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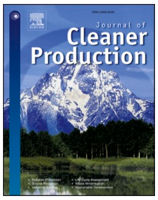

Understanding future water-carbon-land coupled systems in the era of COP 27: The case of the Hanjiang river Basin, China

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ABSTRACT

The 27th Conference of the Parties (COP 27) emphasized addressing this century's interconnected challenges of food, water, and energy. This study proposes a coupled ecosystem service and multi-scenario land-use change simulation model designed to investigate the future dynamics of water-carbon-land coupled systems in the Hanjiang River Basin (HJRB), the primary objective is to provide valuable insights that can inform strategic spatial management decisions, aligning with the ambitious objectives outlined in COP 27. Specifically, this study utilized the PLUS model, InVEST model, and redundancy analysis to comprehensively analyze the interplay between ecosystem services and land-use changes, with a specific focus on water, carbon, and land dynamics. The results showed that regardless of the simulated scenarios, there was a consistent pattern observed in the changes of land use types within the HJRB, with a decrease in farmland and an increase in forest. However, the water area showed an increasing trend in all scenarios, especially in the ecological land protection (ELP) and sustainable development scenarios. Furthermore, the ELP scenario effectively suppressed the expansion of building land and the erosion of ecological land. Ecosystem services under different scenarios showed similar spatial distribution patterns but presented varying degrees of change related to the impact of future land use and urban development on ecosystem services. The water yield (WY), carbon storage, and soil conservation in the upstream areas increased to varying degrees, while those in the downstream areas decreased. In conclusion, precipitation, land use/land cover change, DEM (Digital Elevation Model), and NDVI (Normalized Difference Vegetation Index) were the main driving factors affecting ecosystem services, with precipitation having the most significant and enduring impact on WY. This study supports the adoption of targeted spatial management measures to promote sustainable development and enhance human well-being.

1. Introduction

Ecosystems are the foundation for sustaining life on Earth, providing numerous vital ecosystem services (ESs) that are extremely important for human life and socioeconomic development, meeting the material needs of human life, and ensuring the sustainable development of human society (Liu et al., 2024; Costanza et al., 1997). ESs include various benefits directly or indirectly obtained from the structure, function, and processes of ecosystems; these benefits are both material and nonmaterial and have a positive impact on human well-being (Yousofpour et al., 2024; Costanza et al., 2017; Daily, 1997). According to the Millennium Ecosystem Assessment (MA) report, ESs are mainly divided into four categories: provisioning services, regulating services, cultural services, and supporting services (Dade et al., 2024; Reid et al., 2005). Provisioning services (e.g., providing food and water) refer to the material resources produced or provided by ecosystems. Regulating services (e.g., controlling floods and disease) involves regulating and maintaining the role of ecosystems in natural processes and environmental quality. Cultural services (e.g., spiritual, recreational, and cultural benefits) involve nonmaterial benefits related to the spiritual and cultural aspects that ecosystems provide to humans. Supporting services (e.g., nutrient cycling that maintains the life-sustaining environment of the Earth) are the foundational functions of ecosystems that support other services (Yang et al., 2023). ESs constitute an important link between the natural environment and human well-being and are also an important basis for assessing the value of ecosystems

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(Aryal et al., 2022).

The formation and spatial distribution of ESs are primarily determined by natural factors, reflecting the essential characteristics of ecosystems (Zhou et al., 2022). However, human factors, such as population size, socioeconomic conditions, and agricultural processes, also influence the spatial distribution of ESs (Pu et al., 2023). Ecosystems interact with human society and are affected by human activities. Recent research highlights that over 60% of the Earth's terrestrial surface has been altered to varying degrees due to anthropogenic activities, including agriculture, urbanization, and deforestation (Pu et al., 2023; Song et al., 2018), and this trend is likely to intensify in the foreseeable future due to ongoing demographic expansion and economic advancement. These changes affect the composition and structure of ecosystems and thus impact ESs. The MA report states that approximately 60% of ESs are in a state of decline due to improper land use, which further affects the level of ecological protection in declining regions (Cao et al., 2022; Oberle et al., 2019). It is estimated that up to one million species may face the risk of extinction in the future, which could have cascading effects on ecosystem functioning (Exposito-Alonso et al., 2022; Liu et al., 2022a).

The ESs of a river basin mainly include water yield (WY), carbon storage (CS), and soil conservation (SC) (Gao et al., 2019; Souliotis and Voulvoulis, 2021). These services are closely related to human survival, life, and happiness (Gong et al., 2019). Government officials and decision-makers typically aim to enhance one or multiple ecosystem services through the alteration of land use/cover change (LUCC) (Cui et al., 2021). However, complex interactions and feedback mechanisms between these services are not independent (Xu et al., 2022). The coupled relationships among these factors and complex interactions with human activities need to be carefully considered and evaluated, which is highly important for ensuring sustainable regional development.

Many research methodologies have been documented for evaluating LUCC and ESs (Gomes et al., 2021). These include Cellular Automata (CA), Conversion of Land Use and its Effects at Small regional extent (CLUE-S), Multi-Agent System (MAS), Future Land Use Simulation (FLUS), and Patch-Generating Land Use Simulation (PLUS) methods, which have been introduced in succession (Gao et al., 2019; Hasan et al., 2020; Mulazzani et al., 2017). Among them, the PLUS model is suitable for complex land use simulations in multiple scenarios at various scales, and with high precision (Gao et al., 2022; Liang et al., 2021). In the realm of ESs assessment, Costanza et al. (1997) pioneered a model for evaluating the economic value per unit area, marking the beginning of a significant trend in this field. Building on their foundational work, Xie et al. (2015) developed an equivalent factor table for ESs tailored to the specific conditions in China, which has gained widespread application since its introduction. Recently, the utilization and advancement of 3 S technology (Remote Sensing, Geographic Information System, and Global Positioning System) in evaluating ecosystem services have led to the emergence of various assessment models, including the Artificial Intelligence for Environment & Sustainability (ARIES) model, Social Values for Ecosystem Services (SolVES) model, and Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model (Agudelo et al., 2020; Tardieu, 2017). Among these, the InVEST model stands out for its capacity to conduct quantitative analysis, map spatial distribution, and track dynamic changes in multiple ecosystem services, thereby offering insights into how these services may evolve under different future scenarios (Li et al., 2021).

Previous studies have mainly focused on examining changes in ESs without adequately incorporating the intricate interactions with LUCC. For instance, Butler and Oluoch-Kosura (2006), Geneletti (2013) Nyelele et al. (2019), and Van Eerd et al. (2023) have contributed to understanding future ESs changes. However, they have not extensively combined these changes with LUCC to simulate and highlight the contributions of driving factors. One significant gap in the previous literature is the limited focus on the combined simulation of LUCC and ESs functions. The development patterns of different land use types and specific ESs functions vary, necessitating separate simulations to accurately capture their unique dynamics. Furthermore, while many studies have analyzed the impacts of historical and current land use on ESs, indicating a certain lag (Sannigrahi et al., 2020), they have not adequately addressed the predictive aspect of these interactions. In this regard, Liu et al. (2020b) explored the impact of LUCC on ESs under existing trends but did not integrate national policies to explore potential changes under various scenarios. This is a crucial oversight because understanding the implications of different policy scenarios can provide more comprehensive insights into future trends. Accordingly, there are still relatively few related studies that finely depict future LUCC at the large basin scale under different scenarios and their impacts on multiple ESs functions and driving factors.

This study addresses the research gaps by finely depicting future LUCC at the large basin scale under different scenarios and assessing the impacts of LUCC on multiple ESs functions and driving factors. By integrating national policy scenarios into the simulations, this study offers a more nuanced and forward-looking perspective on how these policies may influence both LUCC and ESs. This approach not only differentiates this study from previous research but also enhances its novelty by providing a detailed, scenario-based analysis that can better inform policy and decision-making processes.

Policy-guided LUCC plays a crucial role in shaping the uncertainty surrounding ESs (Albert et al., 2020; Liang et al., 2020). This means that the way policies direct changes in land use (e.g., urban development, agricultural expansion, or conservation efforts) can lead to varying degrees of unpredictability in the benefits that ecosystems provide (e.g., clean water, biodiversity, and carbon sequestration). The impact of human activities on ESs is mixed, with both positive and negative effects (Fang et al., 2021). To fully leverage their positive impacts, scientific planning is the key factor that determines their influence. Therefore, it is necessary to predict ESs under different policy scenarios in the future to understand their change trends under these scenarios. Scenario analysis is the most commonly used method in regional ecosystem management research. Combining scenario simulations with ecological models provides support for exploring the changes in regional ecological functions under different development strategies in the future (Liu et al., 2017).

