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A Framework for Integrating an Ecological Environment Process and Ecological Security Pattern in a Prefecture-Level City in China

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Abstract: Synthetical eco-environmental problems' treatment is a new stage for certain pollutant control or ecological restoration. Traditional urban planners have focused more on social–economic development but less on eco-environmental considerations. Spatial planning is currently an essential administrative management method for regional development and eco-environmental protection in China. National and provincial spatial planning designs general strategies, and prefecture-level planning is the most important scale for spatial management. For scientific, spatial governance for eco-environmental protection, we propose a synthetic spatial analysis and planning method framework that involves atmospheric, edaphic, hydrographic, and ecological processes to identify pivotal regions for regional eco-environmental security goals. The synthetic method was conducted using advanced models including the CMAQ and SWAT models and spatial statistical methods. A Chinese prefecture-level city, Anshan City, was chosen to fulfill the method framework due to its various ecosystem types and environmental problems. A total of 67 eco-environmental management units (EMU) were divided based on atmospheric pollution patterns, hydrographic processes, edaphic heavy metal pollution, and ecological spatial analysis. Each unit was identified with ecological or environmental risk and a proposed management regulation. For considering the whole eco-environmental process, the ecological security pattern (ESP) was constructed. The results showed that 166 corridors were identified with an area of 2241.25 km^2, with enhanced connectivity among 76 ecological sources (12.27% of Anshan City). By coupling two results, the optimized ecological conservation and restoration pattern was proposed, in which priority protection areas were identified. This synthetic method can provide scientific analysis and guidance to support spatial planning and ecological construction for multi-purpose ecological and environmental protection.

Keywords: spatial planning; eco-environmental process analysis; eco-environmental management unit; ecological security pattern

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1. Introduction

In recent decades, China has experienced rapid economic growth accompanied by the intensive development of territorial spatial resources, leading to drastic changes in landscape patterns [1]. This growth has brought many problems and constraints to sustainable development, such as eco-environmental degradation, the reduction and fragmentation of natural vegetation, and the reduction in ecological carrying capacity [2]. Spatial planning, first proposed by the European Spatial Development Perspective (ESDP) in 1999, is an important instrument for optimizing land use patterns, improving land use efficiency, and achieving sustainable development and spatial governance [3,4].

Numerous case studies have been conducted on various aspects of spatial planning, including environmental protection planning [5], main function zoning [6], the major function-oriented zone [7], etc. However, zoning systems from different administrative departments make it difficult to balance spatial unit functions, such as socio-economic development, industry distribution, and eco-environmental protection. Since 2017, China has proposed national territorial spatial planning (NTSP) to integrate main functional unit planning, land use planning, urban and rural planning, and other spatial planning into a cohesive plan and map [8]. The current NTSP mainly involves ecological sensitivity analysis and the construction of ecological security patterns, utilizing spatial superposition as the main method [7,9]. Although progress has been made compared to previous planning efforts, there remain some areas that require further attention. For instance, current assessments often lack the sufficient integration of eco-environmental processes, and there is still a need for more focused research on key ecological process areas.

Spatial process models are powerful tools for eco-environmental process studies, such as the widely used Congestion Mitigation and Air Quality Model (CMAQ) for simulating atmospheric processes and air pollution [10] and the Soil and Water Assessment Tool (SWAT) for hydrological processes and agricultural non-point source (NPS) pollution [11]. Many studies have mainly focused on pollutant distribution patterns [12], pollutant prediction under different scenarios [13], and model simulation [14]. Further research is needed to apply spatial process models to spatial planning, particularly in identifying critical areas for spatial prioritization, which can support the formulation of regional eco-environmental management policies. Simultaneously, few studies have applied this method to spatial control in prefecture-level cities, especially when integrating multiple environmental processes.

Pattern optimization, based on the theory of patterns, eco-environmental processes, and functional impact, seeks to optimize the spatial pattern allocation of landscape to mitigate conflicts between economic development and eco-environmental conservation, while achieving regional ecological security goals [15,16]. Pattern optimization with ecological security as the goal continues to grow in popularity; the theory and methods of its construction has made significant progress in China [17]. Early studies have directly selected the core area of forest parks or nature reserves as the ecological sources [18,19]. As research advances, scholars have incorporated indicators such as landscape connectivity, ecological sensitivity, and ecosystem services into the process of identifying ecological sources for ecosystem assessment [20]. Ecological sensitivity reflects the response of ecosystems to natural environmental changes and human disturbances, playing a crucial role in maintaining the stability of landscape patterns [21]. Ecosystem services functions have a certain ecological maintenance effect, including water conservation, soil conservation, biodiversity conservation, and others [22]. The method of combining these two aspects to identify ecological sources has a stronger theoretical foundation and objectivity [23]. Meanwhile, optimizing the pattern is essential for better regulating the process, but few case studies focus on the issues. Thus, it is necessary to develop a more comprehensive optimization method that incorporates zoning into ESP research to more accurately evaluate the specific location of regional optimization. It offers a valuable decision-making reference for regional priority protection and ecological management [24].

Here, we propose an integrated analysis framework, the eco-environmental management unit (EMU), to delineate eco-environmental management units based on spatial process models (SWAT, CMAQ) and spatial statistical methods, including hydrological environment, atmospheric environment, edaphic environment, and ecological status analysis for scientific, spatial, eco-environmental goals. We employ this approach to inform China's governance process on the selection of EMUs for Anshan City. By combining ESP construction, the ecological distribution pattern and key areas were determined. The main objectives of this study were as follows: (1) to develop a synthetic spatial analysis framework for the scientific management of unit partition that involves multiple eco-environmental processes; (2) to optimize the ecological conservation and restoration pattern for regional eco-environmental goals; (3) to test the validity of the proposed method with a prefecture-level city.

2. Materials and Methods

2.1. Overview of Study Area

The chosen case study area, Anshan City, is located in northeastern China (122°10′–123°41′ E, 40°27′–41°34′ N) (Figure 1), which is in a transition zone from mountains to plains. Anshan City includes forestland, cropland, urban areas, important rivers, wetlands, and mines, and it is also a city with mineral extraction and heavy industry. Its total area is 9255.36 square kilometers, ranging in elevation from −54 m to 1137 m. The region is in a warm and semi-humid continental monsoon climate zone with an annual mean temperature of 6.3 °C to 9.0 °C and annual precipitation of 428.8 mm to 740.7 mm. It is an old industrial base in northeast China due to its rich iron, magnesite, and jade mineral resources. The study area has been developed by the metallurgical industry, which has created a serious risk for the atmospheric environment, hydrological environment, soil pollution, and ecological status. Therefore, Anshan City is an ideal study area to research multi-eco-environmental processes and unit management due to its environmental pressure and diverse landscape.

