International Journal of *Geo-Information*

MDPI

Article

The Ecological Security Pattern and Its Constraint on Urban Expansion of a Black Soil Farming Area in Northeast China

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Received: 31 July 2017; Accepted: 18 August 2017; Published: 24 August 2017

Abstract: Rapid urbanization in China has increased the demand of land resources for urban areas and caused a series of environmental problems. Ecological security under the pressure of urban sprawl has become one typical indicator for illustrating regional environmental conditions and thus inform urban development. As an important farming area and one of the core economic development regions in northeast China, Changchun City is now confronted with severe contradictions between economic growth, habitat conservation and food security. Therefore, with the aim of developing an approach to optimize a regional ecological security pattern and land use structure, this study built a comprehensive ecological security pattern taking into account regional ecological processes including water regulation, soil and water conservation, species protection and recreation. Three patterns of ecological security were identified responding to different levels of ecological conservation: the basic security pattern, the buffer security pattern and the optimal security pattern. Based on the constraint of the ecological security pattern, the preservation area of prime farmland was added to an urban expansion suitability pattern as an additional constraint to simulate scenarios of urban expansion. The results indicate that the basic security pattern covers an area of 374.23 km^2, accounting for 19.27% of the total area of Changchun City. This pattern is considered as the ecological baseline that maintains the basic ecological functions, and it is the area where ecological land cannot be occupied for construction purposes. Furthermore, co-constrained by the preservation area of prime farmland, the ecological conservation area, the ecological restriction area and the suitable development area are 190.34 km^2, 384.75 km^2 and 152.83 km^2, respectively, accounting for 9.80%, 19.80% and 7.87% of the total area. It can be concluded that the suitable expansion area for the city is relatively limited when the conservation of farmland and regional ecological environment is considered. Therefore, positive actions such as industrial structure transformation and land use efficiency improvements should be perceived as a preferable pathway for urban development to balance economic growth, and regional ecological and food security.

Keywords: ecological security; urban expansion; farmland protection; sustainable development; land management

1. Introduction

With rapid social and economic development in China, the urbanization level has increased to 56.1% in 2015 [1]. This has directly caused a series of environmental and land use issues [2–4]. In particular, land urbanization has been occurring at a faster rate than population urbanization. The excessive pursuit of economic development necessarily required a great deal of land for construction. On the other hand, the influx of people to cities and towns has caused a shortage of land resources, and the urban space has had to expand outward to offer more area for human habitation [5,6]. Because of the increasing importance of urbanization in economic growth, China will likely further promote the process in the near future. At present, population urbanization lags behind industrialization and non-agriculturization and inevitably leads to problems of irrational land use. Urban sprawl has converted large amounts of crucial land with high ecological value to other land use types with economic value such as industrial and commercial land [7]. The conflicts between economic growth and environmental protection have become increasingly severe. In addition, the agricultural activities on farmland have induced many environmental issues. Irrational farming practices and the lack of prime farmland protection resulted in not only soil quality problems but also off-site risks including water pollution (contamination and eutrophication), climate change and biogeochemical cycle disorders. The conflicts between the agricultural and ecological environment in regions that are challenged by rapid urbanization processes are increasingly severe, and a balance between them should be achieved as soon as possible. As land is a scarce resource and a material base for social development, land utilization and planning have a far-reaching impact on society and the physical environment [8]. It is a key point to determine how to allocate land resources to meet the demands of land protection and ecological security during rapid urbanization and reach a coupled relationship between systems of ecological land use and urbanization [9,10].

Ecological security generally refers to the state of the environment and ecosystem in a region. Specifically, it reflects several aspects of ecosystem integrity and ecological health, including aesthetic value, habitat protection and the ability to address environmental changes [11,12]. It can be extended to a composite artificial ecological security system and its associated cultural and social meanings [13]. As the basis of ecological process in landscapes, the land use pattern is the essential medium for material exchanges that can influence ecological security. Along with long-standing research on landscape evolution, environmental changes and sustainable land utilization, ecological security has become a specific focus in many domains, including ecology, geography, environmental sciences, etc. [14–16]. The Ecological Security Pattern (ESP) is a potential landscape spatial pattern in an ecosystem that provides a crucial natural life-support system and plays an important role in guaranteeing the health of ecological processes, along with providing a safeguard for ecologically sustainable development [17,18]. In this study, we built a targeted ESP by integrating singular ecological processes involving aspects of the regional environment, social development and land use conditions to seek a suitable pattern to balance the relationship between human activity and ecological security.

The concepts of green infrastructure and greenways such as ecological infrastructure and ecological networks were first proposed as an ecological barrier to restrict urban development in view of the needs for the living environment [19–25]. Warntz advocated that ecological security patterns could be constructed by reference to ecological resistance surfaces [26], and Yu applied the concept of ESP to the construction of greenways, biodiversity conservation and urban planning [17]. Based on comprehensive discussions of landscape ecology and land use [27], multiple models and methodologies have been used to explore deeper connections between ecology and land use, and specific research on individual regions and objectives has been widely discussed [28–32]. Studies on land planning and management have mainly been concerned with ecological security evaluation by establishing an analytical framework and evaluation models such as the multi-objective optimization model, the cellular automata model and the calculation of ecosystem services value [33–36]. Few studies have discussed the relationship between urban expansion and ecological security in a typical black soil farming area. Along with the increasing significance of the urban ecosystem, research on the relationships between society and ecosystem can embody the internal interactions of the environment in a region. Kattel proposed a complementary framework "E-LAUD" for urban ecology, and this explored the interactions between ecosystems and land use, architecture and urban design, to provide an approach in urban planning and promote ecosystem services [37]. Martellozzo discussed the extensive land cover change that caused the loss of natural vegetation and agricultural land, especially on the high-quality agricultural soil in Alberta, Canada and verified that the loss of farmland to urban expansion had been a global problem happening in many regions [38]. Shaker calculated the human wellbeing index and ecosystem wellbeing index in 33 European countries and built a spatial regression model to reveal the relationships between human well-being and the ecosystem. The results indicated that urbanization processes will continue to disconnect the socioeconomic and ecosystem services [39]. As a core city in northeast China, over 60% of Changchun City is located in a black soil area. It is also an economic growth centre in Jilin Province. The black soil is the basic carrier for food production and a crucial component for sustaining energy flow and nutrient cycles in the ecosystem. Urban sprawl along with rapid urbanization has predominantly occurred on farming land with fertile soil and is expected to continue for a period of time. The urban expansion brings risks such as soil degradation, land fragmentation and biodiversity loss. These have directly affected soil quality, food security and natural habitat. With the increase of severe conflicts between economic growth, food security and ecological protection, rational allocation of land resources would show great benefit in preserving the black soil region, especially the farmland and in sustaining the regional ecological environment.