The Hanjiang River Basin (HJRB) is the primary source region for the world's largest interbasin water transfer project, the Middle Route of South-to-North Water Transfer (Gao et al., 2019). This basin exhibits a complex land use structure with pronounced geographical and environmental variations, abundant natural resources, and a rich mosaic of ecosystems, which collectively offer a range of essential ESs to the region (Wang et al., 2022; Zhu et al., 2022a). The present investigation concentrates on the shifts in ESs and their determinants across varying policy contexts (Wong et al., 2015; Maes et al., 2012), with a particular emphasis on the interconnected dynamics of water, carbon, and land use. Amidst the backdrop of the COP 27[1] (Roarty, 2002), the significance of ESs research has been underscored, given its intricate relationships with these three systems and its pivotal role in fostering sustainable development pathways (Gao et al., 2019). The main objectives of this study are threefold: (1) To utilize the PLUS model for projecting land use patterns under various policy scenarios for the year 2035. (2) Subsequently, the InVEST model will be used to predict and quantify the supply of three critical future ESs, examining the shifts in their aggregate provision and the influence of LUCC on these services. (3) Finally, the study will elucidate the diverse influences of natural, economic, and social factors on ESs via redundancy analysis (RDA), assessing their individual contributions. By achieving these goals, this study will provide essential guidance for developing strong regional planning.

The study is organized as follows: Section 2 describes the research

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[1] The 27th Conference of the Parties of the UNFCCC.

area, data, and methodology; Section 3 presents the study's results; Section 4 discusses these results in comparison to other studies; and the final section offers the conclusions.

2. Data and methodology

2.1. Research area overview

The interrelationships between water, carbon, and land systems are crucial for shaping pathways for sustainable development (Biggs et al., 2015); hence, there is a need to coordinate the coupled effects of these systems. In the HJRB (Fig. 1), the agricultural, industrial, and urban sectors have conflicting water resource demands, making the pursuit of sustainable development particularly challenging (Zhu et al., 2022a). Moreover, HJRB is a significant producer of commercial grains, and future policy changes may have a significant impact on food security.

The HJRB possesses abundant ecological resources, fertile farmland, and regional development potential (Zhou et al., 2017b). However, with continuous socioeconomic development, regional ecological issues have gradually emerged. These include drastic changes in land use patterns, intensified conflicts between humans and the environment, and the degradation of local ecological functions (Bao et al., 2023; Yang et al., 2022). The HJRB is tasked with supplying grain and water resources to the nation, playing a crucial role in China's ecological construction.

Therefore, it is necessary to clarify the spatiotemporal variation characteristics of ESs in the HJRB. This knowledge is vital for developing sustainable development strategies that address the basic needs of different sectors and stakeholders.

2.2. Data source and preprocessing

This study amalgamates a comprehensive dataset encompassing geographical, climatic, and socioeconomic information, as outlined in Table 1. Three categories of ESs were assessed: WY, CS, and SC. The assessment employs land use/cover, vegetation, meteorological, soil, and solar radiation data.

The land use/cover data from China exhibit an accuracy rate of over 94.3% for primary classification, surpassing the accuracy of other prominent datasets (Zhu et al., 2023; Gao et al., 2019). The land use classification in this study is categorized into six main types: farmland, forest, grassland, water, building land, and unused land.

The socioeconomic and traffic location data included GDP, population statistics, nighttime light, point of interest (POI) data, and road network data. These data are utilized in the RDA.

Table 1
The data and sources.

Type	Data	Sources
Geography data	Land use/cover	Wuhan University, Yang et al. (https://en.whu.edu.cn/)
	NDVI (Normalized Difference Vegetation Index)	National Ecosystem Science Data Center (http://www.nesdc.org.cn/)
	DEM (Digital Elevation Model)	Geospatial Data Cloud (https://www.gscloud.cn/)
	Soil type, depth, root data	Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn)
Climate data	Precipitation, temperature, and potential evapotranspiration data	The National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)
Socioeconomic data	GDP, population	Resource and Environmental Science Data Platform (https://www.resdc.cn/)
	Nighttime light Dataset	The National Tibetan Plateau Data Center
	POI data	Baidu Map Open Platform (https://lbsyun.baidu.com/)
Location data	Road network data	OpenStreetMap (https://openmaptiles.org/)

2.3. Methods

2.3.1. Research framework

From the perspective of maintaining socioeconomic and ecological sustainability, this study proposes a coupled ESs conservation and multiple scenarios (MS) LUCC simulation model to analyze future water-carbon-land coupled systems (FWCLs) in the HJRB. Fig. 2 illustrates the specific research process. The study can be roughly divided into three steps:

First, we processed the dataset, which includes land use, terrain, climate and environmental factors, etc. Second, we used the InVEST model to assess three types of ESs over the past 20 years. Finally, considering various factors and establishing LUCC conversion rules, four different development scenarios (i.e., business as usual (BAU), rapid economic development (RED), ecological land protection (ELP) and sustainable development (SD)) are modeled and planned to utilize

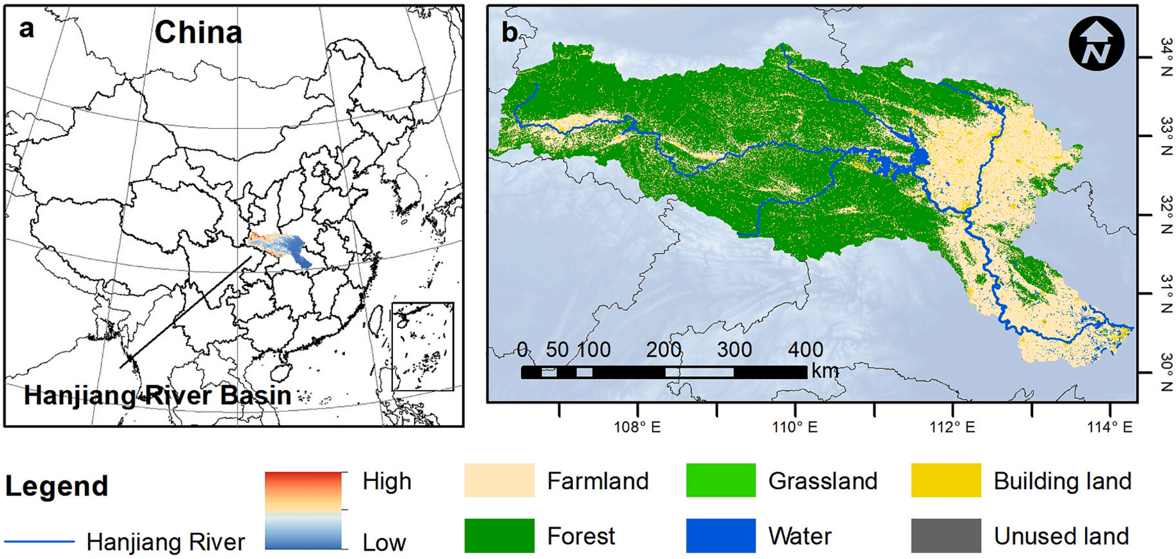


Fig. 1. (a) The geographic location of the Hanjiang River Basin, (b) land use in 2020.

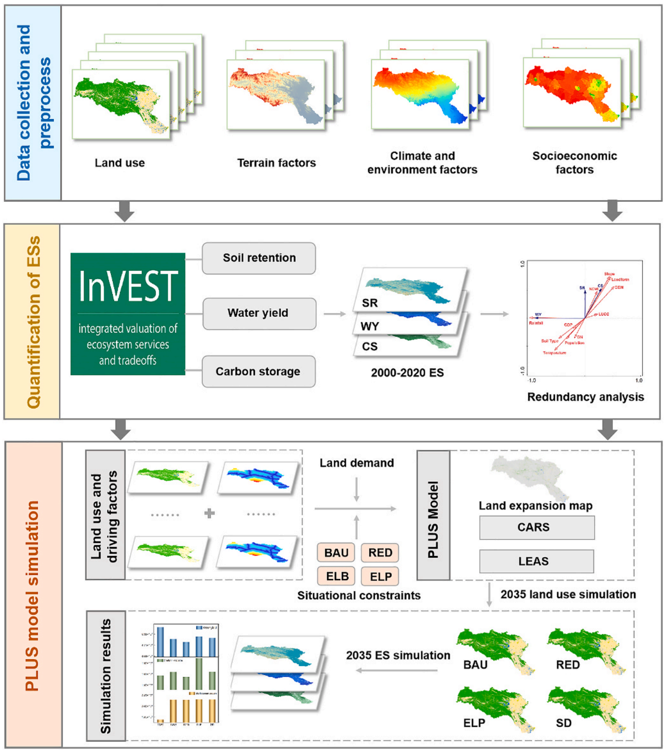


Fig. 2. Study framework.

ecological constraints (water reserve and ecological red line regions) in all scenarios. In this step, we employed the PLUS model to evaluated and analyzed changes in different scenarios at five-year intervals, considering ground data from the same time periods and relatively low uncertainty of climate change in the next five years. Furthermore, RDA was conducted on the HJRB's FWCLs to identify the main driving factors and their causes.

