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Evaluating the spatiotemporal dynamics of ecosystem service supply-demand risk from the perspective of service flow to support regional ecosystem management: A case study of yangtze river delta urban agglomeration

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ABSTRACT

The inappropriate spatio-temporal distribution of natural capital during rapid urbanization has increased ecosystem service supply-demand (ESSD) risks, posing great challenges to the sustainable growth of human well-being, especially in urban agglomerations. Although methods focusing on the spatial match or temporal dynamics of ESSD in risk assessment have been established, a comprehensive understanding of the spatial dynamics underlying ecosystem service flows (ESF) is still missing. Due to the spatiotemporal heterogeneity of various ESSD risks within urban agglomerations, incorporating these elements into a unified spatial planning framework is still difficult. This study integrated the spatio-temporal analysis method of ESSD considering ESF and the spatial clustering method to propose an ESSD risk assessment and management framework: evaluating ES supply, demand and flow, incorporating ESF to quantify ESSD across various timeframes, assessing ESSD risks based on the current status and dynamic trends, and using Self-Organizing Map to identify optimal ESSD risk bundles (ESSDR_Bs). The results showed high ESSD risks of high temperature regulation, nitrogen purification, phosphorus purification, and food production in Yangtze River Delta urban agglomeration. While the ESSD risks of biodiversity conservation, carbon sequestration, soil retention, water yield, and tourism culture were relatively low, a concerning trend of decreasing surpluses was observed in general. In addition, six ESSDR_Bs were identified, and differentiated ecological management strategies were proposed for each bundle. This study provided a novel perspective for efficiently understanding and regulating the ESSD risks in urban agglomerations.

1. Introduction

During the past few decades, rapid urbanization worldwide has resulted in large-scale and dramatic dynamic changes in population and land use/land cover across the urban-rural gradient (Baró et al., 2017). As large-scale population and capital continue to influx into urbanized areas, the urban construction land has expanded outward, occupying a large amount of natural land cover such as forests, grasslands, and water bodies (Lyu et al., 2022). Unfortunately, this phenomenon has seriously undermined the stability of ecosystem structures and processes, and increased ecological risks such as biodiversity loss, land degradation, and climate warming (Vitousek, 1997; IPCC, 2022). Moreover, as population aggregation and socioeconomic activities become increasingly active, the dependency of the urbanized areas on ecological resources in the surrounding areas keeps increasing (Zhai et al., 2019; Zhang et al., 2021), thus aggravating the spatial heterogeneity of ecological risks in the region. However, China's urbanization process will continue to progress, urban agglomerations consisting of multiple cities will be the mainstream mode of urban development in the future (China, 2017), and the demand for ecological resources of urban agglomerations will be much stronger and more diversified (Gómez-Baggethun et al., 2013). Therefore, in order to sustainably cope with ecological risks, how to coordinate the integration of spatiotemporal dynamics in the region and the differentiation of ecological

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management in the subregion has become a key question for the high-quality development of urban agglomerations in China (Mæstad and Norheim, 2012).

Ecosystem service (ES) refers to the material and non-material benefits humans receive from ecosystems, link ecosystem structure, processes, and functioning to human well-being, and provide a systematic conceptual framework for regional sustainable ecosystem management (Millennium Ecosystem Assessment, 2005). The spatiotemporal relationship between the supply of ES (i.e., goods and services that ecosystems provide to humans) and the demand for ES (i.e., goods and services that socioeconomic systems expect or receive from ecosystems) is a key indicator for quantifying ESSD risks (Villamagna et al., 2013; Burkhard et al., 2018; La Notte et al., 2019). Currently, research on ESSD risks mainly focuses on the relationship between supply of and demand for ES in the spatial dimension, and the methods include matrices hypothesized by experts (Jiang et al., 2021), spatial cluster analysis (Xie et al., 2020), supply-demand ratio (Wu et al., 2022; Huang et al., 2023), spatial hotspot analysis (Chen et al., 2022) and supply-demand coordination (Xin et al., 2021), and so on. Most of these studies, however, only consider the static spatial matching of supply and demand. In fact, the ecosystem inevitably presents externalities in the provision of goods and services (Van Hecken and Bastiaensen, 2010), which means that ES supplied in a specific region is not necessarily consumed in situ but also flows to the surrounding areas to generate benefit due to the biophysical effects of ecosystem or human behavior, in other words, there exist certain spatial differences between the supply and consumption areas of ES. So, the ES flow (ESF) refers to the process by which ES that is not consumed in situ flows from the supply area to the demand area (Bagstad et al., 2013; Liu et al., 2016b), and it will change the actual supply of ES in different areas, thereby affecting the relationship between supply of ES and demand for ES (Villamagna et al., 2013; Kleemann et al., 2020; Liu et al., 2022). However, researchers face difficulties in considering ESF since the method to quantify ESF is still being explored (Peng et al., 2023). The popular methods that commonly used in existing ESF quantification researches, such as linear programming models (Shi et al., 2020), supply and demand assessment matrices (Burkhard et al., 2018), expert knowledge modeling methods (Locatelli et al., 2011), gravitational models (Wu et al., 2022), and spatial benefit flow indices (Serna-Chavez et al., 2014), do not take the impact of biophysical factors into account and only capture ESF between administrative units or watersheds instead of the spatial raster scale (Wang et al., 2022b), therefore making it challenging to provide accurate information for spatially fine-scale assessments of the relationship between supply of ES and demand for ES. In the current method, the service path attribute network (SPAN) is a promising approach to take the ecological processes of ESF that involve the natural and socioeconomic factors into consideration so that quantify and map the process of ES supply-flow-consumption at the raster level in space (Bagstad et al., 2013; Li et al., 2017). Although the theoretical framework of SPAN provides valuable insight for modeling ESF, the user interface of SPAN is limited to certain users. So, programming algorithms according to the biophysical characteristics of different ESFs is essential to model ESF based on SPAN, which is a technical challenge for the researcher.

It is worth noting that the relationship between supply of ES and demand for ES is not constant and could shift towards either surplus or deficit over time, and increasing ES deficits will lead to a higher likelihood of ecosystem decline and greater ecological risks (Burkhard et al., 2012; Guan et al., 2020; Wang et al., 2022a). However, previous studies about ESSD risks have mostly been limited to the mono-temporal relationships, neglecting the supply of and demand for ES changes with time. Maron (Maron et al., 2017) and Boesing (Boesing et al., 2020) proposed a theoretical framework for ESSD risk assessment based on the spatiotemporal dynamic of ESSD, which integrates the trend of ES supply, the trend of demand, the supply-demand ratio indicators and their trends, to reasonable guide the long-term sustainable development of the ecological-socio-economic system.

In addition, to make ESSD risk assessments provide practical and effective information to ecosystem management, it is crucial to identify the spatial distribution of risks and develop spatially targeted strategies accordingly (DeFries and Nagendra, 2017; Longato et al., 2021; Xia et al., 2023). However, when involving various ESs, how to synthesize the multiple ESSD risks to formulate spatial strategies has become a key challenge for ESSD risks assessment to support ecosystem management. ES bundles are sets of ESs with similar spatial distribution patterns (Raudsepp-Hearne et al., 2010), and using the clustering method to identify ES bundles is widely recognized as a spatially explicit approach for ecosystem management (Dittrich et al., 2017; Quintas-Soriano et al., 2019; Agudelo et al., 2020; Gou et al., 2021). Therefore, ESSD risks and the clustering method can be combined to identify ES supply and demand risk bundles (ESSDR_B) to develop rational and efficient spatial management strategies.

As one of the three key urban agglomerations in China, the Yangtze River Delta Urban Agglomeration (YRDUA) is China's most economically developed, populated, and urbanized region. However, since the 1990s, rapid urbanization in the YRDUA has driven rapid economic development and inevitably consumed massive ecological resources (Liang et al., 2019; Ma et al., 2019), which has seriously damaged the regional ecosystems, with frequent occurrence of ecological problems such as the loss of biodiversity, excessive greenhouse gas emissions, water shortage, water quality pollution, and soil erosion. Although YRDUA was designated as China's ecological integrated development demonstration area in 2019, the imbalance between the supply of and demand for ES in YRDUA is still worrying for the future, which has become a key factor threatening long-term sustainable development. Therefore, developing the ecosystem management strategy that facilitates the balance between supply of and demand for ES in YRDUA is not only of great significance to the local and even China's ecological-socio-economic sustainable development but also provides a scientific reference for the management of ecosystems in other urban agglomerations in China. Although many studies have assessed supply of and demand for ES in YRDUA, the spatial dynamics of ESF and the temporal dynamics of the supply-demand relationship have rarely been considered. Given this, this study aims to propose and test a framework for assessing and optimizing spatiotemporal dynamic ESSD risks for a given period from the perspective of ESFs to promote integrated and multidimensional sustainable ecological management of urban. So, three key questions need to be addressed: (1) What are the spatiotemporal dynamics of the different ESs supply, demand, and ESFs in the YRDUA from 2005 to 2020? (2) How can ES supply, demand, and ESFs be integrated over the years to construct a classification of ESSD risks with spatiotemporal dynamics in a given period? (3) How to efficiently integrate multiple results of various ESSD risks and inform urban agglomerations' ecological management?

2. Materials and methods

2.1. Study area

The YRDUA (114.56E-124.25 E, 26.57N–35.67 N), with a total area of 358,000 km^2, is located in the geographic center of East Asia and the west coast of the Pacific Ocean, which consists of three provinces in East China, namely Jiangsu, Zhejiang, and Anhui, as well as one centrally-administered municipality of Shanghai (Fig. 1). YRDUA is the key intersection region of China's "One Belt, One Road" and the Yangtze River Economic Belt (Zhang et al., 2018) and has ranked among the top six international world-class city agglomerations since 2012. The terrain of YRDUA is mainly plains and hills, including the eastern part of the plains of the middle and lower reaches of the Yangtze River and the Yangtze River estuary, with significant geographic features of well-developed rivers, making it an important ecological functional area of the country (National Development and Reform Commission, 2015–2030). YRDUA is in the subtropical monsoon climate zone,

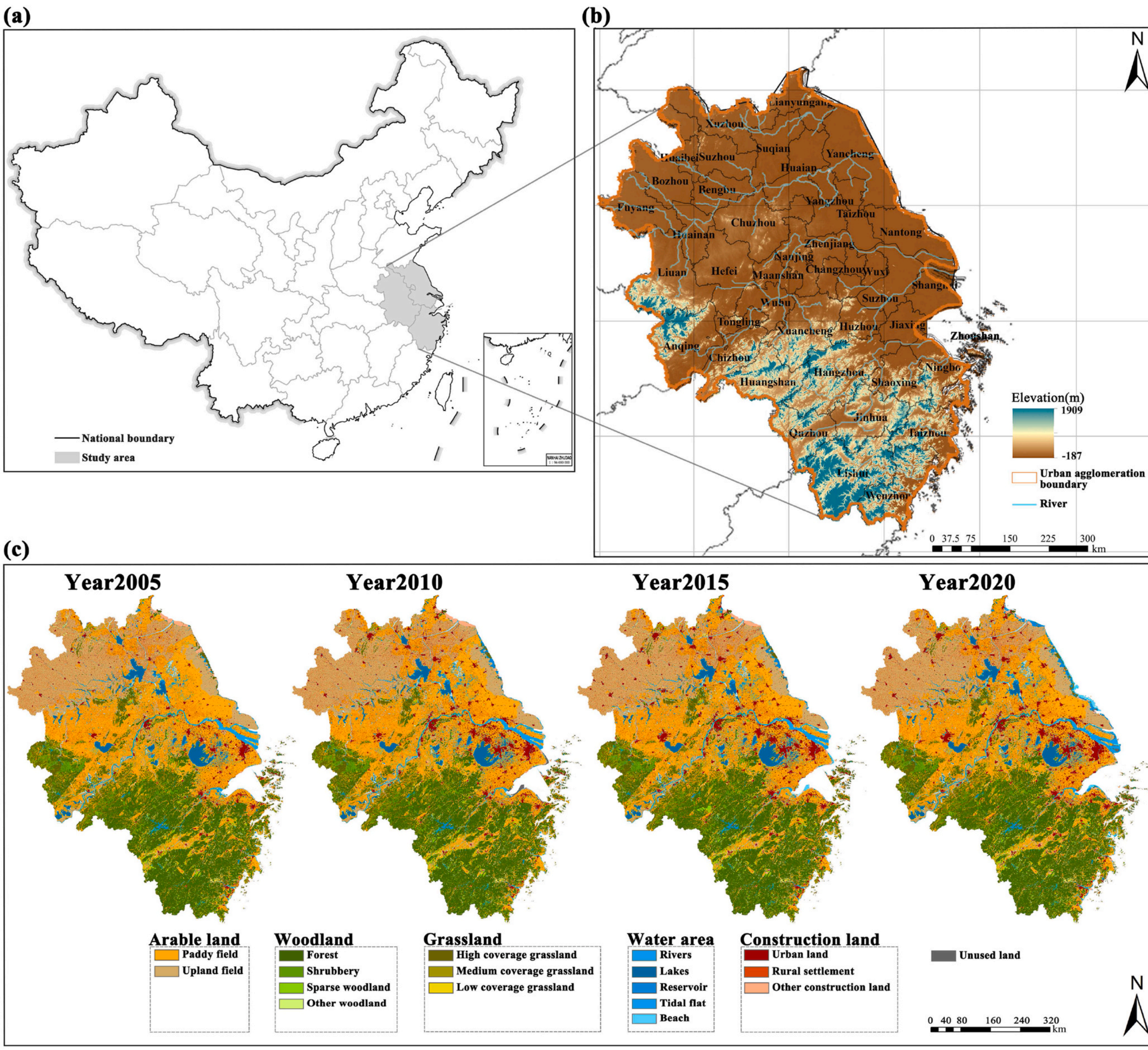

Fig. 1. (a) and (b) Location of the study area; (c) Land use types in the study area from 2005 to 2020.

