




# Assessing the impacts of multi-scenario climate and land use change on water-related ecosystem services: the case of the Yangtze River Economic Belt (2000–2030)

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## ARTICLE INFO

### Keywords:

Climate change  
Land use change  
Water-related ecosystem services  
InVEST model  
Trade-offs

## ABSTRACT

Water-related ecosystem services (WESs) are essential for sustainable development, particularly in regions experiencing rapid land use and cover change (LUCC) and climate change (CC). This study evaluates the spatial and temporal impacts, independent contributions, and trade-offs of LUCC and CC on WESs in the Yangtze River Economic Belt (YREB) from 2000 to 2030. By integrating the BCC-CSM2-MR, InVEST, and PLUS models with dynamic trade-offs analysis, our findings indicate that water yield (WY) could increase by up to 53.65 % under the SSP585 climate with cropland protection scenario (CP585), and the upstream surge is significant. Additionally, water purification (WP) is projected to improve across the region, as evidenced by a 10.31 % reduction in phosphorus (P) export under SSP585 climate with ecological protection scenario (EP585), while upstream degrades in the urban expansion (UE) and CP scenarios. CC exerts a predominant positive influence (over 90 %) on WY, while LUCC significantly affect WP especially in the downstream. Overall dynamic trade-offs reveal lowest upstream and highest downstream trade-offs between WESs. Meanwhile the spatial synergy between WESs is expected to be most extensive under the SSP245 climate and EP scenario (EP245). These findings underscore the importance of integrated land and water management strategies to optimize WESs and support sustainable regional development amid future environmental changes. However, this study is limited by its use of annual average precipitation, which ignores seasonal dynamics, and by focusing on the separate effects of LUCC and CC without considering their combined effects. Future research should address these gaps.

## 1. Introduction

Water-related ecosystem services (WESs) are fundamental to maintaining the functions of ecological systems and human well-being, which is particularly important in regions experiencing rapid environmental and economic changes [35]. Key WESs, such as water yield (WY), water purification (WP), and soil conservation, deliver vital direct and indirect benefits to people and play a central role in the integrated management of water resources [67]. WY reflects the capacity of an ecosystem to provide freshwater, indicating the availability of water resources in an

area [33], WP measures the ability of the ecosystem to trap pollutants, thus reflecting the water quality of the basin [17]. Increased human activity has greatly increased the demand for clean and abundant freshwater, while urbanization, industrialization and unsustainable agricultural practices have led to severe water pollution and degradation of WESs, particularly through increased nutrient runoff and habitat destruction [42,53]. Given the important role of WESs in maintaining ecological integrity and human livelihoods, there is an urgent need for a comprehensive assessment of their spatial and temporal variability, as well as future trends, to support sustainable water resources management.

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<https://doi.org/10.1016/j.sfr.2025.100854>

Received 4 December 2024; Received in revised form 11 May 2025; Accepted 12 June 2025

Available online 16 June 2025

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### Nomenclature

LUCC	Land Use and Cover Change
CC	Climate Change
WESs	Water-related Ecosystem Services
InVEST	Integrated Assessment of Ecosystem Services and Trade-Offs
PLUS	Patch-generating Land Use Simulation Model
BCC-CSM2-MR	Beijing Climate Centre Climate System Model version 2-Medium Resolution
YREB	Yangtze River Economic Belt
WY	Water Yield
WP	Water Purification
CV	Coefficient of Variation
CMIP	Coupled Model Intercomparison Project
CP	Cropland Protection
EP	Ecological Protection
UE	Urban Expansion
SSP	Shared Social Pathways
ET	Evapotranspiration

The management of WESs is further complicated by the effects of climate change (CC) and land use and land cover change (LUCC). As two major drivers of global environmental change, CC and LUCC have significantly altered the temporal and spatial distribution of ecosystem services by altering ecosystem structure and function [20,29,30,57]. WESs are extremely sensitive to these drivers [4,53]. Rapid urbanization contributes significantly to LUCC, altering land-use patterns and hydrological processes and directly or indirectly affecting runoff and water quality [38,67]. Concurrently, global warming alters precipitation patterns and disrupts regional water cycles, posing a threat to the stable provision of WESs [72]. Urbanization and climate change are projected to increase the global population facing water scarcity from 933 million in 2016 to between 1693 million and 2373 million in 2050 [23]. Additionally, the area of watersheds suffering from water shortages due to nitrogen pollution is expected to expand by 4000 square kilometers by 2050 [60]. Therefore, a comprehensive understanding of the interactions between LUCC and CC is therefore essential for the development of effective WESs management strategies, as it helps to identify key controlling factors and informs targeted interventions [39].

Despite the importance of LUCC and CC is well recognized, most studies have examined their impacts on ecosystem services in isolation [45,49,58]. Some recent studies have begun to explore their combined effects [70,82], key climate variables are often overlooked, affecting the validity of assessments [36]. This fragmented approach fails to capture the complex interactions between LUCCs and CC, resulting in an incomplete understanding of their combined impacts on WESs. Therefore, a more integrated approach that simultaneously addresses the combined impacts of LUCC and CC is needed to make reliable predictions of future changes in WESs.

Given the complexity and inherent uncertainty surrounding future LUCC and CC, selecting appropriate methodological frameworks is critical for anticipating their impacts on WESs. Scenario-based approaches offer a valuable framework to integrate multiple uncertainties associated with LUCC and CC, and have been widely adopted in ecosystem service assessments [26]. Most prior studies construct differentiated LUCC scenarios to evaluate how policy-driven land changes affect ecosystem services. For instance, Wang et al. [63] simulated land use change in Wuhan under three scenarios—Business As Usual, Rapid Economic Development, and Ecological Land Protection—and assessed their impacts on ecosystem service values. In recent years, the integration of CC scenarios, especially Shared Socio-economic Pathways (SSPs), has become increasingly prevalent. For

example, Sun et al. [53] combined System Dynamics (SD), Future Land Use Simulation (FLUS), and InVEST models to simulate land use and ecosystem service changes in Yunnan Province under SSP2–4.5 and SSP5–8.5. However, most existing studies emphasize the indirect effects of climate change on land use, lacking systematic coupling of CC and LUCC scenarios. This limitation constrains their capacity to capture the interactive impacts and spatial heterogeneity of ecosystem services under multiple drivers. Therefore, there is a clear need for an integrated multi-scenario framework that explicitly couples LUCC and CC to enhance the reliability and comprehensiveness of future ecosystem service assessments.

Different approaches have been taken in quantifying the impacts of CC and LUCC on WESs, including plot experiments [48], expert evaluations [8,46], and ecological modeling [75]. Ecological modelling, particularly using tools such as the Integrated Assessment of Ecosystem Services and Trade-Offs (InVEST), has proved particularly effective because of its spatial analytical capabilities, cost-effectiveness and reproducibility, becoming a valuable tool for decision makers in land management and climate adaptation strategies [28]. Previous studies have shown that CC primarily drives changes in WY, while LUCC has a greater impact on WP [51,69]. However, the impact of CC and LUCC on WESs varies greatly from region to region, and no generalized pattern has yet emerged [5,40,75]. Furthermore, the trade-offs and synergies between LUCC and CC for WESs under different combinations of scenarios are still not fully explored [43]. Filling these knowledge gaps will require a comprehensive study of the impacts of LUCC and CC on WESs under multiple scenarios, which will provide important insights for ecosystem management.

This study focuses on the Yangtze River Economic Belt (YREB), an ecologically and economically important region in China with significant differences between its upstream, midstream and downstream areas. The YREB has faced enormous anthropogenic pressures that pose challenges to water resource management [6]. To tackle these challenges, this study integrates the CMIP6-based Beijing Climate Centre Climate System Model version 2-Medium Resolution (BCC-CSM2-MR), the Patch-generating Land Use Simulation Model (PLUS), and the InVEST model. CMIP6 provides enhanced climate prediction capabilities compared to CMIP5 [85], PLUS provides higher simulation accuracy and detailed landscape pattern generation [34], and InVEST facilitates comprehensive, quantitative assessments of ecosystem services [65]. This integration of advanced models enhances the scientific robustness of WESs simulations. Meanwhile, in order to address the uncertainties arising from the interactions between CC and LUCC, nine combinations of future scenarios based on three CC and three LUCC scenarios were explored using the scenario analysis approach [44]. Compared with previous work, this study makes two key contributions: first, a coupled multi-scenario design that integrates three CC with three LUCC pathways to generate nine combined scenarios, substantially enhancing the reliability and comprehensiveness of WESs predictions under multiple interacting drivers; and second, an integrated modeling framework that tightly couples the BCC CSM2 MR climate model, the PLUS land use simulation model, and InVEST ecosystem service assessment tool. This framework enables high precision simulations of WY and WP, and reveals the complex, multi-level influences of CC and LUCC on WESs. Together, these contributions provide robust decision-support tools for optimizing ecosystem service management amid the dual imperatives of climate adaptation and sustainable land use planning.

Therefore, this study aims to: (1) analyze and simulate historical and future CC and LUCC scenarios in the YREB, (2) assess changes in WESs under historical and future conditions, (3) quantify the independent contributions of CC and LUCC to WY and WP, and (4) investigate trade-offs and synergies between WESs across different scenarios. This study provides crucial, evidence-based insights for balancing ecological protection and economic growth in the YREB by integrating CC and LUCC scenarios to inform adaptive, resilient WESs resource management policies.

## 2. Materials and methods

### 2.1. Study area

The YREB, spanning 11 provinces and covering 21.4 % of China’s land area, is a key strategic zone for ecological and economic development, linking China’s eastern, central, and western regions (Fig. 1) [56, 21]. Characterized by varied topography and a subtropical monsoon climate, the YREB hosts diverse ecosystems and holds 36 % of China’s water resources, with water availability per square kilometer nearly double the national average [6]. Contributing 46.5 % of China’s GDP and housing 43.1 % of its population, the region faces growing challenges in sustainable water and ecological management due to rapid urbanization and industrialization [12], underscoring its selection as the study area.

### 2.2. Datasets

A comprehensive suite of datasets was utilized to support the assessment of WESS, with data spanning land use, climate, and key drivers influencing LUCC (Appendix Table S1). The main data sources include:

**Land Use Data:** Obtained from the Resource and Environment Science and Data Center (<https://www.resdc.cn/>) for 2000–2020, this dataset categorizes land cover into six classes: cropland, forest land, grassland, waterbody, construction land, and unused land.

**Climate Data:** Sourced from the National Earth System Science Data Center (<http://www.geodata.cn/>), covering the period 2000–2020.

**Key Drivers for PLUS Model:** Population, GDP, and elevation data were sourced from the Resource and Environment Science and Data Center, while accessibility data (e.g., government offices, railways, highways, universities, airports) were obtained from Amap (<http://www.amap.com/>).

**Future Climate Data:** Future climate projections for 2030 were derived from the BCC-CSM2-MR model on the CMIP6-based World Climate Data website (<https://worldclim.org/>).

**Soil Data for InVEST Model:** Sourced from the National Cryosphere Desert Data Center based on the World Soil Database (HWSD) (v1.1) (<http://www.ncdc.ac.cn/>).

All raster data were resampled to a consistent spatial resolution of 1 km × 1 km, ensuring compatibility for input into the PLUS model for future land use simulations and WESS quantification.

### 2.3. InVEST model

The InVEST model was chosen for its capability to simulate ecosystem service trade-offs at regional scales, its modular design, comprehensive documentation, and strong adaptability to integrate LUCC and CC scenarios. These features make it particularly suitable for assessing WESS in the YREB [68]. In this study, we extracted mean WES data generated by InVEST version 3.12.0 (available at <https://naturalcapitalproject.stanford.edu/software/invest>) at the county scale using the Zonal Statistics as Table tool in ArcGIS 10.5, linking national strategic planning with local implementation to support sustainable management [6].

#### (1) Water yield (WY)

Water yield represents the ability of ecosystems to provide freshwater and is critical to maintaining the regional water cycle, supporting human activities and promoting economic development. The annual water yield module of the InVEST model is based on Budyko’s assumption of a hydrothermal equilibrium, and calculates the amount of water yield by relating actual and potential evapotranspiration to precipitation ratios [81]. The formula is as follows:

$$Y_i = \left(1 - \frac{AET_i}{P_i}\right) \times P_i \tag{1}$$

Where  $Y_i$  represents the annual water volume of the grid,  $AET_i$  represents the annual actual evapotranspiration of the grid, and  $P_i$  represents the annual rainfall of the grid. The yield is calculated by multiplying the rainfall on the grid area by the proportion of rainfall not lost to evapotranspiration. The product of the grid area and  $Y_i$  is then used to determine the final water production value for the grid. Model validation results show an error margin of 9.64 %, confirming the model’s reliability (Appendix Figure S4).

