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Eco-risk Assessment in Arid Areas Based on Geographic Information Systems-taking Heihe River Basin as a Case

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Abstract: With increasing occurrence of environmental emergencies in China in recent years, risk management has becoming an important subject in environmental management. Past studies on risk assessment and management have focused on chemical risk but rarely on the ecosystem level risk. Based on the theories of landscape ecology and advanced Geographic Information Systems (GIS) technologies, this study built a set of index system and constructed a quantitative method suitable for the arid areas in this study. The Eco-Risk Index (ER) in time series could be used to monitor changes of eco-risk caused by natural disasters and human activities. This study also conducted a case study on the middle part of Heihe River Basin which is a typical area in Gansu province in western China. The results have shown a decrease Eco-risk Probability (EP) due to the fewer and fewer interference from human activities and natural disaster since 2000. The stability of landscape also improved significantly with Landscape Stability Index (LSI) decreased from 0.48 to 0.41, signifying worse landscape stability. But the net primary productivity (NPP') index increased from 0.67 to 0.94 for the area of interest which indicated improved natural light and temperature. The final Eco-risk Indexes (ER) have decreased from 0.83 to 0.58 in the past 11 years because of a significant reduction of the eco-risk factor in the studied region. All the above indicators points to the improvement of the eco-system at Heihe River Basin region. The current research also confirmed that the area of study is in the moderate risk level.

Key words: GIS, eco-risk, arid-oasis areas, the eco-risk index, Heihe river basin

INTRODUCTION

Arid-oasis area is an important element of the arid areas which provides main place and materials for social and economic sustainable development in arid areas. It is characterized by vulnerability and volatility because of the surrounding desert. It is subject to the interference of human activities and natural disasters. In western China, the arid area covers a large percentage of space and contains rich natural resources. However, issues like the natural disasters and ecological degradation caused by human activities limited the social economic development (Liu *et al*., 2009, 2012; Li *et al*., 2009; Ma *et al*., 2011). Survival and development of the whole arid area depend on the ecosystem stability in the oasis area. Once the oasis ecological environment worsens, the ecological service functions of arid area would gradually collapse, meanwhile the regional social economy would be negatively impacted (Chen *et al*., 2010). Eco-risk describes how exposure to stressors is likely to occur and, given this exposure, the potential and types of unfavourable effects that can be expected (Mao and Ni, 2005). Eco-system level risk assessment is a branch of the eco-risk science. Regional eco-risk assessment is a technical method to describe the potential unfavourable results under the natural disasters and human activities on the eco-system level and in a larger area (Meng and Zhao, 2009; Zhou and Meng, 2009; Yan and Xu, 2010). Based on the theories of landscape and advanced Geographic Information Systems (GIS) technologies, this study constructed a quantitative method to assess the eco-risk in an arid area. The method would assist managers to make decision and give them a technical support for the arid area environmental management in the future.

METHODS

The content of eco-risk assessment includes four elements in the arid area as follows: Stressors, sources, exposure and effects, assessment endpoint and conceptual method (USEPA, 1998).

Stressors: Based on the landscape theory, this study categorizes the landscape into seven types as the stressor: Desertification land, Gobi land, cultivated land,

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grass land, forest area, water area and saline land. They are all classical landscapes which can be easily found in most arid areas.

Sources: Based on the landscape theory, this study categorizes the sources into three types: Natural factors, human activities factors, biological factors (Xiao and Li, 2010):

- **Natural factors:** Indicate natural light and heat condition in a certain area or an ecological system different from others. For example, the factors like annual average precipitation, annual average temperature are all the key elements in the arid ecosystem (Li and Xu, 2011; Guo *et al*., 2011). The Drought and Flood Disaster Index (DFDI) was selected to express the effect of the natural factors. The DFDI could be obtained from the local meteorology data
- **Biological factors:** They are represented by vegetation cover which could protect the arid oasis area from the desertification. Vegetation Cover Index (VCI), as an aggregate indicator, could easily respond to the disturbance of natural conditions and human activities. It could be obtained from the TM data by using GIS method (Liu *et al*., 2007)
- **Human activities factors:** Stands for human disturbance intensity based on the eco-values of different landscape, using Human Activities Index (HAI) to express Li and Nan (2012). Based on the expert grade methods, interference factor of desertification land is lower than other landscape types, at level of 0.05. Interference factor of Gobi land is 0.07. Saline land is 0.09. Forester area is 0.12. Water area is 0.15. Grass land is 0.23. Cultivated land is 0.55. The HAI can be obtained by following equation:

$$\text{HAI} = \sum_{i=1}^{N} \frac{\text{Ai} \times \text{Pi}}{\text{TA}} \qquad (1)$$

