LAND USE AND HABITAT QUALITY PREDICTION BASED ON MULTI-SCENARIO SIMULATION: A CASE STUDY OF JIAOZUO, CHINA

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Abstract. To promote sustainable urban development, it is essential to assess the impacts of urban expansion on land-use change and habitat quality. Based on data from four periods of land use in Jiaozuo City (1990, 2000, 2010 and 2020), China, this study used the CA–Markov and InVEST models to create multi-scenario projections of land use in 2030, 2040 and 2050 and assess habitat quality status, respectively. The results showed that, from 1990 to 2020, construction land in Jiaozuo showed a trend of continuous expansion, with an increase of 57.75%, and areas of cultivated land, forested land, grassland, and water area showed a decreasing trend, with decreases of 5.34%, 9.75%, 10.37% and 33.42%, respectively. In the simulation of the three scenarios, Jiaozuo did not experience any major changes in land use in the next thirty years, and the habitat quality indices were, in descending order, the ecological priority scenario, the natural development scenario and the economic priority scenario. Predicting land-use changes and habitat quality is of great importance for the efficient utilization of land resources and habitat quality in Jiaozuo.
Keywords: *habitat quality, CA–Markov, InVEST, scenario simulation, time–space evolution, land-use change*

Introduction

Since the reform and opening up, China has witnessed rapid economic development, urbanization and urban development, and the expansion of construction land has provided necessary urban development space (Chen et al., 2022). However, it has also had certain negative impacts on sustainable urban development. For example, urban expansion inevitably leads to the loss of land with ecological functions such as cultivated land, forested land, and grassland, thus affecting the quality of the urban habitat (Rima et al., 2019). Habitat quality refers to the ability of the ecological environment to provide suitable conditions for the survival of organisms, which is an important indicator related to regional sustainable development and human well-being (Liu and Wang, 2018). Urban expansion affects habitat quality mainly by changing the land-use structure (Zheng and Li, 2022). Therefore, analysis of the impact of urban expansion on habitat quality and exploration of their relationship can provide valuable reference data for achieving a balance between ecological protection and urban development at the regional level (Bai et al., 2019).

In recent years, scholars all over the world have carried out in-depth research on habitat quality assessment. The main models for the assessment of habitat quality are RSEI (Sun et al., 2022), InVEST (Huang et al., 2021), Maxent (Lei et al., 2022) and SoLVES (Pan et al., 2022). Ahmadi et al. (2022) used the InVEST model to assess the impact of landscape fragmentation on habitat quality in the Shur River basin in southwest Iran and

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found that landscape fragmentation would reduce habitat quality and ecosystem service efficiency. Wang et al. (2022) discussed the temporal and spatial changes in habitat quality caused by land-use change in Changdang Lake National Wetland Park, Changzhou, China, and the research results showed that land-use change caused by human activities was the main reason for the decline in habitat quality. Chen et al. (2023) evaluated the habitat quality of 30 provinces in China from 2010 to 2020 and concluded that key influencing factors such as per capita water resources, night light index, cultivated land area, forest area and deforested area would lead to changes in habitat quality. According to Wu et al. (2022), based on the characteristics of habitat quality of different altitude gradients and ecosystems, the spatial pattern of habitat quality in the fringe area of the Guangdong–Hong Kong–Macao Greater Bay Area in China showed a decreasing trend from the central area to the forest ecosystem. The habitat quality increased as altitude increased. Taking Jeju Island in South Korea as an example, Kim et al. (2022) analyzed the economic value and benefits of habitat quality changes and found that improvement of habitat quality and proper management of ecotourism attractions could increase the interest of tourists and revitalize the local economy. Zheng et al. (2022) used the InVEST model to analyze the changes in habitat quality in the Yangtze River Economic Zone and the Yellow River Basin in China and found that the habitat quality in the study area continued to decline during the study period. The research results provide support for biodiversity conservation strategies in China and other developing countries. Taking Taihang Mountain in China's Hebei Province as an example, Yang (2021) analyzed the relationship between land-use change and habitat quality in mountainous areas and found that the habitat quality in areas dominated by construction or cultivated land, which are closely related to human activities, was relatively low. These research results are significant for ensuring ecological security and the sustainability of the ecological environment.

However, current studies generally focus on assessing habitat quality in the study area rather than predicting habitat quality trends under the influence of land-use change. Currently, there are a variety of models for predicting land-use change. The CA–Markov model is widely used in land-use simulation because it combines the characteristics of the CA model to predict the evolution of spatial form and the ability of Markov model to deduce time series (Matlhodi et al., 2023). Lei et al. (2022) used the CA–Markov model to predict the impact of land-use change on habitat quality in Hainan Province and put forward suggestions for maintaining regional ecological security. Devanantham et al. (2021) adopted the CA–Markov model to study the influence of future Land-Use and Land-Cover Change (LUCC) changes on the northern coastal area of Tamir Nadu, India, to provide suggestions and a basis for urban development planning. Mohamed et al. (2023) used the CA–Markov model to simulate the urban expansion of Nizwa City in Sultanate of Oman over the next 20 years to provide important reference data for future urban planning. Based on land-use change in the Mediterranean water surface area of northern Morocco from 1998 to 2018, Shawky et al. (2020) applied the CA–Markov model to simulate land change from 2028 to 2050, and the research results presented the potential future changes how the possible risks could be prevented was considered. Wang et al. (2022) used the CA–Markov model to simulate the relationship between future land-use change and the landscape pattern index in the context of urban expansion in Wuhan, China, and the research results provided a theoretical basis to support sustainable development and landscape planning policy formulation in the region. The above studies

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indicate that the CA–Markov model can be widely applied to simulate the development trend of land-use change.

