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Temporal-Spatial Evolution of Agricultural-Ecological-Urban Space in Henan Province

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Abstract: Clarifying the spatiotemporal evolution of land use within the "agriculture-ecology-urban" ("three-zones") framework provides a scientific basis for territorial spatial planning and land-use transition. Taking Henan Province as the study area, this study utilizes land use/land cover change (LUCC) data from 2000 to 2020. Land-use dynamics, transition matrices, and landscape pattern indices are employed to quantify changes in land-use area and landscape configuration. The results indicate that the three-zones space exhibits a pattern characterized by "two increases and one decrease." Specifically, agricultural space decreased by 3,660.05 km², ecological space increased by 44.34 km², and urban space expanded by 3,615.71 km². Among these, urban land showed a continuous growth trend, primarily driven by the conversion of agricultural land. The comprehensive land-use dynamic degree in Henan Province was 0.12% in 2000 and 0.11% in 2020, with urban space displaying the most pronounced increase in single dynamic degree. In terms of landscape patterns, agricultural space maintained a contiguous and dominant structure; ecological space exhibited dense patches with complex yet increasingly regular boundaries; and urban space showed a pattern of low connectivity and high complexity with outward sprawl. These findings reflect a profound restructuring of landscape patterns driven by rapid urbanization.

Keywords: Henan Province; agricultural-ecological-urban space; land-use dynamic degree; transition matrix; landscape pattern.

1. Introduction

Henan Province, one of the cradles of Chinese civilization, has experienced pronounced spatiotemporal transformations in its "three-zones" spatial structure—namely agricultural, ecological, and urban spaces—which are of critical importance for regional sustainable development. Investigating the evolution of these spaces not only helps elucidate the interaction mechanisms between human activities and the natural environment, but also provides a scientific basis for regional planning and policy formulation [1]. Such efforts are essential for advancing ecological civilization, promoting urban-rural integration, and facilitating agricultural modernization in Henan Province [2]. Moreover, as the core area of the Central Plains Economic Region, the spatial evolution of Henan has important demonstrative and leading implications for the development of central China as a whole.

Previous studies on the "three-zones" spatial dynamics in Henan Province have primarily focused on the following aspects: (i) urbanization and urban spatial evolution—scholars have employed remote sensing and Geographic Information Systems (GIS) to analyze land-use change, urban expansion patterns, and their environmental effects during the urbanization process [3]; (ii) agricultural spatial evolution—research has mainly examined the relationships among land-use change, agricultural productivity, and agro-ecological conditions [4]; and (iii) ecological space conservation and restoration—existing work has largely concentrated on ecosystem service assessment, ecological zoning, and restoration techniques [5].

The objectives of this study are twofold: (i) to reveal evolutionary patterns by systematically analyzing the spatiotemporal dynamics of urban, agricultural, and ecological spaces in Henan Province; and (ii) to propose optimization strategies based on the findings, thereby supporting spatial governance and promoting sustainable development and ecological civilization construction in the region.

2. Study Area and Data Sources

2.1. Study Area

Henan Province is located in central-eastern China, in the middle and lower reaches of the Yellow River, with geographic coordinates of 31°23′-36°22′N and 110°21′-116°39′E (Figure 1). The region features diverse landforms dominated by plains and mountains: mountainous areas are mainly distributed in the west and south, while the central part consists of the extensive alluvial plain of the Yellow River. Major mountain ranges include the Taihang Mountains, Funiu Mountains, and Dabie Mountains. The province experiences a temperate monsoon climate with four distinct seasons, with a mean annual temperature ranging from 12 to 16 °C. Summers are typically hot, whereas winters are cold. Precipitation is concentrated in summer, with an average annual total of 500-900 mm. As one of the key birthplaces of Chinese civilization, Henan Province is characterized not only by distinctive physical geography but also by a rich historical and cultural heritage.

