Ecological Indicators 84 (2018) 82–95

Contents lists available at ScienceDirect

Ecological Indicators

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

Research paper

An improved method for integrated ecosystem health assessments based on the structure and function of coastal ecosystems: A case study of the Jiangsu coastal area, China

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ARTICLE INFO

Keywords:
Ecosystem health assessment
Community structure
Eco-exergy
Coastal ecosystem
Jiangsu

ABSTRACT

Ecosystem health status assessment is very complex and requires an integrated approach based on combined and synoptic estimates of the environmental background and the study of the structure and function of different ecosystems at a systems level. Here, we present the main results gained over six years (2006–2007, 2009–2012) with the aim of obtaining concise and comprehensive assessment results at 30 routine investigation sites in the Jiangsu coastal area. Our improved approach follows consecutive and interconnected steps. First, we conducted a quantitative assessment of community structure, including species abundance, biomass, and diversity utilizing a multidimensional scaling method. Then, a systemic functional assessment was carried out at the genetic level, including eco-exergy and structural eco-exergy, using a means clustering method, passing through a dimensionless polygonal area to reflect the integrated assessment results. Our results indicate that among the four seasons, the health status was best in autumn, followed by spring and winter, and worst in summer. Among the six assessed years, 2006 had the best health status, whereas 2012 had the worst. The general trend of annual variation in ecosystem health status was in decline. As for the regions, the health status was good or moderate in the southern and northern regions, and worst in the central region. Various human interventions and environmental stresses contributed to the stability and resilience of the ecosystem at different time scales and in different areas; however, these effects were not absolutely negative. This new method has strong applicability for assessing the status of ecosystems composed of several communities, as long as the eco-exergy quality and community structure of the system can be estimated.

1. Introduction

Ecosystem health assessments are a vital part of ecosystem protection and monitoring. The concept of ecosystem health was first proposed by Rapport et al. (1985), who defined ecosystem health as the stability and sustainability of a system; that is, the ability of a system to maintain its organizational structure, self-regulate and recover after stress. Costanza et al. (1992) proposed that "ecosystem health is closely linked to the idea of sustainability, which is seen to be a comprehensive, multi-scale, dynamic measure of system resilience, organization, and vigor." Marine ecosystems, composed of complex biological communities and environmental conditions under anthropogenic influences, not only provide numerous valuable sources of food and services but are also the ultimate destination for many global pollutants. Furthermore, marine ecosystems, and especially coastal ecosystem, can adjust the dynamic balance of the global ecosystem, which is of great significance to human survival and development. Therefore, the definition of the concept of coastal ecosystem health (Birkeet and Rapport, 1996; EU Water Framework Directive in Pollard and Huxham, 1998; Boesch and Paul, 2001; GB/T 12763.9, 2007) as well as the evaluation methods used for and the results of coastal ecosystem health assessments are widely considered by relevant managers (Xu et al., 2004; Jorge and Sara, 2009; Muniz et al., 2011; Berezina et al., 2017).

Coastal areas, at the boundary of continental land and the sea, exhibit a high level of heterogeneity at biological and environmental levels (Guallar and Flos, 2017), particularly in areas of intensive

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http://dx.doi.org/10.1016/j.ecolind.2017.08.031
Received 23 May 2017; Received in revised form 25 July 2017; Accepted 12 August 2017
Available online 31 August 2017

anthropogenic activity, such as the Jiangsu area, which leads to physicochemical alterations, habitat destruction and changes in biodiversity (Borja et al., 2012). Every year from 1997 to 2015, marine environmental bulletin data have been made available by the China Oceanic Information Network (COIN, http://www.coi.gov.cn/gongbao/). The results of these inspections indicated that the ecological monitoring areas of mangroves, coral reefs and seaweed bed ecosystems have basically maintained their health; however, coastal and estuarine ecosystems were mainly found to be in a sub-healthy or an unhealthy state from 2006 to 2012. Direct or indirect human influences have significantly modified coastal ecosystems, leading to alteration of their functions (Franzo et al., 2015).

Integrative assessment of coastal ecosystem health, which should be preceded by a comprehensive and accurate assessment system, has become a focus of ecological research in recent years, and the stabilization and maintenance of costal ecosystems is the ultimate goal for increasing environmental protection among management entities (Tang et al., 2015). Over the last decade, efforts have been made by researchers to develop integral methodologies for assessing environmental and ecological status, including the structure, processes and functions of coastal ecosystems, together with environmental indexes, on the basis of anthropogenic interference in a given area (Borja et al., 2009; Fletcher et al., 2014). However, several well-established assessment systems, such as ecological risk assessment (ERA) (Caeiro et al., 2016), ecosystem services approach (ESA) (Uehara and Mineo, 2017), and weight of evidence (WOE) (Bebianno et al., 2015), focus more on assessing pollution than on evaluating the integrity of the ecosystem. Thus, not all integrative approaches are intended to assess ecological health at the ecosystem level, which would allow a more efficient response to the requirements of an ecosystem-based assessment of ecosystem health than evaluations performed at the species or biochemical level.

