

Scenario Simulation of Built-up Land Expansion in the Central Region of China Based on the PLUS Model and Its Landscape Pattern Analysis

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Abstract. Against the backdrop of new-type urbanization and the transformation of territorial spatial governance, built-up land expansion and its associated landscape patterns vary significantly under different development policy orientations, making quantitative evaluation through scenario simulation essential. This study takes six provinces in the Central Region of China as the study area and employs land-use data from 2010 and 2020 together with the PLUS (Patch-generating Land Use Simulation) model to simulate built-up land evolution from 2030 to 2050. At both regional and provincial scales, changes in the scale of built-up land under different scenarios are systematically analyzed. Landscape metrics, including Patch Density (PD), Largest Patch Index (LPI), Landscape Shape Index (LSI), and Aggregation Index (AI), are used to quantitatively characterize built-up land expansion and landscape pattern evolution. The results indicate that under the Natural Development Scenario, built-up land expands rapidly with strong path dependence, exerting continuous pressure on cropland and ecological space. In contrast, the Balanced Scenario effectively restrains expansion scale and rate, promoting a transition toward compact and intensive development. Based on scenario responses at the provincial scale, the six provinces can be classified into high expansion response, moderate adjustment, and low expansion stability types. Scenario comparison further demonstrates that balanced and coordinated development significantly improves spatial optimization, curbs disorderly expansion, and reduces landscape complexity, highlighting its importance for guiding high-quality built-up land development.

1 Introduction

Built-up land expansion is the most direct form of land-use change during the urbanization process, and its expansion rate, direction, and spatial morphology directly affect the optimization of regional land-use structure and ecological security patterns^[1-2]. Under rapid urbanization, in the absence of effective policy guidance, built-up land tends to expand continuously along existing development paths, often resulting in inefficient, dispersed, or even disorderly expansion patterns^[3].

As an important population concentration area and major grain-producing region, the Central Region of China has experienced continuous urbanization growth under national strategies promoting regional development and new-type urbanization, leading to increasing demand for built-up land^[4-5]. On the one hand, the development of core cities and urban agglomerations has accelerated built-up land expansion^[6-7]. On the other hand, the full implementation of cropland protection redlines, ecological conservation redlines, and permanent basic farmland policies has imposed increasingly strict spatial constraints on built-up land expansion^[8]. Under this context, exploring future expansion rates, directions, and spatial forms of built-up land under policy regulation, and

comparing them with Natural Development Scenarios, has become a key entry point for evaluating the effectiveness of balanced and coordinated development policies.

Existing studies have made substantial progress in built-up land expansion simulation and landscape pattern analysis; however, most focus on historical changes or future trends under a single scenario, or emphasize expansion scale and driving factors alone^[9-11]. Comparative analyses of expansion pathways and spatial morphology under different policy-oriented scenarios remain limited, constraining the application of scenario simulation results in spatial planning and policy evaluation.

With advances in scenario simulation methods, constructing comparative policy-oriented scenarios has become an important approach for evaluating land-use regulation effectiveness^[12-13]. Natural Development Scenarios typically reflect built-up land evolution trends under limited intervention conditions^[14], whereas Balanced Scenarios introduce policy constraints such as ecological protection, cropland preservation, and total built-up land control to simulate coordinated development pathways^[15]. Comparing built-up land expansion scale and landscape morphology under these scenarios helps

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identify potential expansion risks and quantitatively assess the effectiveness and necessity of balanced development policies from a spatial pattern perspective.

This study takes six provinces in the central region of China as the study area. Based on land-use data from 2010 and 2020, Natural Development and Balanced Scenarios are constructed, and the PLUS (Patch-generating Land Use Simulation) model is applied to simulate built-up land evolution from 2030 to 2050. Four landscape indices were then used to quantitatively evaluate the impacts of balanced development policies on built-up land expansion and spatial morphology optimization, and to provide scientific support for territorial spatial planning and refined built-up land management in the Central Region of China.

