

Spatiotemporal Characteristics and Future Scenario Simulation of the Trade-offs and Synergies of Mountain Ecosystem Services: A Case Study of the Dabie Mountains Area, China

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Abstract: Mountain ecosystems play an essential role in supporting regional sustainable development and improving local ecological environments. However, economic development in mountainous areas has long been lagging, and multiple conflicts related to resource assurance, ecological protection, and economic development have emerged. An accurate grasp of the current status and evolutionary trends of mountain ecosystems is essential to enhance the overall benefits of ecosystem services and maintain regional ecological security. Based on the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model, this study analyzed the spatiotemporal evolution patterns and the trade-offs and synergies among ecosystem services (ES) in the Dabie Mountains Area (DMA) of eastern China. The Markov-PLUS (Patch-generating Land Use Simulation) model was used to conduct a multi-scenario simulation of the area's future development. Water yield (WY) and soil conservation (SC) had overall increasing trends during 2000–2020, carbon storage (CS) decreased overall but slowed with time, and habitat quality (HQ) increased and then decreased. The ecological protection scenario is the best scenario for improving ES in the DMA by 2030; compared to 2020, the total WY would decrease by $3.77 \times 10^8 \text{ m}^3$, SC would increase by $0.65 \times 10^6 \text{ t}$, CS would increase by $1.33 \times 10^6 \text{ t}$, and HQ would increase by 0.06%. The comprehensive development scenario is the second-most effective scenario for ecological improvement, while the natural development scenario did not have a significant effect. However, as the comprehensive development scenario considers both environmental protection and economic development, which are both vital for the sustainable development of the mountainous areas, this scenario is considered the most suitable path for future development. There are trade-offs between WY, CS, and HQ, while there are synergies between SC, CS, and HQ. Spatially, the DMA's central core district is the main strong synergistic area, the marginal zone is the weak synergistic area, and trade-offs are mainly distributed in the transition zone.

Keywords: ecosystem services; trade-offs; InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model; PLUS (Patch-generating Land Use Simulation) model; scenario projection; Dabie Mountains, China

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1 Introduction

Ecosystem services (ES) are materials and services ne-

cessary to life-sustaining that people obtain directly or indirectly from the functions, processes, and structures of ecosystem (Costanza et al., 1997; Daily, 2009; Has-

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an et al., 2020). Quantitative studies on ES have been important for measuring changes in regional ecology (Liu Chunfang et al., 2019). Studies have shown that global terrestrial ecosystems are impacted by human activities and climate change, and they have different degrees of degradation; this trend of degradation will be further intensified in the future (Seppelt et al., 2011; Burkhard et al., 2012). Mountains area occupy 27% of the global land surface, directly support 22% of Earth's population (Chaudhary et al., 2017; Grêt-Regamey and Weibel, 2020). Mountain ecosystems consist mainly of forests and grasslands, which have outstanding advantages in terms of water conservation (Immerzeel et al., 2020), soil conservation, carbon storage (Hilton and West, 2020), and biodiversity maintenance (Perrigo et al., 2020), and are one of the ecosystems with the most ecological supply potential (Kokkoris et al., 2018). However, due to the geo-environmental characteristics of mountainous areas (Wang et al., 2018), mountain areas are often face multiple contradictions such as resource assurance, economic development and ecological protection, they are prone to slow economic development and impoverished human populations (Ge et al., 2021). Research on mountain ecosystem services (MES) helps to provide a scientific understanding of the current situation of mountain ecological environments and the evolution of laws regarding regional ES. In addition, this knowledge is essential for coordinating the relationships among resource assurance, ecological protection, and economic development in mountainous areas and exploring appropriate paths of sustainable development (Cumming et al., 2014; Alorda-Kleinglass et al., 2021).

Since the studies conducted on ES by Costanza in the 1990s from the perspectives of economics and ecology (Costanza et al., 1997), the study of ES has become a hot topic in geography, ecology, land science, and other relevant disciplines (Hu et al., 2021). After more than 20 yr of research development, our knowledge on ES has greatly improved. However, research on MES, which have important ecological and livelihood value, has relatively lagged behind (Liu L B et al., 2019). Thanks to subsequent international policy support and the intellectual investment of researchers, research on MES has greatly developed in recent years. This is reflected in the more diversified research methods, refined research contents, and prominent practical significance of studies on MES (Terzi et al., 2019; Mengist

et al., 2020).

Advances in computer technology have simplified the process of assessing ecosystem services and have improved the accuracy of the assessment results (Weitzman, 2019; Yuan et al., 2019). In recent years, researchers have developed numerous ES assessment models that objectively reflect the ecosystem's ability to provide services and products based on the processes of ecosystem functioning (Nedkov et al., 2021), such as the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) (Sun Q et al., 2021b), ARIES (ARTificial Intelligence for Ecosystem Services) (Bagstad et al., 2013), and SoIVES (Social Value for Ecosystem Services) (Wang et al., 2016) models. Among these, the InVEST model is the best and most widely used model for ES evaluation (Yang Y J et al., 2020; Ureta et al., 2021). Furthermore, with the maturation of remote sensing, global positioning system (GPS), and geographic information system (GIS) technologies, ES studies have gradually begun to focus more on dynamic assessments and spatiotemporal characteristics (Gao and Ruan, 2018). Studies have shown that, due to the complexity of ES types, heterogeneity of the spatial distribution, and selectivity of human use, there are trade-offs or synergies among ES (Zheng et al., 2019; Orchard et al., 2020), but early studies on the spatiotemporal dynamics of ES mainly considered regional changes in ES functions from an overall perspective (Rau et al., 2018; Qiu et al., 2020), thereby ignoring the evolution of the internal relationships among regional ES. Revealing the evolution of trade-offs among ES is particularly important for ecological governance in mountainous areas that contain complex terrain, fragile environments. Currently, the main research methods for evaluating ES trade-offs and synergies include correlation analysis (Li J H et al., 2020), root mean squared error (RMSE) (Zhao et al., 2018), and constraint line analysis (Gong et al., 2019). These methods can quantitatively demonstrate the dynamic evolution of the trade-offs and synergies of regional ES. However, they have not been able to provide spatial mapping and visualization of these trade-offs and synergies. To this end, we introduced correlation analysis and bivariate spatial autocorrelation (BSA) analysis methods to compare and analyze the evolutionary laws of the trade-offs and synergies among MES from a spatiotemporal perspective, which will provide scientific guidance for ecological governance in mountain areas.