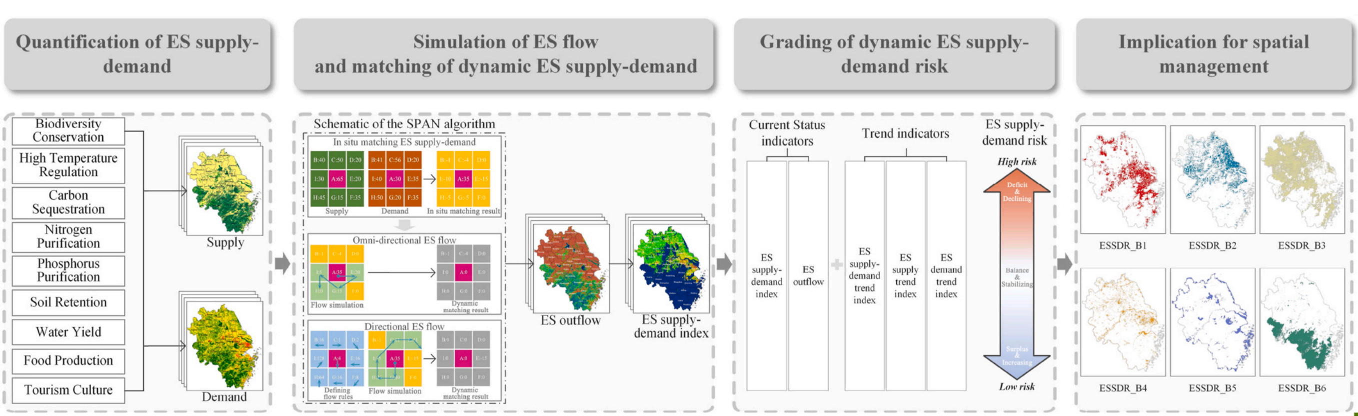

Fig. 2. Research framework.

characterized by high temperatures and rainfall in summer and four distinct seasons, with the average annual precipitation between 1000 and 1400 mm and an average annual temperature of 14–18 °C.

2.2. Research framework

This study introduced ESF into the spatial matching of the supply of and demand for ES based on the consideration of regional ecological integration, integrated the status quo indicators and trend indicators to construct a classification of ESSD risks over a long period, and attempted to integrate the results of various ESSD risks to provide a practical guideline for regional differentiation and refine eco-management. The specific steps involved in the study are depicted in Fig. 2: (1) quantitatively assessed the 9 ESs supply, demand, and flow within the YRDUA in 2005, 2010, 2015, and 2020; (2) combined ESF to identify the 9 ESSD index within the YRDUA in 2005, 2010, 2015, and 2020; (3) based on the classification of ESSD risks, mapping and analyzing the results of the 9 ESSD risks within the YRDUA; and (4) using cluster analysis, identified the bundles of ESSD risk within YRDUA to integrate the 9 ESSD risks and proposed differentiated suggestions of ES management for each zone.

2.2.1. Mapping the supply of and demand for ecosystem services

The selection of ES indicators in this study was based on national policy guidelines and regional status. China's high-quality development and ecological protection highlights 8 key concerns (China Development and Reform Commission, 2013–2020; Ministry of Natural Resources of China, 2020; China Development and Reform Commission, 2021): biodiversity conservation, climate regulation, soil and water conservation, windbreak and sand stabilization, water resource protection, food production, coastal protection, and tourism and culture. In terms of regional status, the YRDUA is positioned as a functional area for soil and water conservation, a functional area for biodiversity conservation (PRC Ministry of Ecology and Environment, 2015), an important water source (Ministry of Water Resources of China, 2016), a major food production area (China Statistics Bureau, 2021), and a tourism demonstration area (Ministry of Culture and Tourism of China, 2021), as well as suffers from several ecological problems (National Development and Reform Commission and Ministry of Natural Resources, 2020; Chen et al., 2024) such as the rapidly diminishing ecological space, excessive carbon emissions, eutrophication of water (e.g., nitrogen and phosphorus), and degradation of soil structure and quality. Therefore, 9 ESs from the 4 categories were chosen as the key ESs for identifying ESSD risks in the YRDUA from 2005 to 2020, including the biodiversity conservation (BC) of supporting service; high temperature regulation (HTR), carbon sequestration (CS), nitrogen purification (NP), phosphorus purification (PP), and soil retention (SR) of regulating service; water yield (WY), and food production (FP) of provisioning service; and, tourism culture (TC) of culture service. Table A1 depicted the procedure for evaluating the supply of and demand for 9 ESs, and Table A.2-A.12 listed the related parameters.

In addition, this study assessed the ES supply, demand, and flow at 1 km^2 raster resolution since the 1 km^2 represents the refined and the minimum integrity spatial scale for official ecosystem management in China (China Development and Reform Commission, 2021).

2.2.2. Quantifying the ecosystem service flows

The simulation of ESF is to comprehend the entire process of ES generation and consumption, which can be divided into the following 3 specific steps.

(1) Based on the characteristics of various ESs, ESFs were accordingly categorized as in-situ, omnidirectional, and directional (Fisher et al., 2009). In-situ ESF indicated that the ES supply and consumption locations were consistent, whereas omnidirectional ESF and directional ESF indicated that the ES supply and consumption locations were inconsistent and that there were flows to supply (Liu et al., 2016a). As a consequence, the simulation of ESF was conducted for the ES with the characteristics of omnidirectional ESF or directional ESF.
(2) Analyzed the ES characteristics and identified the necessary vehicles and influencing factors for the ESF, considering the supply and demand assessment results.
(3) Programming code by Python to simulate the ESF based on the theoretical framework of SPAN (Bagstad et al., 2013). The model's fundamental principles were as follows: First, each 1 center raster and its 8 adjacent neighboring rasters were formed into a 3 × 3 raster matrix, and the 9 rasters within the matrix were designed to contain their respective information of the supply of and demand for ES. Each center raster then calculated the static ES supply-demand index (static ES supply-demand index = ES supply – ES demand) based on the criterion "satisfy local demand first", which may exist in deficit (static ES supply-demand index<0), surplus (static ES supply-demand index>0), or balance (static ES supply-demand index = 0), respectively. If non-surplus, this center raster stopped flowing and became a receiver or transition for subsequent peripheral rasters; if surplus, this center raster was required to channel its surplus portion to the perimeter rasters following the ESF guidelines and the constraints imposed by the surrounding environmental factors until there was no surplus remaining. Notably, the directional ESF required pertinent flow rule information to be included in each raster, whereas the omnidirectional ESF was based on the flow rule "the surplus in the center is preferred to flow to the peripheral raster with the largest deficit." In conclusion, the ESF simulation ended when all rasters ceased flowing (Fig. 3).

This study considers BC, HTR, CS, FP, and TC as omnidirectional ESF, and the reasons are as follows. Areas with a high supply of BC, such as forests and watersheds, typically contain high densities of species community, including native species and exotic species that have moved in for a short time or will survive for a long time due to unsuitable habitats in other areas, such as migratory birds and roaming animals. TC is comparable to BC in that the consumers in areas with a high supply of recreation and leisure activities include locals and foreigners. Therefore, although BC and TC do not involve a spatial transfer, they have real-world effects similar to other ESFs. In addition, HTR and CS are primarily diffused and flowed by air and water through the atmospheric circulation system to purify the air and regulate the climate(Han et al., 2010), and FP delivers food to the surrounding areas via land and water transportation systems.

The NP, PP, SR, and WY belong to the directional ESFs, which are primarily diffused and transferred between regions via the water circulation, reliant on surface or subsurface runoff. Therefore, those 4 ESFs adhere to the water flow rule of "from high to low".

2.2.3. Evaluation of the spatiotemporal dynamics of ecosystem service supply-demand risk

In this study, the supply trend index (STI), demand trend index (DTI), supply-demand index (SDI), and supply-demand trend index (SDTI) were developed to identify the spatial and temporal variations in the regional ESs supply-demand over a specific period. And then, the SDI and ES outflow (ESF_out) in current were combined with STI, DTI, and SDTI to construct a classification of ESSD risks (Jr et al., 2017; Maron et al., 2017; Zhang et al., 2020) (Table 1). The following were the specific formulas for the relevant indicators:

$$STI_{ES_{i\_x}} = STI_{ES_{i\_xt2}} - STI_{ES_{i_{xt1}}} \tag{1}$$

$$DTI_{ES_{i\_x}} = DTI_{ES_{i\_xt2}} - DTI_{ES_{i_{xt1}}} \tag{2}$$

$$SDI_{ES_{i\_xt}} = Cosum_{ES_{i\_xt}} - D_{ES_{i_{xt}}} \tag{3}$$

Table 1
The classification of ESSD risks.

Assessment indicators					Risk index	Explanatory note	
Status quo indicators		Trend indicators					
2020		2005–2020					
SDI	ESF_out	SDTI	STI	DTI			
SDI<0	ESF_out = 0	SDTI<0	STI<0	DTI≥0	−6	High risk, status quo with ES supply-demand deficits	Deeper deficit, −6 to −4, with slowing rates of step-by-step deterioration
			STI<0, DTI<0 or STI≥0, DTI≥0		−5		
			STI≥0	DTI<0	−4		
		SDTI≥0	STI<0	DTI≥0	−3		Weaker deficit, −3 to −1, with accelerated rates of step-by-step improvement
			STI<0, DTI<0 or STI≥0, DTI≥0		−2		
			STI≥0	DTI<0	−1		
SDI = 0	ESF_out = 0	SDTI<0	STI<0	DTI≥0	1	Medium risk, status quo with ES supply-demand balance	Trend deficit, 1 to 3, with slowing rates of step-by-step deterioration
			STI<0, DTI<0 or STI≥0, DTI≥0		2		
			STI≥0	DTI<0	3		
		SDTI≥0	STI<0	DTI≥0	4		Trend surplus, 4 to 6, with accelerated rates of step-by-step improvement
			STI<0, DTI<0 or STI≥0, DTI≥0		5		
			STI≥0	DTI<0	6		
SDI = 0	ESF_out>0	SDTI<0	STI<0	DTI≥0	7	Low risk, status quo with ES supply-demand surplus	Weaker surplus, 7 to 9, with slowing rates of step-by-step deterioration
			STI<0, DTI<0 or STI≥0, DTI≥0		8		
			STI≥0	DTI<0	9		
		SDTI≥0	STI<0	DTI≥0	10		Deeper surplus, 10 to 12, with accelerated rates of step-by-step improvement
			STI<0, DTI<0 or STI≥0, DTI≥0		11		
			STI≥0	DTI<0	12		

$$SDTI_{ES_{i\_x}} = SDI_{ES_{i\_xt2}} - SDI_{ES_{i_{xt1}}} \quad (4)$$

Where $STI_{ES_{i\_x}}$ 、 $DTI_{ES_{i\_x}}$ are the STI and DTI of ES i at pixel x during the period t1-t2; $STI_{ES_{i\_xt2}}$、 $STI_{ES_{i\_xt2}}$ are the supply of ES i at pixel x in t1 and t2; $DTI_{ES_{i\_xt2}}$、 $DTI_{ES_{i\_xt2}}$ are the demand of ES i at pixel x in t1 and t2; $SDI_{ES_{i\_xt}}$ is the SDTI of ES i at pixel x in t (SDI = 0 indicates that the actual consumption is equal to the demand, i.e., ES supply-demand is in surplus or balance; SDI<0 indicates that the actual consumption is less than the demand, i.e., ES supply-demand is in deficit.); $Cosum_{ES_{i\_xt}}$、 $D_{ES_{i\_xt}}$ are the actual consumption and demand of ES i at pixel x in t; $SDTI_{ES_{i\_x}}$ is the SDTI of ES i at pixel x during the period t1-t2; $SDI_{ES_{i\_xt1}}$、 $SDI_{ES_{i\_xt2}}$ are the SDI of ES i at pixel x in t1 and t2.