#### (2) Water Purification (WP)

Water purification measures an ecosystem’s ability to filter pollutants, critical for maintaining water quality amid pressures from urbanization and resource exploitation. This study focuses on phosphorus retention, given its significance as a pollutant in the YREB [84]. The water purification model assesses water quality by measuring the total phosphorus (P) content in the water body, considering only non-point source pollution while excluding other pollution sources. In this model, higher total

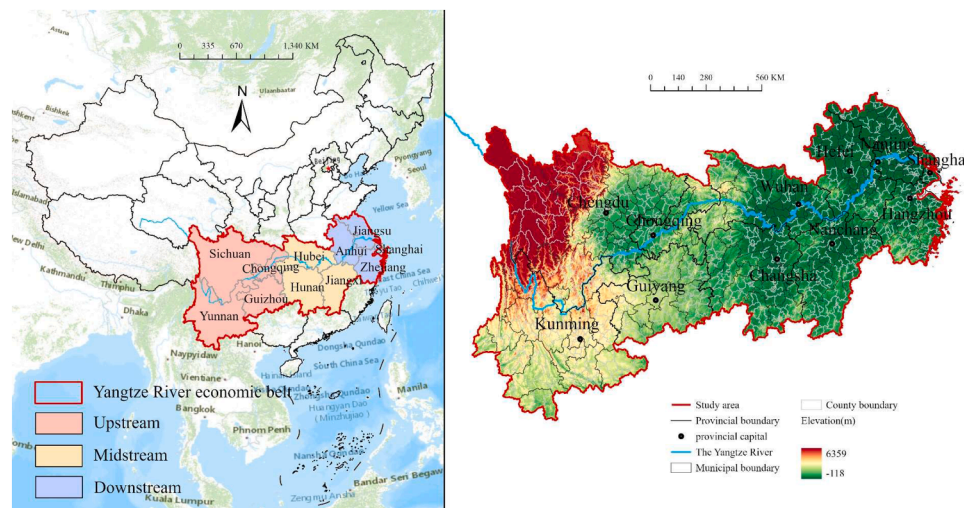


Fig. 1. Location, administrative divisions and topography of the YREB.

phosphorus export values indicate a weaker water purification function [18]. Model evaluation was conducted in two stages: first, the average annual runoff volume was calculated using the water yield model, followed by pollutant retention calculations using the following equations:

$$ALVi = HSSi \times poli \quad (2)$$

$$HSSi = \frac{\lambda i}{\bar{\lambda i}} \quad (3)$$

where  $ALVi$  is the nutrient output value of raster  $i$ ,  $HSSi$  is the hydrological sensitivity score of raster  $i$ ,  $poli$  is the output coefficient of raster  $i$ ,  $\lambda i$  is the runoff index, and  $\bar{\lambda i}$  denotes the average runoff index in the region. Model simulations were validated with a fitting accuracy of 0.79, meeting the study's requirements (Appendix Figure S5).

#### 2.4. PLUS model

The PLUS model, comprising the Land Expansion Analysis Strategy (LEAS) and Cellular Automata Model based on Multi-Class Random Patch Seed (CARS), was employed to simulate land use changes and identify key driving factors [34]. The LEAS module used 12 driving factors, including natural (e.g., DEM, slope, temperature) and social factors (e.g., GDP, population), to model land use changes from 2010 to 2020. These factors generated development probabilities for the six land use types, which were further refined in the CARS module to predict future spatial changes. The predictions of the model were validated using the kappa coefficient, which gave a result of 0.925 with an overall accuracy of 0.949, indicating that the model performed reliably.

#### 2.5. Trade-offs and synergy analysis

Spearman correlation analysis is a widely employed approach for assessing the trade-offs and synergies among ecosystem services [25]. In this study, we introduce an innovative dynamic trade-offs and synergistic approach to quantify these relationships in conjunction with temporal changes. By Min-Max normalizing the difference between WY and WP (positive normalization for WY and negative normalization for WP over the periods 2000–2010, 2010–2020, 2000–2020, and 2020–2030, we conducted Spearman correlation analysis to capture the dynamic interactions of WESs. Compared to static correlation analyses based on specific years, this approach reflects trends in interactions, leading to a more comprehensive understanding of trade-offs and synergistic dynamics of ecosystem services. Spatial trade-offs are calculated using the ratio of the difference between WY and WP over time to derive the Trade-offs and Synergy Index (TSI) as shown in the following equation:

$$TSI = \frac{ESi(t2) - ESi(t1)}{ESj(t2) - ESj(t1)} \quad (4)$$

where  $ESi(t2)$  and  $ESi(t1)$  represent ecosystem service values at time  $s(t2)$  and  $s(t1)$ , respectively, and  $ESj(t2)$  and  $ESj(t1)$  represent ecosystem service values  $j$ .  $TSI > 0$  indicates a synergistic effect, that is, two services change in the same direction, whereas  $TSI \leq 0$  suggests a trade-offs between the services.

#### 2.6. Contribution analysis of CC and LUCC

In this study, we used a factor-control approach to quantify the independent contributions of CC and LUCC to changes in WESs, focusing on the relative importance and directional effects of each factor [62]. This approach involves creating virtual scenarios that isolate the impacts of CC and LUCC in order to analyze in detail how these drivers affect WESs.

The study first quantified the WESs under realistic conditions in 2000, 2010 and 2020, and then designed two sets of virtual scenarios: one controlling for the LUCC while allowing climate factors to vary, and the other controlling for climate conditions while allowing the LUCC to vary. In the CC virtual scenario, the LUCC is held constant, allowing the impact of CC on WESs to be assessed. In contrast, in the LUCC virtual scenario, climate factors are held constant and the focus is on the impact of LUCC. By comparing the differences between the real scenarios and the respective virtual scenarios, the independent contributions of CC and LUCC were identified.

The effects of LUCC and CC on WESs changes were quantified using the following formula:

$$RL = \frac{C}{C+L} \quad (5)$$

$$RC = \frac{L}{C+L} \quad (6)$$

where  $RL$  represented the independent contribution of CC,  $RC$  denoted the independent contribution of LUCC,  $C$  was the change in WESs under the CC scenario, and  $L$  was the change in WESs under the LUCC scenario. This decomposition approach highlighted the dominant factors affecting WESs, providing insights into the key drivers of ecosystem change in the study area.

#### 2.7. Scenario analysis

This study defines 2000–2020 as the historical period based on observed data, while 2030 serves as a near-future projection commonly used in planning. Scenario analysis was employed to explore potential future developments by examining key drivers such as CC and LUCC. By developing, evaluating, and comparing scenarios that incorporated significant uncertainties, this method effectively illustrated the potential impacts of various environmental and policy drivers, helping to identify critical tipping points and guide strategic decision-making [1]. Unlike forecasting, scenario analysis provided a range of possibilities rather than specific predictions, thereby reducing uncertainty in environmental planning.

For future land use/cover change, the study developed three scenarios to simulate the land use patterns in the YREB by 2030, reflecting different policy priorities and regional development goals:

- (1) **Urban Expansion (UE) Scenario:** This scenario reflects the continuation of rapid urbanization observed from 2010 to 2020, emphasizing economic and urban growth to support the region's high-quality development.
- (2) **Cropland Protection (CP) Scenario:** Focuses on safeguarding cropland to ensure food security, aiming to slow the expansion of construction land, control the conversion of cropland to other uses, and implement protective policies.
- (3) **Ecological Protection (EP) Scenario:** Aims to maintain ecological integrity by restricting the conversion of natural landscapes for urban use. This scenario promotes forest and grassland expansion and designates nature reserves as no-conversion zones to enhance ecosystem protection and sustainability.

To account for the effects of climate change, the study incorporates three Shared Socioeconomic Pathways (SSPs):

- (1) **SSP126 (Sustainable Development Pathway):** Characterized by low emissions and strong environmental conservation efforts.
- (2) **SSP245 (Intermediate Pathway):** Represents a moderate scenario with balanced fossil fuel use and green technologies.
- (3) **SSP585 (Fossil Fuel-Based Development Pathway):** Depicts a high-emissions future driven by continued reliance on fossil fuels.

Combining the three land use scenarios with the three climate scenarios results in nine integrated future scenarios for 2030, as shown in Table 1 and Fig. 2:

### 3. Results

#### 3.1. CC and LUCC in the YERB from 2000 to 2030

##### (1) Climate change: Air Temperature and Precipitation Trends

Under the influence of global warming, the Yangtze River Economic Belt (YREB) is projected to experience increased air temperature and precipitation between 2000 and 2030, reinforcing the warm and humid climate trend (Fig. 3). From 2000 to 2020, the average annual air temperature rose from 13.77 °C to 14.47 °C, with the most significant warming observed in the eastern and southern regions (Fig. 3b). By 2030, projections under the SSP585, SSP245, and SSP126 scenarios indicate further air temperature increases of 0.75 °C, 0.68 °C, and 0.59 °C, respectively, relative to 2020, suggesting that rising greenhouse gas concentrations will continue to accelerate warming, particularly in the northwest and central YREB.

Precipitation trends parallel air temperature increases, with annual levels rising from 1171 mm in 2000 to 1249 mm in 2020, averaging an increase of 39 mm per decade (Fig. 3a). Future projections for 2030 show significant increases across all scenarios, with SSP585 predicting the highest rise (352 mm). The spatial distribution of precipitation remains highly variable, generally decreasing from southeast to northwest and showing marked shifts in precipitation centers, particularly northward expansions between 2000 and 2020 (Fig. 3a).

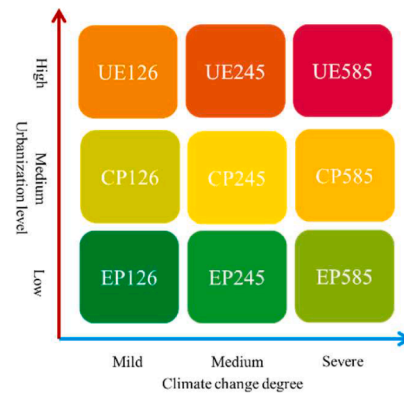
##### (2) Land use change: Patterns and Scenario-Based Projections

The YREB underwent significant LUCC between 2000 and 2030 (Fig. 4). Forests and croplands were the dominant land use types. Forests, accounting for 45.47 % to 49.56 % of the total area, were primarily located in the upper and middle reaches of the basin. Croplands, comprising 27.77 % to 30.36 %, were mainly concentrated in the Sichuan Basin and the middle and lower reaches of the Yangtze River Plain. Grasslands, representing

**Table 1**

Design and Implications of CC and LUCC Combined Scenarios.

Scenario	LUCC Scenario	CC Pathway	Key Features
UE126	Urban Expansion (UE) Scenario	SSP126 (Sustainability)	High urbanization combined with mild climate change.
UE245	Urban Expansion (UE) Scenario	SSP245 (Intermediate)	High urbanization combined with moderate climate change.
UE585	Urban Expansion (UE) Scenario	SSP585 (Fossil-fueled)	High urbanization combined with extreme climate change.
CP126	Cropland Protection (CP) Scenario	SSP126 (Sustainability)	Cropland protection combined with mild climate change.
CP245	Cropland Protection (CP) Scenario	SSP245 (Intermediate)	Cropland protection combined with moderate climate change.
CP585	Cropland Protection (CP) Scenario	SSP585 (Fossil-fueled)	Cropland protection combined with extreme climate change.
EP126	Ecological Protection (EP) Scenario	SSP126 (Sustainability)	Ecological protection combined with mild climate change.
EP245	Ecological Protection (EP) Scenario	SSP245 (Intermediate)	Ecological protection combined with moderate climate change.
EP585	Ecological Protection (EP) Scenario	SSP585 (Fossil-fueled)	Ecological protection combined with extreme climate change.



**Fig. 2.** Combined CC and LUCC scenarios for 2030.

14.65 % to 16.75 % of the area, were the third-largest land category and were predominantly distributed in upstream regions, particularly within the Qinghai-Tibet Plateau and the Yunnan-Guizhou Plateau in the northwest.

Construction land, though occupying a smaller proportion (2.34 % to 4.28 %), exhibited significant spatial variability, with rapid growth primarily concentrated in the central areas of provincial administrative regions, particularly within the middle and lower plains (Fig. 4a and c). Water bodies (2.70 % to 3.00 %) and unused land (0.98 % to 1.07 %) maintained relatively small proportions but also showed notable variability. Notably, due to accelerated urbanization in the YREB, construction land, despite its low overall proportion, experienced the highest growth rate among all land types, increasing by up to 82.72 % over the 30-year period.

