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Eco-environmental spatial characteristics of Fildes Peninsula based on TuPu models

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Abstract This study applies a TuPu analysis to investigate ecological and environmental aspects of an Antarctic ice-free area, using Fildes Peninsula as an example. The TuPu unit was determined using a vector-grid mixed data model. Information from the eco-environment elements was effectively extracted, and was generalized into different classes by means of data mining technology. A series of single-factor thematic information TuPu models, such as topography, soil, animal and vegetation, and human activities for Fildes Peninsula were built in this study. The topography TuPu model contained information on elevation and slope. The soil TuPu model involved soil development stages and soil thickness information. The animal and vegetation TuPu model contained the distribution of animals, plant types, lichen cover and lichen height. The human activities TuPu model included population density and human disturbance index information. The landscape comprehensive information TuPu model of Fildes Peninsula also was established, and contains twenty-nine landscape units and twelve types of combined environments. The study quantitatively revealed the spatial morphology and correlation of the regional eco-environment based on the analysis of these TuPu models. From these models, we can draw the conclusion that there is a regular differentiation of eco-environment from the coastal bands to the central hills in Fildes Peninsula, and that the eco-environment condition of the eastern coasts is different from that of the western coasts. The eco-environmental spatial variation also differs greatly from north to south. Based on analysis of spatial correlation, the vegetation in Fildes Peninsula has the greatest correlation with human activity, and has a certain correlation with topography and soil. This research may provide a new technical approach and scientific basis for the in-depth study of Antarctic eco-environments.

Keywords **eco-environment, Fildes Peninsula, information TuPu model, analysis of TuPu model**

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0 Introduction

Geo-information TuPu is based on the theory of spatial cognition, and it is supported by remote sensing, geographic information systems, as well as computer graphics technology. The system expresses the spatial structural features and temporal variation of objective things and phenomena, with production of an intuitive information series of graphics, images and schemata by means of data mining and special processing[1]. Eco-environment information TuPu can be produced on the basis of eco-environment investigation and dynamic monitoring, and also can show spatial structural characteristics and temporal variations of ecological environments with graphical analysis of topographic maps, thematic maps and remote sensing images[2]. Research on regional ecological environment information Tupu has achieved phased results in China. The classification and database building of eco-environmental comprehensive information TuPu in Fujian Province has already been achieved by Chen et al.[3-5]. Wang studied land use change evaluations by eco-environment information atlas-spatial analysis techniques in the Songnen Plain[6], and Tian studied the geo-informatic TuPu model of ecological environment in the city of Qinhuangdao[7].

Antarctic ice-free areas are mainly distributed in

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coastal zones and inland bare rock areas of Antarctica. The characteristics and evolution of the geology, geomorphology, biology, soil and climate contain a wealth of environmental history information, and are key areas of scientific research. In recent years, a series of Antarctic eco-environmental studies have been carried out, including environmental background value surveys, biodiversity surveys, environmental impact assessments, and ecological baseline spatial differentiation analyses. We took Fildes Peninsula as an example, and we clarified its eco-environmental spatial characteristics by constructing eco-environment information TuPu models. These models deepened the excavation of eco-environment internal laws and their multi-dimensional expression.

1 Overview of study region

Fildes Peninsula is located in the southwestern area of King George Island, which is near the tip of the Antarctic Peninsula. The latitude of Fildes Peninsula ranges roughly from 62°08'48"S to 62°14'02"S, and the longitude ranges from about 58°40'59"W to 59°01'50"W. The length of the region from north to south is about 8 km, and the width from east to west is 2.5—4.5 km. The total area of the peninsula is approximately 38 km^2. Fildes Peninsula is a hilly region with an altitude below 170 m. It has characteristic landform types of mainly denuded hills, eroded tablelands and coastal terraces. The soils of the peninsula show strong physical processes at the surface, and the soil types mainly are cambisols and entisols. Areas with dense vegetation and penguin habitats usually have histosols, and the beach terraces have sandy soils[8]. The peninsula belongs to the sub-Antarctic oceanic climate, with tundra habitat characteristics of low temperature, high winds and precipitation. Snow is mainly seasonal and linked to the distribution of precipitation[9]. The region has unique species, and the plant community is mainly made up of cryptogamic plants, such as lichens, mosses and algae[10]. More than 15 species of seabirds are distributed on the island, and the community structure is mainly made up of penguin-skua-tern. The regional eco-environment has low capacity of self-purification and resistance to external stress. Thus, the eco-environment is very primitive and vulnerable[11]. There are scientific research stations from China, Russia, Chile, Uruguay, Argentina and other countries on Fildes Peninsula. Owing to its special location and particular environment, Fildes Peninsula has several Antarctic Specially Protected Areas (ASPA). At the eighth Antarctic Treaty Consultative Meeting (ATCM), these were identified as having high scientific research importance[12-13].