In this equation, Ai is the total area of given landscape type i. Pi is the interference factor of given landscape type i. TA is the total area of all landscapes of interest.

- **Eco-risk probability (EP):** It is total risk probability of the research area. Based on the previous description, the risk probability could be expressed by following equation:

$$\text{EP} = \text{a DFDI} + \text{b VCI} + \text{c HAI} \qquad (2)$$

In this equation, a, b, c are regression coefficients, assigned 0.59, 0.16 and 0.25 in the experts method.

Exposure and ecological effects: In this section, indexes represent the potential and type of ecological effects that would be expected. This study used indexes of landscape stability index and net primary productivity to represent the potential ecological lost effects:

- **Landscape stability indexes (LSI):** Include levels of landscape fragmentation, landscape dominance, landscape connectivity. Landscape stability stands for the change of landscape structure:

$$\text{LSI} = \text{a C} + \text{b D} + \text{c E} \qquad (3)$$

In this equation, C is CONTAG[1] which represents the landscape conntictivity representing the extended trend. D is 1/SHDI[2] which represents the landscape fragmentation. E is (1-SHEI[3]) which represents landscape dominance. While CONTAG is better, the whole landscape is more stable. SHDI is Shannon diversity index which is bigger when the whole landscape is less stable. SHEI is Shannon evenness index which is bigger when the whole landscape is more stable. CONTAG, SHDI can be obtained based on the GIS tools and software Fragstats3.3. Coefficients a, b and c are the weighting of C, D, E and assigned 0.3, 0.4 and 0.3 in the experts method:

- **Net Primary Productivity (NPP):** It stands for the fragility of the area under the certain natural light and heat condition which also indicates the features of research area which are different from other eco-system. This study constructs the calculation method based on Miami model (Liu, 1997; Lieth, 1975; Lieth and Box, 1975). The equation is following:

$$\begin{aligned} \text{NPP}_T &= 3000/\left[1 + e^{1316 - 0.1196T}\right] \\ \text{NPP}_P &= 3000\left[1 - e^{-0.000664P}\right] \\ \text{NPP}' &= \left[\min(\text{NPP}) - \text{NPP}_{min}\right]/\left[\text{NPP}_{max} - \text{NPP}_{min}\right] \end{aligned} \qquad (4)$$

In this set equation T is the annual average temperature. NPP_T is the net primary productivity calculated using the annual average temperature. P is the annual average precipitation. NPP_P is the net primary productivity calculated by the annual average precipitation. NPP' is the standard value of NPP. NPP_{min} is the minimum value by comparing the NPP_T and NPP_P. NPP_{max} is the maximum value by comparing the NPP_T and NPP_P. The minimum value of NPP is 10 g m^{-2}•a^{-1} and the maximum value is 250 g m^{-2}•a^{-1}, both were calculated by Leith method for desert area.

[1]CONTAG is short for contagion index
[2]SHDI is short for Shannon diversity index
[3]SHEI is short for Shannon eveness index

Assessment endpoint and conceptual method: Risk characterization could be represented by the conceptual method which is based on the following premises. Firstly, Landscape stability is proportional to eco-risk probability. Secondly, Landscape fragmentation is inversely proportional to landscape stability, while landscape dominance and landscape connectivity are all proportional to landscape stability. Thirdly, net primary productivity is inversely proportional to eco-risk. Finally, risk sources probability is proportional to eco-risk. Eco-risk evaluation matrix could be created as following equation.

$$ER=EP / (LSI \bullet NPP') \quad (5)$$

In this equation ER represents the value of eco-risk. Other symbols are the same as that mentioned above.

