Multi-Scenario Prediction of Ecosystem Service Value in Huzhou City Based on the PLUS Model

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Keywords: Huzhou City, Ecosystem service value, Multi-scenario simulation, PLUS model.

Abstract

Assessment and prediction of ecosystem service value is important for future land management policies and spatial optimization. Taking Huzhou City as the study area, this study combined the PLUS model and Markov chain to simulate land use patterns under three scenarios for 2030, and applied a revised equivalence factor method to assess ESV. The results showed that, from 2010 to 2020, construction land expanded continuously, whereas cropland and forest land decreased to different degrees. During the same period, the total ESV increased from 50.91 billion yuan to 53.31 billion yuan. Water bodies contributed the largest share of total ESV, and hydrological regulation remained the dominant ecosystem service function. The multi-scenario prediction results showed distinct disparities in future land use and ESV. Compared with the urban development and natural development scenarios, ecological protection scenario effectively limited the conversion of cropland and forest to construction land, and led to an increase in the conversion of water bodies. Among the three scenarios, the ecological protection scenario had the highest total ESV in 2030 (55.88 billion yuan), followed by the natural development scenario (55.29 billion yuan), while the urban development scenario resulted in the lowest total ESV (54.89 billion yuan).

1. Introduction

Ecosystem services refer to the life-support functions and benefits that ecosystems provide to human society through their structures, functions, and ecological processes (Castro et al., 2014; Costanza et al., 2017). Assessing ecosystem services is essential for understanding the role of ecosystems in sustaining human well-being. It also provides important support for ecological conservation, resource management, and sustainable development. Ecosystem service value (ESV) is the monetary expression of ecosystem service functions and is widely used to quantify ecological benefits in economic terms (Martín-López et al., 2014; Xie et al., 2015a). As an effective approach for linking ecological functions with socioeconomic development, ESV assessment has become an important research topic in the fields of ecology and environmental economics (Xie et al., 2008; Zong et al., 2024). Among the available methods, the equivalence factor method is one of the most commonly used approaches for assessment of ESV. This method was proposed by Xie et al. (2015b) based on China's ecological and socioeconomic conditions, and has since been widely recognized and extensively applied in ecosystem service value research in China (Zhang et al., 2022).

Land use change is one of the most direct drivers of variation in ecosystem services. In recent decades, rapid urbanization and socioeconomic development in China have continuously reshaped land use patterns, altering ecosystem structure, ecological processes, and the supply of ecosystem services (Han et al., 2022; Huang et al., 2023). Previous studies have shown that rapid urbanization may lead to a decline in the value of ecosystem services, especially in rapidly developing metropolitan and peri-urban areas (Zhou et al., 2025). Accordingly, evaluating the impacts of land use change on ecosystem service value and predicting its future trends are of great significance for regional ecological conservation and land use planning (Guo et al., 2022). Land use simulation models, which could simulate future land use change based on historical land use data and driving factors, provide an effective tool for ESV prediction (Gao et al., 2023). Representative land use simulation models include the CA model(Yang et al., 2014; Chen et al., 2014; Geng et al., 2022; Liang et al., 2025), the FLUS model (Liu et al., 2017), and the PLUS model (Liu et al., 2023; Bi et al., 2025). Among them, the PLUS model integrates rule mining based on land expansion analysis with a cellular automata mechanism driven by multi-type random patch seeds, enabling relatively accurate simulation of both land use quantity and spatial configuration (Liang et al., 2021; Chen et al., 2023). Consequently, it has been widely adopted in land use change research and multi-scenario simulation studies. Multi-scenario simulation of ESV could help quantify the ecological costs and benefits associated with different development pathways, thereby providing scientific support for territorial spatial planning and ecological conservation policy-making.

Huzhou City is characterized by abundant natural resources and diverse ecosystem types, and thus serves as an important area for ecological function maintenance. However, as a city located in the economically developed Yangtze River Delta, it is also exposed to intensive human activities and faces increasing pressure from both urban expansion and ecological conservation. By integrating the PLUS model and Markov chain, this study simulated land use patterns under three scenarios for 2030: natural development, urban development, and ecological protection. The equivalence factor method is applied to predict the regional ESV, aiming to provide a scientific basis for future development planning and sustainable development of Huzhou's eco-economic zone.