2.3.2. *Future water-carbon-land coupled systems*

This study used the United Nations Millennium Ecosystem Assessment report and COP 27 to construct FWCLs in the HJRB, and WY, CS, and SC were selected as the three ESs for study (Reid et al., 2005). The HJRB faces significant environmental challenges, such as deforestation, soil erosion, and water scarcity. The selected ESs are vital for achieving land-use planning and sustainable development, balancing economic growth with environmental protection. Furthermore, COP 27 highlights the need to integrate ESs into climate action strategies. As countries work toward their climate goals, recognizing the interconnections between WY, CS, SC is becoming increasingly important. The HJRB can serve as a model for other regions, demonstrating how sustainable practices can address local challenges while contributing to global climate objectives.

(1) Water Yield

WY is involved in the generation and supply of water resources, which is significant for maintaining ecosystem balance and supporting human production and living activities (Zhu et al., 2023b). The essence of WY is the difference between precipitation and actual evapotranspiration, which reflects the overall level of regional water resources and is crucial for ensuring the sustainable use of water resources. The InVEST model, which relies on the natural capital project, can quantify various ESs functions and is an advanced tool for natural capital decision-making (Caro et al., 2020). This study utilized the WY module of the InVEST model to quantify WY at a spatial scale in the HJRB and evaluate its spatial characteristics. The WY module is based on the Budyko water-heat coupling equilibrium hypothesis (Gao et al., 2017). When estimating WY, the model not only calculates based on the difference between precipitation and evapotranspiration but also takes factors such as seasonal variations, soil root depth, and vegetation coverage into consideration, thereby improving the accuracy and applicability of the model in simulating WY. The InVEST model calculates the WY of grid cells on an annual basis. The model calculation formula is as follows (Daneshi et al., 2021):

$$Y(x)=\left(1-\frac{AET(x)}{P(x)}\right)\cdot P(x) \tag{1}$$

$$\frac{AET(x)}{P(x)}=1+\frac{PET(x)}{P(x)}-\left[1+\left(\frac{PET(x)}{P(x)}\right)^{\omega}\right]^{1/\omega} \tag{2}$$

$$\omega(x)=Z\cdot\frac{AWC(x)}{P(x)}+1.25 \tag{3}$$

where $Y(x)$ represents the annual WY of the grid cell; $AET(x)$ represents the annual actual evapotranspiration of the grid cell; $P(x)$ represents the annual precipitation; $AET(x)/P(x)$ is based on the Budyko curve expression; $PET(x)$ represents the potential evapotranspiration; ω is a nonphysical parameter of climate-soil properties, dimensionless; $AWC(x)$ represents the available water content of vegetation; and Z is the Zhang coefficient, characterizing regional precipitation characteristics (Zhang, 2017).

(2) Carbon Storage

CS is an important indicator of terrestrial ESs and plays a significant role in the global carbon cycle and climate change mitigation (Chang et al., 2022; Xiao et al., 2019). Different land types have varying effects on CS and its release, and the evolution process of CS in terrestrial ecosystems is closely related to land type changes. This paper uses the CS module in the InVEST model to quantify the spatial distribution of CS in the HJRB. This module divides ecosystem CS into four basic carbon pools: aboveground biomass carbon pool (carbon contained in living plants in the topsoil), belowground biomass carbon pool (carbon contained in plant roots), soil carbon pool (organic carbon in organic soil and mineral soil), and dead organic matter carbon pool (carbon contained in litter, dead trees, etc.) (González-García et al., 2022; Li et al., 2023; Zhao et al., 2019). The formula is as follows:

$$C_{total}=C_{above}+C_{below}+C_{soil}+C_{dead} \tag{4}$$

where C_{total}, C_{above}, C_{below}, C_{soil} and C_{dead} represent the CS stored in the ecosystem, aboveground organic matter, belowground organic matter, soil, and dead organic matter (Mg · ha-1), respectively.

(3) Soil Conservation

SC function as an essential regulatory service within ecosystems (Liu et al., 2020a). The essence of this function is that ecosystems, through their own structures, resist wind and water erosion caused by natural factors or human activities, providing soil resource protection for human society (Moges and Taye, 2017). Improving the SC functional status of regional ecosystems can effectively reduce the area and intensity of soil erosion. This study used the Revised Universal Soil Loss Equation (RUSLE) to quantify the SC amount with the following formula (Renard et al., 1994a, 1994b):

$$Q_{sr}=Q_{se\_p}-Q_{se\_a} \tag{5}$$

$$Q_{se\_p}=R\cdot K\cdot L\cdot S \tag{6}$$

$$Q_{se\_a}=R\cdot K\cdot L\cdot S\cdot C \tag{7}$$

where Q_{sr} represents the amount of SC, Q_{se_p} represents the potential soil erosion, and Q_{se_a} represents the actual soil erosion.

R is the rainfall erosion factor, an indicator that comprehensively considers factors such as the intensity, duration, and frequency of rainfall, reflecting the potential impact of rainfall and runoff on soil erosion. In this study, the Wischmeier formula is used to calculate the rainfall erosion factor (Wischmeier, 1959), and the calculation formula is as follows:

$$R=\sum_{i=1}^{12} 1.735\times 10^{\left(1.5\ \lg\frac{{p_i}^2}{p}-0.8188\right)} \tag{8}$$

where P_i represents the monthly precipitation and P represents the annual precipitation.

K is the soil erodibility factor, which reflects the sensitivity of soil to erosion by erosive agents, quantifying the difficulty of soil erosion. The soil erodibility factor is closely related to the inherent physicochemical properties of the soil. In this study, the EPIC (Environmental Policy Integrated Climate) model is used to calculate the soil erodibility factor with the following formula (Arunrat et al., 2022):

$$\begin{gathered}K=\left[0.2+0.3e^{-0.0256S_d(1-S_i/100)}\right]\times\left(\frac{S_i}{CL+S_i}\right)^{0.3}\\ \times\left[1-\frac{0.25C}{C+e^{(3.72-2.95C)}}\right]\times\left[1-\frac{0.7S_n}{S_n+e^{(-5.51+22.9S_n)}}\right]\end{gathered} \tag{9}$$

where S_d, S_i, CL and C represent the sand, silt, and clay contents and the organic carbon content (%) in the soil, respectively, and d is calculated accordingly: $S_n\ = 1-S_d/100$.

LS is the topographic factor, where L represents the length of the slope factor and S represents the slope gradient factor. The topographic factor reflects the degree of flow concentration and acceleration by the terrain, as well as the shear force and impact force of the flow on the soil. The topographic factor directly determines the risk of soil erosion (Nigel and Rughooputh, 2010; Morgan et al., 1984). The calculation process and formula are as follows:

$$L=\left(\frac{\lambda}{22.13}\right)^{\alpha} \tag{10}$$

$$\alpha=\frac{\beta}{1+\beta} \tag{11}$$

$$\beta=\frac{\sin\theta/0.089}{3.0\times(\sin\theta)^{0.8}+0.56} \tag{12}$$

$$S=\begin{cases}10.8\sin\theta+0.03 & \theta<5.14^\circ\\ 16.8\sin\theta-0.5 & 5.14^\circ\leq\theta<10.20^\circ\\ 21.9\sin\theta-0.96 & 10.20^\circ\leq\theta<28.81^\circ\\ 9.5988 & \theta\geq 28.81^\circ\end{cases} \tag{13}$$

where λ represents the slope length (m), α represents the slope length exponent, β represents the ratio of rill and interrill erosion, and θ represents the slope gradient (°).

