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An Optimization Strategy for Provincial "Production–Living–Ecological" Spaces under the Guidance of Major Function-Oriented Zoning in China

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Abstract: The comprehensive evaluation of China's major function-oriented zoning, grounded in scientific principles, has evolved into a nationwide initiative aimed at promoting regional coordinated sustainable development. A pivotal focus during this transitional phase is the optimization of a "production–living–ecological" spatial pattern within the main national functional areas. This involves a meticulous examination of the main functions, encompassing the distinct categories of production, living, and ecology, as well as prioritizing scenarios aligned with the functional orientation of towns, agriculture, and ecology in land-use simulation. Utilizing the PLUS model's land-use simulation technology, a detailed investigation into Anhui Province's main function orientation was conducted to achieve an optimal simulation of the "production–living–ecological" spatial pattern. The findings underscore the inadequacy of a singular scenario in attaining a global optimal solution for simulating the three spaces of production, living, and ecology. However, a gradual stabilization was observed in the overall quantitative structure and spatial transition frequency of these three spaces in Anhui Province. The continuous optimization of local spatial patterns and functional layouts was achieved through a multi-scenario optimization simulation based on main function orientation. Noteworthy improvements were identified in the optimization of the three spaces in specific regions: the northern part of Anhui, urban living spaces around Hefei and Wuhu, and ecological spaces in southern and western Anhui. Crucially, the simulation results align with the strategic goal orientation of the provincial main functional areas, the optimization trajectory of the "production–living–ecological" spatial pattern, and the strategic imperative for the coordinated and sustainable development of territorial space in Anhui Province. These findings furnish a robust scientific foundation for decomposing and transmitting the core indicators of provincial territorial spatial planning, as well as delineating the "three zones and three lines" in municipal territorial spatial planning.

Keywords: major function-oriented zoning; "production–living–ecological" spaces pattern; multi-scenario simulation; Anhui Province; China

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1. Introduction

According to the new trends of globalization, regional spatial organization and development strategies have shifted their focus towards fairness in regional development only after a long period of industrialization [1]. By the 20th century, pursuing fairness was clearly elevated to the same level of importance as enhancing regional competitiveness and emphasizing development efficiency. After experiencing rapid industrialization and urbanization, China established the principle of main functional zoning, emphasizing a dual value orientation of "fairness" and "efficiency" in regional development. The strategic goal of China's main functional zoning is to achieve the optimization of the three spaces of production, living, and ecology, promote new urbanization, and optimize the layout of major productive forces through coordinated regional development in order to build a regional economic layout and territorial spatial system with complementary advantages and high-quality development. The twentieth report once again proposes to improve the main functional areas system and optimize the national land spatial development pattern. Since Fan Jie first proposed the spatial equilibrium model of regional development [2], with a theoretical basis and the technical methods of geographic integrated zoning, based on socioeconomic, natural geographic, and strategic choices as the evaluation index system, national major function-oriented zoning has been completed [3]. Simultaneously, there has been a persistent exploration of integrating new technologies into the execution of major function-oriented zoning and territorial spatial planning [4].

Major function-oriented zoning integrates the theoretical approach of natural zoning [5], the geographical theoretical system of the human–land relationship [6], the theory of regional spatial-pattern evolution from point axis to network [7], and the theory of sustainable development [8]. It is a major research result in the optimization of China's territorial pattern [9]. Domestic scholars have carried out a series of research works based on the core theory of main functional areas and the results of zoning, analyzing the provincial point–axis structure based on major function-oriented zoning [10], formulating the methodological guidelines for evaluating the carrying capacity of resources and environment and the appropriateness of territorial spatial development [11], and conducting territorial spatial functional area evaluation based on "double evaluation". At the same time, based on this "double evaluation", the optimized zoning of territorial functions in land space [12] and the technical regulations for major function-oriented zoning [13] have been carried out. At the application level, the discussion has delved into the pivotal role of main functional areas as the foundational system for national land development [14]. The spatial-pattern characteristics of urbanization, agricultural development, ecological security, and the natural shoreline pattern in China have been succinctly summarized [15]. An exploration of optimizing the spatial structure of land in the Yangtze River Economic Belt has been undertaken [16]. The analysis of carbon balance and carbon offset zoning has been conducted from the perspective of major function-oriented zoning [17]. The allocation of land resources in advantageous areas, based on major function-oriented zoning, has been executed [18]. The monitoring and assessment of land development activities within various main functional areas have been conducted [19,20]. Furthermore, a national spatial-type monitoring and evaluation index system for main functional areas has been established [21]. From the perspective of inter-provincial territoriality, the spatio-temporal mechanism and law of the occurrence and feedback of main functional areas have been explored [22]. The main functional areas of counties, established on the foundation of provincial major function-oriented zoning, have been meticulously classified, identified, and optimized, among other processes [23,24].

Optimizing "production–living–ecological" spaces stands as a key objective in the implementation of major function-oriented zoning [25]. The report of the 18th National Congress articulated the imperative of "advancing intensive and efficient production spaces, fostering livable and balanced living spaces, and establishing clear and picturesque ecological spaces". This delineates the trajectory for optimizing "production–living–ecological" spaces [26]. This holds immense scientific value for the theory of geography's territorial function generation and the practical aspects of spatial governance. Additionally, it represents a crucial research domain directly focused on optimizing the spatial structure of national territory [27]. At present, the research on "production–living–ecological" spaces mainly focuses on identifying their conceptual connotation and classification methods [28–30], as well as spatial identification and classification [27,31]. The evolution of the pattern and function of "production–living–ecological" spaces has gradually become a hot-spot for domestic scholars [32,33]. Analyzed in terms of research scale, the existing research works have been conducted by the whole country [34], province [35], city (urban agglomeration) [36], county and township [37,38], etc. The overarching trend indicates a gradual narrowing of the research scale and a concurrent refinement of the research area. Analyzed in terms of geographical features, the existing studies on the spatial and temporal evolution of "production–living–ecological" spaces are mainly inclined to mountainous hills [39], watersheds [40], and so on.

Land Use/Land Cover Change (LUCC) is an important focus of global climate and environmental change research [41,42], serving as a link between human socio-economic activities and natural ecological processes [41]. The LUCC process is closely related to terrestrial surface material cycling and life processes [43], directly impacting biodiversity, biogeochemical cycles, and the sustainable use of natural resources [41–44]. In 1993, the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) jointly developed the LUCC Scientific Research Plan, making it a core component of global change research [45,46]. Building upon this foundation, the Global Land Project (GLP) was launched in 2005, emphasizing the comprehensive integration and simulation studies of human–environment coupled systems within the land system. Monitoring and simulating the dynamic processes of land use/land cover with a focus on human–environment interactions gradually became the center of research attention [47–49]. With the ongoing advancements in metacellular automata technology, there is a continual enhancement in the accuracy of the model. To date, scholars have conducted numerous land-use simulation studies using CLUS [50], CLUE-S model [51,52], FLUS model [53], CA-Markov model [54,55], PLUS model [56], etc. The PLUS model demonstrates superior accuracy when compared to commonly used models such as CLUE-S, SLEUTH, SD, and FLUS [50,51].

