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How does ecological compensation change in Hubei Province based on a multi-scenario simulation of ecosystem services value?

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Ecological compensation (EC) is a significant method for internalizing the economic externalities of environmental protection. The determination of EC standards has become a hot topic for sustainable ecological and economic development. However, EC amounts estimation under different future scenarios is still lacking, which affects the dynamic assessment of EC implementation effectiveness. Therefore, this study predicted the spatio-temporal evolution of ecosystem service value (ESV) and ecological footprint using the FLUS and GM (1,1) models in Hubei Province. Based on this, the spatial and temporal changes of the EC under different scenarios were explored. The results showed an overall decreasing trend in ESV, an increase trend in ecological carrying capacity, and a decrease trend in ecological footprint from 2010 to 2020. The ESV value decreased by 555,704,444 million. The ecological carrying capacity increased by 2610.168 hm², and the ecological footprint decreased by 243744.362 hm². Among the future scenarios in 2030, only ESV in the ecological protection scenario increased compared with 2020. Under the four scenarios, the change direction between the local and overall ecological carrying capacity was the same, and the ecological footprint changed less in general. The EC amounts exhibited a geographic pattern of high in the east and low in the west, with an alternating distribution. The Theil Index of EC in Hubei Province declined from 2010 to 2020 but increased under different scenarios. EC had significant variability in the southwestern, northwestern, southeastern, northeastern, and Jiangnan Plains of Hubei Province. This study considered the differences in different future policy orientations, incorporated multiple possibilities of future development into the study, and explored the ecological compensation amount and spatial differentiation under scenarios. This funding will provide a strong basis for achieving future green and sustainable development in Hubei Province and formulating ecological compensation policies in sub-regions to achieve precise policy implementation.

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Introduction

The ecosystem is a prominent carrier of human activities, providing lots of benefits for human survival and development. However, rapid socio-economic development will inevitably threaten the ecological environment (Kuai et al. 2024), causing environmental pollution, and land degradation. Nowadays, local governments still face a range of short-term problems like slow energy structure adjustment, lack of policy implementation and supervision, inadequate development facilities, etc. Meanwhile, they also deal with long-term conflicts between ecological protection and economic development to achieve sustainable development. Ecological compensation (EC), an internationally recognized effective means of regulating the social-natural relationship, can effectively coordinate the relationship between economic development and ecological protection (Guan et al. 2024). Thus, scientific accounting for EC can effectively alleviate the conflicts between ecological and economic interests between regions to promote regional environmental justice.

EC utilizes economic means to regulate the different stakeholders' interests in the sustainable use of ecosystem services (Zhou et al. 2021). The fact is internalizing the external costs of the ecological environment to regulate the contradiction between economy and ecology (Mao et al. 2002; Cheng et al. 2022). In other words, the reality of EC is subsidizing the ecological consumption capacity beyond the region to repair the damaged ecosystem. The theory of EC originated from the New Public Management in the mid-to-late 20th century (Yuan and Zhou, 2014), usually called ecological services payment abroad (Sun et al. 2021). As a crucial way of ecological protection, EC policy in China began in 1990 and has become an economic incentive to promote ecological environmental protection (Qian et al. 2023). The current research about EC concentrates on theoretical connotation (Wu et al. 2018; Liu et al. 2014), mechanism establishment (Zhang et al. 2024), policies and regulations (Chen et al. 2019; Feng and Zhang, 2022), standard quantification (Yang et al. 2020; Liang and Zhu, 2019), and interactive effect (Liu et al. 2024; Wang et al. 2024). Moreover, the research objects have gradually expanded from forest (Ma and Gao, 2020; Pei et al. 2019), grassland (Yang and Qiao, 2021), mines (He and Cheng, 2014) to cultivated land (Ruan et al. 2021), oceans (Liu et al. 2022), wetlands (Pang et al. 2021), scenic spots (Yang et al. 2020), key ecological function areas (Yang et al. 2024). Additionally, the research scale involves the provincial areas (Ding and Yang, 2022), watersheds (Lv et al. 2023), urban agglomerations (Yang et al. 2022), and other large or middle scales.

Accounting for EC amounts is a key link in the EC mechanisms construction (Lu et al. 2022). EC is typically described in monetary form, compensating for the loss and degradation of ecosystem service functions caused by human economic activities (Wang et al. 2024). Thus, the ecosystem service value (ESV) is the theoretical evidence for constructing the EC mechanism and the value basis for determining the EC amounts (Wang et al. 2009). ESV refers to all the benefits humans directly or indirectly obtain from the ecosystem (Xie et al. 2001), which can effectively respond to the changing trend of regional ecological conditions. Xie et al. (2008) combined the current ecological situation in China to amend and supplement the equivalent factor method, improving the accuracy of value calculation. The corrected equivalent factor method has been widely used in China (Zhang et al. 2024) and gradually introduced into the field of EC (Zhang et al. 2024; Du et al. 2023). Since the ESV assessment method involves a comprehensive ecological service (Xu et al. 2023), scholars usually measure the regional ESV to assess the environmental benefits and formulate the EC amounts. However, the ESV method might result in excessive EC amounts that cannot

serve as a realistic compensation standard (Zhou et al. 2019). The ecological footprint model considers the demand for human use of natural resources and ecosystems' supply and regeneration capacity (Niu et al. 2024), revealing the supply and demand of regional ecosystem service values (Zhao and Ru, 2024). Therefore, the EC amounts can be more scientifically measured by combining the ESV and ecological footprint methods.

In the socio-ecological system, there are complex interaction mechanisms among multiple elements, which are dynamic and uncertain. The EC amounts are complex and dynamic affected by ecological backdrop, socio-economics, humanities, customs, and other factors (Jiang et al. 2022). Existing studies on the EC amounts measurement mainly concentrate on the historical evolution and current situation, neglecting their changes in the future. Nevertheless, the key to formulating an ecological compensation policy is to prejudge the regional EC differences in the future to avoid possible ecological risks. The enthusiasm for ecological protection is not only focused on present EC, but also on future sustainable regional development. Therefore, it is urgent to assess regional EC accounts and their differences in the future to conduct reasonable and scientific ecological protection policy.

As an important water source and ecological barrier in the Yangtze River basin, Hubei Province is facing new opportunities for green development. How to coordinate the relationships between ecological protection and economic development has become the proper meaning of solidly promoting the coordinated development of the Yangtze River Economic Belt. Hubei Province has implemented various policies and measures to support the ecological compensation system based on the province's actual conditions. Hubei Province is exploring replicated diversified compensation models and has carried out several ecological compensation practices in various fields, including technical tools and systems. At the same time, Hubei Province has established a cross-provincial horizontal ecological compensation mechanism for the Yangtze River Basin and has carried out some pilot projects of diversified compensation models within the province. These actions have offered valuable insights for developing ecological compensation mechanisms in China. Although Hubei Province started earlier in the ecological compensation and has achieved results, there are still some problems. Firstly, the scientific of the compensation standard is insufficient, and the accounting standards have not yet unified, making the compensation funds covering the actual cost of governance difficult. Secondly, there is a short board of market-based mechanisms: the existing compensation mainly relies on the vertical compensation of the central government, and the local horizontal compensation lacks a long-term mechanism.

Therefore, this study selected Hubei Province as case study area to assess ecological compensation amounts and their evolution characterization in Hubei Province from a perspective of multi-scenario simulations of ecosystem services value. This study comprehensively considered regional differences in economic development, population, and resource endowment. The land use spatial differentiation in different scenarios was explored based on the FLUS model. On this basis, this study predicted the spatial and temporal evolution of ecosystem service value (ESV) and ecological footprint in Hubei Province using the GM (1,1) model to estimate the ecological compensation standard in each county. Differentiated countermeasures are proposed for the ecological compensation amount in different regions, which provide new ideas to promote ecological compensation mechanism construction and have theoretical and practical significance. This study's objectives were (1) to determine the EC standards combining the green development goals and the situation in Hubei Province. (2)

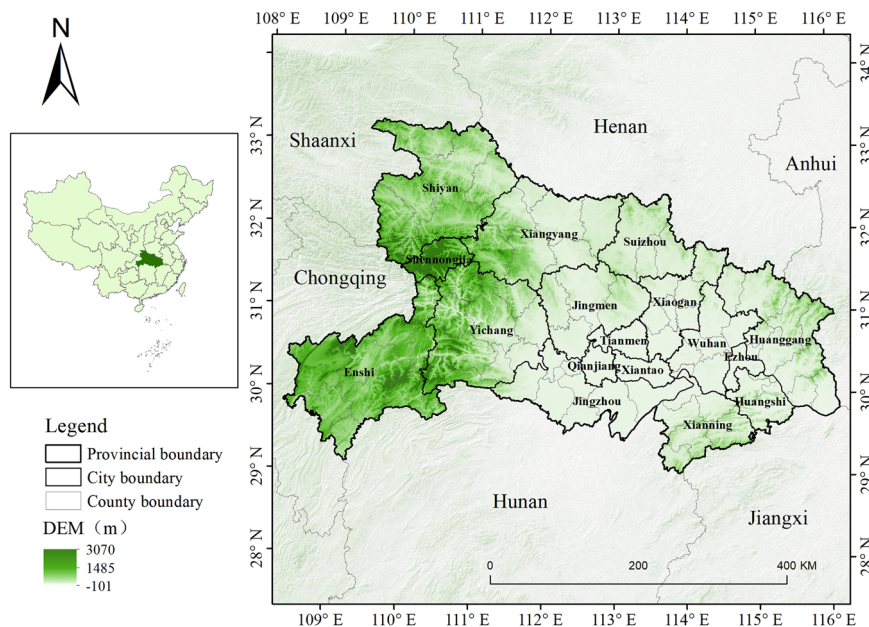


Fig. 1 Geographic location diagram of Hubei Province.

to analyze the spatial and temporal dynamics of the ESV, ecological footprint, and EC amounts and identify appropriate future development scenarios in Hubei Province. (3) to further analyze the variances between and within the EC amounts in Hubei Province and provide targeted policy recommendations. (4) to explore zonal ecological compensation oriented to the main functional areas to help balance incremental development and stock restoration.

Materials

Study area. Located in the central China and the middle reaches of the Yangtze River (29°01'–33°06' N, 108°21'–116°07' E), Hubei Province covers an area of 185,900 km², with 56% is mountainous, 24% is hilly, and 20% is plain and lake area. It has 12 prefectural-level cities, 1 autonomous prefecture, and 4 county-level administrative districts under provincial jurisdiction. By the end of 2023, Hubei Province had a resident population of 58.38 million, a GDP of 5,580.363 billion yuan, and a forest coverage rate of 42.11%. The National key ecological function areas in Hubei Province mainly include the Dabie Mountain Soil and Water Conservation Ecological Functional Area, the Qinba Biodiversity Ecological Functional Area, the Wuling Mountain Biodiversity and Soil and Water Conservation Ecological Functional Area, and the Three Gorges Reservoir Soil and Water Conservation Ecological Functional Area, which account for 43.65% of the province's total area. Meanwhile, Hubei Province has a well-developed water system with many rivers and lakes. The Yangtze, Han, and Qing Rivers all flow through the province, giving Hubei the reputation of being the 'province of a thousand lakes', with Danjiangkou Reservoir, Honghu Lake, and other wetlands of international importance. The abundant forests and water conditions make the ecological protection red line in an overall pattern of 'four screens, three rivers, and one area' playing a vital role in water conservation, biodiversity, flood water storage, carbon sequestration, and oxygen release, and has a huge ecosystem service value Fig. 1.

During the 13th Five-Year Ecological and Environmental Protection Plan period, Hubei Province adhered to the Yangtze River ecosystem restoration, promoted the Yangtze River protection, and designated seven priority areas for biodiversity

protection. Ecological greening of the Yangtze River shoreline reached 8.56 million m², and afforestation along both sides of the Yangtze River amounted to 754,000 acres. These initiatives would play an essential role in promoting the accelerated greening of the central region and the high-quality development of the Yangtze River Economic Belt.

Data sources. The land use data were derived from the 30 m annual land cover datasets provided by Wang and Feng (2024), reclassified into cultivated land, forest land, grassland, water area, construction land, and unused land. Considering that Hubei Province is a key development area of the Yangtze River Economic Belt, the study selected six natural drivers (DEM, slope, aspect, PRE, TEM, and distance from rivers) and four socioeconomic drivers (population density, distance from railroads, highways, and provincial highways) to scenario simulation. All the drivers were processed using ArcGIS and uniformly converted to a resolution of 100 m × 100 m. In light of data unavailability, this study merged some municipal districts. The energy consumption data of each county or district were unavailable, so these data were estimated based on the GDP ratio of each county to its corresponding prefecture-level city. Referring to the research methodology of Huang and Li (2023), energy data were allocated based on the proportion of the county's GDP in the provincial's as a coefficient. Detailed data was shown in Table 1.