Between 2000 and 2020, land use transitions in the YREB were characterized by complexity, with croplands primarily converting to forests and construction land, while forests were mainly converted to croplands and grasslands (Fig. 4b). In 2030, land use changes varied distinctly across the Ecological Protection (EP), Urban Expansion (UE), and Cropland Protection (CP) scenarios:

- **Ecological Protection (EP) Scenario:** Forests, as the dominant land type, expanded primarily through the conversion of croplands and grasslands, resulting in a 6.58 % increase. Conversely, construction land grew modestly by 0.91 %, mainly through the encroachment of a small amount of cropland and unused land. This suggests that urban expansion under the EP scenario was oriented towards intensive, compact development, significantly increasing urban ecological space and optimizing urban spatial structure.
- **Cropland Protection (CP) Scenario:** In the CP scenario, cropland protection policies were effectively implemented, leading to a substantial conversion of forests to croplands, with minimal impact on grasslands and unused land. Construction land grew steadily (2.78 %) by encroaching on forested areas, indicating an attempt to balance cropland preservation with economic development.
- **Urban Expansion (UE) Scenario:** The UE scenario continued the rapid urbanization trend, with construction land showing the highest growth rate among the three scenarios, reaching 5.42 %. Forests were the primary land type converted (90.00 %), followed by croplands (7.67 %) and grasslands (2.21 %). Water bodies remained stable across all scenarios, while grasslands slightly decreased except for a notable conversion to forests under the EP scenario. Unused land consistently declined, reflecting a general increase in land use efficiency.

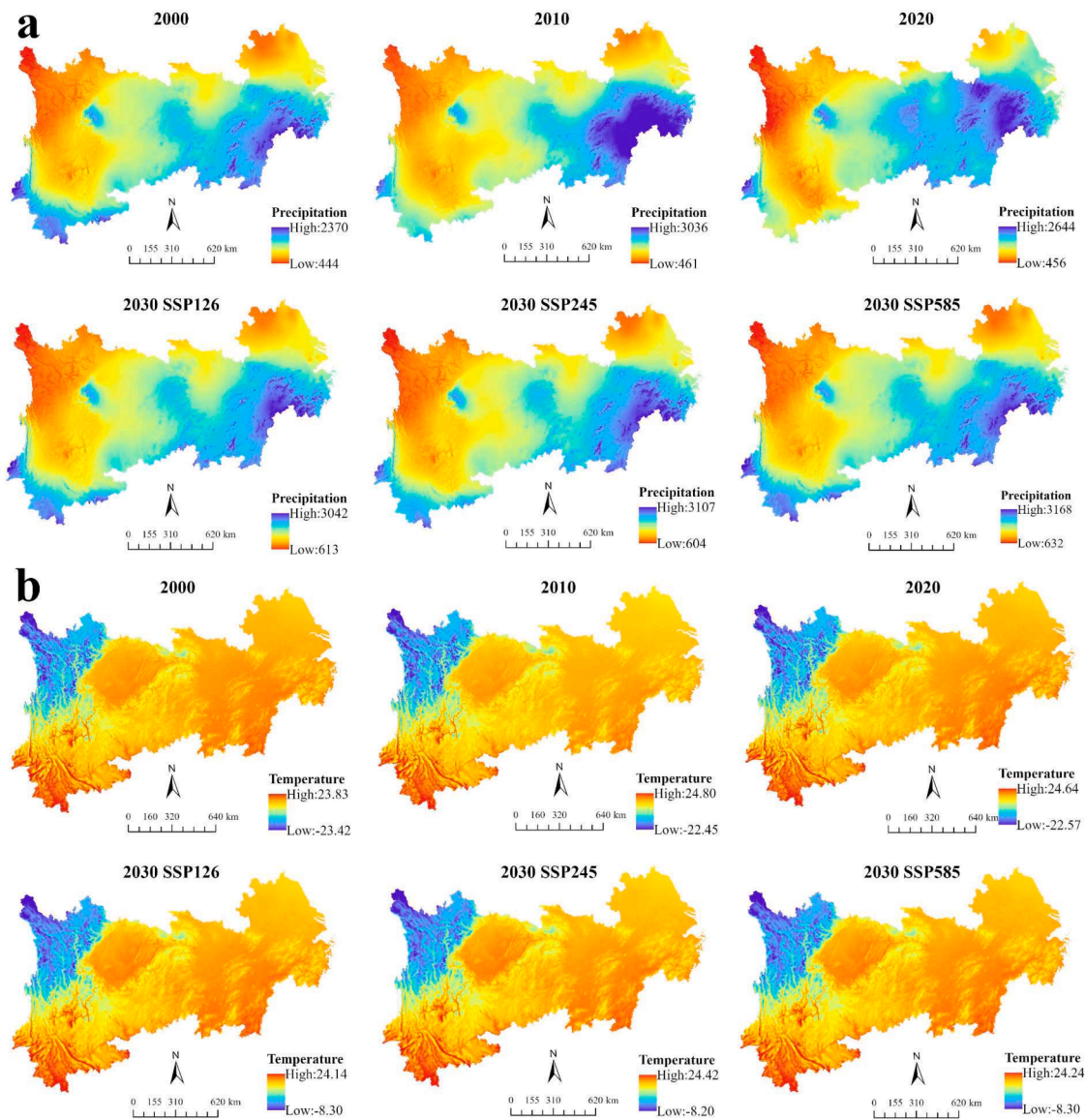


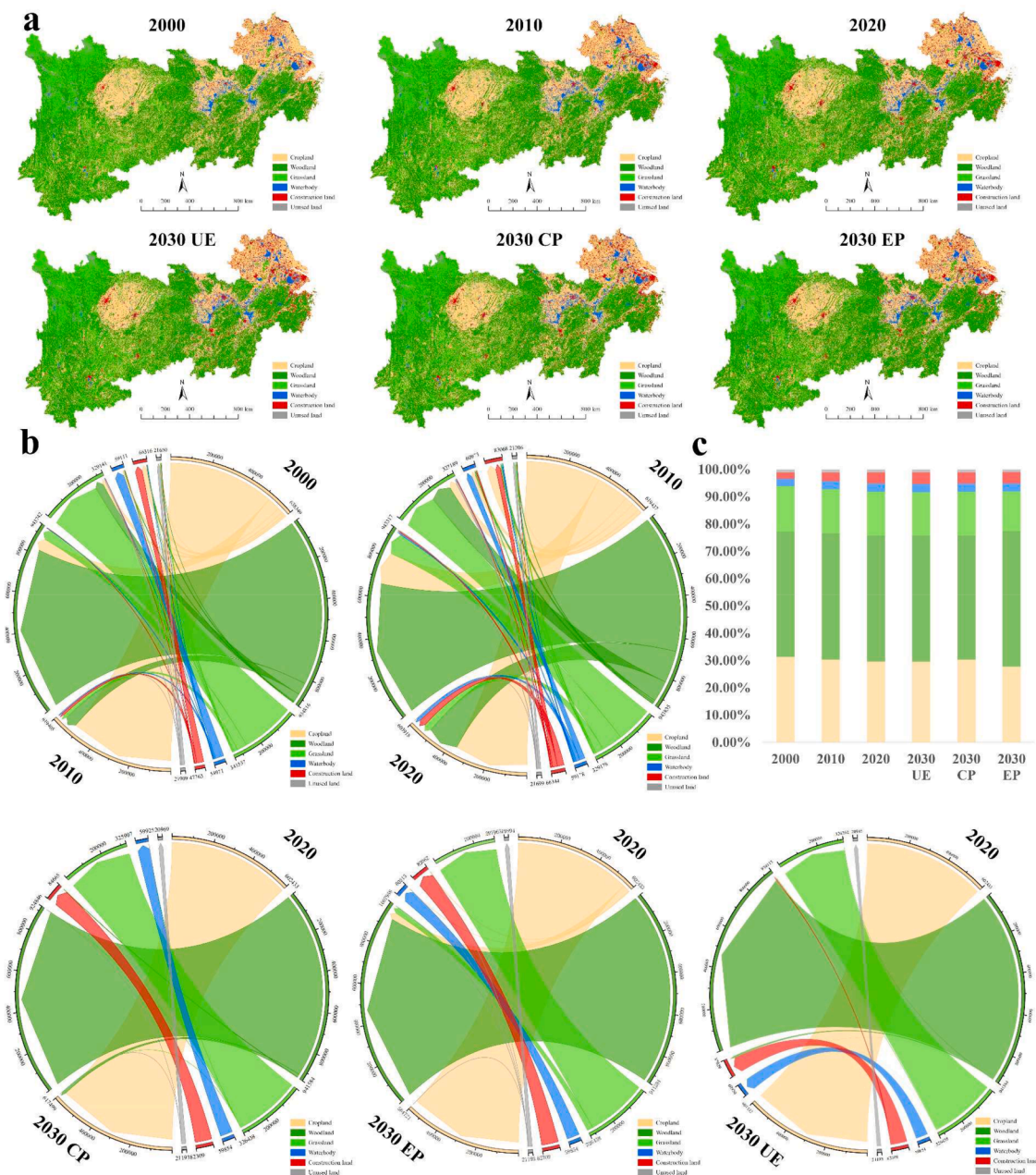
Fig. 3. Spatial distribution of precipitation (a) and air temperature (b) for different CC scenarios in 2000, 2010, 2020, and 2030.

### 3.2. Spatial and temporal changes in WESs in the YREB, 2000–2030

Between 2000 and 2030, WY in the YREB exhibited a notable increase in both total volume and spatial distribution, but the increase is greater in the upstream than in the middle than in the downstream, driven largely by changes in climate and land use (Fig. 5). The average WY increased significantly, rising from 578.40 mm in 2000 to 651.49 mm in 2020, a total increase of 73.09 mm over two decades, and the midstream and downstream showed an upward trend in fluctuations, while the upstream fluctuated down (Fig. 5b). High-yield areas expanded northward, correlating with shifting precipitation patterns (Fig. 5a). By 2030, projections indicate that WY will continue to rise under all scenarios, with the greatest increase observed under the CP585 scenario (up to 53.65 %). The highest WY values were projected under the SSP585 scenario (995.11 mm - 1001.02 mm), followed by SSP245 and SSP126. At the same time, this situation continued in the upstream, and the WY in the middle and downstream showed a pattern of SSP245>SSP585>SSP126, jointly reflecting the intensifying impact of climate change (Fig. 5b).

The capacity of different land types for water yield significantly influenced WY variations among LUCC scenarios. In 2020, construction

land exhibited the highest WY (1034.99 mm), followed by unused land, cropland, and forest, with water bodies showing the lowest values (478.79 mm). Across scenarios, WY was highest in the Urban Expansion (UE) scenario and lowest in the Ecological Protection (EP) scenario, highlighting the contrasting impacts of urban development versus conservation-focused land use, and the upstream and midstream also continue this pattern, but the downstream due to the larger proportion of construction land, resulting in the pattern of UE>CP>EP (Fig. 5b). Changes in WY are closely related to the ecological and biophysical functions of land cover types, as different land cover types are associated with different vegetation cover, which in turn regulates water loss through its effects on infiltration, surface runoff, and evapotranspiration (ET). High vegetation cover areas such as forests play a key role in stabilizing hydrological processes and regulating WY through higher ET and enhanced soil infiltration. In contrast, the high WY of construction land is mainly due to the decrease of ET and the increase of impervious surface runoff, rather than the actual water retention. However, given the abundant precipitation in the YREB, its significant influence on spatial WY variations remains dominant, and these local differences have yet to affect broader spatial patterns. The increasing divergence in WY between EP and CP scenarios under more intense climate change



**Fig. 4.** Distribution, share and transfer of different land uses, 2000–2030. Panel a: spatial distribution of land uses, Panel b: land use transfer chord, and Panel c: share of each category, 2000–2030.

reflects the critical role of natural vegetation and ecosystems in water resource management. Spatially, the distribution of WY remained consistent across climate change scenarios, with slight variations linked to LUCC (Fig. 5a).

Rapid urbanization and agricultural expansion between 2000 and 2020 led to a significant increase in regional P export, indicating a decline in the WP capacity of the YREB. And regional differences still exist, the downstream is the most significant, followed by the midstream, on the contrary, the upstream water purification services are optimized (Fig. 6). P export increased from 0.66 % between 2000 and 2010 to 1.57 % between 2010 and 2020. By 2030, all scenarios throughout the region project a reduction in P export, with the EP scenario showing the most substantial improvement due to reforestation efforts (10.31 % reduction under EP585), demonstrating the effectiveness of ecological restoration in enhancing water quality (Fig. 6b). However, WP in the upstream gets worse in UE and CP scenarios

compared to 2020.

