

Article

From Expansion to Shrinkage: An Assessment of the Carbon Effect from Spatial Reconfiguration of Rural Human Settlements in the Wuhan Metropolitan Area

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Abstract: Nowadays, the reorganization of rural land-use space exhibits a dynamic process of expansion and shrinkage. Taking the Wuhan Metropolitan Area as an example, this study used the InVEST model to quantitatively assess changes in rural built-up land between 1995 and 2020 and its impact on regional carbon storage. Combined with the PLUS model, further simulations were carried out to predict the heterogeneous mechanisms of shrinkage and expansion of rural habitable space under three scenarios in 2030. The results indicate that the area of rural built-up land in the Wuhan Metropolitan Area showed an overall increasing trend, with shrinkage mainly concentrated in the Wuhan-Ezhou border, Tianmen, and southern Xiantao, while expansion displayed a decentralized point distribution. The PLUS model predicts that, in the scenario of rural built-up land expansion, a significant amount of cropland is encroached upon. This study provides a new perspective for understanding the impact of rural habitat changes on the carbon cycle. Future land management and planning should pay more attention to maintaining ecosystem services and considering the environmental effects of changes in rural built-up land layout.

Keywords: rural built-up land; carbon storage; InVEST model; PLUS model; Wuhan Metropolitan Area



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1. Introduction

Environmental issues such as global warming have garnered considerable global attention [1]. Carbon emissions are a major contributor to global climate change [2,3], and the importance of land use management and emission-reduction measures is widely acknowledged [4,5]. Despite rapid urban expansion, approximately half of the world's population still resides in rural areas [6], highlighting the ongoing importance of rural regions amidst globalization and modernization [7,8]. Therefore, it is imperative to revisit and reorganize sustainable development strategies for rural areas [9]. Rural ecological spaces play a critical role in regulating biogeochemical cycles and supporting ecosystem services [10]. Studies show that anthropogenic greenhouse gas emissions from agriculture and food production in rural areas account for 19–29% of total global emissions [11]. Moreover, rural land-use patterns and spatial configurations are significantly changing due to population migration, policy adjustments, and technological advances [12,13]. Residential areas around transportation routes are increasing and fragmenting [14]. Additionally, policy-driven comprehensive reforms of towns and villages, including village consolidation and ecological migration, have expanded human spaces in village centers while small rural settlements gradually disappear [15]. Overall, the reorganization of rural land-use space reflects a dual process of expansion and shrinkage.

China has implemented a policy of “Linkage between Urban-land Taking and Rural-land Giving” to demolish inefficient and disorderly rural settlements. However, the construction of new houses, driven by farmers’ desire for better living conditions, remains common. The phenomenon of simultaneous demolition and construction of built-up land frequently occurs in rural areas of China. New construction often takes place at the expense of cropland and forest land, while demolition leads to the conversion of existing rural construction land to other uses. These activities have resulted in several issues, including rural hollowing [16], the inactivity of rural residential bases [17], and the alteration of rural habitats [18], all of which have complex implications for carbon storage. For instance, Zhang et al. [19] reveal that aboveground carbon storage increases most significantly in the intermediate zone, which is located between two and four kilometers from rural settlements. This study suggests that as the distance from human settlements increases, the pressure to use natural resources decreases. Currently, various models, such as the InVEST model [20,21], CASA model [22], IPCC inventory method [23], and CEVSA model [24], are commonly used in carbon storage assessment studies. Among them, the InVEST model employs distributed algorithms and utilizes 3S technology, facilitating the input and analysis of spatial data. It is capable of elucidating the dynamics and trajectories of carbon storage across various plots, leading to its extensive application in diverse countries and regions, as demonstrated by Piyathilake et al. [25] and Wang et al. [26].

Land use change is a complex, dynamic system influenced by a wide range of factors. Under different environments and conditions, the intensity and mechanism of these factors vary, leading to significant differences in land use evolution patterns. Spatial simulation has become a key tool for studying land use change [27]. The PLUS model (Patch-generating Land Use Simulation model) developed by Liang et al. [28] is a representative model. It is based on a multi-type patch generation strategy, allowing for conductive simulation of land use evolution in both temporal and geographical dimensions, providing more accurate simulation results [29].

In summary, there is a notable gap in existing research. First, specific analyses of the flow of rural built-up land are lacking. The temporal transfer of land use in rural built-up areas and the source categories of new built-up land remain unclear. Second, there is insufficient research on carbon stock changes due to single land use categories, particularly those resulting from changes in rural construction land. Finally, most studies on the impact of land use activities on carbon stock adopt a comprehensive perspective, with limited exploration of the shrinkage and expansion differentiation of rural built-up land. Relevant empirical literature needs further development.

The overall goal of this study is to provide strategic recommendations for the future development of human settlement spaces in the Wuhan Metropolitan Area. The specific objectives of this paper are to:

1. Quantitatively analyze the spatial pattern of rural construction land transfers to comprehensively reflect the evolutionary stages.
2. Assess the impacts of spatial and temporal changes in rural built-up land on regional carbon stocks over time.
3. Forecast the spatial distribution of carbon stock in the Wuhan Metropolitan Area by 2030 under different scenarios of rural built-up land expansion and shrinkage.

2. Materials and Methods

2.1. Study Area

The Wuhan Metropolitan Area, centered on Wuhan (8569.15 km²), the largest city in central China, encompasses a cluster of nine surrounding cities (Figure 1). This region has the potential to transfer industrial resources from the eastern area to the west while exploring market space and development opportunities. Given the Chinese government’s current environmental protection strategy to achieve the “dual-carbon” goal, the geographic advantages of the Wuhan Metropolitan Area position it as a critical hub. Its practices

in carbon emission management and reduction are essential not only for the region’s sustainability but also as a model for other cities to emulate.

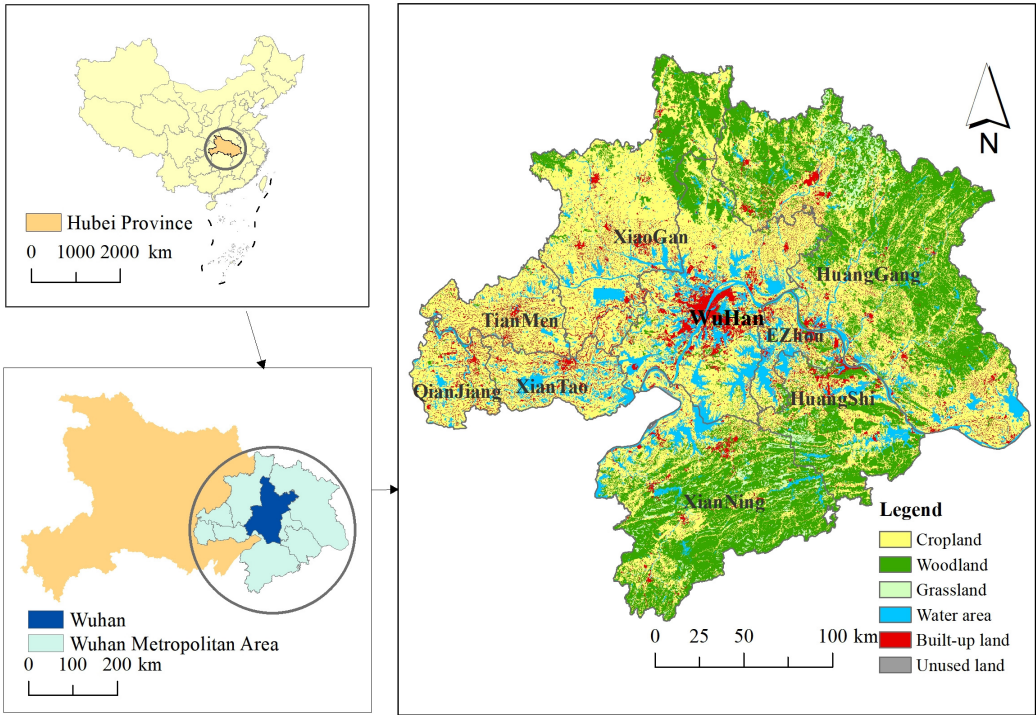


Figure 1. Location of The Wuhan Metropolitan Area.