Methodology

Technical framework. To better assess the EC amounts and grasp its future change in Hubei Province, this study incorporated the FLUS model, the ESV model and the ecological footprint model into study. This study consisted of four key components. Firstly, this study predicted the future land use status under four scenarios (the natural development scenario, the economic development scenario, the ecological protection scenario, and the comprehensive development scenario) by the FLUS model. Secondly, this study measured the ESV under 2010, 2020, and future scenarios according to the modified equivalent factor method and explored its spatial and cold/hotspot distribution. Third, based on existing and modeled land use data, this study used the ecological footprint model to measure ecological carrying capacity and

Table 1 Main data used in the research.			
Data categories	Name	Year	Source
Land use data	Land use	2010, 2020	https://zenodo.org/records/12779975
Basic geographical data	Rivers, Railroads, Expressways, National highways, Provincial highways	2020	https://www.openstreetmap.org/
	Administrative boundary	2020	http://www.resdc.cn
Natural environmental data	DEM	2020	http://www.resdc.cn
	NPP		
	PRE		
	TEM		
	Nature reserve		
	Slope		Calculated from DEM
	Aspect		
Socio-economic data	Population density	2020	http://www.resdc.cn
	GDP		《Hubei Statical Yearbook》, Statistical yearbook of cities
	Agricultural production	2010, 2015–2023	《Hubei Rural Statical Yearbook》, 《Hubei Statical Yearbook》, Statistical yearbook of cities
	Energy use	2010, 2015–2023	《Hubei Statical Yearbook》, Statistical yearbook of cities
	Food price	2010–2020	《National Farm Product Cost-benefit Survey》

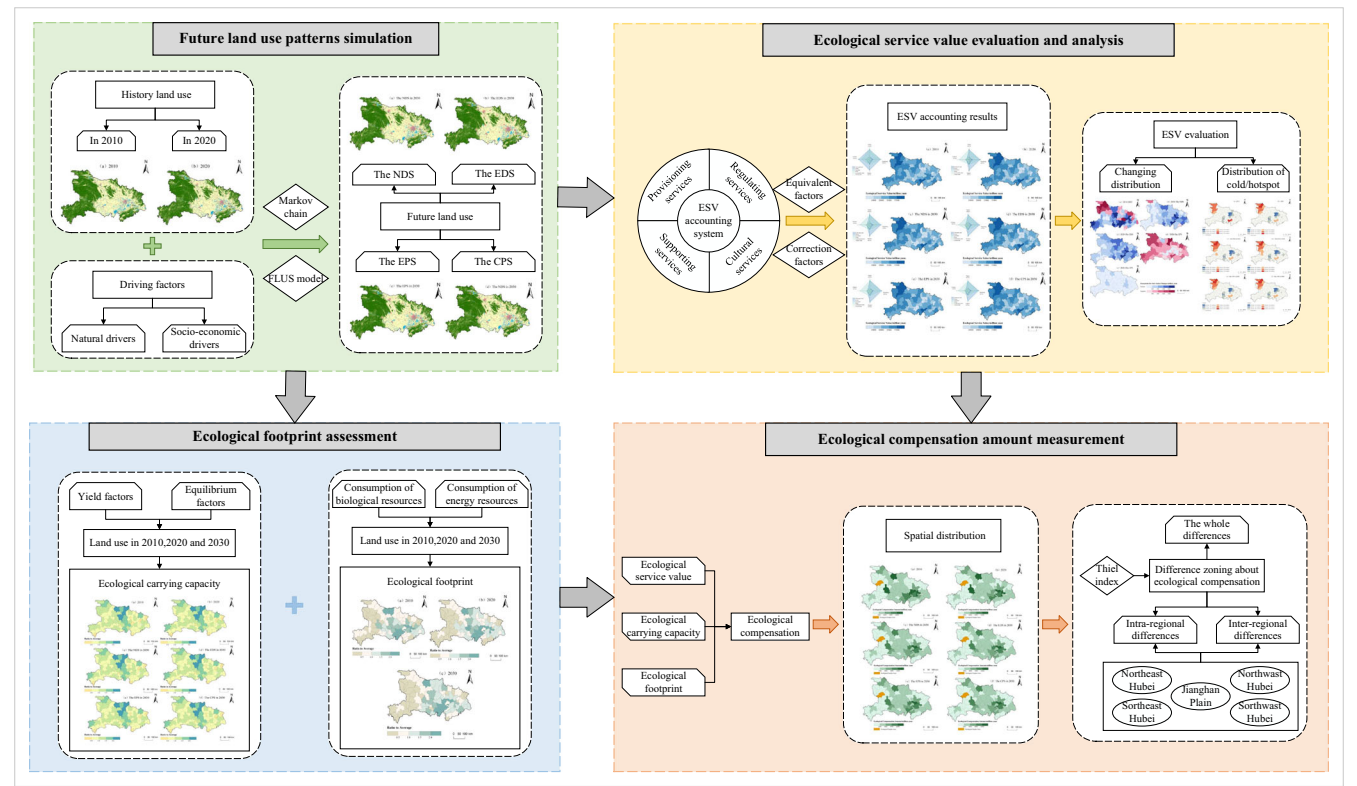


Fig. 2 The framework of this study.

ecological footprint, respectively. Finally, this study combined the above results to obtain the ecological compensation amount in Hubei Province. The ecological compensation differences in different regions were also further analyzed using the Thiel index (Fig. 2).

Accounting method for ESV. The ESV method converts ecosystem services into a uniform economic value by comparing equivalent factors to allocate ecosystem services. This method can provide a direct basis for ecological compensation. It identifies functional differences between different functional areas, such as water conservation areas in mountainous regions and farmland

areas in plains, and avoids one-size-fits-all ecological compensation. The method applies to different areas and multiple scales and achieves multi-functional coverage, requiring only land use data for assessment. It has been used to prepare China’s natural resource balance sheet, supporting policymaking and the design of compensation standards.

This study assessed the ESV of various ecosystems based on the ecosystem service equivalent value per unit area table proposed by Xie et al. (2015). Under the actual situation in Hubei Province, localized corrections were subjected to the benchmark unit value and each equivalence factor. (1) The equivalence factor table of cultivated land, forest land, grassland, and water area equivalence factors were each weighted from their respective secondary land

Table 2 Equivalent factors of ESV in Hubei Province.

	ESV	Cultivated land	Forest land	Grassland	Water area	Construction land	Unused land
Provisioning services	Food production	66.360	15.160	42.040	78.680	0.000	0.000
	Raw material production	14.710	34.830	61.860	43.840	0.000	0.000
	Water resources supply	-78.380	18.020	34.230	653.430	0.000	0.000
Regulating services	Gas regulation	53.450	114.560	217.410	160.360	0.000	1.200
	Climate regulation	27.930	342.780	574.760	353.740	0.000	0.000
	Purify environment	8.110	100.450	189.780	549.530	0.000	6.010
Supporting services	Hydrological regulation	89.790	224.320	421.010	7595.570	0.000	1.800
	Soil conservation	31.230	139.490	264.860	194.590	0.000	1.200
	Maintain nutrient cycle	9.310	10.660	20.420	15.010	0.000	0.000
Cultural services	Biodiversity	10.210	127.020	240.830	625.810	0.000	1.200
	Aesthetic landscape	4.500	55.700	106.300	397.590	36.640	0.600
Total		237.230	1183.000	2173.510	10668.160	36.640	12.010

classes to find the mean value; construction land was adjusted its cultural services with reference to the study of Huang and Li (2023); bare land was taken as unused land equivalence factor for categorization (Jin et al. 2020). (2) As the ESV has spatial heterogeneity, which is affected by geographic location, natural environmental conditions, and so on, NPP and GDP were selected for correction (Gao et al. 2023). (3) Ecosystem service value equivalent factor refers to the relative contribution size of a certain type of ecosystem's certain service value. (Deng et al. 2019). Each equivalent factor is 1/7 of the market value of grain produced per hectare per year. Based on the agricultural prices, unit yield, and sown areas of the main grain crops in Hubei (rice, wheat, and corn) during 2010–2020, the economic value was 2174.08 yuan/hm². The formula is as follows:

$$E_a = \frac{1}{7} \sum_{i=1}^n \left(\frac{m_i \times p_i \times q_i}{M} \right) \quad (1)$$

$$Q = \frac{GDP_i}{GDP_c} \times \frac{NPP_i}{NPP_c} \quad (2)$$

$$ESV = \sum_{k=1}^n A_k \times VC_k \times E_a \times Q \quad (3)$$

Where, ESV is the ecosystem service value in Hubei Province (yuan); E_a is the standard equivalent; n is the quantity of major food crop types; i is the crop specie; m_i , p_i , and q_i are the sown area, the unit price, and the unit yield of crops from 2010 to 2020; M is the planting area of all food crops; A_k is the land area of the different land types (hm²); VC_k is the per-unit ecosystem service value (yuan/hm²); k is the land use type; Q is the correction coefficient; GDP_i is the GDP of Hubei, GDP_c is the national GDP; NPP_i and NPP_c are the NPP of the study area and the country, respectively. The corrected equivalent factors of ESV in Hubei Province were shown in the Table 2.

FLUS model. The FLUS model, which integrates the strengths of System Dynamics (SD), Cellular Automata (CA) models, and the addition of an Artificial Neural Network (ANN) model, along with an adaptive inertia mechanism facilitated by roulette wheel selection. It is employed to simulate land use changes influenced by human activities and the natural environment (Wang et al. 2020). The FLUS model integrates economic and natural drivers through the ANN model and portrays the spatial distribution characteristics of the converted land classes based on the CA model. It improves the accuracy of the model run results and the similarity with the current land use distribution. The land use simulation using the FLUS model can be compatible with multi-scale regions and meet the needs of regional management

policies. However, the FLUS model requires high data accuracy and relies on long-time historical land use series.

Scenario setup. To foster the coordinated development between urban construction and ecological protection in Hubei Province, this study sets up four scenarios for land use simulation (Wei et al. 2022).

Natural development scenario (NDS): This scenario is in accordance with the historical land use rules in Hubei Province from 2010 to 2020, assuming a natural progression without future planning or policy interventions. Under NDS, the water area is designated as the restricted conversion areas, and the results are based on the original 2030 projections, serving as the baseline for other scenarios to consider the constraints.

Economic development scenario (EDS): This scenario focuses on the rapid urbanization of the city and allows for the substantial expansion of urban land. Under the EDS, the probability of transferring cultivated land to construction land is increased by 20%, while the other types of land transformed to construction land are increased by 40%, and construction land to other land types except for cultivated land is decreased by 30%. Concurrently, the water area remains restricted conversion areas.

Ecological protection scenario (EPS): This scenario considers the issue of ecological environmental protection in Hubei Province. In accordance with the principle of ecological priority, this scenario sets nature reserves and water area as restricted conversion areas. Under the EPS, the probability of transferring cultivated land, construction land, and unused land to forest land and grassland is increased by 40%, and forest and grassland to cultivated land, construction land, and unused land is decreased by 30%.

Comprehensive development scenario (CDS): This scenario integrates the dual perspectives of urbanization and ecological protection, focusing on regional coordinated development. Therefore, the study sets nature reserves and water area as restricted conversion areas. Under the CDS, the probability of transferring cultivated land and unused land to ecological land (forest land, grassland, and waters) is increased by 20%, construction land to ecological land is decreased by 20%, ecological land to construction land is decreased by 20%, and unused land to construction land is increased by 30%.

Neighborhood weight setting. The neighborhood weight parameter indicates the expansion intensity of different types of land. The parameter ranges from 0 to 1, the parameter value is closer to 1, the expansion ability of the land use type is greater. Considering that the law of each land type change can well reflect the respective expansion capacity. This study calculated the expansion intensity of each land use type based on the land use data

from 2010 to 2020 and carries out the dimensionless processing (Table 3) (Ouyang et al. 2020).

Conversion cost setting and accuracy test. The conversion cost matrix represents the conversion rules of each land type, reflecting whether different land use type can be converted into each other. When the conversion of the land use type to another is not allowed, the cost matrix value is 0. When allowed, the cost matrix value is 1. This study set the conversion cost matrix based on the development needs of different scenarios. The NDS, considering the difficulty and cost of converting construction land to other land types, this study set that construction land cannot be converted to other land use types. In contrast, all others could convert to each other. The EDS, aiming at rapid economic development, restricted the conversion of construction land to other land types. Forest land was restricted from conversion because of its classification as mainland type. The EPS restricted the ecological land conversion to other land types according to the urgent need for regional environmental protection. Since the mainland type in Hubei Province was forest land, ecological land types except forest land could converted to each other. Meanwhile, other land types could converted to ecological land. The CDS, considering the dual needs of economic development and ecological protection, restricted the conversion of forest and construction land to other land types (Tables 4–6).