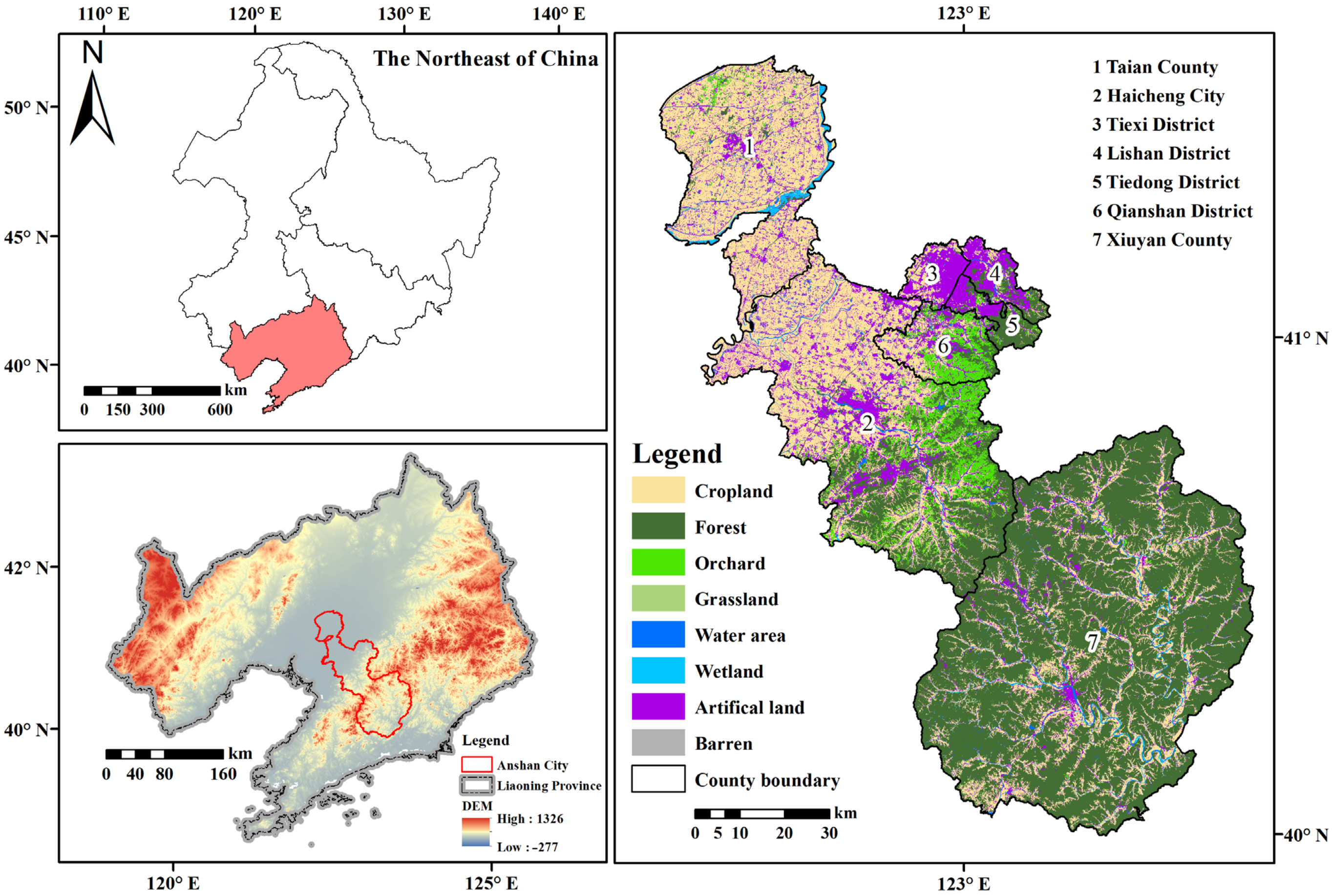

Figure 1. Location of study area.

2.2. Data Collection

The data information and sources are shown in Table 1. The meteorological data include the annual average temperature, total annual precipitation, annual mean maximum temperature, and total annual evaporation from 1990 to 2020, which were obtained from the China Meteorological Data Service Center (http://data.cma.cn/en, accessed on 8 September 2021). The daily hydrological data from 2001 to 2020 were collected from the local Water Resources Bureau. The 1:50,000 soil map, topographic map, and land use map from 2020 were collected from Bureau of Natural Resources of Anshan. The land use map was reclassified as artificial land (including urban land, rural land, industrial and mining land, railways, and roads), forestland, grassland, cropland, barren land, water area, and wetland. The classification accuracy was 90.21%, based on 350 field survey samples. Daily atmospheric pollution data, daily water quality, soil heavy metal data, and industrial sources lists were obtained from the Bureau of Ecological and Environment of Anshan. All the maps were resampled for calculation as 30 × 30 m raster cells. NTSP data were obtained from the Bureau of Natural Resources of Anshan, including the ecological protection red line (EPR) and urban–town development boundary (UTDB). The EPR includes the areas with ecologically sensitive areas, areas with important ecological functions, and national parks and reserves, which are legal ecological protection regions. The UTDB is a regional boundary encompassing cities, towns, and various development zones, focusing on urban development and construction over a specific period.

Table 1. The dataset used in this study.

Data	Time	Data Format	Data Source
DEM	-	1:50,000	Bureau of Natural Resources of Anshan
Soil map and properties	-	1:50,000	Bureau of Natural Resources of Anshan
Land use map	2020	Grid (cell size, 10 × 10 m)	Bureau of Natural Resources of Anshan
Meteorological data	1990–2020	Database file (DBF)	China Meteorological Administration (https://data.cma.cn/, accessed on 8 September 2021); Local Bureau of Meteorology
Hydrology and water quality data	2001–2020	Database file (DBF)	Local hydrographical station and environmental monitoring station
Air quality data	2020	Database file (DBF)	Bureau of Ecological and Environment of Anshan

2.3. Study Methods

We propose a synthetic spatial analysis and planning framework (Figure 2) that involves atmospheric, edaphic, hydrographic, and ecological processes based on meteorological, hydrological, and environmental data and land use maps. Firstly, the EPR area was selected as the ecological sources and the resistance surface was constructed based on habitat quality. Circuit theory was used to identify key ecological elements, such as corridors, pinch points, and barriers, culminating in the construction of an initial ecological security pattern. Secondly, multi-process models were used to identify key areas, and spatial overlay analysis was performed to define control units. Finally, by taking the ESP and EMU into consideration, a decision set of spatial control optimization planning offering planning and management implications was determined to coordinate the protection and restoration of the ecological environment across the region.

2.3.1. Construction of Initial ESP

(1) Ecological source

EPR zones were identified by quantitatively assessing the ecosystem function importance and ecological sensitivity. These areas combined extremely ecologically sensitive areas (including water and soil erosion and land desertification), areas with extremely important ecological functions (including water conservation, soil conservation, and biodiversity conservation), and national parks and reserves. The aim of an EPR zone is to promote sustainable socio-economic development and protect the health of the regional ecosystems and the health of the public [25,26]. The EPR determines an area that cannot be developed or occupied to ensure ecosystem's balance. Therefore, the EPR zones of Anshan City were selected as the ecological source area.