2.2. Data Acquisition and Processing

2.2.1. Urban Built-up Land and Rural Built-up Land Classification System

The rural settlement data utilized in this study were sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn>, accessed on 12 March 2023). The dataset includes six primary land types and twenty-five secondary land types, encompassing arable land, forest land, grassland, watershed, built-up land, and unutilized land. Based on Landsat series data, the integrated valuation accuracy of the secondary land use types exceeds 90% [30]. In this study, we follow the categorization and merging approach by Wang et al. [31] for the three secondary land classes within the primary class of construction land. Specifically, “urban land” and “other built-up land” are merged into urban built-up land, while “rural settlements” are classified as rural built-up land. Detailed descriptions of each land use type are provided in Table 1 [32].

Table 1. Urban built-up land and rural settlement land classification system.

Classification of Built-up Land	Subclasses	Description
Urban built-up land	Urban land	Land in large, medium, and small cities and built-up areas above the county town level.
	Other built-up land	Factories, mines, large industrial areas, oilfields, saltworks, quarries, as well as transportation roads and airports.
Rural built-up land	Rural settlements	The built-up areas in rural settlements.

2.2.2. Data Sources

Fourteen items are chosen as driving factors from five categories: climatic conditions, soil conditions, socioeconomic conditions, topographic conditions, and accessibility (Table 2).

Table 2. Data sources.

	Data Type	Year	Spatial Resolution	Data Sources
Basic data	Land use data	1995, 2000, 2005, 2010, 2015, 2020	30 m	
Climatic data	Temperature Precipitation	2020 2020	1000 m 1000 m	Resource and Environmental Data Center, Chinese Academy of Sciences (http://www.resdc.cn , accessed on 12 March 2023)
Soil data	Soil type	2020	1000 m	
	GDP	2019	1000 m	
Socio-economic data	Nighttime Lighting Data	2020	1000 m	
	Population	2020	1000 m	WorldPop Website (https://www.hub.worldpop.org/ , accessed on 21 March 2023)
Topographic data	DEM	2020	250 m	Geospatial Data Cloud (https://www.gscloud.cn/ , accessed on 21 March 2023)
	Slope	2020	250 m	Calculated from DEM
	Slope orientation	2020	250 m	Calculated from DEM
Accessibility data	Distance to railway	2020	30 m	OpenStreetMap (https://www.openstreetmap.org/ , accessed on 5 March 2023) Calculating Euclidean Distances in ArcGIS 10.8
	Distance to highway	2020	30 m	
	Distance to the main road	2020	30 m	
	Distance to secondary road	2020	30 m	
	Distance to branch road	2020	30 m	

2.3. Research Methods

2.3.1. The Research Framework

The main research steps are as follows: First, land use data from six periods (1995, 2000, 2005, 2010, 2015, and 2020) were utilized to extract the expansion and shrinkage of rural built-up land. The rural built-up land shrinkage rate (RSR) was introduced to quantify the shrinkage of rural built-up land (Equation (1)). The rural built-up expansion rate (RER) was introduced to quantify the expansion of rural built-up land (Equation (2)).

$$RSR = \frac{Area_{RSR}}{Area_{initial}} \times 100\% \quad (1)$$

$$RER = \frac{Area_{RER}}{Area_{initial}} \times 100\% \quad (2)$$

where $Area_{RSR}$ is the area of rural built-up land reduced during the study period, $Area_{REL}$ is the area of rural built-up land increased during the study period, and $Area_{initial}$ is the total area of rural built-up land at the beginning of the study.

Second, the InVEST model was applied to assess the impact on carbon storage in the Wuhan Metropolitan Area. In the carbon storage module of the InVEST model, the carbon storage of an ecosystem consists of four components: above-ground carbon storage, below-ground carbon storage, soil organic matter carbon storage, and dead organic matter carbon storage [33].

Finally, fourteen driving factors were selected. Three development scenarios—natural development (Q1), rural built-up land shrinkage (Q2), and rural built-up land expansion (Q3)—were established to simulate and predict the spatial pattern of rural built-up land and the spatial distribution of carbon storage in 2030.

The research framework is shown in Figure 2.

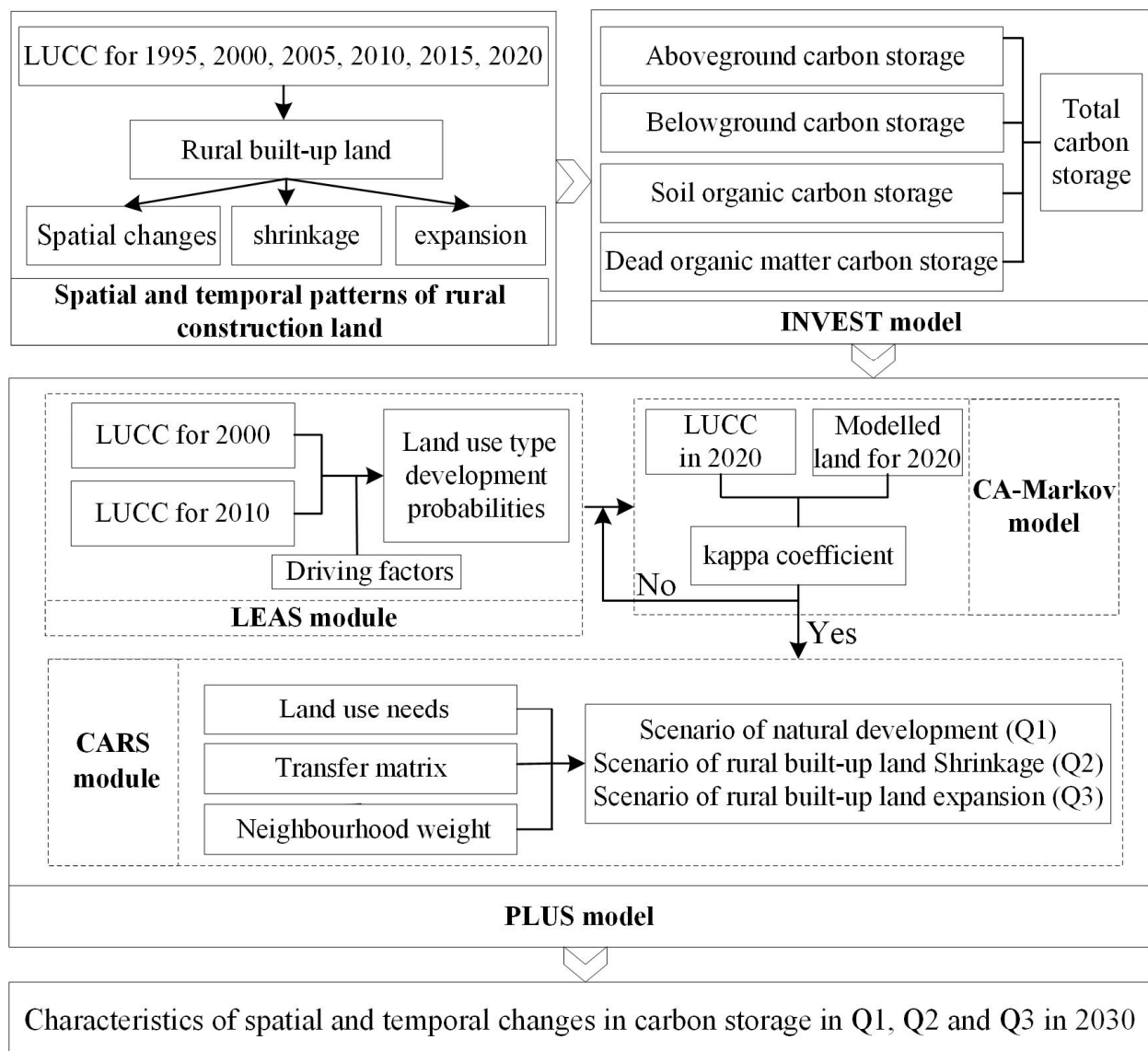


Figure 2. Research Framework.