P export was highest in croplands (98.50 kg/ha in 2020), followed by construction land and grasslands, while water bodies and forests had the lowest values, reflecting their capacity for nutrient retention. The EP scenario consistently showed the lowest P export across all projections, highlighting the benefits of reforestation, while the CP scenario, with expanded cropland, resulted in the highest P export and the lowest WP capacity. The UE scenario showed intermediate results, with urban impervious surfaces slightly reducing P export compared to cropland but still limiting overall WP capacity. Although the upstream and midstream inherited this phenomenon, the downstream UE scenario produced the worst WP capacity. Spatially, the P export of different scenario combinations presents a similar spatial pattern, and the overall P export is still lower in the upstream than in the middle and lower than in the downstream, and the plain is more than the mountain. This is primarily attributed to the higher vegetation cover in the upstream region, where

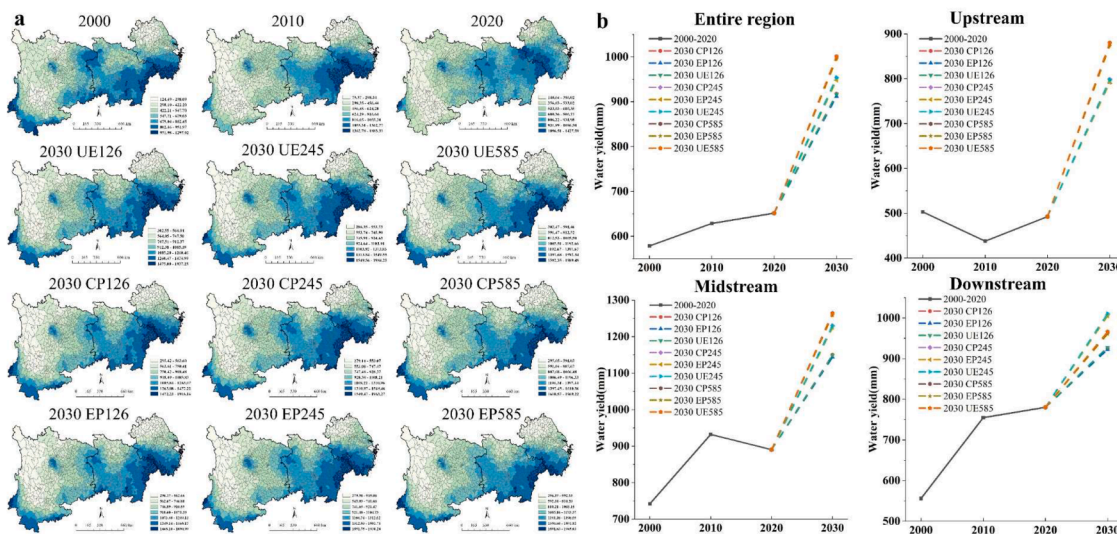


Fig. 5. Spatial and temporal changes in WY for different scenario combinations in 2000, 2010, 2020, and 2030. Panel a presents the spatial distribution of WY, Panel b depicts the regional average WY.

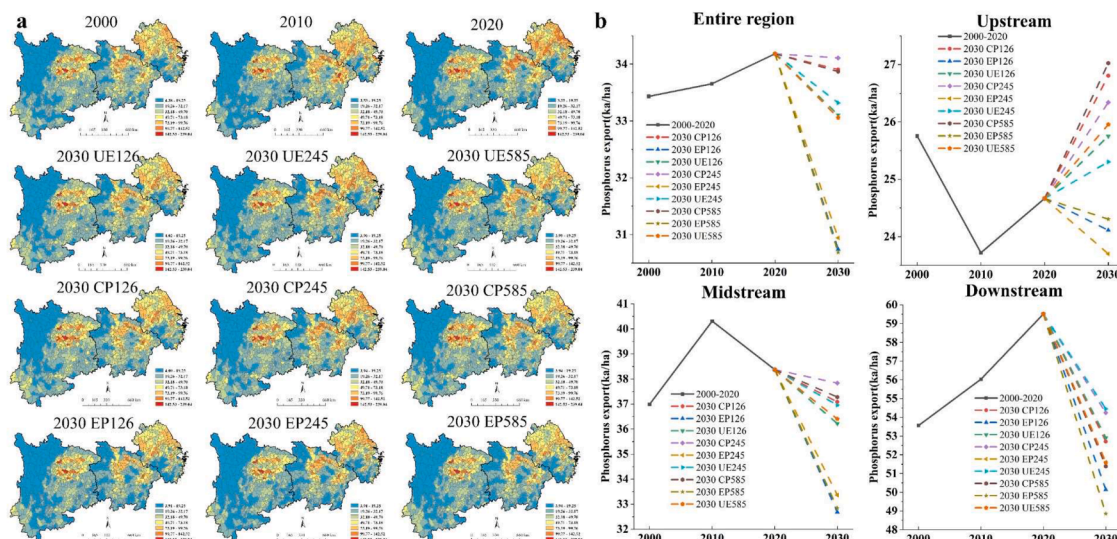


Fig. 6. Spatial and temporal changes in P export for different scenario combinations in 2000, 2010, 2020, and 2030. Panel a presents the spatial distribution of P export, Panel b illustrates the amount of P export per unit hectare.

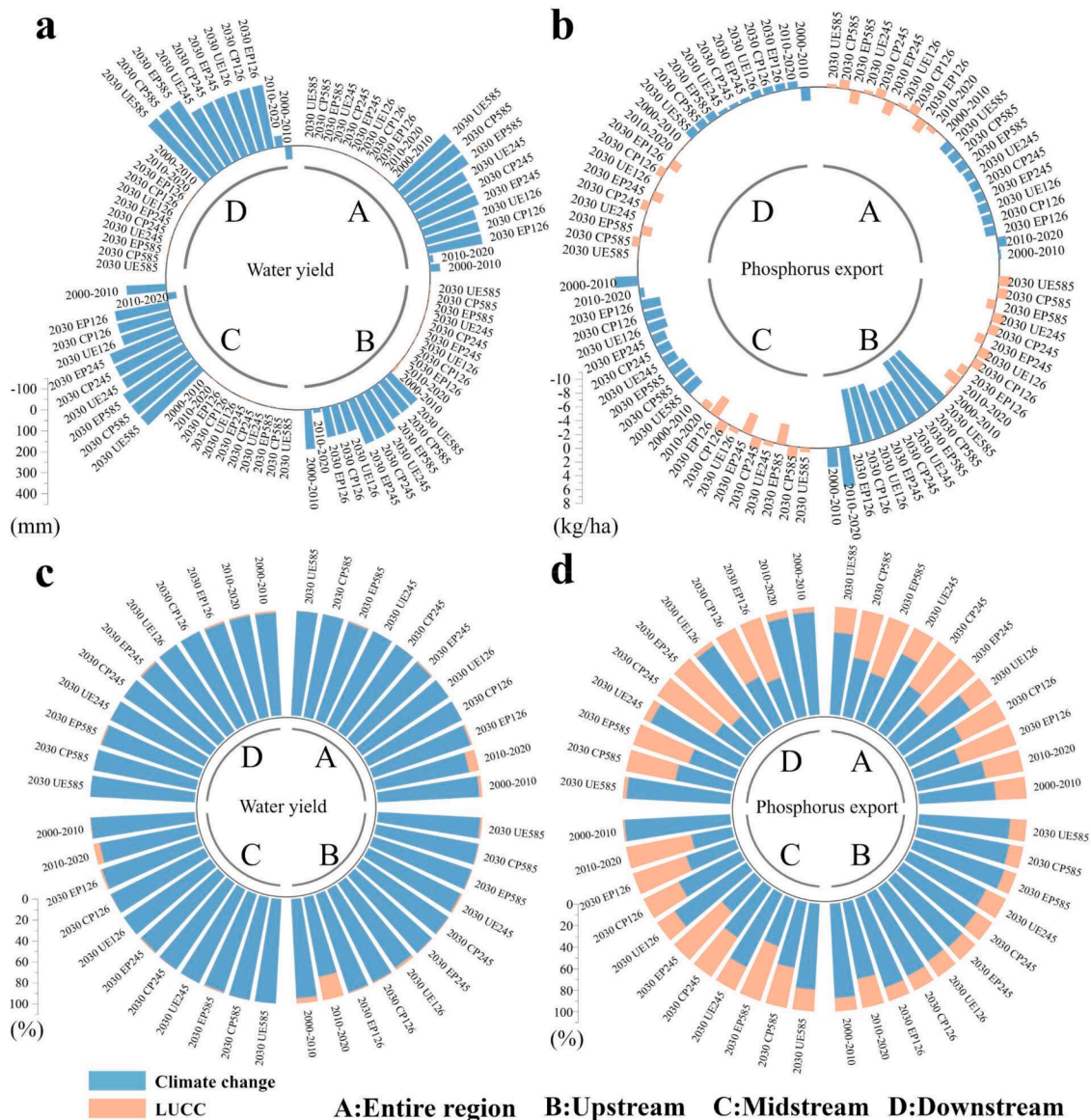
forests exhibit stronger capacities for P retention through adsorption and nutrient cycling. In contrast, croplands in the midstream and downstream areas contribute to excessive P export due to intensive fertilizer and pesticide application.

To assess the uncertainty of WESS, we calculated the coefficient of variation (CV) across historical years and future scenarios (as detailed in the Supplementary Material), following the approach outlined in previous studies [73]. During 2000–2020, the CV for WP was 9.40 %, while that for WY reached 17.88 %, indicating greater variability in WY over the past two decades. In contrast, the projected overall scenario uncertainty by 2030 was lower for both services, with CVs of 4.71 % for WY and 6.27 % for WP, suggesting relatively smaller uncertainty in future WESS projections under complex environmental changes.

### 3.3. Quantifying the independent contributions of CC and LUCC to WESS

This study reveals that both CC and LUCC significantly impact WESS in the YREB, though the magnitude and direction of these impacts vary across different services, time periods, and scenario combinations. CC

consistently exerts a dominant and positive influence on WY, primarily through increased precipitation (Fig. 7a). Between 2000 and 2020, the impact of CC on WY intensified initially and then declined, with changes ranging from 48.67 mm to 20.78 mm. By 2030, this impact is projected to increase in line with the severity of CC scenarios, following the order SSP585 (348.56 mm) > SSP245 (301.34 mm) > SSP126 (265.08 mm), the midstream and upstream maintained this trend on the whole, while the downstream showed a pattern of SSP245>SSP585>SSP126. During 2000–2020, the contribution of LUCC to WY gradually increased, from 1.44 mm to 2.22 mm. However, under future scenarios, LUCC impacts become more complex: this effect is negative in the EP scenario for both the whole region and the upstream, midstream and downstream. This is attributed to the widespread forests and grasslands under the EP scenario, which enhance water yield regulation through stronger evapotranspiration (ET) and higher soil infiltration capacity. While the CP and UE scenarios exhibit an overall positive WY, the underlying drivers differ. In the UE scenario, extensive impervious surfaces significantly increase surface runoff, while in the CP scenario, shallow-rooted crop vegetation limits water retention, similarly leading to elevated runoff.



**Fig. 7.** Independent contributions of CC and LUC to WESs from 2000–2030. Panel a and b depict the impacts of CC and LUC on average WY and P export per unit hectare, with positive values indicating positive impacts and negative values indicating negative impacts. Panel c and d illustrate the ratio of the contribution of CC and LUC to average WY and P export per unit hectare, respectively. Blue represents CC impacts, while red represents LUC impacts.

The independent contribution of CC to WY consistently remains above 90 %, with values projected to rise from 90.32 % in 2020 to as high as 98.31 % - 99.87 % by 2030 (Fig. 7c). In contrast, LUC contributions are generally lower and decrease as CC intensifies, following the order EP (1.29 % - 1.69 %) > CP (0.24 % - 0.32 %) > UE (0.13 % - 0.17 %).

The impact of CC on WP follows a different pattern, with CC no longer exerting dominant control. From 2000 to 2020, the impact of CC on WP increased from 0.34 kg/ha to 1.31 kg/ha, while LUC shifted from -0.14 kg/ha to -0.73 kg/ha, indicating that CC has accelerated WP degradation while LUC has contributed to improvements, the downstream inherited this pattern, while the upstream and midstream only maintained the same negative impact on LUC (Fig. 7b). Over the 20-year period, the total impact of CC on WP remained higher than that of LUC, but projections indicate that CC’s impact will become increasingly negative, suggesting that a warming and humidifying climate may enhance regional WP. This enhancement effect varies across CC scenarios, following the order SSP585 (-1.58 kg/ha) > SSP126 (-1.54 kg/ha) > SSP245 (-1.34 kg/ha), the midstream and downstream have maintained a consistent trend, while the impact of CC

in the upstream is positive, highlighting the complex interaction between CC and WP. Under future LUC scenarios, the EP scenario exhibits the strongest potential to optimize WP (-1.90 kg/ha), while the CP (1.29 kg/ha) and UE (0.50 kg/ha) scenarios are expected to worsen WP, this also maintains a high degree of consistency in the upstream, midstream and downstream.