2.2.4. Identification of ecosystem service supply-demand risk bundles

In this study, the Self-Organizing Map (SOM) proposed by T. Kohonen (1982) was used to integrate 9 ES supply-demand risk results of the YRDUA from 2005 to 2020, and then the ES supply-demand risk bundles were identified.

The SOM is an artificial neural network established on the principle of machine learning using unsupervised learning to train samples. It is commonly used in the study of spatial data clustering analysis, high-dimensional data visualization, and feature extraction. The self-organizing mapping network consists of a 2-layer neural network, containing an input layer and an output layer, where the input layer obtains external multivariate information inputs, and the output layer is composed of multiple neurons representing bundles. The SOM network combines spatial principal component and K-means clustering analysis methods, retains the spatial topology of the input sample data through the nearest neighbor relationship function, and simultaneously combines its spatial information in the clustering, relying on the competition between each neuron carrying the main information of the space and the sample to optimize the classification network and realize the optimal classification gradually. Each input data can identify a clustering neuron that best matches the output layer.

The optimal raster scale and the optimal number of bundles are critical factors that affect the clustering results. In this study, the optimal raster scale was determined by the study area's ecological characteristics and China's Technical Guidelines for the Delineation of Ecological Protection Red Lines (Commission, 2017-07-20/2021-11-05). Then, we ran iterative SOM clustering of the 9 ESs supply demand risk results within the range of 2–30 bundles and determined the optimal number of bundles by pseudo F-statistics, commonly used to characterize the similarity of data within clusters and the differences between clusters.

2.3. Data resource

The sources of biophysical and socioeconomic data utilized in this study were shown in Table A.19 in Appendix A Supplementary material.

3. Results

3.1. Spatio-temporal variations in ecosystem services supply, demand, flow, and supply-demand matching

As illustrated in Fig. 4, there was significant spatiotemporal heterogeneity in the supply of and demand for 9 ESs in the YRDUA between 2005 and 2020. The results of the supply assessment showed that BC, HTR, CS, SR, and WY decreased spatially from southwest to northeast. The average annual supply of BC, HTR, and CS decreased over time while SR and WY increased. The spatial distribution of NP supply and PP supply were similar, decreasing from the central Jianghuai and Taihu Plain to the north and south, and the annual average supply of both decreased and then increased in time with 2010 as the turning point. The high-value supply areas of FP were mainly concentrated in the Taihu Lake and Huaihu Plain in the northern part of YRDUA, and the supply increased yearly. The high-value supply areas of TC showed a point-like scattered pattern, distributed in the core cities of Shanghai, Jiaxing, and Nantong, and the annual average supply with the trend of increasing and then decreasing. In terms of demand, the high-value areas of BC, HTR, CS, WY, FP, and TC were concentrated in densely populated and socioeconomically developed cities, characterized by a significant spatial pattern of being high along the coast and low inland. Over time, the annual average demand for BC, HTR, CS, and TC has increased, while FP

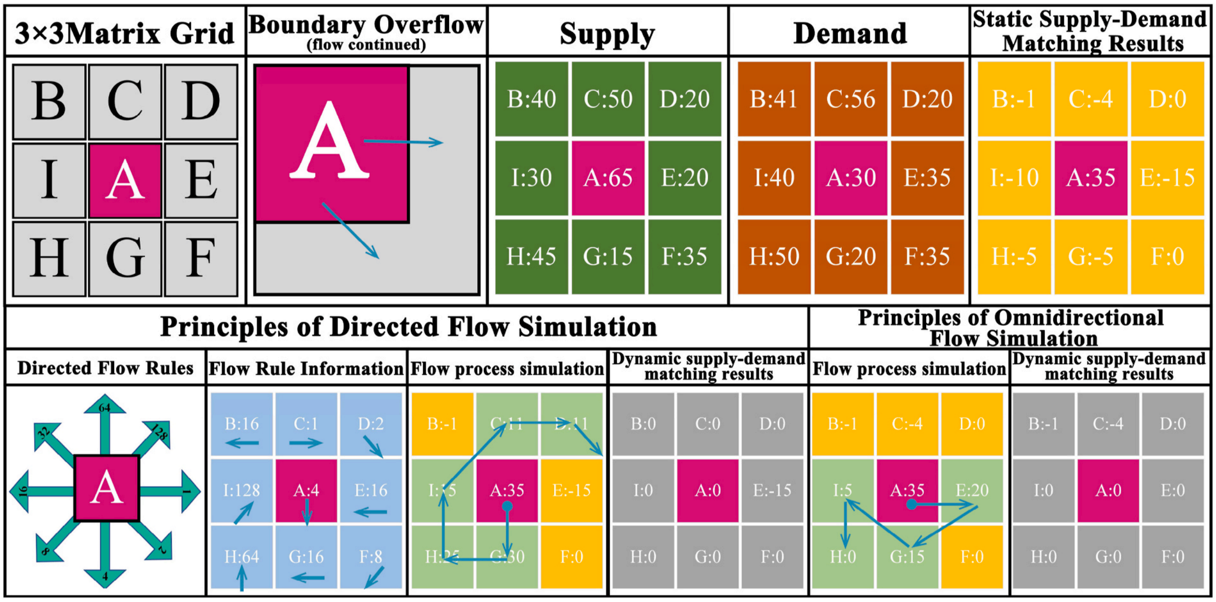

Fig. 3. Illustration of ecosystem service flow simulation.

has decreased, and WY reached its peak in 2010 and has been declining since then. The spatiotemporal distributions of SR demand, NP demand, and PP demand were similar to their supply, mainly because the southwest mountain forested areas, which have a high capacity to retain soil as well as abundant precipitation, which leads to a larger amount of potential soil erosion. The supply of and demand for NP and PP were closely related to the concentration of pollutants in the environmental background, and the north-central part of the study area, as the main agricultural production area, was the area with high levels of nitrogen and phosphorus pollutants discharge.

Simulation of ESF based on the SPAN algorithm resulted in the outflow of 9 ESs from 2005 to 2020 (Fig. 4). Under the constraints of geographic distance and amount of supply, the areas with high outflow values of all-directional ESFs (BC, HTR, CS, FP, and TC) were concentrated around the high supply areas. The outflows of BC and FP increased over time, while the outflows of HTR, CS, and TC decreased due to rising demand for ESs and decreasing supply as ecosystems declined. Outflows of directional ESFs (NP, PP, SR, and WY) increased over time, highlighting an urgent need to prioritize the security of water and soil resources. The areas with high outflow values for NP and PP outflows were mainly in the north-central plains and the eastern built-up areas. The high-outflow-value areas of SR outflows were concentrated in the southwestern forested areas, while the high-outflow-value areas for WY changed with time, moving from the southeastern coastal area to the southwestern mountainous areas.

The results of ES supply-demand matching considering the impact of ESF show that (Fig. 4), although ESF mitigated the imbalance between supply and demand to some degree, the imbalance was still significant in most of the areas of YRDUA. The spatiotemporal distributions of BC, HTR, and CS, which are omnidirectional flows, were similar. The high-surplus areas of those 3 ESs were mainly in the waterbodies (such as the Yangtze River, the Beijing-Hangzhou Grand Canal, and the Taihu Lake) and the southwestern mountainous and forested areas, and the high-deficit areas were the highly urbanized areas in the southeastern of the YRDUA. The deficits of HTR, CS all worsened over time, while the deficits of BC eased, but the deficit areas were all expanded. FP deficits became increasingly prominent, and built-up areas with high population density, such as Shanghai, Ningbo, and Nanjing, faced serious food security problems. However, the imbalance of FP's supply and demand lessened over time. The deficit areas of TC were clustered pointwise in the city's built-up areas, with a worsening deficit level closer to the traffic network, but the gap between supply and demand has narrowed in recent years. The spatial heterogeneity of the supply-demand relationship of NP and PP that directed flow was significant, with high deficits clustered in the paddy fields of the Jianghuai and Lixiahe plain. Over time, the deficits in the paddy fields increased, while the surpluses in the dryland of the Huabei plain increased. The deficit areas of SR were concentrated in the northern agricultural areas and the built-up areas of the central and eastern coasts, and the deficit level increased over time. In contrast, the northern portion of the study area had a surplus of WY, which gradually decreased towards the south, and the gap between supply and demand narrowed over the years.

3.2. *Ecosystem service supply-demand risk*

Fig. 5 shows the results of the 5 indicators of the ESSD risk evaluation for the 9 ESs, and the results of the ESSD risk for the 9 ESs of YRDUA are shown in Fig. 6.

Overall, the mean ESSD risks of NP, PP, FP, and HTR were −2.59, −2.51, −0.97, and −0.70, respectively, and the supply and demand relationship of these 4 ESs remained deficit in 2020, which means that all of these 4 ESs with worrying ESSD risk, but the deficit level improved over the years. The supply and demand relationship of WY, SR, TC, CS, and BC were all in surplus, but the ESSD risks decreased, with mean values of 10.62, 8.78, 8.48, 7.36, and 4.67, respectively.

Specifically, the low ESSD risks areas of BC, CS, SR, WY, and TC accounted for 39%, 71%, 80%, 93%, and 72%, respectively, of the total area of the YRDUA, were mostly concentrated in the southwestern forested area and the central-northern farming area, where have lush vegetation and abundant precipitation. However, most areas' ESs supply and demand surplus levels have been weakening yearly, and the overall situation is not optimistic. YRDUA's HTR high ESSD risk areas account for a relatively high percentage (74%), concentrated in the north-central farming areas, eastern areas, and coastal cities. Most of these areas had worsening deficits of ESs supply and demand at different rates (e.g., Wuhu, Maanshan, Nanjing, Nantong, and Wenzhou), and only some of the northern Anhui areas (Fuyang, Huaibei, Bozhou, and Suzhou) improved their deficits. The spatial distribution of ESSD risk in the HTR was characterized by a concentration of areas with the same ESSD risk level and a mix of areas with different levels of risk. Most of FP's high ESSD risk areas showed decreasing deficits of supply and demand between 2005 and 2020, but the deficits in populated cities with high risk,

