Supplementary material S1

1. Construction of ecological security pattern

Ecological security pattern (ESP) refers to some potential ecosystem pattern existing in geographical space, which is of great significance to maintaining regional ecological security and promoting ecological sustainable development. In this study, we choose three single ecological processes that represent the key ecological functions and eco-economic needs of the research area, which were the soil and water resources protection, the biodiversity conservation and the recreation security. The comprehensive ecological security pattern was built by overlaying the single patterns with equal weights using the MCR model, and the results were divided into four levels: the core ecotope, the basic ecotope, the main ecotope and the ideal ecotope by using the "Jenks Natural Breaks Classification" [1].

1.1 Soil and water resources protection pattern

In this study, the security pattern of water and soil resources protection was constructed from two aspects: (1) water resources regulation and (2) soil and water carrying capacity. Firstly, according to the scale of water body, major rivers, lakes, reservoirs and ponds were selected as the source of water regulation, and multiple ring buffer zones were set to quantify the security levels. The buffering distance were determined by consulting the literature and the scope of study area [2,3]. Separate surfaces of different sources were overlaid to form the water regulation pattern. Taking into account the importance of different sources, the ultimate level in the overlapping area was determined by the following order: lakes and rivers, reservoirs, and then ponds.

Table 1. Classification criterion for water regulation buffer zones

Sources	**Classification criterion**			
	First class	**Second class**	**Third class**	**Fourth class**
Lakes and rivers	<100 m	100 m–200 m	200 m–500 m	500 m–1000 m
Reservoirs	<50 m	50 m–100 m	100 m–150 m	150 m–200 m
Ponds	<10 m	10 m–20 m	20 m–50 m	50 m–100 m

Secondly, considering the impact of human activities, topographic features, vegetation coverage and other factors on soil and water carrying capacity, four indexes including land use type, slope, soil type, and normalized difference vegetation index were selected to indicate the interference effect. In this study, we adopted the Analytic Hierarchy Process (AHP) method to determine the weights of indexes. AHP is a decision-aiding method that can solve multiple-objective problems by hierarchical and quantitative analysis, and is a flexible method widely applied in various fields [4]. The classification criterion for each factor was determined using previous studies as reference and by consulting expert opinion [2,3]. Finally, the distribution of factors was integrated to generate the weighted soil and water carrying capacity pattern of different levels. Specific factors and classification criterion were shown in Table 2.

Table 2. Classification criterion and weight for soil and water carrying capacity

Factors	**Classification criterion**				**Weight**
	First class	**Second class**	**Third class**	**Fourth class**	
Land use type	Cropland	Forestland, grassland	Water, other ecological land	Construction land	0.35
Slope	≤2°	2°-6°	6°-15°	≥15°	0.11
Soil type	Black soil, chernozem, meadow soil, paddy soil, boggy soil, light chernozem, meadow black soil	Dark brown soil, Baijiang soil, meadow Baijiang soil	Salinized chernozem, salinized meadow soil, calcareous chernozem	Meadow alkali soil, meadow saline soil, aeolian sand soil, alluvial soil	0.35
Normalized difference vegetation index	>0.8	0.6-0.8	0.4-0.6	<0.4	0.19

Finally, the soil and water resources protection pattern could be obtained through overlapping the water regulation pattern and the soil and water carrying capacity pattern with equal weights.

1.2 Biodiversity conservation pattern

Protecting core habitats and guaranteeing the connectivity among them is the foundation of maintaining species diversity. In general, the complicated topography and intense human interference cause a fair amount of resistance to species movement. In this study, grassland with an area larger than 0.1 km^2 and the entire forestland were chosen as the suitable source for species habitats, and five resistance factors were selected to build the resistance surface (Table 3). These factors were land use type, relief amplitude (the difference between the highest altitude and the lowest altitude within a limited area, which can describe the regional terrain feature on a large scale) [5], distance to a roadway, distance to urban and rural settlement, and distance to water. The resistance coefficients were set as 10, 20, 50 and 100 based on the literature and expert advice [2,3]. The weights of resistance factors were calculated using the AHP method. By simulating the process of species motion, the MCR model was used to calculate the minimal cumulative resistance value and the results were classified into four security levels using the "Jenks natural breaks classification method" in the ArcGIS software.

Table 3. Resistance coefficients and weights of resistance factors for biodiversity conservation and recreation security

Ecological process	Resistance factors	Resistance coefficient				Weight
		10	20	50	100	
Biodiversity conservation	Land use type	Forestland, grassland	Water, other ecological land	Cropland	Construction land	0.40
	Relief amplitude	<20	20-50	50-100	>100	0.08
	Distance to a roadway	<50 m	50 m-200 m	200 m-500 m	>500 m	0.14
	Distance to urban and rural settlement	<100 m	100 m-500 m	500 m-1000 m	>1000 m	0.14
	Distance to water	<50 m	50m-100m	100 m-500 m	>500 m	0.24
Recreation security	Land use type	Construction land	Forestland, grassland	Cropland, other ecological land	Water	0.42
	Slope	<2°	2°-5°	5°-25°	>25°	0.23
	Elevation	<50 m	50 m-100 m	100 m-150 m	>150 m	0.23
	Distance to a roadway	<100 m	100 m-500 m	500 m-1000 m	>1000 m	0.12

1.2 Recreation security pattern

The recreation security pattern represented a process in which human beings were regarded as subjects engaging in leisure activities and beautiful scenery in the landscape. In this study, we selected places of interest, famous scenery, water bodies and parts of the grassland as the sources, and four indexes were chosen as the resistance factors, which were land use type, slope, elevation and distance to a roadway (Table 3). The resistance coefficients were defined according to the literature and expert opinion, and the weights were set using the AHP model [2,3]. The surface of each factor was integrated as the resistance surface of the MCR model, and the minimal cumulative resistance values were classified according to the “Jenks natural breaks classification method” in the ArcGIS software.

