# Spatial Explicit Evaluation of Land Use Sustainability Based on Grid analysis—A Case Study of the Bohai Rim

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**Abstract.** Identifying the land use sustainability at an explicit spatial level in large areas is critical for optimizing the land use. The evaluation of sustainable land use generally takes the administrative units at the provincial, prefecture, or county level as the spatial scale, which ignore the spatial variation within the administrative units. This paper aims to put forward a novel evaluation method on sustainable land use evaluation and evaluate the land use sustainability at a grid level of 5 km in Bohai Rim of China. This paper first established an index system of sustainable land use evaluation frame with 13 indicators in four criterion levels: ecology, economy, society, and spatial pattern. Then, the 13 indicators were expressed at 5 km grids level. At last, the land use sustainability was evaluated of each grids based on the spatial principal component analysis. The results showed that the ecological environment in the Bohai Rim has the greatest impact on the level of sustainable land use. The high level of sustainable land use is generally distributed in the northwest and northeast in Bohai Rim, and the low level of sustainability is concentrated in the southwest of the Bohai Rim. This paper proposed a novel method to evaluate of the land use sustainability at a spatial explicit level. The method could offer more spatial information of sustainable land use to help government propose more efficient policies regarding improving land use sustainability.

**Keywords:** Spatial explicit evaluation · Land use sustainability · Spatial principal component analysis · Bohai rim

## 1 Introduction

Since the 1990s, sustainable development research has been vigorously developed in response to the shortage of resources, the deterioration of the ecological environment, and rapid urbanization. Among the 17 Sustainable Development Goals (SDGs) proposed by the United Nations, seven of the goals are related to land use [1]. It can be seen that sustainable land use, as an important part of sustainable development research, has attracted much attention from international organizations and countries. The Sustainable Land Use Evaluation Outline (FESLM) promulgated by the United Nations Agriculture

and Food Organization (FAO) defines sustainable land management as based on the existing land use system that enables land users to maintain or enhance the ecological support functions of land resources while maximizing the economic and social benefits of land use [2]. Land sustainable use evaluation can provide data supporting the rational and sustainable use of regional land and is helpful to guide the formulation of regional land management policies. The core of land sustainable use evaluation is the construction of evaluation model, including the research of index system framework, index selection, index weight determination.

The research on the index system framework is the foundation and the core of the land sustainable use evaluation model. The following three frameworks are commonly used in existing research: (1) "Productivity-Security-Protection-Viability-Acceptability" framework [2, 3]; (2) "Economy-society-ecology" framework [4, 5]; (3) "Pressure-state- response" (PSR) framework [6, 7]. First, the "Productivity-Security-Protection-Viability-Acceptability" framework is determined by the FESLM, which specifically refers to the five evaluation criteria for sustainable land use: land productivity, land security, protection of water and soil resources, economic feasibility and social acceptability. This framework lays the foundation for the development of a regional sustainable land use evaluation index system. Under this framework, Chen constructed an evaluation index system for sustainable land use, which is composed of 28 indicators in the five standard levels of "production, protection, stability, economic vitality and acceptability" [8]. At the same time, according to the five-evaluation standard framework proposed by FESLM, scholars have improved and simplified the framework, and formed "Economy-Society- Ecology" evaluation index system framework, which has been widely used in practiced. For example, Peng et al. summarized the goal of sustainable land use as three aspects: the ecological rationality, the economic effectiveness and the social acceptability [5]; Chen et al. proposed a index system from ecological, economic and social aspects, and the evaluation method and comprehensive integration method for each index were developed [9]. In addition, the PSR evaluation index system framework reflects the interaction between humans and the environment. Based on the PSR model, Xie et al. constructed a land use sustainability evaluation index system and comprehensive evaluation model composed of 14 indicators and evaluated the Poyang Lake ecological economic zone [6].