2.3.2. InVEST Model

The InVEST model is a robust tool for quantifying, mapping, and valuing ecosystem services. The aboveground biogenic carbon pool represents the carbon content in all living plant material above the soil, including stems, branches, and leaves of vegetation such as trees, shrubs, and grasses. The below-ground biogenic carbon pool encompasses the carbon in the living root systems of plants. Dead organic carbon pools refer to the carbon content in biomass that has died, including dead trees and other organic material. The soil organic carbon pool, a crucial component of the carbon store, includes organic carbon in both organic and mineral soils [34]. The specific formula is as follows:

$$C_{total} = \sum_{i=1}^n A_i \times (C_{i-above} + C_{i-below} + C_{i-dead} + C_{i-soil}) \quad (3)$$

where C_{total} represents the overall carbon storage; i is the land use type; n is the number of land use types; A_i is the area of land use type i ; $C_{i-above}$, $C_{i-below}$, C_{i-dead} , C_{i-soil} represent the average above-ground, below-ground, dead organic matter, and soil organic matter carbon densities of land use type i , respectively [35].

The carbon density data in this study are based on Zhang et al. [36] (Table 3).

Table 3. Carbon density of different land use types in the study area (t/ha).

Land Use Type	$C_{i-above}$	$C_{i-below}$	C_{i-dead}	C_{i-soil}	Existing Code	Original Code
Cropland	4.02	0.75	2.11	98.13	1	1
Woodland	22.62	18.03	2.78	126.75	2	2
Grassland	3.60	11.7	7.28	90.43	3	3
Water	1.59	0	3.98	64.03	4	4
Urban built-up land	0.83	0.08	0	43.71	5	51, 53
Rural built-up land	0.83	0.08	0	43.71	6	52
Unused land	0.59	0.64	0.96	28.42	7	6

2.3.3. Markov Chain

The Markov Chain is an effective method for modeling land use change. It predicts future land use status by using transition probability matrices. The specific formula is as follows:

$$S_{(t+1)} = P_{ij} \times S_t \quad (4)$$

where S_t and $S_{(t+1)}$ are the land use status of the study area at moment t and moment $t+1$, respectively. P_{ij} is the land use transfer probability matrix ($i, j = 1, 2, \dots, n$).

2.3.4. PLUS Model

The PLUS model consists of three parts: accuracy test, multi-scenario simulation, and weight setting.

(1) Accuracy verification

Land use data for the Wuhan Metropolitan Area between 2000 and 2010 were selected for analysis. The LEAS module was utilized to determine the likelihood of each type of land use shift. The simulation features of the CARS module were then combined with these data to generate land use simulation data for 2020. The specific formula for the kappa coefficient is as follows:

$$\text{Kappa} = \frac{p_o - p_c}{p_p - p_c} \quad (5)$$

where the simulation accuracy index is denoted by Kappa, the actual simulation accuracy by p_o , the required simulation accuracy under random conditions by p_c , and the ideal simulation accuracy by p_p . Generally, a simulation's accuracy is considered high when the Kappa value exceeds 0.75. The simulated data were compared to the actual land-use scenario in 2020. The resulting Kappa coefficient of 0.87 confirms the model's accuracy and reliability.

(2) Multi-scenario settings

Three scenarios for land use in the Wuhan Metropolitan Area in 2030 were forecasted and examined. The principles of land use type conversion under different scenarios are as follows:

Natural Development Scenario (Q1): This scenario, based primarily on historical trends and current land use patterns, assumes that future development will continue to follow existing trends without additional policy interventions or changes. It provides a "no-change" expected outcome, helping to assess the need for and effectiveness of policy adjustments.

Shrinkage of Rural Built-up Land Scenario (Q2): The main purpose of shrinking rural built-up land is to achieve rational allocation and efficient utilization of land resources. To prevent disorderly rural expansion, the layout and utilization efficiency of existing construction land should be optimized. Additionally, to avoid exceeding the red line of converting arable land to construction land, the flow of arable land is strictly limited. Therefore, this scenario increases the probability of transferring rural built-up land to cropland, forest land, water surface, and urban built-up land by 40%, while decreasing the

probability of transferring cropland, forest land, water surface, and urban built-up land to rural built-up land by 40%.

Expansion of Rural Built-up Land Scenario (Q3): The primary purpose of expanding rural built-up land is to support the development of industry and residential space in rural areas based on historical development trends. The Opinions of the CPC Central Committee and the State Council on Comprehensively Promoting Rural Revitalization and Accelerating Agricultural and Rural Modernization clearly propose exploring the implementation of a system for market entry of land for rural collectively operated construction. Therefore, this scenario reduces the probability of rural construction land flow to cropland, forest land, grassland, waters, and urban construction land by 40%, while increasing the probability of cropland, forest land, grassland, waters, and urban construction land flow by 40%.

(3) Weight setting.

All land kinds can be converted into one another in this study, and all of the matrices are 1. In light of He et al. [37], neighborhood weights are established, and values are assigned using the 2010–2020 normalized index. The specific formula is as follows:

$$W_i = \frac{\Delta TA_i - \Delta TA_{min}}{\Delta TA_{max} - \Delta TA_{min}} \quad (6)$$

where W_i is the neighborhood weight of class land use type i . ΔTA_i is the amount of change in land type i . ΔTA_{max} and ΔTA_{min} are the maximum and minimum values of change in land type i , respectively. However, for some types of land, this weight setting approach will result in zero weight; hence, this study manually alters the zero value to 0.1 to better reflect the actual circumstance.

3. Results and Analysis

3.1. Analysis of Spatial and Temporal Patterns of Rural Built-up Land

3.1.1. Analysis of the Overall Pattern of Rural Built-up Land

The rural built-up land area in the Wuhan Metropolitan Area increased from 215,067 ha in 1995 to 223,218 ha in 2020, indicating a general growth trend. However, the quantity of rural built-up land decreased in 2010, contrasting with prior and subsequent years (Figure 3). During this period, rural built-up land was primarily transferred to arable land and urban built-up land, with transfer areas of 8702 ha and 4026 ha, respectively. Additionally, most of the new rural built-up land originated from arable land, amounting to 12,029 ha, demonstrating a dynamic two-way exchange between arable land and rural built-up land. Conversely, the conversion of rural built-up land to urban built-up land is a one-way process. Overall, the area of land compensation is insufficient to balance the outflow of rural construction land.

With the advancement of the “Three Modernizations” (Industrialization, Urbanization, and Informatization) in the Wuhan Metropolitan Area, the total scale of rural built-up land has expanded to meet the demand for public service facilities, residential housing, and industrial zones. However, according to the Wuhan Overall Land Use Plan (2006–2020), the utilization efficiency of rural construction land in 2005 was comparatively low, and the per capita area of rural residential land exceeded the national standard [38]. Consequently, from 2005 to 2010, the government implemented stricter control over rural construction land. Through the remediation of inefficient and abandoned construction land and optimization of the land use structure, the 2010 target of “reducing the quantity but not the quality” of rural construction land was achieved. The primary cause of changes in rural construction land is its conversion to agriculture. As illustrated in Figure 4, changes in rural built-up land are especially concentrated in the cities of Xiantao, Qianjiang, and Tianmen, with significant concentration at the border between Wuhan and neighboring cities. In the main city of Wuhan, there is a noticeable hollow area, indicating a concentration of urban built-up land with no potential for expansion or shrinkage of rural built-up land. Additionally, the shrinkage of rural built-up land is more aggregated, while its expansion is significantly smaller and shows a dispersed point distribution within the study area.

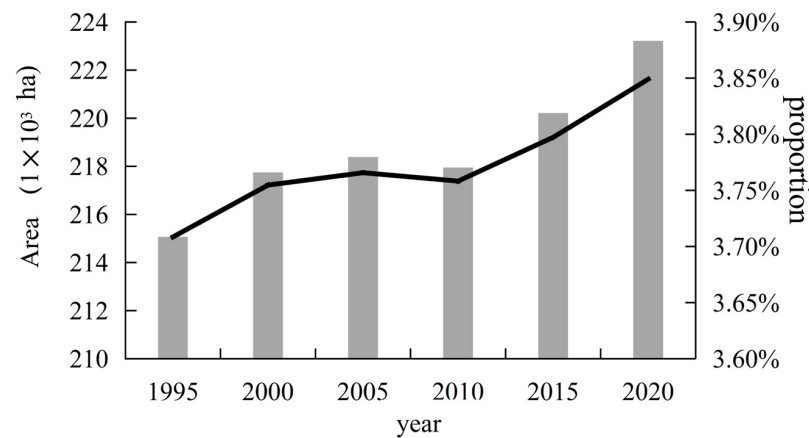


Figure 3. Rural built-up land area and proportion of overall land area, 1995–2020. The bar chart represents the area of rural built-up land. The line represents the proportion of rural built-up land area to the total land area.