In summary, the above two models have achieved good evaluation results in their respective fields, but few scholars have combined the CA–Markov and InVEST models to simulate and predict habitat quality under the influence of future land-use change. The prediction of future land use has important theoretical significance for understanding the complex dynamic evolution mechanism of habitat quality and exploring development policy and management models for ecological environment optimization (Tang and Fu, 2021). Therefore, based on land-use data from 1990, 2000, 2010 and 2020, this study adopted the CA–Markov and InVEST models to analyze the temporal and spatial changes in land use and habitat quality in Jiaozuo City. It is expected that the simulation and assessment of land-use change and habitat quality trends in Jiaozuo City from 2030 to 2050 under different development scenarios will provide scientific reference data for regional biodiversity conservation and natural resource planning and management in Jiaozuo City as well as for ecological environment and regional sustainability research focusing on other similar resource-depleted cities.

Data and methods

Overview of the study area

Jiaozuo City (34°49 'N-35°29' N, 112°43 'E-113 ° 38' E) is located in the northwest of Henan Province, China and has a total area of 4071 square kilometers (*Figure 1*). Jiaozuo has a large plain area, relatively flat terrain in the central and southern parts of the city and rolling hills in the north. The research object of this paper is the whole Jiaozuo City, including Shanyang (including urban-rural integration demonstration zone), Jiefang, Zhongzhan , Macun , Qinyang, Mengzhou, Xiuwu, Wuzhi, Boai and Wenxian. As one of the first cities in China to be declared as resource-exhausted, Jiaozuo has experienced rapid population growth and expansion of construction land since its transformation in the 1990s, with a corresponding continuous decline in habitat quality during the transformation process. Therefore, the maintenance of regional ecological security should be the focus of future urban development in Jiaozuo City.

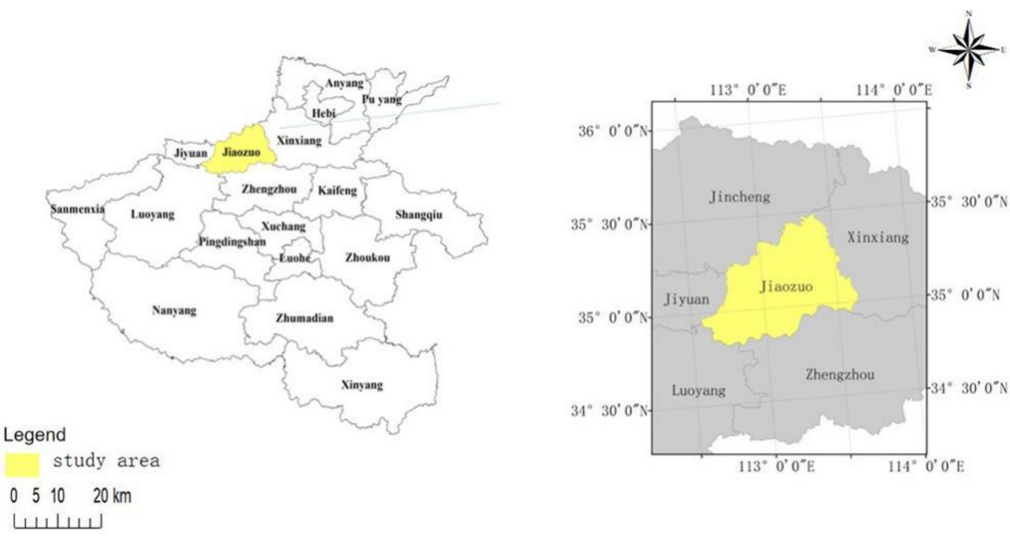

Figure 1. *Location of the study area*

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Data sources

The data used in this study include remote sensing images, land use, Digital Elevation Model (DEM), slope, vector, and road data. The remote sensing image and DEM data were obtained from the geospatial data cloud platform (https://www.gscloud.cn), and the slope data were extracted from DEM elevation data. The land use of the study area in 1990, 2000, 2010 and 2020 was interpreted from remote sensing images. According to the image accuracy, the actual situation in the study area and the "Classification of Land Use Status" classification standard (GB/T 21010-2017), land-use types were divided into six categories with a resolution of 30m*30m: forested land, grassland, cultivated land, construction land, water surface area and unused land. Road data were obtained from the Open Street Map (https://www.openhistoricalmap.org/).

Research methodology

InVST model

InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a model developed by the United States Natural Capital Project team and is used to evaluate the functional volume and economic value of ecosystem services and support ecosystem management and decision-making (Wei and Zhou, 2021). It includes three types of ecosystem service assessment model: terrestrial, freshwater, and marine. In this study, the habitat quality module in the InVEST3.9.2 software was adopted to evaluate habitat quality in Jiaozuo City. In this model, habitat quality and the degree of habitat degradation in Jiaozuo City were evaluated based on the LULC raster data set, combined with maximum impact distance and weight (*Table 1*) and sensitivity of threat factors (*Table 2*). The habitat quality value ranged from 0 to 1, and the higher the value, the better the habitat quality of the region. The calculation formula is as follows (Asadolahi et al., 2018; Wei et al., 2022; Chen et al., 2023):

$$D_{xj} = H_j [1-(\frac{D^z{}_{xj}}{D^z{}_{xj} + K^z})] \quad \text{(Eq.1)}$$

In the above formula, D_{xj} represents the habitat quality of grid x of landscape type j in the land-use/land-cover raster data set, H_j is the habitat suitability of landscape type j in the land-use raster data set, $D^z{}_{xj}$ is the degree of habitat degradation of grid x in landscape type j, z is the default parameter of the model, and the K value is the half-saturation constant, which is generally 0.5 for the first time. The second value is half of the degree of habitat degradation.