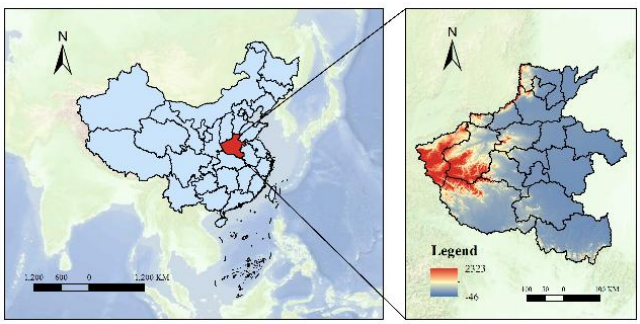


Figure 1. Location Map

2.2. Data Sources and Processing

Henan Province was selected as the study area. The dataset comprises five periods of land-use data (2000, 2005, 2010, 2015, and 2020), obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). Through reclassification, the data were categorized into the three-zones spatial framework (agricultural, ecological, and urban spaces), with a spatial resolution of 30 m.

3. Methods

3.1. Construction of the Three-Zones Spatial Classification System

Based on the geographical characteristics of Henan Province and previous studies, a three-zones spatial classification system was established [6]. The classification scheme is presented in Table 1.

Table 1. Classification of Agricultural-Ecological-Urban Spaces in Henan Province

Three-zones category	Code	Land-use types (CAS classification)
Agricultural space	1	11 Paddy field; 12 Dry land; 52 Rural settlements
Ecological space	2	21 Forest land; 22 Shrubland; 23 Open woodland; 24 Other forest land; 31 High-coverage grassland; 32 Moderate-coverage grassland; 33 Low-coverage grassland; 41 Rivers and canals; 42 Lakes; 43 Reservoirs and ponds; 44 Permanent glaciers and snow; 45 Tidal flats; 46 Bottomland; 61 Sandy land; 62 Gobi; 63 Saline-alkali land; 64 Marshland; 65 Bare land; 66 Bare rock and gravel; 67 Others; 99 Ocean
Urban space	3	51 Urban built-up land; 53 Other construction land

3.2. Land-Use Dynamic Degree

(1) Single land-use dynamic degree (denoted as K) reflects the rate of change in a specific land-use type over a given period [7] It is expressed as:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

Where U_a and U_b represent the area (km²) of a given land-use type at the beginning and end of the study period, respectively, and T denotes the time interval.

(2) Comprehensive land-use dynamic degree (denoted as LC) is used to measure the overall annual rate of land-use change within the study area. It is calculated as:

$$L_c = \frac{\sum_{i=1}^{n} \Delta LU_{i-j}}{2\sum_{i=1}^{n} \Delta LU_i} \times \frac{1}{T} \times 100\% \quad (2)$$

Where ΔLU_{i-j} represents the absolute value of the area converted from land-use type i to non-i types, ΔLU_i denotes the total area of land-use types at the initial stage, and T is the time interval.

3.3. Comprehensive Index of Land-Use Degree

The comprehensive land-use degree index reflects the intensity of human activities and their impact on the natural environment, with values ranging from 100 to 300. Higher values indicate stronger anthropogenic disturbance. It is calculated as:

$$L = 100 \times \sum_{i=1}^{n} (A_i \times C_i) \quad (3)$$

Where L represents the comprehensive land-use degree index of the three-zones in the study area, A_i is the percentage of area occupied by the i-th land-use level, and C_i denotes the grading index corresponding to the i-th level. Based on previous studies, the grading indices are assigned according to the degree of human disturbance associated with different land-use types; higher disturbance corresponds to higher index values. Building upon the original grading system and integrating the three-zones classification framework, a grading assignment table for land-use degree was established (Table 2).

Table 2. Grading Assignment of Land-Use Degree in the Three-Zones Framework

Three-zones	Ecological space	Agricultural space	Urban space
Grading index	1	2	3

3.4. Land-Use Transition Matrix

The land-use transition matrix is employed to characterize the conversion of different land-use types between the initial and final stages within the study area [8]. It quantitatively describes the magnitude of transitions among land-use categories and reveals their conversion rates. The matrix is expressed as:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (4)$$

Where S denotes area; n represents the total number of land-use types; i, j $(i, j = 1, 2, \ldots, n)$ denote land-use types before and after the transition, respectively; and S_{ij} indicates the area converted from type i to type j.

3.5. Landscape Pattern Indices

Landscape indices are highly aggregated quantitative measures that capture landscape structure and spatial configuration [9]. These indices can be categorized into patch-level, class-level, and landscape-level metrics, which are interrelated. To comprehensively reflect landscape heterogeneity, appropriate indices should be selected. Based on the characteristics of the study area, Fragstats 4.2 was used to compute six class-level indices: class area (CA), number of patches (NP), patch density (PD), largest patch index (LPI), landscape shape index (LSI), and patch cohesion index (COHESION). These metrics collectively characterize landscape fragmentation, complexity, and connectivity.

