Ecological zoning for regional sustainable development using an integrated modeling approach in the Bohai Rim, China

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A B S T R A C T

China is in its quick social and economic development which has caused various environmental problems to some extent. Ecological zoning and distinguishing the highly-important ecological areas (also termed as the ecological red-line zone in this study) and protecting them from anthropogenic interference is an effective measure for regional environment protection and sustainable development. In this study, we applied an integrated modeling approach to implement the ecological zoning in the Bohai Rim for regional sustainability, and selected 12 single factors to calculate three integrated indicators: ecosystem sensitivity, ecosystem services and ecological risks. Based on three integrated indicators, we obtained the ecological zoning map with three zones for the study area, which are the highly-important ecological areas, the moderately-important ecological areas and the lowly-important ecological areas. The zoning result showed that the highly- and moderately-important ecological zones cover 23.2% and 37.9% of the Bohai Rim respectively, which should be protected. The remained lowly-important ecological zone covers 38.5% of the Bohai Rim, which can be used for economic and industry development. This study shows that the zoning approach is reasonable and instructive to guide and arrange the land use for regional sustainable development. Such an ecological zoning can greatly solve the conflicts between environmental protection and regional economic and industry development and further forms a safe ecological pattern. Two contributions of our work are that (1) our modeling approach is scientific, reasonable and meaningful for other planning works and can be used for reference to the regions and countries with similar situation, and (2) the zoning pattern mapped in our study is helpful to guide Bohai regional development and the safe arrangement of economic and industry development.

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1. Introduction

With the rapid development of human society in China, the environment was influenced significantly, particularly under heavy resource exploitation (Lu et al., 2004; Liu and Xie, 2005). In some areas, the resource utilization and development activities have been threats to ecological security and human society, such as (1) eutrophication and further algae bloom in Taihu Lake, Jiangsu Province (Song et al., 2011) and Dianchi Lake, Yunnan Province (Liu, 2001); (2) red tide in the mouth region of the Zhujiang River, Guangdong Province (Huang et al., 2010); and (3) Enteromorpha prolifera outbreak in the Bohai Rim (Li et al., 2009). The situation is still accelerating (Luo and Liu, 2007), for instance, the serious haze often occurs in a large area in China (Zhang et al., 2013).

The Bohai Rim is a region surrounding a relatively closed ocean with only an eastern part connected with the Chinese Yellow Sea. Due to this, its sea-water is hardly to be renewed. Currently, the Chinese central government has defined it as an important economical developing region. Therefore, the development and protection on the terrestrial land plays a key role on controlling the quality of the sea-water as well as the coastal ecosystem. The coastal zone can easily attract a variety of competing use, which sometimes cause adverse impacts on each other (user–user conflicts) (Cicin–Sain and Knecht, 1998) or mostly create worse impacts on the coastal marine environment (user–environment conflicts) (Douver et al., 2007). So, many countries have made attempts to manage the conflicts (Tuda et al., 2014).

The Bohai Rim is important not only in China but also in the world. On one hand, it is the last ecological barrier for the Bohai Sea. On the other hand, this region is a major transit area and breeding ground for diverse migratory birds in East Asia – Australia (Yang et al., 1998; Jia et al., 2002). Due to these, the Bohai Rim...
has been identified as an important area for the conservation of wetland ecosystem in China and biodiversity in the world (MEP and CAS, 2008). However, the Bohai Rim is also the center of economic circle of the northeast Asia, which is vital to the economic development among North Korea, South Korea, Japan and China. This area gathered many industry enterprises, such as iron and steel, petrochemicals, equipment manufacturing industry, electric power plants, ship factories, construction materials and port cargo. According to Lu (1998) and Zhu et al. (2001a,b), plenty of industrial development activities in the Bohai Rim have brought this region a heavy burden on environment, which has led to discharging of waste water, waste gas, and waste residue. Moreover, intensification of human interference and population flowing and gathering had also created the significant negative effects on environment (Huang et al., 2008; Lin, 2009), particularly on the existing ecological problems, such as seawater intrusion, soil salinization and erosion, biodiversity losing and red tide. Therefore, guiding rational distribution of economic development, preventing further deterioration of environment and protecting the existing high quality ecological areas will have definitely a great significance for regional sustainable development.