The determination of index weight and comprehensive evaluation are usually complicated, which are the emphases of land sustainable use evaluation model. Entropy method [10], principal component analysis method [11], analytic hierarchy process (AHP) and other methods have been used in existing studies to conduct comprehensive evaluation of multiple indicators. AHP mainly determines the weight of each index based on expert knowledge [12]. AHP is a subjective weighting method, and it has a relative low stability. Entropy method and principal component analysis method use mathematical statistics. They assigned weights based on the numerical characteristics of the indicators, which are objective weighting methods and have good norms. However, when the index is integrated, it faces the problem of matching the index in grids and the administrative unit. In the indicator system of sustainable land use, resources, environment, ecology, and other information are mostly spatially different, while economic and social statistical information is more time-dynamic [9]. When using the above methods for

comprehensive evaluation of weights and indicators, the grid data is usually converted into administrative unit data to solve the spatial matching problem between them. Therefore, the evaluation of sustainable land use generally takes the administrative unit at the provincial, prefecture, or county level as the spatial scale.

The existing land sustainable use evaluation studies have provided a good foundation for the formulation of regional land use management, sustainable development, and other policies. However, two points could be improved to better evaluation the land use sustainability. First, the sustainability of land use includes not only the continuous use of land use in time, but also the optimization of spatial pattern [13]. The traditional land sustainable use evaluation system based on the framework of "Productivity-Security-Protection-Viability-Acceptability", "Economy-Society-Ecology" and "Pressure -State-response" focuses on the evaluation of land function and lacks the research on the impact of land use spatial pattern on land sustainable performance. Certain spatial pattern of land use can realize certain land functions. Therefore, it is necessary to increase the evaluation of the spatial pattern of land, urban structure, and other spatial aspects on the sustainable development process. Secondly, research on quantitative spatial evaluation of sustainable land use at a more spatial explicit scale is insufficient. The sustainable land use evaluation results are commonly a single numerical indicator within an administrative division unit, which is difficult to reflect the spatial heterogeneity of the land sustainable use level within the administrative regions.

This paper aims to (1) improve the framework of current evaluation index by adding land use spatial pattern index into the analysis; and (2) realize more explicit spatial evaluation of sustainable land use at the grid scale with the technology of GIS and land use data. This paper could offer useful spatial information regarding sustainable land use planning and guide the spatial optimize the land use.

## 2    Study Area, Data and Methods

### 2.1   Study Area

The Bohai Rim region is a "C-shaped" region composed of the Liaodong Peninsula, the Shandong Peninsula and the North China Plain, including Beijing, Tianjin, Hebei, Shandong, and Liaoning. The area is a typical example of a rapid urbanizing area in China. The urbanization rate of the Bohai Rim region rose rapidly from 54.73% in 2010 to 59% in 2015 [14, 15], becoming one of the fastest growing regions in China during this period. The economic growth of this area is also leading in China, with an increase in GDP from 12 trillion RMB in 2010 to 16.37 trillion RMB in 2015. The total population (246 million) and land area (523,429 km$^2$) in this region represent 18.3% and 10.95% of the national total number, respectively [16]. At the same time, land exploitation and utilization level is high in Bohai Rim. The used land area accounts for more than 84% of the total area, which was higher than the national average [17]. Therefore, it is necessary and representative to carry out spatial evaluation quantitative of sustainable land use of Bohai Rim in China.

## 2.2   Data Sources

This article uses three kinds of data: (1) Land use raster data with a spatial resolution of 100 m in 2010, from the 1:100,000 remote sensing monitoring database for land use status in China constructed by the Chinese Academy of Sciences. A hierarchical land use classification system with six primacy level types and 25 secondary level types was adopted. The first level types included cropland, woodland, grassland, waterbodies, built-up land and unused land. (2) The social, economic and ecological data include the investment in fixed assets, the income of urban residents, the income of rural residents, and fertilizer use amount from 2011 "Beijing Statistical Yearbook", "Tianjin Statistical Yearbook", "Liaoning Statistical Yearbook", "Hebei Economic Yearbook", "Shandong Statistical Yearbook". The data of GDP and population are from Dataset of the spatial distribution of GDP and population in China at 1 km$^2$ grid [18]. (3) The river vector data from the national basic geographic information system.

## 2.3   Methods

**Evaluation Framework and Choice of Indicators.**  Based on the traditional "Economy-Society-Ecology" framework of sustainable land use evaluation, this paper proposed an "Economy-Society-Ecology-Pattern" Four Dimensions framework by addressing the spatial pattern of land as an important aspect that influencing the sustainability of land use. Then, we adopted the following three requirements when choosing evaluation indicators: (1) the indicators should have a direct or indirect connection with the sustainability of land use; (2) the indicators can reflect the diverse aspects of economy, society, ecology and spatial pattern; (3) data for indicator calculation were available. Finally, thirteen indicators were selected based on the four dimensions framework, three requirements and literature reviews (Table 1).

