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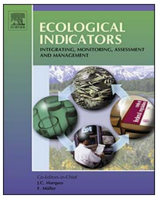

Spatiotemporal characteristics and ecological effects of the human interference index of the Yellow River Delta in the last 30 years

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ABSTRACT

The accurate quantification and spatial evaluation of human activity intensity is highly significant for determining the resource and environment carrying capacities of coastal areas. A human interference index (HII) was established in our study based on the minimum and maximum influences of exploitation types, the different ecological conditions within the same exploitation type and the buffer effect of exploitation on adjacent areas. It was characterized by the comprehensive consideration of the ecological features and their spatial heterogeneity. To validate the accuracy and applicability of HII, the Yellow River Delta was selected as the study area, with the years of 1987, 1995, 2005 and 2016 as the temporal scope. Then, to clarify the ecological significance of HII, the relationships of landscape pattern, vegetation net primary productivity (NPP) and soil property with HII were analyzed. The HII of the study area exhibited a continuous increase and spatial heterogeneities from 1987 to 2016. The proportion of the little interference zone kept on decreasing, the proportions of the intermediate, severe and very severe interference zones continued increasing, and the proportion of the mild interference zone initially increased and then slightly decreased. Human interference spread continuously and has been the main driving factor of ecosystem change. The HII is significantly positively correlated with patch density, edge density, and soil salinity, and negatively correlated with NPP and soil moisture content. The HII was proven to possess high accuracy, good applicability and considerable ecological significance. Therefore, it can be widely used in the evaluation of human activity intensity in coastal areas.

1. Introduction

Human activities have gradually become the main driving force of global ecosystem degradation since the mid-20th century (Simpson and Christensen, 1997; Olson et al., 1997; Franoise and Jacques, 2003). At present, human activities have spread worldwide and profoundly influenced the natural ecosystems (Halpern et al., 2008; Strohbach and Haase, 2012; Chi et al., 2016, 2017a). The influences of human exploitation activities are presented in various aspects, including considerable changes in landscape patterns, increase in fragmentation (Nagashima et al., 2002), destruction of plant communities (Ramalho et al., 2014) and disturbance to soil ecological processes (Li et al., 2014). Many studies on the quantification of human activity intensity have been effectively conducted in the past several years (Sanderson et al., 2002; Brown and Vivas, 2005; Wang and Yu, 2013; Xu et al., 2015; Di et al., 2015; Cen et al., 2015; Xu et al., 2016; Chi et al., 2017b; Peng et al., 2017; Wellmann et al., 2018). In most of these studies, each human exploitation type was assigned an influence coefficient (IC), which was a constant and ranged from 0 to 1 for distinguishing the influence of the exploitation type on the natural ecosystem. Then, human activity intensity was calculated based on the areas and ICs of the exploitation types within a specific region; for example, an area of 1 km^2 contained an exploitation type with an area of 0.5 km^2, and the IC of the exploitation type was assigned 0.8, thus the intensity was 0.4. Several good results have been achieved based on the aforementioned method, but certain problems remained. First, one exploitation type was assigned a constant as the IC, indicating that the human activity intensity of the exploitation type was spatially homogeneous. In fact, differences of ecological influences may occur in different positions within the same exploitation type (Chi et al., 2017a). The IC using a constant neglected the spatial differences within the same exploitation type. Second, the influences of exploitation types on occupied areas have been analyzed; however, analyses of the influences on adjacent areas, which cannot be disregarded, were always lacking (Chi et al., 2017c). Third, the focus was always on the scope of the entire study area, but the exhibition of spatial heterogeneity within the study area

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remained insufficient. Therefore, we establish a human activity intensity index, namely, human interference index (HII) based on the exploitation type, ecological condition and buffer effect. The HII is aiming to cover the deficiencies of the present method and achieve high accuracy, good applicability and considerable ecological significance.

The coastal wetland is the terrestrial and marine ecotone with high ecological values (Costanza et al., 1997). It exhibits various ecological functions, including blue carbon sequestration, biodiversity maintenance, environmental purification and coastal erosion prevention (Barbier et al., 2008; Mcleod et al., 2011; Duarte et al., 2013; Temmerman et al., 2013). However, numerous human activities occur in coastal areas due to the special location and unique natural resources. Consequently, coastal areas suffer from the comprehensive effects of natural and human factors (Shabman and Batie, 1978; Chi et al., 2017a). Human interferences, including coastal reclamation, vegetation occupation and pollutant emission, severely threaten the stability of wetland ecosystem (Selman et al., 2008; Wang and Yu, 2013). Meanwhile, the intensive land-sea interaction results in the obvious spatial heterogeneity of the natural condition, and also constrains the human activities (Xu and Zhang, 2007). The accurate quantification of human activity intensity is highly important for identifying the influences of human activities on natural ecosystems, as well as for determining the resource and environment carrying capacities of coastal areas (Xu et al., 2015; Chi et al., 2017b). The HII is characterized by the comprehensive consideration of the ecological features and their spatial heterogeneity. Therefore, it is suitable for evaluating the spatiotemporal characteristics of human activity intensity in coastal wetland. The Yellow River Delta, a typical coastal wetland in North China, was selected as the study area to validate the accuracy, applicability and ecological significance of HII. The Yellow River Delta is one of the three largest deltas in China. It is a estuarine wetland ecosystem with a large amount of sediment input. It is covered with various wetland vegetations and provides an important habitat for rare and endangered bird species but exhibits obvious vulnerability (Sun et al., 2017; An et al., 2017). In recent years, human activities in the Yellow River Delta have increased intensively. Human interferences, such as urban construction, harbor construction, oil extraction and production, farming and saltern reclamation, have resulted in the complex land cover types, the expansion of artificial landscape and the shrinkage of natural wetlands (Cai et al., 2004; Wang et al., 2012). The Yellow River Delta is among the deltas in the world with the most severe land-sea interaction and the fastest ecosystem change due to the comprehensive effects of natural and human factors (Deng and Bai, 2012). Many scholars have conducted researches on the wetland ecosystem of the Yellow River Delta (Xu et al., 2004; Cui et al., 2009; Chu et al., 2016; Zhang et al., 2017). However, studies on the spatial distribution of human activity intensity in decades remain insufficient; the quantification and ecological effects of the human activity are particularly lacking. Thus, they couldn't provide strong technical support for the coastal ecosystem-based management of the Yellow River Delta. In our study, the modern Yellow River Delta was selected as the spatial extent, and the years of 1987, 1995, 2005, and 2016 were selected as the temporal scope. Remote sensing and field investigation methods were adopted. The spatiotemporal characteristics of HII were analyzed to reveal the variation features of human activities; to clarify the ecological significance of HII, landscape pattern, vegetation net primary productivity (NPP), and soil property were considered to discuss their relationships with HII. The results will provide references for maintaining ecological balance and regulating human activities in the Yellow River Delta.