In this study, the integrated ecosystem health assessment approach (IEHA) was improved by combining indexes of biodiversity and eco-exergy, considering the regional environmental background and using a dimensionless polygonal area to produce integrated assessment results. Based on this approach, community structure and biodiversity measures were characterized based on a range of species functional categories that indicate the macro-community structure and stability of an ecosystem (Annacamilla and Paolo, 2008; Mace et al., 2012; Donohue et al., 2013). Thermodynamic structure and eco-exergy measures were characterized according to the quantity and quality of the system's biomass at a genetic level, and increases in the values of these parameters are generally considered to be a measure of ecosystem efficiency, quality and function (Bendoricchio and Jørgensen, 1997; Pusceddu and Danovaro, 2009; Silow and Mokry, 2010; Vassallo et al., 2013; Tang et al., 2015). The amount of workable energy stored in the various living components of a system is an important aspect of each ecosystem. Eco-exergy (Ex) is a useful integrative metric that synoptically explains the ability and function of a system, whereas structure eco-exergy (Exst) expresses the overall efficiency of a system and its ability to transport biomass through the trophic chain towards higher levels and more complex organisms (Marques et al., 1997; Pacala and Kinzig, 2002; Vassallo et al., 2012; Veríssimo et al., 2016). Thus, eco-exergy indicators are the most important goal function reflecting the total energy of the constituent components and can be considered good indicators of a system's status (Zhang et al., 2003). Therefore, the thermodynamic structure based on eco-exergy indicators varies among different organisms according to their genetic complexity. Compared with the traditional approach, this improved IEHA has the advantage of being able to assess ecological health status at the system level, not only indicating spatial heterogeneity, multilevel phenomena, and multiple variables of interest at multiple timescales in ecosystems but also reflecting the final assessment results concisely and comprehensively. Thus, the aims of this study were as follows: (1) to identify the grade of thermodynamic structure and community structure in coastal ecosystems using eco-exergy and diversity indicators; (2) to reveal the temporal and spatial variability of ecosystem health in the Jiangsu coastal area; and (3) to improve the integrity of the technical routes and methods used for coastal ecosystem health assessment.

2. Materials and methods

2.1. Study area

In situ observations and samplings were conducted in the Jiangsu coastal area, which has a 954-km-long coastline from the mouth of the Xiuzhen River in the south to the north bank of the Yangtze River, as shown in Fig. 1. The coastline is classified into three different geographical areas (Haizhou Bay, the Radial Sand Ridges, and the north shore of the Yangtze Estuary, from north to south) based on a variety of diverse hydrological, physiographic, and nutrient conditions (Tang et al., 2015). The region includes twelve counties and urban districts in the municipalities of Lianyungang, Yancheng and Nantong. The substrata and sediment vary across the region, with silty-muddy coast extending for 884 km, constituting approximately 93% of the Jiangsu coastline. The remaining coastline in Lianyungang is sandy and rocky, accounting for 3% and 4% of the Jiangsu coast, respectively (Zou, 2004; Zhang and Wang, 2009).

2.2. Data collection

This study was based on six years of data, where data from the period 2006 to 2007 were used as the background source for seasonal variation analysis, and data from the period 2009t o 2012 were employed the source for the assessment of annual variability. The 2006–2007 data were obtained from the “908 National Marine Special Investigation Project”, and the 2009–2012 data were obtained from the Marine Biological Survey conducted by the Institute of Oceanology & Marine Fisheries of Jiangsu.

We collected environmental data and biological samples from 30 sites distributed throughout our study area from four cruises conducted in 2006 to 2007 and obtained biological data from the same sites during 2009–2012 (for details, see Supplementary Information SI1). Each cruise dataset included the following physiochemical information about seawater and sediment: the sea surface temperature (SST), salinity (S), depth (D), dissolved oxygen (DO), nutrients, chlorophyll a (Chl-a), pH and alkalinity of the seawater and the total organic carbon (TOC), total nitrogen (TN), and heavy metals contents of the sediment. Biological data for different body sizes (micro, small, medium and large), including the species, number, density and biomass of different communities (phytoplankton, zooplankton, benthos and nekton), were also obtained. Furthermore, missing data for some sites could be eliminated using SPSS Statistics 17.0 (Listwise Deletion) without affecting the overall results (Pigott, 2001; Karanja et al., 2013). We integrated and evaluated the physicochemical properties of the water and sediment samples. Community structure indexes (i.e., species abundance, diversity, and evenness) and eco-exergy indexes for each community were also calculated.

2.3. Assessment methods

2.3.1. Community structure assessment system

Species abundance is a widely used index for measuring biodiversity, that is intuitive and easy to evaluate statistically. The Shannon index, Simpson index and Margalef index are most commonly used in biodiversity index systems, and other indexes are employed relatively rarely. The commonly used biodiversity indexes calculated in this study are provided in the Supplementary Materials (Table S1).

We used multidimensional scaling (MDS) to classify the biodiversity index results. MDS refers to a set of related ordination techniques employed for information visualization, particularly to display the