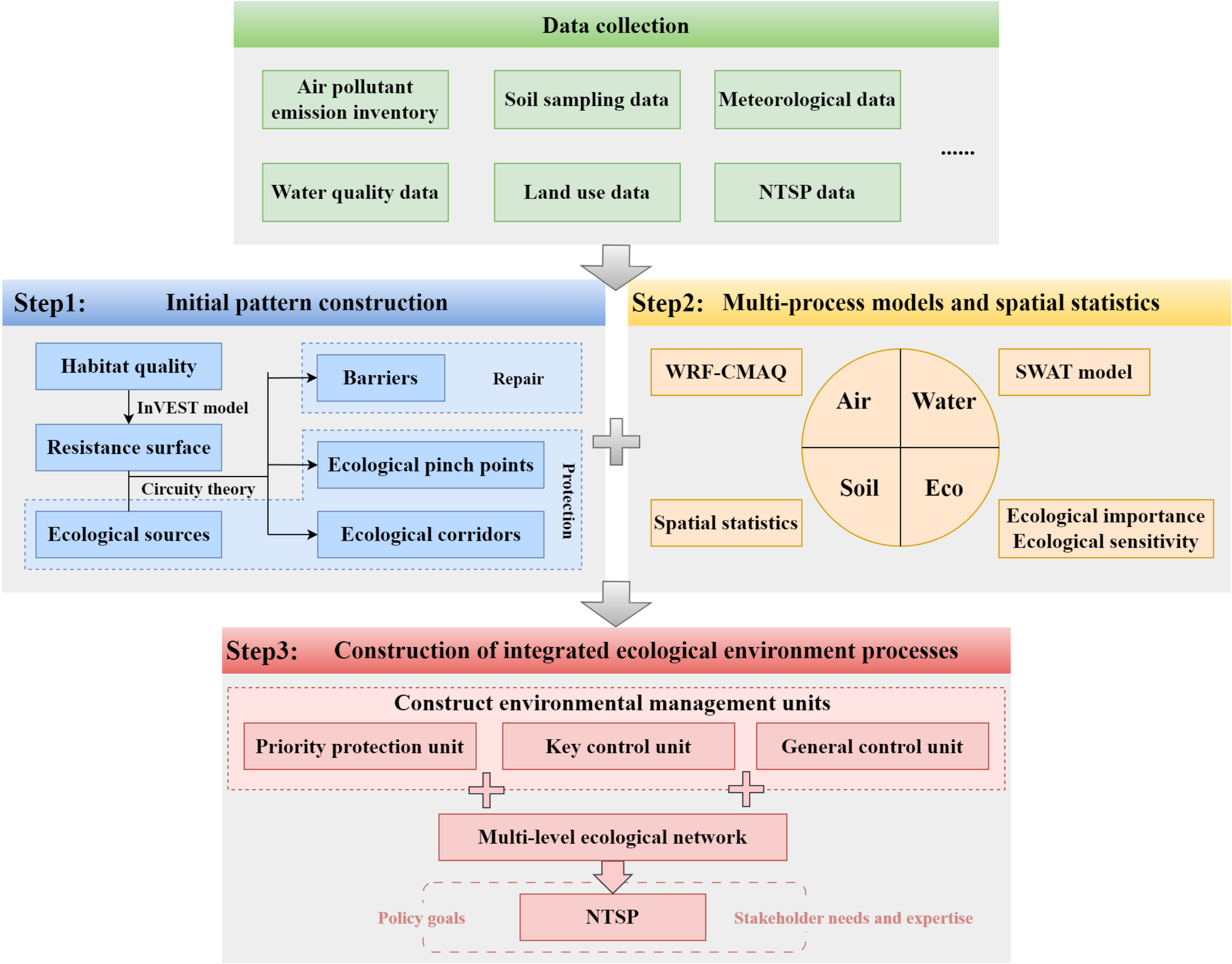

Figure 2. Research methods and analytical framework.

(2) Resistance surface

A high habitat quality represents the richness and diversity of species and a low resistance to energy information flow. Conversely, lower-quality natural areas have a higher potential to impede biological flow due to increased ecological resistance [27]. Therefore, the spatial distribution of resistant surfaces was determined by the quality assessment of natural areas. The habitat qualification model of the InVEST model was used for the habitat quality evaluation. This model generated a habitat quality distribution map combining a land use map, biodiversity threat factors, and sensitivities, with results scored from 0 to 1. Each score was then subtracted from 1 and multiplied by 100 to determine the ecological resistance. According to the InVEST model's guidelines and related studies [28], parameter values for each natural system type and threat source were set (Tables S1 and S2). The specific formula is as follows.

$$Q_{xi} = H_i \times \left[1 - \left(\frac{D_{xi}^z}{D_{xi}^z + K^z}\right)\right]$$

Q_{xi} is the habitat quality index of the ith landscape type x the raster cell, and H_i is the habitat suitability score of the ith landscape type, which ranges from 0 to 1. D_{xi} is the habitat degradation index; Z represents the scaling constant; and K is the half-saturation constant, with a user-defined setting.

(3) Construction of ecological security pattern

The construction of the ecological security pattern included ecological corridors, pinch points, and barriers. Linkage Mapper 2.0.0 and Circuitscape 4.0 software were used to identify these ecological elements with the method of circuit theory [29,30]. Circuit theory regards ecological landscapes as conductive surfaces, assigning corresponding electrical resistance values to each landscape. Individual biological flows analogize individual biological flows, and the random walk behavior of these charges is employed to model ecological flow processes in heterogeneous landscapes. This approach effectively identifies the spatial layout of various ecological elements. Based on the determination of the source and resistance, Linkage Mapper calculates the cost-weighted distance (CWD) in multiple pairs of sources, creates a cost-weighted distance surface to discern least-cost paths (LCP), and determines the location and shape of the corridors. According to circuit theory, the higher the current density value is, the greater the probability of species passing through is. Ecological pinch points, with high current densities, are crucial pathways that cannot be easily replaced. Ecological barriers represent the areas that hinder species' migration and reduce habitat connectivity [31]. Pinchpoint Mapper and Barrier Mapper (Linkage Mapper 2.0.0.) were used to identify pinch points and barriers. The details of identifying the pinch points and barriers are presented in the Supplementary Materials S1.

2.3.2. Atmospheric Environment Process Analysis

The WRF-CMAQ model for air pollutants was built using air emission inventory and meteorological station monitoring data. Based on the air quality targets, the Weather Research and Forecasting Model (WRF v3.9) in combination with the Congestion Mitigation and Air Quality Model (CMAQ v5.1) was used to analyze the spatial distribution characteristics and determine the environmental capacity of various major pollutants using the latest emission inventory data from Anshan City. The WRF model simulated the weather field. The grid in the research area was reassigned using the Inventory Spatial Allocate Tool (ISAT) to create a high-resolution (1 km × 1 km) grid-based emission inventory suitable for this study. The ISAT is a tool for the spatial allocation of non-point source emission inventories based on geographic information data, such as urban facility points, populations, roads, and land use types. The specific details of the model can be found in the Supplementary Materials S2.

2.3.3. Hydrological Environment Process Analysis

The SWAT model was chosen for hydrological process analysis, developed by the United States Department of Agriculture (USDA), which is widely used in hydrological process and NPS pollution analysis [32,33]. The SWAT model was calibrated and validated using observed data from 2001 to 2020. The R^2 and the Nash–Sutcliffe efficiency coefficient (ENS) were used to evaluate accuracy. The detailed process and results for the model calibration and validation are available in our previous publications and the Supplementary Materials S3 [34].

2.3.4. Soil Pollution Analysis

The 487 soil sample points, covering heavy metals such as Cu, Cd, As, Zn, Pb, Hg, Cr, and Ni, were analyzed using the Normal QQPlot in the Explore Data of the Geostatistical Analyst module, with spatial interpolation maps generated using the kriging method in GIS. Soil heavy metal pollution was evaluated based on the National Soil Environmental Quality Standard (GB15618-2018) [35].

2.3.5. Evaluation of Ecological Conservation Important Area

An assessment of the importance of ecological function and ecological sensitivity was conducted based on the primary service functions and ecological sensitivity characteristics of different types of areas with key ecological functions. Three indicators, specifically water conservation (F_{wc}), soil conservation (F_{sc}), and biodiversity conservation (F_{bio}), were selected to evaluate the importance of ecological functions. Water and soil erosion sensitivity (S_{wse}) and land desertification sensitivity (S_{ld}) were selected to evaluate the ecological sensitivity of the study area. Using the natural breakpoint method in a GIS, the evaluation results were divided into 3 levels (Table 2). Details of the analysis can be found in previous studies and the Supplementary Materials S4 [26,36].

