_i is the influence coefficient of land use type *i* on the land sub-ecosystem. The influence coefficient of industry, mining, warehousing and transportation is given as 1.0; the influence coefficient of water conservancy facility and aquaculture pond is given as 0.8; the influence coefficient of residence and public service is given as 0.6; the influence coefficient of farmland is given as 0.4; and the influence coefficient of garden and plantation is given as 0.2 (State Oceanic Administration PRC, 2015b).

SA was calculated using the formula below:

$$SA = \frac{\sum_{i=1}^{n} SA_i \times SR_i}{PM_O} \tag{2}$$

where SA_i is the area of sea area use type i, SR_i is the influence coefficient of sea area use type *i* on the surrounding waters sub-ecosystem. The influence coefficient of infrastructure, urban construction, waste dumping, electric power industry, shipbuilding industry, chemical industry, steel industry, and aquatic products processing industry is given as 1.0; the influence coefficient of reclamation aquaculture, port, and saltern is given as 0.8; the influence coefficient of sewage discharge, cable and pipeline is given as 0.6; the influence coefficient of road, bridge, fairway, and anchorage is given as 0.4; and the influence coefficient of open aquaculture, solid mineral exploitation, and tourism is given as 0.2 (State Oceanic Administration PRC, 2015b). P_{MO} is the marine space exploitation standards, which are calculated based on marine functional zoning (State Oceanic Administration PRC, 2012).

2.1.2.2. Terrain (B3). The terrain has one index, which is the steep region proportion (C4). The calculation method and evaluation standard are shown in Table 2.

2.1.2.3. Ecosystem productivity (B4). Ecosystem productivity is composed of two indices: land net primary productivity (C5) and surrounding waters primary productivity (C6).

Land net primary productivity is calculated based on the Carnegie-Ames-Stanford Approach (CASA) model (Potter et al., 1993), which requires remote sensing data, meteorological data and field investigation. The estimation method is as follows:

$$LNPP(x,t) = APAR(x,t) \times \xi(x,t) \tag{3}$$

$$APAR(x,t) = PAR(x,t) \times FPAR(x,t) \tag{4}$$

$$\xi(x,t) = ft(t) \times fw(t) \times \xi_{\max} \tag{5}$$

where $LNPP(x,t)$ is the net primary productivity of position x in month t; $APAR(x,t)$ is the absorbed photosynthetic active radiation of position x in month t (MJ m^{-2} $month^{-1}$); $\xi(x,t)$ is the actual light utilization efficiency of position x in month t (g C MJ^{-1}); $PAR(x,t)$ is the photosynthetic active radiation of position x in month t (MJ m^{-2} $month^{-1}$), $FPAR(x,t)$ is the fraction of photosynthetic active radiation of position x in month t (%); $ft(t)$ and $fw(t)$ are the temperature and water stress factors in month t (%), respectively; and $\xi_{\max}$ is the maximum light use efficiency of different vegetation (g C MJ^{-1}). The average annual value of *LNPP* is calculated based on the result of each month, and the detailed calculation method was reported by Chi et al. (2015b).

Surrounding waters primary productivity is calculated based on the chlorophyll method, using the simplified formula proposed by Cadée and Hegeman (1974), which is as follows:

$$SPP(x) = P_s \times E \times D/2 \tag{6}$$

where $SPP(x)$ is the daily primary productivity in a season of position x (mg C m^{-2} d^{-1}); P_s is the phytoplankton potential productivity in surface water (< 1 m); E is the euphotic depth, which is given as three times of transparency (m); and D is the daylight hours (h). P_s is calculated using the following formula:

$$P_s = C_a \times Q \tag{7}$$

where C_a is the chlorophyll *a* (*Chl-a*) content of the surface water (mg m^{-3}); Q is the assimilatory coefficient [mg C·(mg $Chl\text{-}a)^{-1}$ h^{-1}], an empirical value of 3.7 is adopted (Ryther, 1969). The surrounding waters annual primary productivity is calculated according to the daily primary productivity in different seasons.