4. Results and Analysis

4.1. Area Changes in the Three-Zones

The spatial distribution of the three-zones land-use types in Henan Province from 2000 to 2020 is shown in Figure 2. Agricultural space dominates the study area and is widely distributed across the province.

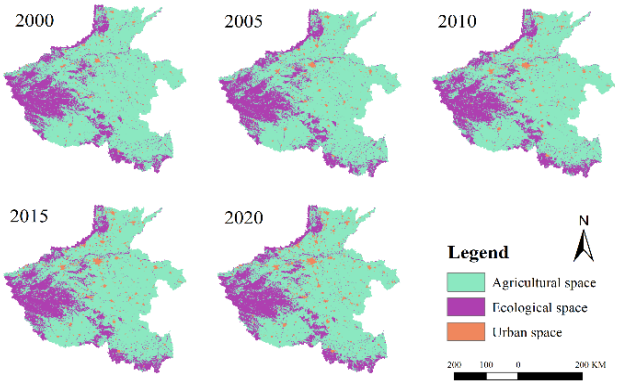


Figure 2. Spatial Distribution Map of the Three-zones

The area structure and change rates of the three-zones are presented in Table 3. From 2000 to 2020, agricultural space accounted for 71.96%-74.17% of the total area of Henan Province and exhibited a gradual declining trend, with a total decrease of 3,660.05 km² over the 20-year period. Ecological space ranked second, mainly distributed in the central-western and southern regions, accounting for 24.18%-24.40% of the total area. Its area showed a fluctuating trend—initially increasing, then decreasing, and eventually stabilizing with a net increase of 44.34 km² (0.03% of the total area). Urban space was scattered across the province and exhibited a continuous growth trend, increasing from 2,678.73 km² to 6,294.44 km², representing the largest absolute change among the three land-use types, with a total increase of 3,615.71 km² over the study period.

Table 3. Spatial Area and Proportion of the Three-zones (km²/%)

Area /km²	2000	2005	2010	2015	2020
Agricultural space	122855	121840	121052	120153	119195
Ecological space	40097	40414	40052	40126	40141
Urban space	2679	3376	4527	5351	6294
Total /km²	165630	165630	165630	165630	165630
Proportion /%	2000	2005	2010	2015	2020
Agricultural space	74%	74%	73%	73%	72%
Ecological space	24%	24%	24%	24%	24%
Urban space	2%	2%	3%	3%	4%

As shown in Table 4, substantial changes occurred in land-use areas in Henan Province from 2000 to 2020. The absolute magnitude of change followed the order: agricultural space > urban space > ecological space.

Table 4. The Change Rate of Spatial Area in the Three-zones

Three-zones	2000-2005	2005-2010	2010-2015
Agricultural space	-0.83%	-0.65%	-0.74%
Ecological space	0.80%	-0.90%	0.18%
Urban space	26.05%	34.07%	18.22%
Three-zones	2015-2020	2000-2020	
Agricultural space	-0.80%	-2.98%	
Ecological space	0.00%	0.08%	
Urban space	17.62%	134.98%	

4.2. Dynamic Analysis of Land Use in the Three-Zones

Analyzing land-use dynamic degrees facilitates an effective understanding of land-use change trends. This study applies both single land-use dynamic degree and comprehensive land-use dynamic degree to quantitatively assess the dynamic characteristics of land-use structure in the study area.

As indicated in Table 5, from 2000 to 2020, agricultural space decreased steadily, though at a relatively modest rate, whereas urban space expanded rapidly with a substantial increase in area. This reflects a strong demand for urban residential land, as well as industrial, mining, and transportation infrastructure. The comprehensive land-use dynamic degree over the 20-year period was 0.11%, indicating that overall transitions among land-use types were relatively limited and that the land-use structure remained broadly stable.