2 Data and Methods

2.1 Study Area

The study area includes six provinces—Shanxi, Henan, Anhui, Hubei, Hunan, and Jiangxi—located in the central part of China (Fig. 1). The total area is 1.024×10^6 km², with a permanent population of approximately 3.62×10^8 in 2024, according to the 2024 Statistical Communiqués on National Economic and Social Development of the six provinces research. The overall economic development level is medium to upper-middle nationally. Significant interprovincial differences exist in economic structure, population density, geomorphology, and resource endowment.

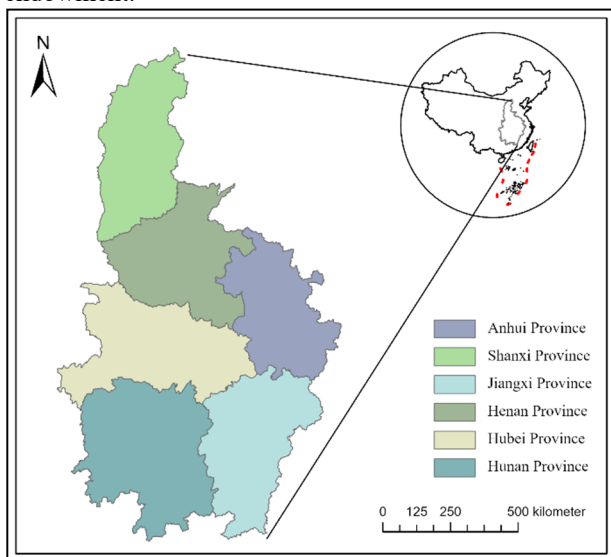


Figure 1. Overview of the study area

2.2 Data Sources and Processing

Land-use raster data for 2000–2020 were obtained from the 30 m resolution China Land Cover Dataset^[16]. According to the Current Land Use Classification standard (GB/T 21010–2017)^[17], land-use types were reclassified into six categories: cropland, forest land, grassland, water area, built-up land, and barren land.

Based on previous studies^[18–19], and considering data representativeness and availability, a total of 12 driving factors were selected, including 4 natural environmental factors, 2 socioeconomic factors, and 6 transportation accessibility factors. Distance-based variables, such as distance to road networks, urban centers, and water bodies, were generated in ArcMap using Euclidean distance analysis based on road and hydrological datasets. Constraint factors in the PLUS model were processed using the Raster Calculator and Reclassification tools to generate a binary constraint map, in which spatially constrained areas were assigned a value of 0 and unconstrained areas a value of 1. The constraint map was then incorporated into the CARS module to restrict land-use conversion during the iterative allocation process, with the aim of protecting ecologically sensitive areas, enforcing policy-related spatial constraints (e.g., ecological conservation zones, water bodies, and permanent cropland), and improving the realism and accuracy of the simulation results. Areas classified as constrained were excluded from land-use change, while only unconstrained areas were allowed to participate in the iterative simulation of land-use transitions.

All datasets were unified to the same coordinate system and resampled to a spatial resolution of 1000 m × 1000 m, ensuring consistency in row and column numbers between land-use data and constraint factor data.

2.3 Research Methods

2.3.1 PLUS Model

Compared with traditional geographic cellular automata models, the PLUS model is more effective in identifying the driving mechanisms of land-use change and enables fine-scale simulation at the land-use patch level. In addition, the simulation results can better reflect land-use planning policies^[20].

The parameter of future pixel quantity, which represents the predicted total number of pixels for each land-use type in future periods^[21], is obtained using the Markov chain-based land-use demand forecasting module embedded in the PLUS model. The cost matrix is used to define whether conversions between different land-use types are permitted. Neighborhood weight parameters determine the expansion intensity of each land-use type under the influence of driving factor. To ensure objectivity in parameter setting, neighborhood weights for each land-use type were determined based on the proportion of its expansion area relative to the total expansion area, calculated from the land expansion maps. To evaluate the simulation accuracy of the PLUS model, a backcasting validation approach was adopted. Land-use data from 2000 and 2010 were used to simulate the land-use pattern in 2020, which was then compared with the observed data. Then, the Overall Accuracy (OA) and Kappa coefficient were calculated. The OA is defined as the proportion of correctly classified pixels to the total number of pixels. The Kappa coefficient is used to measure the agreement between simulated and observed results beyond random chance. These accuracy metrics

were derived using the built-in accuracy assessment module of the PLUS model based on the confusion matrix. The high OA and Kappa coefficient indicate that the model can effectively capture the spatial characteristics and transition mechanisms of land-use change, thereby enhancing the credibility of future simulation results.

