A METHOD FOR ASSESSING THE ECO-ENVIRONMENTAL VULNERABILITY OF FILDES PENINSULA, ANTARCTICA

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Abstract

Global change and sustainable development have become a hot topic in the world today. Recent studies concerning the impact of the global change on Antarctic and the interaction between global change and Antarctic environment have covered different scales and different disciplines in China. However, it is extremely difficult to implement comprehensive researches on the Antarctic environment change issues due to the peculiar conditions in this region. The methodology which combines the multi-scale information is a desirable and effective way for the study on the global change and Antarctic reactions. Focused on ice-free areas along Antarctic coast, this research analyzes the factors that contribute to eco-environmental vulnerability in ice-free areas, and brings forward a new technical framework for eco-environmental vulnerability quantitative assessment based on GIS. The assessment results can serve as a valuable

basis for administration department to protect the Fildes Peninsula from artificial destruction.

The body of this paper begins with a description of the characteristic of eco-environment vulnerability in Fildes Peninsula, which is a typical ice-free area located in the northeast Antarctic and exemplifies the whole evaluation process. Based on the analysis of Fildes Peninsula's vulnerability and the feasibility of field survey, ten factors, including eight causal indexes and two resulting indexes, are extracted to construct a cause-effect eco-environment assessment index system. Eight causal vulnerability indexes are subdivided to two types, i.e., inner vulnerability caused by the structure of the ecosystem itself: climate, soil and physiognomy, and outer vulnerability which is affected by the pressure and interference from the outside, owing to both the human activities and environmental changes. On the other hand the altitude and coverage of lichen (the dominant vegetation type) are selected as resulting indexes.

Afterwards, the methodology of establishing an assessment model based on GIS is explored. Firstly, assessment cells are defined by a 'vector-raster mixed data model'. That is to overlay the physiognomy type map, soil type map and vegetation type map with the help of ArcGIS spatial overlay analysis to generate basic assessment cell, and every cell maintains the values of the ten indexes, each of which are calculated by averaging the initial homogeneous values in every basic statistic unit – 20m*20m regular grid inside the cell. Then a cartographic rank correlation model – Spearman model is adopted to compute the correlation coefficients between each index and the two resulting index, the two numbers are then averaged to educe a new correlation coefficient of each index. Then all the correlation coefficients are normalized followed by the calculation for the final normalized weight of each index. Grounded on the above calculated weights, the comprehensive-factors model is applied to elicit the vulnerability value of each cell. It is noteworthy that the introduction of vector-raster mixed data model and Spearman model in vulnerability assessment process are technical innovations, and most of the complicated calculation is carried out under VBA (Visual Basic for Applications) programming environment in ArcGIS.

Finally, the result is presented and discussed. The degree of the vulnerability is classified into four categories: extremely vulnerable, severely vulnerable, moderately vulnerable and mildly vulnerable. Furthermore, the final results were visualized in 3-dimensional map by ArcGIS to facilitate the decisions. According to the 3D map, some patterns of eco-environmental vulnerability distribution are discovered.

1 Introduction

Currently, the Antarctic eco-environment's response to global climate change and human activities' interference in the South Pole region's eco-environment are two important topics in the field of Antarctic environment research at varying degrees [1], and under such circumstance the research on eco-environmental vulnerability and spatial heterogeneity emerged. The typical ice-free area examined in this article is the Fildes Peninsula, which locates in the southeast of the King George Island, the largest island among South Shetland Islands adjacent to Antarctic Peninsula. Human activities were considered to be the most frequent in Fildes Peninsula, which makes it the ideal site for studying Antarctic environment. Moreover, the Fildes Peninsula is defined as 'Sites of Special Scientific Interest' by Antarctic Treaty Consultative Meeting [2]. Consequently, assessing the eco-environmental vulnerability of Fildes Peninsula provides a valuable basis for administration department to protect the peninsula from artificial destruction.

The evaluation approach based on traditional ecology model has some common defects, for example, the weights of indexes are assigned subjectively by experts. Although some mathematic methods, model theory and 3S (GIS, GPS and RS) technology have been gradually introduced in the assessment process [3], GIS's application is still confined in data management and mapping the results, whereas GIS's capabilities in spatial analysis, geographic analysis, and statistic analysis and 3-dimensional visualization have not been utilized.

Therefore, establishing a GIS model that is competent of quantitatively evaluating the eco-environment vulnerability, and applying it to Antarctic ice-free areas, are of great significance both theoretically and practically.