2 Construction of eco-environment information TuPu

The eco-environment system is complex, and contains a variety of environmental elements and factors. According to information properties, the eco-environment information TuPu can be divided into single-factor thematic information TuPu or multi-factor comprehensive information TuPu. The Antarctic ice-free area forms unique ecological characteristics with its internal and external forces. For the case of Fildes Peninsula, a multi-level and wide-angle information TuPu system should be established under certain refining models using a variety of principles and techniques, such as geographic mechanism exploration, data mining, spatial-temporal analysis and information visualization[14-15].

Figure 1 shows the process of eco-environment TuPu construction, which includes the following important parts:

(1) Collection of regional eco-environment information, including observational data, map data, image data and fieldwork data. Then, the elements phenomena and problems of the eco-environment are analyzed to grasp macro patterns and laws.

(2) Defining TuPu units, which are the basic space-time complex units for organizing geographic information and establishing the computational model or mathematical simulation models. We used a hybrid model, which combines planar vector units and regular grid units to determine TuPu units. A 20 m×20 m regular grid was used as the basic unit for environmental factor analysis, and it was further overlaid on the landform type zoning, soil type zoning and vegetation type zoning to product vector planar units of comprehensive nature zoning, which were used as the TuPu units for overlaying analysis and regional analysis.

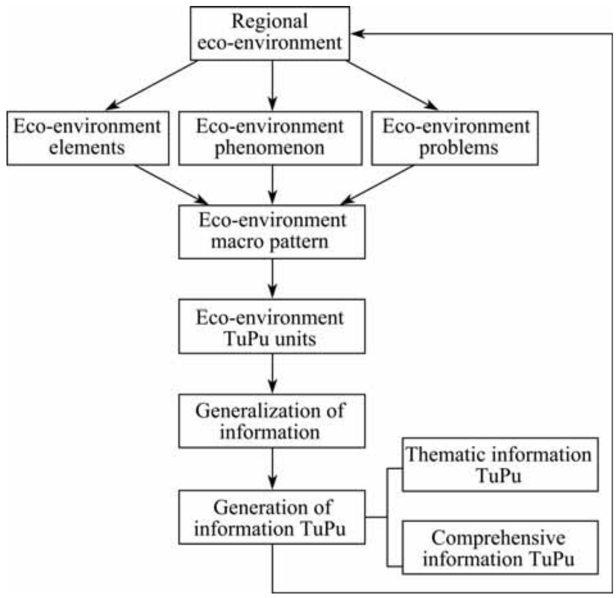

Figure 1 Construction of processes for eco-environment information TuPu development.

(3) Generalizing the eco-environment information to extract the basic eco-environment elements or factors and classifying the eco-environment information by means of data mining and knowledge innovation. In addition, this part includes the establishment of standard types and scoping the distribution of the various characteristic elements through classification and merging of data. The specific

approach of the generalization of environmental factor information is shown in the part of TuPu model generation.

(4) Producing and expressing the TuPu models. We established the database and mathematical models to obtain a series of diagrams in the form of analysis maps, and described the series of graphics with mathematical parameters to quantify and formalize the formation of the regional eco-environment TuPu. In this study, we designed the spatial visualization of TuPu to obtain the function of computer recognition and virtual reality. The TuPu included both the single-factor thematic information TuPu and the comprehensive information TuPu[14].