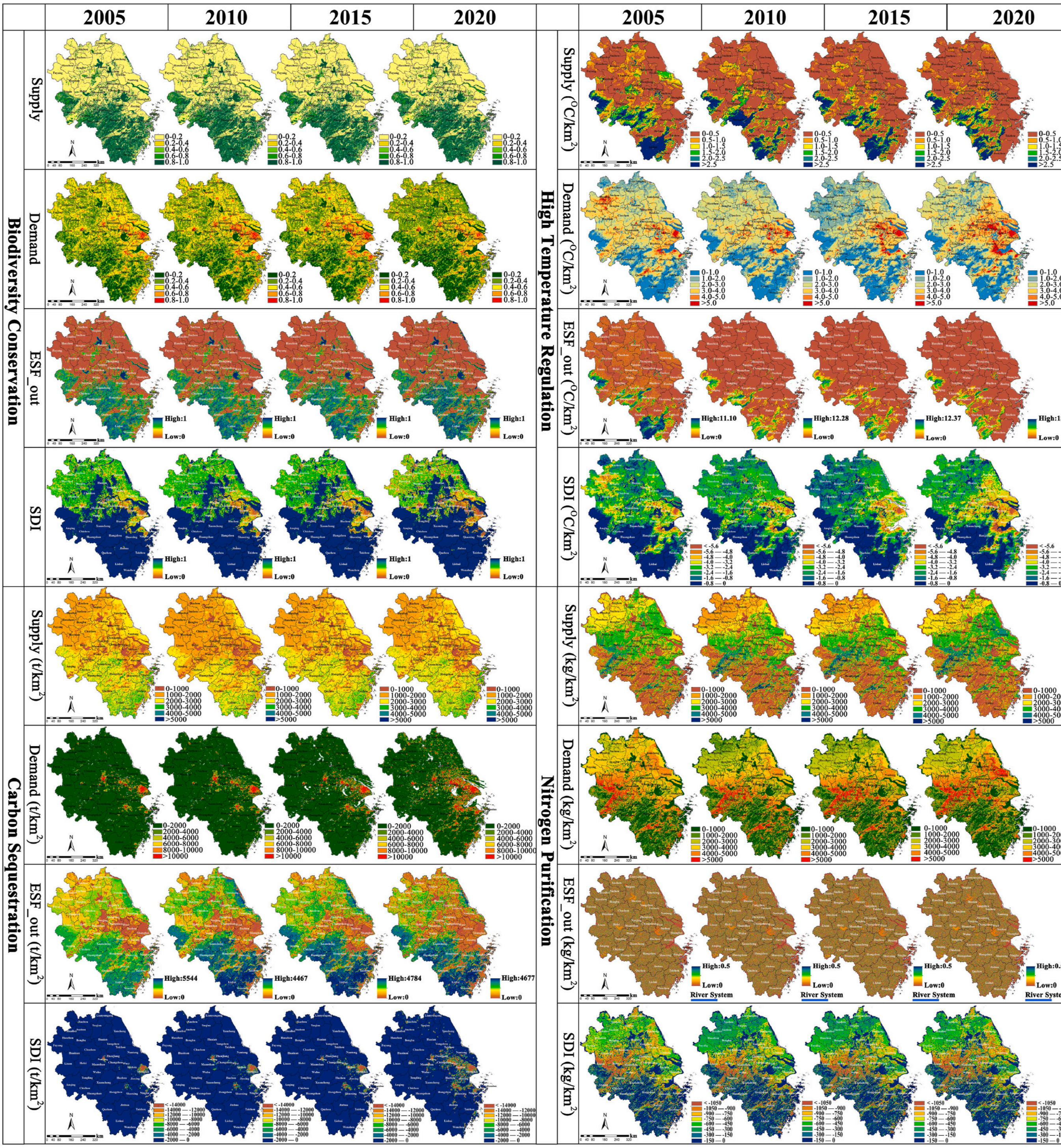

Fig. 4. Spatiotemporal variation of supply, demand, and ESF outflows for 9 ESs in YRDUA.

such as Shanghai, Ningbo, Hangzhou, and Wuxi, were deepening.

3.3. Spatial distribution of ecosystem service supply-demand risk bundles

The optimal number of bundles for the ESSD risk in YRDUA is 6, as shown by the turning point of the pseudo F-statistic, where it changes from an increasing to a decreasing trend (Fig. 7).

As shown in Fig. 8, ESSDR_B1 and ESSDR_B4 account for 13.5% (48,597 km^2) and 4.1% (14,891 km^2) of the total YRDUA, mainly distributed in Shanghai and the 5 major metropolitan (Nanjing, Hangzhou, Hefei, Suzhou, Wuxi, Changzhou, and Ningbo), which had high ESSD risks in HTR, NP, PP, and FP (the mean values of risks as −4.22, −3.4, −3.76, −2.47 in ESSDR_B1 and -2.73, −3.67, −3.59, −1.03 in ESSDR_B4 respectively), suggesting that there is an urgent need to pay attention to livability in these areas. ESSDR_B1 was mainly located in the periphery area of the urban, and ESSDR_B4 was closer to the urban center; the mismatch between supply and demand of CS in ESSDR_B1 and WY in ESSDR_B4 was relatively significant, with mean values of

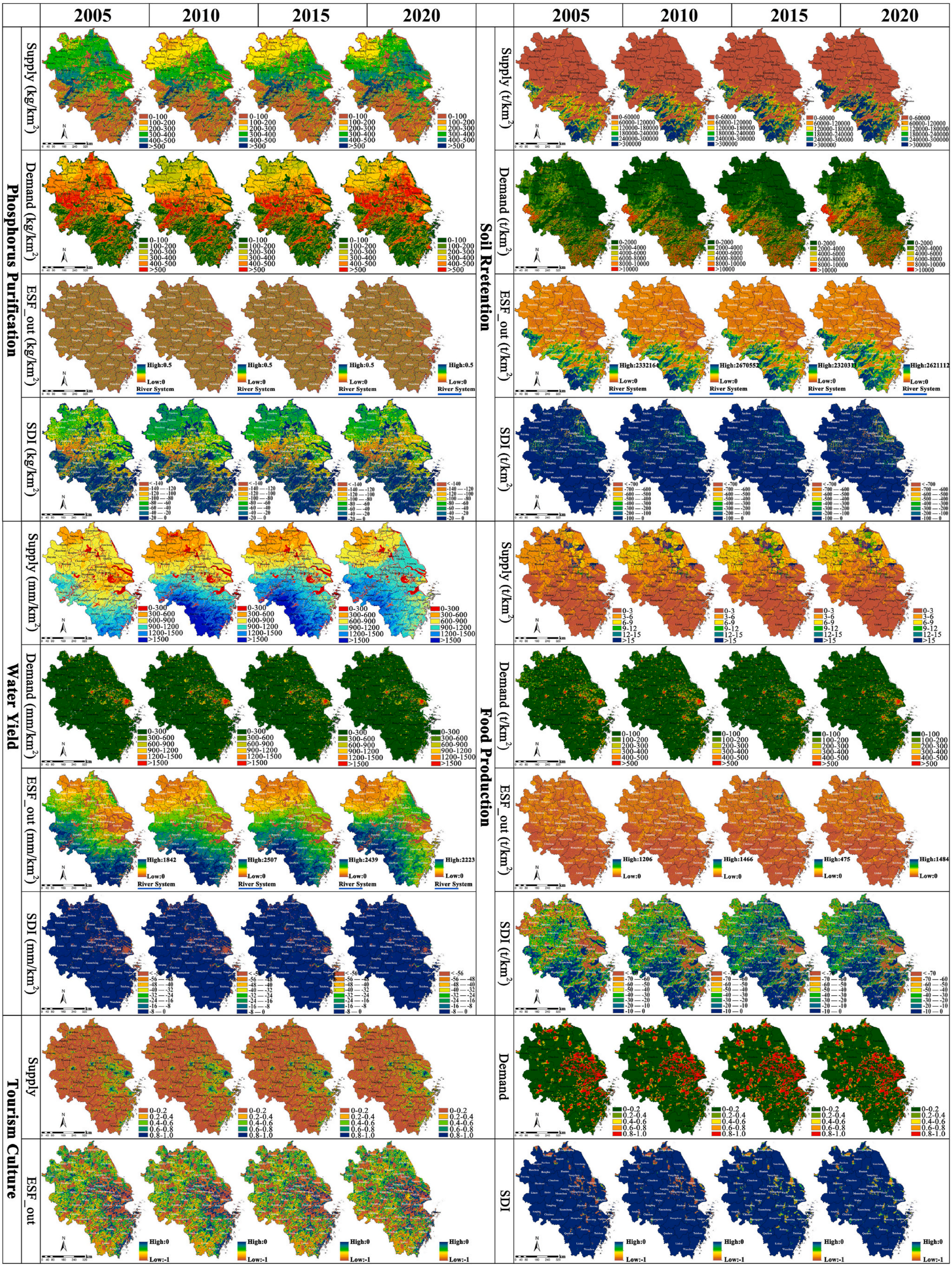

Fig. 4. (*continued*).

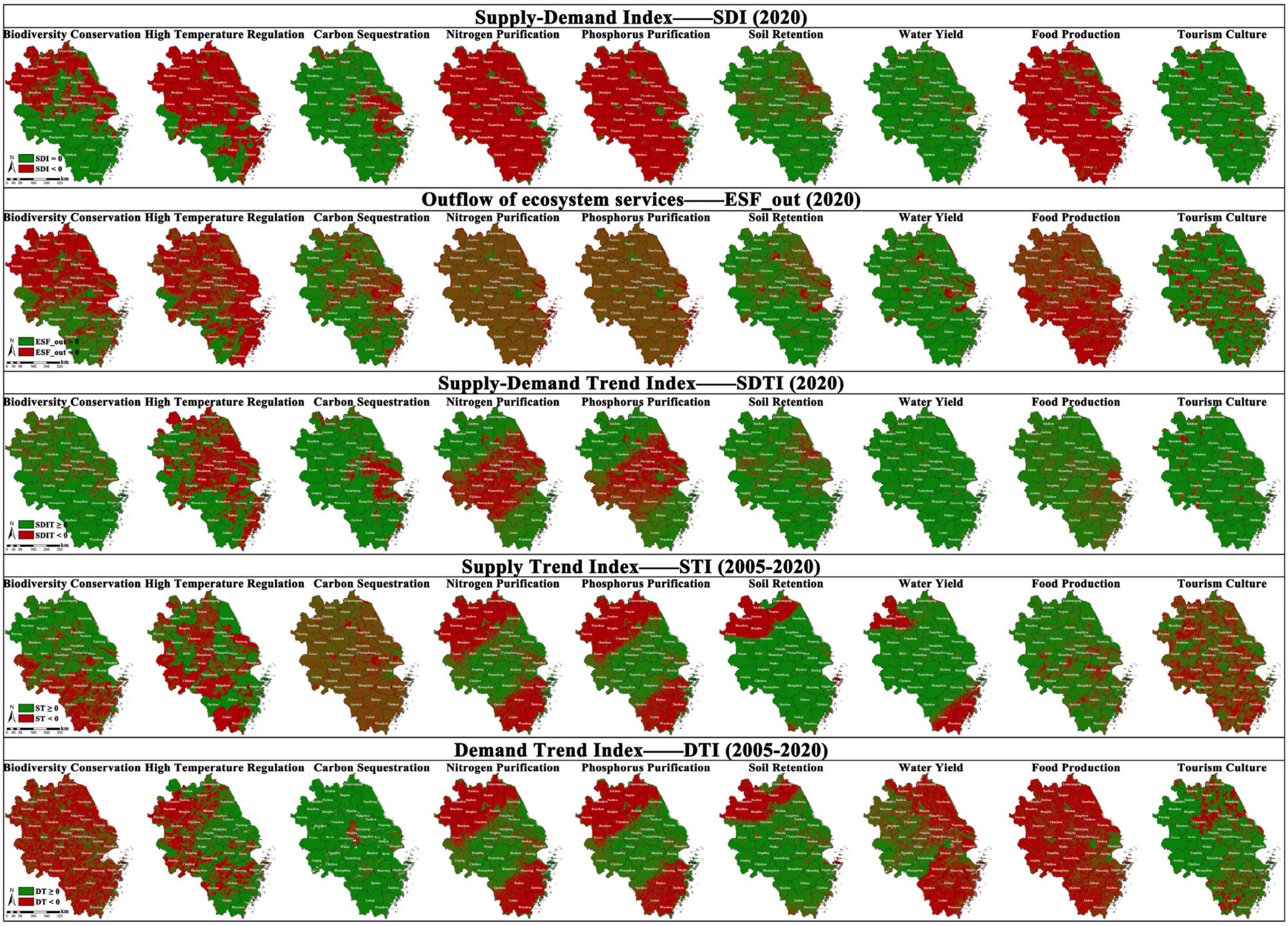

Fig. 5. Spatial distribution of 5 indicators of ESSD risks for the 9 ESs of YRDUA, 2005–2020.

−1.56 and −2.4 respectively. In general, both bundles were located in the economic center of the YRDUA with high population density and intensive industrial manufacturing, and there were extremely vigorous socioeconomic activities all over the year driven by strong demand for development. As a result, natural land cover, such as water and forests, was rapidly disappearing, and carbon emissions and demand for water and food kept rising, approaching the limits of the resources and environmental carrying capacity. Although ESSDR_B1 had a better natural environment than ESSDR_B4, the rapid sprawl of built-up land led to ESSDR_B1 facing a more severe risk of supply and demand for climate regulation in recent years, such as the worsening of the heat island problem, while ESSDR_B4 was more threatened by the ESSD risk for water, which is a necessity of life.

ESSDR_B2 and ESSDR_B3 account for 10.5% (37,956 km^2) and 40.7% (146,424 km^2) of the total area of the YRDUA, mainly distributed in the agricultural farming area in the north-central part, and the southeast's Hangzhou Bay and coastal area. Among them, ESSDR_B3 was widely distributed, and ESSDR_B2 was primarily located in the paddy fields of Huainan, Lu'an, Yancheng, Nantong, and Taizhou in the north-central part, surrounded by ESSDR_B3. The ESSD risks of HTR, NP, and PP in both bundles were high, with the mean values of risks as −3.73, −3.1, and −3 in ESSDR_B2, and -3.96, −3.85, and −3.88 in ESSDR_B3, respectively. This is due to the large amount of arable land within the bundle, the emission of nitrogen and phosphorus was large, and the vegetation was homogeneous with a lower crown density, so that the capacity of nitrogen and phosphorus retention, soil and water conservation, and climate regulation was more limited than that in forest and waterbody. ESSDR_B2 was characterized by densely distributed paddy fields, with loose soils and abundant rainfall, and thus faced a higher ESSD risk of SR (−4.4); ESSDR_B3 covered a vast area of water, which made it face a more serious water pollution problem.