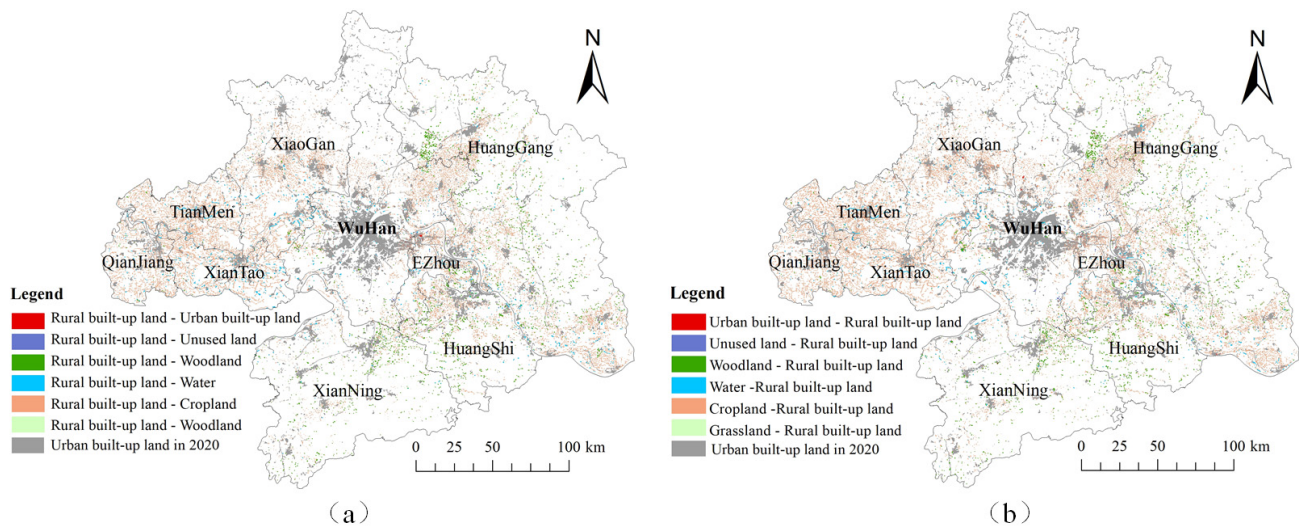


Figure 4. Changes in rural built-up land in the Wuhan Metropolitan Area, 1995–2020. (a) represents the spatial distribution of the shrinkage of rural built-up land; (b) represents the spatial distribution of the expansion of rural built-up land. Note: Due to the small size of the parcel changes, this map bolds the outlines of parcels where rural built-up land has changed. Consequently, the map only represents the location of land type changes, and the pixel occupancy does not reflect the actual area converted. For specific conversion areas, please refer to Tables 4 and 5.

Table 4. Area and percentage of rural built-up land converted to other land use types, 1995–2020 (ha).

	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	1995–2020	
						Area	Percentage
Rural built-up land-into-cropland	1155	60	8702	651	9755	8861	78.10%
Rural built-up land-into-Woodland	117	2	725	62	854	609	5.36%
Rural built-up land-into-Grassland	5	0	130	3	66	33	0.29%
Rural built-up land-into-Water	322	191	992	70	557	778	6.85%
Rural built-up land-into-Urban built-up land	517	26	4026	492	944	1040	9.17%
Rural built-up land-into-Unused land	16	149	21	0	65	26	0.23%
Total	2132	428	14,597	1279	12,240	11,346	100.00%
RSR	0.99%	0.20%	6.68%	0.59%	5.56%	5.08%	/

Table 5. Area and percentage of other land use types converted to rural built-up land, 1995–2020 (ha).

	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	1995–2020	
						Area	Percentage
Cropland-into-Rural built-up land	3434	908	12,029	2700	9049	16,993	87.16%
Woodland-into-Rural built-up land	136	109	962	122	691	894	4.59%
Grassland-into-Rural built-up land	11	6	86	5	120	65	0.33%
Water-into-Rural built-up land	357	41	639	94	994	595	3.05%
Urban built-up land-into-Rural built-up land	874	1	376	616	4369	924	4.74%
Unused land-into-Rural built-up land	1	4	69	5	20	24	0.13%
Total	4812	1069	14,162	3541	15,243	19,496	100.00%
RER	2.24%	0.49%	6.48%	1.62%	6.92%	8.73%	/

3.1.2. Analysis of the Temporal Pattern of Shrinkage of Rural Built-up Land

Overall, the RSR in the Wuhan Metropolitan Area from 1995 to 2020 was 5.08%. Cropland, urban built-up land, water, and woodland accounted for the majority of this loss, with percentages of 78.10%, 9.17%, 6.85%, and 5.36%, respectively. Grassland and unused land accounted for smaller percentages of rural built-up land loss, at 0.29% and 0.23%, respectively (Table 4).

Over time, the RSR during different periods exhibited a fluctuating trend of high-low-high-low-high. This means that after an increase in rural built-up land transfers, a decrease followed in the subsequent period. From 2000 to 2005, only 428 ha of rural built-up land were transferred out, resulting in an RSR of 0.20%, the lowest value among all periods. In contrast, from 2005 to 2010, 14,597 ha of rural built-up land were transferred, yielding the highest RSR of 6.68%. The second highest volume of transfers occurred from 2015 to 2020, with 12,240 hectares transferred, significantly higher than other years. This phenomenon can be attributed to the increased supply of land due to the out-migration of rural built-up land, which subsequently lowered land prices. When land prices fall to a certain level, farmers may choose to retain their land rather than transfer it out, leading to a reduction in the amount of rural built-up land transferred in the next period. Eventually, as land values rise again, farmers may be encouraged to sell land once more, initiating a cycle of meandering upward movement.

3.1.3. Analysis of the Temporal Pattern of Rural Built-up Land Expansion

Cropland, urban built-up land, woodland, and water are the primary sources of supplemental rural built-up land, accounting for 87.16%, 4.74%, 4.59%, and 3.05% of the area's increase, respectively. Grassland and unused land contributed less, at 0.33% and 0.13%, respectively. In terms of periods, the RER was highest from 2015 to 2020 at 6.92%. The period from 2005 to 2010 witnessed the second highest RER at 6.48%, consistent with the RSR results (Table 5). The shrinkage and expansion of rural built-up land tend to occur simultaneously.

While supporting the development of rural industries, China emphasizes the principles of food security, ecological safety, and standardized land use. This means that in promoting rural development, it is essential to ensure that permanent basic farmland is not occupied, the scale of built-up land is not exceeded, and ecological environments are not damaged. Under this policy orientation, the increase in rural built-up land needs to be achieved by optimizing and adjusting existing land resources rather than simply expanding the land area.

3.2. Impact of Spatial Evolution of Rural Built-up on Carbon Storages

3.2.1. Value of Carbon Storage Changes Due to Overall Land-Use Change

All types of land areas have changed to varying degrees, leading to a fluctuating trend of carbon storage decreasing and then briefly recovering (Figure 5). Overall, carbon storage decreased by a total of 1.262×10^7 tons over the 25 years. During the periods 1995–2000,

2000–2005, 2005–2010, and 2010–2015, carbon stocks decreased by 0.412%, 0.318%, 0.778%, and 0.755%, respectively. However, carbon storage increased by 0.415% during 2015–2020. Cropland and woodland accounted for the highest carbon storage, with a total share of more than 85% in every period.

