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Spatial and temporal characterization of critical ecosystem services in China's terrestrial area, 2000–2020: trade-off synergies, driving mechanisms and functional zoning

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Identifying ecosystem service functions, clarifying the spatiotemporal trade-offs and synergies of terrestrial ecosystem services and their driving mechanisms, and exploring differentiated ecological functional zoning are crucial steps in achieving healthy regional ecosystem management, and are conducive to developing diversified ecological restoration strategies, establishing a robust cross-regional collaborative management mechanism, implementing differentiated ecological management strategies, and contributing to the construction of a Beautiful China. This paper, based on the InVEST model, Pearson correlation, GeoDetector, and Spatiotemporal Geographically Weighted Regression models, constructs a spatial quantification model of the trade-offs and synergies among five key ecosystem service functions—habitat quality, soil retention, water conservation, food supply, and carbon sequestration—of China's terrestrial ecosystems from 2000 to 2020. It explores the influencing factors of terrestrial ecosystem services in China and their spatiotemporal heterogeneity, thereby investigating the future strategies for ecological functional zoning and management of China's national land space. The results indicate that: (1) during 2000–2020, China's food supply and soil conservation have increased. However, the habitat quality, water conservation, and carbon sequestration have decreased. (2) Significant spatial and temporal heterogeneities exist in the key ecosystem services of China's terrestrial ecosystems. (3) Natural, economic, and social factors all impact China's terrestrial key ecosystem services. Among them, slope, annual average precipitation, land development intensity, and vegetation coverage are the main influencing factors, and different factors exhibit significant spatial heterogeneity. (4) Significant trade-offs/synergy effects among critical terrestrial

ecosystem services exist in China. (5) China's national territory is divided into four ecological protection functional zones: ecological restoration areas, ecological control areas, resilient development areas, and ecological conservation areas, and explores differentiated zoning optimization control paths.

KEYWORDS

ecosystem services, driving mechanisms, geodetector, geographically weighted regression, trade-offs and synergies

1 Introduction

Terrestrial ecosystems refer to the unity formed by the interaction between biological communities and the natural environment, in contrast, ecosystem services functions (ESS) are the various provisioning, regulating, supporting, and cultural benefits that humans can obtain from ecosystems, which can directly or indirectly promote the natural conditions and utilities that sustain human development (Smith et al., 2013; Le Provost et al., 2023). Meanwhile, various ESS exist in a trade-off/synergistic relationship (Keith et al., 2017). Therefore, clarifying the spatial and temporal patterns of ESS is crucial for protecting sustainable urban development in China.

In recent decades, 60% of the global ESS are continuously degrading (Eger et al., 2023). According to a report from the State Council, China has achieved a rapid urbanization process in the past 20 years, with an urbanization rate reaching 64.7%. However, it has also brought a series of ecological issues. As of 2022, the extent of soil erosion in China covered an area of 2.65 million km², which corresponding to approximately 27.96% of the land area. The degraded area accounts for 38.7% of the national territory. China's ecological environment is gradually deteriorating. Exploring the causes of ecological issues has become a top priority. It plays a vital role in protecting ecosystems according to effectively assessing the trade-offs/synergies of the regional ecosystem services, which can promote more scientific and standardized management of ecosystem services in China.

In recent decades, the research on ESS has achieved fruitful results. In 1997, Costanza proposed the corresponding concept of ESS as the processes and conditions maintaining human survival and production (Chung et al., 2021). Afterwards, ESS rapidly became a hot research topic for scholars domestically and internationally. In existing research, in terms of research methods, Li et al. (2024) and Tsai and Lee (2023) used the single-factor method (Costanza et al., 2014; Zhang et al., 2010; Xie et al., 2015) to calculate the value of ecosystem services in ecological functional areas and agricultural ecosystems, as well as the trade-offs, synergies, and driving factors between different functions. However, the parameter standards and methods for ecosystem service values are difficult to unify in different ecosystems. This method lacks consideration of the threats posed by natural erosion

and human activities to various ecosystem services and cannot accurately reflect the spatial and temporal heterogeneity of different ESS. Therefore, the quantitative measurement of various ESS derived from the InVEST model considers the impact of natural erosion and human activities, enhancing the accuracy and rationality of ESS assessment and better reflecting the spatial heterogeneity characteristics of ESS. The mutual effects and driving mechanisms of various ESS at different spatial scales are the focus of current research by scholars domestically and internationally. Many studies take national (Turner et al., 2014; Ran et al., 2023; Sun et al., 2024), regional (Xu et al., 2023; Zhou et al., 2024), and local (Sun et al., 2023; Pan et al., 2024) areas as research regions, exploring the spatial and temporal evolution characteristics and trade-offs and synergies of ecosystem services functions at multiple scales (Sharp et al., 2015; Feng et al., 2023; Zhang et al., 2023). Some scholars have also attempted to explore the influencing factors of regional ESS based on models such as correlation analysis (Chen et al., 2020), regression analysis (Xue et al., 2024), geographical detector (He et al., 2024), and geographically weighted regression (Xuemaoy et al., 2024). For instance, Zhang et al. (2023) quantified the amount of sand fixation and other ESS in Xinjiang Province using the wind erosion correction equation and analyzed the spatial distribution of the impact degree of its driving factors through the geographically weighted regression model (GWR). However, the geographical detector model mainly reveals the primary influencing factors of different geographical phenomena and cannot explore the spatial differentiation characteristics of different influencing factors. The geographically weighted regression model only considers the spatial heterogeneity of the current situation and cannot scientifically describe the magnitude of the driving forces of the driving factors, while the spatial and temporal geographically weighted regression model (GTWR) further considers the impact in the time dimension based on the geographically weighted regression model. Therefore, combining the geographical detector with the spatial and temporal geographically weighted regression model can reveal the main influencing factors in a region and further explore the spatial heterogeneity characteristics of different major influencing factors. This approach can more scientifically reflect influencing factors' strength and dynamic stability distribution (Huang et al., 2022;

Qiu et al., 2023). Meanwhile, previous studies have mainly focused on the spatial and temporal evolution characteristics, trade-offs and synergies, and driving mechanisms of ESS in the study area, whereas research on ecological functional zoning and control pathways derived from ESS characteristics is relatively lacking.

In summary, scholars from different backgrounds have conducted in-depth research on the spatial and temporal characteristics of ecosystem services, but they have mainly focused on the value of ecosystem services at small spatial scales and explored their driving mechanisms through a single approach. However, research on the comprehensive measurement of the spatial heterogeneity of key driving factors of ESS at large spatial scales and the fine-scale ecological functional zoning and optimization pathways is relatively limited. In view of this, this study constructed spatial quantitative models for five key ESS functions in China from 2000 to 2020, including habitat quality, soil conservation, water retention, food provision, and carbon sequestration, based on the InVEST model, spatial and temporal geographically weighted regression model, geographical detector, and trade-off synergy model. It quantitatively measured the spatial and temporal characteristics, trade-offs/synergies, and driving mechanisms of key ESS in China and measured the spatial and temporal evolution characteristics and trade-off synergy relationships of ESS in China's terrestrial ecosystems from 2000 to 2020 using a combination of InVEST and Pearson. It is expected that the study of the spatial and temporal evolution characteristics and internal mechanisms of ESS will facilitate ecological functional zoning research and provide differentiated land spatial management pathways. These can serve as benchmarks for evaluating regional ESS protection policies, providing a theoretical basis for the scientific management of China's terrestrial ecosystems.

2 Materials and methods

2.1 Study area

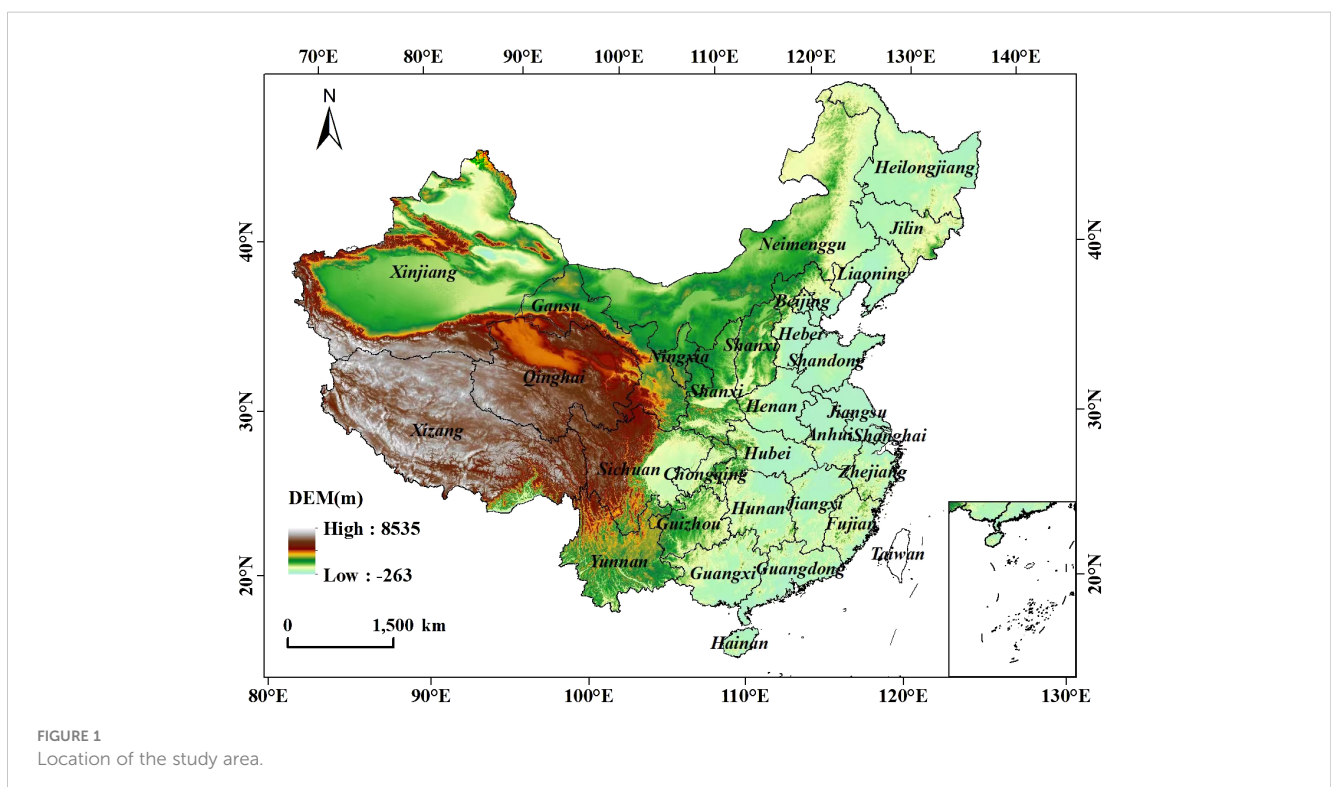
This study selected China as the research area, with 31 provinces (excluding Macao, Taiwan, and Hong Kong), that have experienced rapid urbanization. China accounts for only 6.44% of the world's land area and feeds 18.04% of the world's total population (Figure 1). China has significant regional differences in socioeconomic, natural resources, and ecological environment. The topography is complex. The mountainous environment is widespread within the country, with hills and plateaus. China's overall climate conditions are warm in the south and cold in the north, with a large temperature difference. Rainfall and heat occur in the same season, with rainfall decreasing from southeast to northwest. The diverse and complex climate and topography create different natural features and abundant animal and plant resources in various regions. Along with rapid urbanization, the stability of the country's ecosystem has also been severely disturbed. This has led to serious ecological problems such as habitat degradation in coastal areas, aggravated soil erosion, increasing degradation of arable land fertility, and frequent natural disasters. Severe ecological forms seriously threaten the security and stability of China's terrestrial ecosystems.