**Table 1.**  The indicators for evaluation of sustainable land use in the Bohai Rim

| Goal | Criteria | Indicators | Abbreviation |
|------|----------|------------|--------------|
| Sustainable land use | Economy | GDP | GDP |
| | | Income of urban residents | UPI |
| | | Income of rural residents | RPI |
| | | Investment in fixed assets | IFA |
| | Society | Land urbanization | LU |
| | | Population density | PD |
| | | Per capita cultivated land area | PCCLA |
| | | Per unit area grain yield | PUAGY |
| | Ecology | Forest coverage rate | FCR |
| | | Fertilizer used per area | FUPA |
| | | Distance from water | DFW |
| | Pattern | Shannon's evenness index | SHEI |
| | | Contagion index | CONTAG |

**Spatial Discretization of the Indicators.**  To ensure reasonable results from evaluation, we transformed the indicators of income of urban residents, income of rural residents, investment in fixed assets, grain yield and fertilizer used into a grid size of 5 km$^2$ based on land use data on which the indicator's activity occurs. First, we assumed that each indicator per land area was uniform in a prefectural unit and then we discretized the indicators into 5 km$^2$ grids based on Eq. (1):

$$INDIC_i = INDIC_j/A_j \times A_i \tag{1}$$

where $INDIC_i$ is the indicator value in grid $i$; $INDIC_j$ is the indicator value of the prefectural unit $j$; $A_j$ is the area of corresponding land use type in the prefectural unit $j$; and $A_i$ is the area of corresponding land use type in grid $i$. The corresponding land use type of income of urban residents is urban land, the corresponding land use type of income of rural residents is rural settlements, the corresponding land use type of investment in fixed assets is industrial land, and the corresponding land use type of grain yield and fertilizer used is cropland.

**Spatial Principal Component Analysis.**  Principal component analysis (PCA) involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called principal components, which are linear combinations of the original variables. The main objective of the PCA is to discover or to reduce the dimensionality of the data set and to identify new meaningful underlying various. The SPCA application assists and guides a user in doing PCA in a spatial way. The result of SPCA is a multi-band new spatial dataset with the same number of bands as the original data. The first principal component will have the greatest variance, the second will show the second most variance not described by the first, and so on. SPCA has certain advantages over conventional orthogonal functions, since they are not of any predetermined form, but are developed as unique functions from the data matrix [19].

In this paper, SPCA is introduced into the land sustainable use evaluation, and the formula for defining the land sustainable use evaluation is defined as follows Eq. (2):

$$E = \sum_{i=1}^{m} \sum_{j=1}^{n} (a_{ij}F_j) \tag{2}$$

where E represents the sustainable land use level; $a_{ij}$ is the $j$th principal component corresponding to the $i$th raster; $F_j$ is the eigenvalue contribution rate of the $j$th principal component.