Additionally, studies have shown that ES are affected by numerous factors, such as land use, topography, soil, biology, climate, and economic development; however, at the local scale, the effect of land use on ES is the most significant (Liu et al., 2018; Lang and Song, 2019). Clarifying the evolution patterns and driving factors of land use changes can offer a reference for regional land use management and ecological protection (Othoniel et al., 2019; Pan et al., 2021). Considering the time lag of policy implementation, it is difficult to satisfy the practical needs of ecological conservation by simply considering the evolution of regional land use and ES in terms of only the ‘past’ and ‘present’. There is an urgent need for ecological management practices to adopt a forward-looking perspective for modeling and predicting future ecological changes in the region. Scenario simulation can adjust the parameters of land use change according to the different development goals and relevant policy regulations of the study area, and it can reveal the impact of land use/cover change on the trade-offs, overall benefits and supply capacity of ES (Li J H et al., 2020). The use of this technical method will provide theoretical support for resolving the conflicts between economic development, resource assurance, and ecological protection in mountainous areas. Exemplary existing land use prediction models include CA-Markov (Huang et al., 2021), CLUE-S (Conversion of Land Use and its Effects at Small region extent) (Vu et al., 2022), and PLUS (Patch-generating Land Use Simulation) (Zhang S H et al., 2022). Among them, the CA-Markov model is the most mature model for land use forecasting, but it is lacking in terms of multi-scenario analytical capability and simulation accuracy. The CLUE-S model, which is based on the random forest algorithm, is more advantageous in terms of simulation accuracy and scenario analysis, but the model is generally only applicable to local-scale land use predictions and is therefore not suitable for the simulation of larger areas. The PLUS model, which is based on patch generation simulation, can effectively avoid the aforementioned problems; achieve high-precision landscape pattern change simulation by relying on its strong data mining capabilities; and analyze the driving factors behind land use evolution by coupling geographical, socio-economic, and other multi-indicator factors. Therefore, the PLUS model is used to conduct research on the spati-

otemporal evolution patterns of ecosystem services and their trade-off/synergistic relationships under different scenarios, which can provide a forward-looking perspective for ecosystem conservation and governance in mountainous areas (Li C et al., 2021).

The Dabie Mountains Area (DMA) straddles three Chinese provinces of Hubei, Henan, and Anhui, and it is a typical area in China that combines mountains areas, reservoir areas, severe soil erosion, and poverty. On the one hand, the DMA is an important ecological function area and ecological barrier in the Yangtze River Delta and the entire East China region. On the other hand, the region is in a critical transition period of poverty alleviation and rural revitalization, and the contradictions among guaranteeing resources, economic development, and ecological protection have become increasingly prominent. This study takes the DMA as the research object, aiming to: 1) investigate the spatiotemporal evolution of ES in the DMA from 2000 to 2020; 2) create different regional development scenarios, and explore the evolution of ES in the DMA under different future scenarios; and 3) construct a framework for analyzing the trade-offs and synergies of regional ES and explore the transformation of the relationships among regional ES in both space and time.

2 Materials and Methods

2.1 Study area

The DMA is located the southern of the Huaihe River and northern of the Yangtze River at the junction of Hubei, Anhui, and Henan provinces of China. It encompasses the cities of Huanggang, Lu'an, Anqing, and Xinyang, covering a total area of around 6.70×10^4 km² (Fig. 1). The DMA belongs to the warm and humid monsoon region of the subtropical zone, which has an annual average temperature of 18°C, annual precipitation of about 1800 mm, as well as rich flora and fauna resources (Fang et al., 2022). This area is one of the first in China to implement the ‘Grain-for-Green Program (GFGP)’, which is a Chinese government initiative that aims to prevent regional ecological degradation (Liu et al., 2022). Furthermore, this area is one of the most important ecological function areas in China (Xu et al., 2018; Li S N et al., 2021). The ecological evolution of the DMA has had an important impact on the Yangtze River Delta and the entire region of East China. Addi-

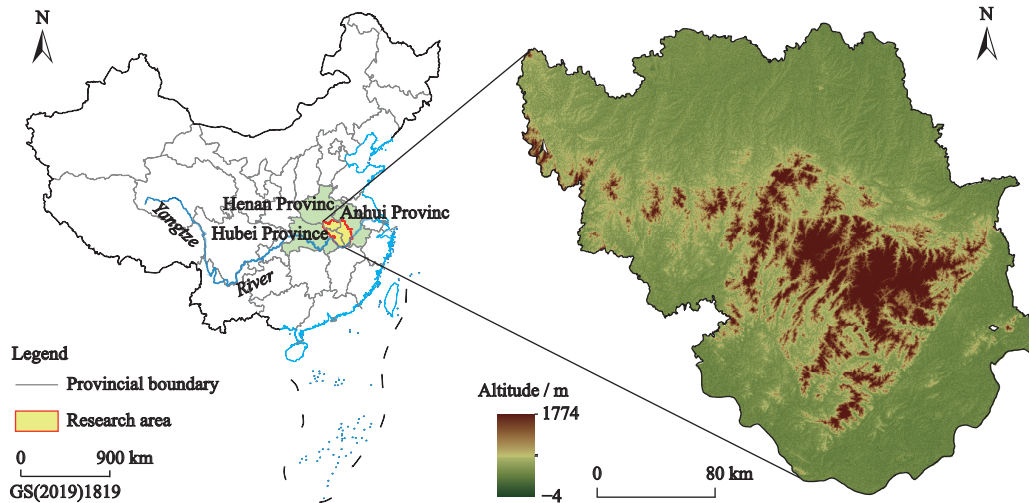


Fig. 1 Geographical location of the Dabie Mountains Area

tionally, the DMA once contained the second largest concentration of poverty in China, and economic development has historically been slow. Now, the region shoulders the important task of developing the economy to improve the livelihoods of the local people while also protecting the environment to ensure the ecological security of East China (Liu et al., 2020; Sun K K et al., 2021a).

2.2 Research framework

Conducting ES assessments and gaining a comprehensive understanding of the spatiotemporal evolutionary laws of regional ES are the premise for formulating regional landscape plans and effectively implementing regional ecological management (Jiang et al., 2021). The purpose of this study is to quantify the spatiotemporal

evolution characteristics of ES in the DMA, and to systematically analyze the evolution status of ES in the DMA under future scenarios based on a land use perspective. In addition, we introduced an analytical model of tradeoffs and synergies to sort out the current and future interrelationships among ES in the DMA based on a spatiotemporal perspective. The overall research framework is visualized in Fig. 2. The study is divided into four parts, starting with data preparation, where we collect land use data, meteorological, socio-economic data, terrain, and accessibility data around the research needs. According to the geographic location and ecological functions of the DMA, we selected water yield (WY) (Immerzeel et al., 2020), soil conservation (SC), carbon storage (CS) (Hilton and West, 2020), and habitat quality (HQ) (Perrigo et al., 2020) as four representative ES.

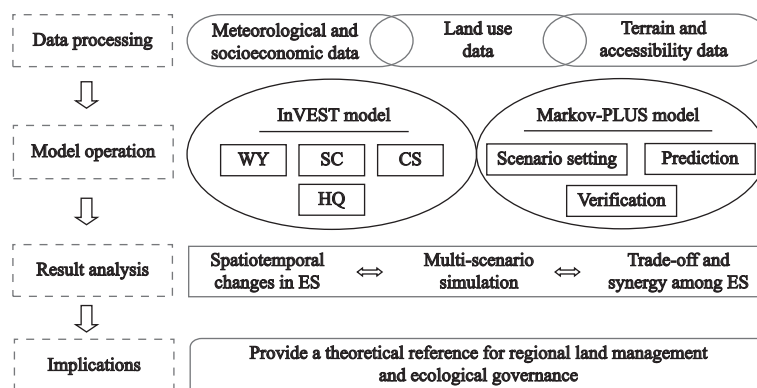


Fig. 2 Research framework for the spatiotemporal characteristics of mountain ecosystem services. WY, water yield; SC, soil conservation; CS, carbon storage; HQ, habitat quality; ES, ecosystem services; InVEST, Integrated Valuation of Ecosystem Services and Trade-offs; PLUS, Patch-generating Land Use Simulation

After completing data preparation, we quantified the major ecosystem services in the Dabie Mountains through the InVEST model (Shao et al., 2021) and conducted multiple scenario simulations on the future land use and ecosystem services of the region with the Markov-PLUS model (Wang et al., 2022). Detailed operations for each step will be provided in subsequent sections. Finally, we explored the trade-offs and synergies among ES in the DMA using correlation analysis and BSA. We believe that this study will provide a more complete analytical framework for the evaluation of MES, and the results will provide theoretical guidance and policy support for ecological conservation, management, and sustainable development in mountainous areas (Li Chunfang et al., 2019).