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2. Data and methods

2.1 Study area

Huzhou is located in northern Zhejiang Province, South China, bordering Jiangsu and Anhui Provinces, and serves as a key node connecting the northern and southern wings of the Yangtze River Delta with the east-central region (Figure 1). The city includes Wuxing District, Nanxun District, Deqing County, Changxing County, and Anji County, with a total area of approximately 5,820 km^2. Endowed with abundant forest and water resources, Huzhou is an important ecological functional zone.

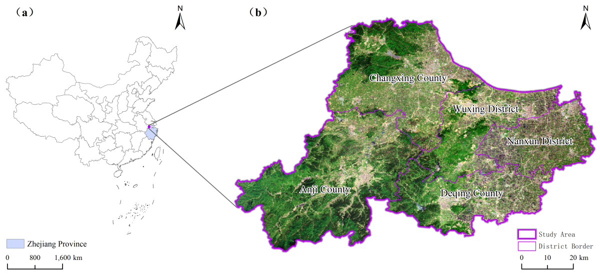

Figure 1. Location of the study area in China

2.2 Data and preprocessing

This study integrated multiple data, including land use, topographic, ecological, climatic, socioeconomic, and statistical data. Specifically, land use data were obtained from the GLC_FCS30D dataset (Zhang et al., 2024) and reclassified into six categories. Elevation data were acquired from the Geospatial Data Cloud at a spatial resolution of 30 m, and slope was further derived from the elevation data. Ecological variables included net primary productivity (NPP), derived from the MOD17A3HGF product, and annual evapotranspiration, obtained from MODIS products provided by the United States Geological Survey (USGS). Precipitation data were obtained from the Big Earth Data Platform for Three Poles (https://portal.casearth.cn/poles). Socioeconomic data included point of interest (POI) data acquired from the Amap platform through Python-based web scraping, population density data from the WorldPop dataset, and road network data from the National Platform for Common Geospatial Information Services of China. In addition, statistical data, including grain output, grain-sown area, and market values, were obtained from the local statistical yearbook. Additionally, all raster data were projected into a unified coordinate system and resampled to a 30 meter resolution.

2.3 Methods

2.3.1 Land use simulation based on the PLUS model The PLUS model is a patch-generating land use simulation framework derived from the FLUS model, with the capacity to incorporate policy-driven constraints and their effects on land use change. It integrates the land expansion analysis strategy (LEAS) module and the cellular automata based on multi-type random patch seeds (CARS) module. The LEAS module is used to identify the transition rules of different land use types. Specifically, land use maps from two time periods are used to detect areas where land use change has occurred, and samples are extracted from these changed areas. A random forest algorithm is then employed to analyze the relationships between the expansion of each land use type and its driving factors, thereby estimating the probability of land use change. The CARS model combines the generation of multivariate random seeds with a threshold-decreasing mechanism to simulate local land use.

Using land use data for 2010 and 2020, the land use patterns in 2030 were simulated with the PLUS model. Based on the regional characteristics of Huzhou City and previous studies (Han et al., 2022; Chen et al., 2023), 12 driving factors were selected, including elevation, slope, precipitation, distance from water bodies, POI density, population density, distance from highways, distance from primary roads, distance from secondary roads, distance from tertiary roads, distance from fourth-class roads, and distance from railways. The spatial distributions of these factors are presented in Figure 2.

2.3.2 Scenario setting Land use patterns for 2030 were simulated under three scenarios: natural development, urban development, and ecological protection. Among them, the natural development scenario was defined as the baseline scenario, in which land use change followed historical transition trends without policy intervention or planning constraints. In this scenario, Markov chain analysis was employed to estimate the future demand for each land use type. The urban development scenario was generated by increasing the probability of conversion from other land use types to construction land by 20%, representing accelerated urban growth. By contrast, the ecological protection scenario introduced conservation constraints into the baseline by defining permanent basic farmland and ecological protection red lines as restricted conversion zones. Accordingly, the probability of cropland, forest, and grassland being converted to construction land was reduced by 20%, while that of water bodies being converted to construction land was reduced by 30%.