The main functional areas strategy and its associated research have yielded fruitful results, particularly in the burgeoning field of optimizing "production–living–ecological" spaces. The rapid evolution of land-use simulation technology, particularly based on metacellular automata, opens up a novel research perspective. Deducing a more optimal configuration of "production–living–ecological" spaces through multi-scenario land-use simulation guided by main functions is not only an exploration of localizing the implementation of macro-spatial policies but also an attempt to integrate the main functional areas strategy into specific territorial spatial planning. This approach signifies a methodological innovation toward achieving "multiple planning integration" in territorial spatial planning in the new era. Its application extends to the implementation of the main functional areas, downscaling the transmission of territorial spatial planning indicators, and the effective governance of territorial space. Taking Anhui Province as a case study, this paper employed major function-oriented zoning, core indicators of territorial spatial planning, and the implicit function-oriented correspondence between "production–living–ecological" spaces and land-use simulation scenarios. A simulation study on optimizing the combination of multiple land-use scenarios in the provincial area was conducted based on the PLUS model. This endeavor aimed to realize a strategy of coordinated sustainable development of territorial land space in provincial areas. The outcomes provide a scientific foundation for the decomposition and transmission of core indicators in provincial territorial spatial planning and the delineation of the "three zones and three lines" for municipal territorial spatial planning.

2. Theoretical Framework

Major function-oriented zoning at the provincial scale, using the county as the fundamental unit, is executed through the application of territorial spatial function theory and the integrated zoning method of geography. Emphasis is placed on the strategic nature at the national level and the necessity for coordination at the provincial level. The "Opinions on the Establishment of Territorial Spatial Planning and Supervision of Its Implementation" advocates the creation of a nationally unified, well-defined, scientific, and efficient five-level and three-category territorial spatial planning system, along with its vigilant supervision. The proposal underscores the hierarchical nature of territorial spatial planning, with national planning focusing on strategy, provincial planning emphasizing coordination, and municipal, county, and township planning concentrating on implementation. Main functional zoning and territorial spatial planning at the provincial level serve as pivotal coordinating elements within China's territorial spatial governance system. They function as critical nodes for cascading national development strategies into actionable plans at the city, county, and district levels. Consequently, conducting a simulation study of land use guided by the main functional areas strategy at the provincial level can prove advantageous for the systematic transmission of national strategic directives, constraint indicators, and the spatial execution of various development and protection activities. This approach contributes to the formation of a spatial planning operation system characterized by organic articulation and efficient functionality.

The formulation and implementation of the main functional area strategy require active participation and guidance from government departments to ensure the coordinated development among various functional areas and avoid the duplication of construction and the waste of resources. The government can promote the smooth implementation of the main functional area strategy through planning, financial support, policy guidance, and other means. Additionally, the government should strengthen the supervision and evaluation of the planning of the main functional area and promptly identify and solve problems, ensuring that the main functional area strategy can effectively serve the coordinated and sustainable development of the region. Furthermore, by encouraging the participation of social capital and promoting the optimization and upgrading of industrial structure, among other methods, the government can promote the development and construction of the main functional area. In summary, the main functional area strategy is an important measure for optimizing the regional spatial pattern. The government should actively guide and support its implementation to promote sustainable urban development and enhance the comprehensive competitiveness of cities.

The major function-oriented zoning strategy, coupled with territorial space protection and development, and the optimization of the three spaces of production, living, and ecology, all converge toward a common "urban, ecological, and agricultural" tri-directional approach. The major function-oriented zoning for the country is categorized into optimized development zones, key development zones, restricted development zones, and prohibited development zones. These categories guide territorial space toward different developmental trajectories. A comprehensive evaluation was conducted based on the natural ecosystems, socioeconomic systems, and regional strategic choices, utilizing a comprehensive evaluation index measuring the degree of suitability for regional functions. This process led to the classification of national territorial space into four distinct categories: urbanized areas, food security areas, ecological security areas, and areas of cultural and natural heritage [1,2]. Building upon the main national functional areas, Anhui's major function-oriented zoning can be further segmented into national key development zones, provincial key development zones, national agricultural products' main production zones, national ecological function zones, and provincial ecological function zones. National and provincial key development zones prioritize urbanization development, while national agricultural products' main production zones focus on agricultural production. National and provincial ecological function zones center on ecological protection. The major function-oriented zoning in Anhui Province distinctly adheres to the "towns, agriculture, and ecology" three-fold functional orientation. Within the core framework of territorial spatial planning, encapsulated by "three zones and three lines", the urban development area's core lies within the spatial growth boundary, emphasizing an urbanization-led development pattern. The agricultural development zone is centered on the red line for the protection of arable land and basic farmland, also signifying an agriculture-led development pattern. The ecological control zone's core revolves around the red line of ecological protection, emphasizing an ecologically dominant development pattern. The territorial spatial planning also outlines a clear functional orientation of "towns, agriculture, and ecology". In the context of "production–living–ecological" spaces, the production and living spaces of towns predominantly signify an urbanization-led development mode. The spaces of production, living, and ecology lean toward an agriculture-led development mode, while ecological spaces emphasize an ecology-led development mode. The quality evaluation of the three spaces—production, living, and ecology—mainly aims for regional coordinated, balanced, and sustainable development within the spatial pattern of "towns, agriculture, and ecology". In summary, the main functional areas, the core framework of territorial spatial planning, and the three spaces of production, living, and ecology align with the spatial pattern of "towns, agriculture, and ecology" in terms of function, emphasizing the integration of urban, agricultural, and ecological elements (Figure 1).