The objectives of this study were to define the city's land-use structure using methodological exploration and to quantify the available development space and ecological conservation area considering natural and social needs. In this paper, the ESP of Changchun City at the landscape level was built as the first constraint in restricting urban sprawl. The prime farmland preservation area delimited by the management department was added as a second constraint. The urban expansion suitability pattern was established as the foundation to simulate an urban expansion scenario. The following two hypotheses are tested in this study: (1) the ESP map can effectively recognize the levels of the regional ecological security situation and restrict urban expansion; and (2) a coordination relationship between the social and natural environment can be realized by optimizing land use structure. This study not only provided an approach to determining the land conservation structure for the regions facing issues between population growth, food security, and environmental conservation caused by rapid urbanization but also researched the balance needed to maximize economic, ecological and natural benefit of land resources within the theory of sustainable development.

2. Study Area and Data

2.1. Study Area

Changchun City (124°18′ E–127°05′ E, 43°05′ N–45°15′ N) is located in the central part of Jilin Province in northeast China. The altitude is between 250 and 350 m, and this region is subject to a northern temperate continental monsoon climate with distinct seasons. The mean annual temperature is 4.8 °C, and the daily average temperature in the coldest month (January) and warmest month (July) are −15 °C and 23 °C. The mean annual precipitation is approximately 556 mm, and the annual frost-free period is approximately 138 days. The major soil types are dark brown soil, black soil and chernozem. Changchun City is located in one of three black soil belts in the world where the black soil was mainly formed in a temperate climate and in regions with multiple vegetation coverage. A rich humus soil horizon has accumulated after a long period of time and the organic matter content in black soil can reach 3–10%. Intensive farming practices have caused severe issues that have led to the rapid loss of black soil in recent years, as well as water and soil loss, soil salinization and gully erosion. Administratively, Changchun City is the capital of Jilin Province, and contains seven districts, two county-level cities and one county. It is the most developed and urbanized city in the province and one of the central regions in northeast Asia at the strategic level. Due to the extremely fertile soil within the black soil belt, Changchun City has been an important production base of commodity grains in China and plays an important role in maintaining national food security. In this paper, a case study was carried out in five main districts of Changchun City including Lvyuan District, Chaoyang District, Kuancheng District, Erdao District and Nan'guan District (Figure 1), covering a total area of 1942 km^2.

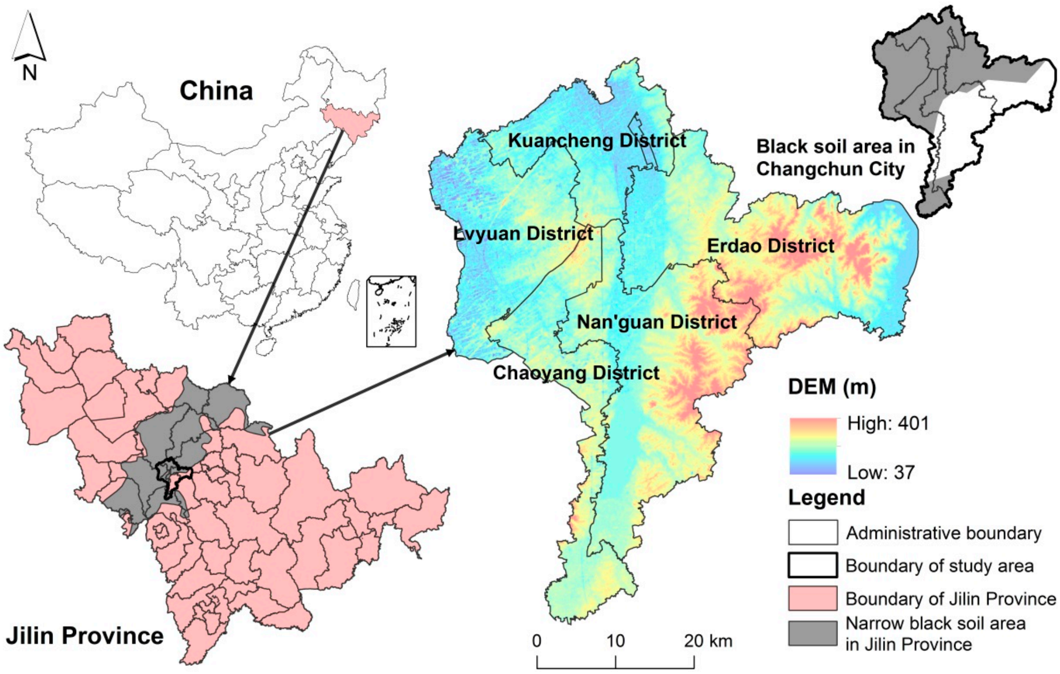

Figure 1. Location of the study area.