This study constructs two future land-use development scenarios based on regional development strategies, ecological security requirements, and relevant previous studies^[22-23].

(1) Natural Development Scenario:

As the baseline scenario, this scenario predicts future land-use change solely based on land-use transition rules derived from the 2010 and 2020 land-use data, combined with the land-use demand forecasting module.

(2) Balanced Scenario:

In this scenario, grassland is only allowed to remain unchanged or convert to water area or forest land with higher ecological value; cropland is prohibited from degrading into unused land. Conversion probabilities from cropland and forest land to built-up land are reduced by 80% and 30%, respectively; the probability of forest land converting to cropland is reduced by 30%, and the probability of water area converting to built-up land is reduced by 90%. Water area constraint zones include water bodies larger than 10 km² and the distribution areas of third-order rivers; nature reserve constraint zones are defined using vector polygon data of national- and provincial-level nature reserves in China in 2020.

2.3.2 Landscape Pattern Evaluation

Built-up land expansion often exhibits diverse spatial forms^[24]. To accurately characterize spatial morphology differences under different development scenarios, four indicators are selected: Patch Density (PD), Aggregation Index (AI), Landscape Shape Index (LSI), and Largest Patch Index (LPI).

Specifically, PD reflects changes in the number of built-up land patches per unit area. A significant increase in PD indicates dispersed and discontinuous expansion, often associated with disorderly sprawl and inefficient land use, causing substantial disturbance to cropland and ecological space. LPI represents the proportion of the largest built-up land patch within the overall built-up land landscape, revealing the dominance of core built-up areas in regional spatial structure and indicating whether expansion is characterized by excessive concentration in a single core city or by a polycentric, networked urban pattern. LSI measures the complexity of built-up land patch shapes and effectively captures outward expansion along transportation corridors or urban fringes; higher LSI values generally indicate fragmented and irregular patch boundaries, typical of extensive and disorderly expansion. AI quantifies the degree of spatial aggregation among built-up land patches, with higher values indicating stronger spatial connectivity and a tendency toward infill-oriented and compact development.

3 Results and Analysis

3.1 Accuracy Assessment of the PLUS Model

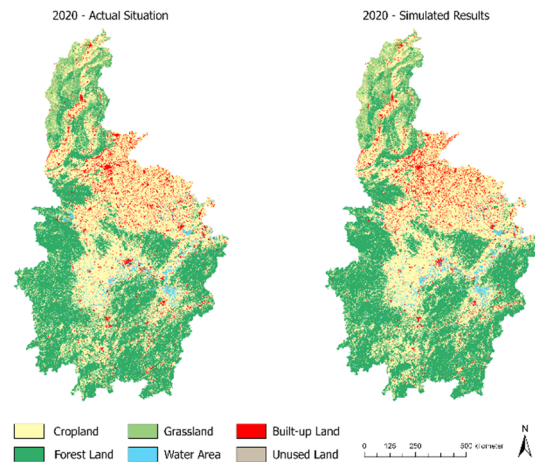


Figure 2. Comparison between actual and simulated land use in 2020

Using land-use data from 2000 and 2010 in the Central Region of China, the land-use spatial pattern for 2020 was simulated and compared with the observed 2020 data for accuracy validation. The comparison chart (Fig. 2) shows the model reliably captures the future spatial distribution and evolution of different land-use types in the study area, confirming the rationality of parameter settings and demonstrating the model's strong capability to reproduce historical land-use patterns, thereby providing reliable support for future scenario simulations (2030–2050).