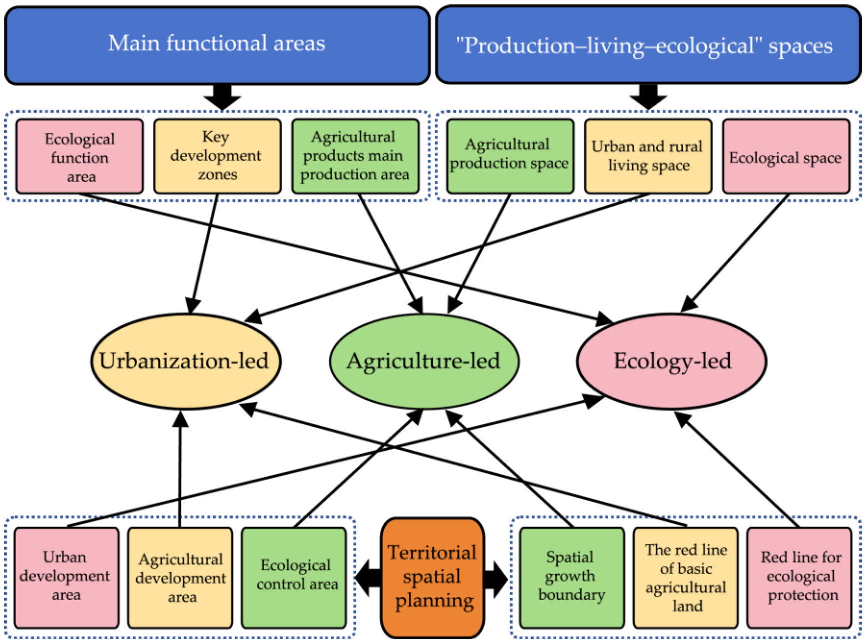

Figure 1. "Three-directional" analysis framework.

A critical challenge lies in achieving the coordinated implementation of the main functional areas' strategic nature and territorial spatial planning at the municipal and county levels, ensuring the same-scale functional coordination and downscaling synergistic transmission. Specifically, addressing how municipal and county territorial spatial planning can optimize "production–living–ecological" spaces, delineate "three zones and three lines", and convey land-use zoning and layout based on the strategic setting of provincial major function-oriented zoning poses a key and pressing research issue. Hence, adopting the "three-directional" principle, which aligns major function-oriented zoning, territorial spatial planning, and the optimization of the three spaces of production, living, and ecology, PLUS land-use simulation technology can be applied. This involves configuring key constraint parameters in the model, in line with the strategic orientation of the main functional areas. Different counties undergo multi-scenario simulation by adjusting key constraints, such as domain weights and land-use type conversion moment control, based on the dominant functions of the "towns, agriculture, and ecology" outlined in the main functional areas. This includes urbanization-, agriculture-, and ecology-led scenario simulations. The spatial integration of the simulation results is carried out, adjusting key parameters with the overarching goal of optimizing the spatial pattern of "production–living–ecological" spaces in provincial areas. This pursuit aims to achieve the optimization objective of creating intensive and highly efficient production spaces, comfortable and livable living spaces, and scenic and beautiful ecological spaces (Figure 2). Ultimately, the provincial land-use layout is determined, and quantitative indicators and spatial information related to the "three zones and three lines" are extracted as the core indicators of provincial territorial spatial planning. These indicators are then transmitted to the municipal and county levels, encompassing core indicators like arable land retention for agricultural production, total urban and rural construction land for cities and towns, the total value of ecological land for ecology, and a schematic range of municipal urban spatial growth boundaries. Leveraging the multi-scenario simulation of land use as a technical tool, this approach establishes a provincial coordination system for major function-oriented zoning and territorial spatial planning, providing a scientific pathway for downscaling the transmission of core indicators.

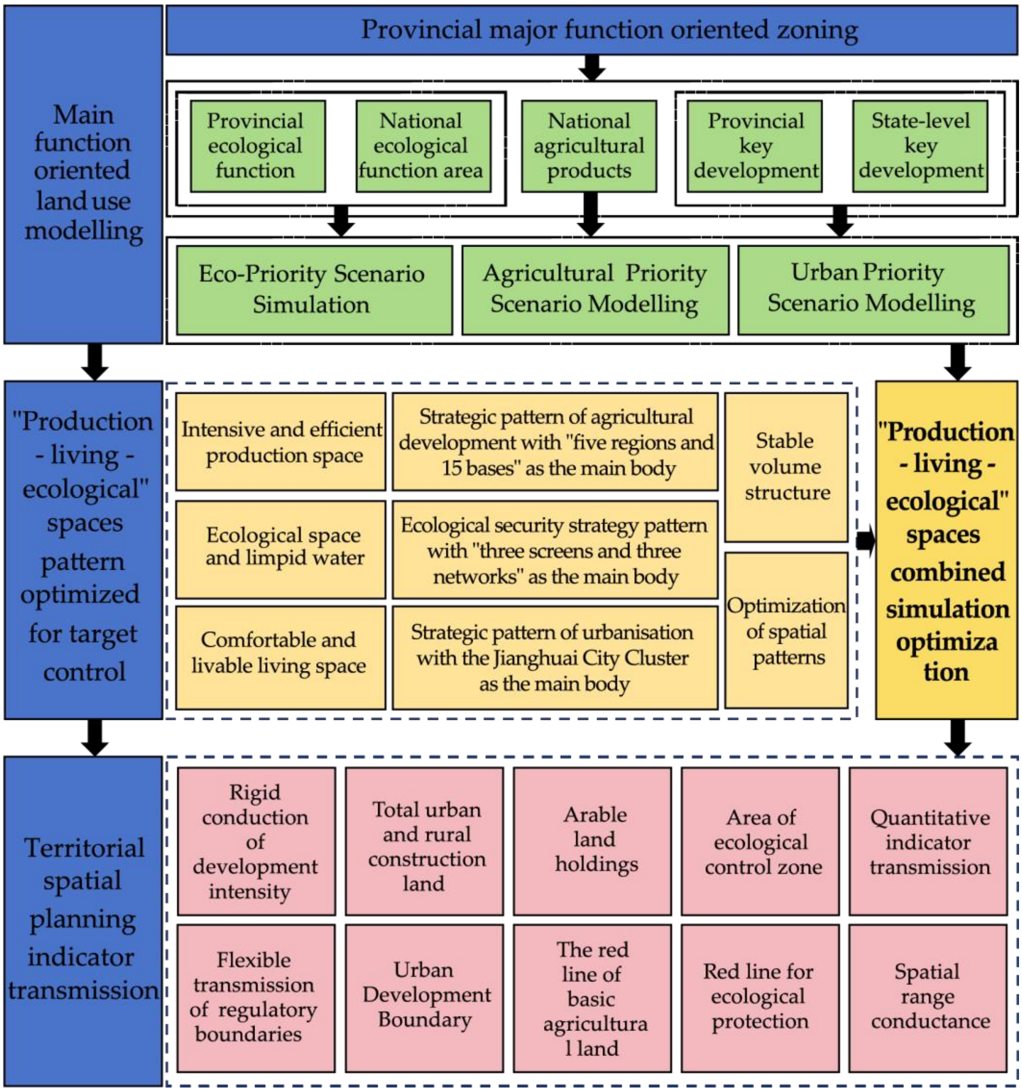

Figure 2. Main function guides the optimization and conduction technology route of three students in the province.