$$D_{xj} = \sum_{r=1}^{R} \sum_{r=1}^{\geq_r} (\frac{\omega_r}{\sum_{r=1}^{R} \omega_r}) \, r_y i_{rxy} \beta_x S_{j_r} \quad \text{(Eq.2)}$$

In the above formula, D_{xj} is the degree of habitat degradation, R is the number of habitat threat factors, r_y is the number of grids on the ground layer of the threat layer, ω_r is the weight of threat factor r, ry is the threat intensity of grid y, i_{rxy} is the threat level of r_y to habitat grid x, β_x is the accessibility of grid x and S_{jr} is the sensitivity of habitat type j to stress factor r.

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$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}} \right) \ if \ \ liner \qquad \text{(Eq.3)}$$

$$i_{rxy} = exp\left[-\left(\frac{2.99}{d_{rmax}} \right) d_{xy} \right] \ \ if \ exponential \qquad \text{(Eq.4)}$$

where d_{xy} is the linear distance between lattice x and y, and d_{rmax} is the maximum range of threat factor r.

Table 1. *Table of threat factors*

Threat factors	Maximum impact distance (km)	Weight	Decay type
Cultivated land	5	0.5	linear
Urban land	9	0.9	exponential
Rural settlements	6	0.7	exponential
Other construction land	7	0.7	exponential
Other unused land	4	0.3	linear

Table 2. *Sensitivity of habitat types to threat factors*

Land-use type	Habitat suitability	Cultivated land	Urban land	Rural settlements	Other construction land	Other unused land
Cultivated land	0.5	0	0.7	0.6	0.5	0.5
Forested land	1	0.8	0.7	0.6	0.6	0.4
Shrubland	0.9	0.6	0.8	0.7	0.7	0.3
Other forested land	0.7	0.8	0.8	0.6	0.6	0.4
Grassland	0.8	0.6	0.7	0.6	0.6	0.5
Rivers	0.9	0.6	0.8	0.7	0.8	0.4
Water surface area	0.7	0.6	0.6	0.7	0.6	0.4
Urban land	0	0	0	0	0	0
Rural settlements	0	0	0	0	0	0
Other construction land	0	0	0	0	0	0
Other unused land	0.4	0.5	0.6	0.5	0.6	0

CA-Markov model

In this study, the CA–Markov model was used to predict land-use change in Jiaozuo City from 2030 to 2050 under three different scenarios: natural development, ecological priority development and economic development. The natural development scenario simulation is based on the land use changes in Jiaozuo City from 1990 to 2020 and predicts the land use changes in Jiaozuo City from 2030 to 2050 without interference

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from external factors (Yang et al., 2023). The ecological priority scenario ensures the ecological priority development of Jiaozuo City by setting the value of ecosystem services and maximizing the capacity of the ecological environment, and each land use type can provide ecological benefits to the greatest extent (Zhang et al., 2022). The economic development scenario simulates the land use structure with the highest economic output, and its goal is to make full use of each land use type to maximize economic benefits. (Wang et al., 2018) The CA–Markov model combines CA with the Markov chain model and uses a transfer probability matrix to simulate the land-use change over time (Shawky et al.,2020; Khwarahm et al., 2020), which is expressed as follows:

$$S_{(t+1)} = P_i \times S_t \quad \text{(Eq.5)}$$

$$P_{ij} = \begin{bmatrix} P_{11} \dots\dots\dots P_{1n} \\ P_{21} \dots\dots\dots P_{2n} \\ \dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots \\ P_{n1} \dots\dots\dots P_{nn} \end{bmatrix} \quad \text{(Eq.6)}$$

$$\left[0 \le P_{ij} \le 1 and \sum_{j=1}^{n} P_{ij} = 1(i,\ j = 1.2.3\dots\dots n \right] \quad \text{(Eq.7)}$$

where P_{ij} is the transfer probability of land use and cover types from i to j, n is the type of land use and cover change, $S_{(t+1)}$ is t+1 in the model and Pij is the transfer probability matrix.

Accuracy verification

The kappa coefficient is an important index of spatial accuracy proposed by Cohen scholars in 1960s and is used to comprehensively evaluate user and mapping accuracy. In this study, the accuracy of the CA–Markov model was evaluated using the kappa statistic, which includes kappa location ($K_{location}$), kappa ($k_{standard}$) and kappa (K_{no}), and the calculation formula is as follows (Singh et al., 2018):

$$K_{no} = \frac{M_m N_n}{P_p - N_n} \quad \text{(Eq.8)}$$

$$K_{location} = \frac{M_m N_m}{P_m - N_m} \quad \text{(Eq.9)}$$

$$K_{standard} = \frac{M_m N_n}{P_p - N_m} \quad \text{(Eq.10)}$$

In the formula, N_n represents meaninglessness, M_m, N_m and P_m represent general grid cell level information, and P_p is perfect grid cell level information for the whole land-use type.

