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RESEARCH ARTICLE

Integrating the functions and structures to assess ecological network sustainability under climate change scenarios

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Abstract
Context Developing ecological networks (ENs) is a widely acknowledged conservation strategy for mitigating habitat fragmentation and ecosystem degradation. Therefore, it is crucial to assess the sustainability of the ENs before or after their development in order to maintain their functions and ecosystem service. While most previous studies have explored ENs based on ecosystem service evaluation and structure construction, the functions and structures of EN have rarely been integrally assessed under climate change scenarios.

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Objective Taking the Yangtze River Delta urban agglomeration as the study area, we aim to assess the future sustainability of the current EN under multiple climate change scenarios by integrating its functions and structures.
Methods Ten scenarios were constructed, including a current scenario and nine future climate scenarios. Ecological sources were derived from the importance of the ecosystem service, and were used to develop EN by using the Linkage mapper toolbox. We then used the range difference between current and future ecological sources to indicate the functional sustainability of the current EN. The NetworkX was used to assess the EN structural stability by integrating the EN functional sustainability.
Results The capacity of 6.23% of the current ecological sources is projected to decline in efficiently providing ecosystem services by 2050 under the selected nine future climate scenarios, and these functional degradations will also lead to a 33.55% decrease in the EN structural stability. Poor, low, and medium functional sustainable sources will be mostly located in forests and water bodies of the central YRDUA with a small average patch area, while high functional sustainable sources will be mainly distributed in the southwestern mountainous regions and water areas in the north-central region with a larger average patch area.
Conclusion Our study provides a prospective assessment of EN, which is particularly crucial for enhancing ecological strategies and ensuring

landscape sustainability. Constructing future climate scenarios and integrally assessing EN functional sustainability and structural stability can provide effective information for long-term EN management.

Keywords Ecological network · Functional sustainability · Network structural stability · Climate change scenario · Urban landscape planning

Introduction

Widespread and rapid climate changes have been verified, and human-induced warming will continue to intensify the negative impacts on the terrestrial environment (Hoegh-Guldberg et al. 2019; IPCC 2018). As a result, the structure and function of regional ecosystems will be affected to varying degrees across diverse geographic areas, compromising their abilities to deliver ecosystem services (Jackson 2020; Pecl et al. 2017). These challenges are anticipated to become more severe in the future when linked with stresses from built-up area expansion and human activities, especially in urban agglomeration areas (Hobbie and Grimm 2020; Mu et al. 2022). Given this, broad and prompt responses in policy sectors are required to deliver effective ecological strategies and actions (Moore et al. 2021).

Ecological networks (ENs) refer to a system of the nested network that connects adjacent habitats (sources) through corridors to maintain the integrity and continuity of the whole landscape (Opdam et al. 2006). Constructing ENs has been widely proposed as an effective and comprehensive spatial regulation strategy for biodiversity conservation, maintaining and enhancing ecosystem benefits (Kong et al. 2010). On the one hand, ENs can frame the location and configuration of regionally important ecosystem services to implement spatial prioritization strategies. On the other hand, ENs can be well-managed to optimize the delivery pattern of ecological flows and actively enhance landscape interface penetration (Metzger et al. 2021). The sources of EN are usually those natural resource patches, which are not only important habitats for the survival of species and of migration but can also provide other kinds of ecosystem services (Dickson et al. 2017; Su et al. 2016). Therefore, identifying and optimizing potential ecological corridors to link to those sources can reinforce broad ecological flows and resist landscape fragmentation caused by the disturbance of land use and climate changes (Hirayama et al. 2020; Kong et al. 2021).

Over the past decades, numerous researches and application policies of EN have been globally documented, e.g. Pan-European Ecological Networks and Mesoamerican Biological Corridors (Hernández et al. 2022; Jones-Walters 2007). EN research frameworks have commonly been divided into functional and structural technical routes according to their aims (Shen et al. 2022). The function-oriented strategies stress the ecosystem service assessment, e.g., providing habitats, conserving soil and water resources, as well as trade-offs and synergy analyses (Metzger et al. 2021; Xiao et al. 2020). In this respect, geospatial models, such as InVEST, SolVES, and ARIES, have been widely used to evaluate ecosystem services and reveal the heterogeneity of spatial distribution (Martínez-López et al. 2019; Sherrouse et al. 2022). These models can effectively identify important natural resources and provide a reliable reference for EN construction. Nevertheless, the structure-oriented strategies concerning EN structural attributes, involve a series of landscape metrics such as quantity, proximity, connectivity, cohesion, and heterogeneity at the patch, class, and landscape levels (Cook 2002; Kupfer 2012). They provide explicit spatial information on landscape patches by graph theory and complex network analysis, aiming to improve environmental benefits by optimizing the network topology (De Montis et al. 2016; Petsas et al. 2021).