2 The Characteristic of the Fildes Peninsula's Eco-Environment Vulnerability

With altitude less than 200m as a hilly area, bordering on Fildes Strait in the south and adjoining Collins Glacier in the northeast, Fildes Peninsula preserve a simple and primordial ecosystem with the moss and lichen making up the main vegetation type. Owing to the icy climate and infertile soil, the plant community maintains a simple structure and a low rate of growth. On the other hand, the peninsula still retains a certain amount of vegetation cover and evidently preponderant community due to oceanic climate.

At regional level, the Fildes Peninsula's eco-environment vulnerability is mainly dominated by inner vulnerability, which was caused by the structure of the ecosystem itself, and less affected by outer vulnerability, which is affected by the pressure and interference from the outside that owing to both the human activities and environmental changes. While at the whole Antarctic continental level, outer vulnerability resulting from human activities manifests itself best in the Fildes Peninsula, and the inner vulnerability does not show evident disparity inside the peninsula [4]. The eco-environment vulnerability is determined by the fundamental substance and the energy basis of the peninsula, such as climate, water, heat, soil and landform. Furthermore, the simple and primitive ecosystem, typical coarse soil and violent surficial physical changes render the peninsula vulnerable to negative effect of human activities, much less than self cleaning capacity. As for outer vulnerability, there are two aspects leading to the eco-system's frangibility. The first is the global human activities and climate change, and the other is the local human activities. The latter generally takes effect in the area of the Peninsula, and the common activities involved are human routines, building construction, burning and storage of fuel, ambulation and usage of transportation tools, logistics back-up, tourism, emergent accidents, etc [5]. These activities are related to numerous and different environmental elements in varying degrees. On the basis of this insight, the factors that constitute the eco-environment vulnerability can be found in five main aspects: physiognomy, soil, climate, plant community and human activity.

3 GIS - Based Assessment Model

3.1 Assessment Index System

Based on the analysis above and according to the possibility of acquiring the desired indexes in field survey, an index system of Fildes Peninsula‘s eco-environmental vulnerability is constructed as below [6]:

Target level	Criteria levelⅠ	Criteria levelⅡ	Index levelⅠ	Index level Ⅱ	10 indexes taken into consideration in practice
Assessment of eco-environmental vulnerability of ice-free areas in Antarctica	Cause	Inner - Vulnerability	Climate	Heat	Annual average temperature/℃
				Wind	Eigenvalue of Wind direction/aspect
			Soil		Eigenvalue of growth Thickness
			Physio-gnomy		Gradient Geomorphic Altitude
		Outer - Vulnerability	Human Activity	Activity's scale	Population Density
				Interference Index	(Area of Roads + Buildings) /total area
	Effect	Vulnerability Factor	Vegetation	Function of plant community	Vegetation (lichen) cover rate Vegetation (lichen) altitude

Tab.1 Index System of Eco-environmental vulnerability of Fildes Peninsula

3.2 Ascertain the Assessment Cell

The assessment cell is the basic evaluation unit, where the physiognomy, climate, soil and other natural elements are deemed to be uniform. The popular adopted assessment units are either vector cells resulted from administrative divisions [7], or raster cells based on mesh segmentation.

In this research, considering the spatial distribution disparity of geographic phenomena, a new approach to define assessment cell is brought forward-- 'vector-raster mixed data model', namely vector area unit in combination of raster grid unit. Firstly, 20m*20m regular grids are introduced as basic assessment unit, on which the physiognomy type, soil type and vegetation type maps are overlaid by ArcGIS to generate final assessment cells. Based on the three maps, the cells can generally reflect the spatial disparity in geomorphology, natural surficial process and community structure.