2.3 Data and methods

2.3.1 ES assessment

(1) Water yield. Water yield was mainly evaluated using the ‘Water Yield’ module of the InVEST model. The module’s core principle is the Budyko hydrothermal equilibrium hypothesis, which uses the discrepancy between water inputs (precipitation) and outputs (evapotranspiration) in the study area to quantitatively assess the water output capacity of different grid cells (Yang Jie et al., 2020), as follows:

$$WY_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \quad (1)$$

where WY_{xj} is the average annual water yield depth of raster cell x on land cover type j (mm); AET_{xj} is the factual yearly evapotranspiration of land cover type j on raster x (mm); P_x is the yearly precipitation on raster x (Bai et al., 2011). Then the total water yield (TWY) equals water yield multiplied area of the study region (m^3).

(2) Soil conservation. Soil conservation was evaluated using the ‘Sediment Delivery Ratio’ module of the InVEST model. This module is based on regional topographic differences, climatic conditions, and the universal soil loss equation, which integrates the interception of upstream sediment by different landscape units to estimate the soil retention in the study area (Zhou et al., 2019). The model expression was as follows:

$$SC = R_i \times K_i \times LS_i \times C_i \times P_i \quad (2)$$

where SC is soil retention for per pixel i (t/hm^2); R_i is the precipitation erosivity factor for per pixel i , ex-

pressed as a multi-year average annual precipitation erosivity index, which can be estimated and verified based on existing studies in the DMA and combined with regional meteorological data; K_i is the soil erodibility factor for pixel i ; which was calculated using the erosion-productivity evaluation model proposed in 1990 by Williams et al. (Williams and Arnold, 1997); LS_i is the field topography factor for pixel i ; C_i is the vegetation cover and management factor; and P_i is the factor describing the supporting conservation practices for pixel i (Yu et al., 2022).

(3) Carbon storage. Carbon storage was assessed using the ‘Carbon’ module of the InVEST model, which estimates the carbon stocks based on four major carbon pools: common above-ground organisms, below-ground organisms, dead organic matter, and soil organic matter (Cai and Peng, 2021). The model expression was as follows:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (3)$$

where C_{total} is the total carbon stock (t/hm^2), C_{above} is the above-ground carbon stock, C_{below} is the below-ground carbon stock, C_{soil} is the soil carbon stock, and C_{dead} is the dead organic matter carbon stock. where the carbon density data required for the carbon module can be found in relevant reference (Zhang Bin et al., 2022).

(4) Habitat quality. Habitat quality was assessed using the ‘Habitat Quality’ module of the InVEST model, which comprehensively considers the relative sensitivity of habitat types to each threat factor, the relative impact of each threat factor, and the distance between the habitat raster and the threat factor based on the ability of the habitat to reflect changes in regional biodiversity functioning (Fan et al., 2021). The model expression was:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^m}{D_{xj}^m + s^m} \right) \right] \quad (4)$$

where Q_{xj} is the HQ index of raster x in land use type j ; H_j is the habitat suitability in land use type j ; D_{xj}^m is the habitat degradation of raster x in land use type j ; m is the default parameter of the model; and s is the half-saturation constant. Roads, construction land, cultivated land, and bare land were selected as threat sources in this study. More detailed model parameter settings can be found in relevant reference (Wu et al., 2021).

2.3.2 Markov-PLUS model

The Markov-PLUS model is a new land use simulation and prediction tool with leading advantages over existing models in terms of land use evolution factor detection, simulation accuracy, and spatial visualization (Li et al., 2021). In this study, the data input, algorithm steps, and parameter settings of the model included:

(1) Extraction of land use expansion. This study took 2015 as the base period, extracted the land use expansion data of the DMA between 2015 and 2020, and performed spatial mapping.

(2) Constructing the index system of land use change drivers. With reference to existing studies and the actual situation of the DMA, and considering the accessibility of data, this study created a list of factors driving land use change (Long and Li, 2012). These factors included physical geographic factors (elevation (*ELE*), slope (*SLO*), and slope aspect (*SA*)), reachability factors (distance to railway (*DTR*), distance to highway (*DTH*), and distance to water (*DTW*)), and socio-economic factors (population size (*PS*) and gross domestic product (*GDP*)).

(3) Extraction of land use expansion strategies. Based on the LEAS module in the PLUS model, the main factors causing regional land use changes were explored.

(4) Land demand analysis and land use simulation prediction. The land demand in the DMA was predicted by Markov chain analysis, and a land use simulation prediction was carried out based on the CARS module in the PLUS model. The multi-scenario simulation analysis is described in Section 2.3.3.

(5) Model accuracy validation. Kappa and FoM coefficients were used to validate the model simulation results.

2.3.3 Scenario design

The future development of the DMA will be affected by a combination of social and natural factors, which will have a significant impact on the land use and ES in the area. We constructed three different development scenarios with reference to existing studies and the actual situation in the study area (Peng et al., 2020; Peng et al., 2021; Liu et al., 2022), namely natural development scenario (NDS), ecological protection scenario (EPS), and comprehensive development scenario (CDS), to analyze the dynamic changes of land use and ES in the DMA by 2030.

(1) NDS. This is a benchmark scenario. In this scenario, based on the historical evolutionary trend of re-

gional land use, the existing economic development and ecological protection policies, and the condition that the transfer probability of each land use type will remain unchanged, we simulated the land use in the DMA in 2030.

(2) EPS. This scenario considered ecological protection as the primary purpose. Conditions considered in this simulation included the slowing of cultivated land degradation, increases in forest and grassland areas, the limitation of the disorderly expansion of urban land, and the future land use changes in the DMA under particular ecological protection measures (i.e., vegetation closure and management, and the 'GFGP').

(3) CDS. This scenario considers the needs for both economic development and ecological protection in the DMA, and it attempts to establish a sustainable development pattern in which the natural environment and human society coexist harmoniously. We believe that along with socio-economic development, human awareness towards ecological protection becomes gradually strengthened, and technical means of ecological management become gradually improved. In this scenario, regional socio-economic development does not necessarily depend solely on land expansion, the growth rate of construction land is effectively controlled, land intensification is significantly improved, arable land protection is effectively implemented, and the ecological space is left relatively intact. In the adjustment of the model parameters, we reduced the probability of cultivated land transitioning to construction land, strengthened the probability of land transfer to forest and grassland, and reduced the growth rate of construction land; however, we did not completely limit the growth of construction land.

2.3.4 Trade-off and synergy analysis of ES

In order to analyze the correlations among various ES in the DMA and reveal their trade-offs and synergies, we created 2000 random points using the 'create random points' tool in ArcGIS 10.5 and extracted the ES values of each point (Li Z Z et al., 2020). Correlation analysis was performed using R 4.1 software to draw a schematic diagram of the ES trade-offs and synergies in the DMA. Negative correlation values represented trade-off relationships, whereas positive values represented synergistic relationships.