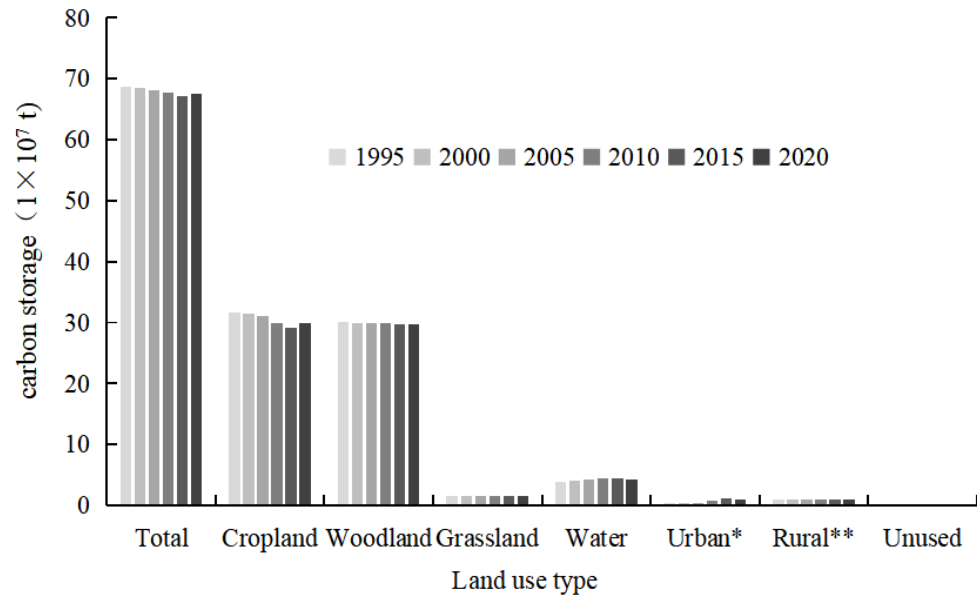


Figure 5. Carbon storage in seven land use types in Wuhan urban area, 1995–2020. Note: * is urban built-up land, ** is rural built-up land.

This study isolates rural built-up land as a separate land category to analyze the changes in carbon storage due to changes in rural built-up land (Table 6). The carbon stock showed a negative change in all periods except 2015–2020. In 1995–2000 and 2000–2005, changes in carbon stocks due to the alteration of rural construction land were -1.41×10^5 tons and -0.63×10^5 tons, respectively. During 2005–2010, 2010–2015, and 2015–2020, carbon storage showed a sustained decline after a brief rebound. Previous analysis shows that the area of rural construction land, which is the least carbon-intensive, decreased from 2005 to 2010, but the change in total carbon storage also had a negative value. This is because during this period, in addition to changes in rural built-up land, other land types also underwent inter-conversion, such as the conversion of woodland to grassland. Therefore, the total land use carbon stocks also declined. In land planning and management, the carbon storage capacity of various types of land needs to be considered in an integrated manner to achieve better carbon management.

Table 6. Changes in overall carbon stock and carbon stock on rural built-up land 1995–2000 (10^5 t).

	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020
Carbon storage changes in rural built-up land	−1.41	−0.63	−2.18	−1.32	0.48
Change in total carbon storage	−28.30	−21.74	−53.03	−51.11	27.89

3.2.2. Value of Changes in Carbon Storages Due to Shrinkage of Rural Built-up Land

After obtaining the raster maps of total carbon stock for different years using the InVEST model, raster subtraction operations were performed in ARCGIS 10.8 for adjacent years. The carbon stock changes caused by the transfer out (shrinkage) and transfer in (expansion) of rural built-up land are shown in Table 7. Since rural built-up land has significantly lower carbon intensity, carbon stocks from shrinkage consistently show a positive increase.

Table 7. Value of change in carbon storage in shrinking area of rural built-up land (t).

	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	1995–2020	
						Carbon Storage	Percentage
Rural built-up land-into-Cropland	69,743	3609	525,406	39,323	589,029	534,993	84.55%
Rural built-up land-into-Woodland	14,702	215	90,991	7809	107,162	76,402	12.08%
Rural built-up land-into-Grassland	363	0	8894	222	4524	2271	0.36%
Rural built-up land-into-Water	8046	4762	24,764	1745	13,915	19,413	3.07%
Rural built-up land-into-Unused land	−227	−2086	−293	−6	−904	−358	−0.06%
Total	92,628	6500	649,762	49,091	713,726	632,722	100.00%

With 84.55% of the total, the conversion of rural built-up area to farmland was the main driver of the change in carbon stock between 1995 and 2020. Woodland followed with a share of 12.08%. The carbon stock increased by just 0.36% due to the conversion of rural built-up area to grassland. The reduction in built-up land in rural areas caused a peak in the growth of carbon storage from 2015 to 2020, totaling about 713,726 tons. In terms of land types, the conversion of rural built-up area to agriculture, woods, and grassland resulted in minimal carbon stock levels between 2000 and 2005. Meanwhile, the value of carbon stock changes due to the conversion to watershed and unutilized land showed minimum values in 2010–2015.

3.2.3. Value of Carbon Storage Changes Due to Expansion of Rural Built-up Land

From 1995 to 2020, the conversion of cropland to rural built-up land caused the largest change in carbon stocks, with a total share of 88.66%. This was followed by woodland, with a share of 9.70%. Water and grassland had smaller shares of 1.28% and 0.39%, respectively (Table 8).

Table 8. Value of carbon storage changes in the area of rural built-up land expansion (t).

	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	1995–2020	
						Carbon Storage	Percentage
Cropland-into-Rural built-up land	−207,365	−54,862	−726,347	−163,053	−546,429	−1,026,136	88.66%
Woodland-into-Rural built-up land	−17,064	−13,673	−120,773	−15,267	−86,697	−112,224	9.70%
Grassland-into-Rural built-up land	−739	−382	−5890	−339	−8186	−4462	0.39%
Water-into-Rural built-up land	−8925	−1007	−15,951	−2338	−24,836	−14,858	1.28%
Unused land-into-Rural built-up land	11	54	970	71	279	342	−0.03%
Total	−234,082	−69,870	−867,992	−180,926	−665,869	−1,157,340	100.00%

From 2000 to 2005, the value of carbon loss caused by the expansion of rural built-up land was the lowest, with a change of −69,870 tons. This was mainly due to the small area of cropland and woodland being converted to built-up land. From 2005 to 2010, besides cropland and woodland, water became the primary source of new rural built-up land expansion. The expansion of rural construction land often involved filling in wetlands, rivers, and lakes, impairing key ecosystem services. Wetlands absorb carbon dioxide, regulate climate, and provide flood control. As an important freshwater resource, wetlands are critical to the regional water cycle and water supply. Landfilling wetlands for the construction of rural settlements weakens natural barriers and may exacerbate the risk of extreme weather and water scarcity, posing a long-term threat to ecological balance and human well-being. The highest carbon loss occurred from 2005 to 2010, with a change of −867,992 tons. During this period, the carbon loss caused by the conversion of woodland into built-up land rose more than tenfold compared to the previous period. Transfers away from rural built-up areas primarily involved converting these areas into croplands, bodies of water, and other types of land known for their lower carbon density values. Consequently, this led to a significant decline in overall carbon storage. The period from 2010 to 2015 witnessed the least carbon loss when grasslands were transformed into rural

built-up areas, with a loss of 339 tons. Furthermore, the increase in rural built-up land from 2015 to 2020 resulted in a significant decline in carbon storage of $-665,869$ tons. This considerable drop was mostly caused by the conversion of these areas into croplands, woods, and water bodies.

3.3. Land Use Modeling and Carbon Storage Projections under Different Scenarios for 2030

3.3.1. Simulation of Land-Use Change under Different Scenarios

Based on the land use data from 2000 and 2010 for the Wuhan Metropolitan Area, the two datasets were initially overlaid to identify modified raster cells. These cells were then fed into the LEAS module along with the driver folder. Integrating this with the simulation capabilities of the CARS module yielded the land use simulation data for the year 2020. These simulation results were then compared to actual land use data for 2020 (Figure 6).