## 3   Results

### 3.1   Spatial Distribution of the Indicators for Sustainable Land Use Evaluation

The spatial distributions of 13 indicators based on 5 km$^2$ are shown in Fig. 1. In the economy criteria layer (a–d), the trends of sustainable use of GDP and investment in fixed assets are similar, showing that areas with higher levels of sustainable land use
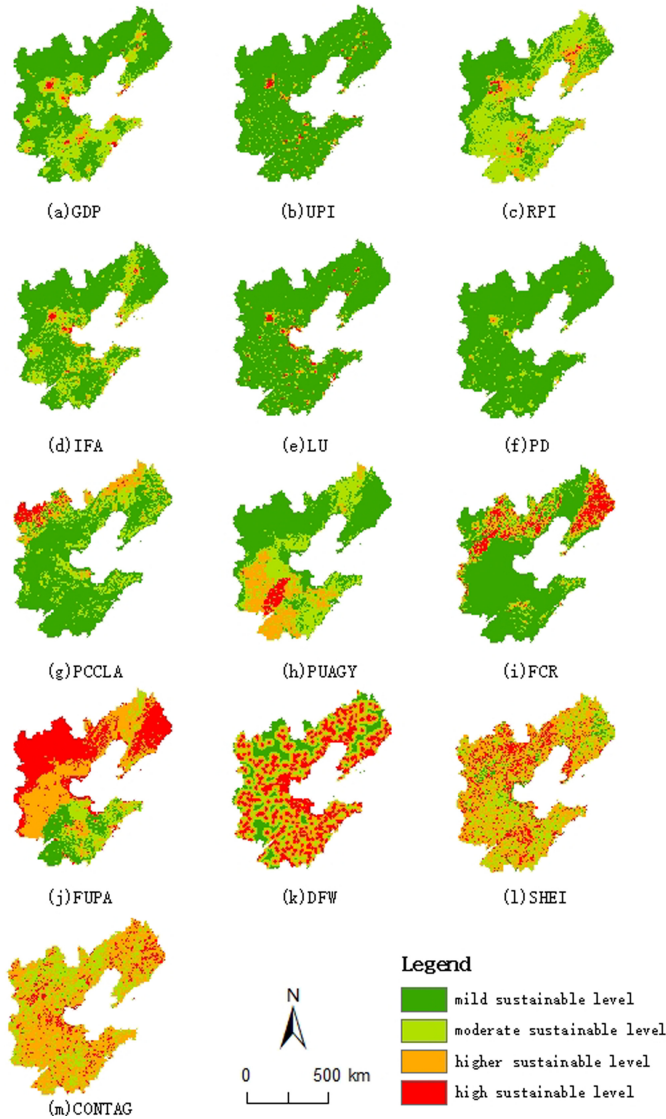
**Fig. 1.** Spatial distribution of indicators for sustainable land use (the abbreviations for the indicators are shown in Table 1)

are concentrated in coastal areas, Handan and Shijiazhuang; the sustainable land use level of rural income per capita indictor presents a decreasing trend from the southeast coast to the northwest inland; the sustainable land use level of urban income per capita indictor presents an overall low trend. In the social criterion layer (e–h), the sustainable land use level trend of land urbanization rate and population density show that the municipalities and provincial capitals have higher levels of sustainable land use. The level of sustainable land use in per unit area grain yield generally shows a downward

trend from southwest to northeast; the sustainable land use level in per capita cultivated area showed a decreasing trend from northwest to southeast. In the ecological criterion layer (i–k), areas with high levels of sustainable land use indicated by forest coverage are mainly concentrate in the north with the highest level of sustainable land use in the northeast; areas with high level of sustainable use of fertilizers per unit of arable land area are concentrated in the northeastern and northwestern regions, and the sustainable land use level in Shandong is low. As for the indictor of distance to waterbodies, areas with higher levels of sustainable land use are all around waterbodies. The farther away from waterbodies, the lower the level of sustainable land use. In the ecological pattern criterion layer (l-m), the sustainable land use levels of the SHEI and CONTAG show spatial heterogeneity.

## 3.2  Spatial Evaluation of Sustainable Land Use

The cumulative contribution rate of the first five principal components reached 82.8%, that is, the information contained in these five components accounted for 82.8% of the total information contained (Table 2). Thus, the first five principal components can effectively summarize the comprehensive information on the level of sustainable land use. The corresponding original evaluation factor loads are shown in the Table 3.

**Table 2.**  Eigen values and accumulative contribution rates of principal components

| PC layer | Eigen value | Percent of eigen values | Accumulative of eigen values |
|---|---|---|---|
| 1 | 1.1489 | 32.4262 | 32.4262 |
| 2 | 0.59281 | 16.7314 | 49.1576 |
| 3 | 0.44832 | 12.6534 | 61.8110 |
| 4 | 0.43119 | 12.1697 | 73.9806 |
| 5 | 0.31147 | 8.7910 | 82.7716 |
| 6 | 0.16481 | 4.6516 | 87.4232 |
| 7 | 0.12985 | 3.6648 | 91.088 |
| 8 | 0.09211 | 2.5997 | 93.6877 |
| 9 | 0.07857 | 2.2176 | 95.9054 |
| 10 | 0.05274 | 1.4885 | 97.3938 |
| 11 | 0.0472 | 1.3321 | 98.7259 |
| 12 | 0.02685 | 0.7578 | 99.4837 |
| 13 | 0.01829 | 0.5163 | 100 |