3. Overview of the Study Area and Research Methods

3.1. Overview of the Study Area

This paper focused on Anhui Province as the study area (Figure 3). Situated in the heartland of the Yangtze River Delta city cluster, one of China's three major city clusters, Anhui Province holds a strategic position in the east-to-west development of mainland China. The province boasts a moderate-to-high level of urbanization and a substantial total economic volume, placing it in the middle-to-upper echelons nationally. Anhui's unique "production–living–ecological" spaces pattern is characterized by 16 provincial municipalities, 9 county-level cities, 50 counties, and 45 municipal districts. The topography and landforms of Anhui Province exhibit considerable diversity. The Yangtze River and the Huaihe River traverse the entire territory from west to east, delineating three distinct natural regions: north of the Huaihe, Jianghuai, and south of the Yangtze River. The northern region, situated north of the Huaihe River, is part of the North China Great Plain. The central area, situated between the Jianghuai River and the Huai River, is a typical hilly terrain. The areas on either side of the Yangtze River belong to the renowned middle and lower plains of the Yangtze River.

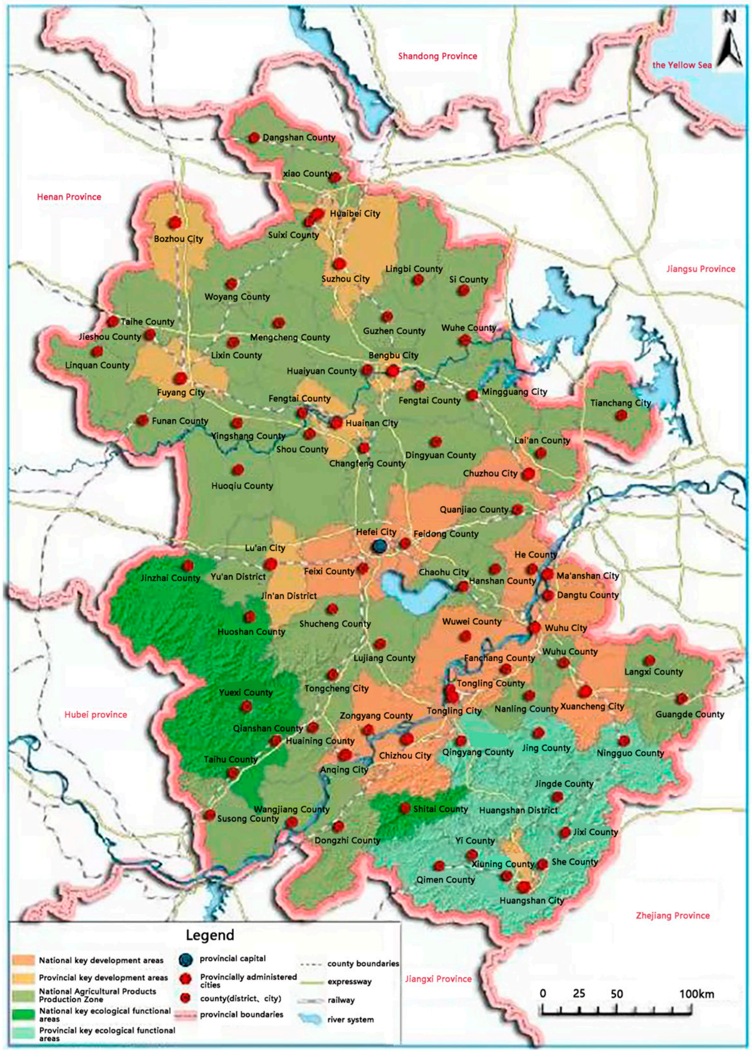

Figure 3. The main function zoning map of Anhui Province.

The positioning of the main functional areas in Anhui Province aligns closely with existing regional development strategies. The Jianghuai area is designated as a national key development area, highlighting its significance in the broader development context. The urbanized portion in northern Anhui holds the status of a provincial key development area, with the majority of this zone identified as a primary production area for agricultural products. In the western Dabie and southern Anhui mountainous areas, the focus is primarily on designating these regions as key ecological function areas. An overarching strategic pattern has been established, comprising a main body of urbanization with the Jianghuai City Cluster, a strategic pattern for agricultural development centered around the "five districts and fifteen bases", and a strategic configuration for ecological security featuring the "three screens and three networks" as its main components. This comprehensive approach ensures a coordinated and balanced development strategy for Anhui Province, integrating urbanization, agricultural development, and ecological protection within a strategic framework.

3.2. Data Sources

Land-use data were derived from national spatial distribution data for the remote sensing monitoring of land-use types. The accuracy of the data was 30 m raster. The land-use types included the 6 primary types of arable land, forest land, grassland, water, residential land, unused land, and 25 secondary types. Combined with previous research results [51–57], 15 driving factors were selected, including 9 socioeconomic indicators and 6 climate and environmental indicators (Table 1). The distances from the road network and water were computed through Euclidean distance processing in ArcGIS.

Table 1. The explanation and driving data of land-use changes.

Data Type	Data Name	Data Interpretation	Data Source
Climate and environmental factors	Average annual temperature Average annual precipitation DEM Elevation Soil type Distance to water	Temperature averages for 2015 Average precipitation for 2015 30 m resolution raster data Processing on the basis of DEM data yields 30 m resolution raster data Distance to water bodies such as rivers, lakes, and reservoirs	Resource Environmental Science and Data Centre (http://www.resdc.cn (accessed on 18 January 2024)) Extracted from 2020 land-use data
Social and economic factors	Demographic GDP Distance to railway According to the national road distance According to the provincial road distance According to the county road distance According to the railway station's distance from Distance to motorway Distance from government premises	Spatialized expression of population size in 2015 Spatialized expression of GDP values for 2015 Distance to railway track Distance to national highway in 2020 China road network data Distance to provincial highway in China's 2020 road network data Distance to county highway in China's 2020 road network data Distance to railway station Distance to motorway Distance to government premises	Resource Environmental Science and Data Centre (http://www.resdc.cn (accessed on 18 January 2024)) OpenStreetMap (https://www.openstreetmap.org (accessed on 18 January 2024))

3.3. Research Methods

3.3.1. Territorial Spatial Transfer Matrix

This analysis was employed to depict the interchangeability of the three lifetimes in space and time. It aimed to elucidate the trends and structures of land use and maintenance under anthropogenic influence, offering insights into the evolving characteristics of the spatial pattern of the national territory [58]. The equation is as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{11} \\ S_{21} & S_{22} & \dots & S_{2n} \\ \dots & \dots & \dots & \dots \\ S_{n1} & S_{n2} & \dots & S_{nn} \end{bmatrix} \quad (1)$$

In the equation, S_{ij} represents the area of land type I in the pre-survey period transitioning to land type j in the post-survey period, where n is the number of land-use types. ArcGIS 10.2 was utilized for spatial overlay, area table analysis, and synthesis to derive a spatial land-use area conversion model for each period in the Anhui Province area.