The reasonable and effective spatial arrangement of conservation and development, i.e., ecological zoning, is urgent for the current rapid-changing society in China. The “ecological red-line zone” has been greatly emphasized by Chinese central government (SEPA, 2014; Liu et al., 2015) and termed as the areas with a good quality environment and need to be strictly protected and managed for maintaining the regional ecological security under a strong developing situation. Since the damage to ecological red-line zones will lead the nature and society loss much more, their identifying and protecting is a significant task to guide human activities in creation of equivalent economic value with lower environmental cost.

There has been some trying in China to identify the ecological areas for being protected from regional social-economic development. Due to that the protected areas and purpose are different, the distinguishing methods and evaluating factors used for zoning are various. In 2005, Shenzhen City designated many areas with high ecological values as “basic ecological line zones of control”, including water source protection areas, scenic spots, nature reserves, basic farmland protection areas, forest and country parks, the mountain with a slope steeper than 25’, woodland, upland, trunk rivers, reservoirs and wetlands, ecological corridor and green spaces, islands and coastal land (SZG, 2005). In 2008, Kunming City delineated the areas which are relatively sensitive or with the most critical ecological functions as the ecological red-line zones in its new revision of land-use master plan (Fan et al., 2008). Moreover, Yunnan Province designated red-line zones for land use planning based on the ecological frangibility and ecosystem services (Fu, 2008). In recent two years (2012–2013), the term of “ecological red-line” has become popular at both the governmental and public levels.

In fact, some world famous disaster cases have shown clearly that unreasonable spatial planning as well as management would result in serious damages to both human and nature. For instance, the Minamata disease, occurred in Minamata, Japan during 1950s, 1960s and even later time, was caused by the mercury-contained wastewater discharged (between 1932 and 1968) by the Shin Nippon Chisso Fertilizer Company (Chisso) directly into Minamata Bay, a small embayment on the Yatsushiro Sea (Balogh et al., 2015). This mercury pollution in Minamata Bay has caused not only the human health problem but also many other nature species died, such as fish, shellfish, cats and birds. The Rhine river pollution disaster happened in the mid of 20 century, which was caused by industries’ wastewater discharging into the Rhine river. The wastewater contained thousands of pollutants. Its consequence were the death of so many aquatic species (Schwabach, 1989). Therefore, more countries paid attention to watershed and river-lake management, especially the developed countries, like the Rhine-related countries (Kiss, 1985; Milich and Varady, 1999). Spatial planning is a way to manage the location of industries and the development planning can help controlling the emission and discharging of wastes from industries. These management measures are also very necessary to the developing countries, such as China, India, Brazil, etc., which are facing the conflicts between social-economic development and environmental protection.
Since ecological zoning with delineation of ecologically key areas is important and requests more approaches and cases to fit to the various purposes and situations, our objectives is to explore the ecological zoning in the Bohai Rim by applying an integrated GIS approach involving the multi-factors, and to provide a basis for preventing the high quality ecological areas from human’s rapid development in the Bohai Rim. We classified the Bohai Rim into three category areas spatially, which are the highly-important ecological areas, the moderately-important ecological areas and the lowly-important ecological areas. The highly-important ecological areas are also termed as the ecological red-line zone. This work is a practical and feasible practice which can provide scientific basis for regional development. As we know, in the functional zoning of urban development, people often uses priority development zones, restricted development zones, and forbidden development zones. They have the similar meaning with three zones used in this study. However, they consider more factors including social-economic factors, while terms here in this study mainly based on consideration of only natural factors.