3.2 Simulation Results and Analysis of Built-up Land Expansion

According to the land-use simulation results for 2030–2050 under different scenarios in the Central Region of China (Fig. 3 and Table 1), built-up land shows a continuous expansion trend under both the Natural Development Scenario and the Balanced Scenario. However, significant differences exist in expansion intensity, growth rate, and temporal characteristics.

Under the Natural Development Scenario, built-up land area increases rapidly with a cumulative increase of 38,401 km² over 30 years, representing a growth rate of 61.4%. In both the 2030–2040 and 2040–2050 periods, expansion increments are markedly higher than those under the Balanced Scenario, with an accelerating trend in the later stage. This indicates the expansion is mainly characterized by outward sprawl from existing built-up areas, with large-scale land consumption exerting sustained pressure on surrounding non-built-up land, particularly agricultural and ecological spaces.

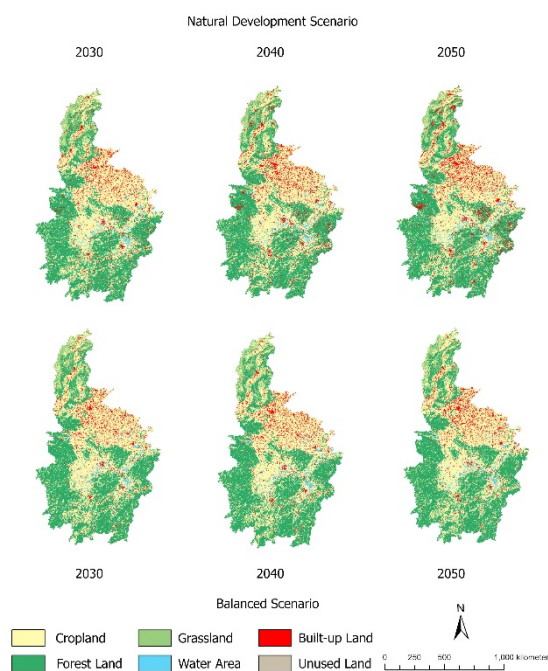


Figure 3. Land-use simulation results of different scenarios in the Central Region of China during 2030–2050

Under the Balanced Scenario, built-up land expansion is significantly restrained. By 2050, the total built-up land area is controlled at 69,829 km², with a cumulative increase of only 7,235 km² from 2020, corresponding to a growth rate of 11.6%, far lower than that under the Natural Development Scenario. Temporally, expansion exhibits moderate growth in the early stage and gradually stabilizes in the later stage, indicating a transition from quantity-driven expansion to compact, intensive, and efficiency-oriented development under integrated constraints of population, economic demand, and ecological protection.

At the provincial scale, the six provinces show pronounced spatial heterogeneity in expansion scale, growth rate, and scenario responsiveness. Under the Natural Development Scenario, Henan consistently has the highest absolute increase and growth rate. This reflects the combined effects of a large population base, a dense urban system, and strong agglomeration of core cities. Anhui, Hubei, and Shanxi form the second tier, all showing continuous growth from 2030 to 2050. Jiangxi and Hunan have relatively smaller built-up land scales but still maintain rapid growth under the Natural Development Scenario, indicating continued urbanization-driven land demand.

Under the Balanced Scenario, expansion intensity decreases across all provinces, though response levels differ. Henan’s built-up land continues to grow but is constrained to 28,414 km² by 2050, substantially lower than under the Natural Development Scenario, indicating strong policy effects in compressing expansion potential in populous provinces. Anhui and Hubei show great deceleration in growth, reflecting a shift from outward expansion to redevelopment and structural optimization. In contrast, Jiangxi and Hunan remain largely stable under the Balanced Scenario, with growth rates below 5% from 2030 to 2050.