2.3.3 Type weights and transition matrix settings The type weight represents the expansion potential of a given land use type and ranges from 0 to 1, with higher values indicating stronger expansion capacity. In this study, the neighborhood factor for each land use class was calculated using the deviation standardization method based on the absolute area change of each class during the study period. The formula is expressed as follows:

$$w_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (1)$$

Where, w_i denotes the neighborhood factor (weight) of land use class i; X_i represents the area change of land use class i during the study period; and $X_{\max}$ and $X_{\min}$ denote the maximum and minimum values of area change among all land use classes, respectively.

The transition matrix describes whether conversion between different land use types is allowed, with values assigned as 0 or 1. A value of 0 indicates that conversion from one land use type to another is prohibited, whereas a value of 1 indicates that such conversion is permitted. Based on the characteristics of land use change in the study area and with reference to previous studies (Chen et al., 2023), the transition matrix was determined, as shown in Table 1.

2.3.4 Assessment the ecological service value Equivalence factor method was employed in the present study to estimate the ESV of the study area. Within this framework, one standard equivalent is defined as the economic value of the annual natural grain yield per unit area of farmland under national average conditionsXie et al. (2015b). To better reflect regional characteristics, the economic value of grain crops in Huzhou

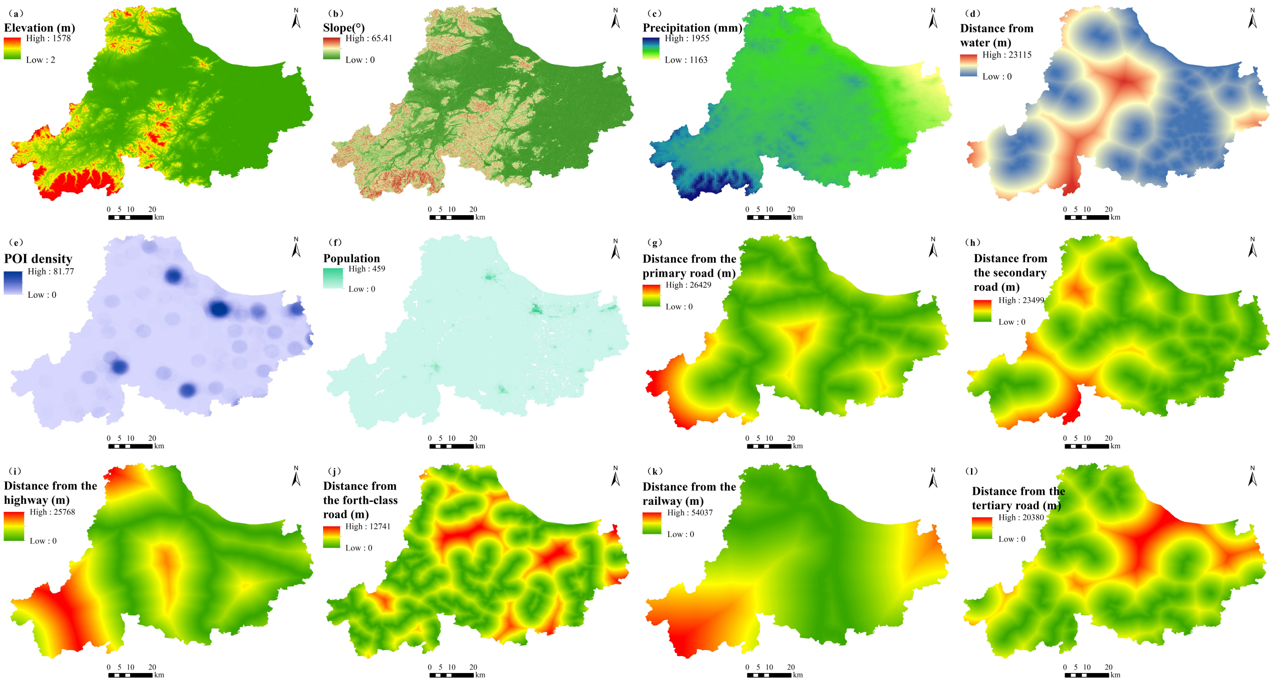

Figure 2. Spatial distributions of drivering factors

Table 1. Transition matrix

	①	②	③	④	⑤	⑥
①	1	1	1	1	1	1
②	1	1	1	0	0	1
③	1	1	1	0	1	1
④	0	0	0	1	0	1
⑤	1	0	1	0	1	1
⑥	0	0	0	0	0	1