2.1 Generation of thematic information TuPu models

In this study, climatic and hydrological factors were not involved because the climatic element spatial variation is not very clear and surface runoff is usually scarce in Fildes Peninsula. The eco-environment information of the research includes topography, soil, animals and vegetation, and human activities. The extraction and summarization of the eco-environment information is as follows:

(1) Topographic elements: Elevation and slope are important factors reflecting the different landform types and morphology of Fildes Peninsula. As the feature contours of 150 m, 50 m, 20 m, and 3 m express basic characteristics of the topographic contours of the region, the classification assignment of elevation was determined according to these feature contours and landform types. The extraction of landform slope indices was based on contour lines and elevation points of terrain data. The regional surface model was established by means of ArcGIS 3D_Analyst module, and the slope was divided into six grades in the comprehensive consideration of the slope shape, soil erosion, periglacial mudslides process, gravity process and other factors. The six grades were $\leqslant$4°, 4°—8°, 8°—15°, 15°—25°, 25°—35°, >35°. The value of 4° was included in the grade $\leqslant$4°, and the values of 8°, 15°, 25°, 35° were respectively included in the grade of 4°—8°, 8°—15°, 15°—25°, 25°—35°. The slope of each grid cell (1 m × 1 m) was calculated, and the thematic raster data layer of the slope indicator was fully established.

(2) Soil elements: Soil elements included soil developmental stage and soil thickness. The soil classification map was used as the data source to complete data collection, data testing and topology building of vector data. As the soil spatial heterogeneity of the peninsula is very strong, the complex domain can be shown in a small area, and the different soil types have different developmental stages. The eigenvalue of soil developmental stages in the complex region was the average of the eigenvalues of corresponding stages of the two main types in the study area. According to the correspondence between soil classification and soil development stage, soil developmental stage of Fildes Peninsula was divided into six stages, and the eigenvalues of soil developmental stages were derived. The discrete point data of soil thickness was obtained from the monitoring data of twenty-one typical observation points of Fildes Peninsula, and the planar distribution data of soil thickness was obtained when the point data were inserted in the ArcGIS. Based on the relationship between soil development extent and topography, soil thickness was divided into six grades, and the respective eigenvalues determined.

(3) Animal and vegetation elements: We studied the distribution of penguins, skuas and other seabirds to reflect the animal character of the peninsula. The data came from long-term surveys by Wang[16]. The plant types of the peninsula also were studied. Lichens are widely distributed in the study region, and are environmentally sensitive. We selected lichen coverage rates and lichen heights as indicators to reflect the vegetation status of the peninsula. On the basis of existing vegetation research, we interpolated the lichen field measurement data of Great Wall Station in the twenty-third Chinese National Antarctic Research Expedition (23rd CHINARE). According to distribution characteristics of the interpolation results, we extracted the information on lichen coverage rate and lichen height. The distribution of field vegetation survey points and routes are shown in Figure 2.

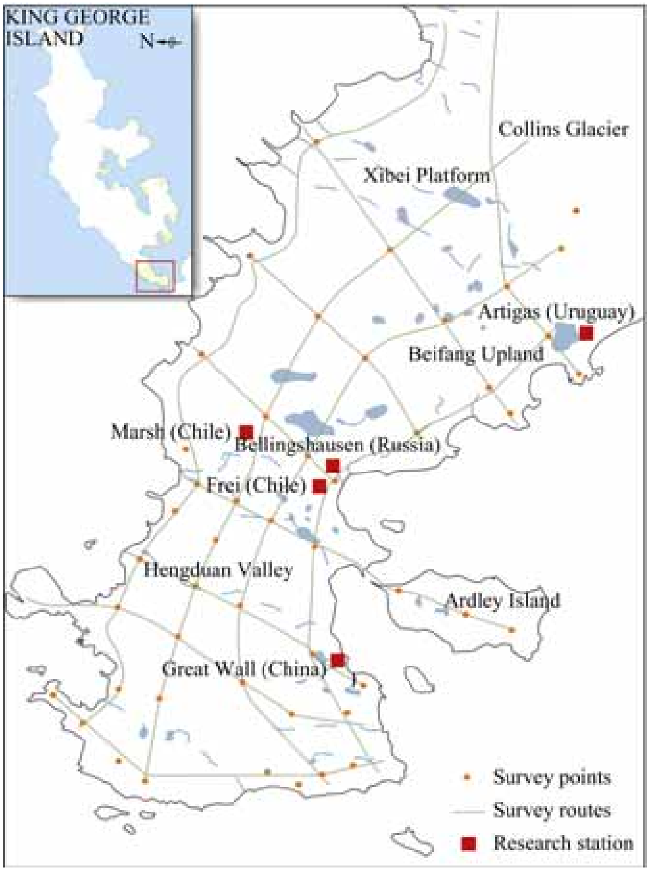

Figure 2 Distribution of field vegetation survey points and survey routes.