2.2 Data sources and processing

2.2.1 Data sources

2.2.2 Data processing

Based on the InVEST model, this study constructed assessment models for five key ESS of China's terrestrial ecosystems for the



years 2000, 2010, and 2020. It explored the spatial and temporal evolution of different ESS, trade-offs and synergies, spatial and temporal driving mechanisms, ecological functional zoning, and optimization management pathways. The data involved in the study mainly included land use, soil types, vegetation cover, topography, climate hydrology, socio-economic statistics, and other basic data (Table 1). The land use data was sourced from the CLCD dataset, which has high spatial and temporal consistency and is based on 5,463 visual interpretation samples, with an overall interpretation accuracy of 80%. Normalization was performed according to the requirements of the InVEST model for raster data such as precipitation, temperature, and vegetation cover. For statistical data such as grain yield and soil texture, after data entry and organization, spatial interpolation was used to fill in missing data for some counties, followed by rasterization. A GIS spatial database was constructed based on the ArcGIS software platform, with the projection coordinate system unified to Krasovsky_1940_Albers.

2.2.3 Model validation

The model's accuracy validation is crucial for measuring of regional ESS and their influencing factors. Therefore, this study carries out model accuracy validation in two main parts. The first part involves ESS measured by the InVEST model, mainly through cross-validation with ESS results calculated by other relevant scholars in the same study area. By comparing the differences in ESS with those of other scholars, the accuracy and reliability of ESS measured by this method are validated. The second part concerns the measurement of influencing factors of ESS. This study mainly uses the geographical detector and geographically weighted

regression model to measure the intensity of influencing factors of different ESS and their spatial and temporal differentiation characteristics. To verify the advantages of this model, this study compares and validates the advantages of the GTWR model by comparing it with three common influencing factor detection models: GTWR, GWR, and OLS. The validation of the models characterizes the superior effectiveness of the InVEST model and the spatial and temporal geographically weighted regression model in accurately revealing China's terrestrial ecosystem services and their driving mechanisms.

2.3 Research methods

2.3.1 Assessment of ecosystem service function

The InVEST model will spatially quantify the five key ESS to characterize the spatial and temporal patterns of key ecosystem services in China. The models for different ecosystem services are constructed as follows:

2.3.1.1 Food supply

The regional food supply function is significantly linearly correlated with food production (Zhao et al., 2012). This study combines each county's grain production, land distribution, and NDVI data to achieve the spatial quantification of China's FP in 1km grids from 2000 to 2020.

$$F_o = \frac{NDVI_o}{NDVI_{SUM}} \times F_{sum} \tag{1}$$

TABLE 1 Data sources and processing.

Data type	Name	Time	Unit	Data format	Data source
Land use data	Type of land use	2000, 2010, 2020	-	Raster	Annual China Land Cover Dataset, CLCD (https://zenodo.org)
Soil data	Soil texture	2009	%	Raster	National Tibetan Plateau Data Center World Soil Database (https://data.tpdc.ac.cn)
Vegetation data	NDVI	2000, 2010, 2020	-	Raster	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn)
Terrain data	DEM	2020	m	Raster	Geospatial data cloud (https://www.gscloud.cn)
Meteorological data	Rainfall	2000, 2010, 2020	mm/km ⁻²	Raster	Month-by-month dataset of meteorological element station observations in China (https://www.resdc.cn)
	EVP	2000, 2010, 2020	mm/km ⁻²	Raster	
	Temperature	2000, 2010, 2020	°C	Raster	
Socio-economic data	Food production	2000, 2010, 2020	t/hm ⁻²	Raster	Annual statistical yearbooks of China and its provinces, cities and counties
	GDP per capita	2000 2010, 2020	10000 yuan/km ⁻²	Vector	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn)
	Population density	2000, 2010, 2020	10000 people/km ⁻²	Vector	
Other geographic data	Drainage basin	2020	-	Vector	
	Railway	2020	-	Vector	
	Administrative divisions	2020	-	Vector	

In the equation, F_o is the total grain production of the o -th grid, $NDVI_o$ is the NDVI value of the o -th grid. $NDVI_{SUM}$ is the sum of NDVI of cultivated land and F_{sum} is the total grain production.

2.3.1.2 Water yield

The Seasonal Water Yield module within the InVEST is used to calculate the WY. The setting and selection of model-related parameters, such as actual evapotranspiration, mainly refer to the InVEST user manual (Allen et al., 1998; Canadell et al., 1996; Zhou et al., 2005; Xie et al., 2017).

$$W_i = (1 - \frac{EVO_i}{P_i}) \times P_i \quad (2)$$

In the formula, W_i represents the water yield of the i -th grid, which is used to characterize the potential WY of the grid unit. EVO_i represents actual evapotranspiration of the i -th grid.

2.3.1.3 Sediment delivery ratio

The Sediment Delivery Ratio module within the InVEST is used to calculate both potential and actual soil erosion and then achieve the spatial quantitative calculation of soil and water conservation (Redhead et al., 2016).

$$SED_{TET_o} = RKLS_o - USLE_o \quad (3)$$

$$RKLS_o = R_o \times K_o \times LS_o \quad (4)$$

$$USLE_o = R_o \times K_o \times LS_o \times C_o \times P_o \quad (5)$$

In the equation, SED_{TET_o} is the quantity of soil and water conservation (measured in metric tons) within a specific grid unit, $RKLS_o$ is the potential soil erosion amount, $USLE_o$ is the actual soil erosion amount.

2.3.1.4 Carbon storage and sequestration

The Carbon Storage and Sequestration module within the InVEST was used to evaluate carbon sequestration across four distinct carbon pools (Xiao et al., 2017).

$$CS_x = C_{above}x + C_{below}x + C_{soil}x + C_{dead}x \quad (6)$$

In the equation, CS_x is the total carbon storage of the ecosystem, $C_{below}x$ is the belowground carbon storage, $C_{dead}x$ is the dead organic matter carbon storage, $C_{above}x$ is the aboveground carbon storage, $C_{soil}x$ is the soil carbon storage.

2.3.1.5 Habitat quality

The Habitat Quality module within the InVEST is used to evaluate the region's habitat. The model comprehensively considers the influence of threat sources (Xu et al., 2022; Sun et al., 2018; Xie et al., 2018; Bhagabati et al., 2014).

$$Q_{xy} = H_{yj}(1 - \frac{D_{xy}^2}{D_{xy}^2 + K^2}) \quad (7)$$

In the equation, Q_{xy} represents habitat quality; H_y represents the habitat suitability index; D_{xy}^2 is the square of the habitat threat index;

2.3.2 Trade-offs/synergy model

Where trade-off is used to characterize the trade-off situation between various ecosystem service functions, and synergy is used to characterize the mutually beneficial relationship between various ecosystem service functions (MEA, 2005; Rodríguez et al., 2006). Therefore, this study calculated the correlation coefficient between ecosystem services based on the Pearson correlation coefficient, with the P value used to test its significance (Terrado et al., 2016).

$$Q = \frac{\sum [(x_o - \bar{x})(y_o - \bar{y})]}{\sqrt{(\sum (x_o - \bar{x})^2) \cdot (\sum (y_o - \bar{y})^2)}} \quad (8)$$

$$P = \frac{Q}{\sqrt{\frac{1-Q^2}{n-2}}} \quad (9)$$

In the formula, Q represents the correlation coefficient, and x and y represents variables linked to two types of ecosystem services and i represents the i -th year. When $|P| < P_{0.05,18}$ $p > 0.05$, the representation of correlation is not significant. When $P_{0.05,18} < |P| < P_{0.01,18}$, the representation of correlation is significant. When $|P| \geq P_{0.01,18}$, the representation of correlation is extremely significant.

2.3.3 Geographic detector model

Geographic detectors assess the relationship between variables by analyzing how their spatial distributions align (Zhao et al., 2020; Zuo et al., 2022).

$$q = 1 - \frac{(\sum_{o=1}^L N_o \sigma_o^2)}{N \sigma^2} \quad (10)$$

In the formula, q represents the extent of the driving factor's influence, o represents the stratification of independent and dependent variables, N represents the total pixel count, N_o represents the number of pixels within the o -th layer.

2.3.4 Spatial and temporal geographically weighted regression model

The GTWR model helps reduce errors and parameter estimation biases, achieving synchronous interpretation of geographical spatial and temporal differentiation mechanisms. Based on the results of geographic detection, this study uses the GTWR model to analyze the spatial heterogeneity of the selected main influencing factors on different ecosystem service functions.

$$Y_x = \beta_0(\mu_x + \nu_x + t_x) + \sum_k \beta_k(\mu_x + \nu_x + t_x)X_{kx} + \varepsilon_x \quad (11)$$

In the equation, Y_x represents the dependent variable; β_0 is the intercept; μ_x , ν_x , and t_x represent the longitude, latitude, and time of the x -th unit, respectively.

3 Analysis of results

3.1 Spatial and temporal patterns of ecosystem service functions

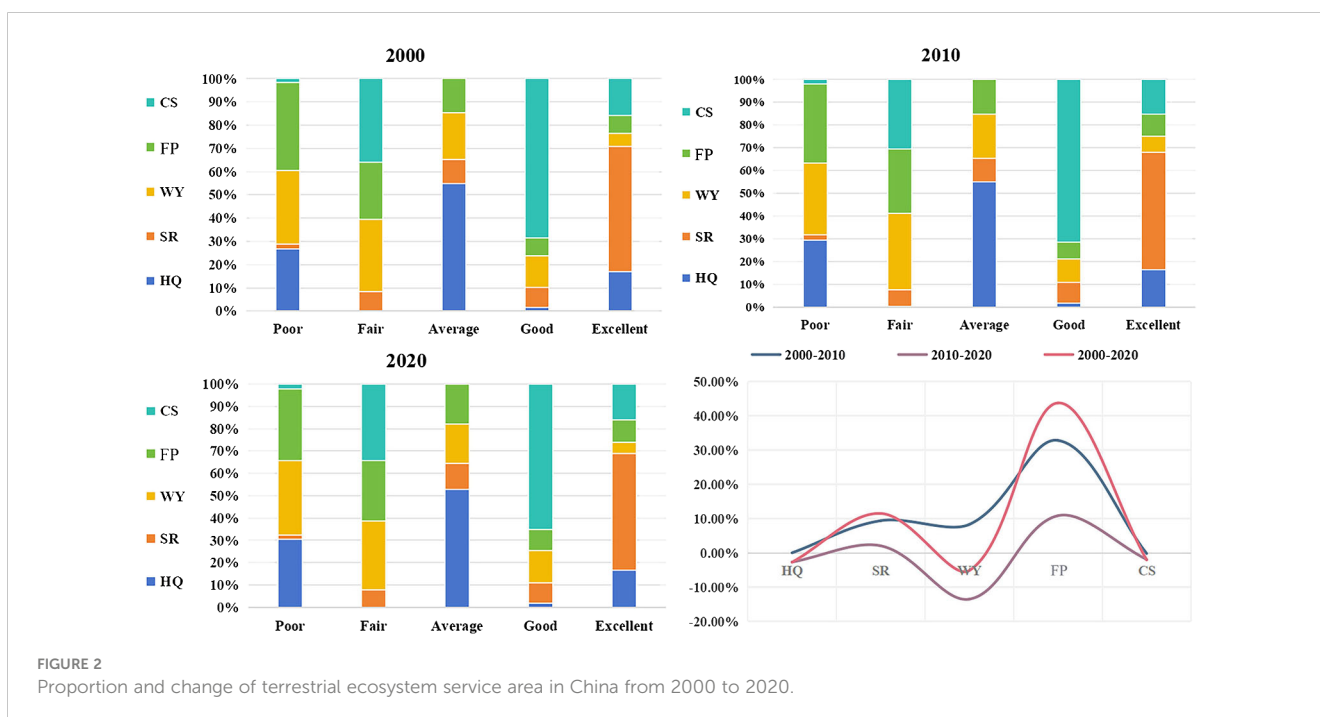
The spatial and temporal patterns and quantity changes of the different ecosystem services in China are shown in Figures 2, 3. Overall, these five ecosystem service functions have undergone significant temporal changes.