Note: ① Cropland, ② Forest, ③ Grassland, ④ Water body, ⑤ Bare areas, ⑥ Construction land

City was determined by integrating local crop yield data with total agricultural output values. In addition, the equivalence factor coefficients were locally calibrated using a biomass adjustment factor, a precipitation regulation factor, and a soil conservation regulation factor, thereby improving the applicability of the method to the study area. The ESV based on the equivalent factor method was calculated using the following equations.

$$VC_i = \frac{1}{7} \times \frac{T_i}{M_i} \tag{2}$$

$$ESV = A_i \times VC_i \times P_i \tag{3}$$

Where ESV denotes the total ecosystem service value of the study area (yuan); VC_i represents the standard unit equivalent value, referring to the ecosystem service value per unit area of the ith land use type (yuan/ha); T_i is the annual economic output value of grain in the study area (yuan); M_i the annual grain planting area in the study area (ha); A_i is the area of the ith land use type (ha); P_i is the corresponding adjustment coefficient.

Table 2. Historical land use area in 2010 and 2020 (unit: km^2)

Land use type	2010	2020
Cropland	2094.27	2032.42
Forest	2477.42	2273.50
Grassland	52.25	77.38
Water body	400.57	491.17
Bare areas	3.35	2.36
Construction land	676.57	927.59

3. Results and discussion

3.1 Analysis of Land Use Changes from 2010 to 2020

As shown in Table 2, land use change in Huzhou City from 2010 to 2020 was primarily characterized by the expansion of construction land and the reduction of cropland and forest land. Construction land increased from 676.57 km^2 to 927.59 km^2, with a net increase of 251.02 km^2, indicating rapid urban expansion. In contrast, cropland and forest land decreased by 61.85 km^2 and 203.92 km^2, respectively. Meanwhile, water bodies and grassland increased by 90.60 km^2 and 25.13 km^2 , respectively, while bare areas decreased slightly. Overall, these changes reflect a clear trend of urban expansion accompanied by the contraction of ecological and agricultural land.

3.2 Results of multi-scenario simulations

The PLUS model was employed to simulate the 2020 land use pattern using the 2010 land use data, and the simulation accuracy was subsequently evaluated. The results showed a Kappa coefficient of 0.79, an overall accuracy of 0.85, and a FOM value of 0.14. The results indicate that the PLUS model used in this study is relatively accurate and reliable. This model can be used to simulate changes in the future spatial pattern of land use in the study area (Wang et al., 2019).

Based on the land use status of Huzhou City in 2020, the PLUS model was employed to simulate future land use patterns in

Table 3. Land use area under different scenarios in 2030 and changes compared to 2020 (unit: km^2)

Land use type	Natural development		Urban development		Ecological protection	
	2030	Change	2030	Change	2030	Change
Cropland	1994.15	-59.45	1994.15	-97.72	2071.74	-20.13
Forest	2264.54	-96.53	2264.54	-105.49	2281.76	-88.26
Grassland	75.76	6.18	75.76	4.56	78.65	7.45
Water body	487.18	41.38	487.18	37.40	497.99	48.21
Bare areas	4.28	-1.71	4.28	0.21	2.01	-2.06
Construction land	978.49	110.12	978.49	161.03	872.25	54.79

2030 under three scenarios. The simulation results are presented in Table 3. Under the natural development scenario, cropland and forest land both declined, with decreases of 59.45 km^2 and 96.53 km^2, respectively, while grassland and water bodies increased slightly. Construction land showed the largest increase with 110.12 km^2. Under the urban development scenario, the declines in cropland and forest land further intensified, reaching 97.72 km^2 and 105.49 km^2, respectively, accompanied by a 161.03 km^2 increase in construction land. By comparison, the ecological protection scenario effectively moderated the rate of urban expansion, resulting in relatively smaller losses of cropland and forest land. Cropland and forest land decreased by 20.13 km^2 and 88.26 km^2, respectively, while the increase in construction land was limited to 54.79 km^2.