Evaluation grade: Then assessment results are classified into five levels: Minimal risk, low risk, moderate risk, high risk and severe risk (Table 1). Five levels stands for the ecological risk level after weighing the relative importance of each index shown in Eq. 5. For example, the final value of ER is in minimal risk level which means lower eco-risk probability but higher landscape stability and net primary productivity than other area or other historical period.

Table 1: Classification of ecological risk grading depending on eco-risk values

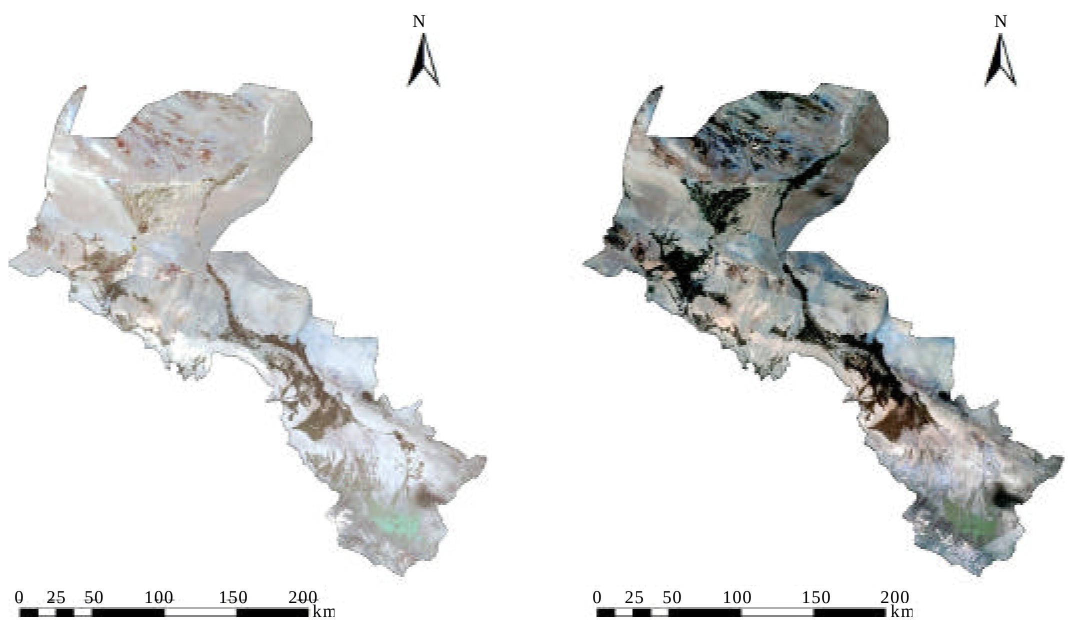
Risk level	Value of eco-risk index
Minimal risk	0-0.2
Low risk	0.2-0.4
Moderate risk	0.4-0.6
High risk	0.6-0.8
Severe risk	0.8-1.0

CASE STUDY

The Heihe River Basin is located at 98°00'-101°30'E, 38°00'-42°30'N and has a drainage area of 130,000 km^2. It consists of the upper mountainous area, the middle Oasis area and the lower terminal arid Oasis-Gobi-desert area. This study focuses on the middle Oasis area and the lower terminal arid Gobi-desert area.

Analysis processing: This research based on the Landsat7 SLC-on data in 2000 and the Landsat5 Thematic Mapper (TM) data in 2011 in the Heihe River Basin which are collected from USGS Global Visualization Viewer. The condition of the data sources is 1:4,000,000. Scale research sites above the Prefecture Level map is derived from the national fundamental geographic information system (Fig. 1). And the left picture in Fig. 1a is the processed remote sensing image in the year 2000, while the right one (b) is in the year 2011.