C is the vegetation cover factor. Increasing vegetation cover will to some extent reduce soil erosion. The C factor represents the influence of vegetation cover on soil erosion, and its magnitude directly reflects the regional vegetation cover. The soil erosion risk decreases with increasing vegetation cover. This study uses the calculation method for the C factor from previous literature, with the following formula (Wei et al., 2019):

$$C=\begin{cases}1 & f=0\\ 0.6508-0.3436\lg f & 0<f\leq 78.3\%\\ 0 & f>78.3\%\end{cases} \tag{14}$$

$$f=\frac{NDVI_x-NDVI_{\min}}{NDVI_{\max}-NDVI_{\min}}\times 100\% \tag{15}$$

where f represents the vegetation cover, $NDVI_x$ represents the normalized vegetation index value of the grid cell, and $NDVI_{\max}$ and $NDVI_{\min}$ represent the maximum and minimum NDVI in the study area, respectively.

2.3.3. *Construction of development scenarios*

To adapt to the different regional development scenarios that may emerge in the future, this study designed four scenarios to simulate future land use. These different simulation scenarios, combined with the corresponding land use requirements and spatial distribution, construct ecological constraints (prohibited areas for changing land use). However, achieving a perfect match for such a coupling is challenging. Therefore, this study utilizes the characteristics of each environmental functional area to adjust the land use transition rules in each scenario. The specific scenario designs are as follows:

In the BAU scenario, future land use is inferred based solely on past land use data and conversion patterns, without considering any external planning policies that may affect LUCC, meaning that future land use demands will only be determined by historical land use conversion patterns, reflecting historical trends and excluding any proactive interventions in land use.

In the RED scenario, land use planning primarily considers economic development needs and prioritizes urban expansion while neglecting other factors, such as environmental protection and agricultural land security. To ensure regional economic development, the probability of transferring ecological land to building land is increased. According to the regional development plan for the HJRB, the expansion scale of some building land is restricted, while the conversion rate of other land types to building land increases, and the probability of building land transferring to other land types decreases.

In the ELP scenario, the main consideration is ecosystem health and expanding the scope of ecological protection, reducing human disturbance, i.e., reducing the encroachment of building land expansion on ecological land. Correspondingly, economic interests and urbanization processes are secondary considerations. Therefore, the ELP scenario will reduce the conversion rate of forest, grassland, and water to other land types, protect ecological resources, and optimize ecological functional areas. Appropriately increasing the probability of farmland converting to forest, reducing the expansion scale of building land, and setting areas designated for ecological protection as restricted development zones.

In the SD scenario, the goal is to balance the contradiction between urban expansion and ecological protection. In terms of ecological protection, the probability of transferring ecological land to building land is reduced but to a lesser extent than in the ELP scenario. In terms of urban expansion, the probability of transferring building land to other land types is reduced, but to a lesser extent than in the RED scenario.

Considering the nondevelopability of important water areas and ecological red lines, they are used as constraint areas in all scenarios.

2.3.4. *The parameter settings of the PLUS*

(1) Neighborhood Weight Parameter

The neighborhood weight parameter is a key parameter for land use conversion, reflecting the expansion ability of different land use types under the influence of external factors (Lan et al., 2024; Liu et al., 2022b; Nie et al., 2023). According to the different development scenarios, the

Table 2
Neighborhood weight parameter.

	farmland	forest	grassland	water	building land	unused land
BAU	0.50	0.35	0.59	0.72	0.80	0.62
RED	0.35	1	0.63	0.76	1	0.66
ELP	0.80	0.90	0.59	0.80	0.79	0.63
SD	0.35	0.50	0.59	0.70	0.68	0.59

weights of the different land use types are shown in Table 2.

In the BAU scenario, which is mainly based on historical development and change patterns and land use conversion from 2000 to 2020, as well as the implementation of policies such as returning farmland to forests during this period (Feng et al., 2022), the intensity of forest expansion in the HJRB is strong; thus, the weight of forestland in this scenario is adjusted to a lower level. Under the RED scenario, the proportion of building land will further increase, and compared to the other scenarios, the expansion ability of building land will increase. In the ELP scenario, ecological resources may further expand while maintaining the existing scale, manifested as an increase in the proportion of forest, grassland, and water, with conversions mainly coming from farmland and unused land. In the SD scenario, regional development will prioritize balancing urban expansion and ecological protection, aiming to maintain ecological functions as much as possible without damage. Therefore, the transfer probabilities of ecological land and building land are slightly lower than those in the RED and ELP scenarios.

(2) Cost Matrix

The different land use types in the cost matrix represent whether they can be converted to each other. Specifically, the land use conversion matrix is a key parameter for distinguishing different scenarios, which indicates whether conversion can occur between two land use types (Liu et al., 2023). This approach can be limited to one-way or bidirectional conversion, as shown in Table 3.

(3) Model Testing

Before conducting the simulation, it is necessary to validate the accuracy of the parameter settings of the PLUS model (Lan et al., 2024). Using the 2015 HJRB land use data as the baseline, the land use spatial distribution pattern of HJRB Province in 2020 was simulated using the PLUS model. The simulated data were compared with the actual 2020 land use data, and the Kappa coefficient was used to validate the accuracy of the model simulation. The results indicate that the simulated results obtained under a 10% random sample compared with real land use data have an overall accuracy of 0.90, with a Kappa coefficient of 0.81. According to related research, a Kappa coefficient greater than 0.70 is an acceptable range (Nie et al., 2023), indicating that the simulation effect of this study is good, the simulated results are within standard levels, and the simulated results are quite consistent with the actual spatial distribution data and are suitable for simulating the FWCLs of the HJRB.

3. Results

3.1. Spatiotemporal analysis of future LUCC under different scenarios

Fig. 3 and Table 4 display the spatial distribution and transition matrix of various land-use types in the HJRB under the four scenarios for 2035. To compare the expansion capabilities of various land-use types under different scenarios, this study extracted the portion of land-use expansion from 2020 to 2035. Additionally, based on the expansion of building land, six samples were selected to explore and compare land-use changes at a smaller spatial scale.

Forests and farmlands were the main land-use types in the HJRB, accounting for 60.15% and 34.33%, respectively, of the total area in 2020. However, farmland decreases in all scenarios, whereas forest exhibits the opposite trend. The HJRB is the core water source area of the world's largest interbasin water transfer project (the Middle Route of the South-to-North Water Transfer Project) (Wang et al., 2022). Due to the implementation of environmental projects and the conversion of farmland back to forest, the area of forest increased to some extent, mainly in the mountainous forest river plain and near the riverbank buffer zones (Bao et al., 2023). Furthermore, to ensure an adequate water supply for the water transfer project, the area of water bodies also increases in all scenarios, with the fastest growth rates observed in the ELP and SD scenarios, at 16.25% and 14.35%, respectively. This result indicates that the ELP and SD scenarios used in this study can effectively mitigate the scale and speed of ecological land encroachment.

There are significant differences in urban expansion among the different scenarios. The amount of building land increased to varying degrees in all four scenarios, with growth rates of 18.42%, 27.74%, 6.58%, and 25.13%, respectively, with the growth rates in the PUB and SD scenarios surpassing those in the BAU and ELP scenarios. However, the increased area in the ELP scenario is much smaller than that in the RED scenario, indicating that policies have suppressed the continuous expansion of urban areas, leading to intensive development. Since the suitable areas for building land and residential sites highly overlap with those for farmland, coupled with the ecological barrier effects of the mountains in the northern and western parts of the HJRB, the phenomenon of both land-use types encroaching on farmland is more prominent in the southeastern plain. Under the ELP scenario, the areas of farmland, grassland, and unused land decrease, while the areas of forest in the western, northern, and mountainous regions increase significantly.

To better explore the changes in land-use structure under scenario constraints, Fig. 4 presents the LUCC from 2000 to 2020 (at 5-year intervals) and from 2020 to 2035 (with a comparison of each scenario). The results show that the average annual growth rate of building land in all scenarios is lower than that from 2010 to 2015 (the main urbanization stage of the HJRB). Furthermore, in terms of land-use transitions, the expansion of building land and forest areas in 2034 is mainly derived from farmland.

3.2. Spatiotemporal analysis of future ESs under different scenarios

Fig. 5 displays the spatial distribution patterns of ESs in 2020 and 2035, focusing on the changed areas, with a particular emphasis on the mountainous regions in the northwest, the Danjiangkou Reservoir area in the central part, and the plain regions in the southeast. The research results indicate that the high CS values in the HJRB are mainly distributed in the northwestern region with high vegetation coverage, while

Table 3
Cost matrix for different scenarios.

–	BAU						RED						ELP						SD					
	a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f
a	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
b	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
c	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
d	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	1	1	0
e	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
f	0	1	1	1	1	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	1	0

Note: a, b, c, d, e, f represent farmland, forest, grassland, water, building land, and unused land, respectively; 0 indicates that no conversion is allowed, while 1 indicates that conversion between land use types is permitted.