### 2. Study area and methods

#### 2.1. Study area

The Bohai Rim is located in the junction of northern, northeastern, northwestern China, being confined by longitudes 115° 41' – 123° 31' E and latitudes 35° 42' – 42° 8' N. This study contains only the terrestrial land part including coastal zone, which is composed of thirteen cities included Dalian, Yingkou, Panjin, Jinzhou, Huludao, Qinhuangdao and Tangshan, Binhai new areas (called also

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as the new coastal zone of Tianjin), Cangzhou, Binzhou, Dongying, Yantai and Weifang (Fig. 1). The total area of the Bohai Rim is about 12.9 km². The climate is dominated by the warm temperate with abundant heat and rich precipitation, mainly concentrated in the summer. Its average annual temperature ranges from 8.2 to 12.7 °C, annual precipitation from 360 to 970 mm.

2.2. An integrated modeling approach

Because the ecological zoning was aimed at providing a basis for rational distribution of economic and industry development in the Bohai Rim with no conflicts with environment protection, we not only took ecological sensitivities and ecological services into account, but also considered ecological risks from natural environment to development as an important factor in this study. In fact, ecological sensitivities, ecosystem services and ecological risks are three integrated indicators, which can be calculated from several individual environmental factors. Some individual factors can play roles on two integrated indicators, such as land cover, normalized vegetation index (NDVI), slope degree, etc. However, we do think the final zoning map will be decided by three integrated indicators, which reflect the different meanings compared with those individual environmental factors used for calculation the integrated indicators. Similar methods have been tried in some other studies (Kang et al., 2007; Peng et al., 2008). We involved totally 12 environmental factors (Table 1) to calculate three integrated indicators respectively.

We designed a detailed spatial modeling scheme (Fig. 2) through spatial analysis tools in geographical information system (GIS). The model applied Sum function to join all selected relevant individual environmental factors (data available) together and the resulted maps were reclassified into five classes. Based on three sub-modeling results, we implemented the ecological zoning through Max function for sustainable development in the Bohai Rim.

### 2.2.1. Modeling of ecosystem sensitivity

Ecological sensitivity here referred to the sensitivity of habitats for important species. For assessing the ecosystem sensitivity of the Bohai Rim, we selected four factors which are natural reserve areas, water-source areas, land cover types and slope degree. The reasons to select them are that (i) they give high contribution to the ecosystem sensitivity and (ii) they are available.

We used the Analytical Hierarchy Process (AHP) method (Satty, 1979) to obtain the weights for four selected factors through pair-comparison method which is very easy for implementers and experts and then calculated the weights from 0 to 1 for all selected factors (Table 2). This is a relatively objective approach to obtain weights. We assigned various sensitivity levels from 1 to 9 to different sub-factors (i.e., classes) of each environmental factor (Table 2).

The national nature reserves and wetlands were given the highest sensitivity level for their importance to nature ecosystem. We then integrated land cover types, important water-source areas, nature reserves and slope, and implemented the modeling in GIS. The Formula (1) was applied for calculation.

\[ V_{\text{sensitivity}} = \sum_{i=1}^{4} w_i \times f_j(j = 1, 2, \ldots, k) \]  

(1)

in which, \( V_{\text{sensitivity}} \) is the ecosystem sensitivity value; \( w_i \) is the weight of factor \( i \); \( f_j \) is the \( j \) pixel value of factor \( i \) and \( k \) is the total pixel numbers of the area in GIS.

### 2.2.2. Modeling of ecosystem services

Ecosystem services refer to the effectiveness and conditions which human-being relies on for survival, and are formed or maintained by ecosystems or ecological processes, including air regulation, temperature regulation, water conservation, soil formation, waste management, biodiversity maintaining, food production, raw materials producing, recreation and culture providing. We selected three key factors including land cover types, NDVI and water-source areas for the assessment of ecosystem services. We calculated weights from 0 to 1 (Table 3) by AHP method for the selected factors. In land cover types, wetland, forest and grassland have high ecosystem services. High NDVI areas represent good vegetation which could hold good biodiversity. Water-source areas also provide high ecosystem services. We assigned service levels from 1 to 9 to different sub-factors (i.e., classes) of each environmental factor (Table 3) and then running the spatial calculation in GIS using Formula (2).

\[ V_{\text{service}} = \sum_{i=1}^{3} w_i \times f_j(j = 1, 2, \ldots, k) \]  

(2)

in which, \( V_{\text{service}} \) is the ecosystem service value; \( w_i \) is the weight of factor \( i \); \( f_j \) is the \( j \) pixel value of factor \( i \) and \( k \) is the total pixel numbers of the area in GIS.