2.2. Data

The land use data in this study were extracted from the detailed land survey database of Changchun City in 2015. Land use classification was based on the "Current Land Use Classification" standard that is the predominant land use classification system in China, issued by the Minister of Land and Resources of China in 2007. A DEM (Digital Elevation Model) was obtained from the Geospatial Data Cloud, and the NDVI (Normalized Difference Vegetation Index) was obtained from the MODIS product of USGS (United States Geological Survey) both with a spatial resolution of 30 m in 2015. Soil data in the study area were extracted from the second national soil survey in China. The range of prime farmland preservation area was extracted from the second national land survey database, which was determined in 2009 by general land use planning in China in order to strictly limit the occupation of farmland to meet the needs for agricultural products. Data in this study were processed and analysed by ArcGIS software (ArcGIS, 10.2, Esri, Redland, CA, USA), and the size of the grid unit was 30 m $\times$ 30 m in the spatial analysis view of the scale of study area.

3. Methods and Process

3.1. Study Methods

3.1.1. Minimal Cumulative Resistance Model

The Minimal Cumulative Resistance (MCR) refers to the costs of overcoming resistance during the horizontal motion from a source to a destination, which represents the movement trend of sources in the landscape. This model was put forward by Knaapen in 1992 and was used in the study of species diffusion at an early stage [40]. Yu modified the model for use in several fields, including landscape ecology, land suitability evaluation, and urban expansion [17,23]. The MCR value can be calculated in the cost-distance module of the ArcGIS software using the formula

$$MCR = f \min \sum_{j=n}^{i=m} \left(D_{ij} \times R_i \right) \tag{1}$$

where MCR is the minimum resistance value; f is the unknown positive function that shows the positive correlation between the resistance value and the eigenvalues of the resistance surface; D_{ij} is the spatial distance from source j to unit i; R_i is the resistance coefficient; the cumulative value of $(D_{ij} \times R_i)$ is the measurement of accessibility from the source to any point in the landscape.

3.1.2. Determination of Weights and Selection of Grading Standard/Resistance Coefficients

Appropriate resistance factors and weights should be chosen and calculated for the simulation of ecological security and urban expansion suitability. In this study, we adopted the AHP (Analytic Hierarchy Process) method to determine the weights of resistance factors. 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 such as resource allocation, urban planning and economic management [41,42].

The resistance coefficients to measure the resistance size in spatial movement were determined based on literature studies and further adjusted after consulting expert opinion. Grading standards of different patterns in this study were not exactly the same, depending on how the processes happened, and mainly came from the literature studies and "Jenks natural breaks classification" method. The grading standard of the water regulation security pattern and the soil and water conservation security pattern was determined from the literature on the objective of ecological process, while the patterns which could be simulated as a spatial movement process and established by an MCR model (species protection security, recreation security pattern, urban expansion suitability pattern) would be classified by the "Jenks natural breaks classification" method.

3.1.3. Jenks Natural Breaks Classification

The threshold of the minimal cumulative resistance value to determine different security levels is calculated by the "Jenks natural breaks classification" method, which is a classification method that arranges partition data into classes based on natural groups in the data distribution that can be realized in the ArcGIS 10.2 software. This method seeks to minimize each class's mean deviation from the class average, while maximizing each class's deviation from the means of the other classes to reduce the subjectivity caused by artificial partition [43].

3.2. Study Process

A regional ESP was built in this study considering the features of urban functions, the natural environment and cultural landscape to indicate urban ecological security. The process generally included three steps. First, the appropriate respective "sources" of singular ecological processes were selected. A "source" normally refers to the existing natural habitat of species, but it could be extended to places of interest and cultural heritage that related to urban ESP in this study. Second, the resistance surface of ecological processes was established by assigning the resistance coefficients and weights of separate resistance factors. Finally, the security pattern was constructed by simulating movement tendency, which indicates the difficulty of overcoming resistance from the source to any point in the landscape [17]. The more difficult it was to move, the less the source was threatened. In this study, the specific implementation would be adjusted according to the objectives and meanings of each process.

Three levels of singular ecological security patterns were identified based on protection requirements: the basic security, the buffer security and the optimal security patterns. The basic security pattern was the minimal sufficient pattern to sustain the ecological process and also was the ecological baseline to prevent urban sprawl. This pattern should be classified as the ecological conservation area where construction activities were strictly limited. The buffer security pattern was the "buffer space" between ecological protection and urban development. Development activity should be restricted conditionally and some safeguards should be implemented to preserve and restore the urban ecosystem. The optimal security pattern was the ideal pattern to sustain regional ecological service. Within this pattern, the ecological processes and ecological patches were better preserved with good connectivity where development activities could be carried on conditionally.

Grades of water regulation security pattern could be recognized by multiple ring buffer analysis. The grading standard of the soil and water conservation security pattern was set by consulting the influence degree of resistance factors. By simulating the space movement of species and human activity, the MCR model would be applied in the species protection security pattern and recreation security pattern to recognize different security grades using the "Jenks natural breaks classification" method. By integrating the security patterns of single ecological processes, the ESPs for all ecological processes could then be combined into a comprehensive pattern that showed the overall ecological security of the city. In addition, the built-up area was chosen as the source to simulate the suitability pattern of urban expansion using the MCR model, and the resistance surface was constructed according to the factors restricting urban sprawl. Three suitability grades were identified as corresponding to the ESP: the suitable expansion, the restrictive expansion and the prohibitive expansion patterns. Ultimately, the comprehensive ESP and the prime farmland preserving area were overlaid on the urban expansion suitability pattern as dual constraints to shape the subareas for urban expansion (Figure 2).