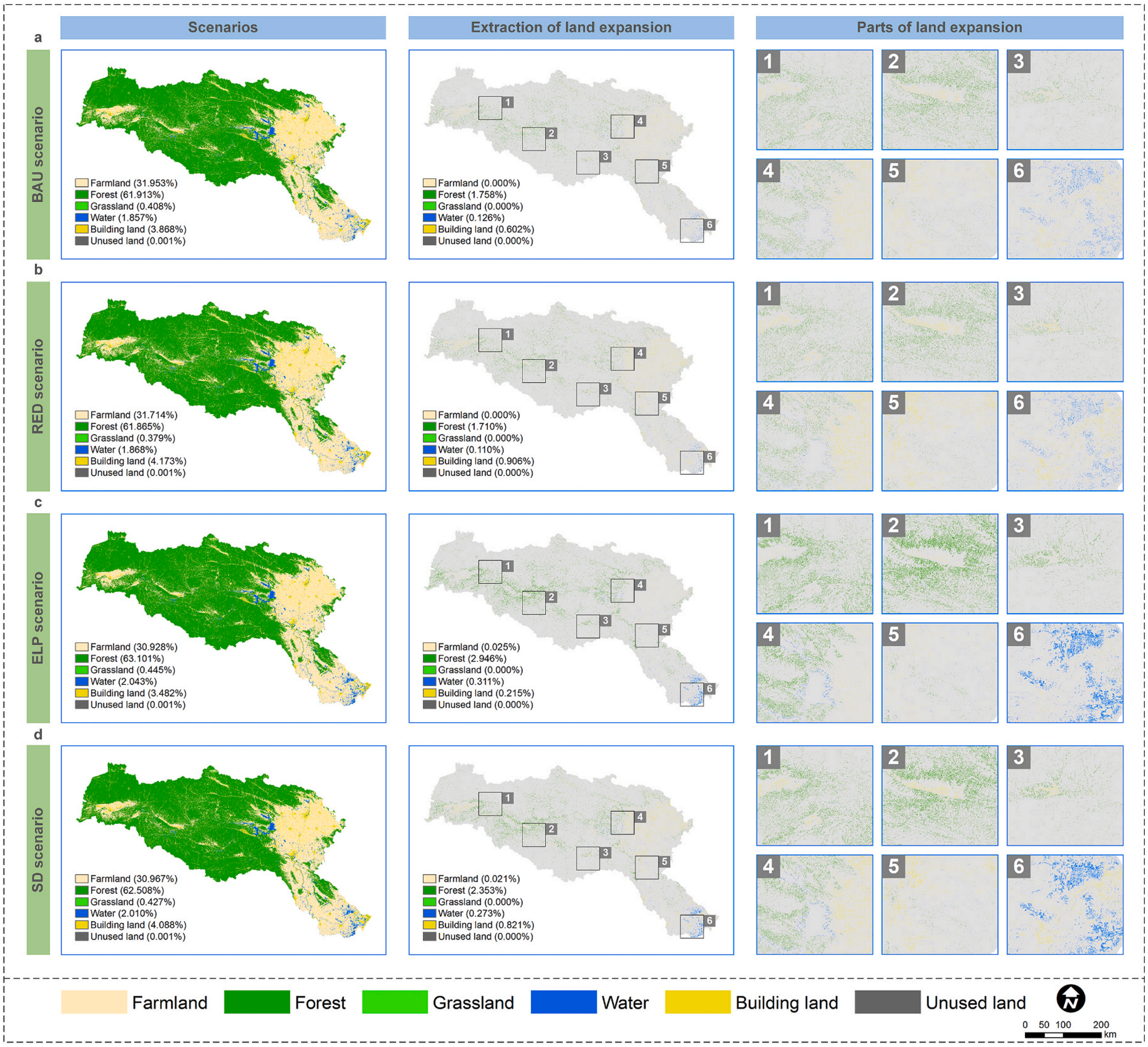


Fig. 3. Comparison of the land use simulation results for the Hanjiang River Basin under the (a) BAU scenario, (b) RED scenario, (c) ELP scenario, and (d) SD scenario in 2035. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Structure of landscape patterns under different scenarios in the Hanjiang River Basin.

Land use type	Areal coverage (km^2)					Trend
	2020	2035				
		BAU	RED	ELP	SD	
Farmland	52657.40	49019.06	48652.32	47446.86	47506.85	
Forest	92280.82	94981.92	94908.25	96804.49	95893.83	
Grassland	758.68	625.68	581.92	682.31	654.72	
Water	2696.49	2848.44	2865.45	3134.55	3083.41	
Building land	5011.51	5934.68	6401.85	5341.48	6270.90	
Unused land	1.54	1.36	1.35	1.45	1.43	

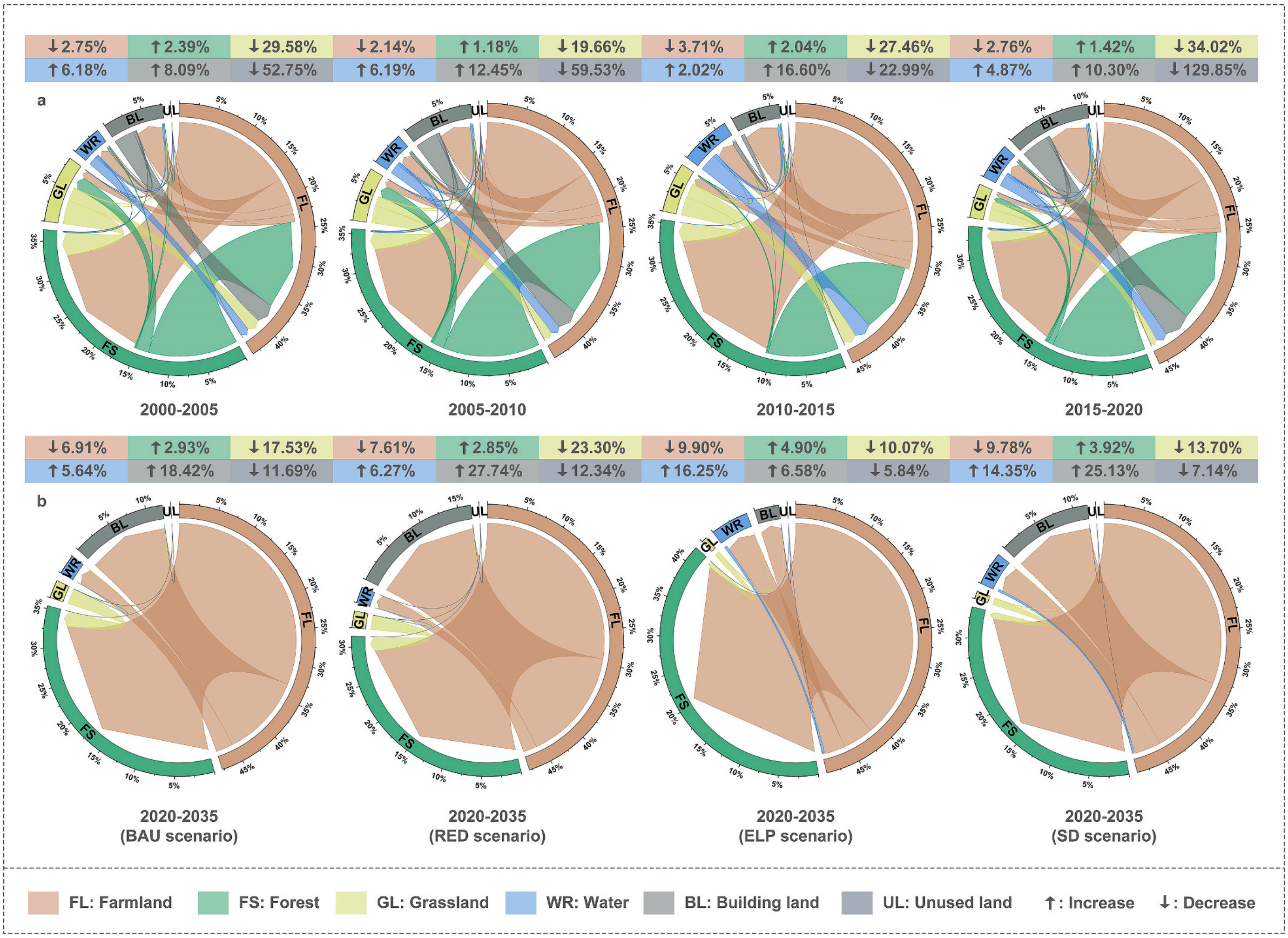


Fig. 4. Land use transfer in the Hanjiang River Basin under different (a) historical periods and (b) scenarios.

low CS values are found in densely populated urban areas, with farmland at an intermediate level. The high values of SC are distributed near the Ta-pa Mountains in the south, with lower values in other regions. Both high-value areas of these ESs are characterized by relatively high vegetation coverage. Furthermore, the spatial distribution pattern of WY was related to precipitation, with high values primarily located in the middle and lower reaches, in line with previous research findings, and low values mainly in the western and northern mountainous areas.