The value of the kappa coefficient is between 0 and 1, and the closer the kappa coefficient is to 1 in the simulation process, the higher the precision and the better the simulation effect (Bhanage et al., 2021). The kappa coefficient of consistency level is as

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follows: kappa≤0.4 indicates a poor simulation effect and inaccurate results; 0.4＜kappa≤0.75 indicates an average simulation effect; 0.75＜kappa≤1 indicates s better simulation effect with more reliable results; and kappa=1 means that the simulation is completely correct under ideal conditions. The kappa coefficient of this study was 0.837.

Results and analysis

Analysis of land-use change

From our analysis of land use and change in Jiaozuo City from 1990 to 2020 (*Figure 2*), it can be seen that land-use types are mainly cultivated, and construction land, forested land and grassland were mainly present in the north of Jiaozuo City, cultivated land and construction land were mainly found in the center, and water surface area and unused land were mainly concentrated in the south. According to the proportion of each land-use type in Jiaozuo City (*Table 3*), cultivated land was the main land-use type, followed by forested land and construction land. From 1990 to 2020, a rapid expansion of urban land and continuous reduction in cultivated land were the main characteristics of land-use change. Of the land-use types, construction land increased by 266.94 km^2, representing an increase of 57.75%, and cultivated land decreased by 142.77 km^2, a reduction of 5.34%. Forested land, grassland and water surface areas decreased by 9.75%, 10.27% and 33.42%, respectively. Cultivated land occupied by construction land mainly occurs on the periphery of counties and cities, and the cultivated land occupied gradually decreases with the increase of distance from the urban center. There is also a tendency to spread to the periphery.

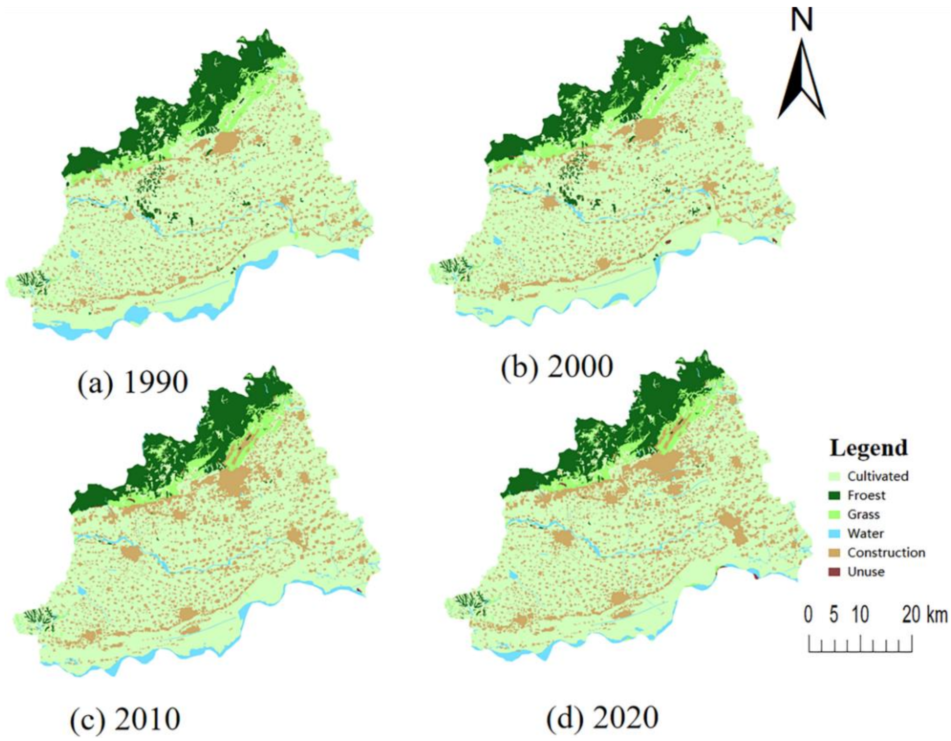

Figure 2. *Land use and distribution in Jiaozuo*

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Table 3. *Proportion of land use types in each period in Jiaozuo/km^2*

Year \ Type	Cultivated land	Forested land	Grass land	Water surface area	Construction land	Unused land
1990	2671.15	535.11	196.73	190.99	462.20	1.45
2000	2704.54	533.76	198.26	101.64	516.37	3.07
2010	2587.00	491.38	173.45	133.43	669.15	3.28
2020	2528.38	485.92	176.53	127.16	729.14	4.65

Validation of simulation results

Model validation is the main component of CA–Markov model and it involves testing the model on the data on which it was constructed (Das and Sarkar, 2019). The predicted land-use data are considered consistent only when validated using existing ground data sets (Shi and Wu, 2014). Two land-use data sets were validated using the CA–Markov model in a metacellular automaton and the validation model: the first was the actual land-use data for 2020 and the second was the predicted land-use data. First, the accuracy of the 2020 land-use data was validated. The 1990 and 2010 land-use data were defined as input data for simulating the 2020 land use. The validity of the simulation was assessed using a spatial raster comparison, in which land-use types at specific spatial locations were compared with the actual 2020 land-use map. The quantitative accuracy of the area of each land-use type in the simulation was assessed by comparing it with the actual area in 2020 (*Table 4*). The prediction error for 2020 was expressed as the absolute value of the error between the predicted and actual values for each land-use type area. With the exception of errors of 1.14% and 1.6% for cropland and mining land, respectively, the prediction errors of the land-use types were all within 1%, indicating that the simulation method had a high degree of accuracy and credibility. Therefore, it was established that the CA–Markov model could effectively simulate land-use changes in the study area and could be used to simulate future land use.