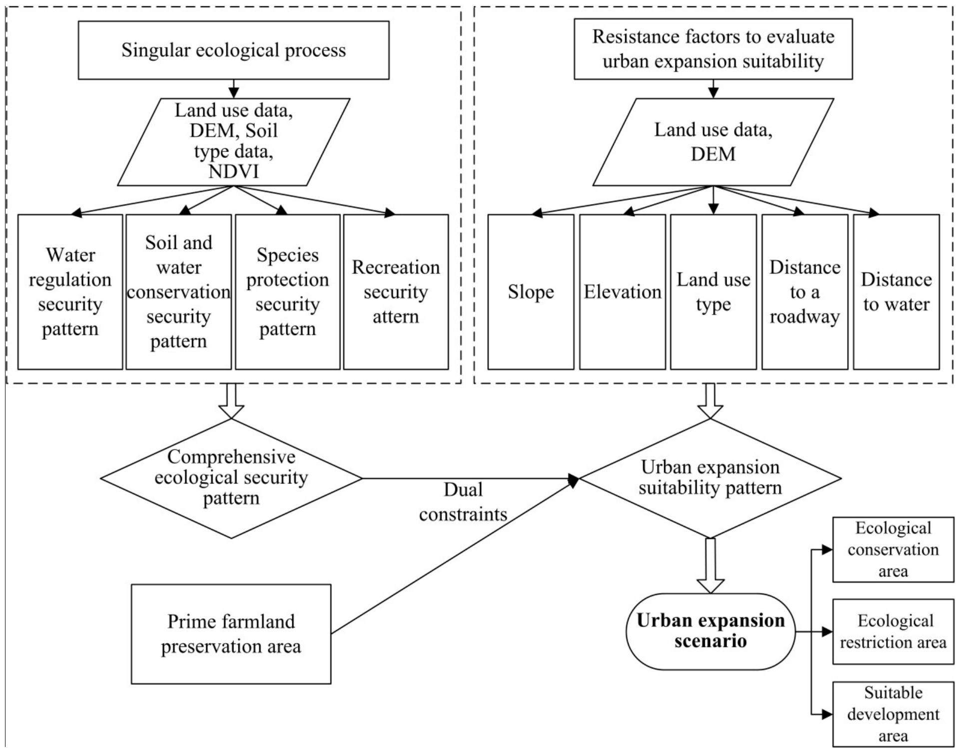

Figure 2. Technology route.

4. Results

4.1. Ecological Security Pattern of Singular Process

4.1.1. Water Regulation Security Pattern

The methodical protection of water resources is beneficial to water conservation and maintaining corridors for species and material flow [44]. The purpose of the water regulation security pattern was to measure the capacity of water storage. In this study, 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. As the difference of water storage capacity and characteristics between water sources, the buffering distance of rivers, lakes, reservoirs and ponds were calculated separately by consulting the literature and the objectives of the study (Table 1). Separate surfaces of different sources were overlaid to form the security pattern of water regulation. Taking into account the importance of different kinds of sources, the ultimate level in the overlapping area was determined by the following order: rivers and lakes, reservoirs, and then ponds. For example, if there was an overlapping area in the resistance surfaces of reservoirs and ponds, the ultimate security level should be consistent with that of the reservoirs. The results are shown in Figure 3.

Table 1. Grading standard for water regulation security pattern of basic, buffer and optimal levels.

Sources	Grading Standard		
	Basic Security Pattern	**Buffer Security Pattern**	**Optimal Security Pattern**
Rivers and lakes	<100 m	100 m–200 m	200 m–500 m
Reservoirs	<100 m	100 m–500 m	500 m–1000 m
Ponds	<50 m	50 m–100 m	100 m–150 m

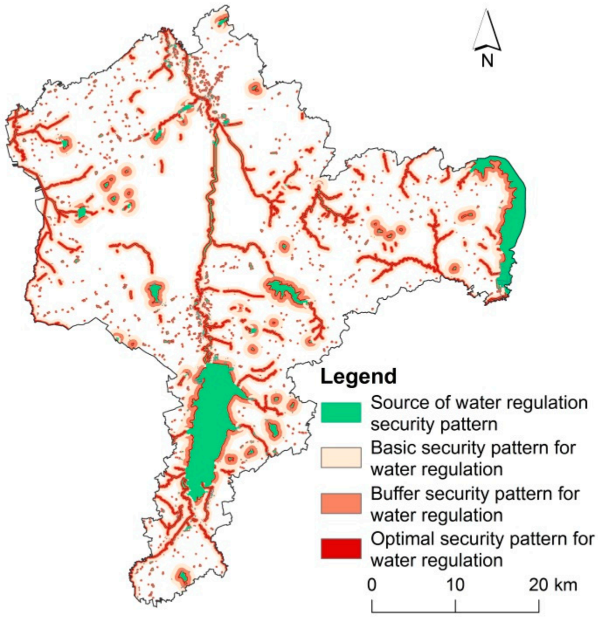

Figure 3. Water regulation security pattern.

4.1.2. Soil and Water Conservation Security Pattern

The study area is located in a black soil belt where the quantity and quality of soil is crucial for grain production and food security. The soil and water conservation security pattern aims at preventing and protecting land surface from the threats of water loss and soil erosion. The process is mainly affected by factors such as climate change, geography, vegetation coverage, and human activity [45]. In this study, four resistance factors were selected to indicate the interference effect. These factors were slope, NDVI, land use type and soil texture. The NDVI generally measures the degree of vegetation coverage and has a significant linear correlation with the spatial distribution of vegetation. It is useful to evaluate regional vegetation coverage and its growth vigour [46]. The soil texture generally refers to the combination of mineral particles with different diameters in the soil. This is one of the physical properties of soil. The soil texture is determined by the parent materials and can be classified into three types: sandy soil, loam and clay. The sand grain content in sandy soil is relatively high and the space between grains is large. The air permeability and water perviousness are favorable while the capacity of water-holding and fertilizer preservation are relatively poor. Clay mainly consists of very small particles of clay and the space between them is relatively small. Therefore, the capacity of water-holding and fertilizer preservation is good with rich nutrients and stable soil temperature. The texture of loam is between clay and sandy soil and the air permeability, water perviousness, water-holding capacity and heat retaining property are more appropriate for farming. Grading standards of security patterns for each factor were determined using previous research as reference and by consulting expert opinion (Table 2) [47,48]. The weights of factors were fixed using the AHP method. The resistance surfaces were then integrated to generate the weighted soil and water conservation security pattern of different levels (Figure 4).