Landscape sustainability primarily refers to the capacity of a landscape to consistently provide landscape-specific ecosystem services (Wu 2013). The interactions between the function and structure of a landscape mainly determine its capacity to sustain these ecosystem services (Wu 2021). Therefore, as a vital spatial form within landscapes, the function sustainability of EN means that EN can consistently maintain the ecosystem service, which can then be quantified through the evaluation of ecosystem services (Fan et al. 2021; Hao et al. 2017). The structural stability of EN is that the EN can still maintain overall connectivity and keep providing ecosystem services when its components are disrupted, which is usually being characterized by topological metrics (Gonzalez et al. 2017; Yu et al. 2018). The sustainability of EN requires the integration evaluation of both the function and structure. However, functional sustainability and structural stability of EN have not yet been integrated into the EN assessment, even under the increasing demand for a more comprehensive assessment. For example, research on ecosystem service spatiotemporal changes has rarely delved into the influence of ecological source range shifts on network structural stability, which are induced by functional degradation (Evans et al. 2013). Since previous series of studies have found that spatial patterns and ecological benefits of current ENs will be compromised in the coming decades due to rising temperatures and extreme precipitation (Koomen et al. 2012; Michalak et al. 2020). These incomplete evaluations may lead to an overestimation of the EN's ability to resist external disturbances caused by climate change (Isaac et al. 2018). Simultaneously, such one-sided landscape evaluation also cannot provide efficient and comprehensive information to support long-term management and ecological restoration of ENs. Therefore, it is crucial to find out the potential risks that EN function and structure may face in the future and then subsequently improve ecological conservation strategies for sustainable EN management (Liu and Wu 2022; Termorshuizen et al. 2007).

Taking the Yangtze River Delta urban agglomeration (YRDUA) as the study area, this study first constructs multiple future climate scenarios using three global circulation models (GCM) of Shared Socioeconomic Pathways (SSP). Then, by integrating an analysis of the functions and structures of EN, this study assesses the sustainability of EN under these future climate scenarios. The results of this study can provide valuable information for developing ecological strategies and implementing effective measures to ensure the sustainability of EN during its management.

Study area and data

Study area

The Yangtze River Delta urban agglomeration (YRDUA) is located in the central-eastern coastline of China and consists of Shanghai City, Jiangsu Province, Zhejiang Province, and Anhui Province, with a total area of 3.58×10^5 km^2 (Fig. 1). Over the past decades, the built-up land area has expanded rapidly, and the population density has reached its highest across the nation (Su et al. 2021). Meanwhile, the regional climate conditions have also evidently changed. The average annual temperature and extreme precipitation have continued to rise (Jiang et al. 2020). As a result, the regional ecosystem is facing significant challenges from both human activities and climate change. However, as a demonstration area of implementing national ecological strategies in China, there is an urgent need to formulate effective measures to address potential regional ecological risks. Establishing and assessing ENs can provide solid support for policy-making and practical actions.

Data sources and preprocessing

The types and sources of input datasets are shown in Table 1, including land use/land cover (LULC), climate, human footprint (HFP), and the geographic auxiliary dataset. The LULC data of YRDUA in 2020 and 2030–2050 were classified into six categories, i.e., forest, grassland, cropland, water body, built-up land, and unused land (Liao et al. 2020). We combined three GCMs under SSP (EC-Earth3, GFDL-ESM4, and MRI-ESM2-0), and used their corresponding annual mean temperature and annual precipitation to produce the future climate prediction. The geographic auxiliary dataset includes the Potential Evapotranspiration (PET), Digital Elevation Model (DEM), Normalized Difference Vegetation Index (NDVI), Net Primary Production (NPP) and road dataset. All datasets were finally converted to a consistent projected coordinate system and resampled to 1 × 1 km raster data.

Methods

Figure 2 illustrates the methodological framework of this study. First, we constructed ten scenarios based on temperature, precipitation and land use, which includes a current scenario (2020) and nine future scenarios (2030, 2040, 2050 under SSP1-1.9, SSP2-4.5, and SSP5-8.5 scenarios). Second, ecological sources were derived from the importance of the ecosystem service, and are used to develop EN by using the Linkage mapper toolbox (https://linkagemapper.org/). Third, we used the range difference between current and future ecological sources to indicate the functional sustainability of the current EN.