(4) Elements of human activity: The elements of human activity included annual average population density of research stations and human disturbance indices. The an-

nual average population density of research stations was determined by person numbers in summer in a buffer zone, the center of which was in the middle of five research stations (Great Wall Station, Frei Station, Marsh Base, Bellingshausen Station, Artigas Station), and the buffer radius was 50 m. The population density index in the TuPu unit was generated in accordance with the statistical unit. Human disturbance index meant that the human impact extent on the eco-environment was reflected by floor-area ratio, and it was defined as follows:

Human disturbance index = (building area × 1+ road area × 0.5 + expedition route area × 0.25)/ TuPu unit area

Building area was defined as the area of the circular buffer zone which had the building as its center and used 50 m as its radius. Road area was the area of the annular buffer zone which used the road centerline as its center and 30 m as its radius. Expedition route area was the area of the annular buffer zone which used the expedition route centerline as its center and 50 m as its radius.

According to the extraction and summary of eco-environment information of Fildes Peninsula, we built a series of thematic eco-environment information TuPu models of the region, including a topography TuPu model (Figure 3), a soil TuPu model (Figure 4), an animal and vegetation TuPu model (Figure 5), and a population TuPu model (Figure 6).

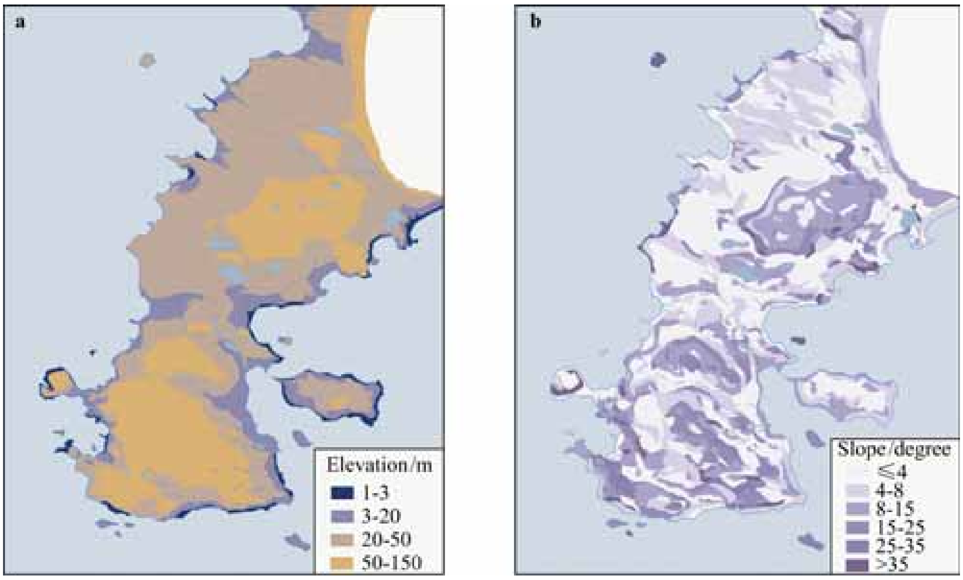

Figure 3 Topography TuPu model of Fildes Peninsula. **a**,The elevation of Fildes Peninsula. **b**,The slope of Fildes Peninsula.