### 2.2.3. Modeling of ecological risks

Ecological risks assessment is an effective manner to predict the adverse effects in the future, or assess possible ecological changes led by the activities in the past. Ecological risks consist of both natural caused and human induced risks on environment. We mainly concerned with natural risks in the region to help locating industry development properly to avoid potential damages. The main risks include rainstorm and mountain-torrent, geological disasters, and others.
storm surges, seawater intrusion and ground subsidence, and soil-water erosion. Here two risk factors of storm surges and soil-water erosion are calculated from several individual factors (Table 4). The ecological risk modeling of this study was mainly based on the historical data in the past 20 years in the Bohai Rim. The AHP method was applied to obtain weights from 0 to 1 for the selected factors, and we assigned the different risk levels from 1 to 9 to the different sub-factors (Table 4). Then the spatial model was implemented in GIS using Formula (3). In this part, soil-water erosion and storm surge were firstly calculated using the similar approach before further calculating the ecological risks.

\[ V_{risk} = \sum_{i=1}^{n} w_i \times F_j (j = 1, 2, \ldots, k) \]  

in which, \( V_{risk} \) is the ecosystem risk value; \( w_i \) is the weight of factor \( i; \) \( F_j \) is the \( j \) pixel value of factor \( i \); and \( k \) is the total pixel numbers of the area in GIS.

### 2.2.4. Ecological zoning

Taking the three model-resulted integrated indicators, i.e., ecological sensitivity, ecological services and ecological risks into consideration, ecological zoning was implemented. Three types of zones were adopted, which are the highly-important ecological areas, the moderately-important ecological areas and the lowly-important ecological areas. Three zones were differentiated by the level of ecological importance \( EI \), calculated from ecosystem sensitivity level \( V_{sensitivity} \), ecosystem service level \( V_{service} \), and ecological risk level \( V_{risk} \), which were all reclassified to be integers between 1 and 5 to represent five classes. The calculation was implemented through Formula (4). The resulted map contains also five classes.

\[ EI = \text{Max}(V_{sensitivity}, V_{service}, V_{risk}) \]  

Through reclassifying the resulted map, we obtained the final ecological zoning map with only three classes. The areas with \( EI \) equaling to 5 were designated as the highly-important ecological areas (i.e., the ecological red-line zone in this study). The areas with \( EI \) equaling to 4 were designated as the moderately-important ecological areas. The rest of the region is the lowly-important ecological areas.

The main advantages of the established integrated modeling approach are (1) sensible and meaningful from the nature protection point of view, (2) data accessible for most situation, and (3) sub-objective on weight assignment due to AHP method application.
3. Results

3.1. Ecosystem sensitivity, services and ecological risks in the Bohai Rim

The ecosystem sensitivity of the study area was divided into five classes: extremely sensitive, sensitive, medium sensitive, insensitive and extremely insensitive (Fig. 3a). The areas with extremely sensitive class are mainly distributed in Changxing Island, southern coast area and northern mountains of Dalian, the northeastern mountains of Yingkou, Liao River Delta, Yiwu Mountain national protected areas of the northern Jinzhou, west Huludao, the northwest parts of Qinhuangdao and Tangshan, the coast areas of Tangshan and Cangzhou, Beidagang wetland reserve of Tianjin, the coast areas of Binzhou and Dongying, south Weifang, and central Yantai.

The pattern of ecosystem services in the Bohai Rim was shown in Fig. 3b. It suggested that the ecosystem services in the northern areas are apparently higher than in the southern areas. Areas with high ecosystem services are mainly concentrated in north Dalian and north Yingkou, Liao River Delta, north Jinzhou, northwest Huludao, northwest Qinhuangdao, and the Yellow River Delta.