**Table 3.** Load matrix of principal components

| Criteria | Indicators | PC1 | PC2 | PC3 | PC4 | PC5 |
|---|---|---|---|---|---|---|
| Economy | IFA | −0.13483 | 0.32195 | 0.14059 | −0.31068 | 0.22656 |
| | GDP | −0.16734 | 0.23899 | 0.19029 | −0.3169 | 0.10227 |
| | RPI | −0.26857 | 0.03696 | 0.01579 | −0.11095 | −0.16213 |
| | UPR | −0.02919 | 0.19305 | 0.09455 | −0.20993 | 0.19538 |
| Society | LU | −0.03597 | 0.24053 | 0.13493 | −0.22974 | 0.26665 |
| | PD | 0.02322 | −0.10513 | −0.05936 | 0.11797 | −0.09739 |
| | PCCLA | −0.4351 | −0.33687 | −0.00659 | −0.01061 | −0.05345 |
| | PUAGY | 0.11146 | −0.00267 | −0.44011 | 0.43671 | 0.48363 |
| Ecology | FCR | 0.54574 | −0.19202 | 0.40108 | −0.0728 | −0.39516 |
| | FUPA | 0.57818 | 0.29609 | −0.01549 | −0.01649 | 0.22384 |
| | DFW | −0.21036 | 0.54738 | 0.38542 | 0.666 | −0.22211 |
| pattern | SHEI | 0.01872 | 0.36995 | −0.50781 | −0.16258 | −0.43441 |
| | CONTAG | −0.02342 | −0.23912 | 0.38967 | 0.11655 | 0.33483 |

Note: the abbreviations for the indicators are shown in Table 1

Based on the first five principal components, the spatial distribution characteristics of land sustainable use level in the study area are shown in Fig. 2. High level sustainable land use areas are mainly concentrated in the northeast, northwest and coastal area of the Bohai Rim. The land types in the northeast and northwest of the region are mainly forest land and grassland, which are less disturbed by human activities. The land types in coastal areas are mostly urban and rural residential land, and the level of economic development is relatively high, so land use sustainability is relatively high. The areas with low sustainable land use levels are mainly concentrated in the southwest. The land types in this area are mostly cultivated land, and the level of land development and utilization is weak.

The area of completely sustainable land use area is 109375 km$^2$, accounting for 21.39%, mainly distributed in the northern of Hebei Province, and the eastern of Liaoning and Beijing. The area of the land with higher sustainable utilization level is 145325 km$^2$, accounting for 28.42%, mainly distributed in Tianjin, Zhangjiakou, Chaoyang, Qinhuangdao, Anshan, etc. The area of the basic sustainable land use level is 166600 km$^2$, accounting for 32.58%, which is mainly distributed in the south of Hebei and the west of Liaoning Province. The area of initial sustainable land use level is 89750 km$^2$, accounting for 17.55%. It is mainly distributed in Linyi, Rizhao, Qingdao, Yantai, Weihai, Dongying, Binzhou, Laiwu and Zibo in the central and eastern parts of Shandong Province (Table 4).
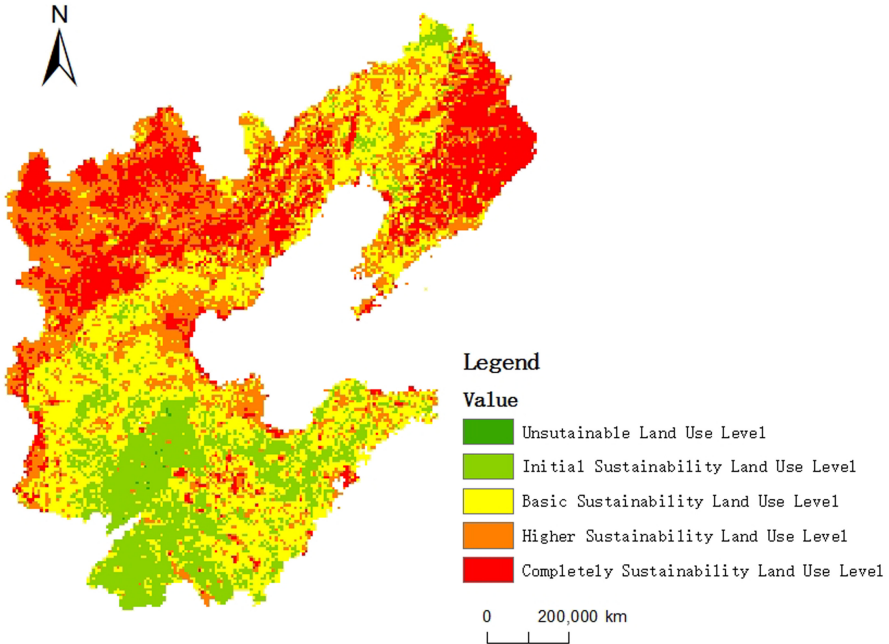
**Fig. 2.** Spatial pattern of sustainable land use level in the Bohai Rim