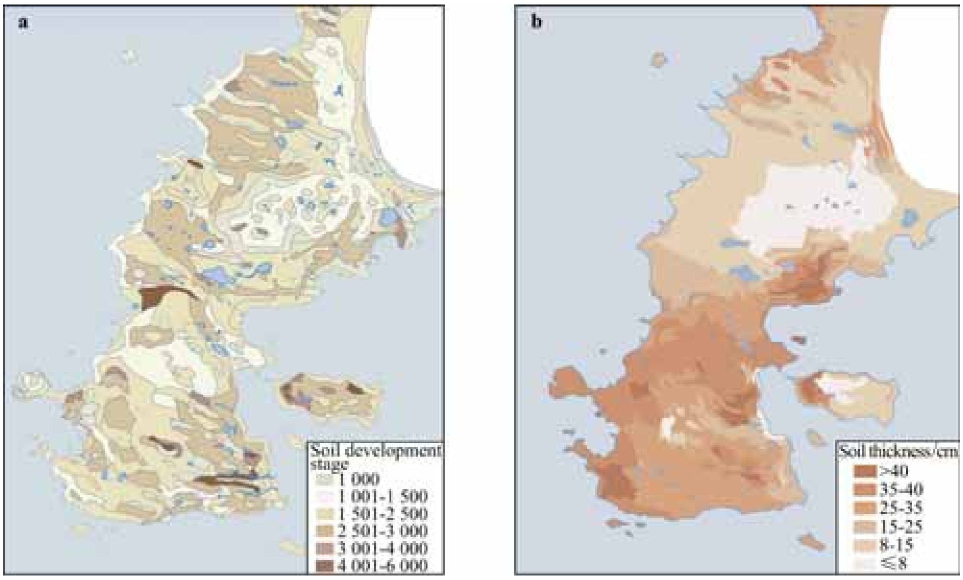

Figure 4 Soil TuPu models of Fildes Peninsula. **a**, Soil developmental stages of Fildes Peninsula. **b**, Soil thickness of Fildes Peninsula.