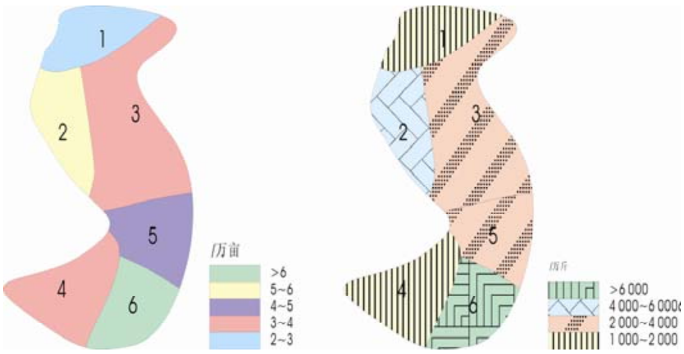
3.3 Assign Weight to Index

In order to reflect the different index's significance level and influence to the eco-environment, weight method is widely used in assessment system. At present there are a variety of ways to determine the weight, some are based on expert's experience or subjective judgement, such as Expert Mark method and Experience Weight method; and some other approaches employ mathematic formulas, for instance, Principal Component Analysis, Fuzzy Variable Weighting [8], Grey Interrelated method, and so on. Mathematic methodologies are relatively more objective but still contain some subjectivity in the process of selecting model and data. So in view of feasibility and flexibility, the frequently used technique in practice usually integrates Expert Mark with mathematic methods.

As the GIS-based assessment system enables the complete quantitative evaluation of indexes, this paper describes the usage of a cartographic rank correlation model – Spearman model, to quantify the vulnerability indexes' weights.

3.3.1 The Principle of Spearman Model

Assuming two thematic features X and Y, and a and b specify the statistic values of X and Y in the same region respectively. As Figure1 shows below, map (a) and (b) illustrate the two features' distribution in the form of a collation map. The two maps could differ in their number of classification, use different intervals, but must be identical in their statistical units. (See Figure 1)



(a) Area under cultivation (b) Grain Yield

Fig.1 Rank Correlation Map

The rank correlation coefficient r_s is:

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(p_{ai} - p_{bi})^2}{n^3 - n} \tag{1}$$

In this formula, Pai means the rank order of the ith unit in map a, likewise Pbi stands for the rank order of the ith unit in map b, n is the number of units (6 in this instance). The rank order of each map unit is assigned from 1 to n, the larger the statistical value of the unit, the smaller is its rank order. In case of two units possessing the same statistical value, the solution is to assign them with the average of the two consecutive rank orders.

3.3.2 Calculate the Correlation Coefficient

According to the formula (1), the correlation coefficient between each of the ten indexes and one of the two resulting indexes is calculated, then educe 20 correlation coefficients (the correlation coefficient between a resulting index and itself is 1). For evaluation usage, the correlation coefficients are subsequently mapped to 0-1 range, and the sum of mapped correlation coefficients equals 1. The mapped value 'W' becomes the weight of index in the comprehensive evaluation.

3.4 Comprehensive Evaluation

Grounded on the acquired values and weights, a quantiative fragility assessment model of ecological environment is introduced as the following formula (2):

$$G_i = 1 - \frac{\sum_{j=1}^{n} p_{ij} \cdot w_j}{\max\left(\sum_{j=1}^{n} p_{1j} \cdot w_j, \sum_{j=1}^{n} p_{2j} \cdot w_j, \cdots, \sum_{j=1}^{n} p_{mj} \cdot w_j,\right) + \min\left(\sum_{j=1}^{n} p_{1j} \cdot w_j, \sum_{j=1}^{n} p_{2j} \cdot w_j, \cdots, \sum_{j=1}^{n} p_{mj} \cdot w_j,\right)}$$

$$(i = 1, 2, \ldots, m, \quad j = 1, 2, \ldots, n) \qquad (2)$$

Where G_i is the eco-environmental vulnerability of number i cell, *m* is the amount of the evaluation cells, *n* is the number of the causal or resulting indexes, *p* is original value from the investigation, and *w* is the normalized weight of each index.

4 Implement the Assessment in ArcGIS

1) The source of the data comes from field survey, map datum and remote sensing image. For example, geomorphologic indexes, such as altitude, gradient and slope direction are calculated on the basis of the relief map of Fildes Peninsula at 1：10 000 scale, soil index is derived from field investigation data in reference article [2], and vegetation and human activity related indexes are acquired through remote sensing image and field measurement.

2) Construct topological relation and attributes table in ArcGIS. Discrete field survey data is interpolated to output raster area data for temperature, vegetation, and soil

indexes. Gradient and slope direction indexes are calculated from TIN (Triangular Irregular Network), which is yielded from contour lines. The population and its coverage area are calculated by creating a buffer and then represented in two indexes, namely the average population in Antarctic stations and interference index.

3) With the assistance of ArcGIS overlay analysis, the ‘Union’ operator is applied on three layers –-physiognomy type, soil type and vegetation type. As a result, they are overlaid and crossed to form the 797 assessment cells, each of which maintains the values of the ten indexes that figured out by averaging the initial homogeneous values in every basic statistic unit-- 20m*20m regular grid inside the cell..