Specifically, the overall HQ in China exhibited a declining trend from 2000 to 2020, with the mean decreasing from 0.578 to 0.563, representing a 2.68% overall decrease. High HQ areas are primarily concentrated in China’s southeastern coastal provinces such as Fujian, Zhejiang, Guangxi, Hainan, and Guangdong, as well as the eastern regions of Heilongjiang, Liaoning, and Jilin provinces; medium HQ is primarily concentrated in Qinghai, Inner Mongolia and the northeastern region of Tibet; low HQ areas are primarily concentrated in Sichuan, Jiangsu, Shandong, and Hebei. Combining China’s land use types and natural environmental data, China’s rapid urbanization has resulted in a steady expansion of both construction land and arable land, as well as an intensification of human activities, leading to a continuous decline in HQ. High-quality areas are mainly found in central and southeastern coastal regions, with a relatively large area of forest cover and ample rainfall, providing good habitat suitability and less threat to the habitat. Areas with medium to low HQ are primarily concentrated in the Sichuan Basin, Jiangnan Plain, and the Songnen Plain. These areas have relatively less vegetation cover, mostly arable land, indicating a close relationship between HQ and vegetation coverage.

China’s overall SR showed an increasing trend, rising from 5862t/hm⁻² to 6543t/hm⁻² from 2000 to 2020, representing an overall increase of 11.53%. The SR showed a basic trend of increase in provinces such as Yunnan, Fujian, Zhejiang, and

Hainan, while it exhibited a basic trend of decrease in provinces such as Sichuan, Hubei, and Hunan. The northern provinces of China, including Xinjiang, Qinghai, Inner Mongolia, Gansu, Shanxi, and Hebei, exhibit a significant concentration of areas with high SR, while low SR areas are mainly concentrated in the southeastern coastal area such as Yungui Plateau, Hengduan Mountains region, including provinces such as Tibet, Yunnan, Fujian, Zhejiang, and Sichuan. Research has revealed that SR is influenced by various factors, including elevation, precipitation, and topographical changes (Huang et al., 2010). The coastal areas have significantly higher rainfall than the northwest region, and some areas have significant topographical variations, coupled with a reduction in forest and grassland areas, further exacerbating erosion. In recent years, Cropland has been converted to forest and grassland, and afforestation projects, have expanded the vegetation coverage area, to some extent alleviating soil erosion in the southeastern coastal areas. Additionally, provinces with high SR have extensive grassland areas and relatively low rainfall, which to some extent reduces water and soil erosion, thus favoring SR. Therefore, these regions have a strong soil and water conservation capacity. On the other hand, provinces with lower SR have extensive unused land with significant topographical variations and steep slopes, coupled with higher rainfall, resulting in weaker SR capacity in these areas.

Between 2000 and 2020, China’s overall WY showed a fluctuating downward trend, with the average decreasing from 375mm/hm⁻² to 355mm/hm⁻², a decrease of 5.09%. The WY in Xinjiang, Inner Mongolia, Qinghai, Gansu, and other provinces showed an overall increasing trend, while in Fujian, Guangdong, Yunnan, Tibet and other provinces mainly showed a decreasing trend. The regional differences in China’s WY are obvious. High WY areas are mainly concentrated in the southeastern coastal provinces of Guangdong, Fujian, Zhejiang, and Yunnan, and the



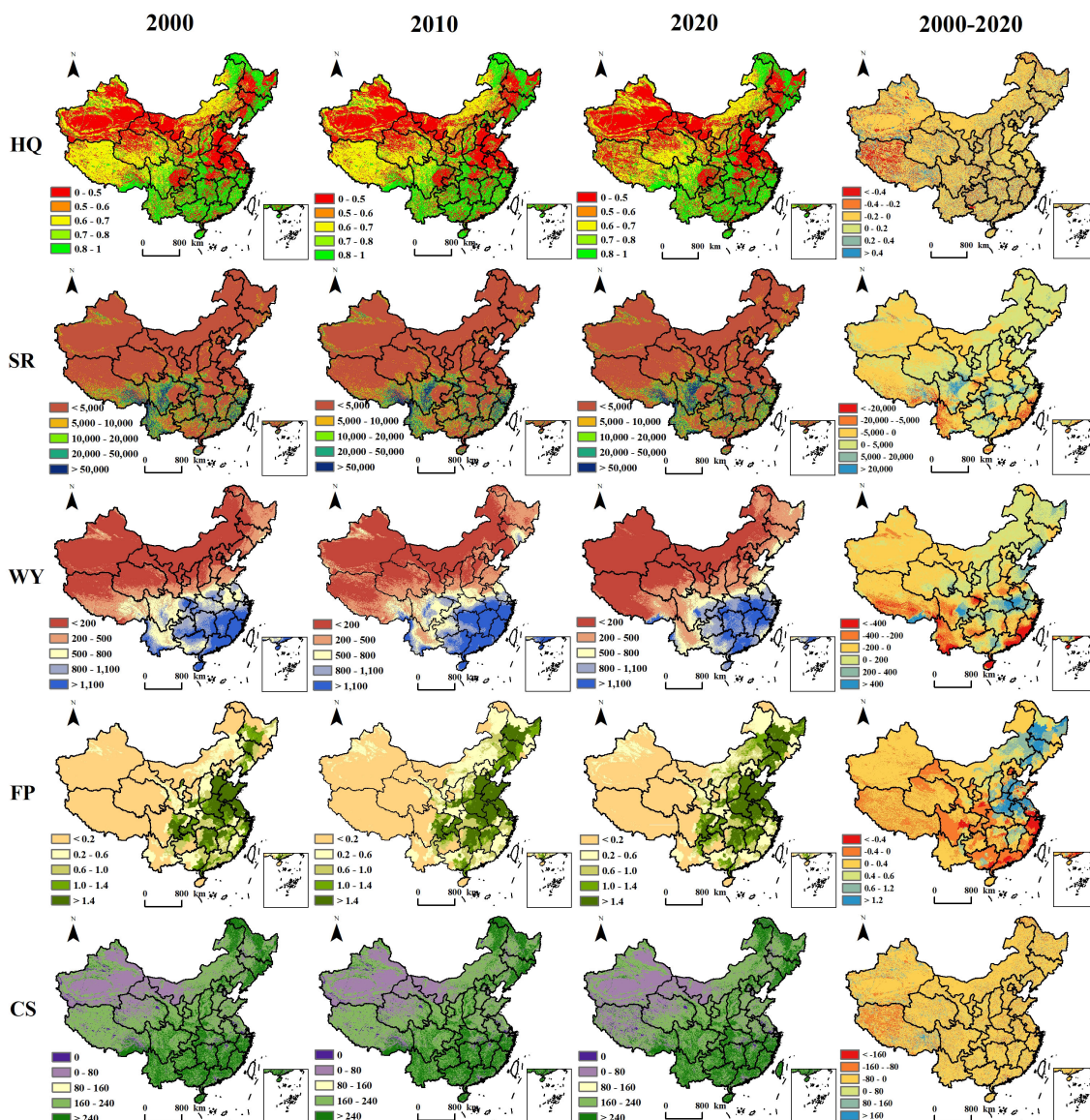


FIGURE 3 Spatial and temporal pattern of the ecosystem services in China from 2000 to 2020(t/hm^{-2}).

low WY areas are primarily concentrated in the northwest of China. In recent years, rapid urbanization has resulted in constant expansion of construction land, and the impervious layers brought about by the expansion of buildings have increased water conservation in these provinces. The northwest region has less precipitation, resulting in lower water conservation. Precipitation increased slightly in 2010 compared to 2000, with small fluctuations in temperature and a slight increase in water conservation. However, from 2000 to 2020, there was a significant increase in temperature, which raised the potential evaporation of plants, leading to a decrease in WY.

Between 2000 and 2020, China's FP showed a significant increase with large fluctuations, increasing from $0.48t/hm^{-2}$ to $0.69t/hm^{-2}$, representing an overall increase of 43.75%. The areas where FP increased spatially are mainly located in provinces such as

Jiangsu, Henan, Anhui, Shandong, and Jilin, while the areas where it decreased are mainly in provinces such as Guangdong, Sichuan, and Fujian. The valuable areas of FP are primarily concentrated in eastern China, such as Jiangsu, Shandong, Hebei, Henan, and Anhui provinces. These regions have gentle slopes, good accessibility, abundant water and soil resources, and favorable conditions for agricultural production, making them the main distribution areas of arable land. Low FP areas are mainly concentrated in the northwestern region of China, encompassing Xinjiang, Qinghai, Tibet, and Gansu provinces. These regions have high altitudes, varied terrain, and relatively low rainfall, which are not conducive to grain production.

During 2000–2020, China's overall CS showed a slight downward trend, decreasing from $174t/hm^{-2}$ to $171t/hm^{-2}$, representing a 2.01% decrease. Spatially, the main areas of decline

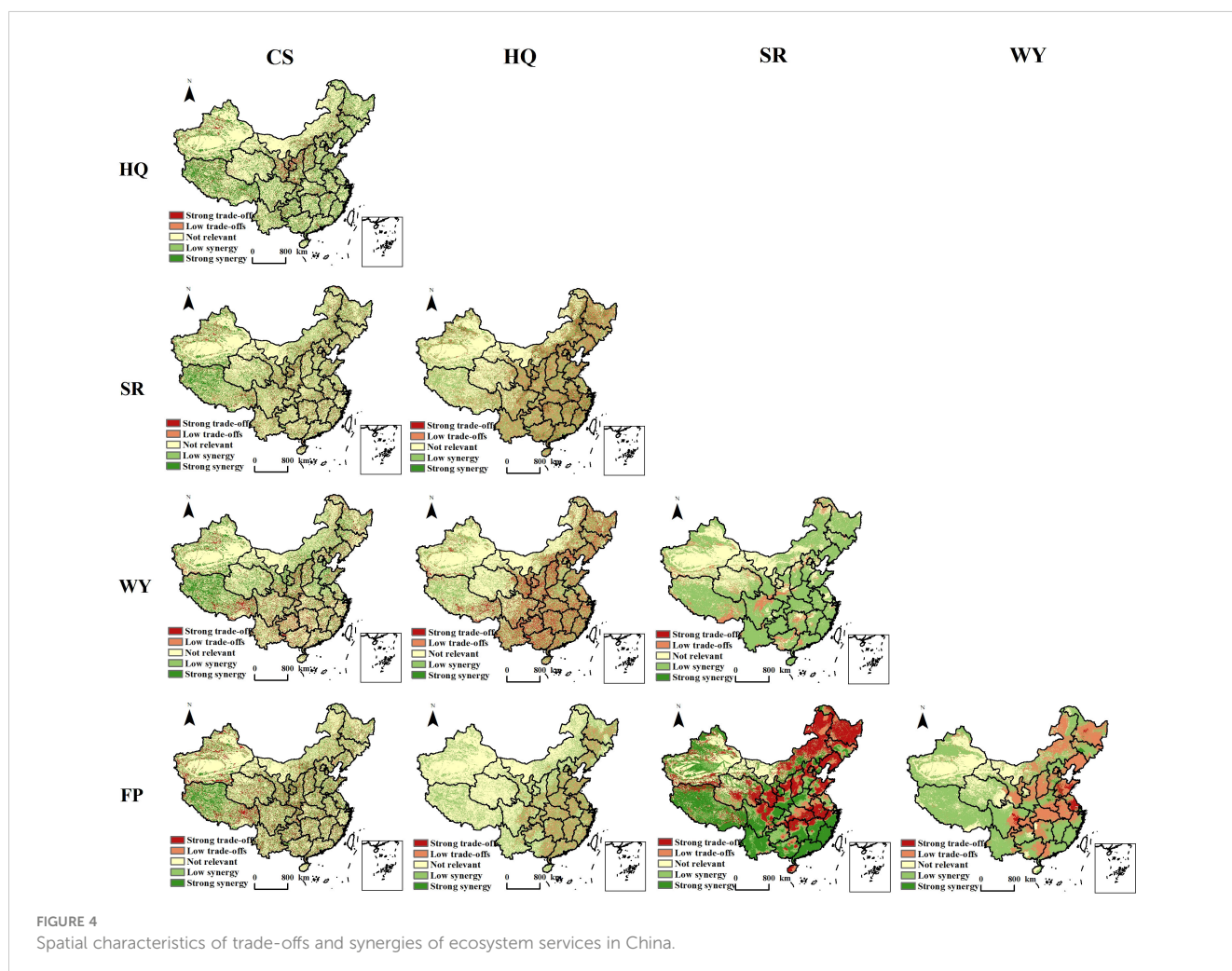
in CS are mainly concentrated in Tibet and Xinjiang, and other provinces are mostly evenly distributed. Recently, rapid development has led to a reduction in carbon sequestration capacity. High CS areas are primarily concentrated in eastern China, specifically Zhejiang, Guangdong, and Fujian provinces. Low CS areas are primarily concentrated in the northwest region, including Xinjiang, Qinghai, and Tibet, showing an east–high–west–low spatial and temporal distribution pattern. Due to the close relationship between CS and vegetation coverage as well as land use types (Wang et al., 2020; Ding et al., 2023). The eastern region of China has a vast forested area with dense vegetation, demonstrating robust carbon sequestration capabilities, while the western region has lower vegetation coverage, complex terrain, and a large area of desert and grassland, resulting in weaker carbon sequestration capacity and much lower carbon reserves compared to the eastern provinces.