Table 2. Grading standard for soil and water conservation security pattern of basic, buffer and optimal levels.

Factors	Grading Standard			Weight
	Basic Security Pattern	Buffer Security Pattern	Optimal Security Pattern	
Slope	≤5°	5–25°	≥25°	0.35
Soil texture	Clay	Sandy soil	Loam	0.19
NDVI (Normalized difference vegetation index)	>0.6	0.2–0.6	<0.2	0.11
Land use type	Land for construction, water	Forest, grassland	Farmland, saline-alkali land, sand, bare land	0.35

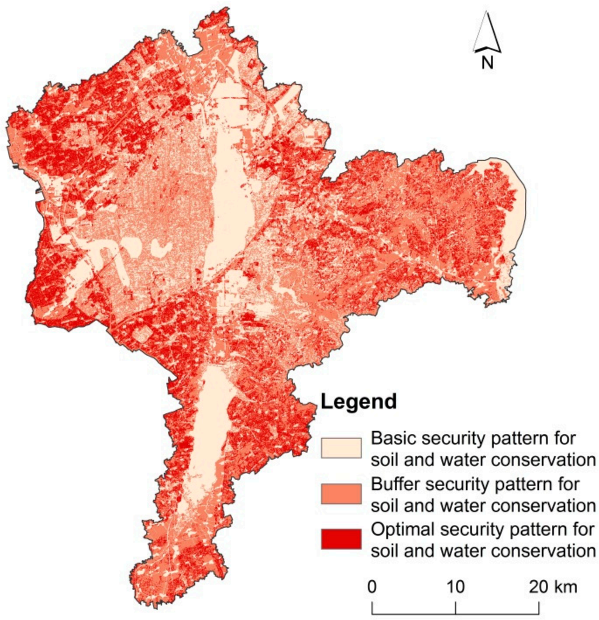

Figure 4. Soil and water conservation security pattern.

4.1.3. Species Protection Security Pattern

Protecting core habitats and guaranteeing the connectivity among them is the foundation of maintaining species diversity [49]. Species in cities were mainly influenced by two factors: nature and human interference. In general, the complicated topography and intense human interference cause a fair amount of resistance to species movement. In this study, forest land with an area larger than 0.5 km^2 and the entire grassland were chosen as the suitable source for species habitats, and five resistance factors were selected to build the resistance surface. 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) [50], distance to a roadway, distance to urban and rural settlement, and distance to water, where water refers to large water surfaces including rivers, lakes and reservoirs. The resistance coefficients were set as 10, 20 and 50 based on the literature and expert advice [47,48]. The weights of resistance factors were calculated using the AHP method (Table 3). By simulating the process of species motion, the MCR model was used to calculate the minimal cumulative resistance value. Three security levels were classified using the "Jenks natural breaks classification method" in the ArcGIS software (Figure 5).

Table 3. Resistance coefficients and weights of resistance factors for species movement.

Factors	Resistance Coefficients			Weight
	10	20	50	
Land use types	Forest, grassland	Farmland	Land for construction	0.40
Relief amplitude	<20	20–50	>50	0.08
Distance to a roadway	>500 m	100 m–500 m	<100 m	0.14
Distance to urban or rural settlement	>1000 m	500 m–1000 m	<500 m	0.14
Distance to water	>1000 m	500 m–1000 m	<500 m	0.24

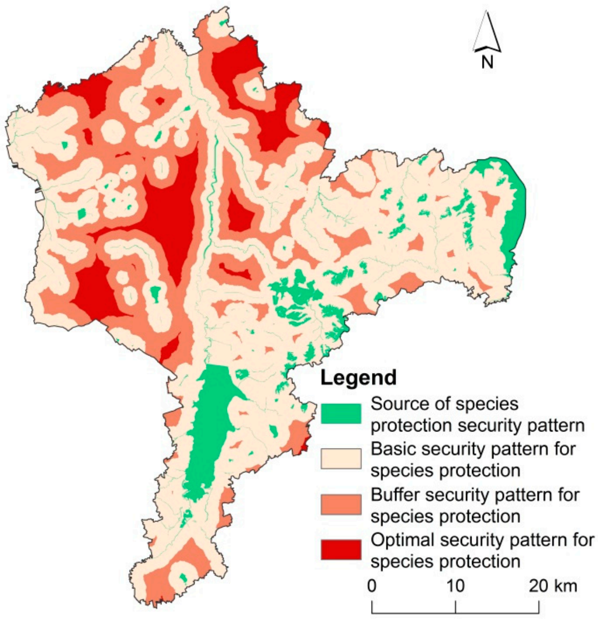

Figure 5. Species protection security pattern.

4.1.4. 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 [51]. The construction of this pattern can be viewed as the formation of a cultural landscape. As a famous historical and cultural city in China, Changchun City possesses much natural and cultural landscape for tourism and recreation with significant cultural and ecological value. To establish a human recreation security pattern, this study selected places of interest, famous scenery, water bodies and parts of the grassland as the sources, and four resistance factors were chosen. These factors were land use type, slope, elevation and distance to a roadway. The resistance coefficients were defined according to the literature and expert opinion [47,48], and the weights were set using the AHP model (Table 4). 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 (Figure 6).

Table 4. Resistance coefficients and weights of resistance factors for recreation activities.