The ESSDR_B5 had the smallest area, accounting for only 7.5% (26,823 km^2) of the YRDUA, and was located in the rivers and lakes (e.g., Yangtze River, Taihu Lake, Dongting Lake, etc.) and the southeastern coastal zone (e.g., the estuary of Yangtze River, Hangzhou Bay, etc.) The ESSD risk for each ES in the ESSDR_B5 was at a medium-to-low level. Notably, the risks of SR, WY, NP, and PP were very low. However, the HTR within ESSDR_B5 was at a critical point between medium and high ESSD risk, which means that this area's future economic development is still subjected to strong constraints of environmental capability, any construction activities in this area must be carried out under strict ecological protection measures.

ESSDR_B6 covered an area of 85,105 km^2, accounting for 23.7% of the entire YRDUA, and was distributed in the core area of important habitats in the southwest, including the Dabie Mountains in western Anhui Province and the area along the southern part of Anhui Province, western Zhejiang Province, and southern Zhejiang Province. This bundle was a key supply area for regulating and supporting services, with very strict constraints of ecological protection policy for economic development due to high ecological sensitivity, so the ESSD risks of ESSDR_B6 were low. However, recent development and deforestation have degraded the woodland habitats in ESSDR_B6, resulting in a certain ESSD risk for NP and PP.

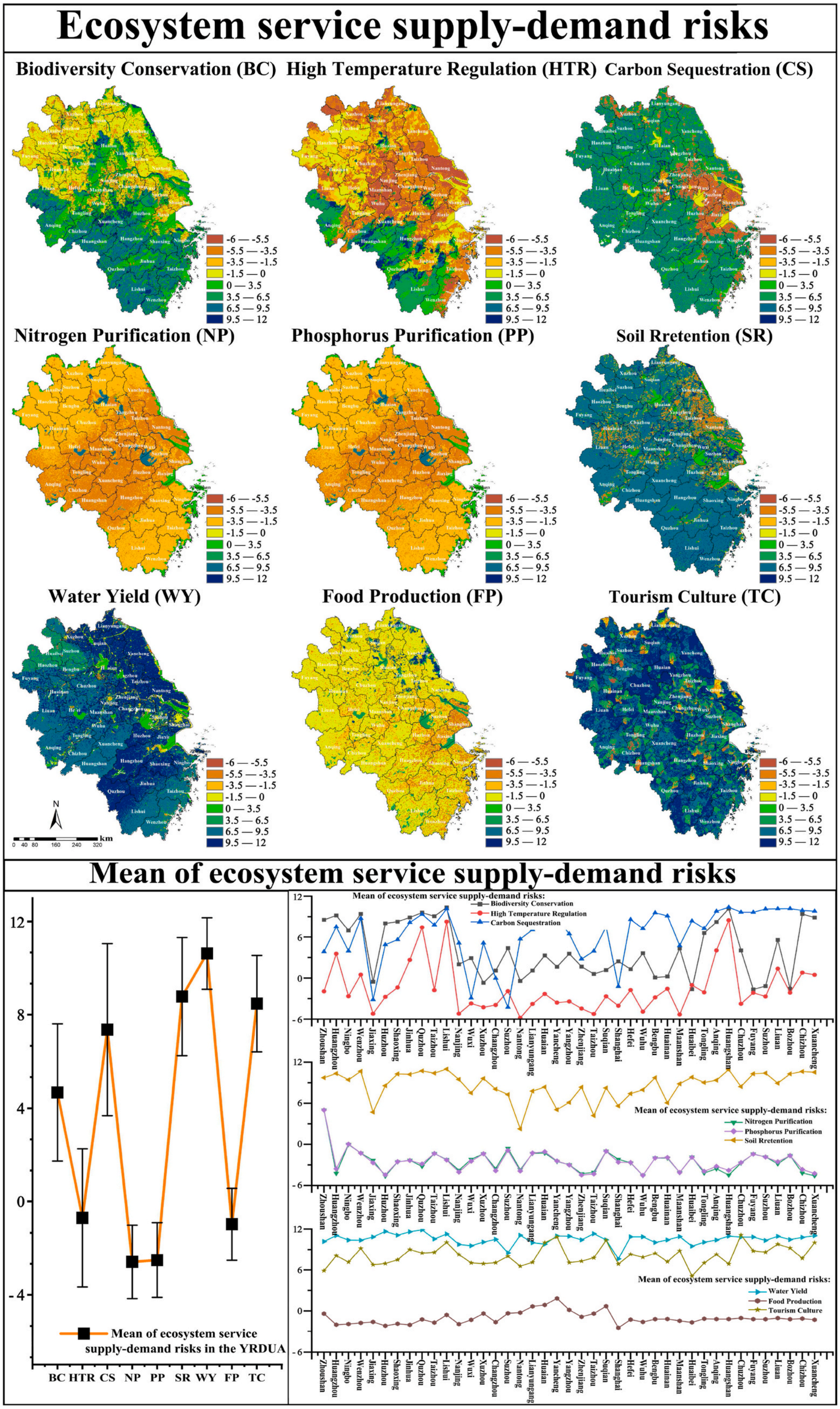

Fig. 6. Spatial distribution of ESSD risks for the 9 ESs of YRDUA, 2005–2020.

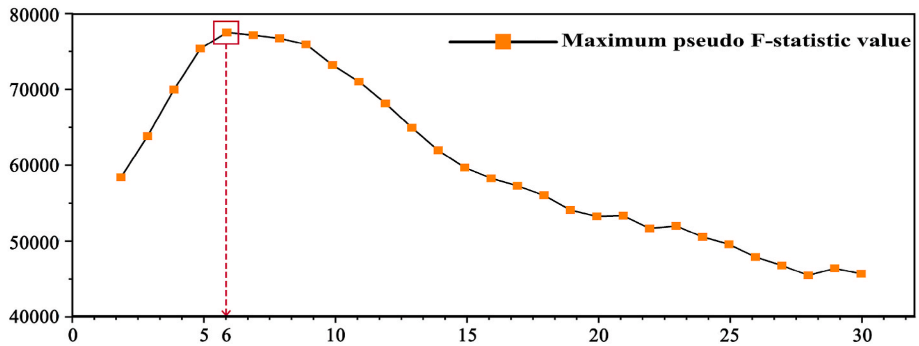

Fig. 7. Simulation of the bundle's optimal number in the YRDUA.

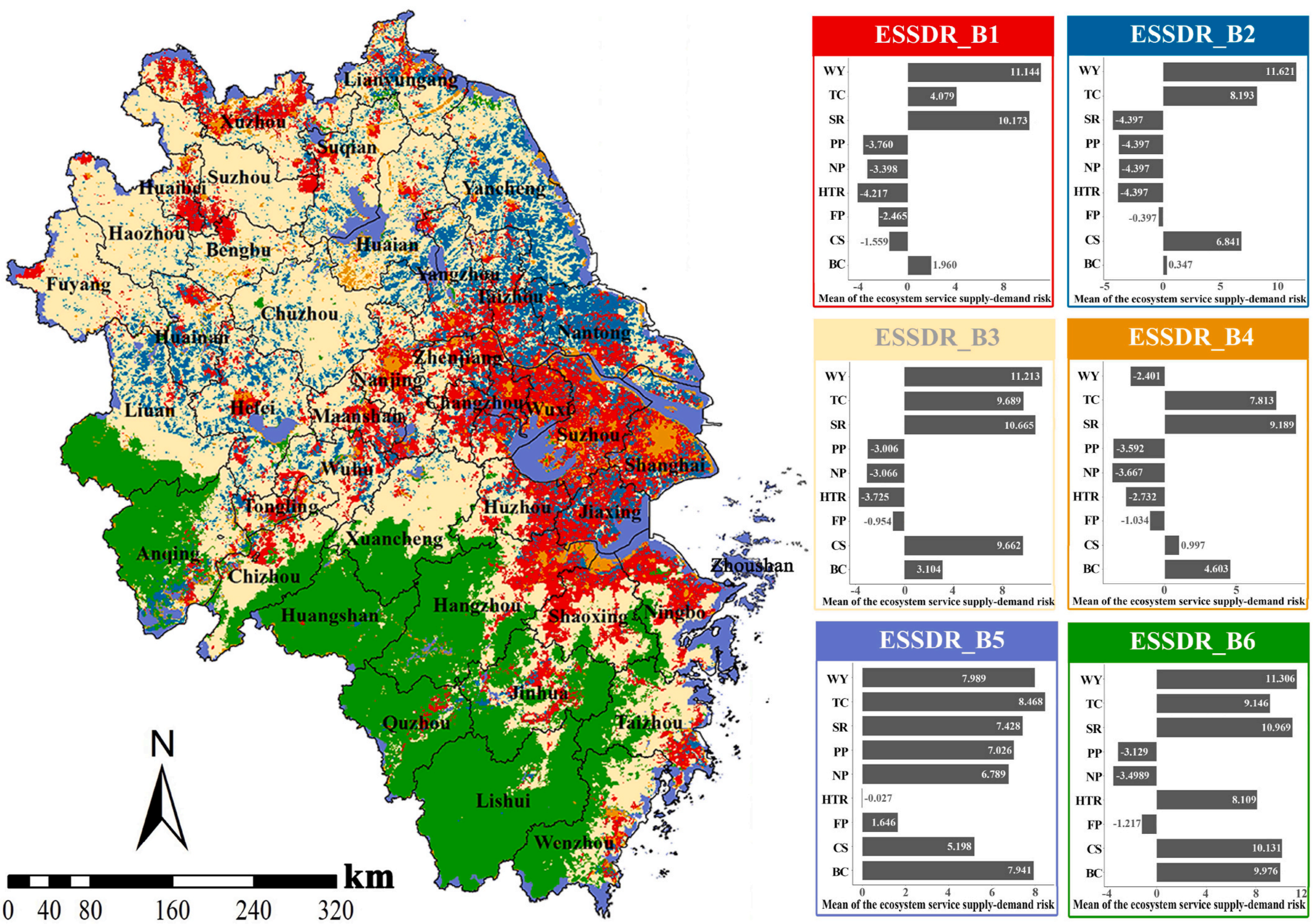

Fig. 8. Spatial distribution of ESSDR_B and mean risk value for each bundle in YRDUA, 2005–2020.

4. Discussion

4.1. Spatial benefits and spillovers of different ESFs

Whether and how to consider ESF significantly impacts the ES supply-demand matching results. However, most of the previous ES supply-demand matching studies have ignored the impact of ESF by assuming that all ESs are consumed in situ, making it difficult to depict the differential supply-flow-demand process of various ESs accurately (Wang et al., 2022b). This study quantified and mapped the ESFs based on the flow characteristics of different ESs, distinguishing the roles (supplier, transition, and demander) undertaken by different rasters in the flowing process. At the same time, this study assumed that the supplier provides all the ES surplus as the maximum reserve for the subsequent flowing process, based on which to conduct a semi-static supply-demand matching, which considering only the ESF outflows on the results of static supply-demand matching (Fig. 9).