Using the basic land use data of Hubei Province in 2010 and 2020, the FLUS model simulated the land use situation in 2020. Then, the accuracy was verified by the Kappa coefficient and Fom coefficient. The Kappa coefficient was obtained to be 0.868, with an overall accuracy of 92.546%, and the Fom coefficient was 0.09. Accuracy results indicated that the model has reliability and stability, with an excellent simulation capability and high accuracy for the land use situation in Hubei Province. Thus, the FLUS model can simulate the land use changes in Hubei Province in 2030 better.

Table 3 Neighborhood weight setting.					
Cultivated land	Forest land	Grassland	Water area	Construction land	Unused land
0	0.53	0.33	0.28	1	0.43

Ecological Compensation Standard Model. The ecological footprint method quantifies human liabilities or surpluses to ecosystems as land area. This method relies on resource occupation and supply to clarify the regional ecological compensation’s spatial responsibilities and priorities. Thus, it can reveal the dependence of developed regions on ecologically fragile areas and measure the degree of sustainable development. The method can compare the ecological footprints of various subjects and visually reflect resource use efficiency. The ecological deficit or surplus analysis supports the spatial optimal allocation of ecological compensation and provides a basis for formulating regional compensation policies.

Therefore, the ESV and ecological footprint method have complementary effects when used together. The ESV method quantifies the economic contribution of ecosystem services. At the same time, the ecological footprint method reveals the dynamic balance between resource depletion and carrying capacity. Realizing a two-dimensional assessment of service supply and resource demand. In this way, it can cover the diversity of ecosystem services and reflect the resource dependence of human activities, providing a scientific basis for constructing a ‘polluter pays, user compensates’ mechanism.

Ecological Footprint Model. The ecological footprint refers to the sum of the bio-productive land area required to sustain the resource consumption and waste assimilation of a specific population. The bio-productive land area that can be provided by the region is called the ecological carrying capacity, with a 12% deduction for biodiversity conservation (Cui et al., 2023; Wei et al. 2022). This study categorized land use types into cultivated land, forest land, grassland, water area, construction land, and fossil fuel land. The yield factors and equilibrium factors of

Table 5 Selection of equilibrium factors and yield factors.		
	Yield factor	Equilibrium factor
Cultivated land	1.74	1.11
Forest land	0.86	0.83
Grassland	0.51	0.63
Water area	0.74	0.49
Construction land	1.74	1.11
Fossil energy land	0	0.83

Table 4 Matrix of conversion cost.													
Natural development scenario							Economic development scenario						
	A	B	C	D	E	F		A	B	C	D	E	F
A	1	1	1	1	1	1	A	1	1	1	1	1	1
B	1	1	1	1	1	1	B	0	1	0	0	0	0
C	1	1	1	1	1	1	C	0	1	1	1	0	0
D	1	1	1	1	1	1	D	0	0	0	1	0	0
E	0	0	0	0	1	0	E	0	0	0	0	1	0
F	1	1	1	1	1	1	F	1	1	1	1	1	1
Ecological protection scenario							Comprehensive development scenario						
	A	B	C	D	E	F		A	B	C	D	E	F
A	1	0	0	0	1	0	A	1	0	0	0	1	0
B	1	1	0	0	1	0	B	0	1	0	0	0	0
C	1	1	1	1	1	0	C	1	1	1	1	1	0
D	1	1	0	1	1	0	D	1	0	0	1	0	0
E	0	0	0	0	1	0	E	0	0	0	0	1	0
F	1	1	1	1	1	1	F	1	1	1	1	1	1
A, cultivated land; B, forest land; C, grassland; D, water area; E, construction land; F, unused land.													

Table 6 Accounts for the consumption of biological resources and energy resources.

Land types	Indicator	Average global production/(kg/hm ²)	Land types	Indicator	Average global energy footprint/(GJ/hm ²)	Average global energy footprint
Cultivated land	grain/t	2744	Fossil energy land	raw coal/t	55	20.934GJ/t
	oil crop/t	1856		coke/t	55	28.47GJ/t
	cotton/t	1000		gasoline/t	93	43.124GJ/t
	hemp crop/t	1500		kerosene/t	93	43.124GJ/t
	sugar crop/t	1500		diesel oil/t	93	42.705GJ/t
	tobacco/t	354		fuel oil/t	71	50.2GJ/t
	vegetable/t	18000		petroleum/m3	55	38.978GJ/t
Forest land	pork/t	74	Construction land	electricity/KW·h	1000	0.0036GJ/(KW·h)
	poultry/t	33				
	poultry egg/t	400				
	fruit/t	3500				
	tea/t	566				
Grassland	camellia seed/t	1600				
	beef/t	33				
Water area	mutton/t	33				
	aquatic product/t	29				

different land use types were referred to the results of Liu et al. (2024), using the net primary productivity model (Table 5).

The ecological footprint measurement included two parts: the consumption of biological resources (the products of agricultural, forest, livestock, and aquatic) and energy resources (electricity, raw coal, gasoline, etc.). Among these, the types of productive areas to which livestock products belong were divided based on the findings of Xie et al. (2009) in combination with the actual situation in Hubei (Table 6).

The formula is:

$$EF = r_j \times \sum_{i=1}^n (a_i) = r_j \times \sum_{i=1}^n (C_i \times P_i) \quad (4)$$

$$ECC = 0.88 \times \sum_{n=1}^6 (a_n \times r_j \times y_i) \quad (5)$$

$$ED = ECC - EF \quad (6)$$

Where, EF is the total ecological footprint; ECC is the total ecological carrying capacity; j is the type of goods and inputs consumed; r_j is the equilibrium factor; a_i is the bio-productive area occupied by the type i consumption item; C_i is the consumption of the type i of good; P_i is the average production capacity of the type i of good; n is the type of bio-productive land; a_n is the area of each bio-survivable land type; and y_i is the yield factor.

ED is the ecological surplus or deficit, when $ED > 0$, it indicates that the region shows ecological surplus, ecological status is good; when $ED < 0$, it indicates that the region shows ecological deficit and the regional ecological pressure is tremendous.

Ecological Compensation Model. According to the ecological economics theory, interregional flows of ecological product values are a cross-regional and ongoing process. The measurement of the EC amounts needs to be solved by the comprehensive application of the ESV, ecological footprints, and ecological carrying capacity. This study used the ESV as the basis for the calculation process and regulated EC amounts with the level of local economic development. The calculation process is as follows:

$$E_i = V_i \times R_i \times Q_i \quad (7)$$

$$R_i = \frac{GDP_i}{GDP} \quad (8)$$

$$Q_i = \frac{ECC_i - EF_i}{ECC_i} \quad (9)$$

Where, E_i is ecological compensation amounts; V_i is the ESV of the district; R_i is the economic correction coefficient; and Q_i is the ecological surplus coefficient.

GM (1,1) Model. The GM (1,1) model is a method to generate an approximate exponential law for the original data and then model it. The model is widely used in dynamic forecasting research, which can solve the problems of small historical data, the integrity of the sequence, and low reliability, as well as predict the data without considering the distribution law or change trend. The GM(1,1) model has the advantages of high accuracy, simple arithmetic, good prediction effect, etc., and is suitable for short- and medium-term, small-sample data prediction. This study used the GDP and the measured ecological footprint data of Hubei Province from 2015 to 2023 to meet the medium-term small sample data requirements. The specific research methods refer to Yin et al. (2023).

Ecological compensation standard zoning. The Thiel index is capable of measuring the gap between individuals and the regional aggregate. It can also be decomposed into inter-provincial and intra-provincial gaps within the study area, thereby assessing their respective contributions to the overall gap. The Thiel index was initially applied to analyze economic income disparities and gradually extended to regional disparity analysis (Li et al., 2020; Yang et al. 2022). With the application of the Thiel Index, the EC amounts in Hubei was partitioned. The calculation formula is:

$$T = \frac{1}{n} \sum_{i=1}^n \frac{y_i}{\bar{y}} \log \left(\frac{y_i}{\bar{y}} \right) \quad (10)$$

$$T = T_{WR} + T_{BR} \quad (11)$$

$$T_{WR} = T_p \sum_{g=1}^G \left(\frac{N_p}{N} \times \frac{\bar{y}}{\bar{y}_p} \right) \quad (12)$$

$$T_{BR} = \sum_{g=1}^G \frac{N_p}{N} \times \frac{\bar{y}}{\bar{y}_p} \ln \frac{\bar{y}}{\bar{y}_p} \quad (13)$$

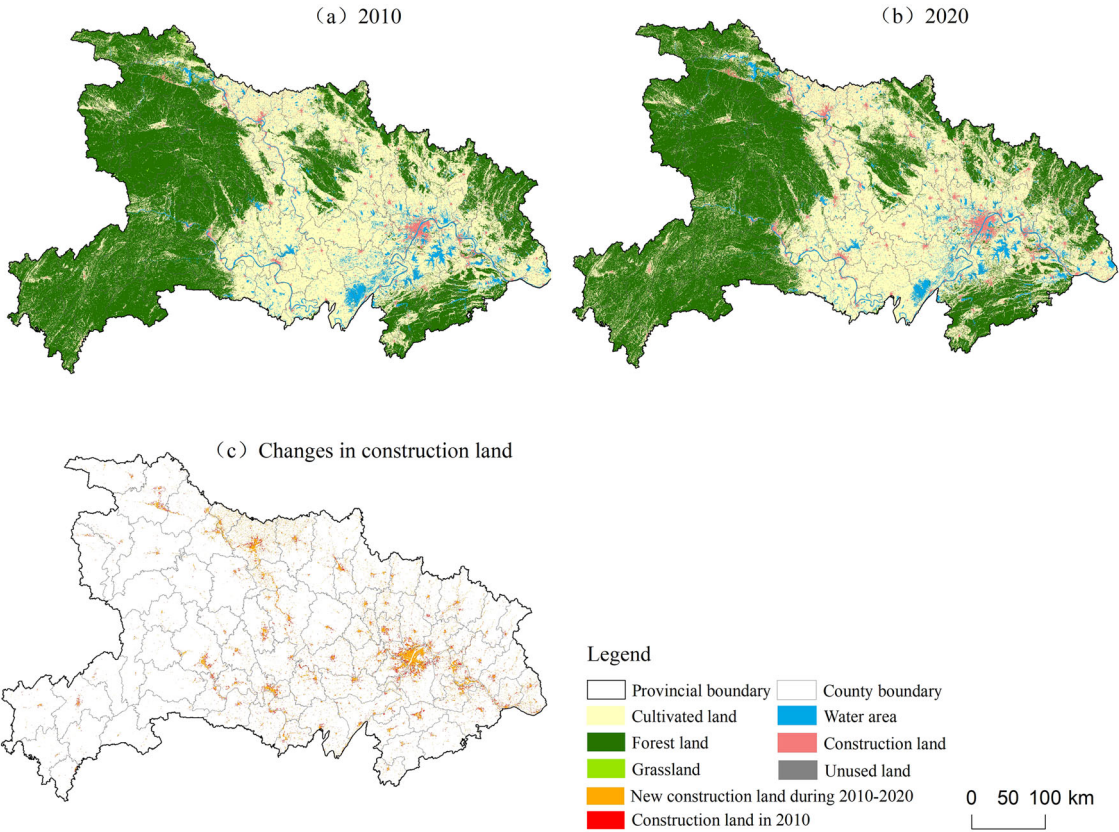


Fig. 3 Status and change of land use in Hubei, 2010–2020. **a** Land use status in 2010; **b** land use status in 2020; **c** construction land changes from 2010 to 2020.

Table 7 Changes of land use area in Hubei Province from 2010 to 2020 (hm ²).							
Land types	2010		2020		Change		Dynamic change
	Area	Proportion	Area	Proportion	Area	Proportion	
Cultivated land	82983.000	44.627%	81626.020	43.897%	−1356.980	−0.730%	−0.164%
Forest land	89938.100	48.368%	90266.410	48.544%	328.310	0.177%	0.037%
Grassland	498.620	0.268%	176.360	0.095%	−322.260	−0.173%	−6.463%
Water area	7968.220	4.285%	7499.580	4.033%	−468.640	−0.252%	−0.588%
Construction land	4554.310	2.449%	6374.290	3.428%	1819.980	0.979%	3.996%
Unused land	4.930	0.003%	4.520	0.002%	−0.410	0.000%	−0.832%
Total	185947.180	100.000%	185947.180	100.000%	0.000	0.000%	

Where, T is the overall Theil Index; T_{WR} and T_{BR} are denoted as intra-group Theil Index and inter-group Theil Index, respectively; n is the total number of counties; y_i is the EC amounts in the type i county; \bar{y} is the mean EC amounts value in all counties; P is the number of all groups; N_P is the number of counties in the type P group; $\frac{\bar{y}_P}{\bar{y}}$ is the ratio of the mean EC amounts of group P to the mean value of EC amounts in all counties; TP is the Thiel Index of the difference of indicators in the type P .