In terms of impact degree, from 2000 to 2020, the influence of CC on WP weakened from 71.29 % to 64.20 %, while the influence of LUC increased from 28.71 % to 35.80 % (Fig. 7d). Under future scenarios, the degree of CC’s impact on WP follows the order SSP585 (45.48 % - 76.17 %) > SSP126 (44.74 % - 75.62 %) > SSP245 (41.33 % - 72.97 %), with this pattern persisting even when considering LUC scenarios, and this situation is consistent in the upstream and downstream, and the midstream shows a pattern of SSP126>SSP585>SSP245. The influence of LUC on WP is most significant in the downstream, and LUC’s impact on WP is highest under the EP scenario (54.52 % - 58.67 %), followed by CP (44.93 % - 49.14 %) and UE (23.83 % - 27.03 %), the upstream, midstream and downstream are also consistent. Notably, this enhancement effect becomes more complex when accounting for CC,

with the highest impact degree observed under SSP245, followed by SSP126 and SSP585.

### 3.4. Trade-offs and synergies in WESs across scales and scenarios

The correlation analysis indicates that the WESs in the YREB generally exhibit a strong trade-offs relationship (Fig. 8). From 2000 to 2020, the intensity of trade-offs across the region has progressively increased, with the lowest intensity observed in the upstream areas and the highest in the midstream. However, projections for 2020 to 2030 suggest that trade-offs intensity will be lowest in the upstream and highest in the downstream. Under different CC scenarios, the regional trade-offs intensity follows the pattern of SSP126 > SSP585 > SSP245. While this pattern is largely consistent in the downstream region, the midstream and upstream regions exhibit the highest trade-offs intensity under the SSP245 scenario. Across different LUCS scenarios, the EP scenario demonstrates the weakest trade-offs intensity throughout the basin. The UE scenario generally performs slightly better than the CP scenario, with consistent trends observed in the upstream and midstream regions. Notably, in the downstream region, the UE scenario exhibits the lowest trade-offs intensity, indicating optimization of the relationships between WESs in this scenario.

The spatial trade-offs analysis reveals that from 2000 to 2020, most of the YREB was dominated by trade-offs, although the area of synergies gradually expanded across the entire region, particularly in the upstream and midstream, while contracting in the downstream (Fig. 9). Spatially, synergy areas were relatively fragmented, forming strip-like patterns mainly along the edges of the Sichuan Basin, the western mountainous areas, and the central parts of the midstream region (Fig. 9a). Between 2020 and 2030, the synergy areas are projected to increase significantly, ranging from 35.65% to 71.09% across the entire region. Under different climate scenarios, the synergy area follows the pattern SSP245 > SSP585 > SSP126, with the midstream and downstream largely maintaining this pattern, whereas the upstream follows the pattern of SSP245 > SSP126 > SSP585. Across different LUCS scenarios, the EP scenario demonstrates the highest synergy area, while the CP scenario shows the lowest, with the UE scenario falling in between. This consistency across the upstream, midstream, and downstream regions highlights the effectiveness of ecological protection policies in optimizing WESs synergies (Fig. 9b). Spatially, synergy areas are predominantly distributed in strip-like patterns in the central parts of the YREB, while trade-offs areas are primarily located along peripheral regions. Under the EP scenario, synergy areas tend to be more concentrated and continuous, whereas under the CP scenario, they are more

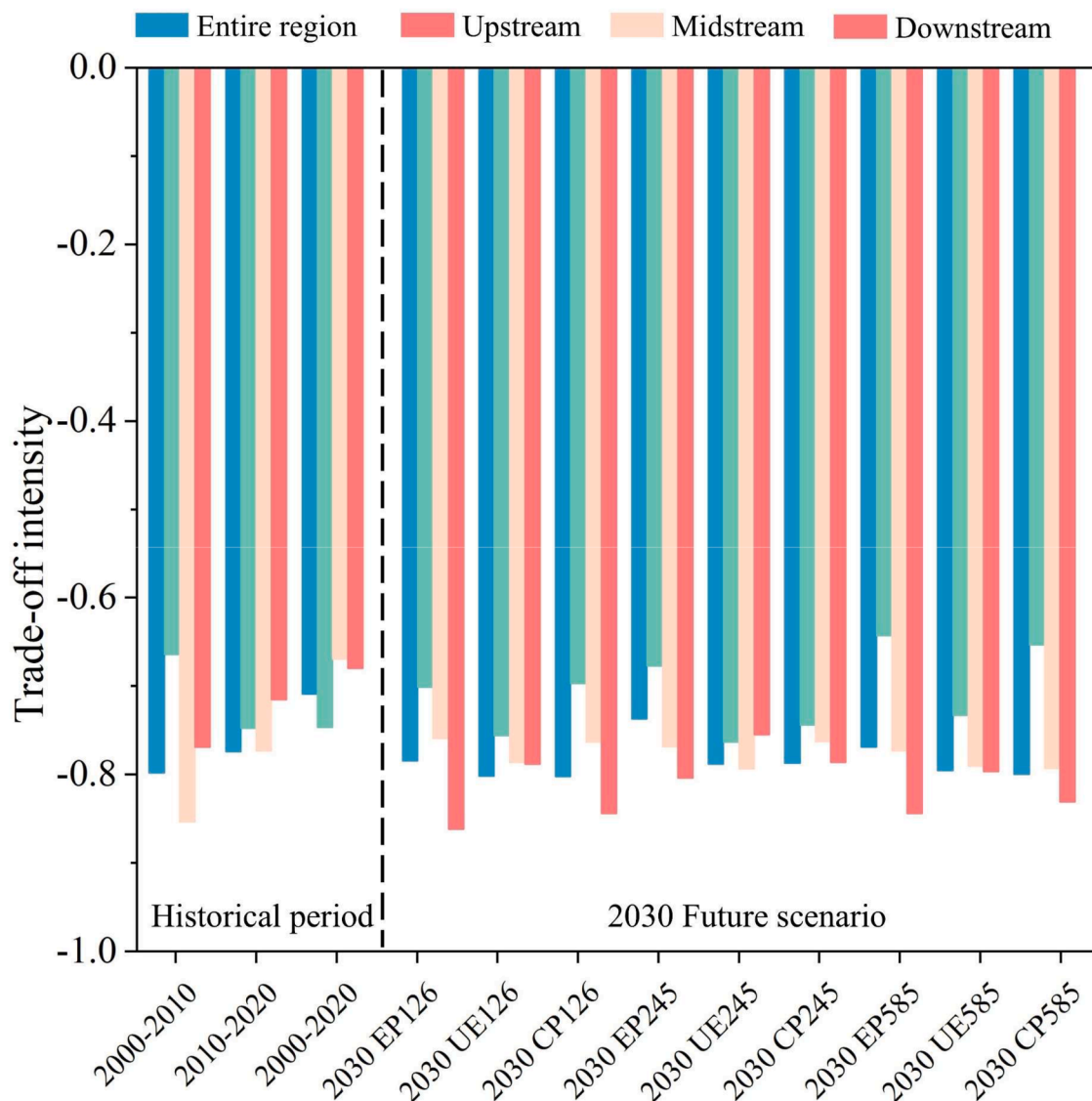
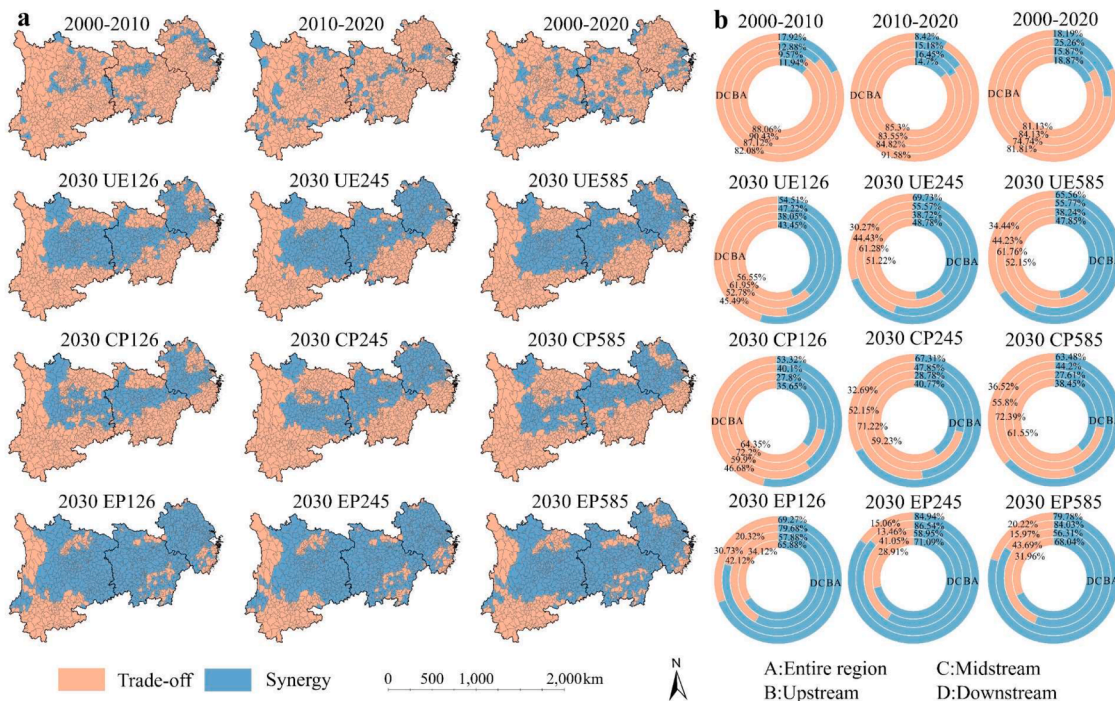


Fig. 8. Overall correlation of WESs for different combinations of scenarios in 2000, 2010, 2020 and 2030 (All results passed the significance test with  $p < 0.001$ ).



**Fig. 9. Spatial trade-offs of WESs at the county scale for different scenario combinations in 2000, 2010, 2020, and 2030.** Panel a represents the spatial distribution of trade-offs and synergies, while Panel b refers to the proportion of the area occupied by trade-offs and synergies.

fragmented and dispersed, with the UE scenario falling in between. Notably, under the same LUC scenario, the spatial distribution of trade-offs and synergies exhibits a high degree of similarity.

#### 4. Discussion

##### 4.1. Impacts of LUC and CC on WESs

LUC and CC are the primary drivers of changes in WESs, with CC significantly influencing hydrological processes that shape WESs patterns. This study confirms that CC has a predominant impact on WY in large regions such as the YREB, contributing up to 99.87 % of the observed changes under the UE585 scenario, consistent with findings from previous studies [31,59,86]. In the nine combined scenarios for 2030, WY increases under all CC scenarios with a pattern of SSP585 > SSP245 > SSP126. This trend aligns with the broader scientific consensus on future warming and increased precipitation in the YREB [66], though it contrasts with some studies reporting variable WY responses due to differing study areas, climate models, and time periods [19,40]. The significant rise in precipitation observed during this period reinforces previous findings of a strong positive correlation between precipitation and WY [80].

In contrast, CC exerts a more limited influence on WP compared to WY. Projections for 2030 indicate varying reductions in phosphorus (P) export across scenarios, following the order SSP585 > SSP126 > SSP245. This suggests that intense CC (SSP585), characterized by increased precipitation, enhances regional WP—a result consistent with findings from the Jianghuai Eco-Economic Zone in China [19]. However, moderate CC scenarios (SSP245) result in the highest P export, slightly exceeding SSP126, indicating that warmer and wetter conditions can optimize WP by accelerating P export and reducing surface accumulation of phosphorus. Notably, this effect is subject to a threshold, where initial increases in P export due to rising precipitation, eventually lead to reductions [72]. The regional differences in the response of WESs to climate impacts should not be overlooked. Under the SSP245 scenario, the midstream and downstream regions exhibit the

highest WY, primarily due to spatial variations in precipitation. In contrast, the upstream region demonstrates better WP capacity under the SSP585 scenario, which can be attributed to a significant increase in precipitation and accelerated runoff. Additionally, the filtration and interception effects of abundant vegetation in the upstream area contribute to maintaining effective freshwater services. Temperature influences WES through relatively indirect and complex mechanisms. In the subtropical humid region of the YREB, rising temperatures increase evapotranspiration, leading to a reduction in WY [3]. Additionally, higher temperatures also intensify the hydrological cycle and enhance the spatiotemporal variability of precipitation [2], thereby indirectly affecting WY reliability. Regarding WP services, elevated temperatures can exacerbate extreme rainfall events [54], which in turn increases surface runoff and P loss, particularly from agricultural lands, thereby aggravating non-point source pollution [37].