3.2 Trade-offs/synergies of ecosystem services

Based on the spatial quantitative assessment of five critical terrestrial ecosystem services in China, the Pearson rank correlation

coefficient model was used. The results revealed that, at a significance level of 0.01, China’s five critical terrestrial ecosystem services were significantly correlated. In this paper, a positive correlation coefficient and a larger value represent a stronger synergy between the functions of the different ecosystem services. Conversely, a negative correlation coefficient and a smaller value represent a stronger trade-off effect between ecosystem services. This study categorized the trade-offs/synergies between different ecosystem services into five levels: strong trade-off ($Q < -0.5$), trade-off ($-0.5 < Q < 0$), unrelated ($Q = 0$), synergy ($0 < Q < 0.5$), and strong synergy ($Q > 0.5$), thus revealing the trade-offs/synergies of ecosystem services in China (Figures 4, 5).

Specifically, HQ and CS show high synergy and unrelatedness, with a strong synergy and synergy area ratio of 30.3%, and an unrelated area ratio of 63.3%. The synergy areas are mainly distributed in provinces such as Tibet, Fujian, Heilongjiang, Jilin, and Zhejiang, while the unrelated areas are mainly concentrated in Xinjiang, Inner Mongolia, and other provinces; the trade-off areas are mainly distributed in Gansu, Ningxia, and Shaanxi. HQ and SR exhibit a combination of balanced, unrelated, and synergistic relationships, with the balanced area ratio of 26%, a synergy area ratio of 32.44%, and the unrelated area ratio of 33.87%. Using the “Hu Huanyong Line” as a dividing line (Zhao et al., 2022). HQ and WY exhibit both synergy and unrelatedness, with a synergy area



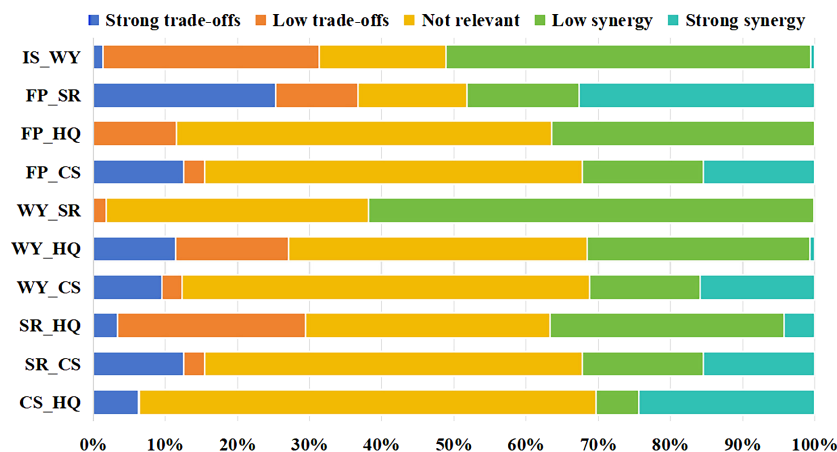


FIGURE 5 Proportion of ecosystem service trade-offs and synergies in China.

ratio of 30.86%, mainly located in Tibet, Xinjiang and Qinghai, and the unrelated area ratio of 41.4%, mainly distributed in Xinjiang, Inner Mongolia, Hubei, and Hunan. HQ and FP mainly exhibit an unrelated and synergistic relationship, with a synergy area ratio of 36.5%, which are mainly located in Yunnan, Sichuan, Tibet, and Xinjiang, and an unrelated area ratio of 51%, which are mainly distributed in Xinjiang and Inner Mongolia. WY and CS mainly exhibit unrelated, synergistic, and strong synergistic relationships, with the synergy and strong synergy area accounts for 31.2%, mainly distributed in Henan, Xinjiang, Tibet, and Inner Mongolia, and the unrelated area accounts for 56%, mainly distributed in Xinjiang, Inner Mongolia, and southeastern coastal provinces. WY and SR mainly exhibit a synergistic and unrelated relationship, with a synergistic area ratio of 61.7%, mainly distributed in Xinjiang, Yunnan, as well as Fujian, Zhejiang, Guangdong, and other eastern provinces of China, and the unrelated area ratio of 36%, mainly concentrated in Qinghai, Xinjiang, Inner Mongolia, and other provinces. WY and FP mainly exhibit a synergistic and balanced relationship, with the synergistic area ratio of 50.55%, mainly distributed in provinces such as Yunnan, Sichuan, Fujian, and Jiangxi, and a balanced area ratio of 29.9%, mainly distributed in provinces such as Heilongjiang, Anhui, Hubei, and Shandong. CS and SR mainly exhibit an unrelated and synergistic relationship, with a synergy area ratio of 21%, mainly distributed in provinces such as Tibet, Heilongjiang, Qinghai, and Jiangsu, and an unrelated area ratio of 54%, mainly located in areas such as Xinjiang and Inner Mongolia. CS and FP mainly exhibit an unrelated and synergistic relationship, with a synergy area ratio of 16.8%, mainly distributed in provinces such as Heilongjiang, Inner Mongolia, and Jiangsu, and an unrelated area ratio of 52%, mainly located in provinces such as Xinjiang and Inner Mongolia. FP and SR mainly exhibit strong balanced and strong synergistic relationships, with a strong trade-off area ratio of 25.3%, mainly concentrated in Heilongjiang, Jilin, Anhui, and Shandong provinces, and the strong synergy area ratio of 32.6%, mainly distributed in provinces such as Fujian, Guangdong, Yunnan, and Tibet.

3.3 Spatial and temporal driving mechanisms of ecosystem services

3.3.1 Geographical detection of main influencing factors

From multiple dimensions such as nature, economy, and society, this study takes HQ, WY, SR, CS and FP as the dependent variables for ecosystem services. It uses ten potential independent variables (X1~X10), including average annual temperature, average annual precipitation, elevation, slope, river network density, NDVI, per capita GDP, population density, construction intensity, and road network density (Table 2). This study employs the factor detection module of the geographical detector model to quantitatively detect the main influencing factors and their effects at the county level. The detection results indicate

TABLE 2 Driving factors of terrestrial ecosystem services in China.

Type	Level 1 indicators	Level 2 indicators	Code
Natural	Climatic conditions	Average annual temperature	X1
		Average annual precipitation	X2
	Topography	Elevation	X3
		Slope	X4
		River network density	X5
		NDVI	X6
Socio-economic	Urbanization of the population	GDP per capita	X7
		Population density	X8
	Urbanization of land	Intensity of land use (IOLU)	X9
	Infrastructure	Road network density	X10

that these ten driving factors all pass significance tests at different levels and can be considered important driving factors of ecosystem services in China. The magnitude of the p-value determines the importance of the influencing factors. Then the key influencing factors of different ecosystem service functions are identified.

The geographical detection results of the main influencing factors of ecosystem services in China from 2000 to 2020 are shown in Figure 6. Overall, the main influencing factors of HQ, WY, SR, CS, and FP exhibit significant differences and change over time. Specifically, slope (X4) is the dominant factor in HQ variation, followed by construction intensity (X9) and population density (X8). The degree of influence q value on ESS fluctuates slightly but tends to be consistent, indicating that social and natural factors impact HQ changes in the region. NDVI (X6) is the dominant factor affecting CS variation, followed by precipitation (X2) and population density (X8). The q value of NDVI's influence on CS significantly increases from 0.42 to 0.60, indicating that the impact of NDVI on forest carbon sequestration efficiency gradually strengthened from 2000 to 2020. Construction intensity (X9) is the dominant factor in FP variation, followed by population density (X8) and slope (X4). Factors such as elevation (X3) and temperature (X1) have a weak impact on FP, and the q value of the impact of construction intensity (X9) on FP decreases from 0.47 to 0.43, indicating the significant impact of urban land expansion and human activities on regional FP. Slope (X4) is the dominant factor in SR variation, with the q-value fluctuating between 0.57 and 0.60, followed by precipitation (X2) and elevation (X3), indicating that the region's slope, precipitation, and other natural background and inducing factors have a significant impact on SR. Precipitation (X2) is the dominant factor in WY, followed by temperature (X1) and water network density (X5), indicating that factors such as precipitation and temperature are decisive factors affecting regional WY. Therefore, natural and social factors both have an important impact on different ESS, and human activities

gradually intensify the interference with the natural environment, affecting the regional ESS.

3.3.2 Comparison of model accuracy

The evaluation of ESS driving factors using OLS and GWR models has been widely applied. This study selected GTWR, GWR, and OLS models to explore the evaluation accuracy of driving factors for ecosystem services, and the comparison results of three models are shown in Table 3. Using the GTWR model, a regression analysis was conducted on the five terrestrial ecosystem services (HQ, SR, WY, FP, CS) in China, with R^2 values of 0.77344, 0.77913, 0.88813, 0.49095, 0.68375, adjusted R^2 values of 0.77341, 0.77910, 0.88813, 0.49087, 0.68370, and AICC values of -13543.2 , -44085.4 , -37266.4 , -9560.2 , -15413.6 , respectively. Therefore, the GTWR model was used to analyze the spatial heterogeneity of influencing factors of ecosystem services, which performed well and outperformed the fitting effects of the GWR and OLS models.

3.3.3 Spatial heterogeneity analysis of influencing factors

Based on the main influencing factors of different ecosystem service functions detected by the geographical detector, the GTWR model is employed to analyze the spatial heterogeneity characteristics of influence factors of ecosystem services. According to the size of the q value, the detection results of the geographic detector found that factors such as slope, rainfall, IOLU, and NDVI are the core influencing factors of the five ecosystem services of HQ, SR, WY, FP, and CS. Among them, the slope factor is the core influencing factor of the HQ and SR; rainfall is the core influencing factor of WY; IOLU is the core influencing factor of FP; and NDVI is the core influencing factor of CS. Thus this study combines ArcGIS with the GTWR model to analyze the spatial heterogeneity characteristics of different dominant influence factors on these 5 ESS (Figure 7).

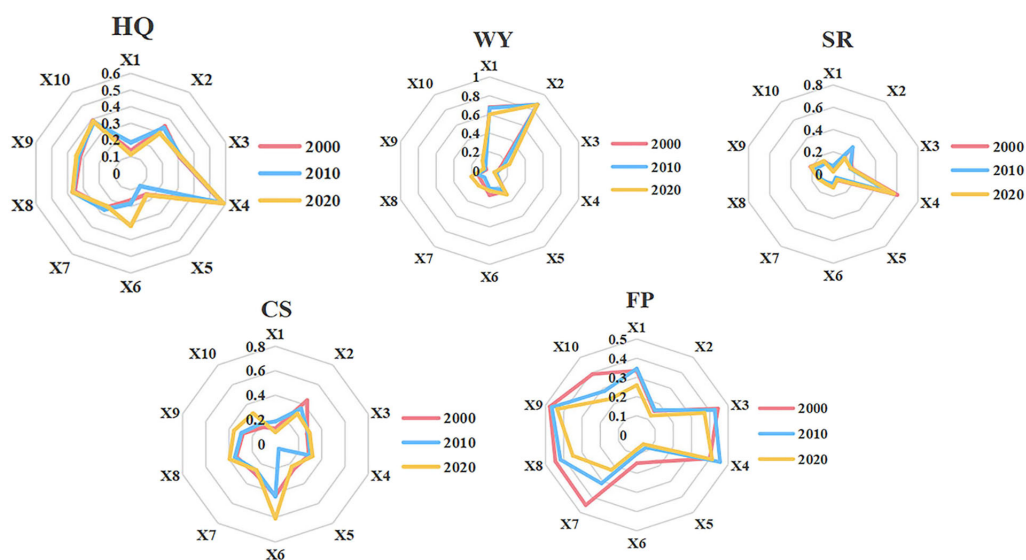


FIGURE 6
q-value of influencing factors of the spatial relationship of terrestrial ecosystem services in China.