Under the different scenarios, the ESs exhibited similar spatial distribution patterns. The WY and SC in the downstream urban areas are most severely degraded. This may be due to the extensive expansion of urban land encroaching upon farmland, forest, and grassland, leading to a significant decrease in ecological land and a decline in SC capacity. However, CS has not shown significant changes, except for an increasing trend in some mountainous regions in the west.

Table 5 illustrates the variations in ESs across diverse scenarios. Unexpectedly, the WY of the HJRB region may have experienced a modest decline, with the extent of this decline differing among the scenarios, culminating in a significant 9.18% reduction under the RED scenario. This decline is attributed to the potential water yield-decreasing effects of expanded building land (Wang et al., 2023). The augmented construction area can perturb the natural hydrological cycle via phenomena such as wetland filling, alterations in land cover, and water source contamination, thereby plausibly causing a decrease in WY (Wei et al., 2019). Moreover, construction activities are prone to exacerbate water resource exploitation and consumption, which may result in water supply insufficiency.

CS generally exhibits a slight uptrend across most scenarios, except for the RED scenario. Typical construction activities, including deforestation, soil structure disruption, and shifts in vegetation, can each contribute to a reduction in CS. For instance, extensive urbanization and industrialization can obliterate vast swathes of forest, diminishing tree biomass and soil organic matter and consequently lowering CS levels. Additionally, transformations in land coverage from natural to artificial impermeable surfaces within construction zones can further diminish CS. Conversely, scenario analysis indicated a consistent increase in SC across all scenarios.

3.3. *Exploring the driving factors of ESs based on RDA*

Fig. 6 illustrates the outcomes of an RDA carried out on three ESs and eleven driving factors in the HJRB from 2000 to 2020. The length of the arrows in Fig. 6 denotes the magnitude of impact on the ESs, while the angle between the ESs and driving factors reflects the degree of contribution, with smaller angles indicating greater influence (Shi et al., 2023). The driving factors examined in this study included rainfall, slope, landform, LUCC, temperature (TEMP), DEM, NDVI, Nighttime-light Dataset (DN), soil type, population, and GDP.

RDA accounted for a substantial portion (over 70%) of the HJRB variability, indicating that the selected factors effectively captured the distribution of its ESs. Among these factors, rainfall, LUCC, DEM, and NDVI are the primary factors influencing overall ES changes, followed by DN. Rainfall had the most notable impact on WY in 2015, which persisted robustly until 2020 without significant attenuation.

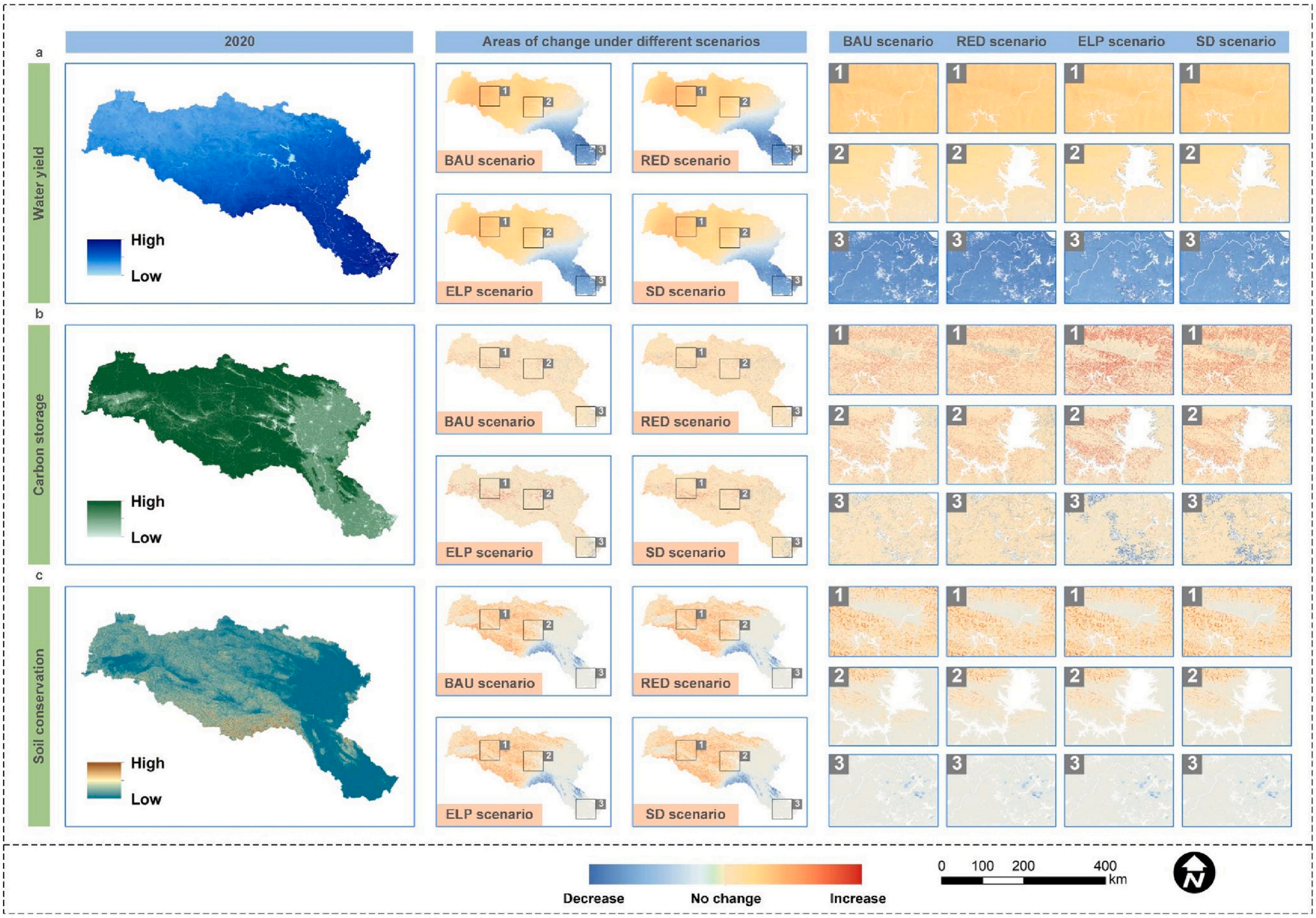


Fig. 5. Comparison of ecosystem services in the Hanjiang River Basin under 2020 and 2035 (different scenarios): (a) water yield, (b) carbon storage, and (c) soil conservation.

Table 5
The supply of ecosystem services for 2020 and 2035 under different scenarios and their relative changes.

Indicator	Water yield	Rate	Carbon storage	Rate	Soil conservation	Rate
2020	9806257754	–	1908708870	–	1756324545	–
BAU	9083597512	−7.37%	1910713478	0.11%	2118935834	20.65%
RED	8906017828	−9.18%	1907746325	−0.05%	2118559750	20.62%
ELP	9228483456	−5.89%	1919280030	0.55%	2122274168	20.84%
SD	9152014509	−6.67%	1910853278	0.11%	2120384759	20.73%
Trend		–		–		–

Conversely, soil type, population, and GDP had relatively limited effects on all ESs.