Results

Dynamics transformation of land use. From 2010 to 2020, land use types in Hubei Province were consistently dominated by forest land and cultivated land, which collectively covered more than 90% of Hubei Province’s total area (Fig. 3). The central plain lake areas covered the vast majority of cultivated land. The forest land was mainly in the western mountainous area regions, as well as the eastern ecological barrier regions. The construction land

increased significantly, with the eastern region changing faster than the western region, rising from 4554.31 hm² in 2010 to 6374.29 hm² in 2020 (Table 7). Rapid economic and social development will encroach on cultivated land. Consequently, the cultivated land area had decreased significantly, with the highest slide rate in Hubei Province. From the view of the land use dynamics index, land use dynamics changes were in accordance with the land use area alterations. Among them, grassland and construction land use dynamics changed drastically, while unused land changed significantly compared with 2010, and the single land use dynamics index was relatively significant.

The land use data in 2010 and 2020 were the basis for modeling its land use under four scenarios (the NDS, the EDS, the EPS, and the CDS) in 2030.

Under different scenarios, the overall land use structure changed subtly, mainly showing quantitative changes. Under the NDS, grassland would be the first to the amount of decrease in 2030, followed by unused land, and the construction land

Table 8 Land use structure of Hubei Province in 2030 under different development scenarios(hm ²).							
Year/Scenario	Indicator	Cultivated land	Forest land	Grassland	Water area	Construction land	Unused land
2020	Area	8,157,311.000	9,006,124.000	17,498.000	748,410.000	636,966.000	449.000
NDS in 2030	Area	8,013,753.000	9,019,773.000	12,433.000	714,001.000	806,429.000	369.000
	Change rate/%	−0.0180	0.002	−0.289	−0.046	0.266	−0.178
EDS in 2030	Area	7,980,745.000	9,014,856.000	10,014.000	704,031.000	856,775.000	337.000
	Change rate/%	−0.022	0.001	−0.428	−0.059	0.345	−0.249
EPS in 2030	Area	7,704,786.000	9,334,451.000	13,027.000	753,677.000	760,470.000	347.000
	Change rate/%	−0.055	0.036	−0.256	0.007	0.194	−0.227
CDS in 2030	Area	7,988,474.000	9,012,495.000	11,081.000	748,412.000	805,967.000	329.000
	Change rate/%	−0.021	0.001	−0.367	0.000	0.265	−0.267

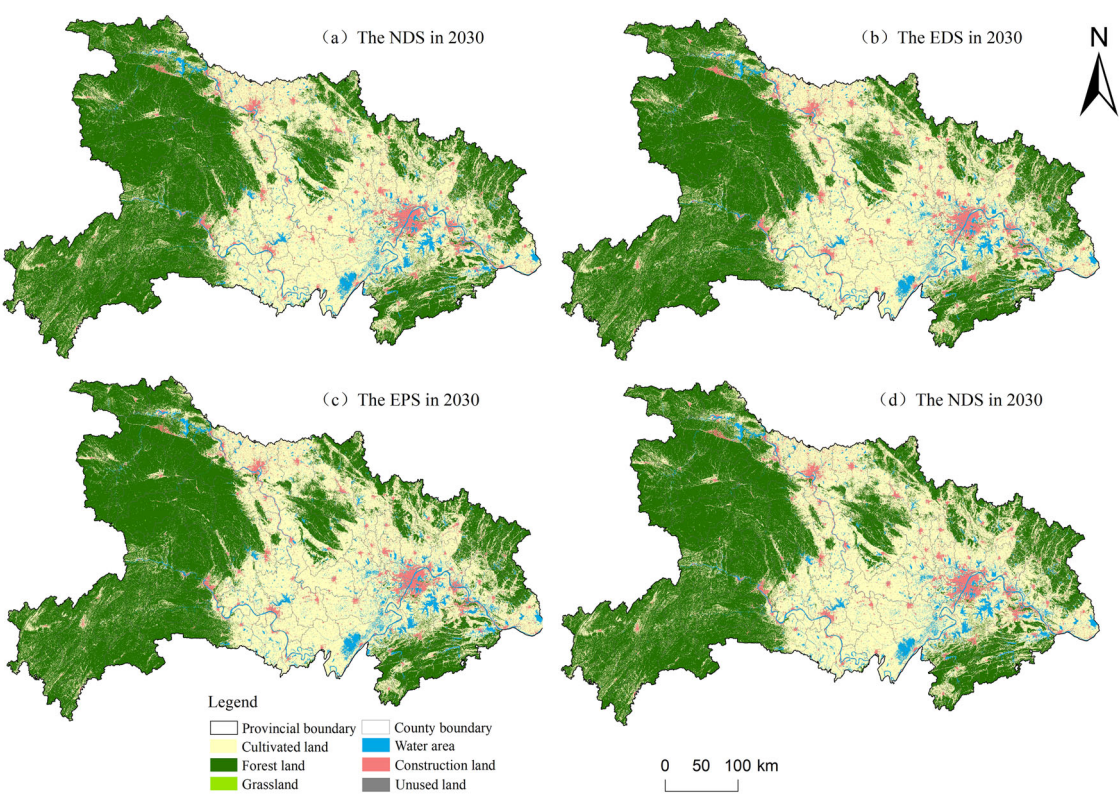


Fig. 4 Multi-scenario land use in Hubei. **a–d** Land use status in 2030 under the NDS, EDS, EPS and CPS scenario, respectively.

change rate reaches 26.6% (Table 8). Under the EDS, the construction land change rate was the largest among the four scenarios, reaching 34.5%. The reduction in grassland was the most significant, followed by unused land, with a decrease of 7484 hm² and 102 hm², respectively (Table 8). In terms of spatial distribution, the construction land increased under this scenario mainly concentrated in the urban areas, with a trend of spreading from the center to the surroundings (Fig. 4b). Under the EPS, the scope of the forest land and water area expanded from the original base in 2030 with a change rate of 0.1% and 5.9%, respectively, and some sporadically distributed areas merged into a whole (Fig. 4c). The cultivated land area was reduced from 8157311 hm² in 2020 to 7704786 hm² in 2030 (Table 8). The grassland area still decreased, but the loss situation improved compared with the NDS and EDS. The water area changed from decreasing to increasing, and the forest land change rate increased. Under the CDS, the grassland and construction land change rates were moderated in 2030, which were −36.7% and 26.5%, respectively. Moreover, the cultivated and forest land change rates were similar to rates under the NDS and EDS (Table 8). Spatially, construction land expanded at a moderate

rate, and the forest land was protected in the western part of Hubei Province (Fig. 4d). This also demonstrated that the NDS can essentially balance cultivated land and ecological environment protection to achieve high-quality green development while the city's economy develops.

Spatial and temporal change features of ESV

Temporal evolution of ESV. The ESV under the four scenarios for 2010–2020 and 2030 were measured, and the results were shown in Table 9. From 2010 to 2020, the ESV showed an overall decreasing trend. Because the forest land and water area had the highest contribution, accounting for more than 90% of the total ESV. One reason is that forest land is the primary land use type in Hubei Province, which contributes significantly to regulating and supporting services. Another reason is that the equivalent coefficient of water area is high, and its ESV is correspondingly high. In 2010, the total ESV was 2,119,062.411 million yuan, then decreased to 2,063,491.967 million yuan in 2020, which totaled 55,570.444 million yuan. This alteration can be attributed primarily to a diminution in cultivated land and water area and an augmentation in construction land area during the past

Table 9 ESV and change rate of various types of land in Hubei Province (million yuan, %).									
Year/ Scenario	Indicator	Cultivated land	Forest land	Grassland	Water area	Construction land	Unused land	Total	
2010 2020	ESV	196,741.015	1,061,526.128	10,766.916	848,360.593	1667.167	0.592	2,119,062.411	
	ESV	193,516.130	1,065,423.043	3803.208	798,415.486	2333.561	0.539	2,063,491.967	
	Change rate/%	-0.016	0.004	-0.647	-0.059	0.400	-0.089	-0.026	
NDS in 2030	ESV	190,110.499	1,067,037.718	2702.325	761,707.427	2954.398	0.443	2,024,512.810	
	Change rate/%	-0.018	0.002	-0.289	-0.046	0.266	-0.178	-0.019	
	ESV	189,327.450	1,066,456.038	2176.553	75,1071.275	3138.844	0.405	2,012,170.565	
EDS in 2030	Change rate/%	-0.022	0.001	-0.428	-0.059	0.345	-0.249%	-0.025	
	ESV	182,780.866	1,104,264.076	2831.431	804,034.404	2786.025	0.417	2,096,697.219	
	Change rate/%	-0.056	0.036	-0.256	0.007	0.194	-0.227	0.016	
EPS in 2030	ESV	189,510.805	1,066,176.732	2408.466	798,417.620	2952.706	0.395	2,059,466.724	
	Change rate/%	-0.021	0.007	-0.367	0.000	0.265	-0.267	-0.002	

decade. The reason is that Hubei Province, in the stage of rapid economic development, expanded construction land to meet urban development needs, encroaching huge cultivated land around the city. Turning lakes into fields accelerates the shrinkage of natural lakes, weakening the waters’ regulatory capacity and thus affecting the regional ecological environment. During the ‘13th Five-Year Plan’ period, Hubei Province actively responded to the national strategic policy, gradually shifting the economic development model from scale and speed to quality and efficiency. This measure solidly pushed forward ecological civilization construction with some improvement to a certain extent in the environment. However, the impact of human activities on the environment is long-term, and thus the recovery period is lengthy. Consequently, the change of ESV from 2010 to 2020 remained negative.

In the view of scenarios, the forest land and water area remain the highest contributors to ESV in general. Except for the EPS, where ESV increases by 1.609%, the ESV of the other scenarios decreases to varying degrees compared to 2020, with EDS, NDS, and CDS in descending order. This phenomenon corresponds to the focus of the different scenarios, and this is closely related to land use change. The variations in ESV under different scenarios demonstrate that the EPS is particularly beneficial to the ESV in Hubei Province. The conservation and expansion of ecological land will increase ESV, which provides a guarantee for maintaining the regional ecological balance. Only focusing on economic development will make it hard to balance the contradiction between the economy and ecology, resulting in a significant increase in construction land area, which will seriously endanger the regional ecological environment. If China’s current demand for green development wants to be satisfied, which means economic growth without harming the local ecological environment, the CPS is the optimal solution.

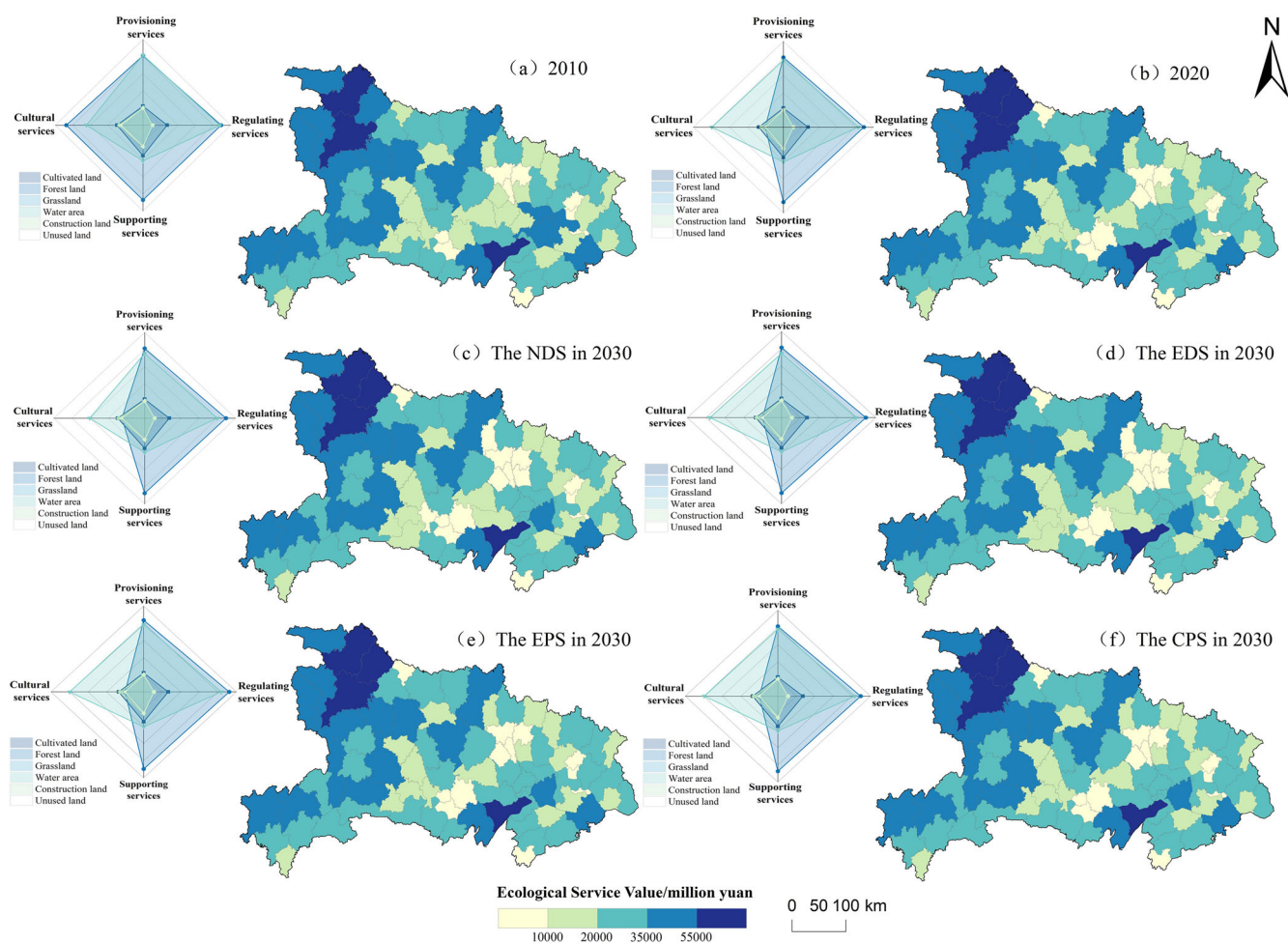
From the perspective of ESV composition (Table 10), regulating services accounted for approximately 70% of the ESV in Hubei Province, followed by supporting services at about 17%, with the two services constituting the core of ESV. This phenomenon was associated with the predominant use of forest land in the Hubei Province’s land use structure. In addition, provisioning services and cultural services accounted for a smaller share, both below 10%.