Using ERDAS 9.2 software, images were pre-processed. Pre-processing procedures include image conversion, geometric correction, multi-band combination, mosaic, landscape classification, cluster analysis, filter



(a) (b)

Fig. 1(a-b): Thematic mapper (TM) data of the research areas, year 2000 and 2011

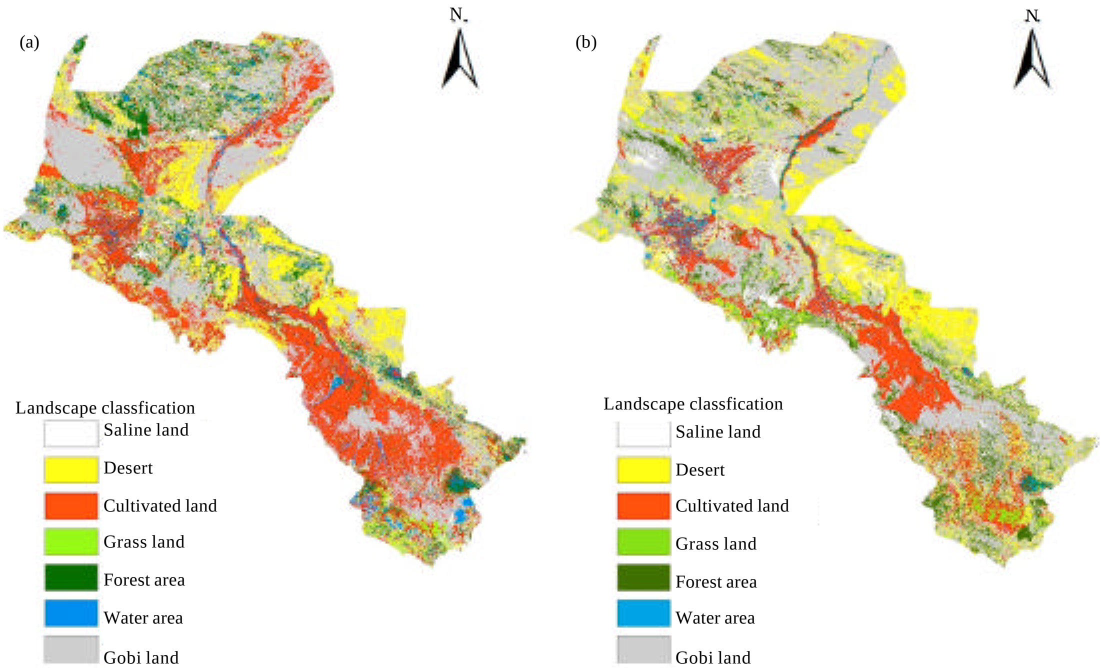


Fig. 2(a-b): Landscape classification of research area in the year 2000 and 2011

analysis, sieve and eliminate analysis, recoding and human-computer interactive interpretation. Then land-use data were derived. Using ARCGIS 9.3 and spatial pattern analysis tool-FRAGSTATS, this study obtained a classified map of different landscapes (Fig. 2). And the left picture in Fig. 2a is the processed landscape classification image in the year 2000, while the right one Fig. 2b is in the year 2011. Finally, basing on the Fragstats3.3 combing with the statistical analysis tool EXCEL, this study computed the eco-risk values based on the Eq. 1-5.

RESULTS

Calculated results can be seen in Table 2-4.

In Table 2, factors such as CONTAG, SHDI and SHEI indicate different landscape stability indexes which are calculated basing on Fragstats3.3. And landscape stability index (LSI) was calculated by using formula 3. It can be seen that, CONTAG, SHDI and SHEI have increased in the past 11 years. The increase in CONTAG indicates an increase of landscape connectivity in this area from 2000 to 2011. During the same period, the diversity of landscape in the region also increases, as evidenced by the increase in SHDI. Furthermore, this study observed an increase in landscape evenness as SHEI in 2011 is greater than 2000. These findings lead us to conclude that the number of patches and the area of dominant landscape have declined but other kinds of landscape have become dominant. This also suggests that the landscape stability is decreasing which is further confirmed by the decreased LSI in Table 2.

In Table 3, this study reported the annual average temperature and precipitation of the region in 2000 and 2011. Based on the formula 4, minimum values are picked by comparing the value of NPP_T and NPP_P in 2000 and 2011. The final values of NPP' indicate an increase of net primary productivity in the past ten years. The increase in the value of NPP' shows that the natural light and heat condition in the research area has improved since 2000.