To further explore the spatial expression of the trade-offs and synergies among ES in the DMA, we constructed 3 km × 3 km grid cells based on ArcGIS 10.5 and

analyzed the spatial relationships among ES in DMA with the help of BSA. Additionally, we produced LISA (Wu et al., 2022) clustering maps using GeoDa 1.18 software. H-H clustering indicated strong synergistic areas, and L-L clustering indicated weak synergistic areas. H-L and L-H thus denoted strong trade-off areas and weak trade-off areas, respectively. By combining correlation coefficient analysis and BSA analysis, we systematically analyzed the trade-offs and synergies of ES in the DMA in both space and time.

2.3.5 Data resources and process

We assess the dynamic evolution of ES in the DMA by leveraging multi-source datasets. This included five periods of land use data from 2000 to 2020 (90% accuracy) obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn/>). Temperature and precipitation data were obtained from the National Meteorological Information Center (<http://data.cma.cn/>). In order to reduce the influence of interannual fluctuations of meteorological factors at the regional scale, we arithmetically averaged the temperature and precipitation data from 77 meteorological stations in the DBA for the last 30 yr and created precipitation and temperature raster maps by kriging interpolation for input into the InVEST model. In addition, the reference crop evapotranspiration (ET₀) data required for the study were obtained from the CGIAR Consortium for Spatial Information (<https://cgiarcsi.community/>). DEM data were obtained from the Geospatial Data Cloud (<http://www.gscloud.cn/>), and a unified soil database was derived from the International Institute for Applied Systems Analysis and the Food and Agriculture Organization (<https://www.fao.org/soils-portal/data-hub/en>). As land use drivers, rail and road data were derived from Open Streets (<https://www.openhistoricalmap.org>), and the spatial distributions of population and GDP were derived from the Resource and Environmental Science and Data Center (<https://www.resdc.cn/>). All raster data in this study were resampled using the ArcGIS 10.5 resampling tool to unify the spatial resolution to 30 m × 30 m and the projection to Krasovsky_1940_Albers.

3 Results

3.1 Spatiotemporal change of ES in the DMA

The spatial distribution of ES and the changes in ES

quality in the DMA are shown in Fig. 3 and Table 1, respectively. The WY in the DMA showed a spatial distribution pattern of high in the south and low in the north. The high WY values were mainly distributed along the southern slope of the DMA, near the urban clusters distributed along the Yangtze River. Regional TWY showed an overall upward trend from 2000 to 2020, rising from $331.76 \times 10^8 \text{ m}^3$ in 2000 to $333.27 \times 10^8 \text{ m}^3$ in 2020, with a total increase of $1.51 \times 10^8 \text{ m}^3$. SC in the DMA showed a spatial distribution pattern of low in the north and south and high in the center, which was consistent with the spatial patterns of CS and HQ. Both SC and HQ showed an increasing trend between 2000 and 2020. SC increased by nearly $0.45 \times 10^6 \text{ t}$, and the regional average HQ index increased by 0.51%. It is worth noting that HQ showed a slight decrease after 2015. The regional CS capacity exhibited a large reduction from $818.13 \times 10^6 \text{ t}$ in 2000 to $814.26 \times 10^6 \text{ t}$ in 2020 (a total reduction of $3.87 \times 10^6 \text{ t}$). Based on these results, the overall ecological function of the region was stable during the study period, except for a significant decline in CS. The increases in WY in the DMA alleviated a persistent water shortage problem in northern Anhui Province, China (Jun and Chen, 2001), but also increased the risk of flooding along the Yangtze River.

3.2 Land use simulation and change in ES under multiple scenarios

By validating the simulation results, we found that the Kappa coefficient reached 0.88, the FoM coefficient reached 0.38, and the overall simulation accuracy reached 0.93. These results indicate that the simulation results were extremely accurate and met our experimental research needs (Zhang et al., 2021). In addition, by analyzing the drivers of land use change in the DMA from 2015 to 2020 (Fig. 4), we found that the reachability factors and *ELE* had a particularly significant impact on regional land use change, followed by the socio-economic factors of GDP and population size. The other factors had a low impact on regional land use change.

Spatially, the changes in WY, SC, CS, and HQ in the DMA under different scenarios were not significant (Fig. 5). Overall, all ES maintained their historical characteristics in spatially. Compared with the 2020 data, the highest decline in TWY was observed under the EPS for 2030, with a decline of $3.77 \times 10^8 \text{ m}^3$; the second highest decline in TWY was in the CDS, with $2.43 \times 10^8 \text{ m}^3$.