Overall, all types of ESV declined from 2010 to 2020, related to the rough land use practices in the previous development process, which consumed enormous amounts of water resources and encroached on cultivated land and grassland. ESV rises in the EPS, but provisioning and regulating services were still smaller than in 2020, owing to the reduction in cultivated land and grassland. During development, the encroachment of cultivated land still exists, or the quality of the compensated cultivated land is not as good as the encroached cultivated land, reducing food production services. Furthermore, the unstable ecological pattern in the process of ecological conservation may result in the loss of the grassland area, lowering the ESV of the grassland. However, the ESV of ecological land remains higher than in other scenarios, indicating that strengthening environmental management and adopting green development may successfully boost ecological quality. In the NDS and EDS, ESV decreases, and the total ESV levels are similar. Although there is a reduction in the CPS’s ESV, the decreases in secondary services are lower than in the NDS and EDS, taking into account the dual needs of ecology and economy.

Spatial patterns of ESV. Referring to the results of Yang et al. (2022), the ESV at each time point was classified into lower, low, middle, high, and higher value zones using the natural breakpoint method (Fig. 5). The spatial distribution of ESV in Hubei Province exhibited a ‘high in the west and low in the east’ trend that remained relatively stable throughout each time point.

Table 10 Temporal evolution of the ESV in Hubei Province (million yuan).

ESV		2010	2020	NDS in 2030	EDS in 2030	EPS in 2030	CDS in 2030
Provisioning services	Food production	75,110.074	73,754.843	72,530.816	72,215.693	71,272.228	72,617.065
	Raw material production	47,252.859	46,764.129	46,418.249	46,293.877	47,237.394	46,498.203
	Waters resources supply	3300.621	1256.546	140.548	-269.362	5723.681	2569.466
	Total	125,663.554	121,775.518	119,089.612	118,240.208	124,233.302	121,684.735
Regulating services	Proportion	5.930%	5.901%	5.882%	5.876%	5.925%	5.909%
	Gas regulation	160,955.825	159,159.275	157,886.399	157,441.165	160,489.040	158,190.302
	Climate regulation	361,723.706	358,975.641	357,534.278	356,781.834	368,895.695	358,353.763
	Purify environment	141,498.266	138,538.105	136,571.747	135,901.782	141,673.692	138,343.463
Supporting services	Hydrological regulation	881,853.326	844,462.619	817,130.959	809,049.658	851,576.820	842,820.928
	Total	1,546,031.121	1,501,135.640	1,469,123.384	1,459,174.439	1,522,635.247	1,497,708.456
	Proportion	72.958%	72.747%	72.567%	72.517%	72.621%	72.723%
	Soil conservation	167,849.209	166,124.558	16,5062.885	164,633.137	169,275.051	165,516.207
Cultural services	Maintain nutrient cycle	18,581.096	18,353.950	18,172.855	18,116.977	18,281.479	18,190.470
	Biodiversity	173,406.656	169,984.836	167,736.305	166,957.955	173,915.254	169,738.949
	Total	359,836.961	354,463.343	350,972.045	349,708.069	361,471.783	353,445.625
	Proportion	16.981%	17.178%	17.336%	17.380%	17.240%	17.162%
Aesthetic landscape	Aesthetic landscape	87,530.776	86,117.467	85,327.770	85,047.847	88,356.886	86,627.907
	Proportion	4.131%	4.173%	4.215%	4.227%	4.214%	4.206%
Total		2,119,062.412	2,063,491.967	2,024,512.811	2,012,170.564	2,096,697.219	2,059,466.723

**Fig. 5 Spatial distribution of ESV and the proportion of services provided by each type of land. a-f** ESV spatial distribution in 2010, 2020, 2030 under the NDS, EDS, EPS and CPS scenario, respectively.

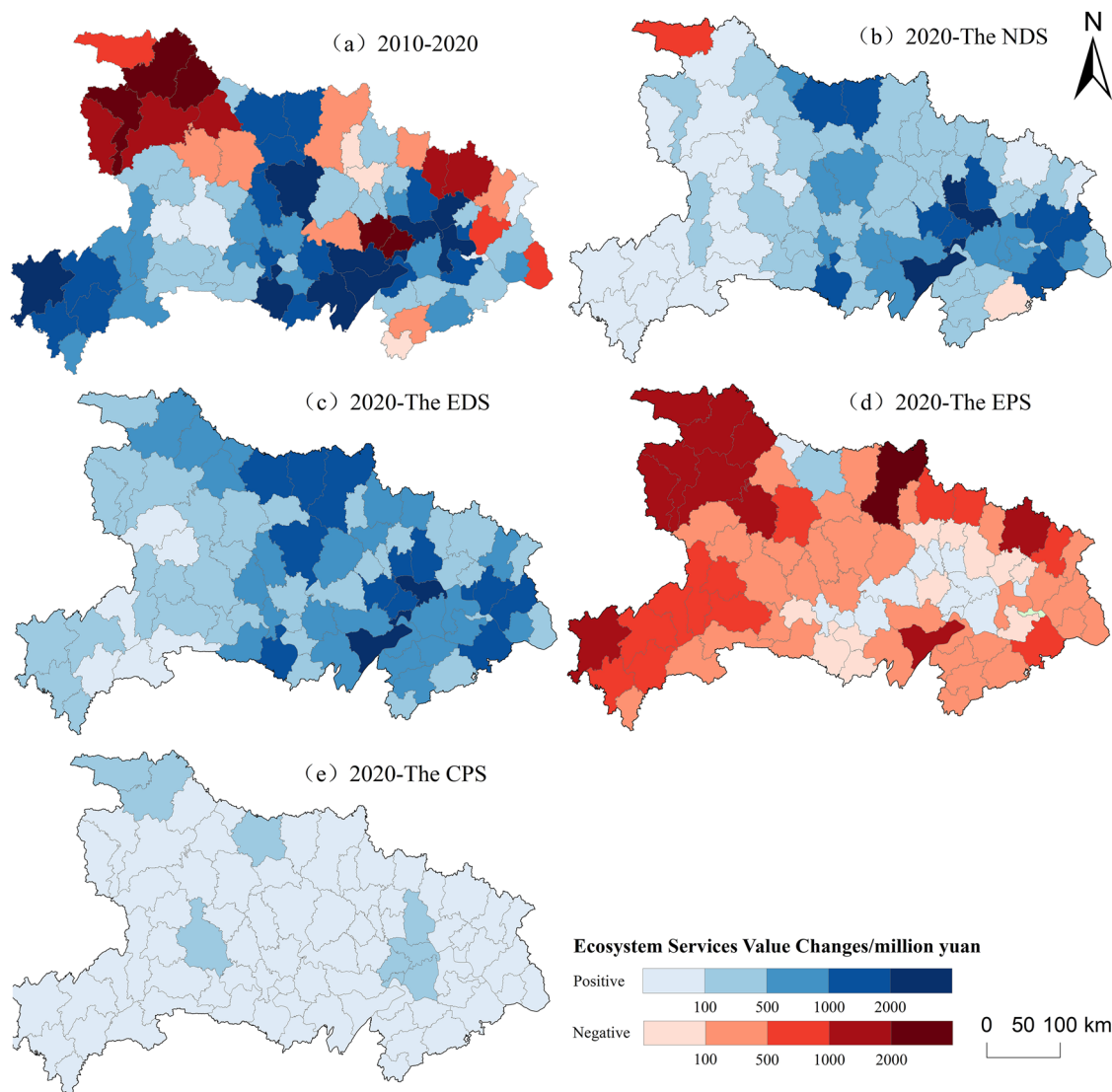


Fig. 6 The distribution of changing ESV characteristics. **a** ESV changing from 2010 to 2020; **b-e** ESV changing from 2020 to NDS, EDS, EPS and CPS scenario, respectively.

Specifically, the high, higher, and middle ESV values mainly concentrated on western Hubei, the region with the highest ecological level in the study area. This region provides superior vegetation growing conditions due to its good soil, precipitation, temperature, and other self-conditions and natural topographic advantages. At the same time, the construction of the Western Hubei Ecotourism Circle and the Qinba Mountains' ecological barrier has significantly increased its vegetation cover compared to the rest of Hubei Province. The above reasons contributed to the highest contribution of ESV. In addition, the ESV of Jiangxia District, Honghu City, and Suixian County were typically high in value, which might be related to the transformation of land use structures and the vigorous development of green pillar industries. The Jiangnan Plain was mainly a low-value and lower-value area due to the Jiangnan Plain being a grain-producing area, where the land use type primarily exists as cultivated land. At the same time, its flat and open terrain, combined with the Yangtze River flowing through, is suitable for human habitation and social development. The ESV of the Wuhan Metropolitan region was generally low because of its strong economic foundation, population concentration, and infrastructure. Land use intensity has increased to satisfy the

demand for construction land for urban development, which poses a threat to the environment. As an old industrial base, eastern Hubei is rich in energy, which has been heavily utilized in the development model and has led to the region's current resources depleting while also causing irreversible damage to the local ecosystem. Thus, the ESV of eastern Hubei are generally low-value and lower-value.

To visualize the ESV changes in Hubei Province, Fig. 6 depicted the ESV evolution at each time point. From 2010 to 2020, the increasing area of ESV mostly gathered in northern Hubei with a strip-like distribution. In contrast, the ESV declined significantly in the southern Hubei, Hanzhong Plain, and eastern Hubei. The reason is that southwest Hubei is hilly and prone to landslides and other natural disasters, weakening the natural barriers of forest land and grassland. Counties and cities in the Three Gorges Reservoir Area essentially completed the resettlement of immigrants in 2009, following the massive demand for construction land on factory relocation, infrastructure construction, and other work, which will damage the ecological environment. The Han River Plain, Wuhan Metropolitan region, and other counties with rapid economic development, urban construction, large-scale projects, transportation, and other high-

intensity human activities weakened their ecological virtuous cycle and reduced their ESV. Affected by the traditional development model, Huanggang, Ezhou, and other traditional industrial cities experienced economic scale expansion while simultaneously encroaching on the ecological territory. Following the 'dual-carbon' objective and a green development transformation, local governments initiated industrial structure transformation, alleviating ecological pressures to a certain extent. Nevertheless, the ecological damage restoration caused by previous development was time-consuming, so the ESV continued to decline.

In terms of scenarios, the EPS shows an increasing ESV across the whole region, and the areas with declining ESV are more concentrated, including some districts and counties in the Wuhan Metropolitan region, Xiangyang municipal district, and Laohekou City. Xiangyang City and Laohekou City have predominantly cultivated land, and their ecological conditions are unfavorable. Furthermore, the development of the 'Xiangsui Shishen' City cluster in recent years has resulted in Xiangyang playing a prominent role in driving economic development, neglecting ecological protection efforts. The districts and counties in the Wuhan Metropolitan region are influenced by the central city radiation and are bound to impact the local ecological environment under rapid urbanization. It is clear that in the newly active areas of construction land, the ESV decline is more obvious. The ecological land expansion, including the forest land and water area, leads to the increase of local ESV. Under the NDS, Yunxi County and Tongshan County show an increasing trend in ESV, while the remaining districts and counties' ESV decrease. This scenario follows the current development trend, in which the local government accelerates the green transformation of the economy and strengthens the restoration and management of ecological land. However, ecological and environmental governance cannot be achieved overnight. Short-term implementation of governance and insufficient local economic support will may lead to the short-term failure to achieve the effect of enhancing ESV. Under the EDS and CPS, ESV in all districts and counties shows a decreasing trend, but the decrease in the CDS is much smaller than that in the EDS. This result implies that if ecological protection and restoration neglects in favor of economic development, the region's environment will deteriorate, putting the development conditions and living environment at risk. In summary, under the NDS, regional development lacks the intervention of proactive ecological protection policies, leading to a continuous loss of ecological land through urban expansion and agricultural land reclamation. As a result, the spatial mismatch between ecosystem service supply and demand increases. In the EDS, the region prioritizes meeting the demand for land for urbanization, resulting in high-intensity development that exceeds the ecological carrying capacity threshold and exacerbates ecological problems. Under the CDS, proactive policy constraints and efficiency gains of ecological restoration techniques buffered regional development, which reduced the ecological pressure of development.