4. Discussion

4.1. *The significance of simulating future water-carbon-land coupled systems in the era of COP 27*

In the era of COP 27, simulating future water-carbon-land coupled systems is of great importance for deepening the understanding of environmental dynamics and formulating effective sustainable resource management strategies. The model constructed in this study can limit and simulate future changes in LUCC and ESs in both quantity and space, and it analyses the reasons for these changes and discusses the main driving factors. The research results validated the effectiveness of the model in ecological land protection, providing valuable insights into the complex relationships among these key components of the Earth's ecosystems, which aids in identifying potential risks and impacts of climate change, land use patterns, and human activities on water resources, carbon cycles, and soil health. From the perspective of ecological protection, given that this region is a water source for water transfer projects and an important ecological guaranteed space, it is necessary to reduce disturbances to the ecology from development and construction (Zhu et al., 2023b). Therefore, the ELP scenario is the best choice for maintaining ecological land, with an effective increase in water area. If economic development needs are considered, the HJRB can choose the BAU or SD scenarios to ensure that urban development is not overlooked. In all the simulated scenarios, both farmland and grassland decreased to varying degrees, which is contrary to the historical trend (Zhang et al., 2022; Yu et al., 2010). The main reason for this difference

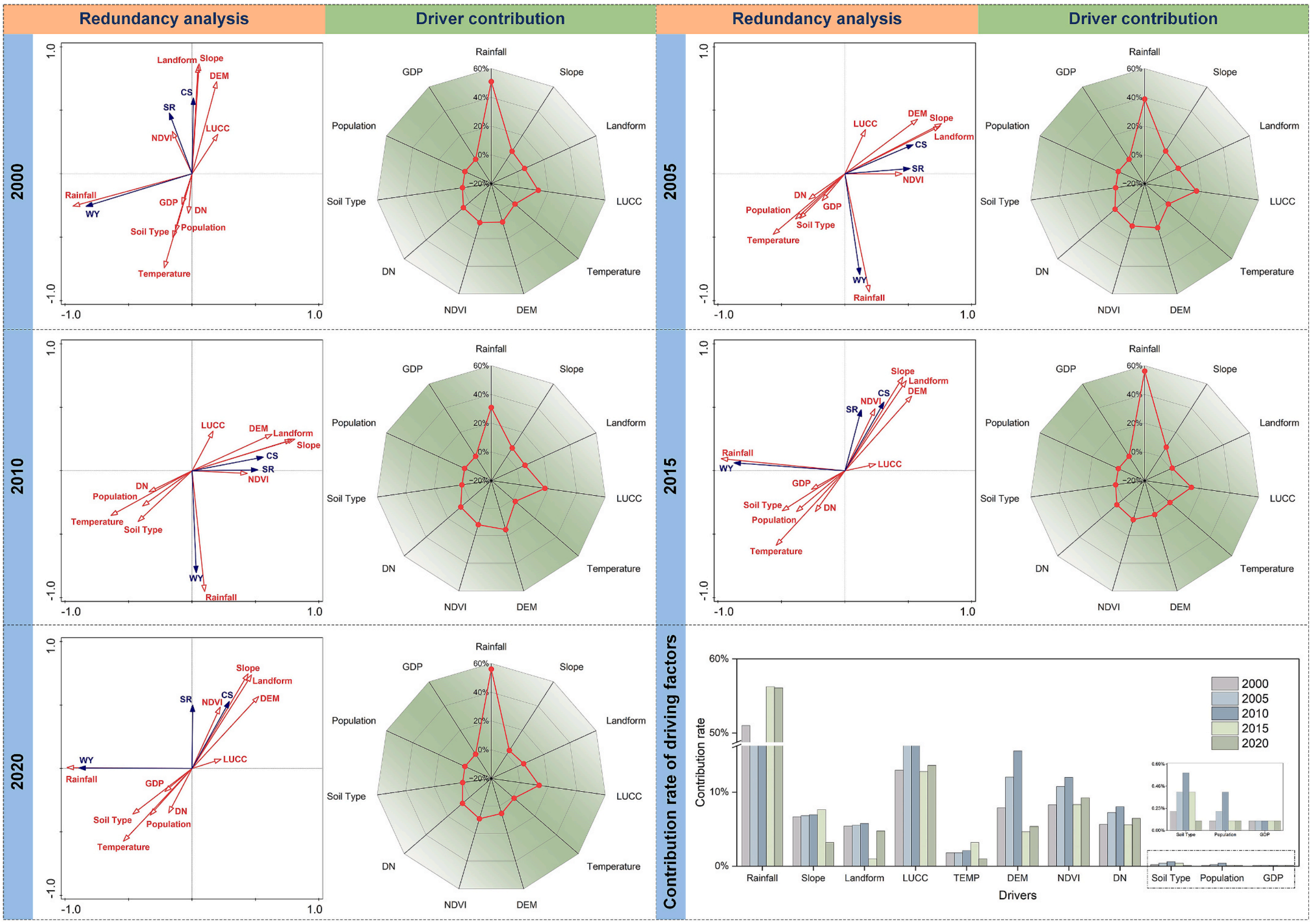


Fig. 6. Redundancy analysis chart and driver contributions of ecosystem services in the Hanjiang River Basin from 2000 to 2020.

is the impact of the grain-for-green policy implemented during this period, the grain-for-green project has been a significant intervention in China's efforts to restore and conserve natural ecosystems. This policy, initiated in the late 1990s, aimed to convert steeply sloped or marginal farmland into forest or grassland in order to reduce soil erosion and improve ecological conditions. Its impact on land use dynamics and environmental sustainability has been well-documented (Cao et al., 2020; Feng et al., 2005), under which the area of returning farmland to forests exceeded the area of forest converted to other land uses. Forests show a growth trend in all scenarios, confirming this point.

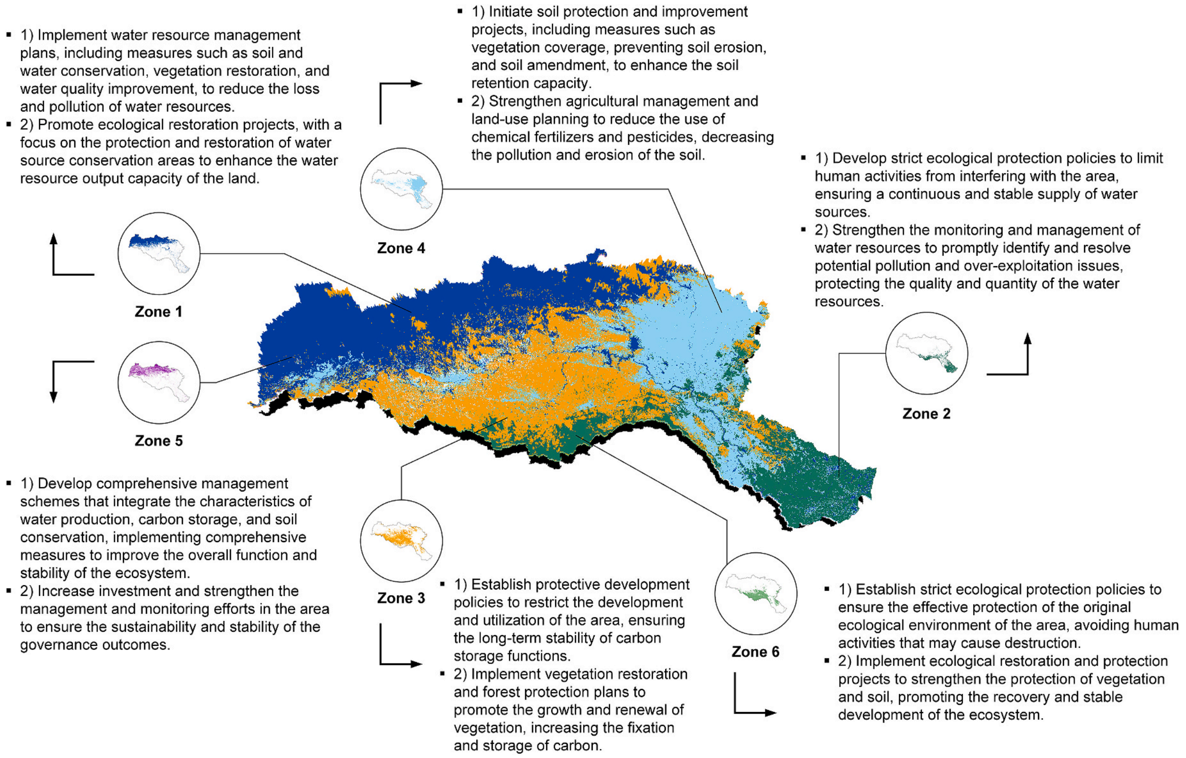
During the historical period and in the simulation results, the expansion of building land mainly came from farmland, and this trend was more pronounced in the simulation results. Moreover, this study used ecological redline areas as spatial constraints, concentrating LUCC in a more compact space, which to some extent changed the original direction of land use transfer. Under this constraint, forests with high ES values were not transferred to building land, while the increase in forest transfer to building land beyond the constrained space was more significant. In summary, the model constructed in this study, which combines ecological constraints with multiple scenarios, can more accurately simulate the complex processes of LUCC and ESs.