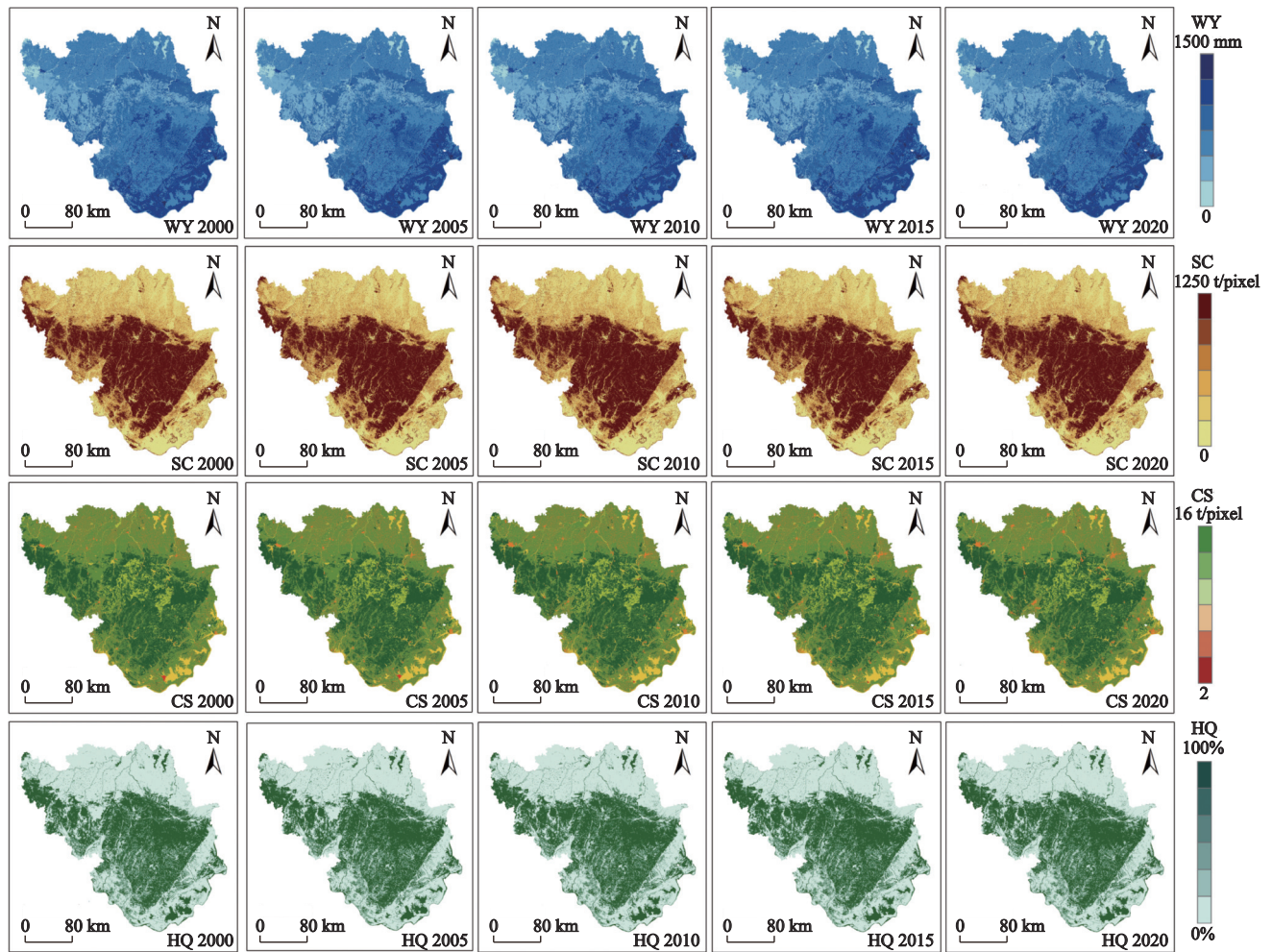


Fig. 3 Spatial distributions of ecosystem services in the Dabie Mountains Area of China from 2000 to 2020. WY, water yield; SC, soil conservation; CS, carbon storage; HQ, habitat quality

Table 1 Ecosystem services in the Dabie Mountains Area of China in 2000, 2005, 2010, 2015 and 2020

Year	WY / 10^8 m^3	SC / 10^6 t	CS / 10^6 t	HQ / %
2000	331.76	614.22	818.13	49.19
2005	331.72	614.22	816.73	49.26
2010	330.81	614.61	817.49	49.72
2015	331.81	614.63	815.37	49.75
2020	333.27	614.67	814.26	49.70

Note: WY_p, water yield; SC, soil conservation; CS, carbon storage; HQ, habitat quality

Although the TWY also showed a decreasing trend under the NDS, it only decreased by $1.14 \times 10^8 \text{ m}^3$. The predicted SC in the DMA in 2030 showed increasing growth trends under the three different scenarios. The predicted SC had the fastest growth under the EPS, with an increase of $0.65 \times 10^6 \text{ t}$. The next-highest SC growth occurred under the CDS with an increase of $0.47 \times 10^6 \text{ t}$, and the lowest growth occurred under the NDS with an

increase of only $0.40 \times 10^6 \text{ t}$. Under the NDS, CS in the DMA will continue to show a significant downward trend until 2030, with a decrease of $5.52 \times 10^6 \text{ t}$ compared to 2020. In contrast, under the EPS, the CS in the region will significantly increase compared to 2020, with an increase of $1.33 \times 10^6 \text{ t}$ over the decade. Additionally, although the CS will continue to exhibit a decreasing trend under the CDS, the reduction will slow

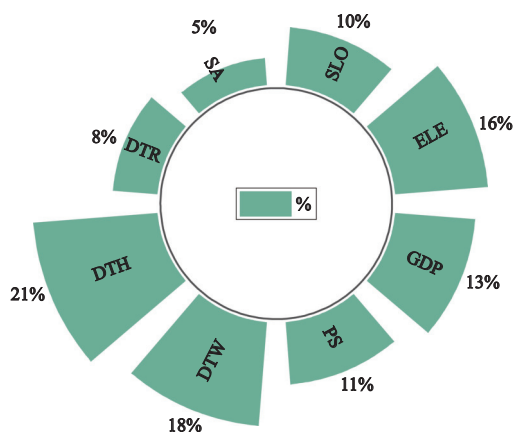


Fig. 4 Contribution rates of different factors driving regional land use change in the Dabie Mountains Area of China from 2015 to 2020. ELE, elevation; DTH, distance to highway; DTR, distance to railway; DTW, distance to water; GDP, gross domestic product; PS, population size; SA, slope aspect; SLO, slope

down significantly and gradually improve with time. The HQ of the DMA increased in all scenarios, but these increases were slow. The largest relative increase in HQ occurred under the EPS, which is 0.06%. The dynamic evolutionary trend of the ES under the different scenarios for 2000–2030 is shown in Fig. 6.

3.3 Analysis of trade-offs and synergies among ES

3.3.1 Correlation analysis

The trade-offs and synergies among ES in the DMA from 2000 to 2030 were studied by correlation analysis (Fig. 7). Overall, there were no significant trade-offs or synergistic relationships between WY and SC. However, WY presented trade-offs with CS and HQ. There were synergies between CS, SC, and HQ. In terms of the temporal changes in the regional trade-offs, the trade-