In the YREB, LUC is deeply influenced by urbanization, human activities, and regional development policies, which have drastically altered the structure and function of ecosystem services [61]. This study shows that LUC affects WY much less than CC, accounting for <10 % of the observed changes. LUC affects WY primarily by altering hydrologic processes such as evapotranspiration, infiltration, and soil moisture dynamics [31]. Different types of land have different WY capacities, with construction land usually having the largest WY capacities because impervious ground increases runoff. Between 2000 and 2020, rapid urbanization leads to significant expansion of built-up land, which increases impervious surfaces and reduces infiltration, resulting in a 3.66 mm increase in average WY [31].

Future LUC scenarios show different impacts based on policy priorities. In the EP scenario, the lower WY is due to the expansion of forest cover, which has higher water interception and water demand [7]. In contrast, the UE scenario characterized by rapid urbanization has the highest WY due to extensive built-up land, which increases runoff. The CP scenario, which is dominated by conservation of cropland, shows the highest percentage of cropland (30.36 %) and moderate WY due to limited water absorption capacity of shallow rooted crops [71].

The impact of LUC on WY shows a threshold effect, with the

maximum change of  $-4.56$  mm in the CP scenario and the minimum impact in the scenarios with a significant increase in precipitation (e.g., UE585). Previous studies conducted in arid regions such as the Yarkant River Basin emphasized that LUCC is the main driver of WY [75]. In contrast, the impact of CC is greater in humid regions (e.g., YREB). This emphasizes that the relative contributions of LUCC and CC depend on regional climatic conditions and their interactions. It is worth noting that the impact of LUCC is more pronounced in WP than WY, and tends to outweigh the impact of CC in future EP scenarios, which is consistent with previous studies [4,27]. The spatial variability of P export is shaped by topography and human activities, with croplands exhibiting the highest P export due to intensive fertilizer application and flat terrain conducive to nutrient accumulation [78]. In contrast, woodlands help reduce P export by slowing runoff and capturing pollutants [13]. Therefore, the EP scenario showed the strongest environmental sustainability, which further supports the conclusion that increasing vegetation cover can significantly improve sustainability [24]. However, in the UE scenario, the growth of highly impervious areas downstream resulted in the largest P export, suggesting that WESs are limited by the regional land base.

#### 4.2. Impacts of trade-offs and synergies between LUCC and CC on WESs

This study confirms that both LUCC and CC can have significant impacts on the supply and spatial and temporal distribution of WESs, and that their impacts can be further complicated by interaction [22]. Among the different CC scenarios, the highest trade-offs were observed in the YREB under the SSP126 scenario, which was characterized by a significant increase in WY in absolute terms across the region, while WP remained at a moderate level. These different responses lead to the trade-offs observed in the SSP126 scenario, suggesting that the trade-offs reflect not only different directions of change in WESs, but also different rates of change [9]. Regional differences are particularly pronounced in the midstream and upstream areas under the SSP245 scenario, where trade-offs between WESs are evident. This is largely due to the abundance of WY in this scenario, along with further deterioration of WP in the upper reaches, and the lowest WP efficacy in the middle reaches. These localized trade-offs suggest that regional differences in response to CC make interactions between WESs more complex and difficult to predict [11,76]. Spatially, the YREB shows the greatest area of synergy in the SSP245 scenario, as the moderate CC enhances regional precipitation and WP capacity over a larger spatial scale. Whereas LUCC has a more consistent and clearer impact on trade-offs [83]. The EP scenario shows the lowest degree of trade-offs between all types of land scenarios, regulates WY, optimizes WP, and reflects the effects of ecological protection measures such as afforestation and returning farmland to forests. In contrast, the UE scenario in the downstream region exhibits fewer trade-offs, likely due to the concentrated nature of urban expansion, which, unlike agricultural expansion, minimizes extensive disruptions to ecosystem connectivity, thereby reducing trade-offs effects. Spatially, the EP scenario fosters synergies among WESs by limiting development, resulting in concentrated and continuous synergy areas. Conversely, under the CP scenario, agricultural expansion fragments ecosystem connectivity, intensifying trade-offs between WP and WY and producing fragmented and dispersed areas of synergy. This highlights the differential impacts of land-use patterns on spatial trade-offs and underscores the importance of ecological protection [74], which can guide the development of land-use and ecological management policies that account for regional differences. These complex interactions emphasize the importance of integrating CC and LUCC considerations into regional water management strategies to address the challenges facing WESs [75].

In summary, this study reveals that CC and LUCC exert complex, regionally diverse impacts on trade-offs and synergies among WESs, with distinct regional patterns. Future research should further investigate these mechanisms, focusing on the cumulative effects of CC and

LUCC over extended time scales. These findings have practical implications for developing targeted water resource management strategies, particularly in the face of CC and urbanization pressures [32].

#### 4.3. Challenges, prospects, and limitations

Future CC and LUCC are expected to have significant impacts on WESs, creating significant risks and challenges for their management. The complex interactions between these drivers, coupled with the uncertainty of global change scenarios, complicate accurate projections of WESs. For example, under different CC scenarios, WY may increase or decrease even with global warming, posing significant challenges for future water management [40,72]. Similarly, WP is affected by regional differences, scenario combinations, and the dynamic interplay of CC and LUCC [75]. These interactions complicate the understanding of trade-offs and synergies between WESs, especially at smaller scales such as the county level. Additionally, while CC primarily affects WY, the differences in how different regional WP are affected by CC and LUCC under different future scenarios remain unpredictable, further complicating management of WESs. Similarly, the inherent uncertainties in ecological modeling further exacerbate these challenges.

Despite these uncertainties, exploring the impacts of CC and LUCC on WESs remains critical. Scenario analysis can provide valuable insights into potential future pathways and help decision makers to understand the sources of uncertainty and their implications for policy and management [15]. By comparing various CC and LUCC scenarios, adaptive management strategies can be developed to unexpected unforeseen impacts and guide management practices.

CC is a global phenomenon with largely irreversible impacts, whereas LUCC driven by human activities and policies are more controllable. Our screening of scenarios suggests that EP scenarios can provide the greatest overall benefits to WESs, suggesting that sustainable land use policies tailored to local conditions can significantly improve regional water resources and environmental quality. These policies can also mitigate the effects of CC; for example, restoring and protecting upstream ecosystems such as forests and wetlands not only enhance and regulate WESs like WY and WP but also contribute to carbon sequestration, thereby offering co-benefits for climate mitigation [50]. We further recommend promoting sustainable land management practices, including controlled grazing and reduced fertilizer use, to minimize nutrient runoff and improve WP in regions impacted by elevated P loads. Additionally, we stress the importance of cross-regional cooperation through mechanisms such as payments for ecosystem services, to incentivize upstream communities to adopt conservation practices, that benefit the entire watershed [14].

Location-specific sustainable land use management involves proactive policies that balance multiple objectives, mitigating CC impacts or leveraging beneficial opportunities. For example, policies that protect arable land for food security must be balanced with efforts to improve regional WP [55]. In the midstream where arable land is widespread, sustainable farmland management that reduces chemical inputs in areas with deteriorating WP can help achieve environmental goals while maintaining agricultural productivity [64]. This study demonstrates that afforestation-led ecological protection enhances regional WESs, fostering synergies between them. Greening measures in rural, forested, and urbanized areas can optimize WESs and should be adapted to regional needs; for instance, thinning forests can increase WY and improve economic returns [52].

In the downstream of extensive urban areas, future urbanization will likely degrade WESs; however, urban green infrastructure offers a means to mitigate these effects [77]. Incorporating vegetation and optimizing urban ecological networks can enhance pollutant retention and mitigate flooding caused by excessive WY, improving water retention and flood prevention services [10]. Meanwhile, the integration of regional ecological networks and cross-regional water management measures can stabilize synergies while enhancing water resource regulation,

allocation, and use. Given future climate projections of increased precipitation, engineering measures will be essential for maintaining sustainable land management impacts on WESs.

Despite the strengths of this study, limitations remain. The differences in projected WY across future scenarios are influenced primarily by precipitation patterns, and uncertainties in climate models necessitate cautious interpretation of these results [79]. Although the trend towards a warmer and wetter climate is widely acknowledged [16,41], the potential for dry years remains significant [47], underscoring the need for comparative studies using multiple climate models. Our analysis relies on annual average precipitation, overlooking seasonal dynamics and ecosystem responses, which limits the applicability of our WESs evaluation. Furthermore, our focus on the supply side of WY and WP neglects demand factors, such as spatial and temporal water resource needs and WP impacts under different scenarios of population growth, industrial development, and afforestation. Finally, we acknowledge that while this study has focused on the independent contributions of LUCC and CC to WESs, their interactive and combined effects remain unexplored. Considering the potential coupling and feedbacks between LUCC and CC, examining their integrated impacts is crucial for a more comprehensive understanding of WESs' responses to environmental changes. This represents an important avenue for future research.

## 5. Conclusions

This study assessed the impacts of LUCC and CC on WESs in the YREB from 2000 to 2020, with projections for 2030 using the InVEST model and dynamic trade-off analysis. Results show that CC, especially increased precipitation significantly influenced WESs, with CC having a stronger impact on WY than LUCC, particularly under high-intensity CC scenarios. In contrast, WP declined due to urban expansion and agricultural activities.

Projections for 2030 reveal distinct regional variations across scenarios. WY is expected to increase most under CP585 (up to 53.65 %), particularly in upstream areas. Among LUCC scenarios, WY is highest in the order CP > UE > EP, with UE maximizing WY downstream. WP is generally improved but may decline upstream in the UE and CP scenarios. WP shows a non-linear response to CC, with SSP585 having the highest capacity and SSP245 underperforming downstream. The EP585 scenario optimizes WP (up to 10.31 %), following the order EP > UE > CP, though WP under UE performs worst downstream.

CC's impact on WY is primarily positive (over 90 %), while LUCC substantially affects WP, especially in downstream. The EP scenario reduces P export and enhances WP downstream. Trade-offs are highest under SSP126 across the YREB, with the middle and upper reaches showing peak intensity under SSP245. Among LUCC scenarios, EP minimizes trade-offs, particularly downstream. Future trade-off areas may expand to 35.65 %–71.09 %, with SSP245 showing the most synergies and EP the highest overall.

Policy recommendations emphasize regional strategies: enhancing ecological protection upstream, promoting sustainable agriculture in the middle reaches, and prioritizing green infrastructure and ecological networks downstream. Integrated engineering solutions are recommended to optimize water resource management. Future WESs management should incorporate scenario planning and localized ecomanagement to address CC and LUCC uncertainties, optimizing WESs across regions.

## CRedit authorship contribution statement

**Pengguang Shan:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Yuan Wang:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Bowei Wu:** Writing – review & editing, Validation. **Hanlu Chen:** Writing – review & editing.

**Qing Zhang:** Writing – review & editing. **Linxuan Yang:** Writing – review & editing. **Yixuan Jiang:** Writing – review & editing. **Zhanfeng Dong:** Project administration, Funding acquisition.

## 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.

## Acknowledgments

This work was financially supported by grants from the Key Projects of the Natural Science Foundation of Fujian Province in China (No. 2021J02030), the Social Science Foundation of Fujian Province in China (No. FJ2021B042) and the National Social Science Foundation major project (No. 20 & ZD092).

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.sfr.2025.100854](https://doi.org/10.1016/j.sfr.2025.100854).

## Data availability

Data will be made available on request.