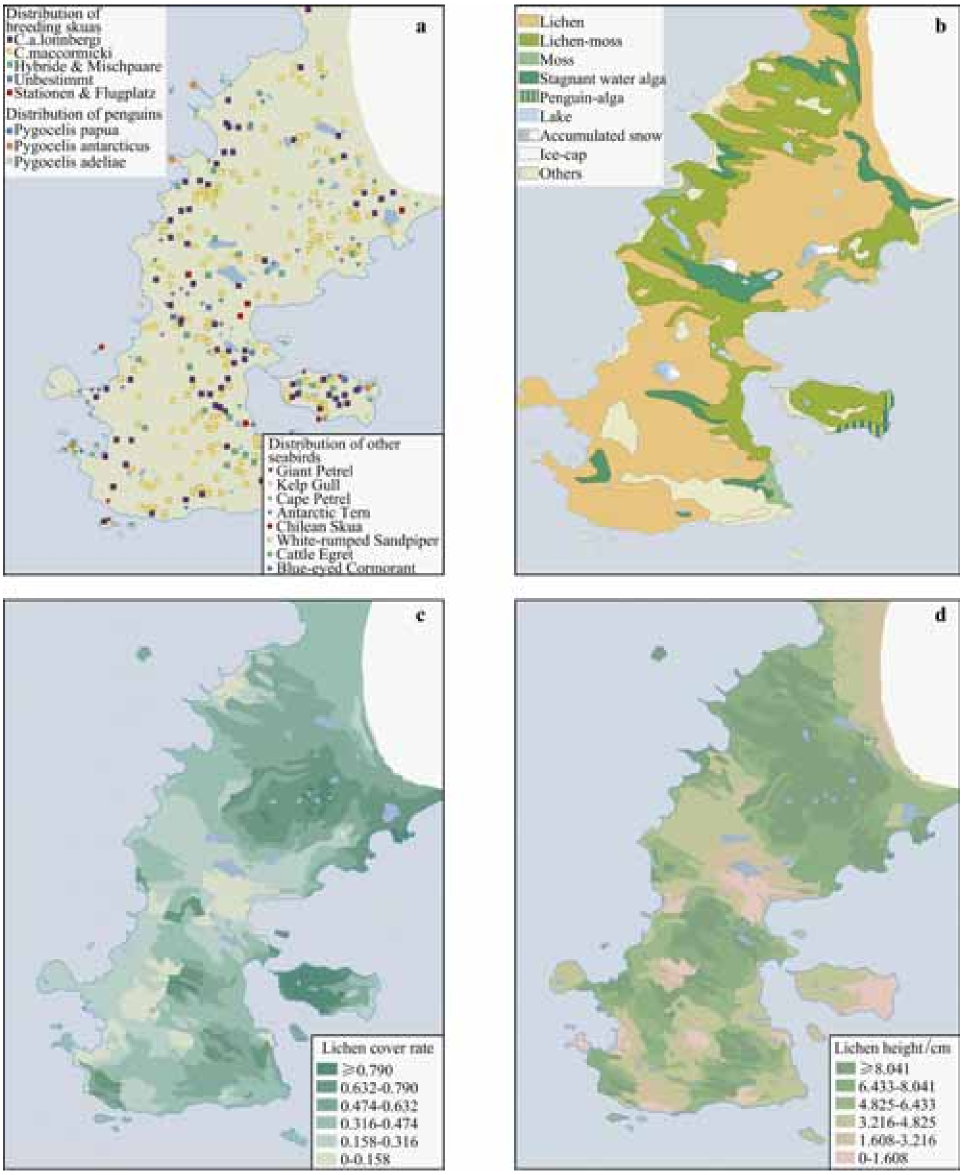

Figure 5 Animal and vegetation TuPu models of Fildes Peninsula. **a**, The animal distribution of Fildes Peninsula. **b**, The plant types of Fildes Peninsula. **c**, The lichen cover rate of Fildes Peninsula. **d**, The lichen height of Fildes Peninsula.

2.2 Generation of landscape comprehensive information TuPu model

Landscape is the complex product of many ecosystems, which are impacted by topography, soil and other outside factors. It is the basis of the modeling and prediction of the geographical things trend. The classification of landscape TuPu should be under the principle of combining the comprehensive factor and dominant factor, and it should reflect both effect of the natural environment background and impact of human activities. On the basis of emphasizing natural differentiation, such as the basic geological structure and landform types of the region, we focused on the role of human activities and associated regional differences and changes of the spatial landscape pattern. Zhao[17] conducted a systematic study of eco-environmental types of Fildes Peninsula, and he divided the regional environment into four types. The four environmental types are coastal environment, periglacial environment, ice water environment and artificial environment. The four types were divided into 29 environmental landscape units according to soil classifications, soil macro-character composition and biome characteristics. The numbers of specific environmental types and landscape units were identified systematically in Zhao's study. The coexistence of two landscape units can be seen in the same local area, which is called a composite environment. The composite environment was not numbered individually in this study, and it was represented by the sum of the numbers of the corresponding landscape units. Based on Zhao's research, we conducted the visualization of the landscape comprehensive information TuPu of Fildes Peninsula by drawing different colors or textures to indicate different types. The environmental landscape types and their spatial distributions at Fildes Peninsula are shown in Figure 7.

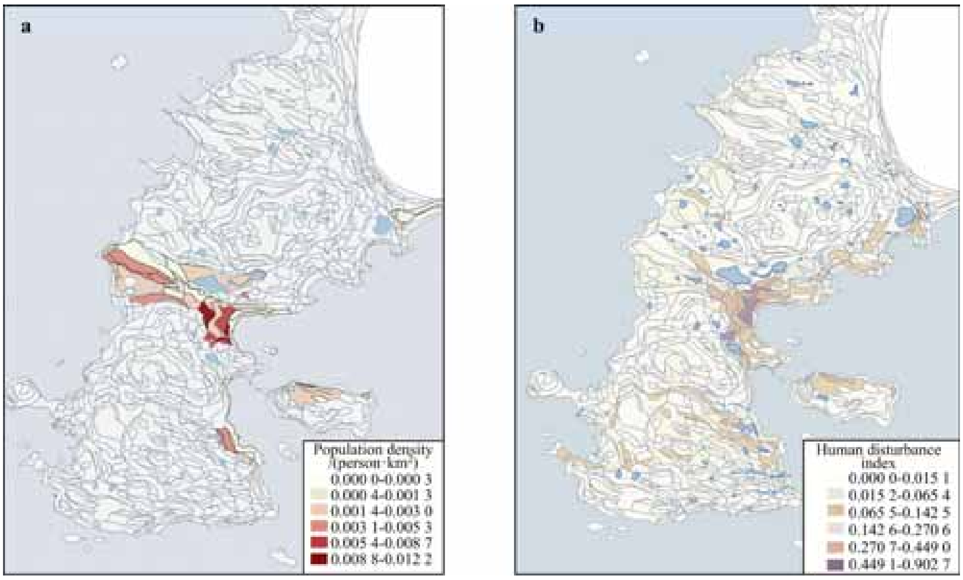

Figure 6 Population TuPu model of Fildes Peninsula. **a**, The population density of Fildes Peninsula. **b**, The human disturbance index of Fildes Peninsula.