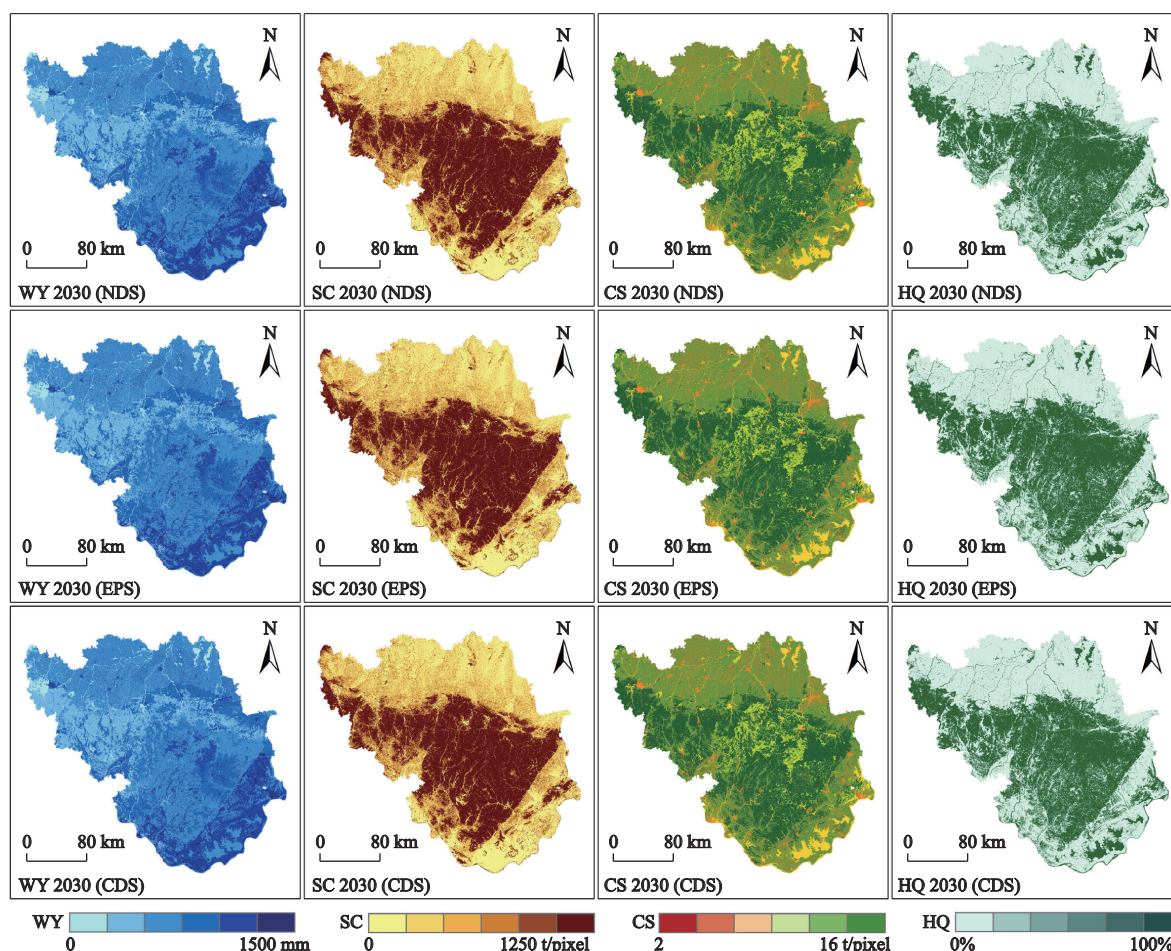


Fig. 5 Spatial distribution of ecosystem services in the Dabie Mountains Area of China under different scenarios in 2030. NDS, natural development scenario; EPS, ecological protection scenario; CDS, comprehensive development scenario; WY, water yield; SC, soil conservation; CS, carbon storage; HQ, habitat quality

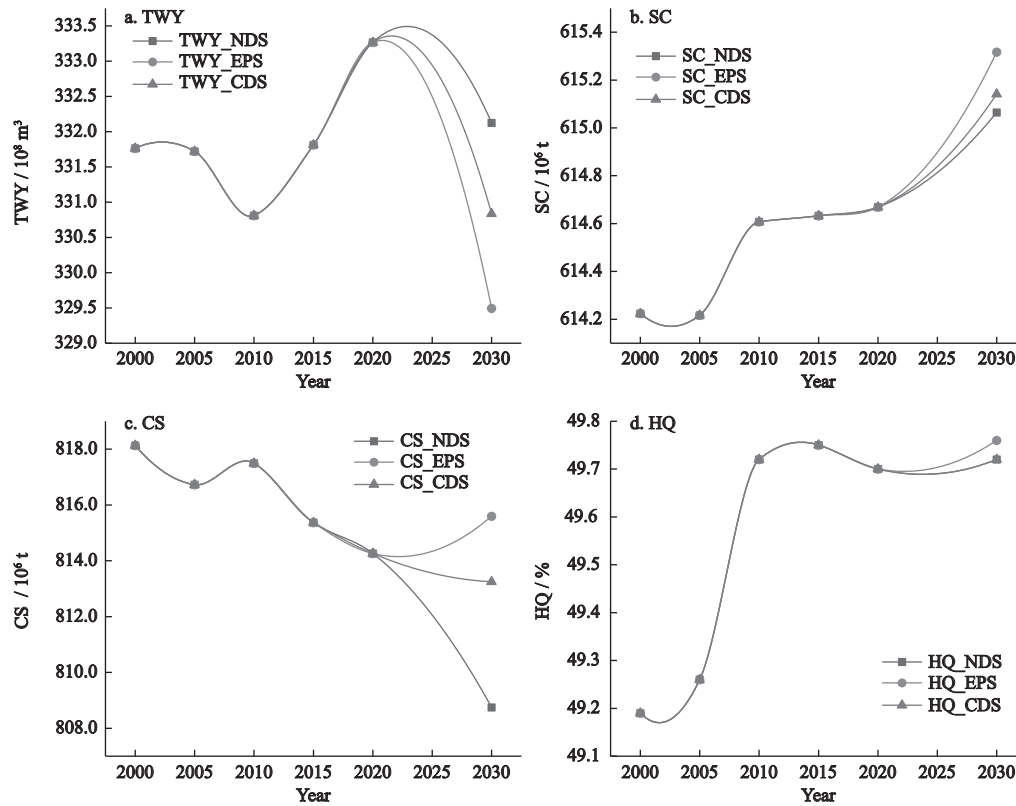


Fig. 6 Dynamic evolution trends of ecosystem services in the Dabie Mountains Area under different scenarios from 2000 to 2030. a. TWY, total water yield; b. SC, soil conservation; c. CS, carbon storage; d. HQ, habitat quality; NDS, natural development scenario; EPS, ecological protection scenario; CDS, comprehensive development scenario

offs between WY and CS gradually increased from 2000 to 2020. Under the NDS, the CS and WY trade-offs will increase further up to 2030. Under EPS and CDS, the CS and WY trade-offs will increase more slowly. The synergies between CS and SC showed an overall increasing trend during 2000–2020. Compared with 2020, the synergies between CS and SC showed a decreasing trend under different scenarios for 2030, but the decreasing trend of synergies between CS and SC is projected to be most moderate under the EPS. From 2000 to 2020, the synergies between HQ, SC, and CS changed relatively steadily, and these synergies showed a decreasing trend under different future scenarios. However, the synergies between HQ, SC, and CS were relatively high under EPS.

3.3.2 BSA analysis

The BSA analysis of ES in the DMA showed that there was a common trend in the spatial distribution of trade-offs and synergies among ES under different scenarios (Fig. 8). The spatial distribution characteristics of trade-offs and synergies between WY and regional SC, CS,

and HQ were relatively similar, with strong synergistic areas mainly distributed in the south-central part of the study area and the geological fault zone in the southern part of the DMA (Li et al., 2022). Weak synergistic areas were mainly distributed in the relatively flat topographic areas in the northern part of the study area, and strong trade-offs were mainly distributed in the north-east and southeast parts of the DMA. Weak trade-offs were mainly distributed near the northwest leeward slope of the DMA. Additionally, the spatial distributions of trade-offs and synergies between SC and regional CS and HQ were relatively consistent. Strong synergistic areas were mainly distributed in the core district of the DMA from the northwest to the southeast along the main body of the mountain range. The weak synergistic areas were mainly distributed in the outermost part of the study area, and the trade-off areas were sporadically distributed within the strong synergistic and weak synergistic areas. In summary, the strong synergies were mainly distributed in the core district of the DMA, the weak synergies were mainly distributed in the