The Liao River Delta and the Yellow River Delta are the main areas where the coastal wetlands exist. These areas have better vegetation cover and abundant animal resources with the Shuangtai Estuary national nature reserve (NNR) and the Yellow River Delta NNR there. The northwest Huludao and north Jinzhou are covered by natural pine forest and coniferous and broadleaved mixed forest on the flora of the north China. High biodiversity, magnificent landscape and good vegetation conditions have made the region very important in providing ecosystem services of entertainment, culture and climate regulation so that a national nature reserve and a national forest park had been established. The north Dalian and the northwest Qinhuangdao with four reservoirs have significant functions of supplying freshwater for big cities nearby. The northwest Qinhuangdao is of great strategic significance for drinking water safety of Qinhuangdao, Tangshan and Tianjin cities due to its location on the upstream of three reservoirs. In addition, Liujiang NNR is located here.

Fig. 3c displays the spatial pattern of ecological risks in the Bohai Rim. The sources of natural risks in the Bohai Rim are very complicated containing geological factors and disastrous-weather factors, which functioned together sometimes and have caused great harms to the coastal zone. The ecological risks here are mainly concen-
trated on four areas: Liaodong Bay, Bohai Bay, Laizhou Bay and the eastern coast of Dalian. The main risks in the Liaodong Bay are salt water intrusion, storm surges, soil salinization, while the Bohai Bay has risks mainly from ground subsidence and storm surges. The Laizhou Bay has risks from soil erosion and serious seawater intrusion, and the eastern coast of Dalian has frequent torrential rains and debris flow. The areas with high and extreme high risks are not suitable for arranging the economic and industrial development.

3.2. Ecological zoning pattern in the Bohai Rim

The ecological zoning pattern was established (Fig. 4) through spatial calculation with considering three integrated indicators assessed previously. It contains three categories: the highly-important ecological areas (i.e., the red-line zone), the moderately-important ecological areas and the low-important ecological areas.

The identified red-line zones account for 23.2% of the studied Bohai Rim. Most of these patches are the regions with important ecological functions and covered by hills, mountains or wetlands with good vegetation coverage and high biodiversity. The ecological red-line zones can be designated as 14 region patches (Table 5), based on the reasons for protection and their spatial locations. The ecological red-line zones defined in this study are the areas which must be strictly managed and maintained for the ecological security of the Bohai Rim, including the region with high ecosystem sensitivity or significant ecosystem services or high ecological risks. These areas need to be conserved requested by laws, regulations and relevant planning.

The moderately-important ecological areas account for 37.9% of the entire study area, which dispersed around the red-line zones and play a role of buffering the human impacts to the red-line zones. The importance of the moderately-important zones is their spatial locations, just next to the highly-important ecological zones, which has the role of buffering the impact from human disturbance. Although they have the relevant lower values on ecosystem sensitivity, ecosystem services or ecological risks, they still play an important role on environment security and sustainability. To develop and use these regions, we should restrict the development and construction activities with negative impacts on environment in these regions, and then further influence the red-line zones.

The remained areas are the lowly-important ecological areas, which account for 38.9%, which are available and can be used for economic and industry development. They relatively concentrated in the central Dalian, north Jinzhou, east Tangshan, Central Binzhou and Weifang and most parts of Cangzhou and Dongying. This zone contains the areas recommended to be used for economic and industry development in the future, where human can create the economic value with less damage to the environment.

4. Discussion

The contribution of this work can be reflected from two aspects. The most important contribution is to provide a clear ecological security pattern in the Bohai Rim to the society. The established three zones in this study have been assigned the different functions: the highly-important ecological areas (i.e., the red-line zones) for strict protection, the moderately-important ecological areas for buffering function, and the remained lowly-important ecological areas available for economic and industry development. This can protect the environment of the Bohai Rim region and make the region follow a sustainable developing approach. As Tuda et al. (2014) mentioned that most coastal areas of the world are multiple-use areas where different human activities take place, the Bohai Rim has been one of the five new economic developing regions.
in China and has received much attention from different social sectors, including industry enterprises, tourism and service sectors. Several heavy industries have been shifted into the Bohai Rim, including the Beijing capital iron and steel plant. However, it is well known also that the Bohai Rim is the very good breeding base for many aquatic species and has a high biodiversity (Xu et al., 2013) due to its special physical shape which caused typical sea water movement and due to also its two delta wetlands, i.e., the Liao River Estuary wetland and (area 4 in Fig. 4) and the Yellow River Delta wetland (area 11 in Fig. 4). The Bohai Rim also has a famous swimming beach, i.e., Beidaihe swimming beach (area 7 in Fig. 4). If the Bohai Sea has no reasonable zoning in advance, it will get polluted and its coastal and ocean ecosystem will be destroyed due to the unordered developing activities. We should take the historical responsibility to protect the Bohai Rim and its rich biodiversity for our generation and future generation as well.