2. Materials and methods

2.1. Human interference index (HII)

We established HII based on exploitation type, ecological condition and buffer effect. The formula for HII is as follows:

$$\mathrm{HII}=\begin{cases}\displaystyle\sum_{i=1}^{5}[EA_i\times IC_i,\ \min+EA_i\times(IC_i,\ \max-IC_i,\ \min)\times(1-EV_i)]/TA & D_i=0\mathrm{m}\\ \displaystyle\sum_{i=1}^{5}\frac{200-D_i}{200}\times[EA_i\times IC_i,\ \min+EA_i\times(IC_i,\ \max-IC_i,\ \min)\times(1-EV_i)]/TA & 0\ \mathrm{m}<D_i\le 200\mathrm{m}\end{cases}\tag{1}$$

where EA_i is the occupied or adjacent area of exploitation type i, and $i = 1, 2, 3, 4$ and 5 are traffic land, industrial land, building land, saltern and farmland, respectively; IC_i is the IC of exploitation type i; $IC_{i,\min}$ and $IC_{i,\max}$ are the minimum and maximum values of the IC_i, respectively; EV_i is the ecological value of exploitation type i; TA is the total area of the evaluation unit; D_i is the distance from exploitation type i. A high HII indicates that human interference is considerable.

Influence coefficient is the decisive factor of HII. Traffic, industrial and building lands not only profoundly change surface landforms, affect biological habitats and community structures, and split natural landscapes during the construction period, but also produce traffic, industrial and domestic pollution during the operation period (Chi et al., 2015a). The three exploitation types possess artificial interlayer that impedes the exchange of water, nutrients, air and heat between aboveground and underground areas (Xu et al., 2015). Saltern affects the ecosystem in a manner similar to that of the aforementioned exploitation types. However, it is always distributed continuously with regular shape and without artificial interlayer (Xu et al., 2015). Farmland is covered by large areas of specific crops instead of natural plants; it influences native community structure and biodiversity and may cause non-point source agricultural pollution; but it has a distinct ecological function and has no artificial interlayer (Swift and Anderson, 1993; Xu et al., 2015; Chi et al., 2017a). Moreover, differences of ecological influences may occur in different positions within the same exploitation type due to the variations of specifications, such as structure, technology and management, in different positions. Therefore, the actual influence within the same exploitation type may change. Accordingly, $IC_{\min}$ and $IC_{\max}$ were proposed and each exploitation type was assigned specific $IC_{\min}$ and $IC_{\max}$ based on ecological features and previous studies. For traffic, industrial and building lands with artificial interlayer, $IC_{\max}$ was set as 1.0 (Xu et al., 2015). For saltern, which greatly affects the ecosystem but has no artificial interlayer, $IC_{\max}$ was set as 0.8 (Chi et al., 2017b). For farmland, which has a little ecological influence and has no artificial interlayer, $IC_{\max}$ was set as 0.4 (Chi et al., 2017b).We use $IC_{\min}$ to represent the minimum ecological influence of an exploitation type; it is homogeneous within an exploitation type. The difference between $IC_{\min}$ and $IC_{\max}$ is generally 0.2 (Xu et al., 2015; Chi et al., 2017b, 2017c). Variations in specifications in different positions within building land are greater because ecological constructions, such as urban greening, are always performed in certain parts of building land. Therefore, the difference between $IC_{\min}$ and $IC_{\max}$ of building land was given as 0.4, and the differences of other exploitation types were given as 0.2 (Chi et al., 2017d) (Table 1).

We use ecological value (EV) to reflect differences of IC within the same exploitation type. The specifications within the same exploitation type involve various factors that are too complex to quantify. Therefore, EV, which indicates the actual condition of an ecosystem under various specifications, was used to represent the differences of IC. A widely used vegetation index, namely, normalized difference vegetation index (NDVI), can accurately and rapidly reflect the ecological condition (Xu, 2013). The EVs in different years were calculated based on the NDVI using the following formula:

$$\mathrm{EV}=\frac{1}{n}\sum_{x=1}^{n}mNDVI_x\tag{2}$$