Based on the combined scenario outcomes, built-up land expansion patterns in the six provinces can be classified into three types: high expansion–responsive, characterized by strong expansion under natural conditions but high sensitivity to coordinated policies; moderate expansion–adjustment, with stable demand yet clear regulatory responses; and low expansion–stable, exhibiting generally mild expansion and limited scenario sensitivity. This typology provides a basis for differentiated built-up land regulation and regional coordinated development.

Table 1. Built-up land expansion area under different scenarios in the Central Region of China during 2030–2050

Region	Built-up Land Area(km ²)						
	2020	Natural Development Scenario			Balanced Scenario		
		2030	2040	2050	2030	2040	2050
Anhui	132	1547	1797	2070	139	145	150
Jiangxi	76	8	9	3	43	48	91
Hunan	634	8178	9870	1168	641	644	646
Hubei	5	6763	7759	8578	502	506	512
Henan	495	8	5	8	2	3	7
Shanxi	642	8752	1094	1278	655	667	677
Central China	9	2669	3001	3348	254	269	284
	43	7	9	9	04	33	14
	804	9876	1197	1375	774	782	795
	3	2	2	8	5	5	
	625	7574	8854	1009	650	674	698
	94	4	4	95	82	92	29

3.3 Prediction of Changes in Built-up Land Landscape Patterns

Based on the simulated built-up land results for 2030–2050 under different scenarios in the Central Region of China, the spatial morphological characteristics of built-up land expansion were further examined.

According to the landscape index results (Table 2), under the Natural Development Scenario, PD declines during 2030–2050, reflecting fewer patches and larger average patch size. This does not imply reduced expansion pressure; rather, newly added built-up land increasingly connects with existing areas through merging and edge expansion, forming larger continuous urban areas. The expansion pattern shifts from scattered development to edge expansion and patch integration, showing clear large-scale consolidation. Under the Balanced Scenario, PD remains stable at around 0.01, suggesting limited new development under strict spatial control. Newly added land mainly occurs through infill or adjacent expansion, without generating scattered patches.

Under the Natural Development Scenario, LPI rises sharply to 17.92% in 2030, indicating highly concentrated expansion in core cities. It then declines and fluctuates by 2050. This suggests uncoordinated, multi-center expansion and higher spatial complexity. In contrast, under the Balanced Scenario, LPI remains low with minor variation, indicating controlled core expansion. Built-up land is more evenly distributed through optimization of the urban system, reducing risks of over-concentration.

Table 2. Landscape pattern indices of built-up land under different scenarios in the Central Region of China during 2030–2050

Area	Index	Natural Development Scenario			Balanced Scenario		
		2030	2040	2050	2030	2040	2050
Central	PD	0.02	0.01	0.01	0.01	0.01	0.01
	LPI	17.92	7.93	9.00	5.28	5.61	5.80
	LSI	179.20	180.71	180.6	175.66	175.35	175.36
	AI	35.07	39.43	43.31	31.28	32.57	33.71
Anhui	PD	0.03	0.03	0.03	0.04	0.04	0.03
	LPI	40.84	45.23	48.91	39.92	43.17	45.44
	LSI	86.33	87.34	87.54	84.98	85.14	85.10
	AI	30.79	35.19	39.39	28.30	29.72	30.91
Jiangxi	PD	0.01	0.01	0.01	0.02	0.02	0.02
	LPI	24.98	27.72	30.16	21.82	22.83	23.55
	LSI	59.71	61.33	62.53	58.72	58.48	57.86
	AI	34.33	38.54	42.61	26.91	27.61	28.14
Hunan	PD	0.01	0.01	0.01	0.01	0.01	0.01
	LPI	22.19	46.60	51.46	13.50	13.79	14.02
	LSI	52.22	53.52	54.65	50.89	50.51	50.19
	AI	36.72	39.62	41.11	28.42	29.04	29.86
Hubei	PD	0.01	0.01	0.01	0.01	0.01	0.01
	LPI	43.93	50.71	91.57	38.82	39.41	40.17
	LSI	58.97	59.92	59.44	56.07	56.11	55.95
	AI	37.07	42.99	47.81	30.79	31.58	32.40
Henan	PD	0.04	0.03	0.03	0.04	0.04	0.04
	LPI	55.64	68.24	77.50	45.48	48.28	49.91
	LSI	105.09	105.42	104.71	106.04	106.40	107.00
	AI	35.84	39.30	42.87	33.63	35.23	36.60
Shanxi	PD	0.02	0.01	0.01	0.01	0.01	0.01
	LPI	38.48	54.05	60.30	36.12	36.63	37.20
	LSI	61.15	61.08	60.45	56.38	55.75	55.30
	AI	38.56	44.37	48.69	36.06	37.11	37.98