By comparing the result of static, semi-static, and dynamic ES supply-demand matching, this study found that ESF does alleviate the ES supply and demand imbalance within the YRDUA to a certain extent, which is manifested by the relatively lower proportion of deficit area and degree of deficit in the results of dynamic supply-demand matching. As shown in Fig. 9, the improvement effect of ESF on TC's supply and demand deficits within the YRDUA is significant and generalized, with most of the cities showing improvement in the degree of deficits, while the improvement effect on CS's supply and demand deficits is more

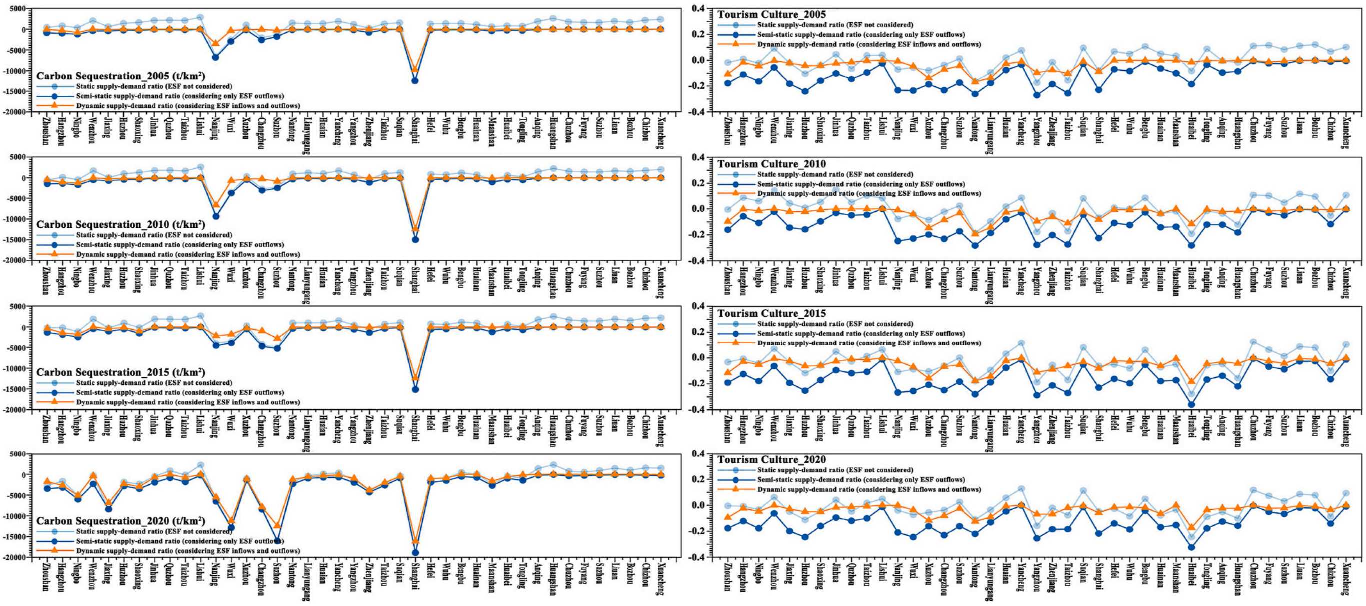

Fig. 9. Static, semi-static, and dynamic supply-demand ratios for CS and TC in YRDUA, 2005–2020.

concentrated, with the major areas in the core cities such as Nanjing, Wuxi, Suzhou, and Shanghai. This difference suggests that policymakers should pay more attention to improving the coverage and benefit efficiency of ESFs in the future.

It should be noted that while ESF can alleviate the deficit of supply and demand to some extent, it cannot curb the worsening trend of deficit over time. For example, the dynamic supply-demand ratio of CS in Suzhou has decreased from −1051.6 t/km2 in 2005 to −12512.2 t/km2 in 2020, indicating that the prevention and control of the ESSD risk requires consideration of both spatial integration and temporal sustainability.

The differentiated flow mechanism of ESFs also impacts the

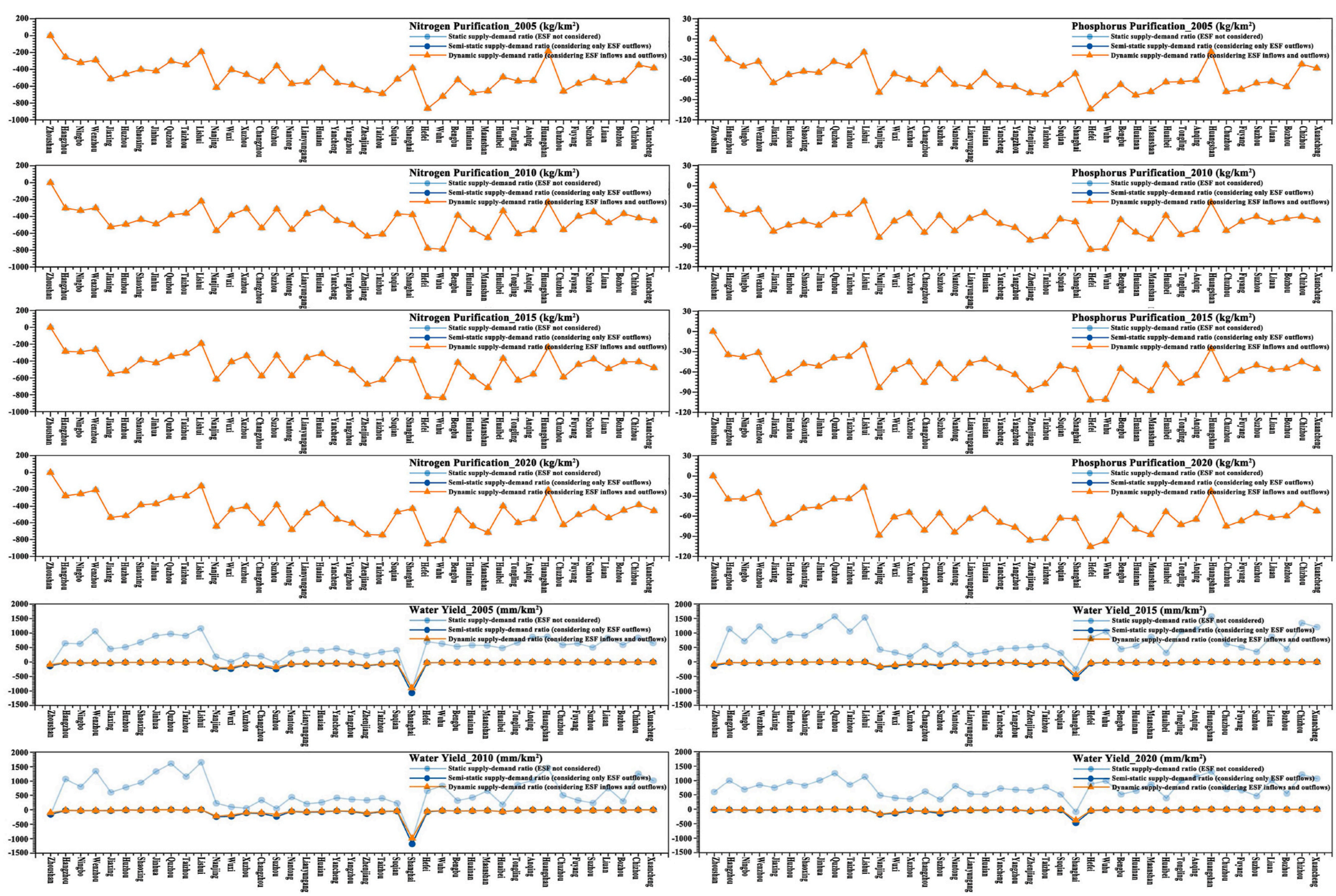

Fig. 10. Static, semi-static, and dynamic supply-demand ratios for NP, PP, and WY in YRDUA, 2005–2020.

matching results of supply and demand. Specifically, the dynamic matching results of this study showed that the spatial relationship between ES supply surplus areas and demand areas and their surrounding geographic characteristics greatly impact the ESF's flow range and improvement effect of supply-demand relationships, resulting in differentiated supply-demand matching results for ESs subjected to the same flow rules (Fig. 10). For example, NP, PP, and WY are both runoff-based directional flows. However, compared with the ESF of WY from the southwestern mountains broadly alleviated the deficit in the north-central plains, the ESF of NP and PP had a relatively poor improvement effect. Since the overall topography of the high nitrogen/phosphorus nutrient discharge areas is lower than that of the high retention areas, and under the restriction of the flow pattern of water flow from high to low, nitrogen/phosphorus can only flow to the lower topography at a smaller scale, making it difficult to achieve effective retention of nitrogen/phosphorus nutrients across a large area.

In addition, ESF is a socioecological process not restricted by administrative boundaries and has spatial continuity. The results of this study showed that all the ESFs did spill over to the bordering provinces of YRDUA like Jiangxi, Fujian, and Hebei, and the benefits of different ESFs vary in terms of object and extent (Fig. 11). Therefore, policymakers should be aware of the specific ESF exchanges between administrative units, and collaboratively utilize regional ecological integration management to enhance the ecological risk prevention and control capacity of each administrative unit.

4.2. Implications of the comprehensive ESSD risk identification framework

Assessing the ESSD risks is essentially an analysis of the potential of ecosystems to provide sustainable benefits to humans over the long term in response to disturbances (Boesing et al., 2020). This study comprehensively considered the spatial externality and time lag of ES consumption to provide a more precise framework for the ESSD risks classification framework, which integrates the status quo of the actual supply-demand ratio considered ESF impacts, as well as the trends of ES supply, demand, and actual supply-demand ratios over the historical period.

The combined status of SDI and ESF_out indicates whether the ecosystem can continue supplying ES to the surrounding area after meeting the local demand of the socioeconomic system, which is an important indicator to characterize whether the social-ecological system interaction is in a positive state. ESF_out ≤ 0 suggests that the ES supplied by the ecosystem is unable to or barely meet the local demand, which means the social-ecological system interaction is in a negative or balanced state, i.e., it may face relatively high risks (Villamagna et al., 2013). Moreover, the current status alone cannot accurately assess the social-ecological system interaction, leading to underestimating the risk, which will seriously reduce the effectiveness and efficiency of ecosystem management (Liu et al., 2022). For example, some areas currently in supply-demand balance have a downward trend in ES supply and outflow over the years, and this suggests that the ecosystems may not be able to supply ES sufficiently in the long run and are at risk of decline. Similarly, in some areas, the supply of ESs has remained relatively stable for many years, but the demand for ESs has been rising, which suggests that the area's improvement effects on neighboring areas may diminish in the future or even that there is a risk of supply and demand deficit may occur in this area.

Therefore, historical trends of ES supply and demand can help in understanding and even predicting the dynamics of socio-ecosystem

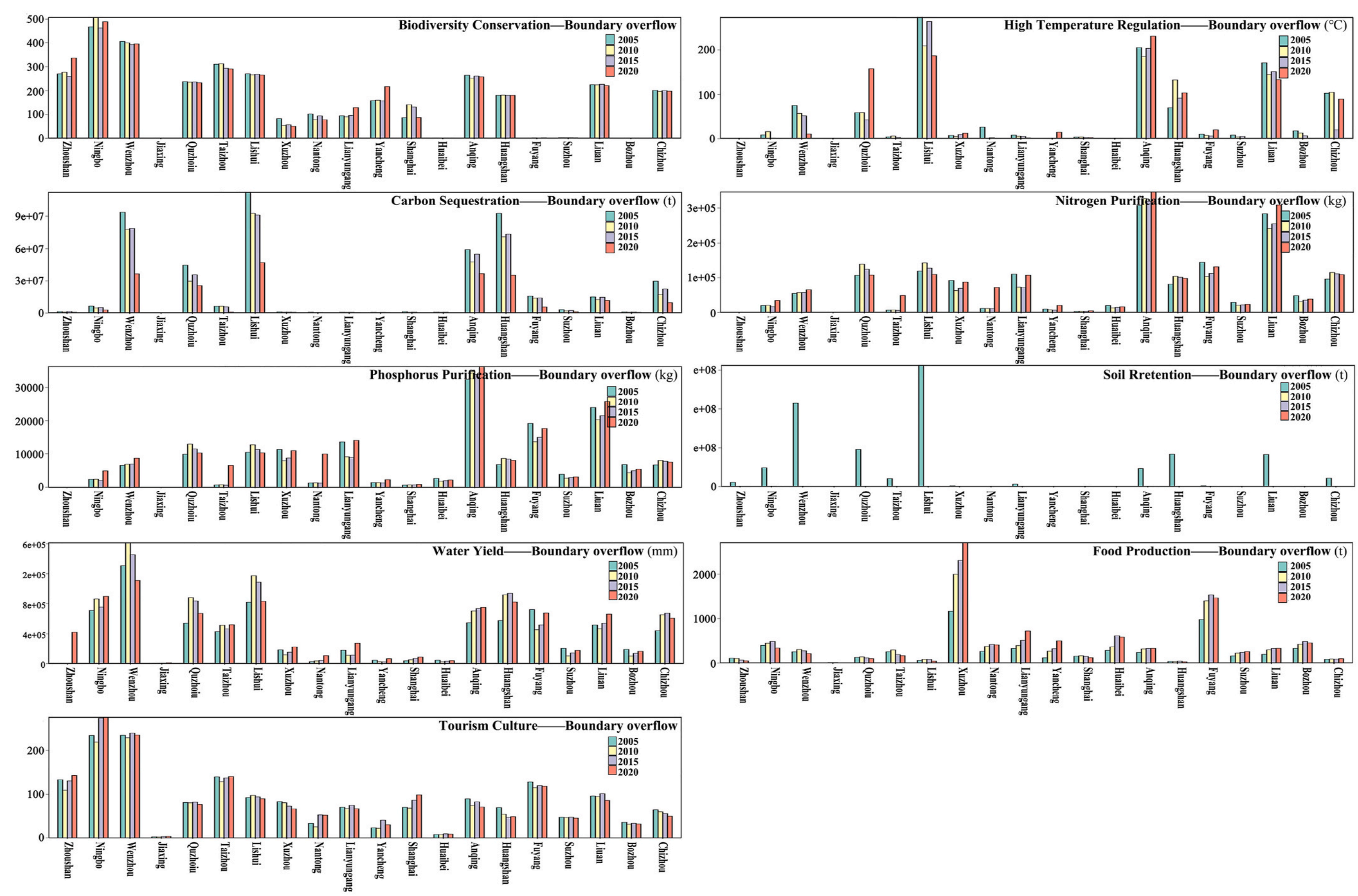

Fig. 11. Spatial spillover of 9 ESs for YRDUA, 2005–2020.

interactions over time and are indispensable indicators for accurately assessing the ESSD risks (Boesing et al., 2020), which can provide effective information for early warning and Identification of potential ecosystem decline.