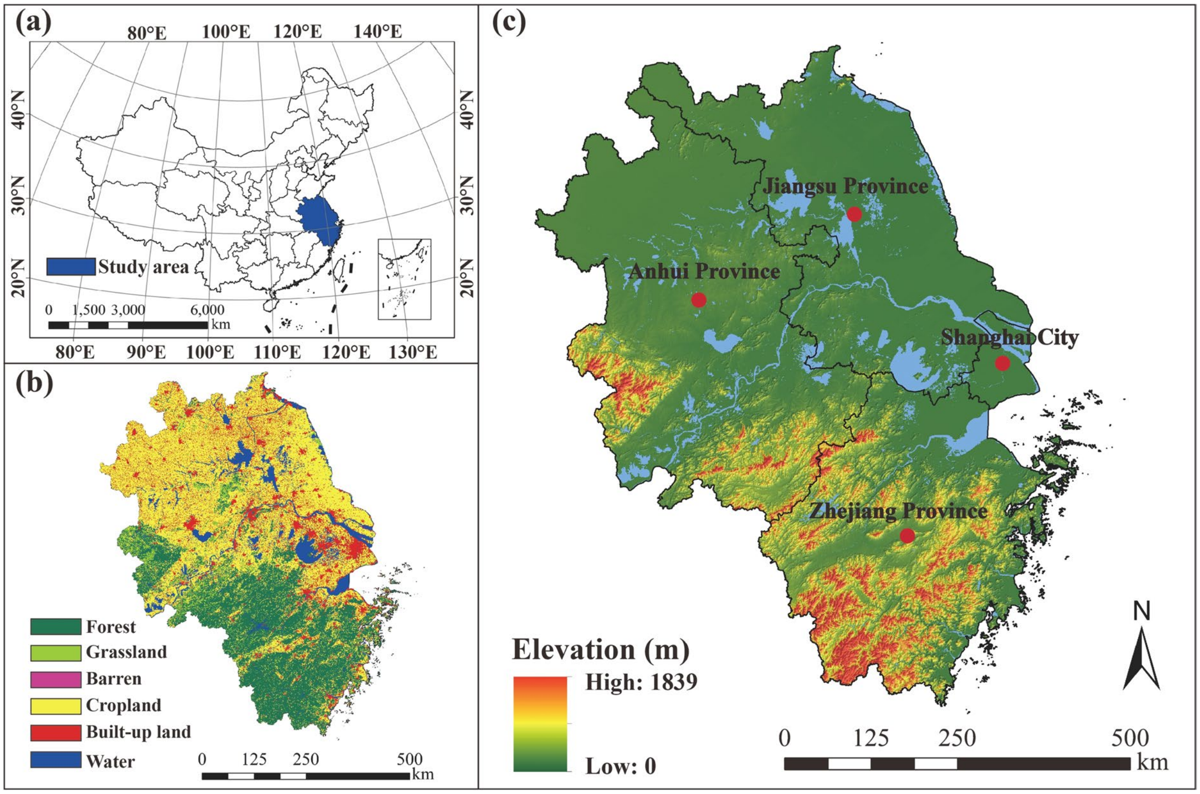


Fig. 1 Maps of the study area. **a** Location of YRDUA, **b** Land use types, and **c** landforms

Table 1 Datasets and data sources

Data	Resolution	Time	Data source
LULC	1 × 1 km	2020	Resources and environmental science data center (https://www.resdc.cn/)
LULC	1 × 1 km	2030, 2040, 2050	Liao et al. (2020)https://www.geosimulation.cn/China_PFT_SSP-RCP.html
Annual precipitation	1 × 1 km	2020, 2030, 2040, 2050	National Earth system science data center (http://www.geodata.cn)
Annual average temperature	1 × 1 km	2020, 2030, 2040, 2050	
PET	1 × 1 km	2020	National tibetan plateau data center (https://doi.org/10.11866/db.loess.2021.001)
DEM	500 × 500 m	2020	GEBCO Compilation Group (https://doi.org/10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c)
NDVI	500 × 500 m	2020	Modis (https://modis.gsfc.nasa.gov/)
NPP	500 × 500 m	2020	Modis (https://modis.gsfc.nasa.gov/)
HFP	1 × 1 km	2018	Mu et al. (2022)https://doi.org/10.6084/m9.figshare.16571064.v5
Road	–	2020	OpenStreetMap (https://www.openstreetmap.org/)

Finally, using the NetworkX (https://networkx.org/), we calculated three structural metrics (i.e., maximum connectivity, transitivity, and efficiency) of the EN to assess the structural stability of the EN when the