TABLE 3 Comparative analysis between regression models.

	Type	AICC	R ²	AdjustedR ⁻²
OLS	HQ	-6509.3	0.38524	0.38524
	SR	-39204.3	0.55675	0.55675
	WY	-16945.3	0.79186	0.79186
	FP	-6309.5	0.18867	0.18867
	CS	-11701.2	0.46190	0.46190
GWR	HQ	-13680.7	0.77669	0.77666
	SR	-43182.4	0.74775	0.74772
	WY	-19001.3	0.84476	0.84473
	FP	-8225.5	0.38275	0.38266
	CS	-15076.5	0.66676	0.66671
GTWR	HQ	-13543.2	0.77344	0.77341
	SR	-44085.4	0.77913	0.77910
	WY	-37266.4	0.88813	0.88813
	FP	-9560.2	0.49095	0.49087
	CS	-15413.6	0.68375	0.68370

Overall, slope, rainfall, IOLU, and NDVI show significant spatial heterogeneity in influencing crucial terrestrial ecosystem service functions in China. Specifically, between 2000 and 2020, the slope's trend on HQ was relatively consistent, showing a positive correlation nationally. Its impact changes are relatively small and show a slight decreasing trend, with an overall stable trend and slight downward trend from northeast to southwest. The areas of lower impact are mainly distributed in Yunnan, Tibet, and Sichuan provinces; the regions with moderate impact are primarily located in Gansu, Inner Mongolia, and Xinjiang provinces, while the areas with significant impact are primarily located in Heilongjiang, Jilin, and Liaoning provinces. The degree of slope's impact on SR gradually decreases, continuously decreasing from the southeastern coast to the inland areas. Regions with higher slopes are more affected by rainfall, resulting in higher degrees of soil erosion. The higher impact areas are mainly distributed in Hainan, Fujian, Zhejiang, and Guangdong. Rainfall and WY show a spatially positive correlation, indicating that WY is mainly influenced by rainfall. The higher the rainfall, the greater the WY. There is a southeast-to-northwest trend of varying values, with rainfall's impact on WY gradually expanding from inland China to the southeastern coast. The regions with lower impact primarily include Tibet, Xinjiang, Qinghai, and other provinces while the areas of moderate impact are mainly concentrated in Yunnan, Sichuan, and other provinces, and the areas of higher impact are mainly concentrated in Zhejiang, Anhui, Jiangsu, and other provinces. IOLU and FP show a significant positive correlation spatially. The impact of IOLU on FP gradually weakens, decreasing from inland China to the southeastern coast. Lower impact areas are mainly concentrated in Tibet, Xinjiang, and other provinces, while moderate impact areas are mainly distributed in Hainan, Guangxi, Guangdong, and other provinces, and the areas of higher impact

intensity are mainly distributed in Sichuan, Hubei, Hunan, and other provinces. NDVI and CS show a significant positive correlation spatially, with the impact of NDVI on CS gradually expanding from western to eastern China. The areas of lower impact are mainly distributed in Inner Mongolia, Beijing, Hebei, Shanxi, and other provinces, while the areas of moderate impact are mainly concentrated in Tibet, Xinjiang, Qinghai, and other provinces, and the areas of higher impact are mainly distributed in Heilongjiang, Fujian, Zhejiang, Guangdong, and other provinces.

4 Discussion

4.1 Validation of ecosystem service measurements

Quantifying ESS based on the InVEST model is widely recognized domestically and internationally due to its mature and scientific evaluation system. In light of this, this paper conducts an assessment of China's terrestrial ecosystem ESS using the InVEST model. Its evaluation results serve as an important basis for subsequent comprehensive ESS assessments and functional zoning. The accuracy of the evaluation results determines the reliability of subsequent work. To ensure the scientific nature of the evaluation results, we conduct accuracy validation analysis through the evaluation results of other scholars. Considering the current lack of relevant research on the assessment of China's terrestrial ecosystem ESS, we conduct a comparative analysis with the evaluation results of related studies from similar years.

For HQ, the average annual HQ values in the study area for 2000, 2010, and 2020 were 0.578, 0.578, and 0.563, respectively. Yu et al. (2024) measured HQ at the provincial scale for 31 provinces in China using the InVEST model, showing average HQ indices of approximately 0.614, 0.613, and 0.612 for 2000, 2010, and 2020, respectively. Su et al. (2024) measured HQ at the city scale in China from 2010 to 2020 using the InVEST model, showing a slight downward trend, consistent with this study's conclusions. For FP, the average annual FP values in the study area for 2000, 2010, and 2020 were 0.483t/hm⁻², 0.642t/hm⁻², and 0.695t/hm⁻², respectively. Tian et al. (2024) estimated FP in China from 2000 to 2020, showing significant improvement in FP across major urban agglomerations over 20 years, consistent with this study's results. For CS, the average annual CS values in the study area for 2000, 2010, and 2020 were 174t/hm⁻², 174t/hm⁻², and 174t/hm⁻², respectively. Zhang et al. (2017) estimated CS in China's terrestrial ecosystems for 2010 using the InVEST model, with results around 190t/hm⁻², slightly different from this study's results but within the same range. For SR, the average annual SR values in the study area for 2000, 2010, and 2020 were 5862t/hm⁻², 6415t/hm⁻², and 6543t/hm⁻², respectively. Yu et al. (2024) estimated SR in China from 1990 to 2020 using the InVEST model, with results ranging between 5000t/hm⁻² and 5500t/hm⁻², slightly different from this study's SR measurements but generally consistent and showing a significant upward trend. For WY, the average annual WY values in the study area for 2000, 2010, and 2020 were 375mm/hm⁻², 406mm/hm⁻², and 355mm/hm⁻², respectively. Su et al. (2024) measured WY at the

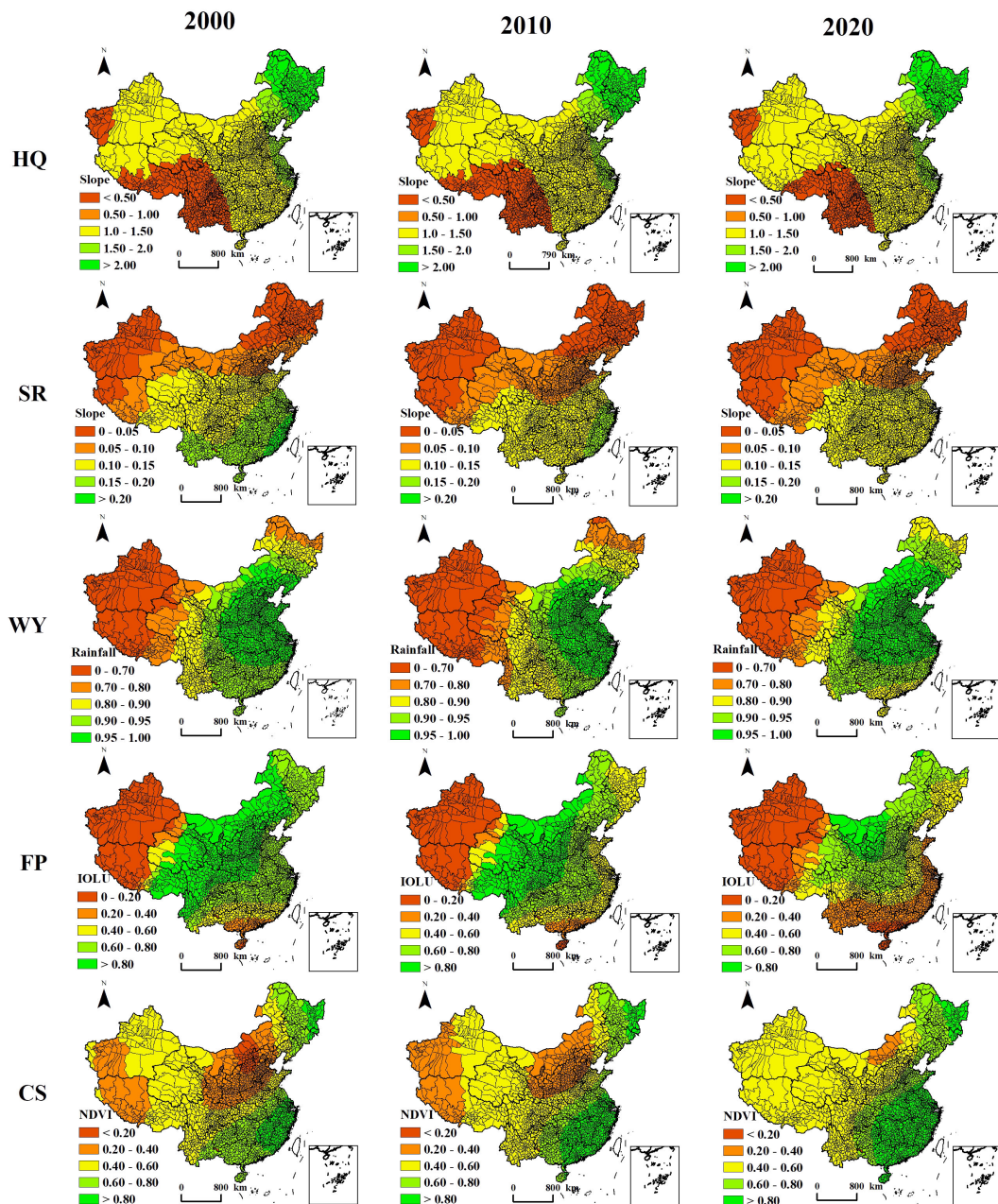


FIGURE 7 Spatial distribution characteristics of influence factors of ecosystem services.

city scale in China from 2010 to 2020 using the InVEST model, with results of 631mm/h^{-2} and 583mm/hm^{-2} for 2010 and 2020, respectively, showing a downward trend over the decade. Yu et al. (2024) measured WY in China for 2000, 2010, and 2020 using the InVEST model, with results ranging between 330mm/hm^{-2} and 380mm/hm^{-2} , showing a rising then falling trend, consistent with this study's results.

In summary, the results of measuring China's terrestrial HQ, CS, SR, WY, and FP using the InVEST model, despite some differences with those of other scholars, likely due to differences in scales and model parameters chosen, generally fall within the same range as those measured by other scholars at city, provincial,

and urban agglomeration scales. ESS results measured are largely consistent. Therefore, the results of measuring ecosystem services at the county scale in China using the InVEST model in this paper have strong scientific validity and feasibility.

4.2 Spatial and temporal pattern of comprehensive ecosystem services

This study standardized the five types of ESS and constructed a comprehensive ecosystem service index using the method of equal weight allocation from 2000 to 2020, and further explored the

spatial and temporal pattern of comprehensive ecosystem services in China (Figure 8). Between 2000 and 2020, the comprehensive ecosystem services in China remained consistent, the basic trend shows higher levels in the southeast and lower levels in the northwest. The low-value areas of comprehensive ecosystem services are mainly distributed in provinces such as Xinjiang, Inner Mongolia, and Qinghai; the regions with intermediate impact levels are primarily concentrated in provinces like Tibet, Gansu, and high-value areas are concentrated in Guangdong and Zhejiang. Between 2000 and 2020, the overall comprehensive ecosystem service function slightly decreased. The average ecosystem service function index declined slightly from 0.284 in 2000 to 0.266 in 2020, suggesting a minor overall decrease nationwide. This may be due to China's rapid economic development and continuous urbanization, which have caused a certain degree of damage to the domestic ecology (Wang et al., 2022). The areas with increasing comprehensive ecosystem service functions are mainly in Heilongjiang, Inner Mongolia, and Anhui provinces. The southeastern and coastal terrains are mostly low mountains, hills, and plains, with small fluctuations in terrain and influenced by the ocean, resulting in low-temperature differences, high rainfall, suitable for plant growth, and relatively high

vegetation coverage. Inland terrains are mostly high mountains and basins with large fluctuations in terrain, large temperature differences, low rainfall, and relatively low vegetation coverage (Hu et al., 2021). Meanwhile, the southeastern region has a large population and rapid economic development, leading to relatively prosperous agricultural development in the east.