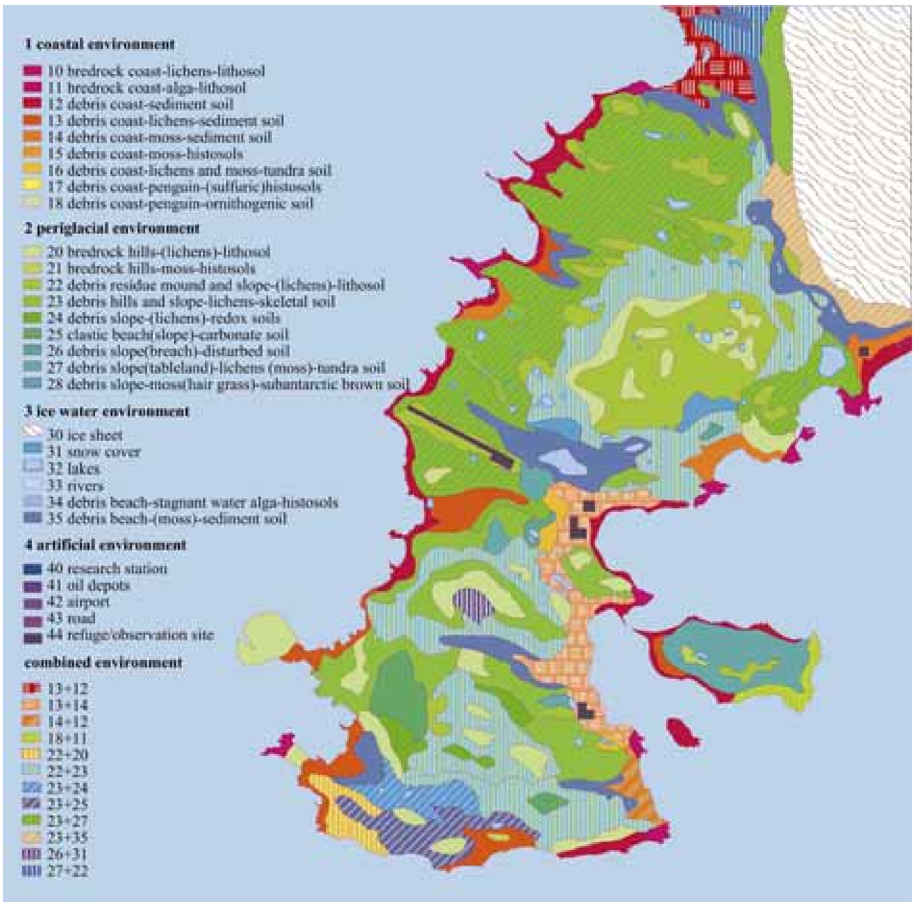

Figure 7 Landscape TuPu model of Fildes Peninsula.

3 Analysis of eco-environment information TuPu model

3.1 Analysis of spatial variation

When we overlay and contrast the series of thematic information TuPu models with the landscape comprehensive TuPu model, it can be seen that the characteristics of the natural environment of Fildes Peninsula is based on its eco-environment spatial variation. However, this variation also is affected by the disturbance of human activity[18]. The environmental landscape around the stations and the airport have significant heterogeneity with unique artificial environment characteristics. Specific ecological environmental spatial variation characteristics are summarized as follows:

(1) The eco-environment from coastal bands to central hills shows generally a regular differentiation. This differentiation can be expressed as follows: The landscapes below altitude 20 m are mostly debris coast-lichen and moss-tundra soil (or sediment soil). The landscapes between altitude 20 m and 60 m are mainly terraces, slopes and beach-lichen, moss and algae-tundra soil, skeletal soil, lithosol, disturbed soil and a small amount of histosols. The landscapes above altitude 60 m are mostly hilly steep slopes and tableland-lichen-skeletal soil, redox soil, carbonate soil and lithosol[17].

The reason for this regular differentiation can be generalized as follows. In altitudes lower than 20 m, lichens and mosses are relatively dense, and more marine animals can inhabit these locations in summer. With bio-organic matter entering into the terrestrial ecosystem, surface biological processes are apparent, and results in more soil humus layers. The marine salt enters the surface ecosystem with summer storms, which have an important impact on regional soil material and the growth of terrestrial plants. For altitudes between 20 and 60 m, regional surface processes are mainly frost weathering, frost sorting, peristalsis movement and snow thawing. Biological processes are significantly weakened and show permafrost landscapes. In altitudes higher than 60 m, regional surface processes are mostly frost weathering and strong erosion processes. Because there is only minor accumulation of surface debris, the landscapes of this region are trough and exposed bedrock on steep slopes[17].