Table 2. Indicators of ecological functions' importance and ecological sensitivity assessment.

Indicators	Calculation Process	Indicator Interpretation
Water conservation	$F_{wc} = NPP_{mean} \times F_{sic} \times F_{pre} \times (1 - F_{slo})$	NPP_{mean} is the average net primary productivity; F_{sic} is the capacity factor of the soil seepage, where there is a 0–1 equal assignment between the clay and sand; F_{pre} is the rainfall factor (average annual precipitation rate) and interpolated by kriging; F_{slo} is the slope factor and calculated by DEM; K is the soil erodibility factor and calculated by the RUSLE model.; F_{tem} is the average annual temperature and interpolated by kriging; F_{alt} is the altitude index and normalized to 0–1 from the altitude of the research area; R_i is the rainfall erosive factor; LS_i is the topographic relief factor; C_i is the vegetation coverage factor; I_i is the dryness index; and Wi is the number of days on which wind-blown sand speeds are ≥10 m/s. Ii and Wi were obtained by kriging interpolation. The detailed calculations for Ri, LSi, and Ci are presented in Supplementary Materials S4.
Soil conservation	$F_{sc} = NPP_{mean} \times (1 - K) \times (1 - F_{slo})$	
Biodiversity conservation	$F_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt})$	
Water and soil erosion	$S_{wse} = \sqrt[4]{R_i \times K_i \times LS_i \times C_i}$	
Land desertification	$S_{ld} = \sqrt[4]{I_i \times W_i \times K_i \times C_i}$	

2.3.6. Environmental Management Unit Delimitation

The unit delimitation was based on the identification of critical atmospheric, hydrological, edaphic, and ecological areas. The hydrological sub-catchment zone was taken as the base unit; we then overlaid the atmospheric environment management zones and progressively integrated ecological and soil management zones, which were concentrated within specific areas. This process was aligned with administrative boundaries to define environmental management units. Each unit was marked with whether there was a critical area and what kind of eco-environmental problem or importance there was. The environmental management units were delineated by imposing and fitting the legal boundaries, including industrial parks, nature reserves, and water source reserves, which were set as individual units.

The management policies for legal units follow corresponding legal regulations, such as the law on the management of nature reserves and the water source protection act. Legal boundaries for other management units were based on the characteristics of their eco-environmental processes and problems.

3. Results

3.1. Preliminary Identification of Ecological Corridors and Ecological Security Patterns

3.1.1. The Extraction of Ecological Corridors

The resistance values ranged from 1 to 100, with an average value of 45.68 (Figure 3a). A total of 166 ecological corridors were constructed (Figure 3b), with a total length of 1715.56 km (ranging from 0.2 km to 65.7 km). To determine the scope of the ecological corridors, the cumulative resistance was tested, ranging from 1000 to 12,000 in increments of 1000 (Figures S1 and S2). Although the area of the ecological corridors increased with higher thresholds, there was no substantial change in their spatial distribution.

The expansion of corridor areas can provide species with more spatial path choices during migration, but it may also occupy construction land and require higher maintenance costs. The ecological corridor and the urban and town development boundary (UTDB) were spatially superimposed (Figure S3). A total of 556.46 km^2 was designated for the UTDB in the study area. Based on the observation that there were significant alterations in both the average current density and the overlapping area above this threshold, a threshold of 8000 was selected to determine the spatial range of the ecological corridors.

The ecological corridors covered an area of 2241.25 km^2, accounting for 24.23% of the study area (Figure 3c).

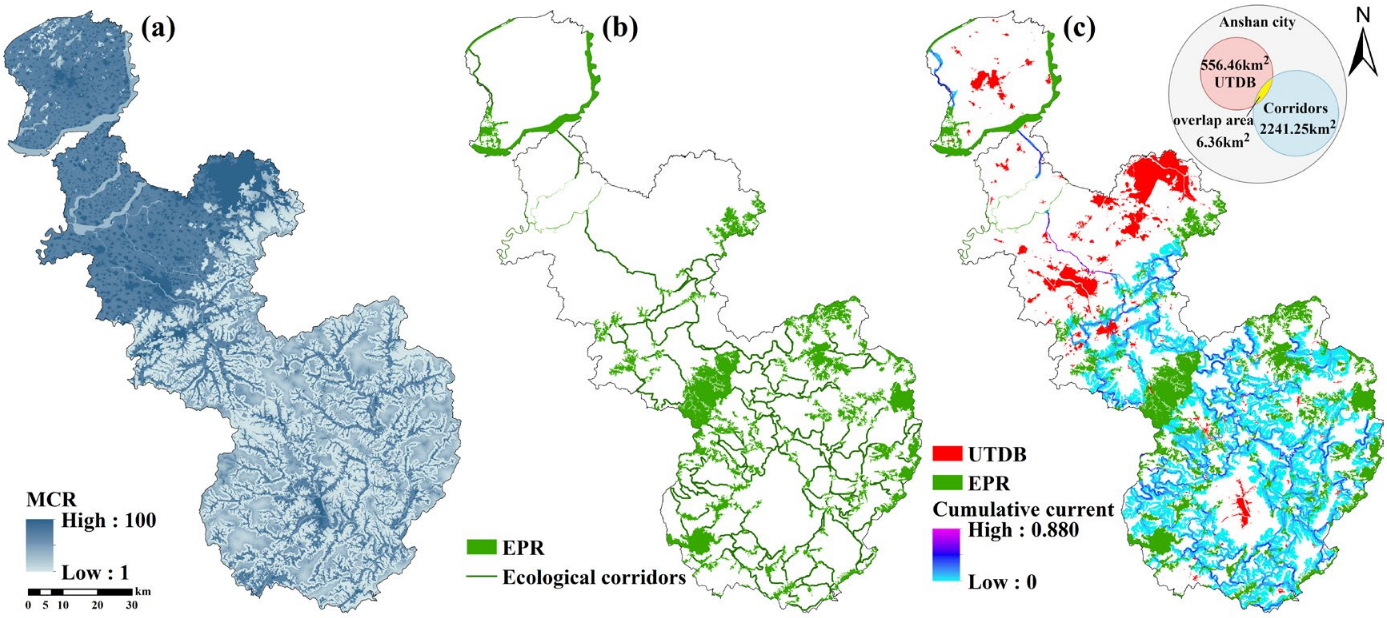

Figure 3. Spatial patterns of (**a**) resistance surface and (**b**) ecological corridors, as well as (**c**) spatial range of corridors and UTDB.

3.1.2. Construction of Initial Ecological Security Pattern

The ecological elements of the source areas, corridors, pinch points, and barriers together composed the ESP (Figure 4). A total of 76 sources area were involved, with a combined area of 1135.11 km^2, consisting of key ecological function zones which have important ecological functions. And, 166 corridors were preserved for linking ecological patches, guaranteeing landscape connectivity. Meanwhile, 40 pinch points were set, mostly composed of forest with a high current density and irreplaceable for enhancing the overall connectivity of the landscape. There were a total of 86 barriers, with a total of 20.16 km^2, which were useful for restoring the barriers and increasing the connectivity of the landscape corridors.