Figure 3 shows the land use patterns of Huzhou City in 2020 and the simulated results for 2030 under the natural development, urban development, and ecological protection scenarios. Overall, forest and cropland remain the dominant land use types under all three scenarios, and the general spatial pattern of land use changes slightly. Forest land is mainly concentrated in the western and southwestern parts of the study area, particularly in Anji County and the surrounding mountainous areas, whereas cropland is primarily distributed in the relatively flat northeastern and eastern regions. Water bodies are mainly located in the eastern and southeastern parts of the study area, especially in Nanxun District and Deqing District. Construction land is concentrated in the central urban area, particularly in northeastern of study area. Compared with the 2020 land use pattern, the urban development scenario shows the most pronounced expansion of construction land, mainly at the expense of surrounding cropland, especially in and around Wuxing District, Nanxun District, and Deqing District. The natural development scenario presents a moderate expansion trend and remains relatively similar to the current land use pattern. In contrast, the ecological protection scenario more effectively restrains the outward spread of construction land and preserves larger contiguous areas of cropland and forest land.

3.3 Analysis of changes in ecosystem services value

Using the equivalence factor method, this study estimated the ESV of the study area in 2010 and 2020. The ESVs of different land use types are shown in Table 4. In 2010, the total ESV was 50.909 billion yuan, with water bodies contributing the largest, with 27.518 billion yuan (54.05%), followed by forest land with 20.444 billion yuan (40.16%) and cropland with 2.849 billion yuan (5.69%). The ESVs of grassland and bare land were comparatively low. In 2020, the total ESV had increased significantly to 53.305 billion yuan. This growth was primarily driven by the marked increase in the ESV of water bodies, while the ESVs of grassland and bare land also increase slightly. In contrast, the ESVs of forest land and cropland decreased.

Table 4. ESV of different land use types in the study area from 2000 to 2020

Land use type	2010		2020	
	ESV	Proportion	ESV	Proportion
Cropland	28.49	5.60	27.16	5.10
Forest	204.44	40.16	195.57	36.69
Grassland	0.97	0.19	1.32	0.25
Water body	275.18	54.05	308.99	57.97
Bare areas	0.002	0.0004	0.003	0.0005
Total	509.09		533.05	

Table 5 presents the values and proportions of different ecosystem service types in 2010 and 2020. Regulating services contributed the largest share of total ESV in both years, followed by supporting services, whereas provisioning services and cultural services accounted for relatively small proportions. Among all secondary service types, hydrological regulation was the dominant contributor in both years, increasing from 30.49 billion yuan in 2010 to 33.09 billion yuan in 2020, with its proportion rising from 59.89% to 62.08%. This indicates that hydrological regulation was the principal driver of the overall increase in ESV. In addition, water supply increased from 0.79 billion yuan to 1.08 billion yuan, while environmental purification rose slightly from 2.65 billion yuan to 2.67 billion yuan. In contrast, food production, raw material production, gas regulation, climate regulation, soil conservation, nutrient cycle maintenance, biodiversity, and aesthetic landscape all showed slight declines. Overall, the increase in total ESV from 2010 to 2020 was mainly driven by the enhancement of water-related ecosystem services, particularly hydrological regulation and water supply.

3.4 ESV predictions under different scenarios

Table 6 presents the ESVs of Huzhou City under three development scenarios for 2030. It was indicated that the total ESV of Huzhou City in 2030 shows an increase compared to 2020 across all three scenarios. Overall, the ecological protection scenario yields the highest total ESV, reaching 55.876 billion yuan, followed by the natural development scenario with 55.286 billion yuan, whereas the urban development scenario records the lowest ESV with 54.886 billion yuan. The ecological conservation scenario maximized the total value of ecosystem services by simultaneously restricting the encroachment on both the ecological protection red line and permanently protected farmland. The urban development scenario, characterized by an exclusive focus on rapid urban economic growth, leads to a certain degree of decline in ecological benefits.