1.4 Comprehensive ecological security pattern

A comprehensive security pattern could be obtained by integrating individual ecological security patterns. Each individual ecological process was considered equally important and given the same weight in overlay analysis. If two ecological patterns possessed different security levels, the higher level was used.

2. Construction of urban development pattern

The urban development pattern could be considered as the outward expansion process of the construction land and could be simulated using the MCR model. The existing construction land in Changchun City was chosen as the source of the process. Five specific resistance factors that affected urban expansion were selected from the aspects of land development cost, natural elements and locational conditions, which were slope, elevation, land use type, distance to a roadway and distance to water (Table 4). The resistance coefficients were assigned depending on the difficulty of traversing the area under different constraints [6]. Individual weights of the resistance factors were determined using the AHP method. Using the MCR model, the minimal cumulative resistance value was calculated and four levels of urban development pattern were identified using the “Jenks natural breaks classification” method, which were the suitable area, the buffer area, the restricted area and the forbidden area.

Table 4. Resistance coefficients and weights of resistance factors for urban development pattern

Resistance factors	Resistance coefficient				Weight
	10	20	50	100	
Land development cost (Land use type)	Construction land	Forestland, grassland, other ecological land	Cropland	Water	0.30
Slope	<5°	5°-10°	10°-25°	>25°	0.17
Elevation	<50 m	50 m-100 m	100 m-150 m	>150 m	0.30
Distance to a roadway	<100 m	100 m-500 m	500 m-1000 m	>1000 m	0.12
Distance to urban and rural settlement	<100 m	100 m-500 m	500 m-1000 m	>1000 m	0.11

3. Assessment of cropland ecological quality

Land ecological quality could be regarded as an inverse function of ecological risk, which can be expressed by measuring the vulnerability of landscape and the structural changes to external influences [7,8]. Thus, this study built an evaluation model using the landscape fragmentation index and the vulnerability index to measure the ecological quality of cropland. The detailed methods are as follows.

3.1 Fragmentation Index

The fragmentation index can effectively indicate the external disturbance on landscape. Considering the current circumstances of the study area, four landscape metrics were selected to calculate the fragmentation index: patch density (PD), edge density (ED), landscape shape index (LSI), and aggregation index (AI). The specific implications are detailed in Table 5.

Table 5. Landscape metrics of fragmentation index and descriptions

Landscape metric	Formula	Weight	Description
PD (Patch density)	$PD = N / A$	0.14	where *PD* is the patch numbers per unit area, *N* is the total number of cropland patches, and *A* is the total area of cropland. The higher the value, the greater the fragmentation degree of the landscape.
ED (Edge density)	$ED = E / A$	0.14	where *ED* is the total boundary length per unit area, *E* is the total length of cropland patch boundary, and *A* is the total cropland area. The higher the value, the greater the fragmentation degree of the landscape.

LSI (Landscape shape index)	$LSI = \frac{e}{\min e}$	0.46	where *LSI* is a metric used to measure the complexity of the cropland patches. The variable *e* is the total landscape length of the cropland. The higher the value, the greater the complexity of the landscape.
AI (Aggregation index)	$AI = \left[\frac{g_{ii}}{\max \rightarrow g_{ii}} \right] (100)$	0.26	where *AI* is the aggregation index and g_{ii} is the number of similar adjacent patches. The lower the value, the greater the complexity of the landscape.

The abovementioned metrics comprehensively describe the landscape characteristics of cropland from the aspect of patch area (PD and ED), patch shape (LSI), and aggregation (AI). To calculate the fragmentation index, the relevant metrics were integrated as follows:

$$F = \alpha \cdot PD + \beta \cdot ED + \gamma \cdot LSI + \mu \cdot AI \quad (1)$$

where *F* is the fragmentation index, and α, β, γ, and μ are the weights of each metric, which were determined to be 0.14, 0.14, 0.46, and 0.26, respectively, using the AHP method. All the metrics were processed using the normalization method to eliminate the effects of dimension.

3.2 Vulnerability Index

Vulnerability (V) in this study referred to the ability of the cropland to resist external interference. Land use types endowed with multiple attributes showed differences in their ability to maintain landscape functions over long-term natural and cultural successions. For example, the landscape structure of ecological land, which mostly embodies natural attributes, is relatively unstable and easily disturbed by external factors, so its vulnerability is relatively high. However, construction land is mainly developed by human activities and has a relatively stable land structure, giving it a high resistance to external interference and a low vulnerability. Based on Yu’s study, we determined the vulnerability degree by combining the real situations in the study area as follows: other ecological land-6, water-5, cropland-4, grassland-3, forest land-2, and construction land-1 [8]. A normalization analysis was used to eliminate the effect of dimension on the results. Ultimately, the vulnerability index was calculated as other ecological land-0.2857, water-0.2381, cropland-0.1905, grassland-0.1429, forest land-0.0952, and construction land-0.0476.

3.3 Cropland ecological quality index

Synthesizing the fragmentation index and vulnerability index can comprehensively denote the ecological quality of land use. Therefore, the cropland ecological quality index was constructed as follows [7,8]:

$$CEQ = 10 \times F \times V \tag{2}$$

where CEQ is the cropland ecological quality, F is the fragmentation index, and V is the vulnerability index. The higher the value, the lower the quality to which the cropland is presented.

References:

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