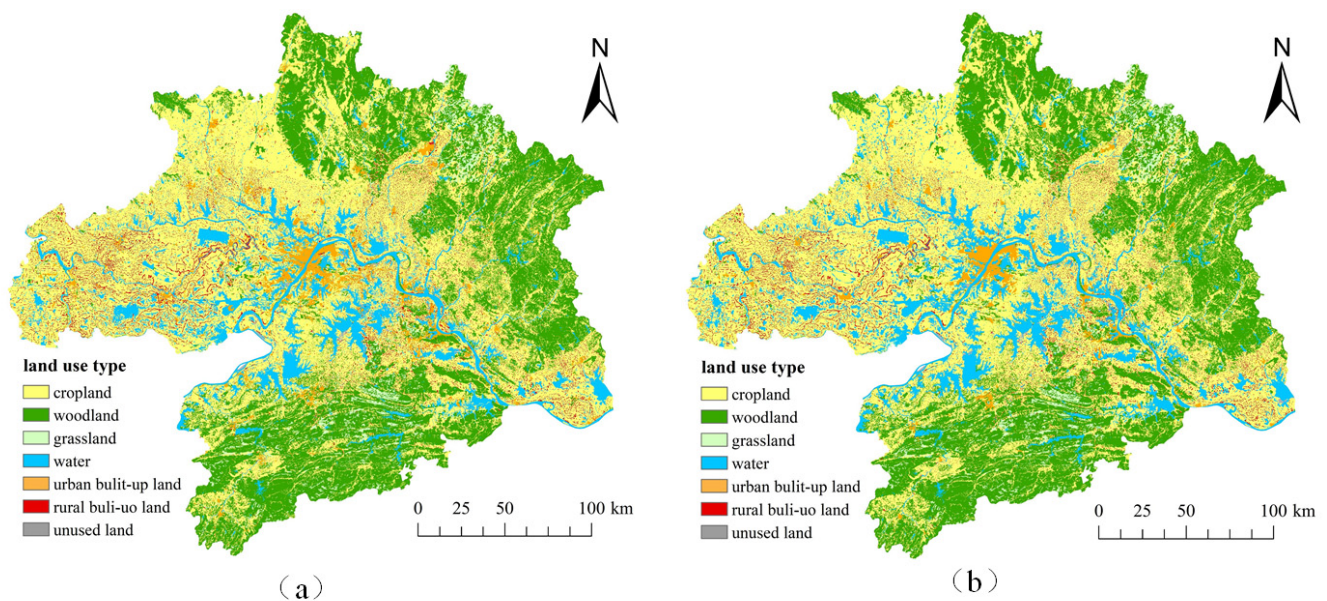


Figure 6. Comparison between the current land use status in 2020 and PLUS simulation. (a) represents the actual land use; (b) represents the land use simulated by PLUS model.

Three potential scenarios for the year 2030 were also simulated (Figure 7 and Table 9). Under Q1, each land category is transformed according to the original transfer probability. Cropland and woodland are projected to increase by 0.153% and 0.188%, respectively. Grassland, water, urban built-up land, and rural built-up land are expected to decrease by 0.013%, 0.146%, 0.195%, and 0.008%, respectively. Rural built-up land will primarily be transferred to cropland, with a total decrease of 437 hectares. Much of this decrease is concentrated in three county-level cities under provincial jurisdiction. This phenomenon may be attributed to local governments' comprehensive remediation and restoration plans to effectively respond to the hollowing out of rural areas caused by population exodus. As a result, inefficient or abandoned rural built-up land has been substantially converted into cropland. Under Q2, the trend of decreasing total rural built-up land area intensifies, with a total reduction of 5849 hectares. The area of cropland increases significantly, rising by 17,157 hectares. The area of woodland decreases slightly but remains more stable, indicating that ecological land has been protected. Under Q3, the total rural built-up land area increases by 181 hectares. The magnitude of change in cropland is the most prominent among all land changes. This trend indicates that rural built-up land remediation activities have played a key role in optimizing land-use structures and improving food security.

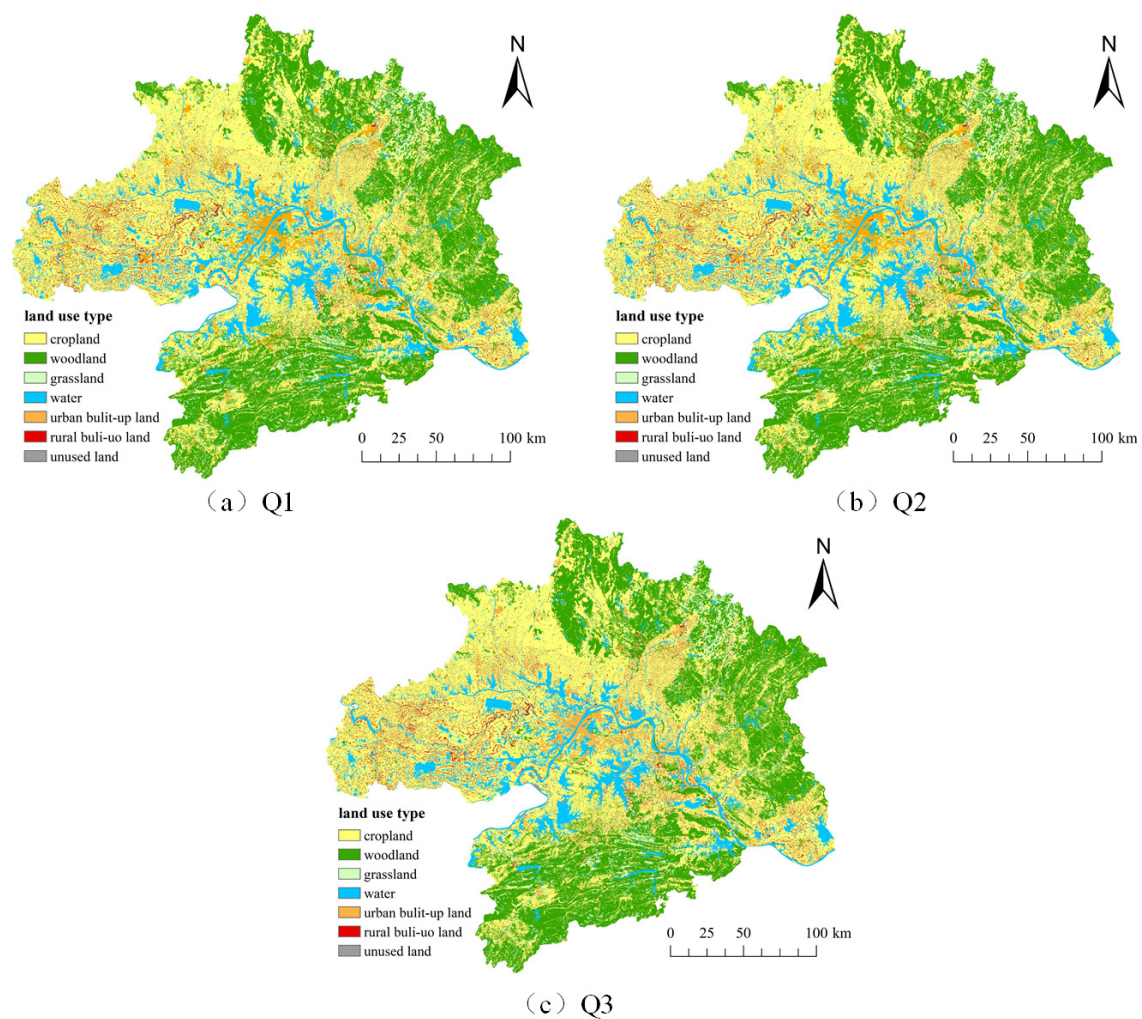


Figure 7. Spatial simulation of land use under three different scenarios in Wuhan Metropolitan Area in 2030. (a) represents a natural development scenario; (b) represents a scenario of rural built-up land shrinkage; (c) represents a scenario of rural built-up land expansion.

Table 9. Area of different land types under different scenarios.