4.3. Suggestions for ecological management in the YRDUA based on ESSDRBs

For urban agglomerations pursuing ecologically integrated management, understanding and integrating multiple ESSD risks in the region based on the SOM provides a spatial reference for developing differentiated zoning management strategies that balance regional coordination and ecological heterogeneity. Furthermore, in rapidly developing urban agglomerations facing uncertainties and diverse ecological problems, developing resilient ecosystem management strategies requires timely responses to potential ESSD risks and prioritization of multiple ESSD risks. Based on the results of this study, the management for ESs of the 6 risk bundles in YRDUA was prioritized according to the level of supply and demand risks (Table 2). We proposed the following targeted ecological protection and restoration strategies.

While ESSDR_B1 should prioritize HTRS with the highest risk and ESSDR_B4 should focus on NP, given that ESSDR_B1 and ESSDR_B4 have relatively large numbers of ESs in high-risk status, improvement measures need to be formulated with a focus on the factors that have a joint impact on the supply and demand of these ESs. Specifically, ESSDR_B1 is distributed around highly urbanized areas, so the supply of multiple ESs can be increased by constructing the green infrastructure network that regulates the important driven factors of HTR, CS, NP, and PP supply, such as NDVI, forested land percentage, and construction land percentage, and restrain excessive demand by reducing the population that influx into the peri-urban area. ESSDR_B4 is mainly the highly urbanized areas with prominent water-related WY, NP, and PP risks, encountering serious urban heat island effects and worrying food security. Therefore, on the one hand, from the supply side, micro-renewal approaches that synergistically improve the urban water cycle, microclimate, and food supply can be encouraged, such as urban agriculture, three-dimensional greening, and small parks; on the other hand, from the demand side, the demand for water-related ESs provided by nature capital can be reduced by enhancing hydrologically relevant grey infrastructures and low-impact development of rainwater systems.

ESSDR_B2 and ESSDR_B3, mainly located in the central, northern, and southern coastal agricultural zones of YRDUA, face similar ESSD risks regarding HTR, NP, and PP. Because the high-intensity farming activities within these areas have resulted in monoculture plant communities, soil degradation, and water contamination, making them encounter water and heat-related risks. Given that ESSDR_B2 is mainly plains paddy fields and hillside wasteland, it is possible to emphasize agricultural diversification, such as polder systems, mulberry-based fish ponds, and crop rotation to slow down soil erosion and regulate the climate, and also upgrade agricultural cultivation techniques and promote organic agriculture to reduce the ESSD risk of NP and PP. ESSDR_B3 consists of plain dry fields and coastal forests, with mixed distribution of paddy fields, so consideration can be given to improving the efficiency of agricultural cultivation and returning farmland to forests in order to restore the natural vegetation while maintaining FP appropriately.

The ESSDR_B5 located in and along water bodies only has a medium-high risk of HTR, so the heat environment is a key concern in this area. The cooling effect of water bodies should be fully maximized by optimizing the vegetation configuration along the water bodies and controlling the height of buildings. The risks of ESSDR_B6, dominated by woodland, are mainly BC, NP and PP. Therefore, the nature reserve area should be enlarged, and the regulation should be strengthened to minimize habitat disturbance caused by human activities. In addition, the function of forest ecosystems should be restored and even strengthened through the restoration of the vegetation structure.

4.4. Limitations and prospects

A novel approach for assessing ESSD risks was proposed in this study by considering the spatiotemporal dynamics of the ecological-socio-economic system. Also, SOM was employed in this study to develop spatially explicit management strategies for mitigating multiple ESSD risks. But this study has the following limitations and uncertainties.

First, the flow process of ESF in space involves a series of complex biophysical processes influenced by various factors in the ecological and socioeconomic system. However, as this study focused on large-scale urban agglomeration, the spatial modeling of ESF at the raster scale was based on the simplified hypothesis. Future studies should further consider the impacts of different characteristics of the flow carriers and regional ecosystems (e.g., land cover, climatic conditions, and atmospheric conditions), as well as the socioeconomic context of the demand area (e.g., grey infrastructure, policy orientations, and trade and consumption patterns) on the pathways, losses, and receiving efficiency of ESFs, to make spatial simulations of ESF more consistent with real-world processes.

Second, although this study has integrated the current and historical temporal dynamics in assessing ESSD risks, the following studies could further expand the temporal scale to consider future ES supply and demand trends. Particularly for urban agglomerations facing multiple uncertain disturbances such as the coupling impact of urbanization-climate change, protecting areas that will face low-to-high ESSD risks transition is crucial to mitigate or even curb the predictable loss of human well-being promptly.

In addition, it should also be noted that, although the spatially-targeted ecosystem management strategies were proposed in this study, future studies could incorporate the management cost-benefit ratio perspective by using methods such as cost-function analysis or multi-scenario simulation to clarify the prioritized intervention in space. This would help to develop a phased implementation plan, which is of strong practical meaning for improving the efficiency of ecosystem management in the large-scale urban agglomeration.

Table 2
Prioritization of ES protection and restoration within the 6 risk bundles of the YRDUA.

		Bundle					
		ESSDR_B1	ESSDR_B2	ESSDR_B3	ESSDR_B4	ESSDR_B5	ESSDR_B6
Prioritization of ecosystem management objectives	1	HTR	SR	HTR	NP	HTR	BC
	2	CS	HTR	NP	PP		NP
	3	NP	PP	PP	HTR		PP
	4	PP	NP	FP	WY		
	5	FP			FP		

Note: Ecosystem management priorities were ranked in ascending order based on the average ESSD risk for each ES within each bundle (ESs at medium to low risk are not involved in the ranking).

5. Conclusion

This study proposed an ESSD risk assessment and management framework, including four key steps: evaluating ES supply, demand and flow, incorporating ESF to quantify ESSD across various timeframes, assessing ESSD risks based on the current status and dynamic trends, and using Self-Organizing Map to identify optimal ESSDR_Bs along with the formulation of targeted ecological management strategies. The results showed significant spatiotemporal heterogeneity in the supply, demand, ESF, and supply-demand relationships of 9 ESs from 2005 to 2020. Despite ESFs mitigating the mismatch between ES supply and demand to some extent, most areas within the YRDUA still faced deficits in ESSD. Notably, HTR, NP, and PP exhibited high ESSD risks. Conversely, the ESSD risks of BC, CS, SR, WY, and TC were low, generally maintaining surpluses, yet a concerning trend of decreasing surpluses was observed across most YRDUA. The high ESSD risk areas of the 9 ESs were mainly located in the eastern, coastal cities, and the north-central farming regions of YRDUA. Specifically, the highly urbanized areas in the southeast showed severe ESSD deficits in BC, HTR, CS, FP, and TC, with the ESSD deficits of BC, HTR, and CS worsening over time in both magnitude and scope, while the ESSD deficits of FP and TC lessened. The plains and paddy fields of the north-central region experienced deepening ESSD deficits in NP and PP year by year, whereas the dry land areas saw some relief. Additionally, high ESSD deficits of SR were observed in the grain farming areas and the built-up regions of the central and eastern coasts, with these deficits intensifying annually.

The bundle identification results from the SOM showed six ESSDR_Bs within the YRDUA. ESSDR_B1 and ESSDR_B4 were predominantly located in the central city like Shanghai and within the five major metropolitan areas. There was an urgent need within ESSDR_B1 to enhance climate regulation services, whereas ESSDR_B4 was more significantly characterized by risks of water scarcity and pollution. Influenced by agricultural practices and water system distribution, ESSDR_B2 and ESSDR_B3—located in the northern and central farmlands, near Hangzhou Bay, and in the southeast's coastal regions—should prioritize the management of soil erosion and water pollution, respectively. ESSDR_B5, located along the water bodies' coastlines and the southeast coast, saw HTR at a medium to high ESSD risk threshold. ESSDR_B6, found in the ecological barrier of the western Anhui Dabie Mountains and southern Anhui-western Zhejiang-southern Zhejiang, facet lower ESSD risks. Considering the predominant ESSD risks and the ecological-socioeconomic context within each bundle, we proposed differentiated ecological management strategies. Overall, the ESSD risk assessment and management framework introduced by this study is also applicable to other highly urbanized urban agglomerations, providing a fresh perspective for achieving more efficient and precise urban agglomeration ESSD risk regulation.

CRediT authorship contribution statement

Yuting Huang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Yarong Cao:** Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Juanyu Wu:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Abbreviations list

ES	ecosystem service
ESSD	ecosystem service supply-demand
ESF	ecosystem service flow
SPAN	service path attribute network
ESSDR_B	ecosystem service supply-demand risk bundle
YRDUA	Yangtze River Delta Urban Agglomeration
BC	biodiversity conservation
HTR	high temperature regulation
CS	carbon sequestration
NP	nitrogen purification
PP	phosphorus purification
SR	soil retention
WY	water yield
FP	food production
TC	tourism culture
STI	supply trend index
DTI	demand trend index
SDI	supply-demand index
SDTI	supply-demand trend index
ESF_out	ES outflow
SOM	Self-Organizing Map

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142598.

References

Agudelo, C.A.R., Bustos, S.L.H., Moreno, C.A.P., 2020. Modeling interactions among multiple ecosystem services. A critical review. Ecol. Model. 429, 109103 https://doi.org/10.1016/j.ecolmodel.2020.109103.

Bagstad, K.J., Johnson, G.W., Voigt, B., Villa, F., 2013. Spatial dynamics of ecosystem service flows: a comprehensive approach to quantifying actual services. Ecosyst. Serv. 4, 117–125. https://doi.org/10.1016/j.ecoser.2012.07.012.

Baró, F., Gómez-Baggethun, E., Haase, D., 2017. Ecosystem service bundles along the urban-rural gradient: insights for landscape planning and management. Ecosyst. Serv. 24, 147–159. https://doi.org/10.1016/j.ecoser.2017.02.021.

Boesing, A.L., Prist, P.R., Barreto, J., Hohlenwerger, C., Maron, M., Rhodes, J.R., et al., 2020. Ecosystem services at risk: integrating spatiotemporal dynamics of supply and demand to promote long-term provision. One Earth 3, 704–713. https://doi.org/10.1016/j.oneear.2020.11.003.

Burkhard, B., Kandziora, M., Hou, Y., Müller, F., 2018. Ecosystem service potentials, flows and demands -concepts for spatial localisation, indication and quantification. Landscape Online 34. https://doi.org/10.3097/LO.201434.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecol. Indicat. 21, 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019.

Chen, H., Yan, W., Li, Z., Wende, W., Xiao, S., Wan, S., et al., 2022. Spatial patterns of associations among ecosystem services across different spatial scales in metropolitan areas: a case study of Shanghai, China. Ecol. Indicat. 136, 108682 https://doi.org/10.1016/j.ecolind.2022.108682.

Chen, M., Tan, Y., Xu, X., Lin, Y., 2024. Identifying ecological degradation and restoration zone based on ecosystem quality: a case study of Yangtze River Delta. Appl. Geogr. 162, 103149 https://doi.org/10.1016/j.apgeog.2023.103149.

China Development and Reform Commission, 2013. C. National Ecological Protection and Construction Plan (2013-2020), vol. 2020. https://www.ndrc.gov.cn/fzggw/jgsj/njs/sjdt/201411/t20141119_1194736.html.