3.3.2. Patch Generation Land-Use Change Modeling

The PLUS model is a cellular automaton (CA) model that integrates a mining method grounded in the analysis rules of land-use expansion with a CA model based on the multi-type random seed mechanism. This integration provides a more comprehensive interpretation of the driving factors influencing various types of land-use changes, resulting in higher accuracy in the simulation results [59]. Initially, the model extracts the expansion component of each land-use type between two periods, utilizing the land-use data from those periods. The random forest algorithm (RFC) is then employed to systematically mine each land-use type's expansion and driving factors. This process is conducted individually for each land-use type, resulting in the determination of the development probability for each land-use type and the contribution of specific driving factors to the expansion of each land-use type during that time-frame. Consequently, this yields a development potential map corresponding to each land-use type. Subsequently, the development potential map is input into the cellular automaton based on the multiple random seeds (CARS) module. This process incorporates spatial policy constraint data, coupled with the transfer of land-use types in the study area, to set parameters such as predicted land-use demand, cost matrix, and neighborhood weights. In the final step, the model simulates and predicts the spatial distribution pattern of land use based on the input parameters and constraints.

(1) Projections of the scale of land-use requirements

Markov chain is a stochastic process model that uses transfer probabilities to model changes between land-use types. Let $E(0) = [x_1,\ x_2,\ x_3,\ \ldots,\ x_i]$ be the initial state and $x_1, x_2, x_3, \ldots, x_i$ be the initial areas of the first initial areas of the kind of land use.

$$p_{ij} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{11} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \quad (2)$$

Based on the initial state vector and the transfer matrix, the future land-use area $E(i)$, $i = 1, 2, 3, \ldots, k$ can be obtained.

$$E(i) = E(i-1) \times P \quad (3)$$

The forecasting and simulation of multiple scenarios in this study relied on calculating the scale of land-use demand for each land type in 2030 using Markov chains. This calculation was combined with a specific proportion of changes in the demand for actual development, allowing simulation of the demand for each land-use type under three development scenarios in 2030. Additionally, the number of image elements obtained in the actual 2020 scenario was considered, along with the projections for 2030.

(2) Domain weight setting

Domain weights primarily serve to articulate the complexity of land-type conversion, as expressed in the following equation:

$$\Omega_{i,k}^{t} = \frac{con\left(c_i^{t-1} = k\right)}{n \times n - 1} \times w_k \quad (4)$$

In the equation are the metacellular unit and the study set $n = 3$. The total number of grid cells occupied by the metacellular land class at the last stage of the iteration is the domain weight parameter of the ground class k, which is between [0, 1]. The domain weight parameter (Table 2) was set with reference to an existing study [60,61]. I is the domain weight of ground class k at spatial cell i at time t. Table 2 displays the recommended domain weights for various land classes provided by the model developer. Throughout the simulation process, these domain weights are iteratively adjusted based on different simulation scenarios to attain the desired simulation outcomes.

Table 2. Domain weight parameters.

Land-Use Type	Agricultural Land	Woodland	Grassland	Body of Water	Urban Land	Rural Residential Land	Industrial and Mining Area	Unused Land
Domain weighting	0.5	0.4	0.4	0.3	1	0.4	0.8	0.5

(3) Transition matrix and calculation of the development probability of the final site

The transition matrix establishes the rules governing the conversion of different land-use types. It is employed to model the ultimate land-use outcomes by curbing unreasonable conversions and restricting the spontaneous growth of land-use types through deliberate settings, as expressed in the following equation:

$$\text{if} \sum_{k=1}^{N}\left|G_c^{t-1}\right| - \sum_{k=1}^{N}\left|G_c^{t}\right| < step,\ \text{then } \mathrm{l} = \mathrm{l} + 1 \quad (5)$$

$$\begin{cases} P_{i,c}^{d=1} > \tau,\ TM_{k,c} = 1 & \text{Shift in land-use type} \\ P_{i,c}^{d=1} \leq \tau,\ TM_{k,c} = 0 & \text{Constant land-use type} \end{cases} \quad \tau = \delta^{l} \times \mathrm{R}_1 \tag{6}$$

In the equation, R_1 is a normal distribution with a mean value of 1, which is a positive number less than 1; *STEP* is the step size; l is the number of threshold decay steps; $TM_{k,c}$ is the cost matrix, with a value of 1 indicating that the land-use type *k* can be transformed to *c*. The cost matrix and land-use demand were set according to the characteristics of land-use changes and related policies (Table 3).

Table 3. Transition matrix.

		Priority for Cities and Towns							Production Priority							Ecological Priority						
		A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
Land-use type	A	1	1	1	1	1	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1
	B	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1
	C	1	1	1	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	0	1
	D	1	0	0	1	1	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0
	E	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
	F	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	G	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Note: A, B, C, D, E, F, and G denote arable land, forest land, grassland, waters, urban construction land, rural settlements, and industrial and mining construction land, respectively. The value 1 indicates convertibility, while 0 signifies non-convertibility.

3.4. Model Accuracy Validation

In this study, the Kappa coefficient was employed to assess the precision of the urban expansion simulation results. The overall accuracy and Kappa coefficient were computed by comparing the actual land use in 2020 with the simulated land use in 2020, derived from the land use and related data from 2010. The overall accuracy of the validation was 0.91, and the Kappa coefficient was 0.87. These results meet the required accuracy standards for land-use simulation, affirming the model's robust applicability in this study.

3.5. Setting of "Production–Living–Ecological" Spaces

Aligning with the correspondence between the three spaces of production, living, and ecology and the various land-use types, paddy fields and drylands in the second class of land-use classification were designated as agricultural production spaces. Concurrently, urban land and rural settlements fell under the classification of urban and rural living spaces. The remaining land-use types were categorized as ecological spaces.