4.3 Ecosystem service responses to land use

Based on the spatial overlay of land use types in 2020 with five ESS: HQ, SR, WY, FP, and CS, to investigate how various terrestrial ecosystem services in China respond to land use, as shown in Table 4. Different ESSs also exhibit significant spatial heterogeneity in response to land use types (Muvi et al., 2019). Specifically, HQ has low values in unused land and high values in forest areas, SR and WY have low values in unused land and grassland, with high values in forest areas, FP has low values in water areas and high values in cultivated land. CS have low values mainly concentrated in construction land areas, while high values are mainly concentrated in forest areas. Different land use types exhibit distinct spatial

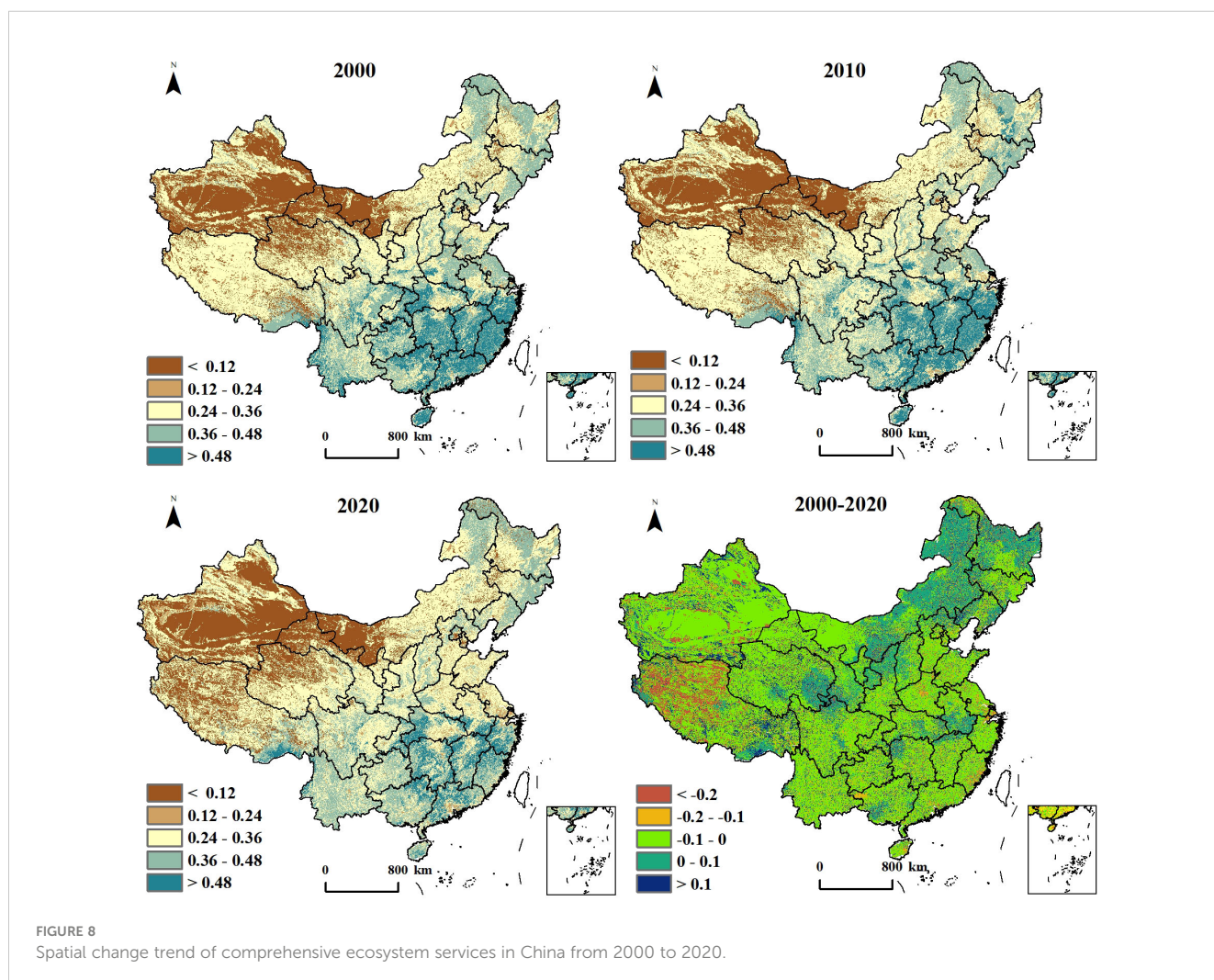


TABLE 4 Responses of land use types to terrestrial ecosystem services in China.

ESS	Level	Cultivated land	Forest land	Grassland	Water	Construction land	Unused land
HQ	Low	1579420	486	8664	1964	145736	2077120
	Lower	54781	3126	13120	3548	68448	84452
	Moderate	56478	7589	2535791	10071	35248	8647
	Higher	43254	15200	68944	112819	7546	3548
	High	18546	2171897	56447	146288	872	524
SR	Low	1540126	1055568	2043662	240215	246214	2142566
	Lower	72513	297311	235727	10395	4716	10610
	Moderate	64678	317060	188453	9872	3086	8685
	Higher	51810	320762	144680	8211	1630	7083
	High	20414	204070	65195	2938	464	2285
WY	Low	239194	305362	1684095	148317	94844	2095178
	Lower	632658	705814	659688	50970	55615	70777
	Moderate	278180	350063	205156	21116	34370	3611
	Higher	324850	489454	73391	31949	45401	1981
	High	276290	345035	56736	20284	26674	90
FP	Low	4	70	2846	25277	173	12847
	Lower	123227	582550	1575882	132068	22412	1964068
	Moderate	378951	703584	607858	32242	47705	115785
	Higher	458040	557851	397723	36682	65028	40978
	High	783067	342077	83356	45163	120421	29713
CS	Low	32113	13764	29683	129319	7095	41659
	Lower	119231	37048	310780	38621	62753	1582514
	Moderate	184773	276696	1946528	52988	18051	503975
	Higher	1161333	250561	154774	36956	148546	15396
	High	254046	1618434	239265	16006	20898	28543

heterogeneity in response to ESS. The response of cultivated land to HQ, SR, and WY is mainly concentrated in low values, while the response to FP and CS is mainly concentrated in high values. The response of grassland to SR, WY, and FP is mainly concentrated at low values, while the response to HQ and CS is mainly concentrated at moderate values. The response of water areas to SR, WY, CS and FP mainly focuses on low values, while the response to HQ mainly focuses on high values. The response of construction land to HQ, SR, and WY mainly focuses on low values, while the response to FP and CS mainly focuses on high values. Unused land consistently exhibits a low response to various ESS. It can be seen that forest land exhibits a significant response to high ESS values, while unused land shows a notable response to low ESS values. ESS demonstrates a significant response to land use types, with both low and high values for HQ, primarily low values for SR and WY, mainly moderate values for FP, and primarily high values for CS.

4.4 Functional zoning of ecosystem services

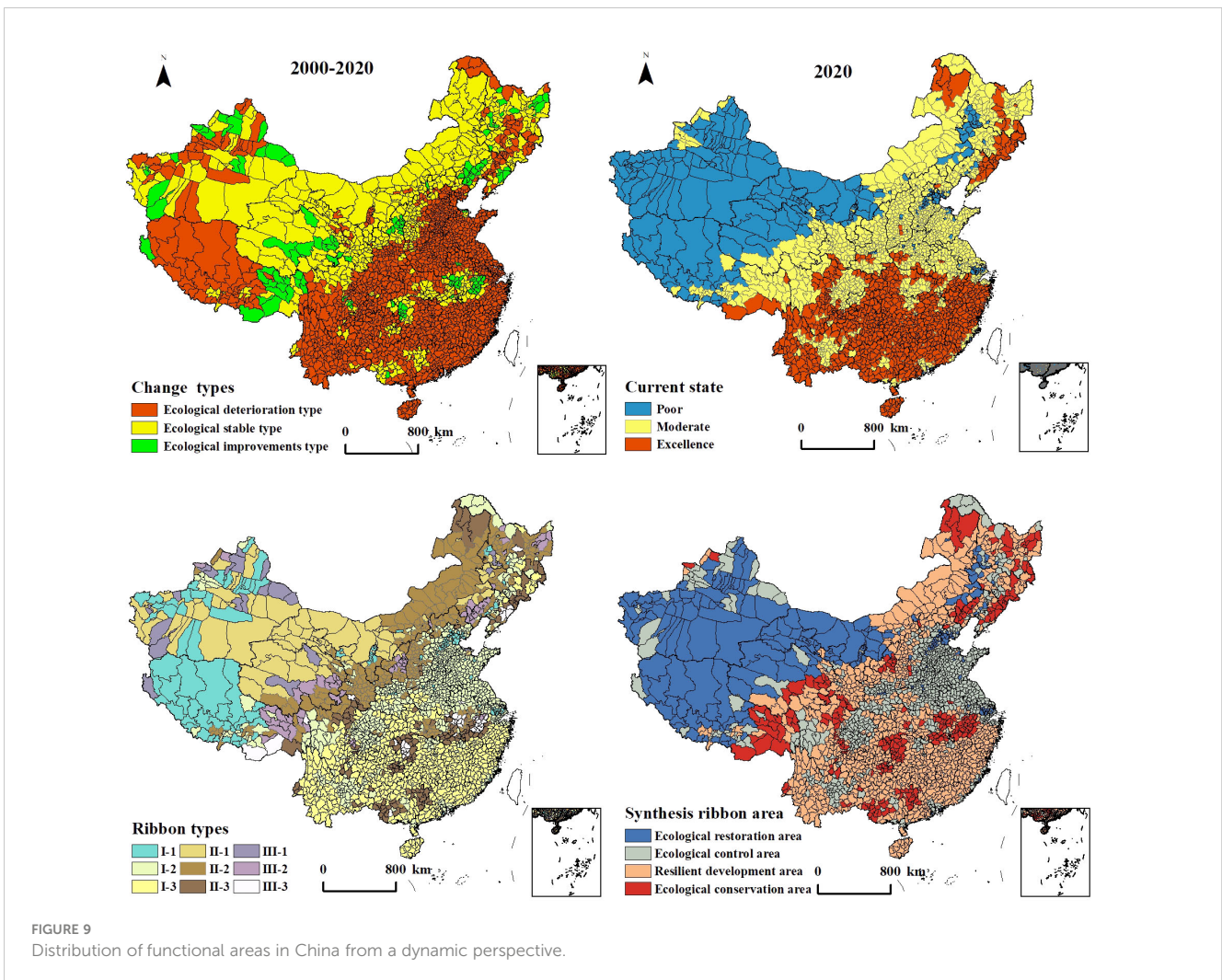
Based on the comprehensive ecosystem services from 2000 to 2020, Chinese county-level units are used as the basis. It combines cumulativeness with spatial dynamics, covering the current stage characteristics and long-term evolution process of comprehensive ecosystem service functions. First, based on the long-term evolution process, it is divided into three evolutionary characteristics: ecological degradation type, ecological stability type, and ecological development type. Then based on the comprehensive ecosystem service function regions in 2020, it is divided into nine ecological function precautionary areas (Figure 9).

Among them, the ecological degradation type includes I-1, I-2 and I-3 which represent the current status of low-level ecosystem

service supply, and have shown a trend of degradation, stability, and optimization over the past 20 years. The ecological stability type includes II-1, II-2 and II-3, which represent the current status of moderate-level ecosystem service supply, and have shown a trend of degradation, stability, and optimization over the past 20 years. The ecological development type includes III-1, III-2 and III-3, representing the current status of high-level ecosystem service supply and have showing a trend of degradation, stability and optimization.