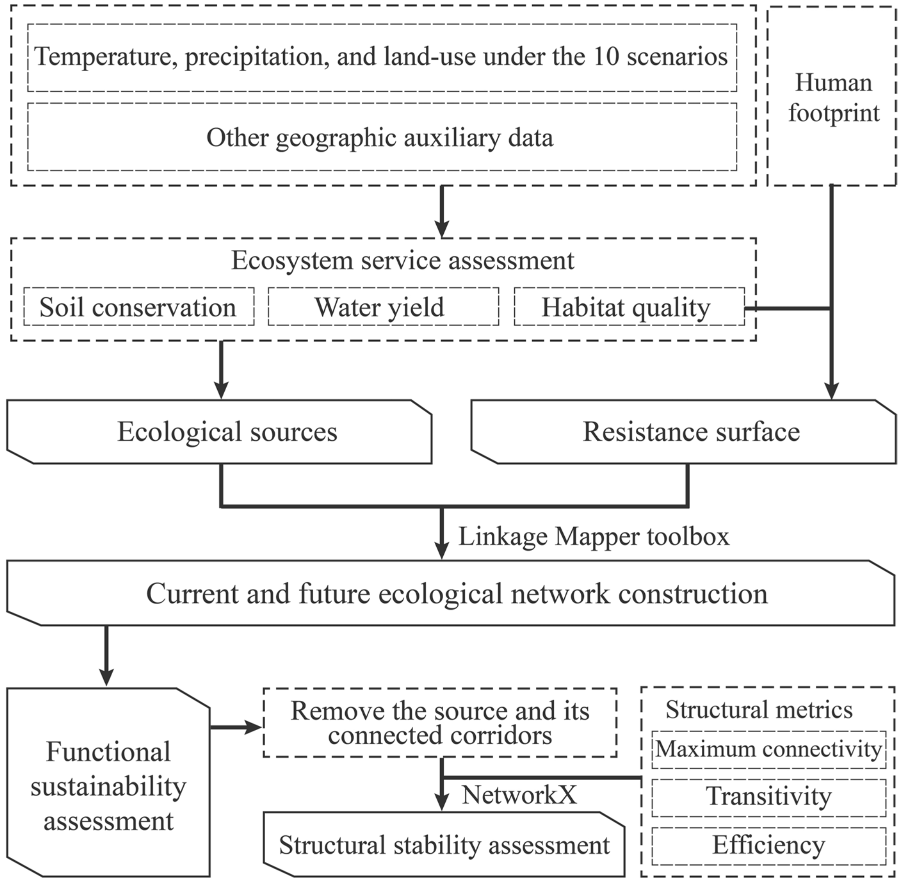


Fig. 2 Illustration of the methodological framework

source and corridors connected to this source were removed from the EN. We repeated this calculation process until the last source was removed. Detailed descriptions are provided in the following sections.

Climate scenarios construction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment assessed and reported five scenarios, namely SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, as uniformly distributed and of high priority climate scenarios. These five scenarios correspond to radiative forcing levels associated with an approximate global temperature increase of 1.9 °C, 2.6 °C, 4.5 °C, 7.0 °C, and 8.5 °C above pre-industrial levels by the century's end, respectively. In order to represent the possible range of future temperature increases and highlight the differences between climate scenarios, we selected SSP1-1.9, SSP2-4.5, and SSP5-8.5 scenarios to analyze the climate and land use change impact on EN. Using the data from the years 2030, 2040, and 2050, we constructed nine future scenarios, i.e., SSP1-1.9-2030, SSP2-4.5-2030, SSP5-8.5-2030, SSP1-1.9-2040, SSP2-4.5-2040, SSP5-8.5-2040, SSP1-1.9-2050, SSP2-4.5-2050, and SSP5-8.5-2050. Hence, the scenarios of this study include one current scenario and nine future scenarios.

Ecological network development

Identifying ecological sources through ecosystem service assessment

Ecosystem services including habitat quality, soil conservation and water yield which are all sensitive to climate or land use change, have been widely used and now accepted as important indices to select the ecological sources for the EN construction (Mengist et al. 2021; Peng et al. 2018). The assessments of these ecosystem services are shown as follows.

Habitat quality Habitat quality (HQ) represents the potentiality to provide suitable environments for organisms (Moreira et al. 2018). In this study, we used the HQ module in the InVEST model (https://naturalcapitalproject.stanford.edu/software/invest) and the biodiversity maintenance formula together to evaluate HQ (Kang et al. 2021). The built-up land, cropland, unused land, railroads, state highways, and urban roads were used to indicate the threats to the HQ. The main formulas are as follows:

$$Q_{xj} = H_j\left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right) \quad (1)$$

where Q_{xj} is the habitat quality of grid x within landscape type j; H_j is the habitat suitability of the landscape j; D_{xj} is the threat level of grid x in the landscape type j; z is a constant and k is the scaling parameters.

$$S_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt}) \quad (2)$$

where S_{bio} is an index indicating the capacity of maintaining biodiversity, NPP_{mean}, F_{pre} and $F_{tem}$is the annual average of vegetation net primary productivity, precipitation, and temperature, respectively, F_{alt} is normalized elevation factor.

Soil conservation Soil conservation service is the ability of an ecosystem to conserve soil and nutrients, which is important for preventing the degradation of land functions (Phinzi and Ngetar 2019). In this study, we used Revised Universal Soil Loss Equation (RUSLE) to assess soil erosion. The formula is as follows:

$$A = R \times K \times LS \times (1 - C \times P) \quad (3)$$

where A is the average annual soil conservation; R is the rainfall erosion factor; K is the soil erodibility factor; LS is the terrain factor; C is the crop management factor and P is the erosion control practice factor.

Water yield Water yield refers to the amount of water runoff from the landscapes, which is determined by various factors such as land use type, climate, and topographic conditions (Sharp et al. 2014). This study used the water yield module in the InVEST model to quantify the water yield capacity of different landscape types. The formula is as follows:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \quad (4)$$

where Y_x is the amount of annual water yield for grid x, AET_x is the actual annual average evapotranspiration of grid x, P_x is the average annual rainfall of grid x.

Referring to previous studies (Michalak et al. 2020), we selected those areas that had ecosystem service values in the top 30% for each type of service, and mosaiced these areas to create potential ecological sources, and then we removed small fragmented patches less than 10 km^2 as they contributed weakly to the regional EN, to generate the final ecological sources.