Land Type	2020	2030			Amount of Change in 2030		
		Q1	Q2	Q3	Q1	Q2	Q3
	Area/Ha Percentage/%	Area/Ha Percentage/%	Area/Ha Percentage/%	Area/Ha Percentage/%	Area/Ha Percentage/%	Area/Ha Percentage/%	Area/Ha Percentage/%
Cropland	2,847,700 (49.104)	2,856,550 (49.257)	2,864,857 (49.400)	2,848,240 (49.114)	8850 (0.153)	17,157 (0.296)	540 (0.009)
Woodland	1,741,555 (30.031)	1,752,434 (30.218)	1,750,387 (30.183)	1,753,326 (30.234)	10,879 (0.188)	8832 (0.152)	11,771 (0.203)
Grassland	141,267 (2.436)	140,533 (2.423)	140,623 (2.425)	140,443 (2.422)	−734 (−0.013)	−644 (−0.011)	−824 (−0.014)
Water	607,744 (10.480)	599,264 (10.333)	596,969 (10.294)	605,841 (10.447)	−8480 (−0.146)	−10775 (−0.186)	−1903 (−0.033)
Urban built-up land	218,079 (3.760)	206,780 (3.566)	208,128 (3.589)	207,100 (3.571)	−11299 (−0.195)	−9951 (−0.172)	−10979 (−0.189)
Rural built-up land	223,218 (3.849)	222,781 (3.842)	217,369 (3.748)	223,399 (3.852)	−437 (−0.008)	−5849 (−0.101)	181 (0.003)
Unused land	19,703 (0.340)	20,924 (0.361)	20,933 (0.361)	20,917 (0.361)	1221 (0.021)	1230 (0.021)	1214 (0.021)

This study provides a comparative analysis of a specific land parcel within the Wuhan Metropolitan Area under different scenarios (Figure 8). According to the Q2 and Q3 simulation results, the dynamic changes in rural built-up land do not occur randomly but follow a certain spatial pattern. From a macroscopic perspective, the expansion of rural construction land shows a tendency to agglomerate on a large scale. Due to the concentration of economic activities and better infrastructure, new built-up land tends to expand around existing built-up areas, forming continuous zones of built-up land. From a micro perspective, different villages or townships are often affected by topography, land ownership distribution, and rural road layout. Farmers will develop land according to their actual needs and land location. In short, most dynamic changes occur around the original homesteads, forming a tendency of clustering in large areas and dispersing in small areas. Currently, there is a mismatch between the ideal goals of land use planning and the real needs of farmers' individual land use choices. On the one hand, planners aim to achieve intensive use of land resources and ecological protection by merging villages and optimizing the layout. On the other hand, farmers make land-use decisions based on their life and livelihood needs that align with their own interests. This contradiction not only reduces the effectiveness of land use planning but also may negatively impact regional carbon stocks.

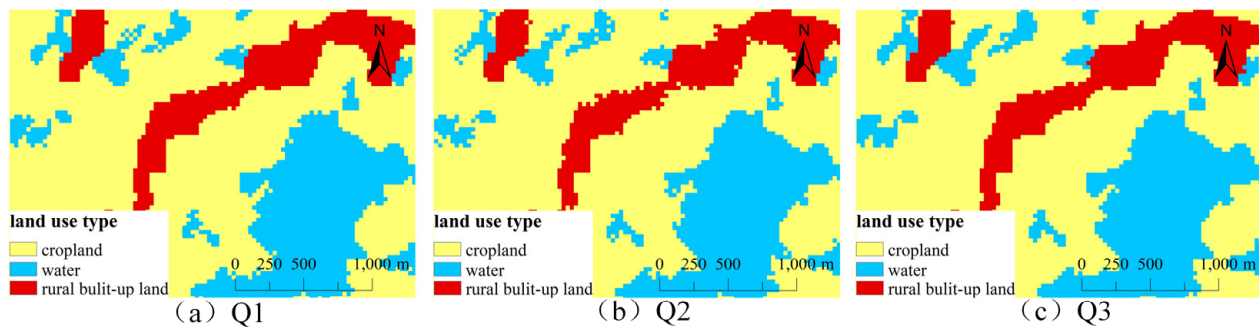


Figure 8. Changes in the spatial pattern of rural built-up land in Wuhan Metropolitan Area. (a) represents a natural development scenario; (b) represents a scenario of rural built-up land shrinkage; (c) represents a scenario of rural built-up land expansion.

3.3.2. Simulation of Carbon Storage Distribution under Different Scenarios

The spatial distribution of carbon in the Wuhan Metropolitan Area in 2030 changes little compared with 2020 under the three different projection scenarios (Figure 9). High values of carbon stocks are clustered in the three densely forested cities: Huanggang, Huangshi, and Xianning. The carbon storage of land resources under Q1 is 6755.94×10^5 tons, which increases by 0.241% compared with 2020. The carbon storage of rural built-up land decreased by 0.196%. Under Q3, the value of carbon storage in land resources is 6753.62×10^5 tons, and the carbon storage in rural construction land rises by 0.081% (Table 10). The growth and loss of carbon storage in land resources show a specific geographical distribution pattern: high values are more dispersed and sporadically distributed on the fringes of the Wuhan Metropolitan Area, forming a hollow pattern with high values surrounding a lower center. Meanwhile, areas of high carbon storage loss are concentrated in the main urban area. Due to urbanization and industrialization pressures, the main urban areas have experienced large-scale land development and utilization changes. The original natural land surface has been replaced by buildings, roads, and other infrastructures, leading to the destruction of ecosystems and the decline of carbon storage capacity. Overall, radiating outward from the main urban area of Wuhan, the carbon stock of land resources has gradually increased, showing a sporadic point-like distribution. The increase is lower in the east and larger in the west, with an overall arrow-shaped distribution, reflecting the gradient change and uneven growth from the city center to the periphery.

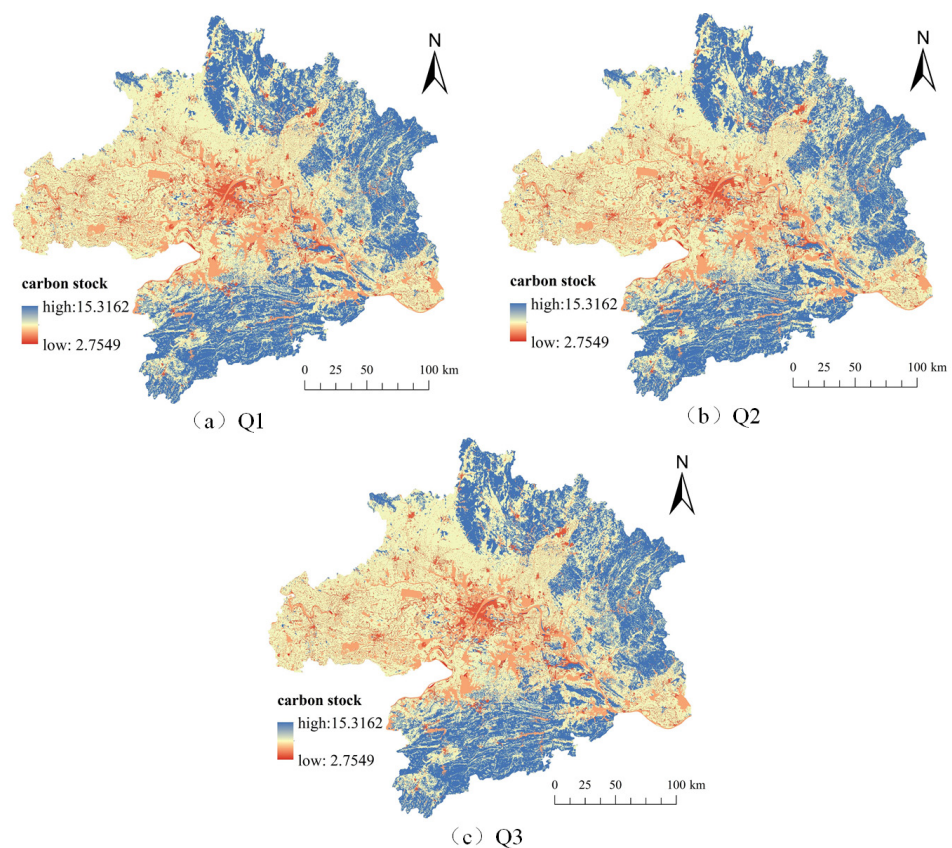


Figure 9. Simulation of the spatial distribution of carbon storages in Wuhan Metropolitan Area under three different scenarios in 2030 (t/ha). (a) represents a natural development scenario; (b) represents a scenario of rural built-up land shrinkage; (c) represents a scenario of rural built-up land expansion.

Table 10. Changes in carbon storages under different scenarios (10^5 t).