Cold/hot spot distribution of ESV. To further detect whether and to what degree there is a spatial aggregation of high and low values of ESV changes in Hubei Province, the Getis-Ord G_i^* was employed to obtain the cold/hot spot distribution pattern of ESV changes at each time point (Fig. 7).

Overall, the spatial pattern of cold/hot spots of ESV in Hubei Province was relatively stable, with hotspot and cold spot areas showing a patchy 'Z' form. Specifically, the hotspot areas were mainly concentrated in the widespread forested regions such as mountains and hills in northwestern Hubei, like Shiyan City and Shennongjia Forest District, which were important ecological

barrier areas in Hubei Province. In addition, Honghu City and Jiayu County also have high-value clustering. There exist several reasons. Initially, counties and cities in the hotspot area set up ecological protection zones strengthened the restoration of barren mountains, and increased the forest land cover. Furthermore, implementing 'recovering farmland to the lake' has yielded better results. In contrast, the ESV cold spot areas are mainly distributed in Jingzhou City, Jingzhou District, Shayang County, and the surrounding areas of the Wuhan Metropolitan region. Due to the influence of key regional development policies, these areas are significantly disturbed by human activities, with a higher proportion of non-ecological land, such as construction land, leading to the aggregation of ESV cold spots.

In terms of scenarios, the spatial distribution of cold/hot spots is similar between the future scenarios. Compared with the NDS and EDS, the cold spot area of the EPS and CPS decreased, and some of the significant cold spot areas turned into cold spot areas, with only Xingshan County and Zigui County changed from hotspot areas to non-significant areas. The overall ESV increased. This result indicates that the region should pay attention to local ecosystem protection while developing the economy, ensure the ecological backdrop quality, maintain local ecosystem features, and avoid damaging the ecological environment quality in urbanization.

EC standard characterization

Spatial and temporal changes in ecological footprint/carrying capacity. In Fig. 8, the overall level of ecological carrying capacity in Hubei Province was slightly lower, and the districts and counties with carrying capacity levels above and below the provincial average showed an alternating distribution. Moreover, each district and county's ecological carrying capacity was different, and the distribution was relatively scattered (Fig. 8g). In 2010 and 2020, the average ecological carrying capacity was 254765.176 hm^2 and 257375.344 hm^2 , respectively, representing a 2610.168 hm^2 increase due to the strengthened ecological protection in Hubei Province over the last decade. Specifically, the government had effectively solved a series of ecological problems and reduced the ecological loads through a series of initiatives such as returning ploughland to forest and grassland, ecological restoration of the Yangtze River shoreline, and carrying out environmental protection inspections. This study separated the ecological carrying capacity into five categories based on the ratio with the provincial average. The ecological carrying capacity of Hubei Province was mainly middle and low-value (the ratio with the average ecological carrying capacity value between 0.5 and 1.5). The lower-value areas were fewer, with only six districts and counties distributed sporadically. The higher and high-value areas were in the central area of Hubei Province, extending in a linear configuration.

Generally, the forest land and water area have high equivalent factors, providing ecological functions like water conservation, carbon sequestration, oxygen release, and climate regulation. As a result, districts and counties with land use types dominated by forest land and water area, such as Lichuan City, Dawu County, and Qianjiang City, had greater ecological carrying capacity. The ecological carrying capacity remained minimal changes, indicating that the overall ecological carrying capacity will undergo a similar change in future scenarios. This result indicated that under minor development circumstances, the land use type remains stable, and the ecological carrying capacity will may change positively for the local ecological backdrop to strengthen.

The average ecological footprint of Hubei Province in 2010 and 2020 was 2,820,072.799 hm^2 and 2,576,328.437 hm^2 , respectively, and decreased by 243,744.362 hm^2 total, which echoed the reason

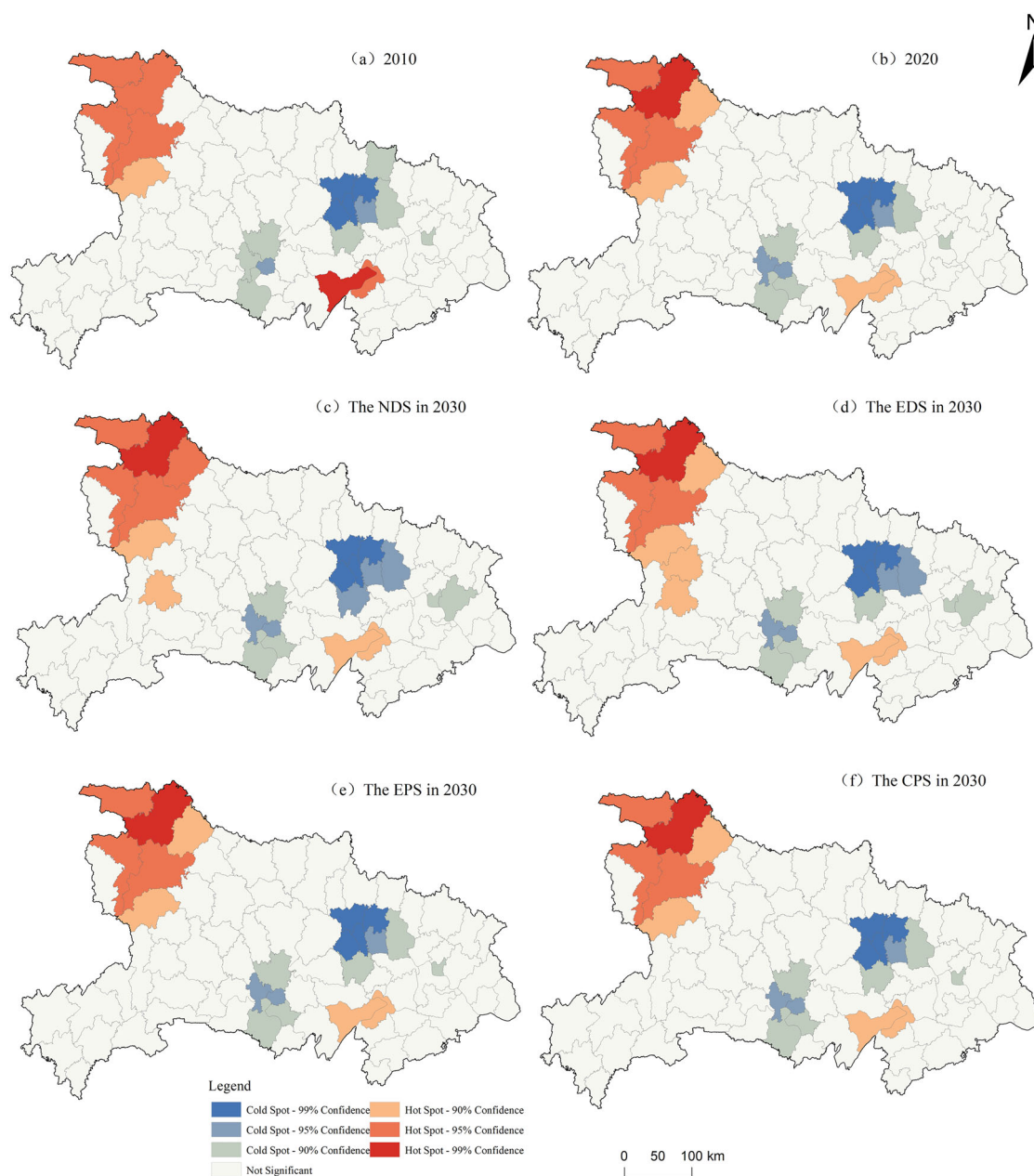


Fig. 7 Spatial distribution of cold/hotspot of ESV. a–f ESV's spatial distribution of cold/hotspot in 2010, 2020 and 2030 under the NDS, EDS, EPS and CPS scenario, respectively.

for the ecological carrying capacity change. The ecological footprint values of each district and county were relatively concentrated and had normal distribution (Fig. 9). This tendency indicated that the ecological construction of Hubei Province was quite effective in 2010–2020. Meanwhile, based on the ecological footprint results from 2015–2023 as the original data, this study predicted the ecological footprint in 2030 by the GM (1,1) model. The GDP of the districts and counties from 2015–2023 was also used as a sample to forecast the GDP in 2030 for further ecological footprint measurement.

Similarly, by the ratio with the provincial mean, this study classified the ecological footprint of each district and county into five categories. From Fig. 8, the ecological footprint had evident differences, and its distribution tended to concentrate. Low-value areas were basically concentrated in the eastern and western mountainous and hilly regions, encompassing the key ecological functional zones in Hubei Province (Dabie Mountain Soil and

Water Conservation Ecological Functional Zone, Qinba Biodiversity Ecological Functional Zone, Wuling Mountain Biodiversity and Soil Conservation Ecological Functional Zone, and Three Gorges Reservoir Area Soil and Water Conservation Ecological Functional Zone). These districts and counties are less economically developed than the central region, and their ecological footprint values are lower than the provincial average. The ecological footprint exceeded the annual average value of high-value areas distributed in the more economically developed or flat terrain areas. On the one hand, regional development depends on resource consumption. With the acceleration of urbanization, so will the demand for resources. On the other hand, because the residents' consumption capacity is high and the consumption structure is complex, the types and quantities of bioproducts required will be higher than in other regions.

Overall, the ecological footprint distribution pattern in Hubei Province had been consistent during the study period. The area

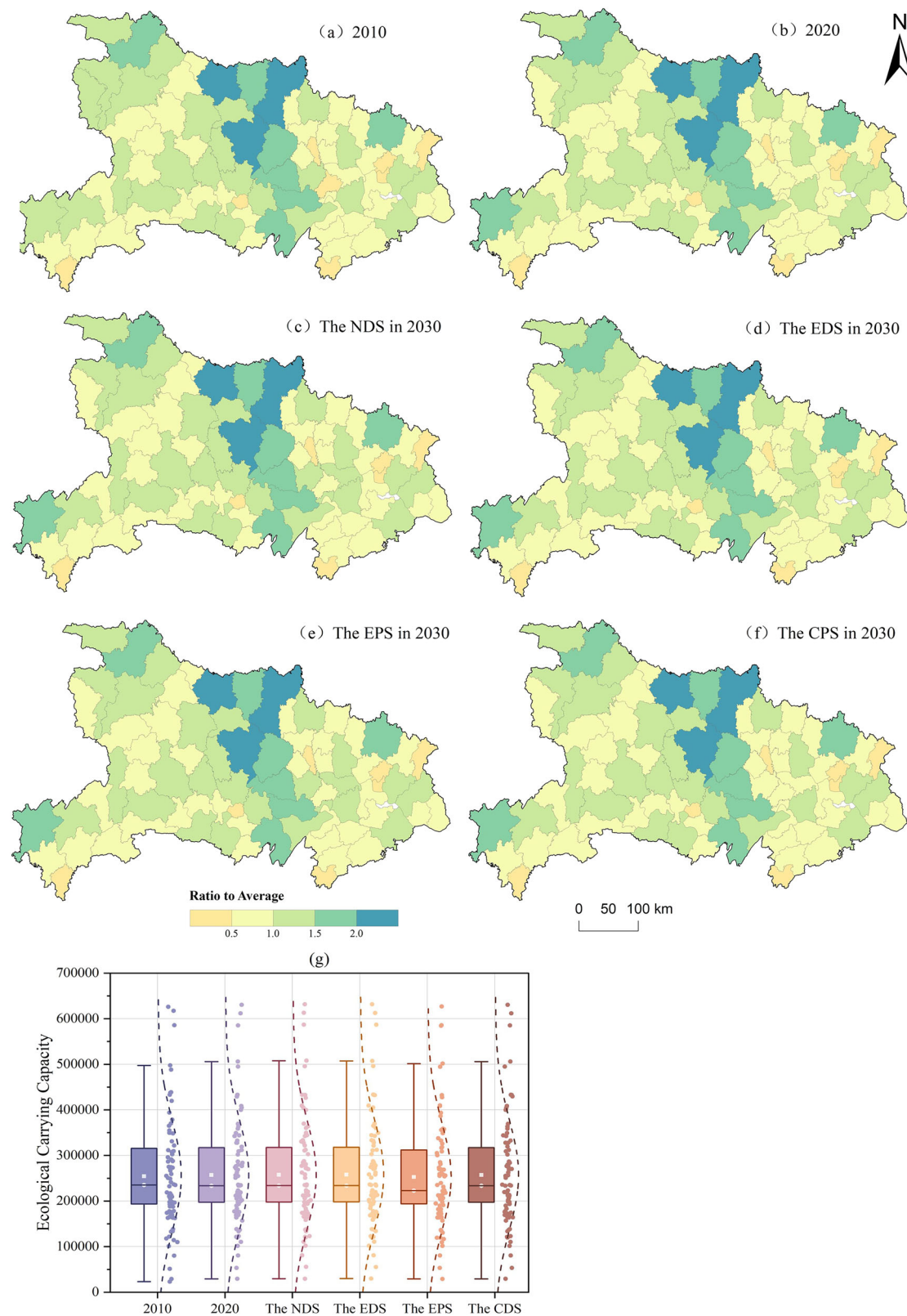


Fig. 8 Quantity and spatial distribution of ecological carrying capacity. **a–c** ECC's spatial distribution in 2010, 2020 and 2030, respectively; **d** quantity distribution of ECC.