Table 4. *Relative Error of Land -Use Simulation of the CA–Markov Model in Jiaozuo in 2020*

Land-use type	2020 Actual size (%)	2020 Simulation area (%)	Inaccuracies (%)
Cultivated land	62.4	63.67	1.27
Forested land	11.99	12.21	0.22
Grassland	4.36	4.23	0.13
Water surface area	3.14	3.41	0.27
Construction land	18.00	16.39	1.61
Unused land	0.11	0.08	0.03

Simulation of land use change in Jiaozuo City under multiple scenarios

Based on the land-use change in Jiaozuo City from 1990 to 2020, three future land-use scenarios were simulated (*Figure 3*). Under all three scenarios, the distribution of land-use types in Jiaozuo City over the next 30 years did not change significantly in comparison with 2020, with woodland and grassland mainly found in the north, and construction and cultivated land distributed in the middle and in the south. As show in *Table 5*, under the natural development scenario, the scale of construction land expanded

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from 18% in 2020 to 18.80% in 2050, an increase of 4.44%, and the cultivated land decreased from 62.4% to 60.84% in 2050, a decrease of 2.5%. Other types of land use continued to develop in line with the original trend. Under the ecological priority scenario, in order to protect the urban ecological environment, the rate of expansion of construction land in Jiaozuo was greatly reduced by 2050, from 18% in 2020 to 18.04% in 2050, and the forest and grassland areas were further expanded. In the economic priority scenario, compared with the first two scenarios, the area of construction land further expanded to 19.68% by 2050, an increase of 9.33%, and the area of arable, forest and grassland decreased further.

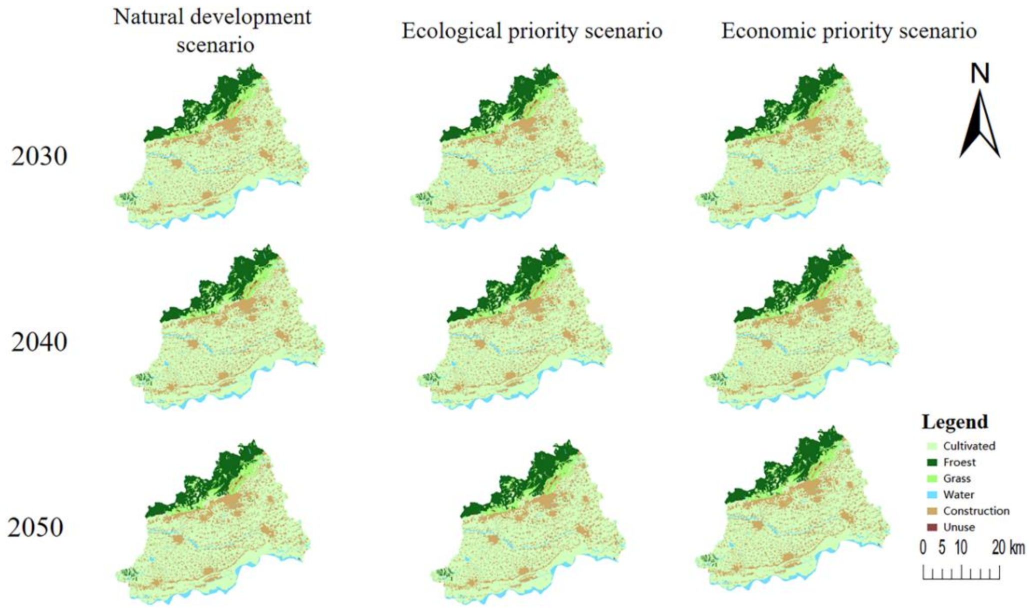

Figure 3. *Land-use types in Jiaozuo City under multiple scenarios 2030–2050*

Table 5. *Proportions of land-use types in Jiaozuo under multiple scenarios 2030–2050* （%）

Scenario	Year / Type	Cultivated land	Forested land	Grass land	Water surface area	Construction land	Unused land
Natural development scenario	2030	61.38	12.10	4.20	3.90	18.34	0.08
	2040	61.11	12.09	4.17	3.99	18.56	0.08
	2050	60.84	12.16	4.13	4.00	18.80	0.07
Ecological priority scenario	2030	61.42	12.14	4.27	3.90	18.20	0.08
	2040	60.68	12.20	4.13	4.10	18.81	0.08
	2050	61.52	12.20	4.27	3.90	18.04	0.07
Economic priority scenario	2030	61.53	12.08	4.20	3.90	18.20	0.08
	2040	60.57	12.08	4.11	4.02	19.12	0.08
	2050	59.98	12.07	4.14	4.04	19.68	0.08

Simulation of habitat quality changes in Jiaozuo City under multiple scenarios

The InVEST model was used to evaluate the habitat quality in Jiaozuo City under three different scenarios from 2030 to 2050, and the results are shown in *Figure 4*. The areas

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with high habitat quality are mainly distributed in Xiuwu County, Boai County and the north of Qinyang City. The areas are mainly forested land and grassland, which are less affected by human activities and rich in biodiversity. The areas with high habitat quality are mainly distributed in Xiuwu County, Boai County, Qinyang City, the north of Zhongzhan District, Mengzhou City, Wuzhi County and a small part of the south of Wen County, showing relatively rich biodiversity. The general and lower grade habitat quality is mainly found in the Jiefang District, the Zhongzhan District, Ma Cun District, Shanyang District, Qinyang City, Mengzhou City, Boai County, Wuzhi County and Wen County. These areas mainly consist of arable and urban construction land, with intensive human activity utilization. Compared with 2020, the average habitat quality of Jiaozuo City from 2030 to 2050 varies under the different scenarios. Under the natural development and economic priority scenario, the habitat quality of Jiaozuo City declined further, whereas under the ecological priority scenario, the habitat quality increased.