3.2. Critical Regions' Recognition

The spatial distribution of air pollutants was simulated based on the annual pollutant emissions in 2020 with the WRF-CMAQ two-way coupled system to recognize critical zones (Figure S4). From the model simulation results, we obtained the industrial emission intensity, urban upwind direction, diffusion channels, and circulation. With the results combined with pollution-sensitive targets and land use types, there were five levels of area divisions for the environment: (1) priority protection zones, including nature reserves, scenic spots, and forest parks; (2) high-emission zones, including industrial parks and high-emission towns; (3) layout-sensitive zones, including urban upwind, diffusion channels, circulation channels, and other layouts that affected air quality; (4) receptor-sensitive zones, including urban centers, built-up areas, and concentrated residential, medical, and education areas (Figure 5a).

The SWAT model was well calibrated and validated, and the values of R^2 and E_{NS} were greater than 0.7, indicating a good model performance for the study area and satisfying the accuracy requirements for our research. Detailed information can be found in our former work [37]. Using the water quality results and water environment functional zoning, we defined the zones for water environment control based on hydrological sub-catchment. The priority protection zones included water source protection areas and water ecological protection areas. The key water control zones were further divided into industrial, urban, and agricultural control zones based on the primary sources of pollution (Figure 5b).

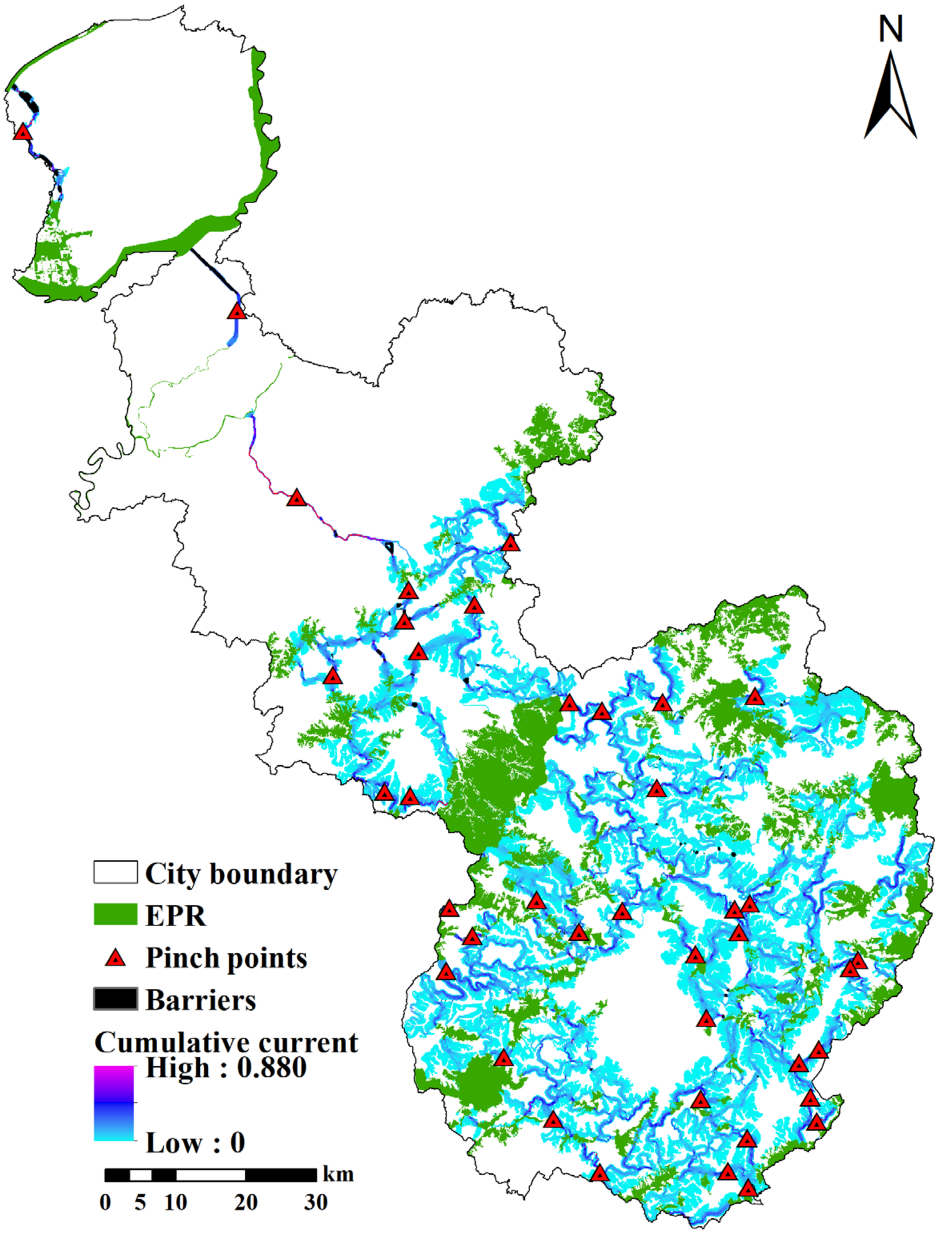

Figure 4. Spatial distribution of ecological security pattern.

Since no areas exceeded the soil environmental quality standard "Cropland Soil Pollution Risk Control Standard (GB15618-2018)", the concentrated distribution cropland areas were designated as soil priority protection zones. Based on the inventory of industrial pollution, industrial pollution areas and potential industrial pollution areas were identified as the key soil risk control zones (Figure 5c).

The ecosystem services functions and ecological sensitivity were estimated using methods outlined in the "Ecological red line assessment standard ([2015])" [36]. Spatial overlay analysis based on ecosystem importance evaluation resulted in the identification of three ecological control zones: (1) ecological red lines, (2) general ecological space, and (3) ecological general control zones (Figure 5d).