4) Rank correlation coefficient is then obtained by programming in ArcGIS’s VBA (Visual Basic for Applications) environment, where functions and procedures are edited directly, namely interactive programming method.

The assessment is realized in the following steps:

First of all, the initial value of every single index for each cell is extracted. The ten indexes’ initial values for each cell are obtained from raster layers in the database, and they are subsequently stored in the corresponding cell’s attribute tables.

Then the lichen cover rate and lichen altitude are taken as benchmarks, to which rank the index belongs is ascertained and the rank correlation coefficient is calculated between each of the ten indexes and the benchmark index. Afterwards, the average of the two rank correlation coefficients, (one with lichen cover rate and another with lichen altitude) is carried out for the correlation coefficient between every index and lichen.

Subsequently Extreme Value Method is employed to normalize all the correlation coefficients, at the same time the weight of each index is generated.

Finally, each cell’s eco-environmental vulnerability is evaluated in the way of formula (2).

The vulnerability of 797 assessment cells are classified into 4 groups based on their vulnerability, varying from extremely, severely, moderately to mildly vulnerable. The assessment result is presented in Tab.3 and distribution map (Fig.2).

Numeric Class of vulnerability	Degree of Vulnerability	Number of Cells
0.75 ~0.902	extremely vulnerable	68
0.65~0.75	severely vulnerable	270
0.55~0.65	moderately vulnerable	324
0.33~0.55	mildly vulnerable	135

Tab.3 Vulnerability Statistics Units

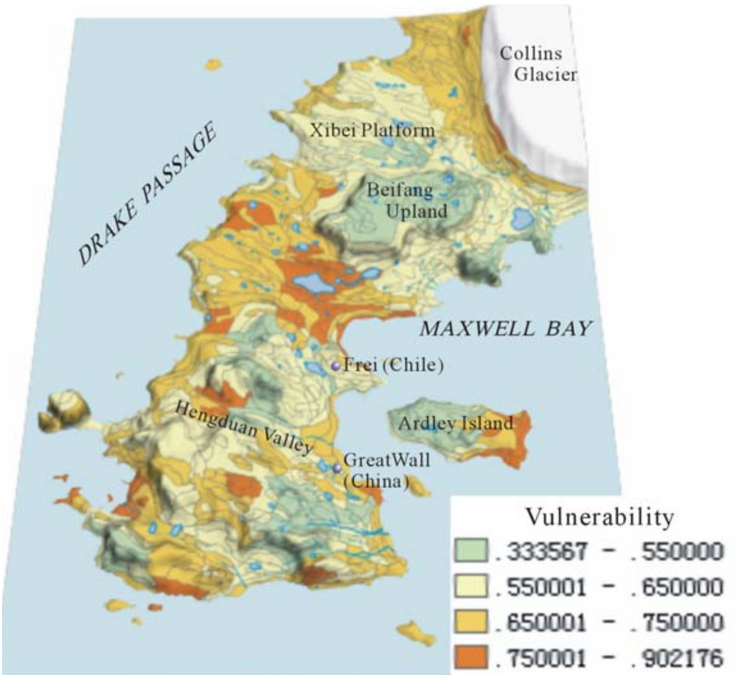


Fig.2 3D Map of vulnerability Distribution

5 Analysis and Conclusion

Looking at the map above, it is explicit that the extremely vulnerable areas mainly distributed in the central section of the peninsula and along the east coast of Ardley Island, and are distributed discontinuously in the south of the peninsula. Whereas the severely vulnerable areas mainly spread near the Collins Glacier in the north, along the coasts of Ardley Island and the peninsula, or around the extremely vulnerable areas .The Hengduan Valley neighborhood and Xibei Platform are moderately vulnerable. Moreover, the enormous Beifang Upland, together with south peninsula and west part of the Ardley Island account for the least vulnerable region. Generally speaking, from south to north, the degree of vulnerability shows an alternative weak-strong pattern because of the peninsula's natural elements' distribution disparity in physiognomy, soil, and climate. Furthermore, from coastal to terrestrial areas, the vulnerability undergoes a gradual change from extreme to mild, except for the neighborhoods of Frei station （Chile）and the airport. Last but not the least, thanks to the spatial disparity and intensity of human activities, the vulnerability presents a relative continuous distribution in the north of the peninsula, whereas rather dispersed in the south part.

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