where changes mainly occurred was the Jiangnan Plain, with the Wuhan City District as the origin point spreading to all sides. This result meant that the economic operation of Hubei Province was relatively stable, and the areas with higher ecological footprints were in areas with more intense and frequent human

activities and amounts of industry. According to an analysis of the ecological footprint structure of each region, Wuhan, Huangshi, Qianjiang, and Xiangyang had the highest contribution of fossil energy in their ecological footprint consumption structure. The results were, first, as the core cities of Hubei

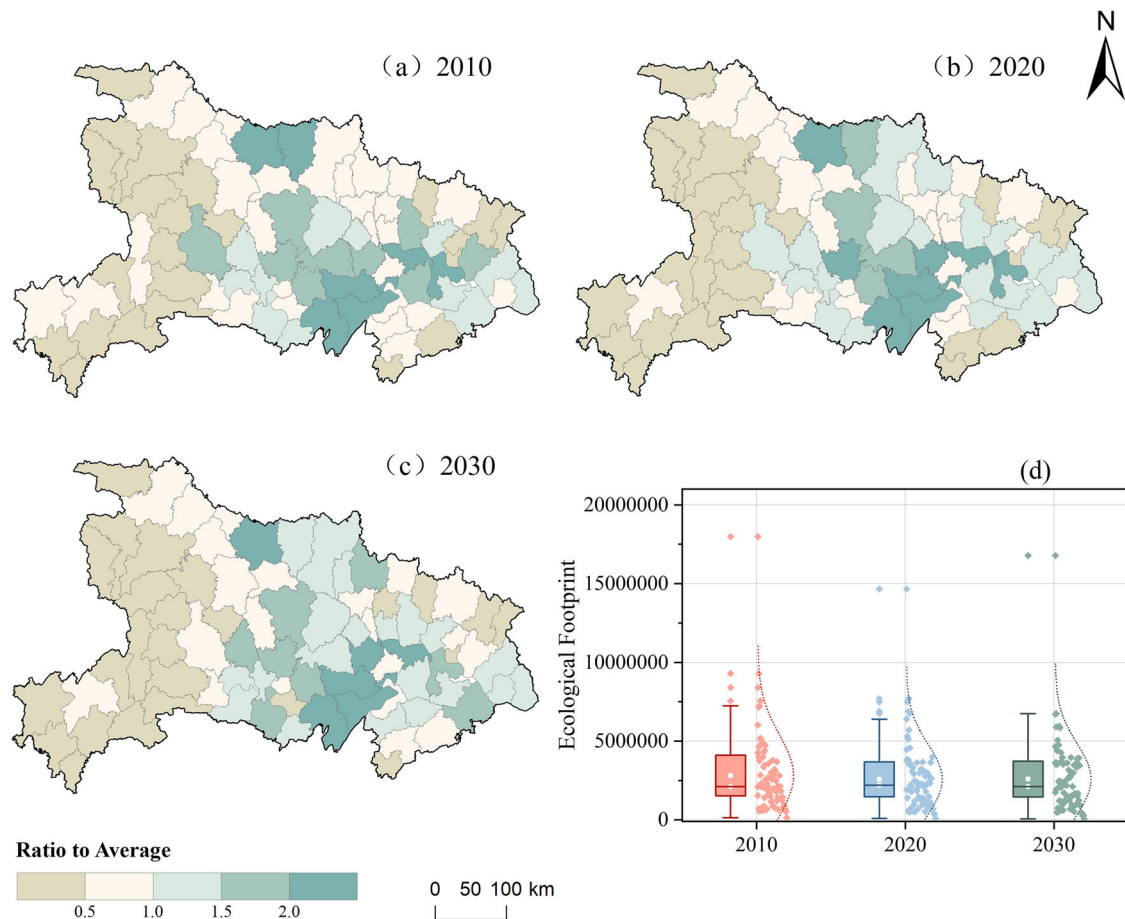


Fig. 9 Quantity and spatial distribution of ecological footprint. **a–f** EF's spatial distribution in 2010, 2020 and 2030 under the NDS, EDS, EPS and CPS scenario, respectively; **g** is quantity distribution of EF.

Province's 'one main city and two wings' development strategy, Wuhan and Xiangyang had a significant demand for fossil energy for both their industrial development and the living conditions of their residents. Secondly, influenced by the leading industries in the cities, Huangshi, the traditional industrial base of Hubei, and Qianjiang, the location of Jiangnan Oilfield inevitably consumed a large amounts of fossil energy in the production process. This phenomenon must result in a local ecological footprint higher than the provincial average. In contrast, Shennongjia Forestry District, Shiyan, and other places had a wide distribution of forest land and grassland, and the main animal husbandry and forestry industry was more developed. The districts and counties in the Jiangnan Plain had many rivers and lakes, and the demand for aquatic products was relatively strong. According to the above, the ecological footprint consumption in these areas was relatively low.

Spatial distribution of EC amounts. According to the socio-economic development under different scenarios and the ecological footprint value predicted by GM (1, 1), this study referred to previous studies (Wang and Li, 2022), setting the GDP growth rate. Under the NDS, the GDP growth rate was to continue the rate in 2010–2020, the GDP growth rate under the EDS was increased by 20%, the rate lowered by 10% under the EPS, and the GDP growth rate was increased by 15% in the CPS. The reason was to get the economic coefficients under different scenarios and then measure the ecological compensation amounts. By evaluating and testing the GM (1, 1) model, the a posteriori ratio $C=0.211$ and the small probability error $P=0.881$. Based on the

model fitting accuracy level, the model had high credibility and can predict ecological footprint.

All areas in Hubei, except for Shennongjia Forestry District, were in ecological deficit and needed ecological compensation (Fig. 10). The compensation amounts of Shennongjia Forestry District under each time point were 106.62 million yuan, 145.22 million yuan, 158.7 million yuan, 160.1 million yuan, 157.73 million yuan, and 159.75 million yuan, respectively. The amounts changed according to the level and speed of economic development in Hubei Province, and were proportional to economic development. In general, the higher the level of economic development, the more drastic the damage to the regions' ecological quality. Correspondingly, the EC amounts provided by areas with ecological surpluses was more plentiful, and the EC amounts provided by the compensation area to the compensated area was also more plentiful.

The EC amounts in Hubei Province was divided into five levels (lower, low, middle, high, and higher) to better visualize the EC amounts according to the actual situation (Fig. 10). Overall, the EC amounts presented a spatial pattern of high in the east and low in the west, alternately distributed. Specifically, the western Hubei, Dabie Mountainous Region's Dawu County, Hong'an County, Macheng City, Lutian County, and Mugao Mountainous Region's Tongcheng County, Tongshan County, Chongyang County, basically had been in the low-compensation area, lying in these districts and counties were designated ecological function zones. With the thick ecological backdrop, the ecological structure was solid and a vital ecological function-providing area in Hubei. Central Hubei, such as Zhongxiang City, Jingshan City,

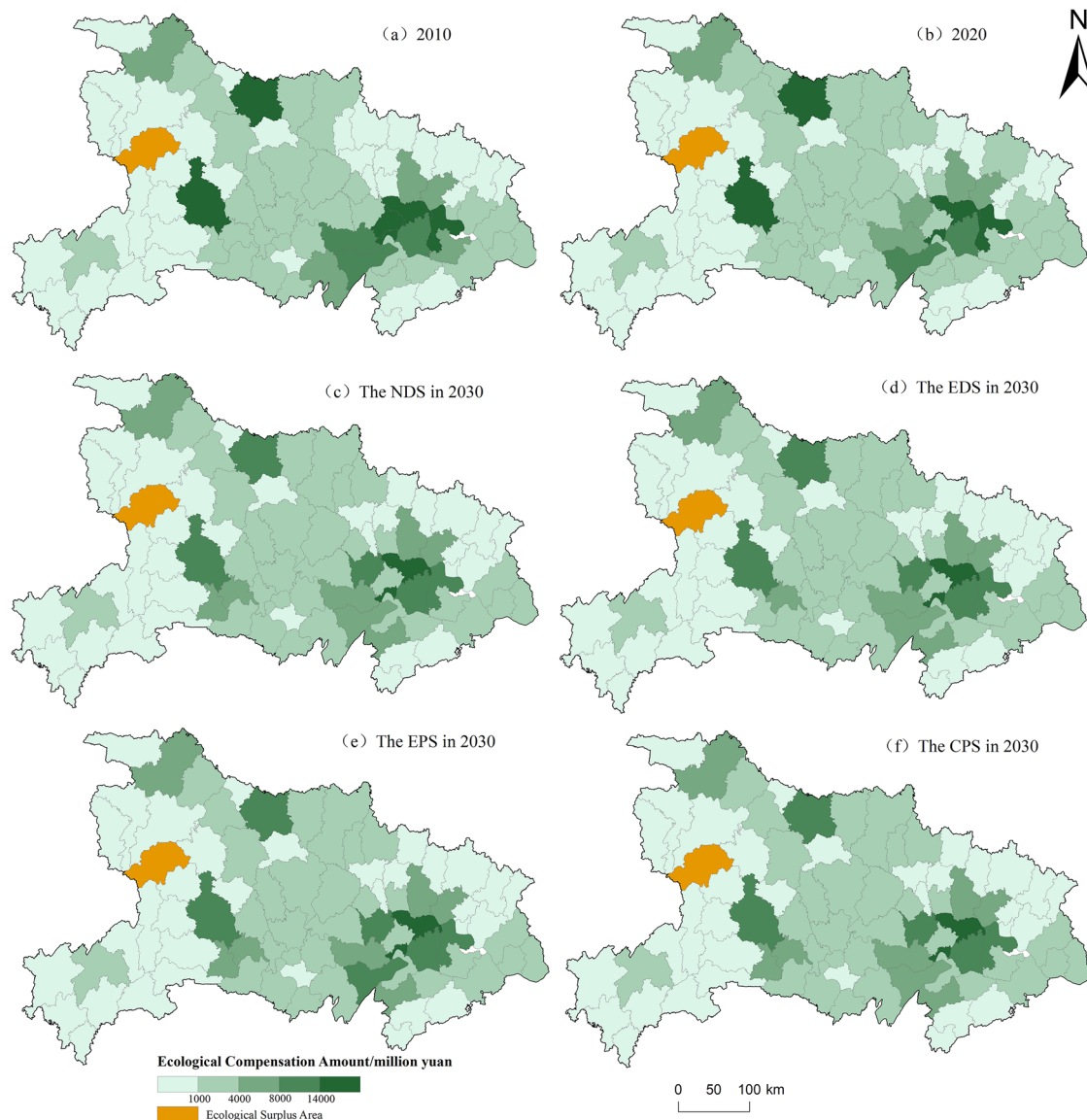


Fig. 10 Spatial distribution of EC. a–f EC's spatial distribution in 2010, 2020 and 2030 under the NDS, EDS, EPS and CPS scenario, respectively.

Tianmen City, and others, was in the middle-compensation and low-compensation area. These districts and counties were mostly in the Jiangnan Plain, the main concentration of cultivated land in Hubei. While cultivated land maintained a production function, its positive ecological function in the local environment could not be underestimated. The high-compensation area was centered in Wuhan City and radiated around the surrounding districts and counties. Driven by the central city, the rapid economic development of the area would neglect ecological conservation, bringing high EC amounts and making spatial distribution of EC amounts show a continuous gathering layout. Also, Yichang and Xiangyang, as the more economically developed regional center cities in Hubei Province, must combine the industrial structure, population density, resource consumption, and other governance costs when carrying out ecological protection and environmental management. Undoubtedly, their EC amounts were often higher, and areas with high compensation tend to overlap with key development zones. Thus, economically developed regions undertake high human activity intensity and develop predominantly non-agricultural modern industries. These regions demand huge ecological functions and hence higher levels of EC amounts.