LSI increases from 176.19 to 180.71 and then stabilizes, indicating more irregular boundaries under the Natural Development Scenario. This is associated with outward expansion along transport corridors and urban fringes. Under the Balanced Scenario, LSI slightly declines and stabilizes, reflecting compact and continuous development guided by constraints on ecological and agricultural land.

AI rises from 29.73% to 43.31% under the Natural Development Scenario, showing strong clustering and formation of large continuous urban areas, but with risks of excessive concentration. Under the Balanced Scenario, AI increases more slowly to 33.71%, reflecting infill-oriented growth rather than large-scale outward expansion. This supports a more balanced and sustainable spatial structure.

At the provincial scale, responses vary. Under the Natural Development Scenario, Henan, Hubei, and Hunan show significant increases in LPI and AI. Henan’s LPI reaches 77.50% by 2050, indicating extreme concentration in major urban areas, accompanied by higher LSI and potential sprawl risks. Under the Balanced Scenario, PD remains stable, LSI decreases or changes little, and AI increases gradually, indicating a shift toward compact infill development. Jiangxi and Hunan show the highest stability, while Anhui and Hubei exhibit more orderly expansion under policy constraints.

Overall, the Natural Development Scenario leads to rapid expansion with increasing complexity, whereas the Balanced Scenario effectively controls scale and improves spatial form. Interprovincial differences highlight the need for differentiated regulation strategies.

4 Discussion

Built-up land expansion does not necessarily degrade landscape patterns; outcomes depend on expansion modes and policy guidance. Compared with the Natural Development Scenario, the Balanced Scenario not only controls expansion scale but also reduces fragmentation and improves spatial form. This provides important guidance for achieving high-quality urbanization while preventing disorderly sprawl. Coordinated policy frameworks are essential to balance development demand and environmental capacity.

Significant differences exist among provinces due to variations in development stage, population, urban structure, and resource capacity. Differentiated strategies are needed: high-pressure regions should restrict new expansion and utilize existing land, while stable regions should focus on efficiency and spatial optimization.

Uncertainty remains due to model sensitivity to driving factors, scale, and resampling. Landscape indices are also scale-dependent. Future studies should incorporate multi-scale analysis and sensitivity testing to improve robustness.

5 Conclusion

(1) Under the Natural Development Scenario, built-up land in the Central Region of China continues to expand rapidly, exerting continuous pressure on cropland and ecological space. In contrast, the Balanced Scenario significantly restrains the scale and rate of expansion, promoting a transition from extensive outward growth to compact and intensive development. At the provincial scale, built-up land expansion shows clear spatial heterogeneity in terms of scale, growth rate, and scenario response. Based on scenario response characteristics, the six provinces can be classified into three types: high expansion-responsive, moderate adjustment, and low expansion-stable, providing a basis for differentiated built-up land regulation.

(2) Changes in built-up land expansion profoundly influence the evolution of landscape patterns. Under the Natural Development Scenario, the aggregation of built-up land faces risk of disorderly sprawl. Under the

Balanced Scenario, built-up land expansion mainly occurs through infill development and compact growth, helping maintain the overall stability of the built-up land landscape structure.

(3) Scenario comparison shows that the Balanced Scenario achieves significant effects in controlling expansion scale and optimizing spatial patterns. It not only curbs disorderly expansion but also reduces landscape complexity and alleviates excessive concentration in core areas, highlighting its necessity in guiding high-quality built-up land expansion.

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