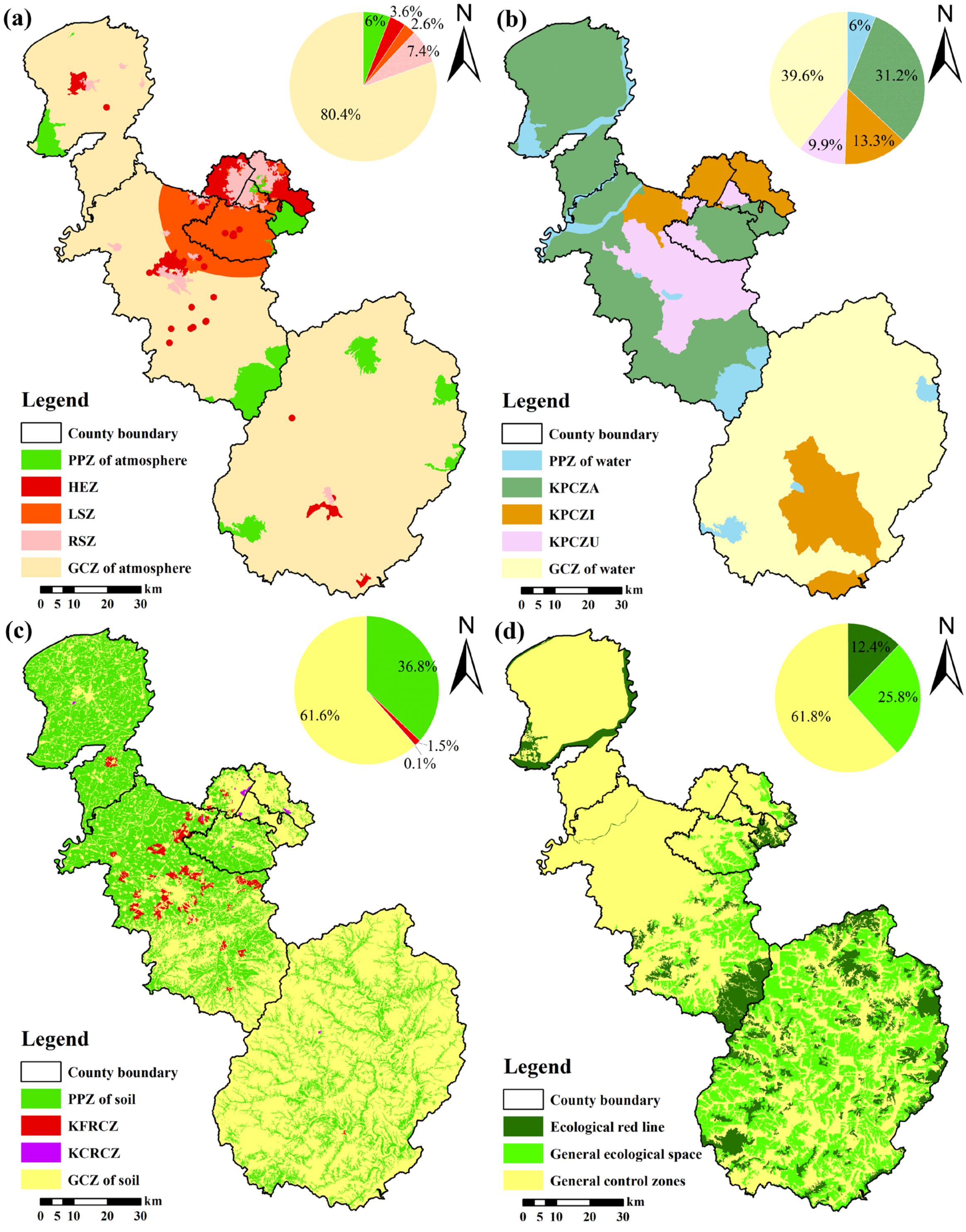

Figure 5. The result of the partition control environmental zone. (**a**) Atmosphere; (**b**) water; (**c**) soil; (**d**) ecological space. PPZ: priority protection zones; GCZ: general control zones; HEZ: high-emission zones; LSZ: layout-sensitive zones; RSZ: receptor-sensitive zones; KPCZA: key pollution control zones for agriculture; KPCZI: key pollution control zones for industry; KPCZU: key pollution control zones for urban areas; KRCZ: key risk control zones.

3.3. Eco-Environment Management Units' Division

A total of 67 eco-environmental management and control units were divided, including 37 priority protection units, with a total area of 3458.82 km^2, accounting for 37.37% of the total area of the city; 29 critical control units in Anshan, with a total area of 4165.77 km^2, accounting for 45.01% of the total area of the city; and one general control unit in Anshan, with a total area of 1630.77 km^2, accounting for 17.62% of the total area of the city (Figure 6).

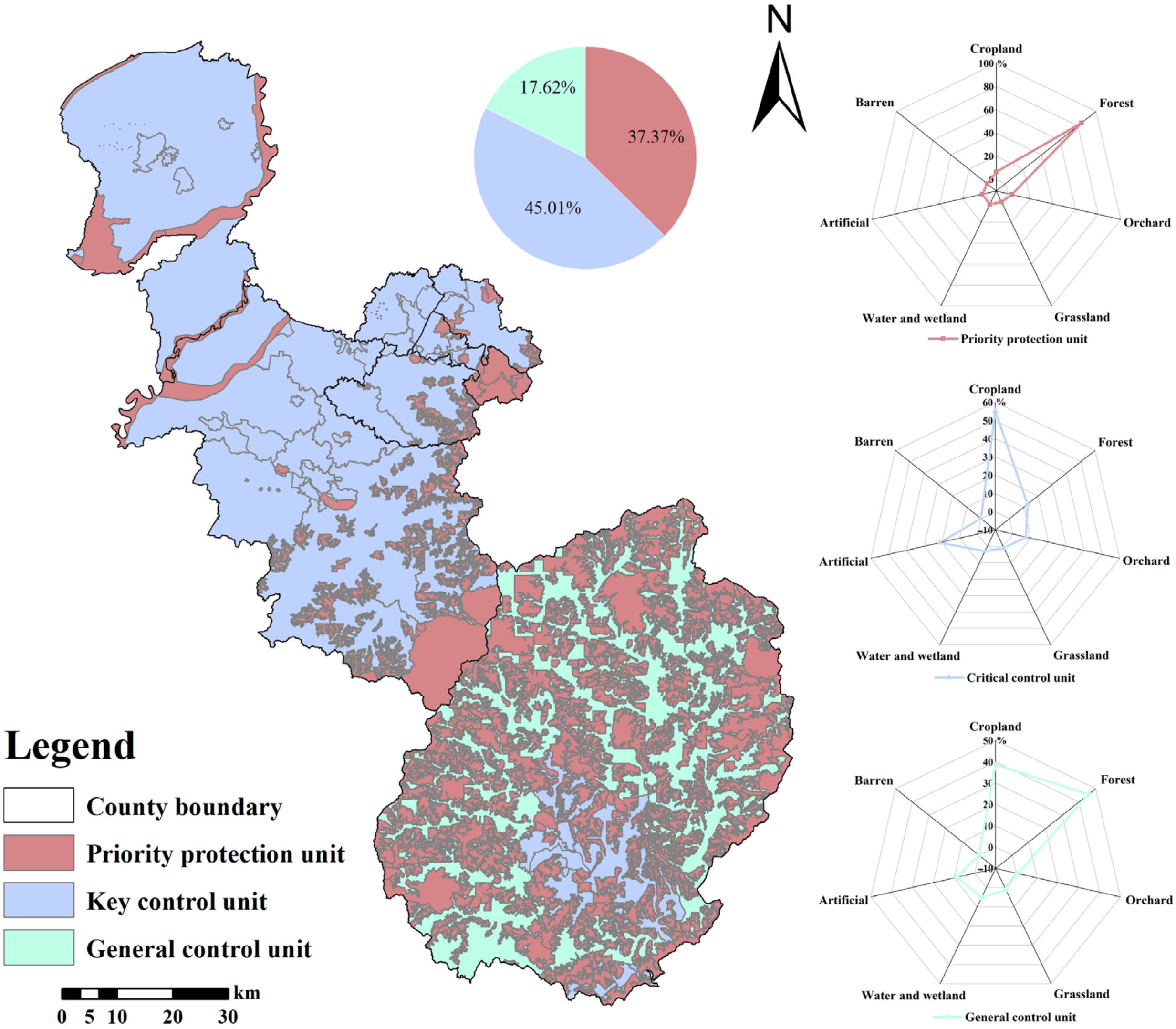

Figure 6. Classification map of environmental management units.

The priority protection units include the ecological protection red line, water environment priority protection area, atmospheric environment priority protection area, and cropland priority protection area, mainly consisting of forest land (83.93%). The priority protection units focus on ecological environment protection and prohibit or restrict large-scale industrial development, minerals' and other natural resources' development, and urban construction.

The key control units include industrial parks outside the ecological protection red line, atmospheric, edaphic, and hydrographic critical areas, and densely populated areas with a high resource development intensity. The land use types are mainly cropland (55.1%) and artificial land (21.18%). According to the quality objectives and control requirements of water, atmosphere, soil, and ecological importance in the unit, as well as the control requirements of natural resources, the list of accesses and treatments was comprehensively determined.