Developing ecological network

Resistance surface describes the difficulty of species when moving over different landscapes (Kong et al. 2010). In this study, we calculated the inverse of the habitat quality and corrected them with HFP to obtain the resistance surface (Su et al. 2021). Then, the ecological corridors and cumulative current values near the corridors were identified using the Linkage Mapper toolbox (Grafius et al. 2017; Mcrae and Beier 2007).

Assessing functional sustainability and structural stability of ecological network

Assessing functional sustainability of ecological network

Due to the impact of climate and land use change, some current ecological sources (CESs) will experience a decline in their capability to provide ecosystem services and may not be recognized as sources in the future. Given this, we defined the duration of efficient ecosystem service provision of CESs as its functional sustainability. The longer the duration, the higher do CESs have the functional sustainability. We then classified CES into four levels according to the functional sustainability, i.e., poor, low, medium, and high levels. The first three levels indicate that under multiple future climate scenarios, CES could efficiently provide multiple ecosystem services until 2030, 2040, and 2050, respectively, and CES at the high level could still provide services beyond 2050. Thereafter, we abbreviated the CES with poor, low, medium, and high functional sustainability as PFSS (poor functional sustainable sources), LFSS (low functional sustainable sources), MFSS (medium functional sustainable sources), and HFSS (high functional sustainable sources), respectively, to indicate the functional sustainability of the current EN.

Assessing structural stability of ecological network

NetworkX is a Python package that offers several tools to load the EN structure in the Python environment, and automatize deterministic attacks to the EN (Hagberg et al. 2008). In this study, ecological sources were recognized as nodes, and corridors were recognized as edges through the NetworkX. The deterministic attack for the EN includes three rules: (1) All edges directly connected to the node will be removed when removing the node (De Montis et al. 2019). (2) Nodes with low functional sustainability will be removed first. Therefore, PFSS will be removed first, followed by LFSS, MFSS, and finally HFSS. (3) The nodes with a high human footprint will be removed in priority, when the nodes have the same functional sustainability level (Fig. 3).

Then, the network's maximum connectivity (NS), transitivity (T), and efficiency (E) were calculated and normalized, and we used the equal-weighted sum of these three metrics to describe the EN structural stability (Hong et al. 2022). We repeated these calculations until the last node was removed. The formulas are as follows:

$$NS = \frac{n\prime}{n} \tag{5}$$

$$T = 3\frac{\#triangles}{\#triads} \tag{6}$$

$$E = \frac{1}{N(N-1)} \sum_{\forall i,j,i \neq j} \frac{1}{d_{ij}} \tag{7}$$

where *NS* is the proportion of the number of nodes in the maximum connected portion to the total number of nodes in the original network; $n\prime$ is the number of nodes in the maximum connected portion after the network is disturbed; n is the total number of nodes in the original network; T is the overall probability that neighboring nodes in the network are interconnected. E is the reciprocal of the average shortest path length. d_{ij} represents the shortest path length between the node pair i and j.

Results

Characteristics of current ecological network

A total of 246 and spatially heterogeneous ecological sources were identified in the current ecological network, encompassing an area of 1.2114×10^5 km^2 (Fig. 4). Thereinto, ecological sources are mainly concentrated in the southwest, which are primarily vast mountain forests and closely interconnected, while a few ecological sources are distributed in the north, which are mostly water bodies. Ecological sources in the central region are small and seriously fragmented primarily composed by lakes and forests around lake margins. In the current EN, 634 ecological corridors were identified with the average

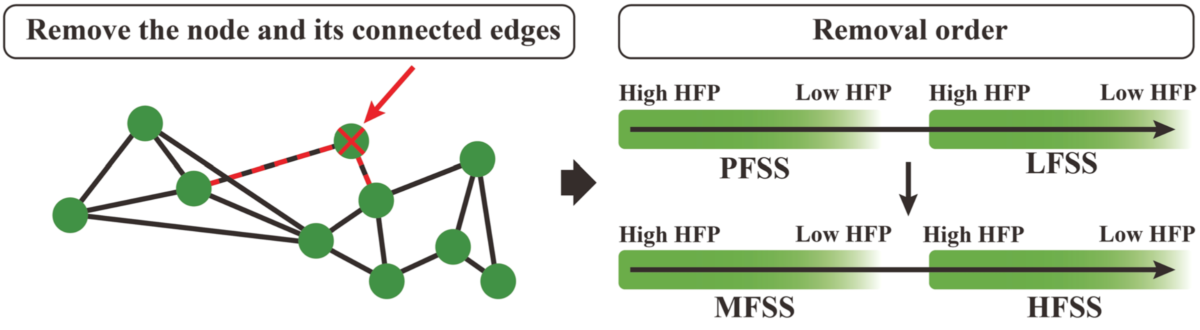


Fig. 3 The rules of deterministic attack. *PFSS* poor functional sustainable sources, *LFSS* low functional sustainable sources, *MFSS* medium functional sustainable sources, *HFSS* high functional sustainable sources, *HFP* human footprint