**Table 4.** Sustainable land use level results evaluation

| Sustainable land use level | Level | Area (km$^2$) | Proportion (%) |
|---|---|---|---|
| Unsustainable level | 1 | 275 | 0.05 |
| Initial sustainability level | 2 | 89,750 | 17.55 |
| Basic sustainability level | 3 | 166,600 | 32.58 |
| Higher sustainability level | 4 | 145,325 | 28.42 |
| Completely sustainability level | 5 | 109,375 | 21.39 |

## 4   Discussion

The level of sustainable land use in the region was influenced by many factors. The results of the study on the ecological criterion level indicate that the area of forest coverage and the amount of fertilization are the dominant determinants, which are related to the water and soil conservation capacity of the forest land and the influence of chemical fertilizers on the fertility of the soil. In the social criterion layer, the per capita arable land area is the dominant factor affecting the level of sustainable land use, which is closely related to the total population in the region, the available arable land area, and the stability of arable land. The higher the food production, the higher the level of sustainable land use. Locally, the level of sustainable land use in urban areas is generally higher than that in

rural areas. The reason is that investment in fixed assets and GDP has increased the level of sustainable land use in urban and rural areas mainly from the socio-economic aspects.

In order to further improve the level of sustainable land use in the Bohai Rim region, the government should take corresponding effective measures against weak links. At the ecology level, the resource types with higher benefits such as forest land and waters are defined as high-quality land resources. In order to maintain their long-term availability and stability, the government should make overall plans for land use and rationally optimize the development and utilization structure of land resources. Comprehensively considering economic, social, and other factors, give full play to the utilization efficiency of high-quality land resources and increase the economic benefits of land and nature. In view of the low level of sustainable land use in the south, we should vigorously promote land development and land reclamation, increase the effective arable land area in Shandong, consider spatial differences in agricultural productivity, and highlight regional land use characteristics to improve sustainable land use level. The increasing population has caused the demand for cultivated land to increase. The analysis of the demographic composition in the social norms indicates that the sustainable land use level of municipalities and provincial capitals is low. In response to the problem of sustainable land use in urban areas, the government should reasonably control the population, increase the carrying capacity of arable land through technical means, and improve the overall level of sustainable land use.

## 5   Conclusion

This paper established a four-dimensional evaluation model of sustainable land use, namely "Economy-Society-Ecology-Pattern" framework, and proposed a novel method to evaluate the land use sustainability at an explicit spatial level. First, based on the "Economy-Society-Ecology-Pattern" framework, an index system of sustainable land use evaluation with 13 indicators was established. Then, the indicators were discretized at 5 km grids level with spatial analysis and land use data. At last, the spatial principal component analysis method is used to get the comprehensive sustainability level of the region. The level of sustainable land use in the Bohai Rim is generally at the stage of basic sustainable development. High level sustainable land use areas are mainly concentrated in the northeast in Liaoning and northwest in Hebei. The ecology factor has the strongest impact on the sustainable land use level, and the economy factor has the weakest impact on the sustainable land use level.

The method could offer more spatial information of sustainable land use to help government propose more efficient policies regarding improving land use sustainability. Due to the limitation of the data acquisition, the sustainable land use index system constructed in this paper need to get improved in the future. If the soil quality index could be added into the index system, the reliability of the research results would be more convincing.

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