Factors	Resistance Coefficients			Weight
	10	20	50	
Land use type	Forest, grassland	Farmland, water	Land for construction	0.42
Slope	<6°	6–25°	>25°	0.23
Elevation	<50 m	50 m–100 m	>100 m	0.23
Distance to a roadway	<500 m	500 m–1000 m	>1000 m	0.12

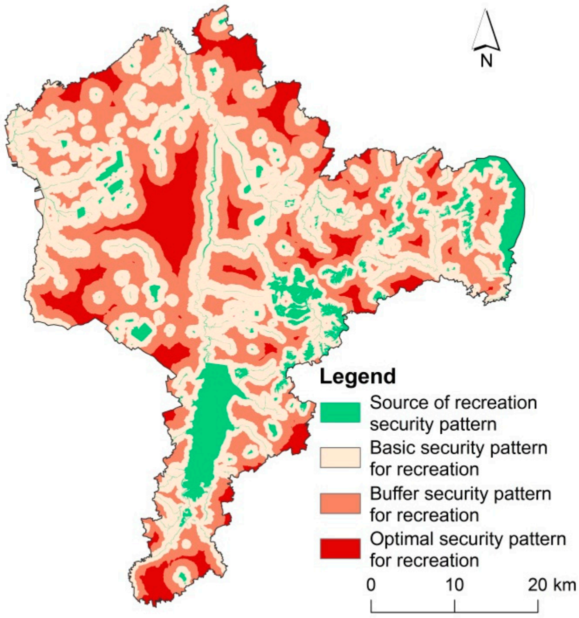

Figure 6. Recreation security pattern.

The distribution of different security levels in separate processes was not exactly the same, which indicates features of both heterogeneity and similarity. However, land use types with high ecological value, such as water, grassland and forest, were mainly concentrated in the source area or the basic security pattern. It demonstrated that these regions play an important role in the maintenance of urban ecological security. Restricted by water-holding capacity, the coverage of the water regulation pattern was relatively small and was distributed around the important rivers, reservoirs and ponds. The security levels of the soil and water conservation pattern showed an increasing trend of spreading from the source to the periphery. The forest land in the eastern region was the primary area in need of protection in the species conservation security pattern, and the security level increased from the eastern to the built-up areas in the central and western parts of the city. The basic security pattern for recreation was mainly distributed around the area with high recreation value and connected components, and the recreation value was higher in the built-up areas of the city centre than in fringe regions.

4.2. Comprehensive Ecological Security Pattern

A comprehensive security pattern could be obtained by integrating individual ecological security patterns (Figure 7). 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. The statistical results showed that the basic security pattern covered an area of 374.23 km^2, constituting 19.27% of Changchun City. The ecological land within this pattern was mainly distributed around land use types with high ecological value, which directly protected crucial ecosystem services. The area of the buffer security pattern was 926.64 km^2, constituting 47.70% of the city. This very large area could provide potential land for regional land planning and could be conductive to easing the conflicts between urban expansion and ecological land protection. The area under the optimal security pattern was 641.66 km^2, constituting 33.03% of the city. In this pattern, urban ecological needs had been satisfied, and the space could be used for production activities.

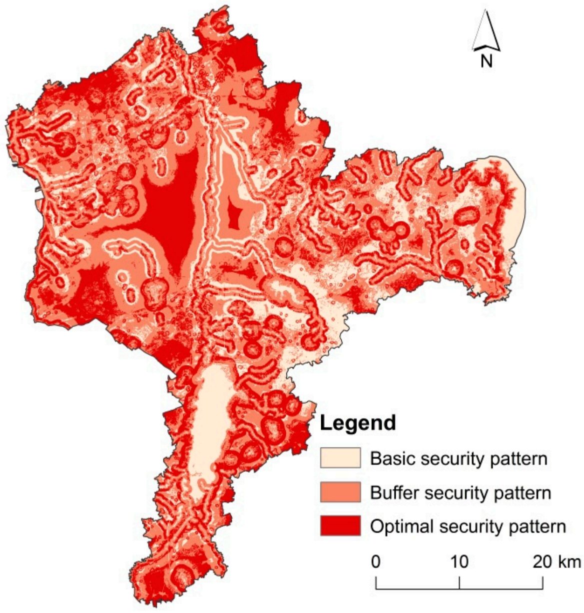

Figure 7. Comprehensive ecological security pattern.

4.3. Urban Expansion Suitability Pattern

The urban expansion suitability pattern could be considered as the outward expansion process of the built-up area and could also be simulated using the MCR model. The built-up area in Changchun City was chosen as the source of the process. Five resistance factors that affected urban sprawl were selected: slope, elevation, land use type, distance to a roadway and distance to water. The resistance coefficients were assigned depending on the difficulty of traversing the area under different constraints [52]. Individual weights of the resistance factors were determined using the AHP method (Table 5). Using the MCR model, the minimal cumulative resistance value was calculated and formed a minimal cumulative resistance surface (Figure 8a). Three levels of urban expansion area were determined according to the minimal cumulative resistance value using "Jenks natural breaks classification" method in the ArcGIS software. These levels were the suitable area for urban expansion, the restrictive area for urban expansion and the prohibitive area for urban expansion (Figure 8b).

Table 5. Resistance coefficients and weights of resistance factors for urban expansion.

Factors	Resistance Coefficients			Weight
	10	20	50	
Slope	<5°	5–25°	>25°	0.30
Elevation	<50 m	50 m–100 m	>100 m	0.30
Land use type	Land for construction	Forest, grassland	Farmland, water	0.17
Distance to a roadway	<500 m	500 m–1000 m	>1000 m	0.12
Distance to water	<500 m	500 m–1000 m	>1000 m	0.11