Since Shennongjia Forestry District was ecologically surplus and belonged to the EC area, this study divided the districts and counties of Hubei Province except for it into five clusters (Northwest Hubei, Southwest Hubei, Jiangnan Plain, Northeast Hubei, Southeast Hubei) based on geographical division to investigate further the degree of EC amounts difference in different regions.

According to formula (12), the Theil index of EC amounts in Hubei Province and its decomposition results were calculated. From a general point of view, in 2010–2020, the overall Theil index declined from 2.958 to 2.837, implying that the regional disparities in the EC amounts have eased (Table 11). Hubei Province has strengthened ecological conservation and pursued green development in all aspects, including energy development, environmental governance, and urban planning. Differences in EC among districts and counties have gradually converged under the supervision and constraints of environmental policies and regulations.

In terms of scenarios, the Theil Index of all four scenarios had increased compared to 2020, with the CPS, EPS, EDS, and NDS ranked in descending order. This result was due to the varying emphasis on development under different scenarios. The NDS

Table 11 Theil index of the amounts of EC and its decomposition.														
Year/Scenario	TR	TWR				TBR								
	Northeast Hubei				Southeast Hubei		Jiangnan Plain		Northwest Hubei		Southwest Hubei			
	Variance	Proportion%	Variance	Proportion%	Variance	Proportion%	Variance	Proportion%	Variance	Proportion%	Variance	Proportion%	Variance	Proportion%
2010	2.958	2.600	67.414	0.961	2.584	0.456	1.158	1.048	1.331	1.511	2.093	0.752	25.420	
2020	2.837	2.522	46.259	0.836	1.786	0.306	0.512	0.868	0.920	1.252	1.135	0.738	26.017	
NDS in 2030	2.956	2.533	47.474	0.568	0.979	0.355	0.495	0.771	0.708	1.014	0.873	0.819	27.696	
EDS in 2030	2.959	2.533	47.564	0.569	0.977	0.351	0.492	0.774	0.709	1.017	0.867	0.821	27.728	
EPS in 2030	2.983	2.534	51.708	0.555	0.993	0.372	0.548	0.763	0.747	1.000	0.899	0.835	27.975	
CDS in 2030	2.995	2.538	51.474	0.559	0.994	0.361	0.530	0.782	0.740	1.018	0.884	0.839	28.023	

followed the development pattern of 2010–2020, but there were differences in policy implementation and economic infrastructure between regions. Inevitably, these differences would increase with the number of years of implementation measures. Under the EDS, some damage has been to the better ecological background of some districts and counties. As more attention was paid to economic construction than environmental protection, regional disparities in the EC amounts were higher than in the NPS. Under the EPS, the ecological patterns construction and environmental management-restoration were more value. Driven by ecological protection policy, districts and counties with broad ecological land or high ecological sensitivity would shrink their ecological deficits faster while regional differences will increase. The CPS is the ideal scenario, focusing on the effectiveness of economic development and the importance of the ecological environment. Nevertheless, since economic development and the ecological environment are mutually constraining and reinforcing, finding a balance between the two is a top priority.

Using the spatial decomposability of the Thiel Index, the total difference in the EC amounts was divided into the inter-regional differences among five regions (Northeast Hubei, Southeast Hubei, Jiangnan Plain, Northwest Hubei, and Southwest Hubei) and their respective intra-regional differences. The inter-regional and intra-regional differences in the five regions were measured separately. From 2010 to 2020, the inter-regional differences in each region were consistent with the overall differences, showing a decreasing trend. In terms of scenarios, Northeast Hubei, Northwest Hubei, and Southwest Hubei had the highest Thiel index under the CDS, Jiangnan Plain had the highest Thiel index under the EPS, and Southeast Hubei had the highest under the EDS. The order of intra-region differences in the Thiel Index was Northeast Hubei, Southwest Hubei, Northwest Hubei, Southeast Hubei, and Jiangnan Plain, from largest to smallest. The contribution rate of intra-regional differences was around 30%, implying that future ecological work in Hubei will focus on coordinating intra-regional differences.

Discussion

Changes in ecological compensation under different scenarios.

This study integrated the ESV and ecological footprint method for scenario analysis to simulate and assess future ecological compensation amounts and further explored the impacts of different decision-making objectives on ecological compensation. As a link between the ecological environment and human society, changes in land use are closely related to human activities and affect the structure and function of ecosystems (Ouyang et al. 2024). Land use change and policy can affect ecological sustainability, resulting in either positive or negative impacts on local ecological compensation (Zhang et al. 2024). In EPS, ecological compensation was the smallest, at 0.8, 0.81, and 0.76 times NDS, EDS, and CDS, respectively. Therefore, limiting urban sprawl and implementing targeted and preventive ecological protection measures are crucial for ecological health and structural stability. Several results have shown that implementing ecological compensation policies and accounting for ecological product value limit ecological destruction to a certain extent (Deng et al. 2024; Yan and Ma, 2024). Therefore, ecological protection projects need to be further strengthened to maintain regional ecosystem stability and ecological security. Meanwhile, the increase in forest land under this scenario was significantly higher than the other three scenarios, and the decrease in water area and grassland was the lowest. These land use changes can effectively promote ecosystem recovery (Su et al. 2023). Under the NDS, ecosystem succession is mainly governed by natural factors, with less intervention from human activities. At this time, ESV is centered

on fundamental values such as natural provisioning and regulating services, but cultural services and economic values are less developed (Nie and Liu, 2024). Therefore, the scenario lacks proactive conservation measures. Over-exploitation leads to various ecological problems, increases restoration costs, and makes the compensation mechanism passive. Under the EDS, human activities might exacerbate ecosystem pressure, leading to a decline in ESV, and the cost of repairing damaged ecosystems was much higher than protection in the natural state (Ouyang et al., 2021). Under the economic development scenario, short-term economic benefits conflict with long-term ecological costs, leading to the overloading of ecological resources. Therefore, the ecological compensation amount under the NDS and the EDS was similar. The ecological compensation under the CDS was the largest because it needed to balance ecological protection, economic growth, and social equity. The scope of ecological compensation in this scenario included the ecological restoration costs and the loss of economic opportunities due to the development restriction. At the same time, this scenario faced more complex types of ecological restoration, which made policy coordination more difficult to balance the interests of multiple parties (Cui, 2022; Zhu and Chen, 2025).

Policy recommendations. Carrying out and improving natural resource asset accounting. Specifically, it is imperative to enact strategies like converting ‘net assets’ into ‘living capital’, positively investigating approaches to achieve the value of ecological products, monetizing the ESV, and transforming ecological resources into ecological capital. From one perspective, the government should complete the natural resources asset balance sheet, which allows for ascertaining the quality and quantity of land, forests, minerals, and other resources in the region. Meanwhile, the governments should refine the national unified accounting methods and standard systems for natural resource assets. Concurrently, information technology, like the ongoing establishment of natural resource asset databases, is being developed to render data public, transparent, and real-time through setting up columns on government media websites and specialized software. These initiatives provide a basis for scientifically determining ecological compensation standards and performing appraisal work.

Perfecting the ecological compensation mechanism. Given the varying ecological values and functions of different environmental elements, such as forests, wetlands, and oceans, the criteria for classification should be further refined. Concurrently, it is crucial to comprehensively consider the socio-economic development, the government’s financial capacity, the main ecological types, and the sensitivity and vulnerability of the ecological environment to implement differentiated compensation. Then, the EC standards should be subject to regular, dynamic adjustments to conform to fluctuations in the ecological products’ value, strengthening the protection of the ecological red line. Additionally, the inter- and intra-provincial ecological synergies should be strengthened. Hubei Province enhances cooperation with Hunan, Jiangxi, and other provinces to jointly advance the horizontal ecological compensation mechanism within the Yangtze River Basin and also explores synergistic governance and co-development between municipalities and states to achieve cost-sharing and benefit-sharing.

Enriching ecological compensation methods. Currently, EC operates as a self-circulation between governments. In response to this phenomenon, the government must deeply explore market-diversified compensation methods to attract more enterprises and civil organizations to participate. Initially, one of the approaches is collaborating with private enterprises, jointly investing with these enterprises in ecological protection and restoration through

counterpart collaboration, joint construction of industrial parks, and such, which advances the implementation of ecological compensation initiatives. Another approach is releasing the vitality of financial institutions, like providing support to enterprises with green bonds and other financial instruments, which contributes to reducing the ecological protection costs owing to the extended loan terms and the reduced interest rates on loans. To attract more enterprises to participate in the ecological compensation work. The third way is setting up a working group responsible for ecological compensation to help build a trading market for ecological compensation and improve trading regulations. In these ways, the government generally forms a multi-dimensional ecological compensation environment, mainly dominated by the market and assisted by the government.

Improving the mechanism for monitoring, legislating, and publicizing. Accelerating the relevant legal system construction includes clarifying the relationship between the rights and responsibilities of ecological beneficiaries and providers and regularly examining and evaluating the implementation of the ecological compensation policy. The evaluation results are the basis for policy modification, compensation standard adjustment, and government performance evaluation. Additionally, to strengthen information disclosure efforts, the government should publicize the importance and criteria for ecological compensation and the content of laws like the Regulations Governing Ecological Protection Compensation within communities and enterprises. To increase the public’s awareness of ecological compensation work, encourage the participation of all people, and promote the realization of the value of eco-products.

Innovations and shortcomings. The previous ecological compensation methods analyzed static changes under specific conditions, which neglect the future impacts of changes in population growth, resource depletion, and production capacity on the ecological compensation. Therefore, this study integrated the FLUS, ESV, and ecological footprint models and established a dynamic compensation prediction model with ‘spatial pattern-service value-carrying capacity’. Through the comparative analysis of multiple scenarios, this study demonstrated the urgency of regional synergistic management and provided a quantitative basis for policy formulation. The model accounted for regional development uncertainty and revealed the corresponding changes in ecological compensation demand patterns with different development stages. It could better think about the uncertainty of future development and predict the trend of regional ecosystem change. Moreover, this study attempted to partition the EC amounts at different time points and explore the reasons for their differences, which are helpful in proposing reasonable countermeasures for regional ecological problems.

The results were encouraging, but some limitations were listed as follows. Initially, due to the availability of data, this research used crop production data to replace the consumption data, ignoring data such as cross-regional redeployment and chain losses. Therefore, scholars should collect mass monitoring data and integrate valuable information into the ecological footprint model in future research. In addition, the response of the FLUS model to the policy variables needs to be further optimized, and machine learning algorithms will be introduced in the future to improve the fit of the policy simulations. Meanwhile, the ecological footprint model only uses crop production and energy consumption data and biological footprints of industrial agricultural products such as wood are not included, which may bias the implied biological footprint. Future research should integrate microdata such as residential consumption surveys and cross-border trade flows for assessment.

Conclusion

This study sequentially used the FLUS, the ESV, and the ecological footprint model to measure EC amounts and analyze their changes at different time points in Hubei Province. This study found that the land use structure evolution shows significant scenario differences, highlighting the profound impact of policy orientations on land use. Forest and cultivated land always dominate, but the land use changes under different scenarios were very different. In the NDS, the ecological degradation of grassland was the most serious. In the EDS, the construction land expansion was the most drastic, which confirmed the ecological damage caused by the rough development mode. In the EPS, ecological land degradation was reversed, improving land quality and demonstrating the effectiveness of the rigid protection policy. The CDS realized the dynamic balance between ecological protection and construction and development, which provided empirical evidence of the balance of the policy. ESV had policy sensitivity, and the decline from 2010 to 2020 correlated with land use changes. Only the EPS achieved a counter-trend growth in ESV, while the rest showed different degrees of decline. This finding highlighted the critical underpinning role of ecological policies on service values, suggesting that ecological conservation policies are decisive for maintaining ecosystem services. The ecological carrying capacity increased and footprint declined supporting a double benefit, but with significant regional differences. The compensation amount showed a pattern of 'high in the east and low in the west', revealing the regional imbalance between economic development and ecological protection. This finding indicated that the compensation mechanism should coordinate cross-regional distribution to optimize effectiveness. At the same time, the variations of EC amounts increased between different regions, and increased or decreased within different regions under four scenarios. There was an urgent need to build a framework for regional synergistic development.

Data availability

Sequence data that support the findings of this study have been deposited in the Open Street Map, Hubei Statical Yearbook, and Resource and Environmental Science Data Platform.

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Author contributions

Methodology, visualization, writing-original draft and editing, SXW; Conceptualization, writing-review, polish language and supervision, CL; Writing-review, and supervision, XHL; Writing-review and polish language, SYY; Writing-review and polish language, XH.

Competing interests

The authors declare no competing interests.

Ethics approval

Ethical approval was not needed, as the study did not involve human participants.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

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