The comprehensive dynamic degree declined slightly from 0.12% during 2000-2005 to 0.11% during 2015-2020, suggesting that land-use change in Henan Province was generally stable with a slow rate of change. In terms of single dynamic degree, urban space exhibited the most pronounced increase during 2005-2010, indicating a rapid expansion phase in that period. Ecological space and agricultural space both experienced relatively higher rates of change during 2000-2005. Over the entire study period, urban space increased continuously at an average annual rate of 6.75%, ecological space showed a slight increase at an average annual rate of 0.004%, and agricultural space declined at an average annual rate of 0.15%. The dynamic degree of urban space remained positive throughout, indicating continuous expansion; agricultural space remained negative, indicating persistent decline; while ecological space fluctuated but ultimately showed a net increase.

Table 5. The Dynamics of Spatial Land Use in the Three-zones

Three-zones		2000-2005	2005-2010	2010-2015
Single dynamics	Agricultural space	-0.17%	-0.13%	-0.15%
	Ecological space	0.16%	-0.18%	0.04%
	Urban space	5.21%	6.81%	3.64%
Comprehensive dynamics		0.12%	0.14%	0.11%
Three-zones		2015-2020	2000-2020	
Single dynamics	Agricultural space	-0.16%	-0.15%	
	Ecological space	0.00%	0.00%	
	Urban space	3.52%	6.75%	
Comprehensive dynamics		0.11%	0.11%	

Table 6 shows that the comprehensive land-use degree index in Henan Province ranged from 170 to 180 between 2000 and 2020, exhibiting an overall increasing trend, which indicates a relatively moderate level of land-use intensity. The

fastest growth in the index occurred during 2005-2010, while the slowest growth was observed during 2010-2015.

Table 6. Comprehensive Index of Land Use in the Three-zones

Three-zones	2000	2005	2010	2015	2020
Agricultural space	148.35	147.12	146.17	145.08	143.94
Ecological space	24.21	24.4	24.18	24.23	24.23
Urban space	4.85	6.16	8.2	9.69	11.4
comprehension	177.41	177.68	178.55	179	179.57

4.3. Land Use Transformation Matrix of the Three-Zones

The land use transfer matrix can intuitively analyze the conversion between land types. The transfer matrix of land use spatial change in Henan Province from 2000 to 2020 is shown in Figure 3 and Figure 4, Table 7.

Figure 3 and Figure 4 shows that from 2000 to 2020, the main land use types changed from agricultural space to urban space, followed by ecological space to agricultural space.

As shown in Table 7, during 2000-2020, the total area of land converted out of/into different land-use types reached 11,380.62 km², accounting for 6.87% of the total area of Henan Province. In terms of total area converted out, the ranking was: agricultural space > ecological space > urban space. Agricultural space had the largest conversion-out area (7,313.56 km²), primarily transformed into urban space (56.60%). Ecological space recorded a conversion-out area of 3,229.34 km², mainly converted into agricultural space (90.25%). Urban space had the smallest conversion-out area (837.72 km²), with most of it converted into agricultural space (88.41%).

For conversion-in areas during 2000-2020, the ranking was: urban space > agricultural space > ecological space. Urban space received 4,453.43 km², predominantly from agricultural space (92.93%). Agricultural space gained 3,655.32 km², mainly from ecological space (79.72%). Ecological space increased by 3,271.88 km², almost entirely from agricultural space (97.03%).

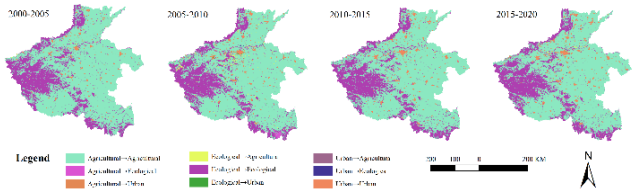


Figure 3. Spatial Distribution of Land-use Transitions in the Three-zones

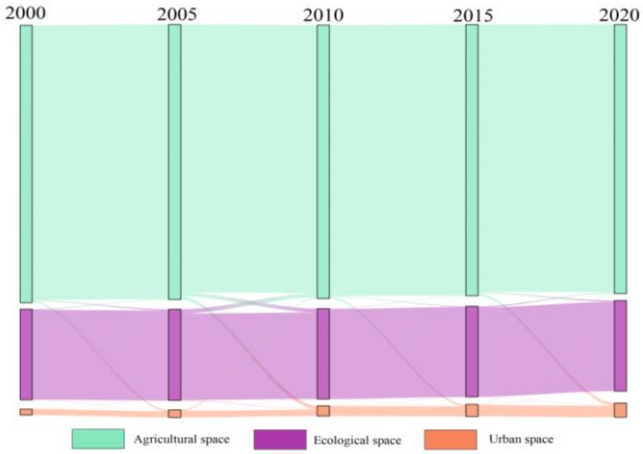


Figure 4. Spatial transfer of Sanjitu in the Three-zones

Table 7. Land-use Transition Matrix in the Three-zones (km²)