Year	Scenario	Carbon Storage on Rural Built-up Land	Total Carbon Storage
2020	/	99.60	6739.72
2030	Q1	99.40	6755.94
	Q2	96.99	6757.87
	Q3	99.68	6753.62
Rate of change (over 2020)	Q1	−0.196%	0.241%
	Q2	−2.620%	0.269%
	Q3	0.081%	0.206%

Under Q2, the carbon storage value of land resources is 6757.87×10^5 tons, which increased by 0.269% compared with 2020, showing significantly better performance than the other two scenarios. The carbon stock of rural built-up land decreased by 2.620%. Rural built-up land was substantially converted to cropland, enhancing the carbon sink function of ecosystems and thereby increasing regional ecosystem carbon stocks. In some hilly areas, woodlands and grasslands that might have been converted to cropland have been preserved, as the demand for cropland has been met by the transfer of rural construction land. As a result, these ecosystems have maintained or even enhanced their carbon sequestration capacity due to reduced anthropogenic disturbances, creating high carbon storage areas. This phenomenon shows that a single-dimensional land policy can produce different environmental effects in different regions. When formulating land management policies, the unique ecological characteristics of each region and the specific requirements of sustainable development must be fully considered [39]. Only by ensuring that land resources are

rationally developed and utilized can the ecological environment be comprehensively protected [40].

4. Discussion

4.1. Analysis of Factors Related to Changes in Land Use Types

The contribution of relevant factors to changes in different land use types was obtained using the PLUS model (Table 11). Although the degree of influence varies, the factors most associated with changes in key ecological sites are temperature, precipitation, and population density. For grasslands, DEM is also a significant factor. First, temperature directly affects the growing conditions of plants in ecosystems and the ecological structure of water, which in turn influences the persistence of woodland cover and changes in aquatic habitats. Second, the amount and distribution of precipitation profoundly impact all types of ecological land use by influencing agricultural irrigation, the frequency of woodland fires, and the health of grasslands. Third, aside from major ecological land use, population density is closely related to changes in urban built-up land, with a contribution rate of 0.233. As the population concentrates, the demand for housing, commercial space, industrial areas, and public service facilities increases, driving the city to expand to the periphery or reorganize its internal space.

Table 11. Contribution of factors related to changes in different land use types.

Factors	Cropland	Woodland	Grassland	Water	Urban Built-up Land	Rural Built-up Land	Unused Land
Distance to secondary road	0.036	0.026	0.027	0.030	0.035	0.033	0.027
DEM	0.058	0.066	0.169	0.074	0.112	0.100	0.035
Distance to highway	0.067	0.049	0.035	0.049	0.054	0.053	0.033
GDP	0.104	0.087	0.102	0.109	0.071	0.075	0.070
Precipitation	0.129	0.143	0.150	0.115	0.064	0.127	0.080
slope	0.041	0.036	0.036	0.041	0.081	0.068	0.231
Population density	0.116	0.144	0.152	0.151	0.233	0.124	0.031
Slope orientation	0.029	0.033	0.034	0.032	0.027	0.039	0.022
Temperature	0.137	0.161	0.122	0.144	0.067	0.076	0.201
Distance to railway	0.065	0.051	0.046	0.057	0.093	0.057	0.029
Soil type	0.033	0.034	0.023	0.038	0.022	0.043	0.063
Nighttime Lighting	0.115	0.096	0.063	0.101	0.096	0.138	0.107
Distance to branch road	0.032	0.033	0.025	0.026	0.019	0.026	0.022
Distance to the main road	0.038	0.041	0.016	0.033	0.026	0.041	0.049

The top three relevant factors for changes in rural built-up land are nighttime lighting, precipitation, and population density. The least contributing factors are distance to branch road, distance to secondary road, and slope orientation. Areas with more intense nighttime lighting tend to have a higher concentration of human activity, resulting in a greater demand for building land. Additionally, transportation accessibility has the least relevance to land use change among all the factors involved. Improvements in transportation infrastructure often respond to land development activities that have already occurred or are anticipated, and their correlation with land use change may take a longer period to become apparent.

4.2. Comparison with Existing Research

Existing research on the impact of land use changes on carbon storage primarily focuses on comprehensive and macro-level analyses. For example, Schulp et al. [41] investigated the effects of land use changes on ecosystem services across the European Union. Similarly, Sil et al. [42] assessed carbon storage dynamics under different land use scenarios in Portugal. While these studies provide valuable insights, they often lack a specific focus on the unique role of rural built-up land in carbon storage dynamics.

Moreover, research on the spatial heterogeneity of carbon storage changes due to the expansion and shrinkage of rural settlements remains limited. Li et al. [21] projected the regional distribution characteristics of land use/land cover carbon stocks in Liaoning

Province but assessed them in terms of overall change. Wang et al. [38] investigated the effects of land use changes on carbon storage in the Pinggu District of Beijing but did not specifically target rural built-up land. Focusing on urban areas, Li et al. [43] examined the potential impact of urban growth on carbon stocks. Although Ye et al. [6] addressed the impact of rural built-up land changes on ecological land carbon stocks, their analysis was conducted mainly from the perspective of rural settlement expansion and lacked the exploration of shrinkage.

This study aims to fill these research gaps by focusing on the specific impacts of rural built-up land changes on carbon storage in the Wuhan Metropolitan Area. By distinguishing between the expansion and shrinkage of rural settlements and quantifying their effects on carbon storage using the InVEST model, this research provides a more nuanced understanding of the role of rural built-up land in carbon dynamics. Furthermore, the application of the PLUS model to simulate future scenarios of rural settlement changes and their impacts on carbon storage offers valuable insights for land use planning and policy-making in the region.

4.3. Policy Implications

Based on the findings of this study, several policy implications are drawn to guide future land management and planning practices in the Wuhan Metropolitan Area and serve as a reference for other regions undergoing similar transformations.

- (1) In response to the ongoing increase of rural constructed land and its impact on ecosystem carbon storage, the government should improve rural built-up land transfer management, optimize the transfer mechanism, and encourage reasonable transfers to avoid land idleness and waste. Additionally, it should intensify ecological restoration activities in critical areas such as the Wu-E border, Tianmen, and southern Xiantao to enhance regional carbon storage capacity and promote the recovery and expansion of ecosystem carbon stocks.
- (2) The government should promote a shift in land-use planning to a “demand-oriented” approach. The actual needs and interests of farmers should be fully considered and respected in the planning process to ensure that planning programs are closely integrated with the production and life of farmers. By enhancing the flexibility and operability of planning, the planning objectives will be closer to the actual situation of farmers, thus improving the implementation and acceptance of planning and reducing negative impacts on regional carbon stocks.
- (3) To strengthen the management of carbon stock in land resources, the government should establish a carbon stock monitoring system to regularly assess and report changes in carbon stock. At the same time, it should implement differentiated carbon stock protection policies based on the geographical distribution characteristics of carbon stock changes. Through policy guidance and market mechanisms, the rational flow and optimal allocation of factors of production within the region should be promoted to achieve the harmonious unity of economic, social, and ecological benefits.

5. Conclusions

This study analyzes the changes in rural built-up land in the Wuhan Metropolitan Area over six equal intervals: 1995, 2000, 2005, 2010, 2015, and 2020. Assuming the accuracy of PLUS simulations has been validated, this study utilizes fourteen driving factors to simulate three scenarios: natural development, shrinkage of rural built-up land, and expansion of rural built-up land.

The main conclusions are as follows:

- (1) The area of rural built-up land generally increased between 1995 and 2020. However, unlike previous years, the area decreased in 2010. Compared to the expansion of rural built-up land, the shrinkage is more concentrated, primarily at the Wu-E border, Tianmen, and southern Xiantao. The carbon stock of terrestrial ecosystems in the

Wuhan urban area showed a cyclical pattern of continuous decline followed by brief recovery.

- (2) According to the PLUS model's prediction results, under the rural construction land expansion scenario, a significant amount of arable land is encroached upon. Additionally, most changes in rural built-up land occur around the original home base, forming a pattern of large-scale agglomeration and small-scale dislocation.
- (3) In the natural development scenario, the carbon storage value of land resources is 6753.62×10^5 tons. The total carbon storage under the rural built-up land shrinkage scenario surpasses that of the other two scenarios. Concurrently, the alteration in carbon storage across land resources exhibits a distinct geographical distribution pattern, characterized by a gradient radiating from the primary urban zone of Wuhan City and demonstrating disparate growth rates in various directions.

Future research directions include:

- (1) Monitoring changes in land cover status through high-resolution, multi-temporal remote sensing data, and establishing more accurate and comprehensive simulation and prediction models of land use changes.
- (2) Studying the changing patterns of rural built-up land to deeply explore and understand the phenomena of expansion and contraction in rural built-up land.
- (3) Combining remote sensing data with other data sources to assess the impact of these changes on functions such as the carbon cycle, biodiversity, and soil and water conservation.

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