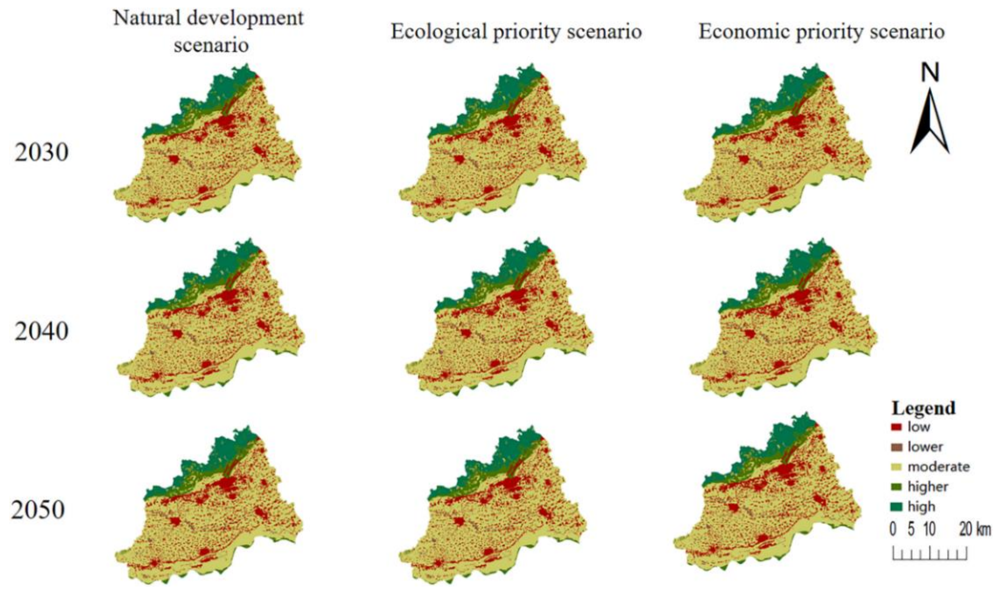

Figure 4. *Habitat quality distribution in Jiaozuo City under different scenarios from 2030 to 2050*

In general, the spatial distribution of low-quality habitat areas and construction land is highly consistent, that is, the expansion of construction land will directly affect the distribution of low-quality habitat areas in this region. It can be seen from *Table 6* that under the three scenarios, the ranking of average habitat quality is as follows: ecological priority scenario > natural development scenarios > economic priority scenario. In the natural development scenario, the average values of the habitat quality index in 2030, 2040 and 2050 are 0.4398, 0.4374 and 0.4363, respectively, indicating that the overall habitat quality of Jiaozuo City decreased during the period. The quality of low-grade habitat increased from 18.38% in 2030 to 18.84% in 2050, and the quality of low-grade habitat increased from 1.08% to 1.09% in 2030, mainly because Jiaozuo City will still need some construction land in the future to support the further promotion of urbanization and continued economic and social development. In the ecological priority scenario, the average values of the habitat quality index in 2030, 2040 and 2050 were 0.4411, 0.4375 and 0.4429, respectively, indicating that the overall habitat quality of Jiaozuo city will increase during the forecast period under the ecological priority scenario, and the area of

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poor habitat quality will be mainly concentrated in the urban center. From 2030 to 2050, the proportion of high habitat quality in Jiaozuo City gradually increased from 6.94% in 2030 to 7.06% in 2050. The high-grade habitat increased from 9.11% in 2030 to 9.13% in 2050. In addition, under the ecological priority scenario, the area of high habitat quality increased mainly in the forested land expansion area. Therefore, it can be said that forested land is better protected under the ecological priority scenario. In the economic priority scenario, because of the acceleration of urban expansion and rapid development of the social economy, the area of construction land continued to increase, while the cultivated, forested and grassland areas decreased, resulting in the decline in average habitat quality under this scenario. The quality of low-grade habitat increased from 18.24% in 2030 to 19.72% in 2050, and the quality of high-grade habitat decreased from 9.39% in 2030 to 8.99% in 2050.

Table 6. *Percentage of habitat quality classes under different scenarios for Jiaozuo City from 2030 to 2050*

Scenario	Class	2030			2040			2050		
		P	Avg	SD	P	Avg	SD	P	Avg	SD
Natural development scenario	Low	18.38			18.60			18.84		
	Lower	1.08			1.07			1.09		
	Moderate	64.54	0.4398	0.2575	64.25	0.4374	0.2578	64.00	0.4363	0.2590
	Higher	6.89			7.02			6.95		
	High	9.11			9.06			9.13		
Ecological priority scenario	Low	18.24			18.85			18.08		
	Lower	1.10			1.08			1.07		
	Moderate	64.61	0.4411	0.2571	63.88	0.4375	0.2594	64.65	0.4429	0.2574
	Higher	6.94			7.06			7.06		
	High	9.11			9.13			9.13		
Economic priority scenario	Low	18.24			19.16			19.72		
	Lower	1.07			1.04			1.02		
	Moderate	64.82	0.4240	0.2548	63.78	0.4340	0.2590	63.18	0.4293	0.2607
	Higher	6.48			7.02			7.09		
	High	9.39			9.00			8.99		