The general control unit encompasses areas outside the priority protection and critical control zones and implements basic regional ecological environment protection measures.

3.4. Spatial Pattern Optimization for Integrated Multi Environmental Processes

Based on the results of the proposed ESP and from the perspective of optimizing the current NTSP, a general pattern of ecological conservation and restoration with EMU was constructed (Figure 7).

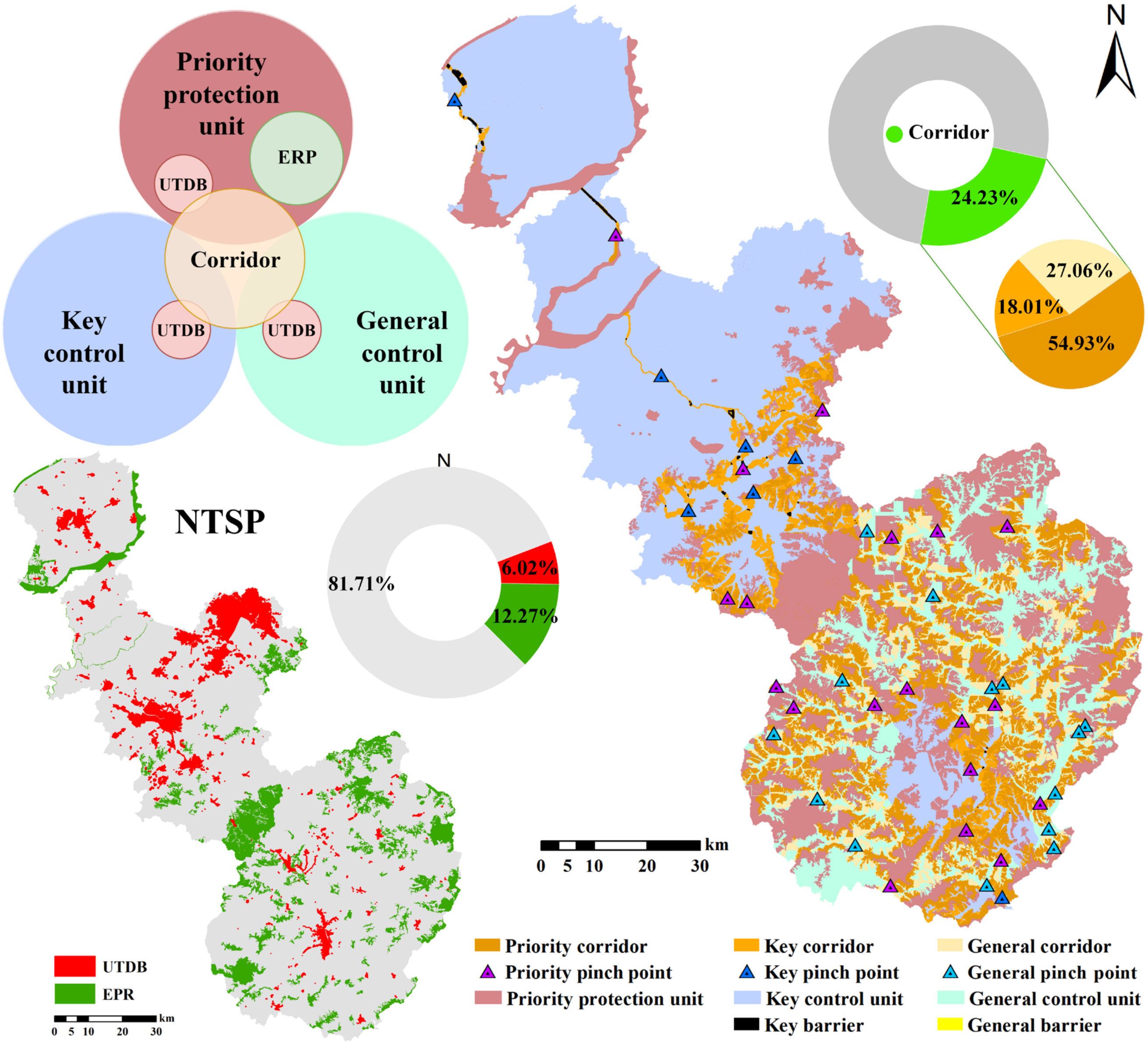

Figure 7. Comprehensive pattern of protection and development in Anshan City. EMU: eco-environmental management unit; ESP: ecological security pattern; NTSP: national territorial spatial planning; UTDB: urban and town development boundary; EPR: ecological protection red line.

The current NTSP includes the ecological protection red line (EPR), the urban and town development boundary (UTDB), and permanent basic farmland (PBF), which are based on assessments of resource and environmental carrying capacity and suitability for spatial development. The purpose of the UTDB is to prevent disordered urban sprawl. However, it is defined based on the current situation of urban and town development and lacks consideration of environmental processes. The EPR refers to the areas with important ecologically sensitive areas, ecologically functional areas, and national reserves and parks. However, due to the lack of consideration for connectivity, there are still challenges for achieving ecological civilization.

The delineation of EMUs provides spatial control zones for decision-makers in the study area, and coupling it with the ESP can provide high-priority protection and restoration areas for each control unit. The constructed corridors account for 24.23% of the study area and are mainly distributed in priority protection units, representing 54.93% of the total corridor area. These areas have low protection costs and greater environmental improvement potential. Simultaneously, the important protection areas of three control units were determined through the coupling of the ESP and EMUs, accounting for 35.59%, 9.69%, and 37.19% of each unit, respectively. Barriers are mainly distributed in critical control units, with an area of 17.09 km^2, which accounts for 84.77% of the total barriers, while the others are distributed in general areas. The 19 ecological pinch points located in the priority protection units are mainly concentrated in the southern region, as the most important areas for ecological preservation.

4. Discussion

4.1. Integrated Multi-Ecological and Environmental Processes Approach

Rapid urban expansion and population growth often lead to the degradation and fragmentation of ecological space, causing a series of ecological issues [24]. Therefore, the studies of the ESP and eco-environmental spatial planning are widely concerned with effectively ensuring regional ecological security. Many case studies have mainly focused on optimizing the ESP from a quality or layout perspective, lacking a comprehensive optimization method [38,39]. At present, restoration efforts have evolved from focusing on single elements or processes to a more systematic and comprehensive approach to ecosystem restoration and governance, aiming to achieve the effective control and improvement of spatial development. In this study, we propose a novel integrated framework for estimating landscape patterns and multi-ecological processes, incorporating atmospheric, edaphic, hydrographic, and ecological processes through advanced processing models and spatial analysis techniques. Unlike most existing studies that address isolated ecological or environmental issues [40,41], our framework provides a comprehensive approach to ecosystem restoration and governance, enabling a more holistic view of ecological spatial management.

The innovation of this framework lies not only in its integration of multiple processes but also in its ability to provide policymakers with a new approach for identifying priority protection areas. The construction of the ESP is of great significance for the comprehensive management of ecological space and the formulation of protection policies [42]. The EMU provides a new reference for studying the relationship between landscape patterns and processes. These methods can effectively explore the spatial distribution and process of air pollution, NPS pollution, and soil pollution [43–45]. This approach is both practical and reliable at the city level, with primary data sourced from governmental departments making it easier to integrate it into planning processes and enhancing its ability to optimize ecological protection patterns and develop targeted conservation strategies. The exploration of this methodology in Anshan City is transferable to the numerous middle-sized and small cities in China.