Specifically, the proportion of areas with ecological degradation type is 46.92%. Among them, I-1 is mainly located in China's western region, encompassing the northern regions of Tibet, Tianjin, and Xinjiang provinces, mainly consisting of unused land and construction land. I-2 is predominantly situated in Jiangsu, Shandong, Henan, Shaanxi and other provinces, mainly consisting of arable land and construction land, and is the core construction area of China. I-3 is mainly situated in southern China, such as Fujian, Zhejiang, Jiangxi and other provinces. The proportion of areas with ecological stability type is 43.58%. Among them, II-1 is primarily situated in the northern part of Qinghai the western part

of Inner Mongolia, and the eastern region of Xinjiang, mainly consisting of unused land, combining production and living areas in various locations (Yang et al., 2023). II-2 is mostly located in Ningxia, Shanxi and other provinces, as well as the eastern counties of Inner Mongolia, mainly composed of grassland and construction land. II-3 is mostly located in the southern part of Jilin Province, the northern part of Inner Mongolia, and the southeastern counties of Guangxi. These areas consist primarily of woodland and construction land. The proportion of areas with ecological development type is 9.51%. Among them, III-1 is mostly located in Hotan and Pishan County in Xinjiang Province and Qumalai County in Qinghai Province, which are primarily grassland-dominated regions, with scattered construction land in each county, and are easily affected by disturbances from other areas. III-2 is mostly located in the northeastern counties of Tibet and Maduo County in Qinghai Province. These areas consist predominantly of grassland. III-3 is primarily situated in the southern region of Tibet and the northwest area of Hunan Province. These areas consist predominantly of grassland and woodland, strongly resistant to disturbances (Liu et al., 2023).



4.5 Optimization path of territorial spatial zoning

Based on the spatial and temporal evolution characteristics and cumulative overlay, China's land space is divided into four major types of ecological protection functional zones: ecological restoration area, ecological control area, resilient development area, and ecological conservation area. The basis for division, control objectives, and zoning characteristics are shown in (Table 5). Among them, the ecological restoration area mainly includes two ecological system functional zones, I-1 and I-2, which are concentrated in western China, such as Tibet and Xinjiang. These areas are characterized by high altitude, low vegetation coverage, natural constraints, high degree of fragmentation in construction, high sensitivity, and once damaged, the ecological system functions will suffer losses, making a recovery more difficult (Chen et al., 2019). The ecological control area mainly includes two types of ecological system functional zones, II-2 and III-1. These areas are primarily situated in the northeastern part of China.

The Sichuan Basin, Jiangsu, Shandong, Sichuan, Inner Mongolia, Heilongjiang, and other provinces. These areas are the main grain-producing region of China, where the contradictions between agricultural production, construction expansion, and ecological protection are particularly prominent. The resilient development area mainly includes two types of ecological system functional zones, I-3 and II-1, which are mainly situated in the southern and southeastern coastal, such as Hainan, Yunnan, Fujian and Zhejiang. These areas have relatively high vegetation coverage, which is important for maintaining biodiversity. Mountainous and hilly terrain, superior coastal and natural conditions, and a land use pattern with intersecting distribution of woodland, water, and construction land characterize it. The ecological conservation area mainly includes three types of ecological system functional zones, II-3, III-2, and III-3, which are mainly situated in the southern and northern parts of Jilin Province, the western and eastern parts of Guangxi, the southern part of Anhui Province, and the southern part of Tibet. The overall ecological environment in these areas is relatively good, with abundant forest resources,

making it a core area with good ecological system service functions in China.

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TABLE 5 Classification and regional distribution characteristics of functional areas.

Type	Include regions	Manage goals	Regional characteristics
Ecological Restoration area	I-1, I-2	Development is strictly prohibited to promote the comprehensive improvement of ecosystem services	Concentration lies primarily in the western region, and the unused land accounts for a relatively large proportion, mostly mountainous and plateau, and the terrain is relatively high.
Ecological Control area	I-3, II-1	Rely on resources to improve the quality of ecosystem services	It is mainly distributed in the eastern and northern plains, the main agricultural production area, with a significant amount of cultivated land, construction land, and flat terrain.
Resilient Development area	II-2, III-1	Take into account the overall planning and optimize the regional layout	It is concentrated in the southern and southeastern coastal areas, mostly mountainous and hilly, with a relatively large proportion of woodland and construction land, and a high vegetation coverage rate.
Ecological Conservation Area	II-3, III-2, III-3	Strengthen supervision and strictly prevent sabotage	It is distributed in Tibet, Xinjiang, Jilin Province, Guangxi Province, and the northern and southern counties with a large proportion of woodland and grassland.

4.6 Research contributions, shortcomings and prospects

This study, based on the InVEST model, explores the spatial and temporal patterns, driving mechanisms, trade-offs, synergies, and functional zoning characteristics of key ESS in China's terrestrial ecosystems from 2000 to 2020. The study found that the capacities of three ecosystem services, HQ, CS, and WY, have declined over the 20 years, while FP and SR have increased. Multi-dimensional factors, including natural, social, and economic aspects, have a significant impact on each ESS. Meanwhile, the synergy between WY and SR and between FP and WY is the most significant, while the trade-off and strong trade-off relationships between FP and SR are the most significant. Therefore, this study attempts to construct a long-term quantitative assessment system for various ESS in China's terrestrial ecosystems. This system can scientifically identify the current status of ESS in different regions of China, the trade-offs and synergies, and the driving mechanisms. It can further explore the functional areas of China's future ecosystems and the zoning and regulation pathways. This provides new insights for improving the ESS assessment framework and analytical pathways, especially exploring the driving mechanisms of regional ESS based on the geographical detector model and the spatial and temporal geographically weighted regression model. It also explores ecological functional zoning and optimization pathways for land space, providing important theoretical guidance for future large-scale ESS assessments and optimizations. Additionally, this study calculated the spatial and temporal patterns and driving mechanisms of finely scaled terrestrial ESS at a 1km grid scale in China from 2000 to 2020. This can effectively maximize ESS benefits and more scientifically and systematically manage China's terrestrial ecosystem ESS. It plays a significant role in protecting regional ecosystem security, promoting high-quality sustainable natural development, and providing decision-making support for China's land spatial planning from a planning and management perspective. Therefore, this study has important practical significance for ensuring China's ecological security and optimizing regional land spatial patterns.

However, although this study effectively reveals the spatial and temporal patterns and driving mechanisms of key ESS in China's terrestrial ecosystems from 2000 to 2020, there are still some limitations due to data and technical methods. For example, this study only quantitatively represents key ESS in China's terrestrial ecosystems through supporting, provisioning, and regulating functions and does not include cultural functions in the assessment model of regional ESS. Furthermore, the current research mainly focuses on measuring ESS at a 1km grid scale in China from 2000 to 2020. It does not explore the spatial and temporal evolution patterns of ESS over a longer time dimension. The revelation of the spatial and temporal patterns of ESS and the analysis of the fine-scale phenomena and internal mechanisms of regional ESS are relatively general and require further research in the future. Therefore, in future research on the spatial and

temporal characteristics and internal mechanisms of regional ESS, current advanced technologies such as big data, machine learning, and deep learning can be integrated to construct refined and differentiated models for calculating ESS. This can reveal the spatial and temporal evolution characteristics and internal driving mechanisms of key ESS in China's terrestrial ecosystems over time series. Additionally, the fine-scale differential characteristics and mechanisms of regions can be deeply analyzed, studying the spatial differentiation and internal mechanisms of ESS in different functional zones, thereby improving the accuracy and depth of regional ESS assessments.

5 Main conclusions

This study comprehensively applies methods such as the InVEST model, the balance and coordination model, geographic detector, and GTWR model to quantitatively evaluate the spatial and temporal balance/coordination of five key ecosystem services in China's terrestrial areas from 2000 to 2020. It analyzes the main factors influencing different ecosystem service functions and their spatial heterogeneity, and then explores the functional zoning of ecosystem services in China and differentiated zoning control strategies. The main conclusions are as follows:

1. From 2000 to 2020, the average annual values of other key ecosystem services in China, except for food provision and soil conservation, have declined. The overall ecosystem services show a decreasing trend from high in the southeast to low in the northwest.
2. From 2000 to 2020, the functions of key terrestrial ecosystem services in China have been comprehensively affected by multiple dimensions, including natural, economic, and social factors. Among them, slope, average annual rainfall, construction land intensity, and vegetation coverage are the dominant influencing factors. There are significant differences and spatial heterogeneity characteristics among different factors.
3. From 2000 to 2020, key terrestrial ecosystem services in China had more synergy and strong synergy relationships and fewer trade-off and strong trade-off relationships among key terrestrial ecosystem services in China. The synergy between water retention and soil conservation, and between food provision and water retention, was the most significant, while the trade-off and strong trade-off relationships between food provision and soil conservation were the most notable.
4. Based on the evolution trends and current characteristics of ecosystem services, the land space is divided into four major types of ecological functional control zones: ecological restoration zone, ecological control zone, flexible development zone, and ecological conservation zone. Future differentiated zoning optimization pathways are formulated for different control zones.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JH: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. SY: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. WZ: Data curation, Resources, Writing – original draft. JL: Funding acquisition, Investigation, Supervision, Writing – review & editing. YZ: Data curation, Methodology, Supervision, Writing – review & editing. JR: Methodology, Resources, Supervision, Writing – original draft. YD: Formal analysis, Project administration, Supervision, Writing – review & editing. AZ: Funding acquisition, Resources, Supervision, Writing – original draft.

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References

- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). Guidelines for computing crop water requirements. *Irrigation drainage paper* 56, 300. doi: 10.1016/j.eja.2010.12.001
- Bhagabati, N. K., Ricketts, T., Sulistyawan, T. B. S., Conte, M., Ennaanay, D., Hadian, O., et al. (2014). Ecosystem services reinforce Sumatran tiger conservation in land use plans. *Biol. Conserv.* 169, 147–156. doi: 10.1016/j.biocon.2013.11.010
- Canadell, J., Jackson, R. B., Ehleringer, J. B., Mooney, H. A., Sala, O. E., and Schulze, E. D. (1996). Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108, 583–595. doi: 10.1007/BF00329030
- Chen, T., Feng, Z., Zhao, H., and Wu, K. (2020). Identification of ecosystem service bundles and driving factors in Beijing and its surrounding areas. *Sci. Total Environ.* 711134687. doi: 10.1016/j.scitotenv.2019.134687
- Chen, F., Li, H., and Zhang, A. (2019). Ecological risk assessment based on terrestrial ecosystem services in China. *Acta Geogr. Sin.* 74, 432–445. doi: 10.11821/dlxb201903003
- Chung, M. G., Frank, K. A., Pokhrel, Y., Dietz, T., and Liu, J. (2021). Natural infrastructure in sustaining global urban freshwater ecosystem services. *Nat. Sustain.* 4, 1068–1075. doi: 10.1038/s41893-021-00786-4
- Costanza, R., De Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., et al. (2014). Changes in the global value of ecosystem services. *Global Environ. Change* 26, 152–158. doi: 10.1016/j.gloenvcha.2014.04.002
- Ding, Y., Wang, L. Z., Gui, F., Zhao, S., and Zhu, W. Y. (2023). Ecosystem carbon storage in Hangzhou bay area based on inVEST and PLUS models. *Environ. Sci.* 44, 3343–3352. doi: 10.13227/j.hjck.202204080
- Eger, A. M., Marzinielli, E. M., Beas-Luna, R., Blain, C. O., Blamey, L. K., and Byrnes Jarrett, E. K. (2023). The value of ecosystem services in global marine kelp forests. *Nat. Commun.* 14, 1894. doi: 10.1038/s41467-023-37385-0
- Feng, X., Li, Y., Wang, X., Yang, J., Yu, E., Wang, S., et al. (2023). Impacts of land use transitions on ecosystem services: a research framework coupled with structure, function, and dynamics. *Sci. Total Environ.* 901, 166366. doi: 10.1016/j.scitotenv.2023.166366
- Hu, S., QIU, H., WANG, N., Cui, Y., Cao, M., Wang, J., et al. (2021). The influence of terrain on loess landslides in Loess Plateau. *Acta Geographica Sin.* 76, 2697–2709. doi: 10.11821/dlxb202111008
- Huang, B., Wu, B., and Barry, M. (2010). Geographically and temporally weighted regression for modeling spatio-temporal variation in house prices. *Int. J. geographical Inf. Sci.* 24, 383–401. doi: 10.1080/13658810802672469
- Huang, C., Zhao, D., and Deng, L. (2022). Landscape pattern simulation for ecosystem service value regulation of Three Gorges Reservoir Area, China. *Environ. Impact Assess. Rev.* 95, 106798. doi: 10.1016/j.eiar.2022.106798
- Keith, H., Vardon, M., Stein, J. H., Stein, J. L., and Lindenmayer, D. (2017). Ecosystem accounts define explicit and spatial trade-offs for managing natural resources. *Nat. Ecol. Evol.* 1, 1683–1692. doi: 10.1038/s41559-017-0309-1
- Le Provost, Schenk, V., Penone, C., Thiele, J., Westphal, C., and Allan, C. (2023). The supply of multiple ecosystem services requires biodiversity across spatial scales. *Nat. Ecol. Evol.* 7, 236–249. doi: 10.1038/s41559-022-01918-5
- Li, W., Chen, X., Zheng, J., Zhang, F., Yan, Y., Hai, W., et al. (2024). A multi-scenario simulation and dynamic assessment of the ecosystem service values in key ecological functional areas: A case study of the Sichuan province, China. *Land* 13, 468. doi: 10.3390/land13040468
- Liu, T., Yu, L., Chen, X., Wu, H., Lin, H., Li, C., et al. (2023). Environmental laws and ecological restoration projects enhancing ecosystem services in China: A meta-analysis. *J. Environ. Manage.* 327, 116810. doi: 10.1016/j.jenvman.2022.116810