Note: P stands for proportion; Avg stands for average; SD stands for standard deviation

Simulation of changes in degree of habitat degradation in Jiaozuo City under multiple scenarios

Based on the spatial distribution of land-use types in Jiaozuo City from 2030 to 2050 under different future development scenarios, the InVEST model was used to calculate the habitat degradation index for Jiaozuo City from 2030 to 2050, as shown in *Figure 5*. The areas with a high degree of habitat degradation were mainly concentrated in the areas around the urban districts and counties and particularly in the areas around Qinyang, Mengzhou, Wuzhi and the municipal districts. Areas with low habitat degradation index values were mainly concentrated in the protected mountainous areas in the north and the water surface area in the south. The ecological environment in these areas is better, mainly comprising forest, grassland and water surface area which receive less human interference, reducing the degree of habitat quality degradation.

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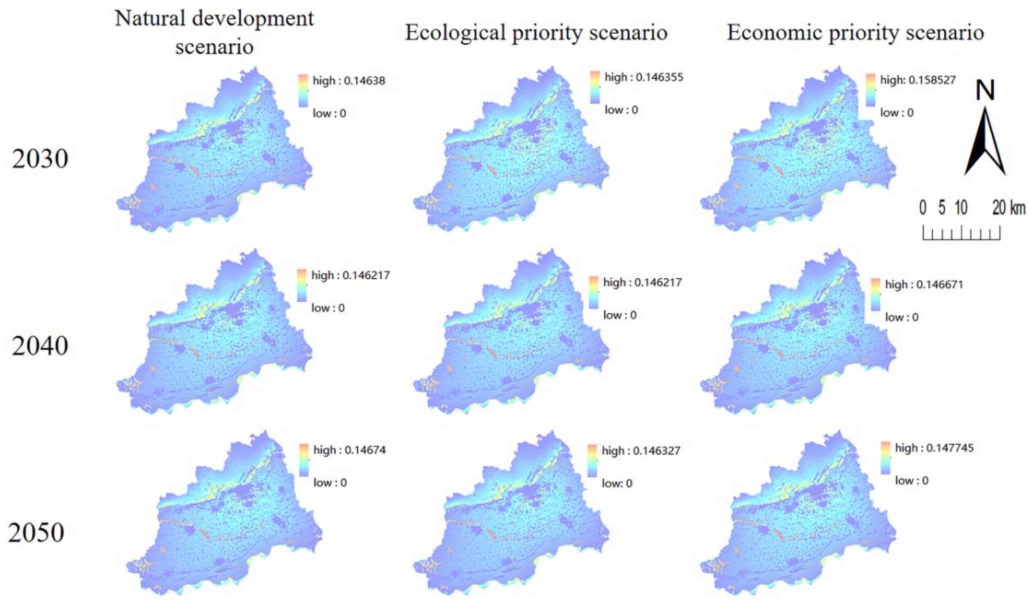

Figure 5. *Degree of habitat degradation in Jiaozuo City under different scenarios from 2030 to 2050*

Table 7 shows that from 2030 to 2050 the mean and maximum values of habitat degradation in Jiaozuo City were, from high to low, under the economic priority scenario, the natural development scenario, and the ecological priority scenario. Although the maximum and average values of habitat degradation in the economic priority scenario were the highest of the three scenarios, they showed a decreasing trend, indicating that the intensity of habitat degradation was decreasing, and the habitat quality degradation trend was significantly slowing down. Under the natural development scenario, the mean value of habitat degradation in Jiaozuo City increased from 0.02115 in 2030 to 0.02147 in 2050, and the maximum value increased from 0.14638 in 2030 to 0.14674 in 2050. Both the mean and maximum values of habitat degradation showed an upward trend, indicating that the intensity of habitat degradation was increasing. The habitat quality degradation trend was obviously intensified. The standard deviation of habitat degradation in the natural development scenario and the economic priority scenario also showed an overall upward trend, indicating that the difference of habitat degradation among the grid units was increasing in space.

Table 7. *Statistics for the degree of habitat degradation parameters under different scenarios in Jiaozuo City from 2030 to 2050*

Year	**Natural development scenario**				**Ecological priority scenario**				**Economic priority scenario**			
	Min	Max	Avg	SD	Min	Max	Avg	SD	Min	Max	Avg	SD
2030	0	0.14638	0.02115	0.01661	0	0.14636	0.02111	0.01665	0	0.15853	0.02789	0.01981
2040	0	0.14622	0.02151	0.01673	0	0.14622	0.02154	0.01689	0	0.14667	0.02175	0.01707
2050	0	0.14674	0.02147	0.01682	0	0.14633	0.02089	0.01640	0	0.14775	0.02213	0.01729

Note: Min represents the minimum value; Max represents the maximum value; Avg stands for average; SD stands for standard deviation

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Discussions

Land-use evolution and simulation in Jiaozuo City

In Jiaozuo City, land-use types, topography, and intensity of human activity have a strong spatial coupling (Zhang et al., 2022), generally showing a "high in the south and low in the north" distribution pattern. High-intensity land-use areas are often found in densely populated, economically developed locations with excellent conditions, and low-intensity areas are mainly concentrated at higher elevations and in sparsely populated areas (Guarderas et al., 2022). Influenced by socioeconomic and urbanization factors, land-use changes are mainly reflected in the counties around the city center, generally with the expansion of construction land into the arable land, whereas further away from urban areas the degree of change in land use is relatively stable (Devkota et al., 2023).