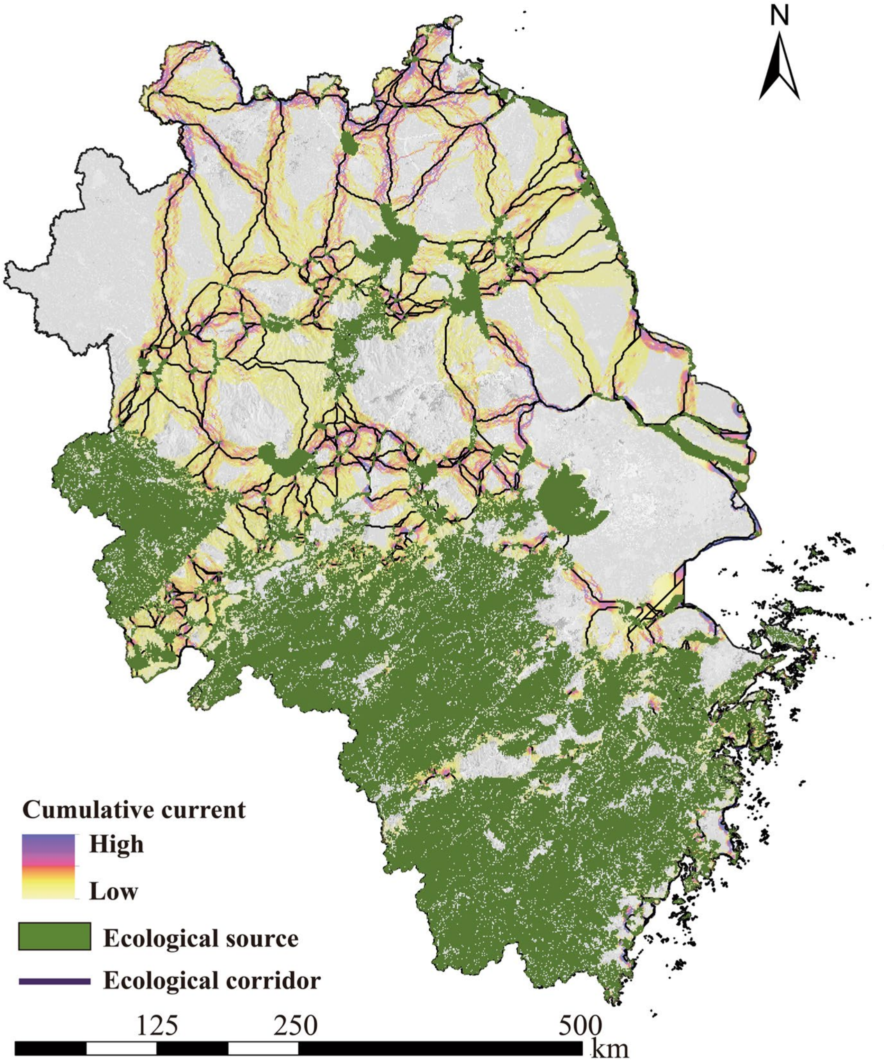


Fig. 4 Spatial distribution of the ecological network in 2020

length 36.49 km, and the longest corridor is 390.72 km. The longer corridors and the higher cumulative current values of the corridors are mainly located in the northern part of the YRDUA, indicating a much greater scarcity and fragmentation of sources, in contrast, short corridors are mostly found scattered in the south due to the clustered and nearly connected sources.

Assessment of ecological network functional sustainability

The functional sustainability of ecological networks exhibited variations across nine future scenarios. Compared to the current scenario, the ecological source areas under SSP1-1.9 are projected to decrease by 4.88×10^3 km^2, 5.08×10^3 km^2, and 5.98×10^3 km^2 by 2030, 2040, and 2050, respectively, while the ecological source areas under the SSP2-4.5 are projected to decrease by 5.93×10^3 km^2, 6.55×10^3 km^2 and 6.69×10^3 km^2 by 2030, 2040 and 2050, respectively (Table 2). On the other hand, the ecological source areas under the SSP5-8.5 are expected to decrease by 5.59×10^3 km^2, 6.57×10^3 km^2, and 6.85×10^3 km^2 by 2030, 2040, and 2050 correspondingly. These decreased areas are mostly located in foothill forests and water areas in the central region, which indicates that changed temperature and precipitation patterns, and expansion of croplands and built-up lands

Table 2 Area of ecological sources under nine future scenarios

Scenarios	Area (10^5 km^2)	Compared to the current (10^3 km^2)
Current (2020)	1.2114	0
SSP1-1.9 2030	1.1626	− 4.88
SSP2-4.5 2030	1.1521	− 5.93
SSP5-8.5 2030	1.1555	− 5.59
SSP1-1.9 2040	1.1606	− 5.08
SSP2-4.5 2040	1.1459	− 6.55
SSP5-8.5 2040	1.1457	− 6.57
SSP1-1.9 2050	1.1516	− 5.98
SSP2-4.5 2050	1.1445	− 6.69
SSP5-8.5 2050	1.1429	− 6.85

under future climate scenarios will weaken the capacity of these foothill forests and water bodies to provide ecosystem service (Fig. 5).