## References

- [1] M. Amer, T.U. Daim, A. Jetter, A review of scenario planning, *Futures*. 46 (2013) 23–40, <https://doi.org/10.1016/j.futures.2012.10.003>.
- [2] O.O. Ayantobo, J. Wei, Quantifying Climate-Induced Changes in the Tibetan Plateau's Hydrologic Cycle Through Atmospheric Moisture Depletion and Restoration Times, *Water Resour Res* (2025) 61, <https://doi.org/10.1029/2024wr037644>.
- [3] H. Bai, Y. Zhong, N. Ma, D. Kong, Y. Mao, W. Feng, Y. Wu, M. Zhong, Changes and drivers of long-term land evapotranspiration in the Yangtze River Basin: a water balance perspective, *J Hydrol* 653 (2025), <https://doi.org/10.1016/j.jhydrol.2025.132763>.
- [4] Y. Bai, T.O. Ochuodho, J. Yang, Impact of land use and climate change on water-related ecosystem services in Kentucky, USA, *Ecol. Indic.* 102 (2019) 51–64, <https://doi.org/10.1016/j.ecolind.2019.01.079>.
- [5] J. Balist, B. Malekmohammadi, H.R. Jafari, A. Nohegar, D. Geneletti, Detecting land use and climate impacts on water yield ecosystem service in arid and semi-arid areas. A study in Sirvan River Basin-Iran, *Appl. Water Sci.* 12 (2022), <https://doi.org/10.1007/s13201-021-01545-8>.
- [6] Y. Bi, L. Zheng, Y. Wang, J. Li, H. Yang, B. Zhang, Coupling relationship between urbanization and water-related ecosystem services in China's Yangtze River economic Belt and its socio-ecological driving forces: a county-level perspective, *Ecol. Indic.* 146 (2023), <https://doi.org/10.1016/j.ecolind.2023.109871>.
- [7] G.B.S. Bispo, R.F. Santos, M.L.M. Pompeo, S.F.B. Ferraz, C.B. Rodrigues, B. M. Brentan, The effects of natural forest and eucalyptus plantations on seven water-related ecosystem services in Cerrado landscapes, *Perspect. Ecol. Conserv.* 21 (2023) 41–51, <https://doi.org/10.1016/j.pecon.2023.01.001>.
- [8] M.E. Borsuk, G. Mavrommati, N.R. Samal, S. Zuidema, W. Wollheim, S.H. Rogers, A.M. Thorn, D. Lutz, M. Mineau, C. Grimm, C.P. Wake, R. Howarth, K. Gardner, Deliberative multiattribute valuation of ecosystem services across a range of regional land-use, socioeconomic, and climate scenarios for the upper Merrimack River watershed, New Hampshire, USA, *Ecol. Soc.* 24 (2019), <https://doi.org/10.5751/es-10806-240211>.
- [9] J.B. Bradford, A.W. D'Amato, Recognizing trade-offs in multi-objective land management, *Front Ecol Env.* 10 (2012) 210–216, <https://doi.org/10.1890/110031>.
- [10] Y. Cao, Z. Zhou, Q. Liao, S. Shen, W. Wang, P. Xiao, J. Liao, Effects of landscape conservation on the ecohydrological and water quality functions and services and their driving factors, *Sci. Total Environ.* 861 (2023), <https://doi.org/10.1016/j.scitotenv.2022.160695>.
- [11] J. Chen, Y. Wang, J. Sun, E. Liang, M. Shen, B. Yang, X. Jia, J. Zhang, Precipitation dominants synergies and trade-offs among ecosystem services across the Qinghai-Tibet Plateau, *Glob. Ecol. Conserv.* 32 (2021), <https://doi.org/10.1016/j.gecco.2021.e01886>.
- [12] S. Chen, Z. Tan, S. Mu, J. Wang, Y. Chen, X. He, Synergy level of pollution and carbon reduction in the Yangtze River Economic Belt: spatial-temporal evolution characteristics and driving factors, *Sustain. Cities Soc.* 98 (2023), <https://doi.org/10.1016/j.scs.2023.104859>.

- [13] R.A. Chisholm, Trade-offs between ecosystem services: water and carbon in a biodiversity hotspot, *Ecol. Econ.* 69 (2010) 1973–1987, <https://doi.org/10.1016/j.ecolecon.2010.05.013>.
- [14] G.C. de Mendonca, M.T.V.N. Abdo, L.M. da Costa, R.C.A. Costa, F.A.L. Pacheco, M. C. Ribeiro, M.J.B. Zakia, L.D.S. Borma, T.C.T. Pissarra, Watershed's spatial targeting: enhancing payments for ecosystem services to scale up agroecosystem restoration through nature-based solutions, *Ecosyst. Serv.* 71 (2025), <https://doi.org/10.1016/j.ecoser.2024.101679>.
- [15] B. Enserink, J.H. Kwakkel, S. Veenman, Coping with uncertainty in climate policy making: (Mis)understanding scenario studies, *Futures.* 53 (2013) 1–12, <https://doi.org/10.1016/j.futures.2013.09.006>.
- [16] X. Fan, C. Miao, Q. Duan, C. Shen, Y. Wu, Future climate change hotspots under different 21st century warming scenarios, *Earths. Future* 9 (2021), <https://doi.org/10.1029/2021ef002027>.
- [17] J. Gao, F. Li, H. Gao, C. Zhou, X. Zhang, The impact of land-use change on water-related ecosystem services: a study of the Guishui River Basin, Beijing, China, *J. Clean. Prod.* 163 (2017) S148–S155, <https://doi.org/10.1016/j.jclepro.2016.01.049>.
- [18] M. Gou, L. Li, S. Ouyang, N. Wang, L. La, C. Liu, W. Xiao, Identifying and analyzing ecosystem service bundles and their socioecological drivers in the Three Gorges Reservoir Area, *J. Clean. Prod.* 307 (2021), <https://doi.org/10.1016/j.jclepro.2021.127208>.
- [19] M. Guo, S. Ma, L.-J. Wang, C. Lin, Impacts of future climate change and different management scenarios on water-related ecosystem services: a case study in the Jianghuai ecological economic zone, China, *Ecol. Indic.* 127 (2021), <https://doi.org/10.1016/j.ecolind.2021.107732>.
- [20] S. Guo, C. Wu, Y. Wang, G. Qiu, D. Zhu, Q. Niu, L. Qin, Threshold effect of ecosystem services in response to climate change, human activity and landscape pattern in the upper and middle Yellow River of China, *Ecol. Indic.* 136 (2022), <https://doi.org/10.1016/j.ecolind.2022.108603>.
- [21] Y. Guo, B. Fu, P. Xu, Y. Wang, X. Liu, Mapping regional differences in payment for ecosystem service policies to inform integrated management: case study of the Yangtze River Economic Belt, *J. Env. Manage* 278 (2021), <https://doi.org/10.1016/j.jenvman.2020.111396>.
- [22] H.-q. Han, Y. Liu, H.-j. Gao, Y.-j. Zhang, Z. Wang, X.-q. Chen, Tradeoffs and synergies between ecosystem services: a comparison of the karst and non-karst area, *J. Mt. Sci.* 17 (2020) 1221–1234, <https://doi.org/10.1007/s11629-019-5667-5>.
- [23] C. He, Z. Liu, J. Wu, X. Pan, Z. Fang, J. Li, B.A. Bryan, Future global urban water scarcity and potential solutions, *Nat. Commun.* 12 (2021), <https://doi.org/10.1038/s41467-021-25026-3>.
- [24] C. Huang, D. Zhao, Q. Liao, M. Xiao, Linking landscape dynamics to the relationship between water purification and soil retention, *Ecosyst. Serv.* 59 (2023), <https://doi.org/10.1016/j.ecoser.2022.101498>.
- [25] F. Huang, L. Zuo, J. Gao, Y. Jiang, F. Du, Y. Zhang, Exploring the driving factors of trade-offs and synergies among ecological functional zones based on ecosystem service bundles, *Ecol. Indic.* 146 (2023), <https://doi.org/10.1016/j.ecolind.2022.109827>.
- [26] H. Huang, J. Xue, X. Peng, J. Zhao, H. Sun, Y. Hu, Y. Ma, Thriving arid oasis urban agglomerations: optimizing ecosystem services pattern under future climate change scenarios using dynamic Bayesian network, *J. Env. Manage* 350 (2024), <https://doi.org/10.1016/j.jenvman.2023.119612>.
- [27] P. Hung Vuong, A. Sperotto, S. Torresan, V. Acuna, D. Jorda-Capdevila, G. Rianna, A. Marcomini, A. Critto, Coupling scenarios of climate and land-use change with assessments of potential ecosystem services at the river basin scale, *Ecosyst. Serv.* 40 (2019), <https://doi.org/10.1016/j.ecoser.2019.101045>.
- [28] A. Krause, V. Haverd, B. Poulter, P. Anthoni, B. Quesada, A. Rammig, A. Arneeth, Multimodel Analysis of Future Land Use and Climate Change Impacts on Ecosystem Functioning, *Earths. Future* 7 (2019) 833–851, <https://doi.org/10.1029/2018ef001123>.
- [29] E. Krueger, P.S.C. Rao, D. Borchardt, Quantifying urban water supply security under global change, *Glob. Environ. Change-Hum. Policy Dimens.* 56 (2019) 66–74, <https://doi.org/10.1016/j.gloenvcha.2019.03.009>.
- [30] L. Kuglerova, J. Jyvasjarvi, C. Ruffing, T. Muotka, A. Jonsson, E. Andersson, J. S. Richardson, Cutting Edge: A Comparison of Contemporary Practices of Riparian Buffer Retention Around Small Streams in Canada, Finland, and Sweden, *Water Resour. Res.* 56 (2020), <https://doi.org/10.1029/2019wr026381>.
- [31] Y. Lang, W. Song, Y. Zhang, Responses of the water-yield ecosystem service to climate and land use change in Sancha River Basin, China, *Phys. Chem. Earth* 101 (2017) 102–111, <https://doi.org/10.1016/j.pce.2017.06.003>.
- [32] D. Li, S. Wu, L. Liu, Z. Liang, S. Li, Evaluating regional water security through a freshwater ecosystem service flow model: a case study in Beijing-Tianjin-Hebei region, China, *Ecol. Indic.* 81 (2017) 159–170, <https://doi.org/10.1016/j.ecolind.2017.05.034>.
- [33] Y. Li, P. Chen, Y. Niu, Y. Liang, T. Wei, Dynamics and attributions of ecosystem water yields in China from 2001 to 2020, *Ecol. Indic.* 143 (2022), <https://doi.org/10.1016/j.ecolind.2022.109373>.
- [34] X. Liang, Q. Guan, K.C. Clarke, S. Liu, B. Wang, Y. Yao, Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: a case study in Wuhan, China, *Comput. Environ. Urban Syst.* 85 (2021), <https://doi.org/10.1016/j.compenurbysys.2020.101569>.
- [35] J. Liu, X. Pei, W. Zhu, J. Jiao, Water-related ecosystem services interactions and their natural-human activity drivers: implications for ecological protection and restoration, *J. Env. Manage* 352 (2024), <https://doi.org/10.1016/j.jenvman.2024.120101>.
- [36] L. Liu, J. Wu, Scenario analysis in urban ecosystem services research: progress, prospects, and implications for urban planning and management, *Landsc Urban Plan* 224 (2022), <https://doi.org/10.1016/j.landurbplan.2022.104433>.
- [37] W. Liu, M. Li, Y. Huang, D. Makowski, Y. Su, Y. Bai, B. Schaubberger, T. Du, K. C. Abbaspour, K. Yang, H. Yang, P. Ciaia, Mitigating nitrogen losses with almost no crop yield penalty during extremely wet years, *Sci. Adv.* 10 (2024), <https://doi.org/10.1126/sciadv.ad9325>.
- [38] Z. Liu, J. Ying, C. He, D. Guan, X. Pan, Y. Dai, B. Gong, K. He, C. Lv, X. Wang, J. Lin, Y. Liu, B.A. Bryan, Scarcity and quality risks for future global urban water supply, *Landsc. Ecol.* 39 (2024), <https://doi.org/10.1007/s10980-024-01832-0>.
- [39] Y. Lu, S. Liu, B. Fu, Ecosystem service: from virtual reality to ground truth, *Env. Sci. Technol.* 46 (2012) 2492–2493, <https://doi.org/10.1021/es300475w>.
- [40] X. Ma, P. Zhang, L. Yang, Y. Qi, J. Liu, L. Liu, X. Fan, K. Hou, Assessing the relative contributions, combined effects and multiscale uncertainty of future land use and climate change on water-related ecosystem services in Southwest China using a novel integrated modelling framework, *Sustain. Cities Soc.* 106 (2024), <https://doi.org/10.1016/j.scs.2024.105400>.
- [41] M.T. McCulloch, A. Winter, C.E. Sherman, J.A. Trotter, 300 years of sclerosponge thermometry shows global warming has exceeded 1.5°C, *Nat. Clim. Change.* 14 (2024), <https://doi.org/10.1038/s41558-023-01919-7>.
- [42] H. Ojaveer, H. Einberg, M. Lehtiniemi, O. Outinen, A. Zaiko, A. Jelmert, J. Kotta, Quantifying impacts of human pressures on ecosystem services: effects of widespread non-indigenous species in the Baltic Sea, *Sci. Total Environ.* 858 (2023), <https://doi.org/10.1016/j.scitotenv.2022.159975>.
- [43] J. Peng, P. Xia, Y. Liu, Z. Xu, H. Zheng, T. Lan, S. Yu, Ecosystem services research: from golden era to next crossing, *Trans. Earth Environ. Sustain.* 1 (2023) 9–19, <https://doi.org/10.1177/2754124x231165935>.
- [44] G.D. Peterson, G.S. Cumming, S.R. Carpenter, Scenario planning: a tool for conservation in an uncertain world, *Conserv. Biol.* 17 (2003) 358–366, <https://doi.org/10.1046/j.1523-1739.2003.01491.x>.
- [45] Y. Qian, Z. Dong, Y. Yan, L. Tang, Ecological risk assessment models for simulating impacts of land use and landscape pattern on ecosystem services, *Sci. Total Environ.* 833 (2022), <https://doi.org/10.1016/j.scitotenv.2022.155218>.
- [46] J.E. Sample, I. Baber, R. Badger, A spatially distributed risk screening tool to assess climate and land use change impacts on water-related ecosystem services, *Environ. Model. Softw.* 83 (2016) 12–26, <https://doi.org/10.1016/j.envsoft.2016.05.011>.
- [47] Y. Satoh, K. Yoshimura, Y. Pokhrel, H. Kim, H. Shiogama, T. Yokohata, N. Hanasaki, Y. Wada, P. Burek, E. Byers, H.M. Schmied, D. Gerten, S. Ostberg, S. N. Gosling, J.E.S. Boulange, T. Oki, The timing of unprecedented hydrological drought under climate change, *Nat. Commun.* 13 (2022), <https://doi.org/10.1038/s41467-022-30729-2>.
- [48] F. Scherzinger, M. Schaedler, T. Reitz, R. Yin, H. Auge, I. Merbach, C. Roscher, W. S. Harpole, E. Blagodatskaya, J. Siebert, M. Ciobanu, F. Marder, N. Eisenhauer, M. Quass, Sustainable land management enhances ecological and economic multifunctionality under ambient and future climate, *Nat. Commun.* 15 (2024), <https://doi.org/10.1038/s41467-024-48830-z>.
- [49] U. Schirpke, E. Tasser, S. Borsky, M. Braun, J. Eitzinger, V. Gaube, M. Getzner, S. Glatzel, T. Gschwantner, M. Kirchner, G. Leitinger, B. Mehdi-Schulz, H. Mitter, H. Scheffinger, S. Thaler, D. Thom, T. Thaler, Past and future impacts of land-use changes on ecosystem services in Austria, *J. Env., Manage* 345 (2023), <https://doi.org/10.1016/j.jenvman.2023.118728>.
- [50] T.D. Searchinger, S. Wierseni, T. Beringer, P. Dumas, Assessing the efficiency of changes in land use for mitigating climate change, *Nature* 564 (2018) 249, <https://doi.org/10.1038/s41586-018-0757-z>.
- [51] D. Sun, Y. Liang, S. Peng, Scenario simulation of water retention services under land use/cover and climate changes: a case study of the Loess Plateau, China, *J. Arid. Land.* 14 (2022) 390–410, <https://doi.org/10.1007/s40333-022-0054-4>.
- [52] G. Sun, P.V. Caldwell, S.G. McNulty, Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States, *Hydrol. Process* 29 (2015) 5016–5030, <https://doi.org/10.1002/hyp.10469>.
- [53] L. Sun, H. Yu, M. Sun, Y. Wang, Coupled impacts of climate and land use changes on regional ecosystem services, *J. Env., Manage* 326 (2023), <https://doi.org/10.1016/j.jenvman.2022.116753>.
- [54] Y. Tang, M. Luo, S. Wu, X. Li, Increasing synchrony of extreme heat and precipitation events under climate warming, *Geophys. Res. Lett.* 52 (2025), <https://doi.org/10.1029/2024gl113021>.
- [55] D. Tilman, K.G. Cassman, P.A. Matson, R. Naylor, S. Polasky, Agricultural sustainability and intensive production practices, *Nature* 418 (2002) 671–677, <https://doi.org/10.1038/nature01014>.
- [56] D. Tu, Y. Cai, M. Liu, Coupling coordination analysis and spatiotemporal heterogeneity between ecosystem services and new-type urbanization: a case study of the Yangtze River Economic Belt in China, *Ecol. Indic.* 154 (2023), <https://doi.org/10.1016/j.ecolind.2023.110535>.
- [57] M.G. Turner, Disturbance and landscape dynamics in a changing world, *Ecology.* 91 (2010) 2833–2849, <https://doi.org/10.1890/10-0097.1>.
- [58] B. Uniyal, E. Kosatica, T. Koellner, Spatial and temporal variability of climate change impacts on ecosystem services in small agricultural catchments using the Soil and Water Assessment Tool (SWAT), *Sci. Total Environ.* 875 (2023), <https://doi.org/10.1016/j.scitotenv.2023.162520>.
- [59] H. Wang, W.J. Wang, L. Wang, S. Ma, Z. Liu, W. Zhang, Y. Zou, M. Jiang, Impacts of Future Climate and Land Use/Cover Changes on Water-Related Ecosystem Services in Changbai Mountains, Northeast China, *Front Ecol Evol* 10 (2022), <https://doi.org/10.3389/fevo.2022.854497>.
- [60] M. Wang, B.L. Bodirsky, R. Rijnveld, F. Beier, M.P. Bak, M. Batool, B. Droppers, A. Popp, M.T.H. van Vliet, M. Stokral, A triple increase in global river basins with