The second contribution of this study is to have established an integrated zoning approach which can be a guiding work to the regions or countries with similar protection purpose. This is typically useful to some developing countries, such as India, Brazil, Malaysia, etc. For establishing the secure ecological pattern based on three integrated indicators, i.e. ecological sensitivity, ecosystem service and ecological risk, we involved multi-factors and their different weights into analysis, and so this is a multi-criteria decision analysis (MCDA) case (Malkiewski, 1999, 2006). All weights were calculated through AHP method. According to Satty (1979), weights of multi-factors can be obtained through pair-comparison method and then mathematical calculation, which can avoid the subjectivity for assigning the weights to the selected factors to some extent. Three integrated indicators were modeled from the individual environmental factors but has been the new information, although some individual factors were used two times to get the integrated indicators in this study. The whole study applied GIS technique, which was described as a GIS based multi-criteria analysis (GIS-MCDA) by Malkiewski (1999, 2006) and Tuda et al. (2014).

This modeling approach can support analysis and visualization of spatial incompatibilities and overlapping interests (Heywood et al., 2002), and therefore has been widely applied and also used in coastal areas for addressing conflicts and for conservation planning (Brown et al., 2001; Brody et al., 2006) as well as for nature reserve (Liu and Li, 2008). This approach has now been successfully applied in our study to provide convenient visualization of the ecological pattern to help decision makers to make a sustainable developing plan.

We do need to remember those environmental disasters happened in the world which made serious impacts on both human and also nature, such as the Minamata disease (Balogh et al., 2015) and the itai-itai disease caused by cadmium pollution (Kaji, 2012) in Japan, the Rhine River pollution event in Europe (Milich and Varady, 1999) and the London smog incidents, etc. All these tell us that we, the human beings, should plan our environment with ecological protection and ecological function maintaining as the base. Spatial zoning should be completed before the economic development implementing. As we stated in the Introduction section, spatial planning is a way to manage the industries' location, and the development planning can control the industries' emission and discharging of wastes. These management measures are also necessary to the developing countries to solve the conflicts between social-economic development and environmental protection.

The approach for delineating the red-line boundary has been tried many years in China as described in Introduction section of this paper. Recently the Chinese government has also been making strong efforts on land management and tried to push the red-line zone identifying for protection under the strong development situation (SEPA, 2014). The ocean part of the Bohai Rim has been researched and its ecological red-line zone has been mapped by Xu et al. (2013). Our study focus on the terrestrial part surrounding the Bohai Sea. When these two planning work together in the future, the whole Bohai region will maintain its safe ecosystems and provide a natural space with strong resistance and resilience to socio-economic development. Through this ecological zoning, the Bohai Rim region is on its way to the sustainable development.

5. Conclusion and recommendations

The ecological red-line zones are the most important areas for ecological security and sustainable development in the Bohai Rim due to their high values in ecosystem sensitivity, ecological services and ecological risks. In this study, we showed our integrated approach of ecological zoning. We combined the assessment of ecosystem sensitivity, ecosystem services and ecological risks to get the spatial distribution of the highly-important ecological areas (i.e., the red-line zones). The results showed that three zones cover 23.2%, 37.9% and 38.9% of the Bohai Rim respectively. Two contributions of our work are that (1) our modeling approach is scientific, reasonable and meaningful for other planning works and can be used for reference to the regions and countries with similar situation, and (2) the zoning pattern mapped in our study is helpful to guide Bohai regional development and the safe arrangement of economic and industry development.

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