The spatial pattern and their corresponding land -use composition of different functional sustainability levels of the CESs imply the differences in facing the risk under climate change scenarios (Fig. 6). The HFSS are mainly located in the southwestern mountainous regions and water areas in the north-central of the YRDUA, but the PFSS are mostly small patches located in forests and grasslands in the center and water bodies in the north, while the LFSS and MFSS are mostly scattered in forests and water bodies of the north-central region (Fig. 6a). The area of HFSS is 1.13×10^5 km^2, accounting for 93.77% of the area of CESs. In contrast, the area of MFSS, LFSS, and PFSS is 0.37×10^3 km^2, 0.90×10^3 km^2, 6.26×10^3 km^2, accounting for 0.31%, 0.75%, 5.17% of the total area of CESs, respectively, which indicates that the capacity of 6.23% of the CESs is projected to decline in efficiently providing ecosystem services by 2050 under multiple climate scenarios.

PFSS, LFSS, and MFSS show a similar land use composition, including mostly forests and water bodies and a relatively small proportion of grasslands and croplands (Fig. 6b). In general, the results show that small and scattered ecological sources close to urban areas will be much more vulnerable to the impact of climate and land use change in the coming decades.

Assessment of ecological network structural stability

With the removal of nodes and edges, the trend of EN structural stability decreases relatively slowly at the first stage, but subsequently the structural stability becomes unstable and shows a tendency towards rapid collapse (Table 3; Fig. 7). Specifically, the EN structural stability decreased by 28.98% when completely removing the PFSS, but decreased by 2.22% when removing the LFSS. After the removal of MFSS, the EN structural stability decreased by 2.35%, however the removal of HFSS caused a significant decrease of 66.45% (Fig. 7), which indicates that the functional degradations of CESs will lead to a 33.55% decrease in EN structural stability by 2050.

When gradually removing the nodes, there are several rapid decreases in the EN structure stability, e.g. removing the 214th node, the stability decreased by 8.56%, declining from 65.53 to 56.97%, however, by removing the 225th node, the stability decreases by 10.86%, declining from 53.63 to 42.77%, but by removing the 228th node, the stability experiences a substantial decline of 42.94%, dropping from 48.58 to 5.64%. These rapid decreases imply the significant consequences that EN structures may face in the future as CESs gradually become incapable of efficiently providing ecosystem services.

Discussion

Integrating climate change scenarios in ecological network planning

Integrating the impacts of climate and land use change under future climate scenarios into EN planning has emerged as an urgent imperative to improve the robustness and sustainability of EN. In this study, we revealed the changes in the function and structure of the current EN in the YRDUA under nine future climate scenarios, which can help regional planners dynamically adjust the range of protected areas and improve ecological restoration measures during the EN management.

We found that HFSS are mainly located in the southwestern mountainous regions and water areas of the north-central region, accounting for 93.77% of the CES area (Fig. 6a). HFSS can be effective against the climate and land use change impact, so we propose