4. Analysis of the Results

4.1. Simulation of a Single Scenario of "Production–Living–Ecological" Spaces

The simulation predicted land-use changes in Anhui Province for 2030, 2040, and 2050 under three distinct scenarios: urban priority, ecological priority, and agricultural priority. The outcomes were then classified into the layout of "production–living–ecological" spaces (Figure 4). While the evolutionary trend of the three spaces—production, living, and ecology—simulated under a single scenario was able to achieve local optimal solutions, it fell short of achieving a global optimal solution. The results indicated that, under the urban priority scenario, the area of living space in Anhui Province increases from 2030 to 2040 and from 2040 to 2050, while the areas of production and ecological space decrease. This suggests that the urban priority scenario exerts the most significant impact on living and production space, with a comparatively lesser impact on ecological space. In the ecological priority scenario, there was a substantial change in production and living space in Anhui Province during the 2030–2040 period. Conversely, under the agricultural priority scenario, the years 2030–2040 and 2040–2050 have a greater fluctuation in ecological space and living space (Table 4).

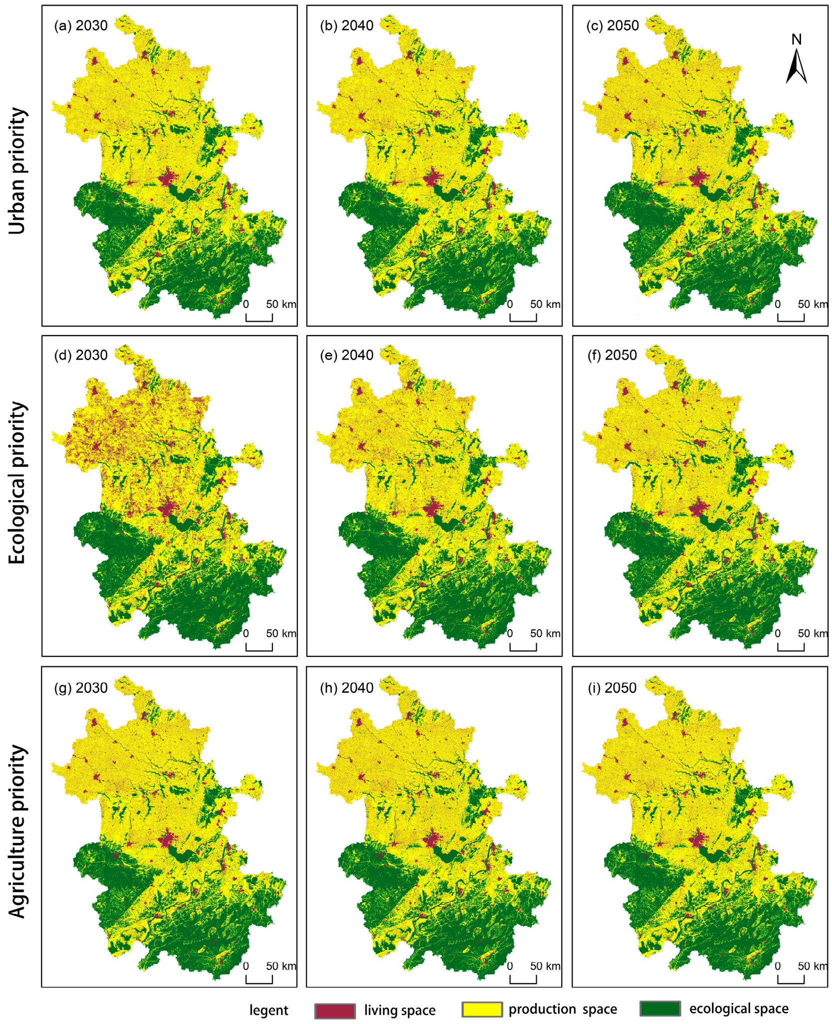

Figure 4. Land-use simulation results for different scenarios.

Table 4. Changes in the spatial area of "production–living–ecology" spaces in various functional areas of Anhui Province.

	2030–2040			2040–2050		
	Urban Priority/km^2	Ecological Priority/km^2	Agriculture Priority/km^2	Urban Priority/km^2	Ecological Priority/km^2	Agriculture Priority/km^2
Living space	1037	−412.9	−532.4	2028.2	−68.9	−832.1
Production space	−1013.5	−102.7	1371.6	−2022.4	−153.0	1088.9
Ecological space	−23.5	515.6	−15.6	−22.4	221.9	−256.8

4.2. Multi-Scenario Optimal Combination Simulation of "Production–Living–Ecological" Spaces Based on Major Function-Oriented Zoning

Major function-oriented zoning serves as a comprehensive blueprint guiding the rational development, utilization, and protection of national land space [2]. The priority scenarios for major function-oriented zoning and the simulation of "production–living–ecological" spaces exhibited a correlation aligned with their function-oriented nature. This correlation is evident in the spatial alignment of national and provincial key development zones, national agricultural products' main production areas, national and provincial key ecological function zones, and the five types of main functional areas with town production and living spaces, agricultural production and living spaces, and ecological spaces within the "production–living–ecological" spaces framework. These spatial units were defined at the county-level administrative divisions of the provincial area. To elaborate, counties situated within the national and provincial key development zones corresponded to the production and living spaces of towns, leading to the prioritization of the town simulation scenario. Counties within the national agricultural product main production areas aligned with agricultural production and living spaces, necessitating the adoption of an agricultural priority simulation scenario. Similarly, counties within national and provincial key ecological function zones corresponded to ecological spaces, making the ecological priority simulation scenario the fitting choice. Utilizing the PLUS land-use simulation method, three distinct scenarios—urban priority, agricultural priority, and ecological priority—were simulated by adjusting the parameters and directing land-type transformations. Furthermore, the simulation results were spatially fitted to determine the evolutionary trend and spatial pattern of the optimization of "production–living–ecological" spaces in the province.

4.3. Analysis of the Quantitative Changes in "Production–Living–Ecological" Spaces in the Provincial Area Based on Combined Simulation

Based on the simulation results of the optimal combination, from 2020 to 2030 (Figure 5), the area of urban living space in Anhui Province increased from 12,117.2 to 12,997 km^2, with an increase of 879.9 km^2, resulting in a rate of change in the area of 7.3% per 10 years. The area of agricultural production and living space increased from 76,395.4 to 76,539.4 km^2, with an increase of 143.9 km^2, resulting in a rate of change in the area of 0.2% per 10 years. The area of ecological space decreased from 47,767.3 to 46,711.0 km^2, with a decrease of −1056.4 km^2, resulting in a rate of change of −2.2% per 10 years. From 2030 to 2040, the areas of production and living space of the cities and towns in Anhui Province increased by 410.8 km^2, while the area of living area in 2040 increased to 13,407.9 km^2, resulting in a rate of change in the area of 3.2% per 10 years. The area of agricultural production and living space increased by 286.6 km^2, with an area change rate of 0.4% per 10 years. The area of ecological space decreased by 697.6 km^2, with an area change rate of −2.2% per 10 years. From 2040 to 2050, the area of urban production and living space in Anhui increased by 410.8 km^2, with an area change rate of 0.9% per 10 years. The area of agricultural production and living space increased by 128.8 km^2, with an area change rate of 0.2% per 10 years. The area of ecological space decreased by 697.6 km^2, with an area change rate of −0.5% per 10 years.