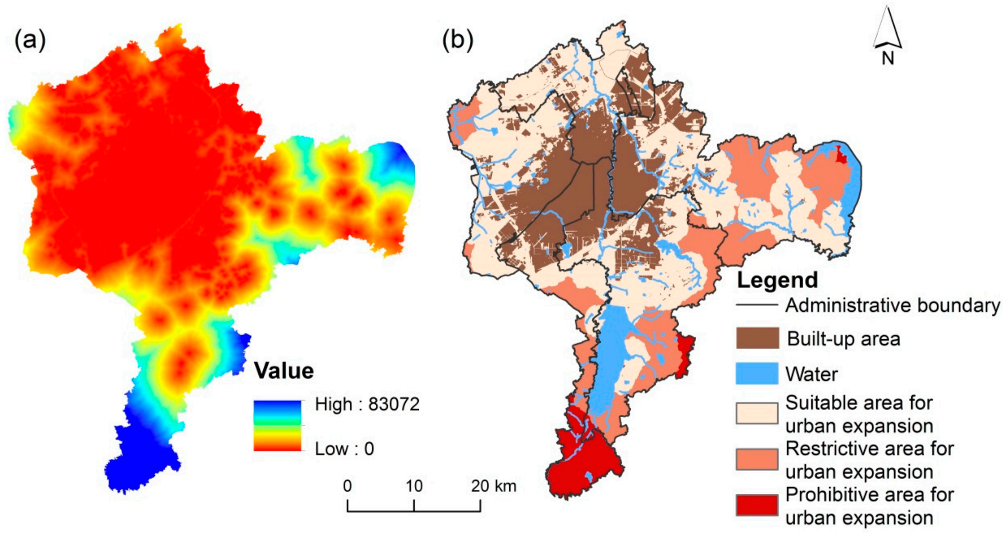

Figure 8. (**a**) Minimal cumulative resistance surface and (**b**) urban expansion suitability pattern.

4.4. Urban Expansion Scenario

In view of the principle of "ecology first", the ESP was added to the foundational urban expansion pattern as the first constraint (Figure 9a). The basic security pattern of the ESP and the prohibitive area of urban expansion pattern were integrated and classified as the ecological conservation area where construction activities were strictly prohibited. The optimal security pattern of the ESP and the suitable area of urban expansion pattern were intersected into the suitable development area, and the remaining region was classified as the ecological restriction area. The ecological conservation area, the ecological restriction area and the suitable development area under the first constraint of ESP covered areas of 294.84 km^2, 718.03 km^2, and 322.83 km^2, respectively, and represented 15.18%, 36.96% and 16.62% of Changchun City. In addition, the prime farmland preservation area was added as the second constraint to restrict the expansion pattern and to protect the black soil farming area from being occupied (Figure 9b). The results showed that the ecological conservation area, the ecological restriction area and the suitable development area reduced to 190.34 km^2, 384.75 km^2 and 152.83 km^2, respectively, accounting for 9.80%, 19.80% and 7.87% of the total area of Changchun City.

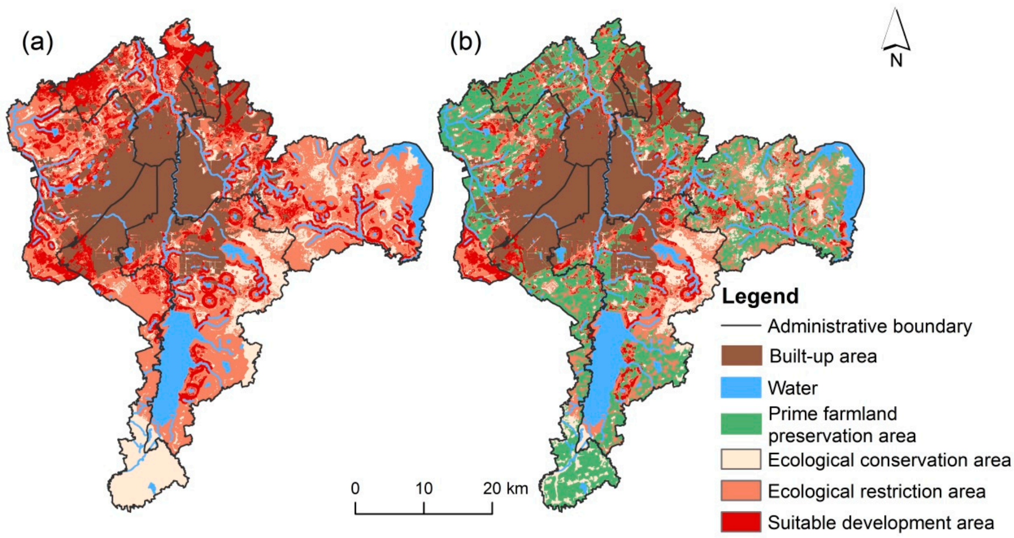

Figure 9. Urban expansion scenarios under the constraints of (**a**) the Ecological Security Pattern (ESP) and (**b**) the ESP and prime farmland preservation area.

5. Discussion

The urban expansion scenario under dual constraints of the ESP and the prime farmland preservation area reflected the interaction between urban construction land, ecological land and farmland. This also showed the conflicts of land use allocation in the urban–rural system. Studies on urban expansion have received increasing attention on consequential issues such as population growth, land scarcity and environmental pollution [53,54]. Land use competition has been much more intensely reflected in aspects of food production, urban–rural settlement and infrastructure construction [55]. In the early stage of urbanization, urban expansion usually occupies fertile farmland for construction activity which directly induced the degradation and reduction of black soil. Urbanization-related loss of farmland in China has been going on for a long time [56]. With policies focusing on farmland protection, large amounts of land with high ecological value were transformed into low-quality farmland, which damaged ecological patches and corridors. The irrational use of land resources has caused plenty of land utilization and environmental issues which influence the biogeochemical cycles, the pollution of air resources and soil erosion in the world [38]. The proposed prime farmland preservation policy constituted a rigid constraint to protect farmland from being occupied. Meanwhile, the conservation of land ecological security has received increasing attention and become an indispensable part of sustaining the integrity and connectivity of the urban ecosystem. In the mixture region of farmland and construction land, prime farmland has been proved as an effective way to form the peripheral constraint of the city and guide the direction of urban expansion to provide economic and ecological services simultaneously.