4.2. Governance Implications

This study provided a valuable decision-making basis for the development of the planning of Anshan City. In response to the demand for the coordinated development of its economy and eco-environment, Anshan City needs a new protection and development pattern emphasizing the targeted implementation of eco-environmental protection and restoration. Accordingly, the implications for eco-environmental governance in different units are outlined (Figure 8).

Priority protection units

Units with legal boundaries and ecological red-line control should be implemented according to regulations, while others need to formulate policies based on environmental pollution characteristics. For atmospheric environmental protection, the government should prohibit any construction projects other than ecological protection and restoration, and the existing enterprises and industrial land in the area should be gradually removed. For water environmental protection, it is necessary to strengthen water ecological construction, avoid the deterioration of water quality, promote water-saving irrigation, and ensure drinking water security.

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Key control units

Industrial layout and structure should be optimized. The construction of highly polluting industrial projects in the region should be prohibited and total pollutant control should be implemented. Agricultural nonpoint source pollution should be rectified, and the impact of planting and livestock on the aquatic environment should be reduced. In urban areas, the government should promote the construction of rain and sewage diversion and improve green coverage.

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General control units

The government should restrict the entry of highly water-consuming industries and projects involving the emission of toxic gases and high levels of pollution to control the total amount of pollution. All types of development and construction activities should comply with the relevant spatial layout requirements of the NTSP of Anshan City.

Figure 8. Management policy for each unit.

4.3. Advances to Traditional Planning

Traditional planning is often conducted by individual administrative departments, each focusing on a specific social, economic, ecological, or environmental goal. For example, the socio-economic plan issued by the National Development and Reform Commission is about socio-economic-related fields. The Ministry of Housing and Urban–Rural Development issued a sponge city plan in response to the impact of floods, focusing only on the impact of water on the city [46]. Environmental management has been demonstrated in ecological function zoning [47], and the environmental protection administration has enforced this policy with single elements, including ecological conservation, the aquatic environment, and the atmosphere. The main purpose of ecological function and the red line is conservation, while environmental factors and their control requirements are not included [48,49]. Water environmental function zoning has implemented different water discharge standards and control requirements according to the zone [50]. Similarly, air function zoning focuses primarily on control objectives, but the zones are often unclear and insufficiently comprehensive. Moreover, the current severe and complex environmental problems cannot be resolved by a single-element approach [51].

In addition, these plans suffer from several flaws, such as content duplication, overlapping planning spaces, and conflicts between spatial control boundaries, leading to the waste of spatial resources, social conflicts, and unbalanced regional development [52,53]. Since 2017, the Ministry of Natural Resources of the People's Republic of China has proposed national and territorial spatial planning to achieve multiple-plan coordination. The territorial space planning carried out in recent years has implemented multi-planning, integrating main functional area planning, land use planning, urban and rural planning, and other spatial planning into one [8]. However, at present, this planning has rarely given consideration to the eco-environmental process.

Current spatial planning needs further improvement. We integrated multiple-process models to identify critical areas of the entire domain and proposed management and control requirements according to the control unit by integrating the comprehensive requirements of the environment and partitioning them into priority protection, key control, and general protection units. The ESP is an effective approach for identifying priority conservation areas and ensuring regional ecological security. We clarified the industries or development content that can be developed in each region and effectively carried out comprehensive control of the whole area without exceeding the environmental carrying capacity. This comprehensive spatial planning framework has proven to be an effective method for regional eco-environmental protection, providing scientific analysis and guidance for spatial planning and ecological construction. It is of great significance to promote the establishment of the NTSP and the national spatial governance system in Anshan City (Figure 9).

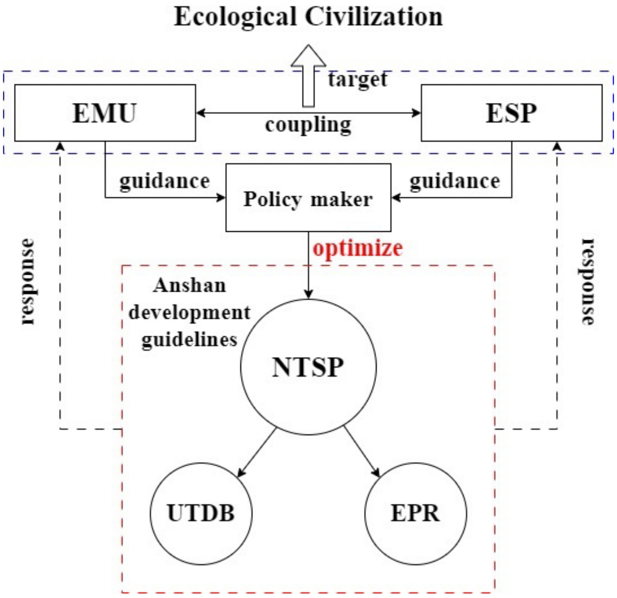

Figure 9. NTSP optimiztion route. EMU: eco-environmental management unit; ESP: ecological security pattern; NTSP: national territorial spatial planning; UTDB: urban and town development boundary; EPR: ecological protection red line.

5. Conclusions

In this study, a synthetic spatial planning and management method considering atmospheric, edaphic, hydrographic, and ecological processes was proposed. Based on circuit theory, this study constructed the ecological security pattern of Anshan City, a region with various ecosystem types and environmental problems. On this basis, the spatial control zones were delineated based on the spatial character of each eco-environmental process. By imposing and fitting these four types of control zones, a comprehensive environmental control unit was defined, and management and control strategies were enacted based on its eco-environmental risk. A comprehensive management pattern was proposed, which involves implementing differentiated optimization, protection, and strengthening measures based on divided units and corridors. This approach is essential for effective governance and ecological management at the regional level. The application of this framework in Anshan illustrates its capacity to identify priority areas for ecological protection and management, thereby facilitating the development of a sustainable and adaptive spatial plan.

Traditional planning studies have mainly focused on social, economic, or certain eco-environmental issues. In the background of China's implementation of multiple-plan coordination and the overall planning of various departments, ecological protection has received more attention. Our results indicate that integrating spatial and ecological data can significantly enhance the effectiveness of conservation efforts, aligning them more closely with regional sustainability objectives. This study provides valuable insights for guiding land use planning and facilitating long-term ecological restoration initiatives.

The limitation of this synthetic method is that these complex models are hard for planners to handle. To improve the applicability of this approach for urban planners, future iterations of the model could explore potential simplifications. Additionally, it is crucial to address potential data biases, including inaccuracies in environmental variables or spatial data resolution, which could affect the results. Future research should also investigate how these techniques could be adapted for broader use across diverse urban contexts, while accounting for the limitations inherent in both the data and the modeling process. For scientific development purposes, the spatial plan or 'all-in-one' plan needs to cooperate with multiple departments and research institutions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13122177/s1, Figure S1: Ranges of ecological corridors under the thresholds from 1000 to 12000; Figure S2: Corridor area and proportion under different cumulative resistance thresholds; Figure S3: Area of overlap between different corridor areas and urban and town development boundary; Figure S4: Indicators for recognition of Critical regions; Table S1: The maximum distance over which each threat affects habitat quality and its weight; Table S2: Sensitivity of habitat types to threat factors; Table S3: Simulated area grid parameter settings; Table S4: WRF model configurations. References [31,32,36,54–56] are cited in the Supplementary Materials.

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