Time	Three-zones	Agricultural space	Ecological space	Urban space	Total /km²
2000-2005	Agricultural space	121588	593	676	122857
	Ecological space	245	39820	32	40098
	Urban space	7	4	2668	2679
	Total /km²	121840	40417	3376	165633
2005-2010	Agricultural space	118637	1699	1505	121840
	Ecological space	1929	38302	186	40417
	Urban space	488	53	2835	3376
	Total /km²	121053	40054	4527	165633
2010-2015	Agricultural space	119960	278	815	121053
	Ecological space	176	39847	31	40054
	Urban space	19	3	4505	4527
	Total /km²	120154	40128	5351	165633
2015-2020	Agricultural space	118406	605	1143	120154
	Ecological space	565	39498	65	40128
	Urban space	228	37	5087	5351
	Total /km²	119198	40140	6294	165633

4.4. Evolution of Landscape Pattern Characteristics in the Three-Zones

From 2000 to 2020, all class-level landscape indices of the three-zones in Henan Province exhibited notable changes. As illustrated in Figure 5, the magnitude of change during 2000-2010 was significantly greater than that during 2010-2020, indicating more intensive human development activities in the first decade, with stronger disturbances to agricultural, ecological, and urban spaces.

The indices CA, NP, and PD represent changes in patch area, number, and density, reflecting landscape heterogeneity and fragmentation. Over the study period, NP and PD for ecological space were consistently higher than those for agricultural and urban spaces. This is primarily because ecological space encompasses diverse land-use types such as forests, grasslands, and water bodies, which are often distributed in a mosaic pattern, resulting in numerous and densely distributed patches. In contrast, agricultural space, although extensive in area, is dominated by contiguous cropland with fewer patches, while urban space tends to develop in clustered forms with the lowest number of patches.

The largest patch index (LPI) represents the proportion of the largest patch relative to the total landscape area and helps identify dominant landscape types, indirectly reflecting the direction and intensity of human disturbance. Over the past two decades, agricultural space consistently exhibited higher LPI values than ecological and urban spaces, indicating that contiguous cropland remained the dominant landscape matrix. This suggests that agricultural intensification has been the primary mode of human intervention, while farmland protection policies have effectively maintained spatial continuity.

The landscape shape index (LSI) reflects the complexity of patch boundaries, with higher values indicating more irregular shapes. LSI for agricultural space showed a slight increase, from 42.97 in 2000 to 47.05 in 2020. Urban space exhibited a rapid increase, from 29.38 to 45.15, whereas ecological space showed a slight decline, from 68.31 to 67.49. Overall, ecological space maintained the highest LSI, indicating the most complex boundaries, although with a tendency toward regularization. Urban space experienced rapid boundary complexity growth, reflecting sprawling expansion, while agricultural space showed a gradual increase in fragmentation. These patterns indicate substantial restructuring of landscape edges driven by urbanization.

The cohesion index (COHESION) reflects patch connectivity, with higher values indicating stronger connectivity. During the study period, agricultural and ecological spaces exhibited higher COHESION values than urban space, with average values of 99.92 and 99.09, respectively, compared to 85.15 for urban space. This indicates that agricultural and ecological spaces maintained relatively continuous distributions, whereas urban space remained more fragmented and spatially dispersed.