By simulating these interconnections, the effectiveness of different adaptation and mitigation measures can be assessed, identifying potential synergies and common interests among water, carbon, and land management strategies, thereby contributing to the global economy. Understanding these interconnections is crucial not only for environmental sustainability but also for economic stability and growth. These simulations can evaluate the long-term consequences and trade-offs of different land management practices, policy interventions, and resource allocation strategies, providing valuable insights for policymakers and stakeholders in making informed decisions that not only benefit the environment but also have positive economic impacts. Furthermore, in a world where economic activities are increasingly interconnected, these simulations can shed light on how environmental and resource management strategies can impact global trade, investment patterns, and economic development. This is essential for addressing global environmental challenges while also promoting economic prosperity and achieving the sustainable development goals proposed in the COP 27 agenda.

4.2. Targeted spatial management strategy based on future water-carbon-land coupled systems

This study utilized the RDA method to identify the driving factors of ESs, which contribute to formulating corresponding spatial management and planning strategies. These strategies aim to simultaneously manage a variety of ESs, providing valuable insights for enhancing spatial multifunctionality and promoting regional sustainable development (Xia et al., 2023; Dittrich et al., 2017). Fig. 7 demonstrates the targeted spatial management strategy based on future water-carbon-land coupled systems.

Currently, the task of China's national territorial spatial planning task is to construct a new pattern of harmonious coexistence between humans and nature (Liu and Zhou, 2021). China's territorial spatial planning is multilevel (Zhou et al., 2017a). Clearly, basin-level management strategies are crucial, but this does not mean that subregional



- 1) Implement water resource management plans, including measures such as soil and water conservation, vegetation restoration, and water quality improvement, to reduce the loss and pollution of water resources.
- 2) Promote ecological restoration projects, with a focus on the protection and restoration of water source conservation areas to enhance the water resource output capacity of the land.

- 1) Initiate soil protection and improvement projects, including measures such as vegetation coverage, preventing soil erosion, and soil amendment, to enhance the soil retention capacity.
- 2) Strengthen agricultural management and land-use planning to reduce the use of chemical fertilizers and pesticides, decreasing the pollution and erosion of the soil.

- 1) Develop strict ecological protection policies to limit human activities from interfering with the area, ensuring a continuous and stable supply of water sources.
- 2) Strengthen the monitoring and management of water resources to promptly identify and resolve potential pollution and over-exploitation issues, protecting the quality and quantity of the water resources.

- 1) Develop comprehensive management schemes that integrate the characteristics of water production, carbon storage, and soil conservation, implementing comprehensive measures to improve the overall function and stability of the ecosystem.
- 2) Increase investment and strengthen the management and monitoring efforts in the area to ensure the sustainability and stability of the governance outcomes.

- 1) Establish protective development policies to restrict the development and utilization of the area, ensuring the long-term stability of carbon storage functions.
- 2) Implement vegetation restoration and forest protection plans to promote the growth and renewal of vegetation, increasing the fixation and storage of carbon.

- 1) Establish strict ecological protection policies to ensure the effective protection of the original ecological environment of the area, avoiding human activities that may cause destruction.
- 2) Implement ecological restoration and protection projects to strengthen the protection of vegetation and soil, promoting the recovery and stable development of the ecosystem.

Fig. 7. Spatial management strategies in the Hanjiang River Basin.

management strategies are redundant. In contrast, subregional management strategies provide more detailed insights (Xia et al., 2023). Furthermore, this study divided the HJRB into six subzones and proposed effective measures for these subzones to enhance the resistance of the ecosystem to natural and anthropogenic damage. These six subzones are WY-low, requiring governance Subzone 1; WY-high, requiring protection Subzone 2; CS-high, requiring protection Subzone 3; SC-low, requiring governance Subzone 4; WY, CS, SC all low, requiring focused governance Subzone 5; and WY, CS, SC all high, requiring focused protection Subzone 6.

Specific personalized strategies are shown in Fig. 7. In brief, subzones 1 and 4 require governance measures, including soil and water conservation, vegetation restoration, water quality improvement, and soil protection, to reduce resource loss and pollution and improve the water resource and soil output capacity of the land. Subzones 2 and 3 require focused protection by implementing strict ecological protection policies and vegetation restoration and forest protection plans to maintain CS functionality and water resource stability. Subzone 5 requires comprehensive governance to improve ecosystem functionality and stability through comprehensive measures and to increase management and monitoring efforts. Subzone 6 also requires rigorous ecological protection policies to preserve the natural ecological environment, while implementing ecological restoration and protection projects to promote ecosystem recovery and stability.

Moreover, the study underscores the significance of integrating spatiotemporal analysis of LUCC and ESs interactions into spatial planning. By emphasizing the priority of different subzones and maintaining mutual coordination among them, the study's refined subregional spatial management strategies offer a comprehensive approach to ecosystem functionality and stability. These findings have influenced research globally by providing a framework for addressing multifaceted ecosystem challenges and can guide policymakers and stakeholders in formulating effective spatial management and planning strategies for sustainable development.

4.3. *Limitations and prospects*

Like any other research study, this study also has some limitations. First, although this study assigned different probabilities for land use type conversion in each scenario, it remains challenging to consider comprehensive land conversion rules, making it difficult to fully address this restriction.

Second, this study employed significant water bodies and ecological red lines as spatial constraints. However, even in these areas under highly ecological protection scenarios, there may still be slight changes in land use. Therefore, future research should focus on further zoning to analyze smaller-scale spatial changes.

Finally, this study focused only on three specific ESs (i.e., water yield, carbon storage, and soil conservation), which may not fully represent the entirety of ecological well-being. Future studies should integrate actual regional conditions to comprehensively assess the impact of LUCC on various ESs.

5. Conclusion

This study introduces a model that simulates multiple land-use scenarios and their impact on water, carbon, and land systems in the HJRB and identifies key driving factors. This analysis aims to facilitate more precise spatial management for the sustainable development of regional ecosystems and enhance human well-being, and contributing to the attainment of the ambitious objectives set forth in COP 27.

Regarding future LUCC and ESs, forests and farmlands have historically been the dominant land use types in the HJRB and are characterized by numerous forests and significant reservoirs. However, farmlands exhibit a consistent decrease across all scenarios, whereas forests demonstrate the opposite trend. The area of water bodies increases in all scenarios, with the most rapid expansion observed in the ELP and SD scenarios. On the other hand, the expansion of building land exhibits differing situations of increase across the four scenarios, with noticeably less growth in the ELP scenario compared to the RED scenario. Different scenarios exhibit similar spatial distribution patterns for future ESs but varying degrees of change due to the projected impacts of future land use and urban development. Specifically, areas upstream of the HJRB, including WY, CS, and SC, experienced varying degrees of increase, while downstream areas experienced varying degrees of attenuation. Notably, SC underwent the most pronounced change, whereas CS experienced the most gradual transformation. Rainfall, LUCC, DEM, and NDVI emerge as the primary determinants influencing ESs, with rainfall exerting the most significant and enduring influence on WY. Conversely, soil type, population, and GDP had relatively minor impacts on all the ESs. The equilibrium of ecosystems is influenced by a combination of natural and anthropogenic factors, necessitating appropriate spatial management interventions to rectify ecosystem imbalances. Consequently, governments must recognize the imperative of implementing refined spatial management strategies.

Accordingly, this study offers valuable insights into multiple land-use scenarios and their impacts on the HJRB's water, carbon, and land systems, contributing to the achievement of several Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land). The findings underscore the importance of refined spatial management strategies to address ecosystem imbalances influenced by both natural and anthropogenic factors, aligning with the principles of SDG 11 (Sustainable Cities and Communities).

These insights provide a foundation for sustainable regional ecosystem development, in line with the ambitious objectives of COP 27 and the broader agenda of SDG 17 (Partnerships for the Goals). Furthermore, this study offers valuable lessons for other similar regions, demonstrating the necessity of considering both natural elements and human activities in land-use planning. It highlights the importance of tailored spatial management interventions to achieve sustainable ecosystem balance, which is essential for fostering resilience and promoting sustainable livelihoods, thus supporting SDG 1 (No Poverty) and SDG 2 (Zero Hunger). By integrating these SDG-related considerations, the research emphasizes a holistic approach to land-use planning that prioritizes environmental sustainability and social equity.

CRediT authorship contribution statement

Kai Zhu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Yufeng Cheng:** Software, Methodology, Data curation. **Quan Zhou:** Software, Methodology, Data curation. **Hossein Azadi:** Writing – review & editing, Conceptualization.

Competing interests

The authors declare no competing interests.

Financial disclosure statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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