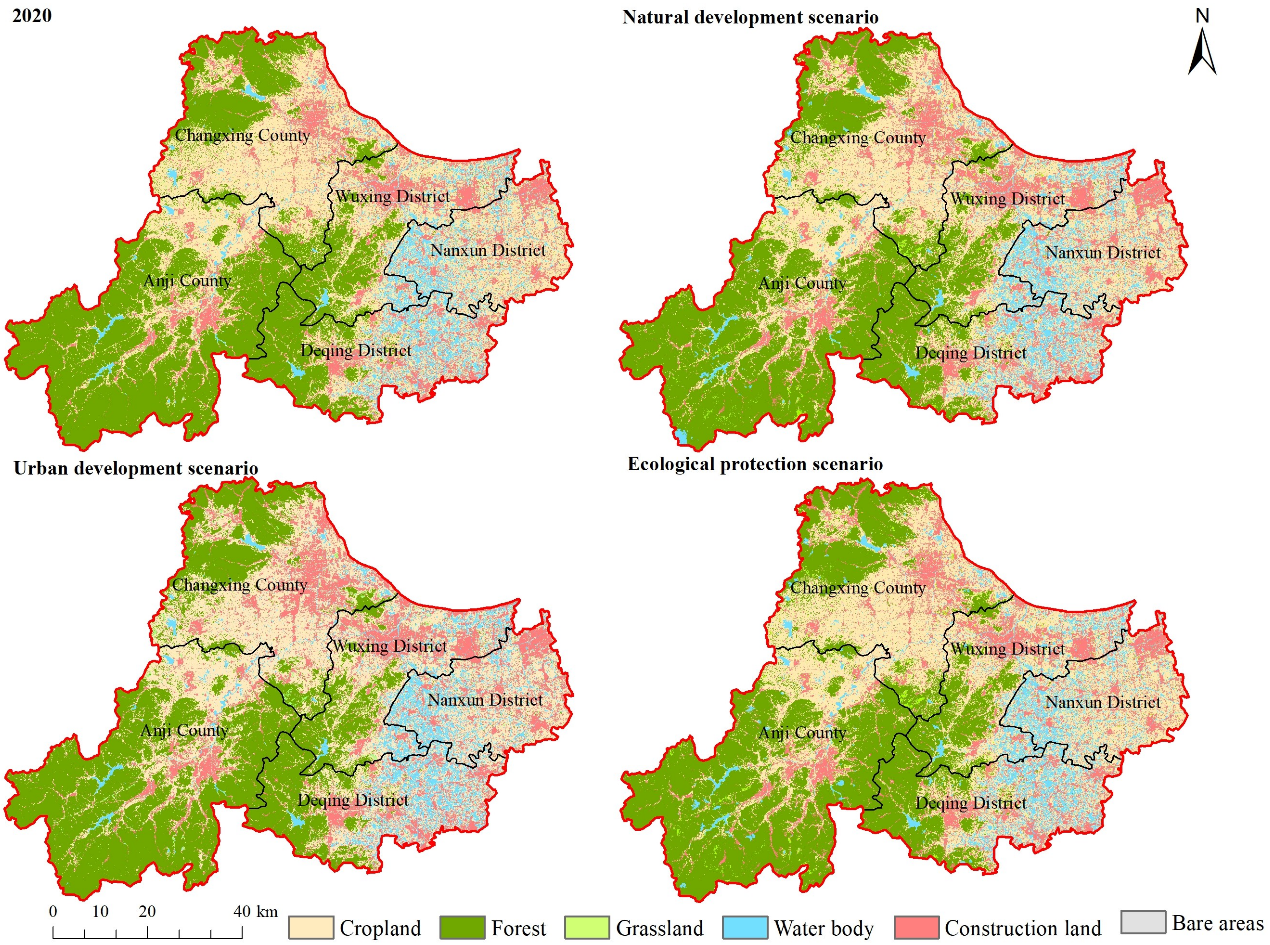

Figure 3. Spatial distribution of land use in (a) 2020, (b) natural development scenario, (c) urban development scenario, and ecological protection scenario.

Table 5. Values and proportions of different service types in 2010 and 2020 (unit: 10^8 yuan)

Service type	Secondary classification	2010		2020	
		Value	Proportion (%)	Value	Proportion (%)
Provisioning services	Food production	12.47	2.45	12.09	2.27
	Raw material production	8.49	1.67	8.18	1.53
	Water supply	7.93	1.56	10.83	2.03
Regulating services	Gas regulation	28.74	5.64	27.69	5.19
	Climate regulation	68.83	13.52	66.47	12.47
	Environmental purification	26.48	5.20	26.67	5.00
	Hydrological regulation	304.91	59.89	330.92	62.08
Supporting services	Soil conservation	6.81	1.34	6.57	1.23
	Nutrient cycle maintenance	3.25	0.64	3.12	0.59
	Biodiversity	27.87	5.47	27.30	5.12
Cultural services	Aesthetic landscape	13.32	2.62	13.21	2.48