China Development and Reform Commission, 2021. C. China's technical guidelines for the delineation of ecological protection red Lines. https://www.mee.gov.cn/gkml/hbb/bgt/201707/t20170728_418679.html.
China, S.C.o., 2017. National new urbanization plan (2014-2020). https://www.gov.cn/xinwen/2014-03/17/content_2639873.html.
China Statistics Bureau, 2021. China Statistical Yearbook. https://www.stats.gov.cn/sj/ndsj/.
Commission, C.N.D.a.R., 2017-07-20/2021-11-05. China's Technical Guidelines for the Delineation of Ecological Protection Red Lines. https://www.mee.gov.cn/gkml/hbb/bgt/201707/t20170728_418679.html.
DeFries, R., Nagendra, H., 2017. Ecosystem management as a wicked problem. Science 356, 265. https://doi.org/10.1126/science.aal1950.
Dittrich, A., Seppelt, R., Václavík, T., Cord, A.F., 2017. Integrating ecosystem service bundles and socio-environmental conditions – a national scale analysis from Germany. Ecosyst. Serv. 28, 273–282. https://doi.org/10.1016/j.ecoser.2017.08.007.
Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.
Gómez-Baggethun, E., Gren, A., Barton, D.N., Langemeyer, J., O'Farrell, P., 2013. Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment. springer, pp. 10–22. https://doi.org/10.1007/978-94-007-7088-1.
Gou, M., Li, L., Ouyang, S., Wang, N., La, L., Liu, C., et al., 2021. Identifying and analyzing ecosystem service bundles and their socioecological drivers in the Three Gorges Reservoir Area. J. Clean. Prod. 307, 127208 https://doi.org/10.1016/j.jclepro.2021.127208.
Guan, Q., Hao, J., Ren, G., Li, M., Chen, A., Duan, W., et al., 2020. Ecological indexes for the analysis of the spatial–temporal characteristics of ecosystem service supply and demand: a case study of the major grain-producing regions in Quzhou, China. Ecol. Indicat. 108, 105748 https://doi.org/10.1016/j.ecolind.2019.105748.
Han, Y., Gao, X., Gao, J., Xu, Y., Liu, C., 2010. Typical ecosystem services and evaluation indicator system of significant eco-function areas. Ecology and Environmental Sciences 19, 2986–2992. https://doi.org/10.16258/j.cnki.1674-5906.2010.12.025.
Huang, Y., Ma, R., Zhou, W., Yuan, Y., Ren, J., Cao, Y., 2023. Risk assessment and regulation between the supply and demand of ecological products: a comprehensive framework and case study. Ecol. Indicat. 154, 110617 https://doi.org/10.1016/j.ecolind.2023.110617.
IPCC, 2022. AR6 Synthesis Climate Change ipcc.ch/report/sixth-assessment-report-cycle.
Jiang, C., Yang, Z., Wen, M., Huang, L., Liu, H., Wang, J., et al., 2021. Identifying the spatial disparities and determinants of ecosystem service balance and their implications on land use optimization. Sci. Total Environ. 793, 148472 https://doi.org/10.1016/j.scitotenv.2021.148472.
Jr, W., Poulsen, V., Gala, W., Marshall, S., Stackelberg, K.V., 2017. Ecosystem services in risk assessment and management. Integrated Environ. Assess. Manag. 13, 62–73. https://doi.org/10.1002/ieam.1835.
Kleemann, J., Schröter, M., Bagstad, K.J., Kuhlicke, C., Kastner, T., Fridman, D., et al., 2020. Quantifying interregional flows of multiple ecosystem services – a case study for Germany. Global Environ. Change 61, 102051. https://doi.org/10.1016/j.gloenvcha.2020.102051.
Kohonen, T., 1982. Self-organized formation of topologically correct feature maps. Biol. Cybern. 43, 59–69. https://doi.org/10.1007/BF00337288.
La Notte, A., Vallecillo, S., Maes, J., 2019. Capacity as "virtual stock" in ecosystem services accounting. Ecol. Indicat. 98, 158–163. https://doi.org/10.1016/j.ecolind.2018.10.066.
Liang, Y., Cai, W., Ma, M., 2019. Carbon dioxide intensity and income level in the Chinese megacities' residential building sector: decomposition and decoupling analyses. Sci. Total Environ. 677, 315–327. https://doi.org/10.1016/j.scitotenv.2019.04.289.
Liu, H., Fan, Y.L., Ding, S.Y., 2016a. Research progress of ecosystem service flow. Chin. J. Appl. Ecol. 27, 2161–2171. https://doi.org/10.13287/j.1001-9332.201607.005.
Liu, H.M., Fan, Y.L., Ding, S.Y., 2016b. [Research progress of ecosystem service flow.]. J. Appl. Ecol. 27, 2161–2171. https://doi.org/10.13287/j.1001-9332.201607.005.
Liu, W., Zhan, J., Zhao, F., Zhang, F., Teng, Y., Wang, C., et al., 2022. The tradeoffs between food supply and demand from the perspective of ecosystem service flows: a case study in the Pearl River Delta, China. J. Environ. Manag. 301, 113814 https://doi.org/10.1016/j.jenvman.2021.113814.
Locatelli, B., Imbach, P., Vignola, R., Metzger, M.J., Leguia Hidalgo, E.J., 2011. Ecosystem services and hydroelectricity in Central America: modelling service flows with fuzzy logic and expert knowledge. Reg. Environ. Change 11, 393–404. https://doi.org/10.1007/s10113-010-0149-x.
Longato, D., Cortinovis, C., Albert, C., Geneletti, D., 2021. Practical applications of ecosystem services in spatial planning: lessons learned from a systematic literature review. Environ. Sci. Pol. 119, 72–84. https://doi.org/10.1016/j.envsci.2021.02.001.
Lyu, Y., Wang, M., Zou, Y., Wu, C., 2022. Mapping trade-offs among urban fringe land use functions to accurately support spatial planning. Sci. Total Environ. 802, 149915 https://doi.org/10.1016/j.scitotenv.2021.149915.
Ma, M., Cai, W., Cai, W., Dong, L., 2019. Whether carbon intensity in the commercial building sector decouples from economic development in the service industry? Empirical evidence from the top five urban agglomerations in China. J. Clean. Prod. 222, 193–205. https://doi.org/10.1016/j.jclepro.2019.01.314.
Mæstad, O., Norheim, O.F., 2012. A universal preference for equality in health? Reasons to reconsider properties of applied social welfare functions. Soc. Sci. Med. 75, 1836–1843. https://doi.org/10.1016/j.socscimed.2012.07.001.
Maron, M., Mitchell, M.G.E., Runting, R.K., Rhodes, J.R., Mace, G.M., Keith, D.A., et al., 2017. Towards a threat assessment framework for ecosystem services. Trends Ecol. Evol. 32, 240–248. https://doi.org/10.1016/j.tree.2016.12.011.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being, vol. 5. Island press, Washington, DC. https://www.millenniumassessment.org/documents/document.356.aspx.pdf.
Ministry of Culture and Tourism of China, 2021. China Culture and Tourism Yearbook. CCTY. https://www.mct.gov.cn/gywhb/jgsz/zgxwcbdw_jgsz/zzs_zgxwcbdw/201904/t20190416_842837.htm.
Ministry of Natural Resources of China, 2020. Resource and environmental carrying capacity and territorial spatial development guidelines for evaluation. https://www.gov.cn/zhengce/zhengceku/2020-01/22/content_5471523.htm.
Ministry of Water Resources of China, 2016. List of National Important Drinking Water Sources, vol. 2016. https://www.mwr.gov.cn/zw/tzgg/tzgs/201702/t20170213_858881.html.
National Development and Reform Commission and Ministry of Natural Resources, C, 2020. Overall plan for major projects for the protection and restoration of nationally important ecosystems (2021-2035). https://www.gov.cn/zhengce/zhengceku/2020-06/12/content_5518982.htm.
National Development and Reform Commission, C, 2015. Development plan of the Yangtze River Delta city urban agglomeration. https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/201606/W020190905497826154295.pdf.
Peng, J., Xia, P., Liu, Y., Xu, Z., Zheng, H., Lan, T., et al., 2023. Ecosystem services research: from golden era to next crossing. Transactions in Earth, Environment, and Sustainability 1, 9–19. https://doi.org/10.1177/2754124X231165935.
PRC Ministry of Ecology and Environment, 2015. M. National ecological function zoning. https://www.mee.gov.cn/xxgk2018/xxgk/xzgfxwj/202301/W020151126550511267548.pdf.
Quintas-Soriano, C., Garcia-Llorente, M., Norstrom, A., Meacham, M., Peterson, G., Castro, A.J., 2019. Integrating supply and demand in ecosystem service bundles characterization across Mediterranean transformed landscapes. Landsc. Ecol. 34, 1619–1633. https://doi.org/10.1007/s10980-019-00826-7.
Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. U.S.A. 107, 5242–5247. https://doi.org/10.1073/pnas.0907284107.
Serna-Chavez, H.M., Schulp, C.J.E., van Bodegom, P.M., Bouten, W., Verburg, P.H., Davidson, M.D., 2014. A quantitative framework for assessing spatial flows of ecosystem services. Ecol. Indicat. 39, 24–33. https://doi.org/10.1016/j.ecolind.2013.11.024.
Shi, Y., Shi, D., Zhou, L., Fang, R., 2020. Identification of ecosystem services supply and demand areas and simulation of ecosystem service flows in Shanghai. Ecol. Indicat. 115, 106418 https://doi.org/10.1016/j.ecolind.2020.106418.
Van Hecken, G., Bastiaensen, J., 2010. Payments for ecosystem services: justified or not? A political view. Environ. Sci. Pol. 13, 785–792. https://doi.org/10.1016/j.envsci.2010.09.006.
Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and flow: a conceptual framework for analyzing ecosystem service provision and delivery. Ecol. Complex. 15, 114–121. https://doi.org/10.1016/j.ecocom.2013.07.004.
Vitousek, P.M., 1997. Human domination of Earth's ecosystems. Science 278, 21–24. https://doi.org/10.1007/978-0-387-73412-5_1.
Wang, L.-J., Gong, J.-W., Ma, S., Wu, S., Zhang, X., Jiang, J., 2022a. Ecosystem service supply–demand and socioecological drivers at different spatial scales in Zhejiang Province, China. Ecol. Indicat. 140, 109058 https://doi.org/10.1016/j.ecolind.2022.109058.
Wang, L., Zheng, H., Chen, Y., Ouyang, Z., Hu, X., 2022b. Systematic review of ecosystem services flow measurement: main concepts, methods, applications and future directions. Ecosyst. Serv. 58, 101479 https://doi.org/10.1016/j.ecoser.2022.101479.
Wu, J., Huang, Y., Jiang, W., 2022. Spatial matching and value transfer assessment of ecosystem services supply and demand in urban agglomerations: a case study of the Guangdong-Hong Kong-Macao Greater Bay area in China. J. Clean. Prod. 375, 134081 https://doi.org/10.1016/j.jclepro.2022.134081.
Xia, H., Yuan, S., Prishchepov, A.V., 2023. Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: implications for spatial planning and management. Resour. Conserv. Recycl. 189 https://doi.org/10.1016/j.resconrec.2022.106767.
Xie, Y., Zhang, S., Lin, B., Zhao, Y., Hu, B., 2020. Spatial zoning for land ecological consolidation in Guangxi based on the ecosystem services supply and demand. J. Nat. Resour. 35, 217–229. https://doi.org/10.31497/zrzyxb.20200118.
Xin, R., Skov-Petersen, H., Zeng, J., Zhou, J., Li, K., Hu, J., et al., 2021. Identifying key areas of imbalanced supply and demand of ecosystem services at the urban agglomeration scale: a case study of the Fujian Delta in China. Sci. Total Environ. 791, 148173 https://doi.org/10.1016/j.scitotenv.2021.148173.
Zhai, T., Wang, j., Jin, Y., Qi, Y., 2019. Change and correlation analysis of the supply-demand pattern of ecosystem services in the Yangtze River Economic Belt. Acta Ecol. Sin. 39, 5414–5424. https://doi.org/10.5846/stxb201808261825.
Zhang, H., Feng, J., Zhang, Z., Liu, K., Gao, X., Wang, Z., 2020. Regional spatial management based on supply-demand risk of ecosystem services-A case study of the

fenghe river watershed. Int. J. Environ. Res. Publ. Health 17, 4112. https://doi.org/10.3390/ijerph17114112.
Zhang, M., Xiao, H., Sun, D., Li, Y., 2018. Spatial differences in and influences upon the sustainable development level of the Yangtze River Delta urban agglomeration in China. Sustainability 10, 411. https://doi.org/10.3390/su10020411.
Zhang, X., Wang, X., Cheng, C., Liu, S., Zhou, C., 2021. Ecosystem service flows in Karst area of China based on the relationship between supply and demand. Acta Ecol. Sin. 41, 3368–3380. https://doi.org/10.5846/stxb202006161566.