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2024.1443683/full#supplementary-material>

- MEA (2005). *Ecosystems and human well-being: Synthesis* (Washington (DC: Island Press)).
- Muyi, H. U. A. N. G., Wenze, Y. U. E., Bin, F. A. N. G., and Shaoru, F. E. N. G. (2019). Scale response characteristics and geographic exploration mechanism of spatial differentiation of ecosystem service values in Dabie Mountain area, central China from 1970 to 2015. *Prog. Chem.* 74, 1904. doi: 10.11821/dlxb201909015
- Pan, H., Du, Z., Wu, Z., Zhang, H., Ma, K., et al. (2024). Assessing the coupling coordination dynamics between land use intensity and ecosystem services in Shanxi's coalfields, China. *Ecol. Indic.* 158, 111321. doi: 10.1016/j.ecolind.2023.111321
- Qiu, H., Zhang, J., Han, H., Cheng, X., and Kang, F. (2023). Study on the impact of vegetation change on ecosystem services in the Loess Plateau, China. *Ecol. Indic.* 154, 110812. doi: 10.1016/j.ecolind.2023.110812
- Ran, L., Fang, N., Wang, X., Piao, S., Chan, C. N., Li, S., et al. (2023). "Substantially enhanced landscape carbon sink due to reduced terrestrial-aquatic carbon transfer through soil conservation in the Chinese loess plateau," in *Earth's Future*. 11, e2023EF002345. doi: 10.1029/2023EF002345
- Redhead, J. W., Stratford, C., Sharps, K., Jones, L., Ziv, G., Clarke, D., et al. (2016). Empirical validation of the InVEST water yield ecosystem service model at a national scale. *Sci. Total Environ.* 569, 1418–1426. doi: 10.1016/j.scitotenv.2016.06.227
- Rodriguez, J. P., Beard, J. T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J., et al. (2006). Trade-offs across space, time, and ecosystem services. *Ecol. Soc.* 11 (1), 28. doi: 10.5751/ES-01667-110128
- Sharp, R., Tallis, H. T., Ricketts, T., Guerry, A. D., Wood, S. A., Chaplin-Kramer, R., et al. (2015). "InVEST version 3.2.0 user's guide," in *The Nature Conservancy, and World Wildlife Fund* (Stanford, CA, USA: The Natural Capital Project).
- Smith, L. M., Case, J. L., Smith, H. M., Harwell, L. C., and Summers, J. K. (2013). Relating ecosystem services to domains of human well-being: Foundation for a US index. *Ecol. Indic.* 28, 79–90. doi: 10.1016/j.ecolind.2012.02.032
- Su, R., Duan, C., and Chen, B. (2024). The shift in the spatiotemporal relationship between supply and demand of ecosystem services and its drivers in China. *J. Environ. Manage.* 365, 121698. doi: 10.1016/j.jenvman.2024.121698
- Sun, X., Lu, Z., Li, F., and Crittenden, J. C. (2018). Analyzing spatio-temporal changes and trade-offs to support the supply of multiple ecosystem services in BeiKingg, China. *Ecol. Indic.* 94, 117–129. doi: 10.1016/j.ecolind.2018.06.049
- Sun, M., Yu, G., Chen, Z. L., Hao, T., Yang, M., Zhu, X., et al. (2024). Climate-shaped vegetation dominated the spatial pattern of the Bowen ratio over terrestrial ecosystems in China. *Agric. For. Meteorology*. 344, 2024. doi: 10.1016/j.agrformet.2023.109816
- Sun, L., Yu, H., and Sun, M. (2023). Yutao Wang, Coupled impacts of climate and land use changes on regional ecosystem services. *J. Environ. Manage.* 326, 116753. ISSN 0301-4797. doi: 10.1016/j.jenvman.2022.116753
- Terrado, M., Sabater, S., Chaplin-Kramer, B., Mandle, L., Ziv, G., and Acuña, V. (2016). Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. *Sci. Total Environ.* 540, 63–70. doi: 10.1016/j.scitotenv.2015.03.064
- Tian, H. Y., Liu, X., and Su, Z. H. (2024). Spatial and temporal characteristics of food ecological total factor productivity in the Yangtze River economic zone. *Chin. J. Ecol. Agric.* 32, 344–354. doi: 10.1016/j.jjggc.2017.09.005
- Tsai, H.-W., and Lee, Y.-C. (2023). Effects of land use change and crop rotation practices on farmland ecosystem service valuation. *Ecol. Indic.* 155, 110998. ISSN 1470-160X. doi: 10.1016/j.ecolind.2023.110998
- Turner, K. G., Odgaard, M. V., Bocher, P. K., Dalgaard, T., and Svenning, J. C. (2014). Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landscape Urban Plann.* 125, 89–104. doi: 10.1016/j.landurbplan.2014.02.007
- Wang, X. M., Liu, X. C., Long, Y. X., and Zhang, Y. (2020). Spatial-temporal changes and influencing factors of ecosystem services in Shaoguan City based on improved InVEST. *Res. Soil Water Conserv.* 27, 381–388. doi: 10.13869/j.cnki.rswc.2020.05.047
- Wang, S., Cui, Z., Lin, J., Xie, J., and Su, K. (2022). The coupling relationship between urbanization and ecological resilience in the Pearl River Delta. *J. Geogr. Sci.* 32, 44–64. doi: 10.11821/dlxb202104013
- Xiao, Q., Hu, D., and Xiao, Y. (2017). Assessing changes in soil conservation ecosystem services and causal factors in the Three Gorges Reservoir region of China. *J. Cleaner Production* 163, S172–S180. doi: 10.1016/j.jclepro.2016.09.012
- Xie, Z., Gao, Y., Li, C., Zhou, J., and Zhang, T. (2017). Spatial heterogeneity of typical ecosystem services and their relationships in different ecological-functional zones in Beijing-Tianjing-Hebei Region, China. *Sustainability* 10, 6. doi: 10.3390/su10010006
- Xie, W., Huang, Q., He, C., and Zhao, X. (2018). Projecting the impacts of urban expansion on simultaneous losses of ecosystem services: A case study in Beijing, China. *Ecol. Indic.* 84, 183–193. doi: 10.1016/j.ecolind.2017.08.055
- Xie, G. D., Zhang, C. X., Zhang, L. M., Chen, W. H., and Li, S. M. (2015). Improvement of the evaluation method for ecosystem service value based on per unit area. *J. Nat. Resour.* 30, 1243. doi: 10.11849/zrzyxb.2015.08.001
- Xu, Z., Peng, J., Dong, J., Liu, Y., Liu, Q., Lyu, D., et al. (2022). Spatial correlation between the changes of ecosystem service supply and demand: An ecological zoning approach. *Landscape Urban Plann.* 217, 104258. doi: 10.1016/j.landurbplan.2021.104258
- Xu, W., Song, J., Long, Y., Mao, R., Tang, B., and Li, B. (2023). Analysis and simulation of the driving mechanism and ecological effects of land cover change in the Weihe River basin, China. *J. Environ. Manage.* 344, 118320. doi: 10.1016/j.jenvman.2023.118320
- Xue, Z., Meng, X., and Liu, B. (2024). Spatiotemporal evolution and driving factors of ecosystem services in the upper Fenhe watershed, China. *Ecol. Indic.* 160, 111803. ISSN 1470-160X. doi: 10.1016/j.ecolind.2024.111803
- Xuemo, Z., Binggeng, X., Kaichun, Z., Junhan, L., Chuan, Y., Jianyong, X., et al. (2024). Mapping ecosystem service clusters and exploring their driving mechanisms in karst peak-cluster depression regions in China. *Ecol. Indic.* 158, 111524. doi: 10.1016/j.ecolind.2023.111524
- Yang, F., Jin, X., Liu, J., Zhang, X., Song, J., Li, Q., et al. (2023). Assessing landscape ecological risk in rapidly urbanized areas from the perspective of spatiotemporal dynamics. *Trans. Chin. Soc. Agric. Eng. (Transactions CSAE)* 39, 253–261. doi: 10.11975/j.issn.1002-6819.202305242
- Yu, C., Zhou, J., and Zhang, Z. (2024). Exploring the classification of China's ecosystem service networks and their driving factors based on current status and evolutionary trends. *Appl. Geogr.* 168, 103321. doi: 10.1016/j.apgeog.2024.103321
- Zhang, B., Li, W., and Xie, G. (2010). Ecosystem services research in China: progress and perspective. *Ecol. Econ.* 69, 1389–1395. doi: 10.1016/j.ecolecon.2010.03.009
- Zhang, Y., Kogure, T., Nishizawa, O., and Xue, Z. (2017). Different flow behavior between 1-to-1 displacement and co-injection of CO₂ and brine in Berea sandstone: insights from laboratory experiments with X-ray CT imaging. *Int. J. Greenhouse Gas Control.* 66, 76–84. doi: 10.1016/j.ijggc.2017.09.005
- Zhang, Z., Wan, H., Peng, S., and Huang, L. (2023). Differentiated factors drive the spatial heterogeneity of ecosystem services in Xinjiang Autonomous Region, China. *Front. Ecol. Evol.* 11, 1168313. doi: 10.3389/fevo.2023.1168313
- Zhao, W. L., He, Z., He, J., and Zhu, L. (2012). Remote sensing estimation for winter wheat yield in Henan based on the MODIS-NDVI data. *Geographical Res.* 31, 2310–2320. doi: 10.11821/yj2012120018
- Zhao, X. Q., Shi, X. Q., Li, Y. H., Li, Y. M., and Huang, P. (2022). Spatio-temporal pattern and functional zoning of ecosystem services in the karst mountainous areas of southeastern Yunnan. *Acta Geogr. Sin.* 77, 736–756. doi: 10.11821/dlxb202203016
- Zhao, R., Zhan, L., Yao, M., and Yang, L. (2020). A geographically weighted regression model augmented by Geodetector analysis and principal component analysis for the spatial distribution of PM_{2.5}. *Sustain. Cities Soc.* 56, 102106. doi: 10.1016/j.scs.2020.102106
- Zhou, W., Liu, G., Pan, J., and Feng, X. (2005). Distribution of available soil water capacity in China. *J. Geographical Sci.* 15, 3–12. doi: 10.1007/BF02873101
- Zhou, S., Huang, Y., He, H., and Zhang, Z. (2024). Focusing on structural changes and future risks of ecosystems: An opportunity-cost based ecosystem service account for riparian ecosystems and its case study. *Ecol. Indic.* 158, 111523. doi: 10.1016/j.ecolind.2023.111523
- Zuo, Y., Li, Y., He, K., and Wen, Y. (2022). Temporal and spatial variation characteristics of vegetation coverage and quantitative analysis of its potential driving forces in the Qilian Mountains, China 2000–2020. *Ecol. Indic.* 143, 109429. doi: 10.1016/j.ecolind.2022.109429