In individual ecosystem services, hydrological regulation is the dominant contributor under three scenarios, accounting for approximately 63.8%–64.0% of the ESV. Its value reaches 35.738 billion yuan under the ecological protection scenario, which is 0.740 billion yuan higher than that under the urban development scenario. This suggests that ecological protection plays a particularly important role in sustaining water-related ecosystem functions. Among the provisioning services, the ecological protection scenario shows the highest values for food production and raw material production, indicating that the protection of cropland and forest land contributes positively to the maintenance of provisioning functions. For regulating and supporting services, the ecological protection scenario also exhibits slightly higher values for gas regulation, climate regulation, environmental purification, soil conservation, nutrient cycle maintenance, biodiversity, and aesthetic landscape than the other two scenarios.

3.5 Discussion

From 2010 to 2020, construction land expanded, while cropland and forest land declined. Nevertheless, the total ecosystem service value (ESV) increased from 50.91 billion yuan to 53.31 billion yuan. This increase was primarily driven by the rise in water-related ecosystem services, especially hydrological regulation and water supply. This suggests that variations in total ESV are shaped by the unequal contributions of different land use types and individual service functions. The scenario analysis further demonstrated that different development pathways may lead to markedly different ecological outcomes. Among the three scenarios, the ecological protection scenario produced the highest ESV, whereas the urban development scenario resulted in the lowest value. This suggests that restricting the conversion of cropland and forest land to construction land is beneficial for maintaining provisioning and regulating services. In particular, the ecological protection scenario showed obvious advantages in sustaining hydrological regulation, food production, and raw material production, highlighting the importance of ecological land protection in future land use planning.

However, some uncertainties remain in this study. The revised equivalence factor method is efficient and suitable for regional assessment, but it simplifies the complex processes of ecosystem service generation. In addition, the scenario simulation mainly focused on land use change and did not explicitly incorporate other factors such as climate change or policy intensity. Therefore, future studies should integrate more dynamic ecological and socioeconomic variables to improve the accuracy of ESV prediction.

4. Conclusions

This study combined the PLUS model and Markov chain to simulate land use change, and to predict future ESV under multiple scenarios. The main conclusions are as follows.

(1) From 2010 to 2020, land use change in Huzhou City significantly influenced ecosystem service value (ESV). Construction land and water bodies increase, whereas cropland and forest land decreased, and the total ESV increased from 50.91 billion yuan to 53.31 billion yuan.

(2) Different land use types and ecosystem service functions contributed unevenly to total ESV. Water bodies were the main contributors to ESV, and hydrological regulation was the dominant ecosystem service function. The increase in total ESV was mainly driven by improvements in water-related ecosystem services.

(3) The 2030 scenario simulation demonstrated that the ecological protection scenario was most beneficial for maintaining ecosystem service functions. The ecological protection scenario created the highest ESV (55.88 billion yuan), followed by the natural development scenario (55.29 billion yuan) and the urban development scenario (54.89 billion yuan). These results indicate that an ecological protection-oriented development pathway is more favorable for regional ecological conservation and sustainable development.

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Table 6. Ecosystem service values and proportions under different scenarios (unit: 10^8 yuan)

Service type	Secondary classification	Natural development		Urban development		Ecological protection	
		Value	Proportion (%)	Value	Proportion (%)	Value	Proportion (%)
Provisioning services	Food production	11.88	2.15	11.70	2.13	12.06	2.16
	Raw material production	7.92	1.43	7.86	1.43	7.98	1.43
	Water supply	13.05	2.36	13.12	2.39	13.09	2.34
Regulating services	Gas regulation	26.82	4.85	26.61	4.85	27.04	4.84
	Climate regulation	64.34	11.64	64.01	11.66	64.67	11.57
	Environmental purification	26.78	4.84	26.62	4.85	27.00	4.83
	Hydrological regulation	352.85	63.82	349.98	63.77	357.38	63.96
Supporting services	Soil conservation	6.36	1.15	6.32	1.15	6.40	1.15
	Nutrient cycle maintenance	3.02	0.55	2.99	0.55	3.05	0.55
	Biodiversity	26.76	4.84	26.62	4.85	26.93	4.82
Cultural services	Aesthetic landscape	13.08	2.37	13.01	2.37	13.17	2.36
Total		**552.86**		**548.86**		**558.76**	

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