The results of our study show that land use in Jiaozuo City has changed in the past three decades. Cultivated land has always been the main land-use type in Jiaozuo City. However, as one of the first resource-exhausted cities, Jiaozuo began its transformation in the 1990s. In order to speed up the development of tourism, Jiaozuo has developed advantageous regional tourism resources and accelerated the construction of public infrastructure, thus promoting the sustainable development of the tourism industry. These measures assisted in resolving the economic development problem of Jiaozuo City, but because of economic construction and urban expansion, construction land surged, and the cultivated land area continued to decrease (Guo et al., 2023).

The CA–Markov model was used to predict the land-use pattern of Jiaozuo City from 2030 to 2050. The results showed that the land-use pattern of the study area in the next 30 years will continue to be dominated by cultivated and construction land, supplemented by other land types. Human disturbance will continue to be the main factor affecting the pattern of land use in Jiaozuo City (Zhang et al., 2022). With the rapid development of the social economy and urbanization, the dynamic land-use change in the study area is obvious, and its main feature is the conversion of cultivated land to construction land, indicating that the contradiction between land protection and economic construction of "farming, forest and grass" is intensifying. The government should strengthen the macroplanning and management of land use to alleviate the contradiction between land-use supply and demand (Wang et al., 2018).

Jiaozuo habitat quality simulation

According to the simulation results, the rapid expansion of construction land is the primary reason for the decline of habitat quality (Tang et al., 2023). The scale of construction land should be scientifically controlled through planning, and the potential of existing construction land should be vigorously explored. The supply of construction land should be strictly controlled according to the following principles: meeting the requirements of the scale and layout of national spatial planning, controlling urban development boundaries, and preventing the expansion of urban construction land (Li et al., 2022).

Through the simulation results from different scenarios in Jiaozuo City over the next 30 years, it can be seen that the adoption of strict ecological protection policies (such as the ecological priority scenario) will promote the improvement of urban habitat quality (Yu et al., 2022). Therefore, the concept of ecological civilization construction should be further implemented; ecological red line management and control and relevant ecological protection policies should be strictly implemented; existing forested land and grassland

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should be protected; comprehensive territorial space improvement and ecological restoration should be increased; and the ecological layout of forested land, grassland and water surface area should be optimized (Yang et al., 2021). This is important because the scale of construction land directly affects the distribution of areas of low-value habitat, thus affecting the overall quality of the urban habitat (Li et al., 2022). Therefore, when conducting national land spatial planning at all levels, Jiaozuo City should reasonably control the total scale of construction land and achieve urban renewal through the redevelopment and reuse of existing construction land, thus reducing the requirement for new construction land.

Simulation of the degree of habitat degradation in Jiaozuo

According to the simulation results, the intensity of habitat degradation is closely related to the reductions in forested land and grassland (Ji et al., 2023), and the area of forested land and grassland in the ecological priority scenario is higher than that in the other two scenarios. Therefore, in the future development of Jiaozuo City, on the basis of strictly observing the red line of cultivated land, ecological restoration work such as returning farmland to forest and grassland should be vigorously implemented to improve the current ecological environment (Zhong et al., 2022).

From the perspective of the degree of habitat degradation, habitat degradation close to cities and around river basins does not give cause for optimism. To strictly control the scale of urban construction land, it is also necessary to strengthen river basin protection, promote green production modes and lifestyle, establish, and improve green development mechanisms, and achieve coordinated development of the social economy and biodiversity protection in river basins in order to achieve the goal of ecological balance and sustainable development (Fazlolah et al., 2020).

Conclusions

In this study, the CA–Markov model was used to simulate and predict land-use change in Jiaozuo City from 2030 to 2050, and the InVEST model was used to evaluate and predict the spatial–temporal pattern of habitat quality in Jiaozuo City under different scenarios. The conclusions are as follows:

(1) The land-use change in Jiaozuo City from 1990 to 2020 is obvious and is manifested in the slight decrease in three types of land, namely, grassland, forested land and water surface area, the fluctuating increase in arable land and the significant increase in construction land. The land-use type changes are concentrated in the central plain area.

(2) From 2030 to 2050, there will be significant differences in the rate of expansion of construction land in Jiaozuo under different development scenarios. Of these, the rate of expansion of construction land is most obvious in the economic priority scenario, followed by the natural growth scenario and finally the ecological priority scenario, but the rate of increase in construction land does not exceed 5% in any of the scenarios.

(3) In the three simulation scenarios, the regions with large differences in the distribution of habitat quality grades were mainly in the northern, central, and central urban areas of Jiaozuo City, and the average habitat quality was ranked as follows: ecological priority scenario ＞ natural development scenario ＞ economic priority scenario. Under the natural development and economic priority scenarios, the habitat quality of Jiaozuo City showed a differentiated downward trend with a different scale of urban expansion from 2030 to 2050. Under the ecological priority development scenario,

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the growth rate of the construction land area slowed down significantly, and the area of forested land gradually increased, which gradually improved the quality of habitat. Therefore, ecological protection and urban expansion constraints play an important role in the improvement of habitat quality.

(4) Compared with the natural development scenario and the economic priority scenario, the ecological priority scenario shows a different degree of habitat degradation. Compared with the former two development models, the ecological priority scenario has a weaker habitat degradation intensity and improved habitat quality, which is conducive to the restoration of regional biodiversity and ecosystem service functions.

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