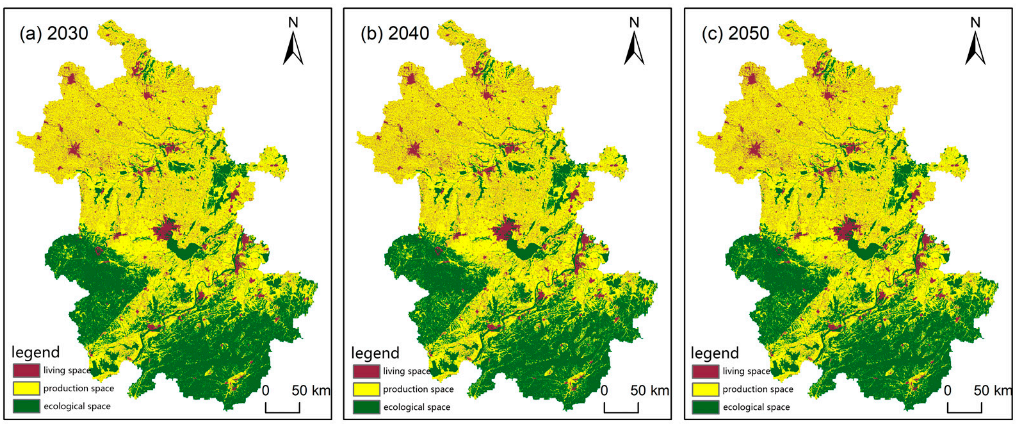

Figure 5. Spatial comparison of the "production–living–ecology" spaces in multi-scenario combination simulations from 2030 to 2050.

Based on the results of the optimal combination simulation from 2020 to 2050 (Table 5), the area change rate was the lowest for agricultural production and living space, higher for ecological space, and the highest for urban production and living space. Over this period, there was an overall decreasing trend in the area change rates for urban production and living space, agricultural production and living space, and ecological space. The largest area change rate for "production–living–ecological" spaces was observed from 2020 to 2030, followed by a slightly reduced rate from 2030 to 2040, and the lowest rate was from 2040 to 2050. Furthermore, the increasing trend in urban production and living space and the decreasing trend in ecological space gradually slowed down, indicating that the changes in the "production–living–ecological" spaces gradually stabilized over time.

Table 5. Comparison of the "production–living–ecology" spaces between reality in 2020 and multi-scenario combination simulations in 2030–2050.

	2020–2030		2030–2040		2040–2050	
	Area/km2	**Rate of Change**	**Area/km2**	**Rate of Change**	**Area/km2**	**Rate of Change**
Living space	879.9	7.3%	410.8	3.2%	115.9	0.9%
Production space	143.9	0.2%	286.8	0.4%	128.8	0.2%
Ecological space	−1056.4	−2.2%	−697.6	−1.5%	−244.7	−0.5%

4.4. Optimization Analysis of the Provincial "Production–Living–Ecological" Spaces Pattern Based on Combinatorial Simulation

The simulation of the expansion of the optimal combination of "production–living–ecological" spaces in Anhui Province from 2030 to 2050 revealed a general optimization in the pattern of these spaces, aligning with the established spatial development strategy pattern of the major function-oriented zoning of Anhui Province (Figure 6). The period from 2020 to 2030 witnessed the fastest changes in "production–living–ecological" spaces, with the expansion trend gradually weakening from 2030 to 2050. During this timeframe, the spatial area of production, living, and ecology in Anhui Province exhibited a localized rapid expansion trend, concentrated in the key development areas at the national and provincial levels, such as the cities of Haozhou, Huaibei, Fuyang, Bengbu, Huainan, Hefei, Wuhu, and Ma'anshan, among others. The spatial area of agricultural production in Anhui Province was primarily located in the main production area of agricultural products in the northern part of the province, aligning with the main function of the provincial area. Notably, there was a significant expansion in the ecological spatial area in the west and south of Anhui Province, focusing on areas such as Anqing City, Lu'an City, and Huangshan City. This expansion aligns with the national and provincial key ecological function areas within the provincial boundaries.

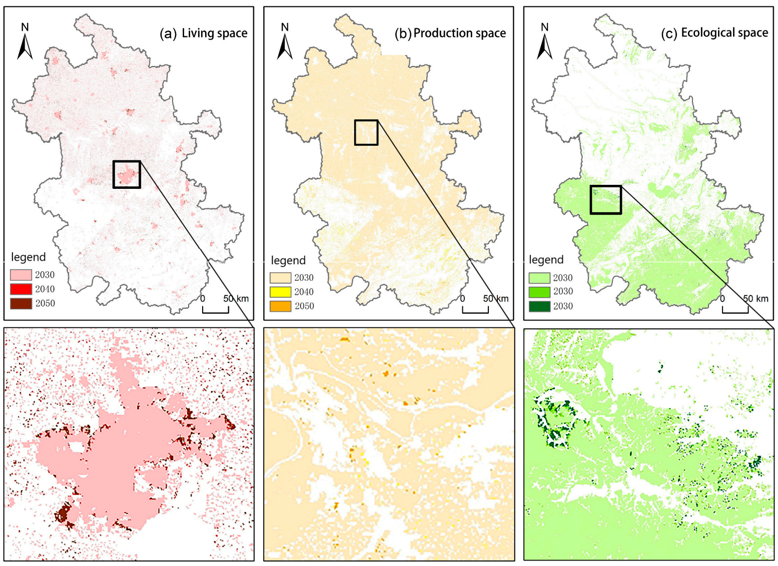

Figure 6. Spatial expansion change chart of the "production–living–ecology" spaces in Anhui Province from 2030 to 2050.