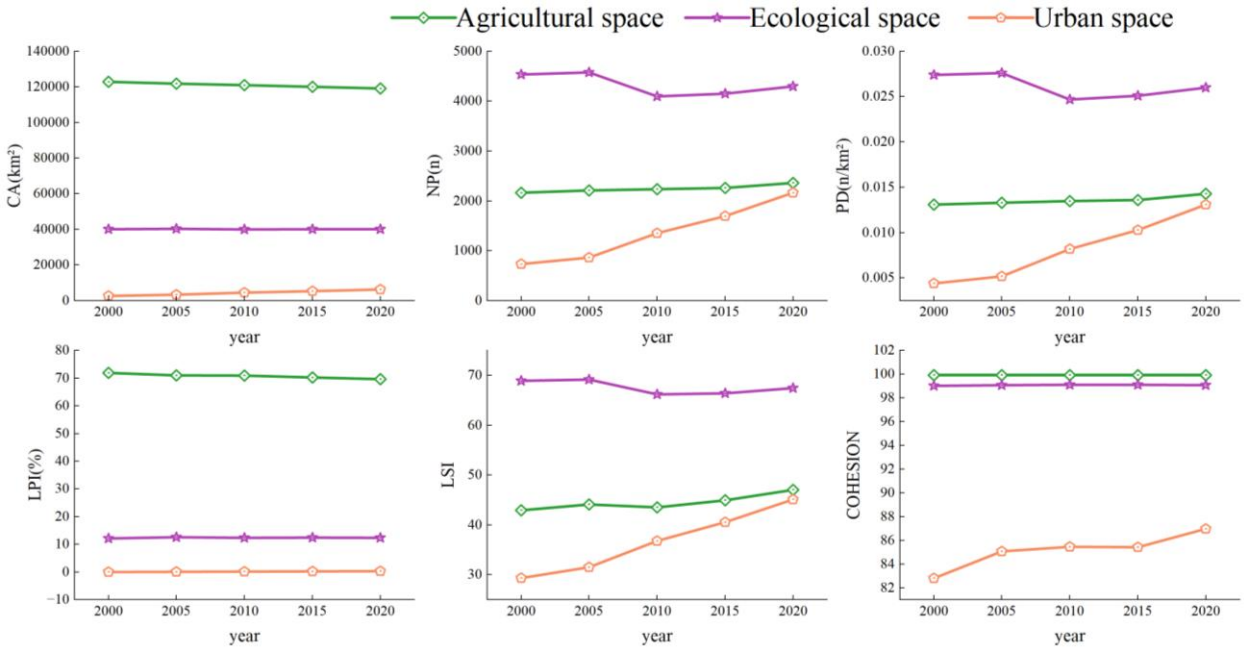


Figure 5. Spatial Landscape Pattern Index in the Three-zones

5. Conclusions and Recommendations

5.1. Conclusions

(1) From 2000 to 2020, agricultural space dominated land use in Henan Province, followed by ecological space, while urban space occupied a relatively small proportion. Conversions among the three-zones were evident: agricultural space was primarily converted into urban space; ecological space was mainly transformed into agricultural space; and urban space was largely converted back into agricultural space.

(2) Significant changes in landscape patterns of the three-zones were observed during 2000-2020. At the class level, agricultural space exhibited a contiguous dominant pattern, characterized by a limited number of patches, high connectivity, and consistently the highest landscape dominance. Farmland protection policies effectively maintained the spatial integrity of cultivated land, preventing a marked increase in fragmentation. Ecological space displayed a pattern of dense patches and complex boundaries, with NP and PD values significantly higher than those of agricultural and urban spaces, reflecting a mosaic distribution. However, the declining LSI indicates a trend toward more regular boundaries. Urban space exhibited a sprawling expansion pattern, with rapidly increasing LSI and relatively low COHESION, indicating irregular growth and

increasingly complex boundaries. This reflects substantial landscape restructuring driven by urbanization.

5.2. Recommendations

(1) Optimize the spatial layout of urban areas. Through scientific planning and rational allocation, promote intensive and efficient urban development, avoiding disorderly expansion and land waste. Strengthen infrastructure development to enhance urban carrying capacity and facilitate urban-rural integration. In particular, differentiated development strategies should be implemented in small and medium-sized cities and towns to improve public services, attract population and industries, and alleviate pressure on large cities.

(2) Promote coordinated development of agricultural and ecological spaces. Encourage the adoption of ecological agriculture by integrating local characteristics and developing green and organic farming practices, thereby reducing the use of chemical fertilizers and pesticides and protecting soil and water resources. Strengthen farmland protection to prevent the loss of arable land. In ecologically fragile areas and water source protection zones, restrict the intensity of agricultural development and implement ecological restoration projects to enhance biodiversity and ecosystem service functions, achieving a sustainable balance between agricultural production and ecological conservation.

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