Based on survey statistical data, this study presented HAI, VCI and DFDI in 2000 and 2011 in Table 4. This study used the Eq. 5 to compute Eco-risk Probability (EP) and Eco-Risk (ER). The final value of EP has decreased due to the lower interference from human activities and natural disaster from 2000. The decreasing landscape stability and increasing net primary productivity in the past 11 years results in a decline in the final ER value. Accordingly, from 2000 to 2011, the area of previous dominant landscapes, like desertification land and Gobi land, in the research area has decreased due the increasing awareness of environmental protection and improved natural light and heat conditions. In contrast, the other landscapes, like cultivated land, grass land, forest and water have become increasingly dominant in

Table 2: Comparison of landscape stability indexes and its parameters between 2000 and 2011

Year	Contagion index (CONTAG)	Shannon diversity index (SHDI)	Shannon eveness index (SHEI)	Landscape stability indexes (LSI)
2000	39.5184	1.466	0.705	0.48
2011	41.7572	1.7061	0.8204	0.41

Table 3: Comparison of net primary productivity indexes and its parameters between 2000 and 2011

Year	Annual average temperature (T(°C)	Annual average precipitation (P (mm)	Net primary productivity basing on annual average temperature (NPPT)	Net primary productivity basing on annual average precipitation (NPPP)	Net primary productivity (NPP')
2000	7.45	89	1186	173.04	0.67
2011	7.42	123	1183	235.875	0.94

Table 4: Results of eco-risk probability (EP) indexes and eco-risk (ER)

Year	Human activities index (HAI)	Vegetation cover index (VCI)	Drought and flood disaster index (DFDI)	Eco-risk probability (EP)	Eco-risk value (ER)
2000	17.90	0.46	0.26	0.26	0.81
2011	16.28	0.41	0.23	0.23	0.58

research area. All the above indicators points to the improvement of the eco-system at Heihe River Basin region. And the current research also confirmed that the area of study is in the moderate risk level.

Zou *et al.* (2010) calculated the ecological security values of the year 1986, 2000 and 2007. The results indicated a fluctuant change of the security status. The situation in 2000 was worse than that in 1986. And in 2007 it was superior to that in 2000 (Zou *et al.*, 2010). Also Zhang and Zhang (2012) calculated the spatial change of the dry-wet conditions by using the method of Inverse Distance Weighted (IDW) under ArcGIS. The results indicated that the values of mean annual humid index were generally in an increase trend in a fluctuation way in the Heihe River Basin and its upper, middle, lower reaches in recent 49 years and the surface humid status was improved to some extent (Zhang and Zhang, 2012). Comparing those results with the eco-risk values in those studies, they have the same change trend. It means the ecological situation of Heihe River Basin is getting better those years. The method constructed in this study is credible.

CONCLUSION

Past studies on risk assessment and management have focused on chemical risk but rarely on the ecosystem level risk. Based on the theories of landscape ecology, this study did a research on arid ecological system. Arid ecological system is a fragile ecological system but few research of risk assessment on it.

Besides, this study did a research on construction of eco-risk assessment methods in arid ecological system. In the method, the influences of precipitation, human activity and vegetation cover are evaluated as the risk stressors. The changes of landscape stability and net primary productivity are used to assess exposure and ecological effects of the arid ecological system.

Furthermore, final value of eco-risk is classified into five levels: Minimal risk, low risk, moderate risk, high risk and severe risk. The method is a first attempt.

This study also did a case study in Heihe River Basin, in Gansu province in western china. The Eco-risk Index (ER) of the Heihe River Basin and the effective policy of environmental protection and effective Ecological Restoration over those years.

The final value of EP has decreased due to the lower interference from human activities and natural disaster from 2000.

The Landscape Stability Index (LSI) declines from 0.48 to 0.41 due to the decreasing landscape dominance and landscape diversity and increasing fragmentation.

The net Primary Productivity Index (NPP) increases from 0.67 to 0.94 due to improved living conditions.

All the above indicators points to the improvement of the eco-system at Heihe River Basin region.

Comparing the previously published studies, the results showed the same change trend in the time series. The method constructed in this study is credible.

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