5. Conclusions and Discussion

5.1. Discussion

The existing simulation studies on the "production–living–ecological" spatial pattern typically involve simulating the entire region under multiple scenarios but lack the optimization of the spatial combination based on downscaled functional positioning within the region. This study aims to innovate by conducting a downscaled and function-oriented simulation of the "production–living–ecological" spatial pattern, taking into account the impact of the main functional area planning on the regional spatial pattern. This approach has theoretical and practical value in scientifically predicting the evolution of the land spatial pattern. The optimization of the "production–living–ecological" spaces pattern is a crucial objective within territorial spatial planning. The primary objective of land-use planning is to achieve a balance between economic development, environmental protection, and community well-being [62]. Zoning and land-use layout constitute the essential components of territorial spatial planning. The integration of multiple planning aspects serves as the primary foundation for territorial spatial planning. Therefore, by prioritizing the optimization of the three spaces of production, living, and ecology, incorporating the strategic concept of main functional areas into territorial spatial planning and spatial control represents a meaningful breakthrough and endeavor. The outcomes of this study hold considerable reference value for enhancing the regional ecological spatial pattern, defining the scope of ecological red lines, delineating agricultural protection spaces and basic farmland, as well as establishing urban development boundaries at various administrative levels.

The simulation of land use and the optimization of the three spaces of production, living, and ecology based on functional zoning present several future research directions [12]. First, there is a need for land-use simulation technology that integrates the ecological red line, the red line of basic farmland protection, and the urban space growth boundary after delineating the "three zones and three lines". This involves defining boundaries for various types of land-use expansion within the model. The simulation results can then predict the spatial expansion of land use after establishing the three lines. Second, conducting land-use simulations for specific territorial spatial planning zones based on accurate three-survey data is essential. This can be applied in the concentrated construction areas of towns and cities within urban development boundaries, simulating the spatial expansion of various land types (residential, commercial, industrial, etc.) according to current standards for construction land classification. Third, for specific geographic spaces, major function-oriented zoning can be combined with diverse natural, humanistic, and economic data, and strategic choices to carry out functional zoning. Subsequently, land-use simulation can provide a basis for the protection and development of national land space in specific geographical areas, such as ecological protection and tourism development in a particular watershed. Lastly, aligned with the macro-expected spatial optimization results derived from various land-use types, the spatial layout guiding territorial spatial planning zoning and land-use layout should be considered. Spatial development strategies and control measures can be established based on the land-use conversion parameters set for each type of zoning district, all aimed at achieving the optimization of "production–living–ecological" spaces.

The concrete implementation of the main functional areas strategy at the local level poses a significant research challenge [3]. Currently, there is a lack of effective transmission mechanisms and technical articulation between main functional areas planning and local action planning, especially considering that the county often serves as the base unit for local development. Additionally, there are instances of secondary anti-functional areas within specific main functional areas, and sub-administrative units may have urban development zones within agricultural and ecological function areas. To address these challenges, it is crucial to establish a refined sub-functional zoning system based on land-use change and "production–living–ecological" space simulations. This sub-functional zoning can guide land-use simulations at various administrative levels. Integrating evolving metacellular automata technology into the process can enhance the prediction of future land-use patterns and "production–living–ecological" spaces. This approach offers a technical route for ensuring the strategic coherence of the main functional areas, protecting local development interests, and promoting urban–rural integration and rural revitalization. Moreover, this research aimed to explore the mechanism for downscaling the transmission of regional functions and the path for downscaling the transmission of main functional areas planning. By establishing a robust connection between the overarching national or provincial strategies and the specific needs and characteristics of local areas, it becomes possible to achieve a more integrated and effective approach to spatial planning and development.

Building upon the optimization of three spaces—production, living, and ecology—guided by major function-oriented zoning, an essential avenue for future research involves exploring the endogenous and high-quality development of county economies under the influence of major function-oriented zoning [2]. This exploration would help to identify distinct urbanization paths tailored to the specific characteristics of each county. Understanding the synergistic development paths and modes of "population, land, and industry" within counties and exploring the internal and external synergistic mechanisms that align with the main function orientation is a crucial research perspective. This research should include the empirical studies of counties with diverse main functional areas, contributing to the gradual development of a comprehensive theoretical framework. Such a framework will provide theoretical support for the coordinated development of regions, the high-quality development of counties, and the unique urbanization paths for counties with Chinese characteristics. This research direction is pivotal for implementing the strategy of main functional areas from the bottom up and enhancing the overall sustainability and resilience of local economies.

5.2. Conclusions

The utilization of major function-oriented zoning to guide multi-scenario simulations for regional land space and land-use changes represents a valuable exploration in scientifically predicting the pattern and trends of regional "production–living–ecological" spaces. This study focused on Anhui Province, analyzing the evolution process and the characteristics of "production–living–ecological" spaces in the provincial area based on historical land-use remote sensing data. The fundamental objectives of achieving "intensive and efficient spaces of production, moderate and livable spaces of living, and ecological spaces with beautiful scenery" are consistently pursued. By applying the coupling mechanism between "production–living–ecological" spaces and major function-oriented zoning and employing PLUS land-use simulation technology, this research aligns with the strategic goal of land space development. Multiple scenarios and spatial optimization combinations were simulated to draw the corresponding conclusions:

(1) Between 1990 and 2020, rapid industrialization and urbanization have significantly impacted the evolution of the pattern and types of "production–living–ecological" spaces in the province. Notably, urban and rural living spaces have experienced substantial growth, with a prominent trend of transforming agricultural production spaces into urban living areas. This transformation is particularly evident in areas surrounding major cities such as Hefei and Wuhu. Concurrently, regional ecological spaces have also been subject to varying degrees of influence.

(2) The simulation analysis of "production–living–ecological" spaces in Anhui Province, based on a single scenario utilizing PLUS technology, revealed significant spatial variability in the pattern of these spaces. In the urban-first scenario, there was a continuous and rapid transformation of agricultural production spaces into urban living areas. Conversely, the agricultural-first pattern resulted in a continuous and rapid reduction in ecological spaces, while the ecological-first pattern imposed substantial limitations on urban living spaces. However, relying solely on consistent single-scenario simulations fails to adequately capture the strategic objective of regional spatial balance within the main functional areas. Moreover, it falls short of

achieving the goal of optimizing the "production–living–ecological" space pattern in provincial areas.

(3) The simulation analysis of the optimal combination of the three spaces of production, living, and ecology guided by major function-oriented zoning revealed that the overall quantitative structure of these spaces in the provincial area remained stable during the 2030–2050 period, with a localized optimization of spatial patterns and functional layouts. The proportion of production, living, and ecology spaces in the provincial area exhibited no significant change. However, there was notable growth in the proportion of production spaces in northern Anhui, living spaces in major cities and adjacent areas, and ecological spaces in southern and western Anhui. These simulation results align with the targeted development of main functional areas and the strategic requirements of land space in Anhui Province. They provide a scientific foundation for the formulation of spatial development strategies and spatial control measures in the province.

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