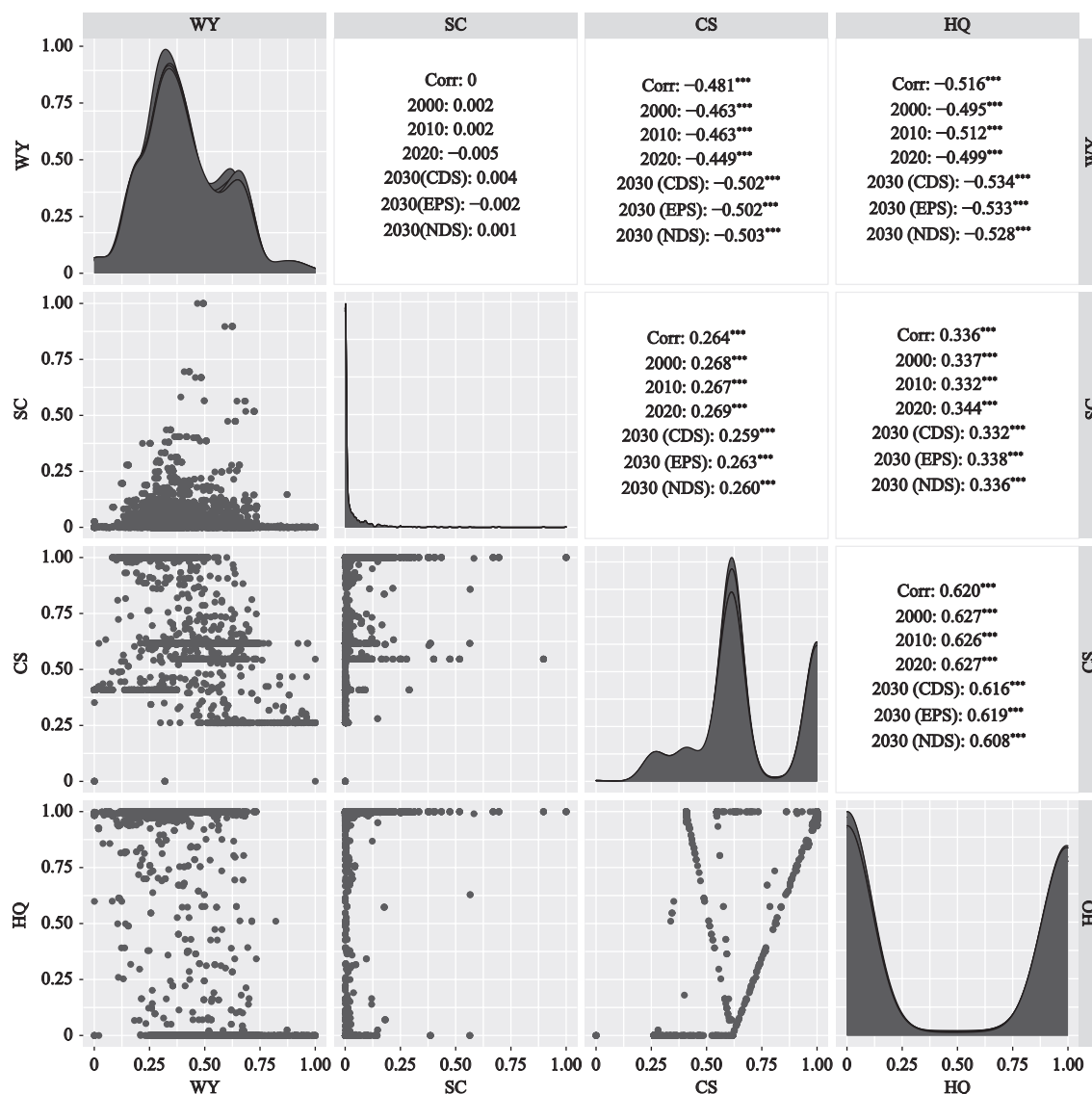


Fig. 7 Trade-offs and synergies of ES in the Dabie Mountains Area of China from 2000 to 2030. NDS, natural development scenario; EPS, ecological protection scenario; CDS, comprehensive development scenario; WY, water yield; SC, soil conservation; CS, carbon storage; HQ, habitat quality; ‘Corr’ indicates the overall correlation coefficient between variables; ‘***’ means significant correlation at 99% confidence interval

marginal zone of the DMA, and the trade-offs were mainly distributed in the transition zone (Fig. 9).

4 Discussion

4.1 Dynamic evolution of ES in the DMA

At the beginning of the 21st century, the Chinese government implemented a series of policies, such as the ‘GFGP’ and the designation of ecological function zones, to protect the ecological environment and ecological security of the DMA. In this context, we conducted a study on the spatiotemporal characteristics of ES

in the DMA, and we found that the spatial fluctuations of ES were not significant and generally maintained their historical characteristics; these findings are similar to the results of Chen et al. (2021). Generally, increases or decreases in a certain land use type or ES present standard ripple-type or regular changes. Under the interference of non-natural disasters or intense human activities, the regional ecological spatial distribution often does not present subversive changes. Compared with urban ecosystems, mountain ecosystems are relatively less disturbed by human activities and tend to show more stable spatial distribution characteristics. Studies

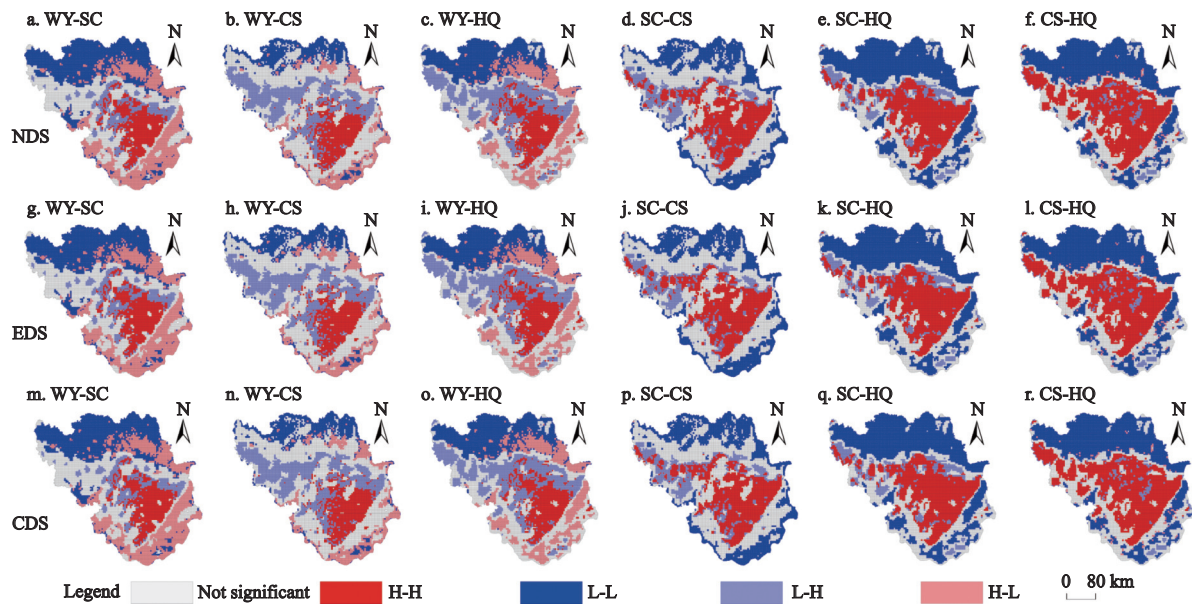


Fig. 8 Spatial correlation map (LISA) of ecosystem services under different scenarios in Dabie Mountains of China. NDS, natural development scenario; EPS, ecological protection scenario; CDS, comprehensive development scenario; WY, water yield; SC, soil conservation; CS, carbon storage; HQ, habitat quality