The comprehensive ESP consisting of singular ecological processes embodied both the features of material flow in a natural environment and the appeal to humanism, which could be considered as a city's typical comprehensive concern. Within this pattern, the basic security pattern was the minimal sufficient pattern to sustain urban ecological security. The boundary could be drawn as the baseline of the core ecological area where production and development activities should be strictly limited. The buffer security pattern provided "buffer space" to both ecological sources and the developing region. Within this region, development activity with a certain ecological value, such as the construction of wetland parks, places of interest and urban green space, would be appropriate. The optimal security pattern was distributed far away from the core ecological land, where the ecological security had been effectively protected and was suitable for developing conditionally.

The simulation of urban expansion suitability was an independent process without considering ecological factors. This provided the foundation for urban expansion scenarios. As a result, urban expansion could be effectively restricted under the dual constraints of the ESP and the prime farmland preservation area. The findings in this study are consistent with previous research in the field of landscape ecology and urban sustainable development, in that urban land use planning would collectively benefit from an understanding of urban ecosystem structures and functions [17,47,57,58]. In terms of spatial distribution, the suitable area for construction was mainly distributed around the existing built-up area and extended out to the city boundary. This mode for urban expansion accorded with urban growth theory and concentric zone theory [59,60]. Under this mode of expansion, the ecological land could be effectively protected and ecological patches were concentrated with satisfactory connectivity. With the further expansion of construction land, ecological patches and corridors would risk being divided and the connection of ecological processes could be severed. Moreover, if construction land expanded into the ecological conservation area, large amounts of ecological land would be converted to other land use types and the increasingly severe fragmentation would not be conducive to regional ecological protection and basic ecosystem services.

Driving forces of regional ecological security and urban development generally include natural and human interference while human interference plays the decisive role in urban ecological security. As urban systems are comprehensive economic–social–natural organisms administered by human beings, urban planning oriented by government mainly decides the direction of urban development and brings irreversible transformation of land use types. This has led to large loss of natural ecological landscape. Considering the effects of urbanization on ecological processes, planning recommendations have been widely proposed to support policy-making. Encouraging environmentally compatible land uses and improving the connectivity between land use types could be useful for Changchun City [61]. The study of urban expansion, along with the needs of ecological protection and food security, embodies the multi-directional complexity of urban organisms. It regards living environments at the same level as the natural environment and creates conditions for achieving a balance between the social and natural environments.

During the process of urban development, it is inevitable that some resources will be sacrificed to meet some needs. The strict constraints of the ESP and farmland protection on urban sprawl have significantly limited the space for urban expansion. The ESP defined the minimum range of ecological land for maintaining ecosystem function and the farmland preservation area constrained the outward expansion of cities. If the constraints can eventually be implemented, how to maximize the benefit of economic development in a limited space will be an important question for decision makers, and rational allocation of land resource appears to be particularly crucial in the process. The management policies made by humans should also take into account the ecosystem service trade-offs at multiple spatial and temporal scales in the allocation of land use. The trade-offs could result in the instability of the ecosystem and further affect land use functions [62]. In addition, scattered patches of ecological land should be prohibited and ecological red lines of urban sprawl should be identified for government action [63]. The transformation of an industrial structure is conducive to adjusting the allocation of industrial land and improving industrial quality. Because of the market economy, the land market has produced large amounts of idle land and inefficient land. Improvement of land use efficiency by regions relying on the rebuilding and renovating of existing construction land is helpful for the transformation and meets the needs of the long-term development of industry. Moreover, with the increasing demand for ecological security, abandoned industry and mining land has become a restriction on comprehensive land management. The effective reconstruction of unserviceable land is an important means of releasing and enriching urban space. As land use planning and allocation are fundamental elements for the harmonious development of a city, the management department should re-evaluate the importance of economic development and the living environment, and reduce the emphasis on economic construction as a central task. The ultimate objective of sustainable development is to realize the interrelated development of urban, natural and human systems.

6. Conclusions

An ESP map was built to recognize different ecological security levels by integrating four natural and cultural singular ecological processes (water regulation, soil and water conservation, species protection and recreation) of Changchun City in northeast China. Additionally, the urban expansion suitability pattern was evaluated using multiple resistance factors to establish a basic pattern for further restricting land expansion. Scenarios of urban expansion were simulated with dual constraints of ESP and the scope of prime farmland preservation area. The statistical results showed that the ecological conservation area, the ecological restriction area and the suitable development area of the urban expansion scenario were 190.34 km^2, 384.75 km^2 and 152.83 km^2, respectively.

This study dealt with the conflicts between economic growth, ecological security and farmland protection in the rapid urbanization process in China. An optimized pattern of land use was formed to improve the benefits of both social and environment and restrict urban sprawl effectively. The constraints of ESP and farmland preservation area on urban expansion embody the dual safeguards on urban ecological security and food security and provide a quantitative and spatial approach to shape the land use pattern. This approach can also be used to solve specific issues in different regions by selecting appropriate resistance factors taking into account specific regional features.

This model of the ecological security pattern has certain limitations such as the subjectivity of factor selection. Further improvements could be made to optimize this model. The watershed management in the water regulation security pattern could be taken into account to improve the result by using mature hydrological modelling. The species protection security pattern could be more specific by simulating the spatial motion of different indicator species in the region. Based on the accessibility of data, multiple and heterogeneous factors could be chosen according to the characteristics of the study area to produce a better result. In addition, a systematic index system should be established to simulate the ESP and urban expansion pattern objectively and comprehensively.

Acknowledgments: This work was supported by National Natural Science Foundation of China for Young Scholars (No. 41201158).

Author Contributions: Shuhan Liu, Dongyan Wang and Hong Li conceived and designed the research; Wenjun Wu and Yuanli Zhu collected the data; Shuhan Liu and Wenbo Li processed and analyzed the data. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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