(2) The eco-environmental states of the eastern coasts differ significantly from those of western coasts because of rock types, wind and peripheral currents. Thus, the state of the environment on the eastern and western coasts of Fildes Peninsula is significantly different. The east coast, with higher plant cover, is mostly a debris sedimentary coast, and sediment soils or tundra soils usually can be seen under the vegetation. The west coast, with a small amount of vegetation, is mainly bedrock erosion coastal, and biological effects on soil development processes are relatively weak from lack of vegetation, and the lithosol landscape usually can be seen here.

(3) The eco-environmental spatial variation of Fildes Peninsula differs greatly from north to south because of the different impacts of lithology and regional ice sheet retreat processes. The eco-environment of the northern peninsula is different from that of the southern peninsula. Flat terraces are the main geomorphologic type in the northern peninsula and vegetation can grow over large areas. The environmental landscape types here are few but are continuously distributed. The terrain is very uneven and the surface is more broken toward the south of the peninsula. The growth of lichens and mosses is greatly limited by the strong disturbance of freeze-thawing and erosion of ice and water. There are many environmental landscape types in the southern peninsula, and the distribution of landscapes is relatively heterogeneous.

3.2 Analysis of spatial correlation

Eco-environmental factors could be mutually linked, and the spatial correlation between factors can be a good indicator of their relationship. A series of single-element thematic eco-environment information TuPu of Fildes Peninsula were used as the foundation, and the Spearman’s map rank correlation model was used as the tool to study the interdependence and mutual influence between the elements. The Spearman’s map rank correlation model does not need to derive the exact value of the phenomenon, but uses the “rank” (grade serial number) of the same partition units instead of specific values to calculate the correlation coefficient[11]. Thus, this approach reflects the correlation between elements. The correlation analysis was conducted between topography, soils, human activities and the sensitive vegetation factor of Fildes Peninsula in this specific study. The rank correlation coefficients between terrain elevation, slope, soil thickness, soil development stage, building area, population density factor and lichen height and lichen coverage were calculated, respectively. The correlation coefficient calculation used formula (1). The correlation coefficient of the same factor is 1, and the correlation coefficients between indicators and lichen cover and lichen height are shown in Table 1.

Table 1 Correlation coefficient of environmental factors in Fildes Peninsula

	Lichen coverage	Lichen height	Elevation	Slope	Soil thickness	Soil development stage	Building area	Population density
Lichen coverage	1	0.434	0.183	0.038	0.265	0.025	0.299	0.477
Lichen height	0.434	1	0.124	0.051	0.063	0.110	0.281	0.517

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

where p_{ai} is the grading number of element a, and p_{bi} is the grading number of element b, and n is the number of statistical areas.

It can be seen from Table 1 that lichen coverage and lichen height have the highest correlation with population density, and the correlation coefficients are 0.477 and 0.517, respectively. At the same time, lichen coverage and lichen height also have a strong correlation with building area, and the correlation coefficients are 0.299 and 0.281, respectively. This reflects the very sizable impact of human activities on vegetation growth on the peninsula. In addition, the vegetation has a certain correlation with topography and soil. Specifically, the correlation coefficient between lichen cover and soil thickness is 0.265, which indicates that the distribution of vegetation on the peninsula is largely impacted by soil thickness. The correlation coefficient between lichen height and elevation is 0.124, which indicates that the growing condition of vegetation on the peninsula is impacted by elevation to a certain extent.

4 Conclusions

In this study, the geographical information TuPu model was introduced into eco-environment research of the Antarctic ice-free area. In this approach, we extracted and generalized the information of topography, soil, animals, vegetation and human activity on Fildes Peninsula, and built a series of single-factor thematic information TuPu models and landscape comprehensive information TuPu models. Based on the analysis of TuPu models, we quantitatively revealed spatial morphology and spatial correlation of the regional eco-environment. From the spatial variation analysis of TuPu models, we can see that there is a regular differentiation of eco-environment from the coastal bands to the central hills in Fildes Peninsula, and the eco-environment condition of eastern coasts is different from that of western coasts. Also, the eco-environmental spatial variation differs greatly from north to south. Based on analysis of spatial correlation, the vegetation on Fildes Peninsula has the greatest correlation with human activity, and has a certain correlation with topography and soil.

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