- water scarcity due to future pollution, *Nat Commun* 15 (2024), <https://doi.org/10.1038/s41467-024-44947-3>.
- [61] S.-r. Wang, W. Meng, X.-c. Jin, B.-h. Zheng, L. Zhang, H.-y. Xi, Ecological security problems of the major key lakes in China, *Env. Earth Sci* 74 (2015) 3825–3837, <https://doi.org/10.1007/s12665-015-4191-3>.
- [62] W.J. Wang, F.R. Thompson III, H.S. He, J.S. Fraser, W.D. Dijak, T. Jones-Farrand, Climate change and tree harvest interact to affect future tree species distribution changes, *J. Ecol.* 107 (2019) 1901–1917, <https://doi.org/10.1111/1365-2745.13144>.
- [63] Y. Wang, X. Li, Q. Zhang, J. Li, X. Zhou, Projections of future land use changes: multiple scenarios -based impacts analysis on ecosystem services for Wuhan city, China, *Ecol. Indic.* 94 (2018) 430–445, <https://doi.org/10.1016/j.ecolind.2018.06.047>.
- [64] R.A. Wittwer, S.F. Bender, K. Hartman, S. Hydbom, R.A.A. Lima, V. Loaiza, T. Nemecek, F. Oehl, P.A. Olsson, O. Petchey, U.E. Prechsl, K. Schlaeppli, T. Scholten, S. Seitz, J. Six, M.G.A. van der Heijden, Organic and conservation agriculture promote ecosystem multifunctionality, *Sci. Adv.* 7 (2021), <https://doi.org/10.1126/sciadv.abg6995>.
- [65] W. Wu, Z. Huang, Z. Huang, J. Zhang, S. Wang, M. Fang, H. Yang, H. Lu, G. Guo, W. Liu, Simulation and attribution analysis of terrestrial ecosystem carbon storage of Hainan Island from 2015 to 2050, *Sci. Total Environ.* 917 (2024), <https://doi.org/10.1016/j.scitotenv.2024.170348>.
- [66] X. Wu, L. Wang, Z. Niu, W. Jiang, Q. Cao, More extreme precipitation over the Yangtze River Basin, China: insights from historical and projected perspectives, *Atmos. Res.* 292 (2023), <https://doi.org/10.1016/j.atmosres.2023.106883>.
- [67] H. Xia, W. Kong, G. Zhou, O.J. Sun, Impacts of landscape patterns on water-related ecosystem services under natural restoration in Liaohe River Reserve, China, *Sci. Total Environ.* 792 (2021) 148290, <https://doi.org/10.1016/j.scitotenv.2021.148290>.
- [68] H. Xia, S. Yuan, A.V. Prishchepov, Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: implications for spatial planning and management, *Resour. Conserv. Recycl.* 189 (2023), <https://doi.org/10.1016/j.resconrec.2022.106767>.
- [69] J. Xiao, F. Song, F. Su, Z. Shi, S. Song, Quantifying the independent contributions of climate and land use change to ecosystem services, *Ecol. Indic.* 153 (2023), <https://doi.org/10.1016/j.ecolind.2023.110411>.
- [70] Y. Xu, Y.-G. Lu, B. Zou, M. Xu, Y.-X. Feng, Unraveling the enigma of NPP variation in Chinese vegetation ecosystems: the interplay of climate change and land use change, *Sci. Total Environ.* 912 (2024), <https://doi.org/10.1016/j.scitotenv.2023.169023>.
- [71] S. Yang, Y. Bai, J.M. Alatalo, H. Wang, B. Jiang, G. Liu, J. Chen, Spatio-temporal changes in water-related ecosystem services provision and trade-offs with food production, *J. Clean. Prod.* 286 (2021), <https://doi.org/10.1016/j.jclepro.2020.125316>.
- [72] X. Yang, R. Chen, G. Ji, C. Wang, Y. Yang, J. Xu, Assessment of Future Water Yield and Water Purification Services in Data Scarce Region of Northwest China, *Int. J. Env. Res Public Health* 18 (2021), <https://doi.org/10.3390/ijerph18178960>.
- [73] Y. Yang, X. Yuan, J. An, Q. Su, B. Chen, Drivers of ecosystem services and their trade-offs and synergies in different land use policy zones of Shaanxi Province, China, *J. Clean. Prod.* 452 (2024), <https://doi.org/10.1016/j.jclepro.2024.142077>.
- [74] Y. Yang, Z. Lu, M. Yang, Y. Yan, Y. Wei, Impact of land use changes on uncertainty in ecosystem services under different future scenarios: a case study of Zhang-Cheng area, China, *J. Clean. Prod.* 434 (2024), <https://doi.org/10.1016/j.jclepro.2023.139881>.
- [75] C. Yu, X. Huang, Q. Guo, Y. Yang, Z. Xu, Predicting water ecosystem services under prospective climate and land-use change scenarios in typical watersheds distributed across China, *Ecol. Indic.* 159 (2024), <https://doi.org/10.1016/j.ecolind.2024.111744>.
- [76] Z. Yuan, Y. Liang, H. Zhao, D. Wei, X. Wang, Trade-offs and synergies between ecosystem services on the Tibetan Plateau, *Ecol. Indic.* 158 (2024), <https://doi.org/10.1016/j.ecolind.2023.111384>.
- [77] B. Zhang, A. MacKenzie, Trade-offs and synergies in urban green infrastructure: a systematic review, *Urban For. Urban Green.* 94 (2024), <https://doi.org/10.1016/j.ufug.2024.128262>.
- [78] J. Zhang, S. Li, C. Jiang, Effects of land use on water quality in a River Basin (Daning) of the Three Gorges Reservoir Area, China: watershed versus riparian zone, *Ecol. Indic.* 113 (2020), <https://doi.org/10.1016/j.ecolind.2020.106226>.
- [79] J. Zhang, X. Shen, B. Wang, Changes in precipitation extremes in Southeastern Tibet, China, *Quat. Int.* 380 (2015) 49–59, <https://doi.org/10.1016/j.quaint.2015.02.009>.
- [80] L. Zhang, L. Cheng, F. Chiew, B. Fu, Understanding the impacts of climate and landuse change on water yield, *Curr. Opin. Env. Sustain.* 33 (2018) 167–174, <https://doi.org/10.1016/j.cosust.2018.04.017>.
- [81] X. Zhang, G. Zhang, X. Long, Q. Zhang, D. Liu, H. Wu, S. Li, Identifying the drivers of water yield ecosystem service: a case study in the Yangtze River Basin, China, *Ecol. Indic.* 132 (2021), <https://doi.org/10.1016/j.ecolind.2021.108304>.
- [82] Y. Zhang, T. Wu, C. Song, L. Hein, F. Shi, M. Han, Z. Ouyang, Influences of climate change and land use change on the interactions of ecosystem services in China's Xijiang River Basin, *Ecosyst. Serv.* 58 (2022), <https://doi.org/10.1016/j.ecoser.2022.101489>.
- [83] Y. Zhao, M. Wang, T. Lan, Z. Xu, J. Wu, Q. Liu, J. Peng, Distinguishing the effects of land use policies on ecosystem services and their trade-offs based on multi-scenario simulations, *Appl. Geogr.* 151 (2023), <https://doi.org/10.1016/j.apgeog.2022.102864>.
- [84] K. Zhou, J. Wu, H. Liu, Spatiotemporal variations and determinants of water pollutant discharge in the Yangtze River Economic Belt, China: a spatial econometric analysis, *Environ. Pollut.* 271 (2021), <https://doi.org/10.1016/j.envpol.2020.116320>.
- [85] H. Zhu, Z. Jiang, L. Li, Projection of climate extremes in China, an incremental exercise from CMIP5 to CMIP6, *Sci. Bull.* 66 (2021) 2528–2537, <https://doi.org/10.1016/j.scib.2021.07.026>.
- [86] K. Zhu, Y. Cheng, Q. Zhou, Z. Kapolnai, L.D. David, The contributions of climate and land use/cover changes to water yield services considering geographic scale, *Heliyon.* 9 (2023), <https://doi.org/10.1016/j.heliyon.2023.e20115>.