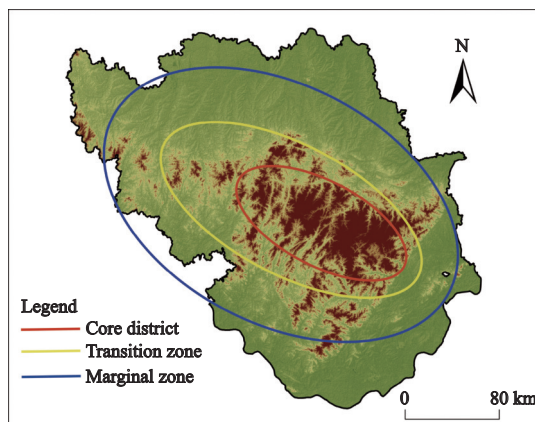


Fig. 9 Spatial distribution of the core district, transition zone, and marginal zone of the Dabie Mountains Area of China

have shown that at the local scale, ES are mainly influenced by land use changes (Hasan et al., 2020), and land use changes in the DMA have been mainly influenced by reachability, topography, population clustering, and economic development. the quality of ES in the DMA changed significantly with time during 2000–2020. The increase in WY in the DMA has been mainly influenced by the overall increase in impervious surfaces in the region due to economic development and urban expansion. Furthermore, the building of railroads and paving of roads has severely compromised the integrity of the biological habitat of the DMA, which explains the observed decline in HQ after 2015. Due to the imple-

mentation of the ‘GFGP’, the restoration of forest grasslands, and the reduction of bare land, the soil and water conservation capacities of the DMA have significantly improved. However, the regional CS is still decreasing because the quality of destroyed forests and grasslands has not yet reached historical levels of restoration. This suggests that special attention should be paid to the irreversible damage to ecosystems that is caused by human activities related to the development of mountain resources. Human activities such as road paving and the development of scenic areas causes long-term damage to the ecosystem, and ecological restoration has a seriously lagging effect; taken together, these factors make it difficult to restore the quality of regional ecosystem service supplies in the short term. Fortunately, the declining trend in CS has slowed significantly since 2015.

4.2 Multi-scenario simulation and mountain ecosystem governance

The DMA is located in a special geographic position, has an important ecological status, and is an important ecological barrier in East China. However, the economic development in the region has long been lagging behind that of other regions, leading to several outstanding conflicts between resource assurance, ecological protection, and economic development. The existence of such conflicts impacts the direction of future develop-

ment and ecological protection policies in the DMA. Therefore, carrying out multi-scenario simulations for the DMA is crucial for coordinating the relationship between mountain ES and regional socioeconomic development, as well as constructing reasonable and scientifically backed patterns of ecological security (Li C et al., 2021). Under the EPS, the mountain ES would significantly improve, the increase in WY would be effectively controlled, the SC and HQ would show positive growth, and the CS would switch from a decreasing to an increasing trend. It is worth noting that WY, SC, and HQ show a gradual improvement under NDS in the DMA, and although CS continues to decline, its downward trend significantly slows under this scenario. Considering this, is it necessary to sacrifice local development rights and enhance ecological protection in the DMA in the future? Based on our results and those of existing studies, we found that although the ecological decline in the DMA has been contained at the local scale, the decline in regional ES is still evident in the Yangtze River Delta as a whole (Li et al., 2019b). ES often have obvious scale effects, particularly local increases at the micro level and overall decreases at the macro level. On the macro scale, it is critical to strengthen the ecological protection of the DMA. However, there is substantial poverty in the mountainous areas of the DMA; thus, there is an urgent need to improve the well-being of the impoverished people through economic development. Compared to the other development scenarios, the CDS, which combines resource assurance, ecological protection, and economic development, is therefore the most appropriate. In the future, it is necessary to develop the rich tourism resources in the mountainous areas of the DMA alongside achieving local ecological protection goals, to promote local economic sustainable development. However, this study mainly simulated future scenarios by strengthening land management factors and controlling land use change. Mountain ecosystems are giant, complex, open systems that include biological activities and the natural environment, and they are easily disrupted by regional socio-economic development and natural environmental changes; therefore, only considering land use changes may impact the accuracy of simulation results for such areas. In the future, multiple factors such as population size, economy, and technology need to be considered to optimize comprehensive development scenarios and bet-

ter serve the ecological management practices in mountain areas.

4.3 Spatiotemporal characteristics of trade-offs and synergies among ES from 2000 to 2030

There are obvious spatial heterogeneity and scale effects present in the trade-offs and synergies among ES. We found that WY, CS, and HQ in the DMA showed obvious trade-offs, while SC showed synergistic relationships with CS and HQ. In a previous study in the Qilian Mountains, which are located in the interior of northwestern China, WY, SC, CS, and HQ showed synergistic relationships (Lü et al., 2021). The Qilian Mountains have clear inland mountainous climatic features, and WY is influenced by the region's own water cycle. In contrast, the DMA is relatively low in elevation and closer to the ocean. Its WY is heavily influenced by monsoons from the western Pacific Ocean. Therefore, the significant differences in climate and geographic location may be the main reasons for the differences in ES trade-offs and synergies between the two regions. In addition, we found that there are differences in the trade-offs and synergies among ES in the DMA under different future development scenarios. Under EPS, there are stronger synergies of SC with CS and HQ than under the other scenarios, however, the trade-offs among WY, CS, and HQ also increase; this suggests that it is difficult for multiple ES to increase simultaneously due to the complex nature of the ecosystem. These results also show the importance of determining the spatial distribution patterns of trade-offs and synergies among ES for the hierarchical zoning management of mountainous areas. Taking the DMA as an example, we found that the trade-offs and synergies among ES have common features in their spatial distributions. There are obvious strong synergies between different ES in the core district of the study area, which indicates that the destruction of the ecological environment in this area will lead to a decline in the supply of various ES. Therefore, the core district should be regarded as the key area for ecosystem protection in the DMA. However, the marginal zone can be used as the main economic development space in this region because this zone exhibits weak synergies between different ES, and the supply capacity of the ecosystem is low, and the degradation of a given ES in the marginal zone has a low impact on the overall ecological environment of the

area. The transition zone is located at the periphery of the core district, and this area exhibits obvious trade-offs between different ES. In other words, the improvement of one ES will lead to the degradation of another ES. Therefore, the type of ES provisioning in the transition zone should be reasonably selected based on the objectives of future regional ecological protection and governance. According to the spatiotemporal evolutionary law of the trade-offs and synergies of MES, the targeted delineation of economic development and ecological protection areas can alleviate the conflicting relationship between economic development and ecological protection to a certain extent in mountainous areas. However, due to the limitation of existing research methods, this study lacks information on complex non-linear relationships among ES. In the future, research methods and model selection should be improved to address this issue.

5 Conclusions

As one of the first implementation sites of the ‘GFGP’ and a national key ecological function area, the DMA has exhibited steady improvements in SC and HQ during 2000–2020, but the WY has increased sharply and the CS has significantly decreased. These results demonstrate that the conflicts between resource assurance, ecological protection, and economic development in the DMA are still strongly apparent.

By simulating different future development scenarios for the DMA, we found that the EPS would greatly improve the regional ecological environment, but it is not easy nor feasible to sacrifice the region’s right to local economic development and endanger the well-being of the population. Considering the non-ideal evolution of trends in ES under the NDS, we believe that the CDS, which considers both economic development and ecological protection, is the most suitable path for the future development of the DMA.

Additionally, our research shows that WY, CS, and HQ in the DMA show trade-offs, while SC, CS, and HQ show synergistic relationships. There is no obvious linear relationship between WY and SC. Additionally, there is a common pattern in the spatial distribution of trade-offs and synergies in the DMA. Specifically, the core district of the DMA is the main area of strong synergism, the transition zone at the periphery of the core

district is the main trade-off area, and the marginal zone is the area characterized by weak synergisms. The knowledge of these spatial distribution patterns is particularly important for future grading and zoning governance of the mountain ecosystems.

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