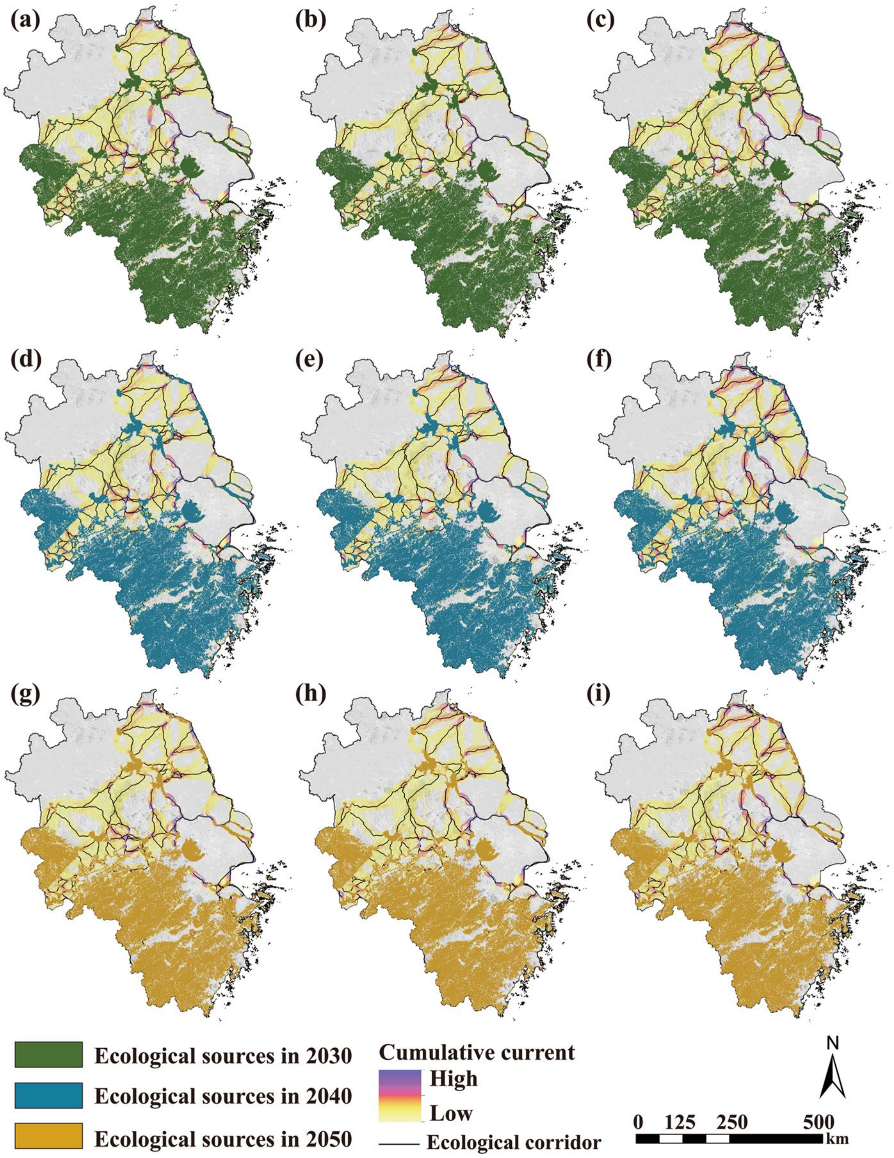


Fig. 5 Ecological networks under nine future scenarios. **a** SSP1-1.9 2030. **b** SSP2-4.5 2030. **c** SSP5-8.5 2030. **d** SSP1-1.9 2040. **e** SSP2-4.5 2040. **f** SSP5-8.5 2040. **g** SSP1-1.9 2050. **h** SSP2-4.5 2050. **i** SSP5-8.5 2050

that ecological policies in the YRDUA should always be sensitive to the ecological risks posed by human activities to HFSS. Maintaining the integrity of HFSS by implementing ecological conservation, such as prohibiting human intervention and supporting ecological succession, is necessary for the long-term EN development. Besides, the accelerating climate changes are expected to force species out of their current geographical range, and the HFSS in the study area could also serve as stable stepping stones, providing more options for species migration within the YRDUA by 2050 (Doxa et al. 2022). In the future, it will become increasingly important to monitor the robustness of these areas and track the responses of biodiversity and ecosystem services to climate change (Stralberg et al. 2020).

In contrast, the sparsely scattered forest and water bodyd patches in the central YRDUA are susceptible to the impact of urban sprawl and climate change, and mitigating the degradation and fragmentation of these areas will be the primary challenge for YRDUA EN maintenance, especially in the next 10 years (Fig. 6b). In addition, the area of water bodies in the CESs is projected to show an obvious decrease by

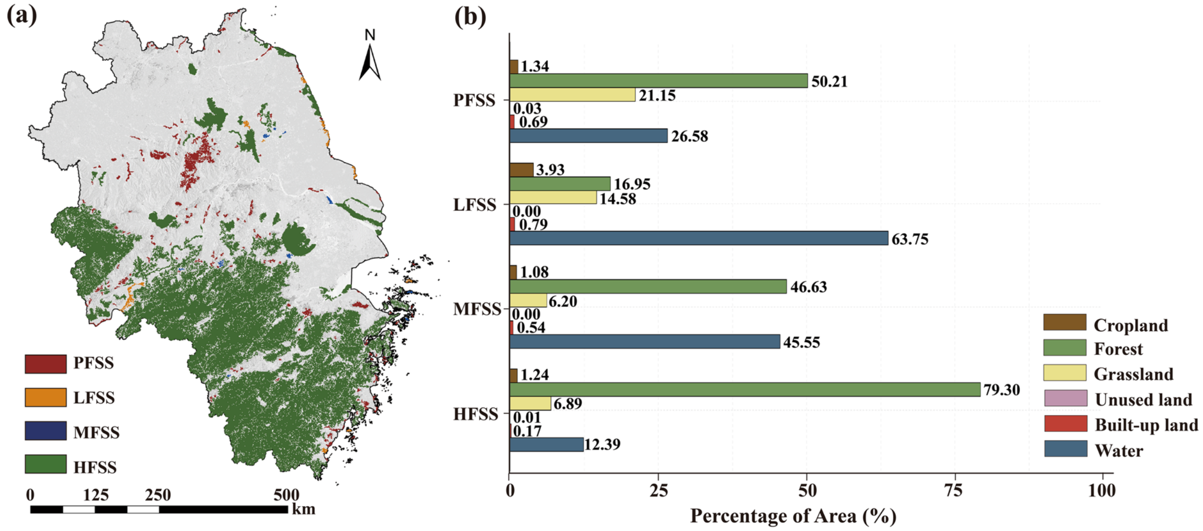


Fig. 6 **a** Current ecological sources of different functional sustainability levels. *PFSS* poor functional sustainable sources, *LFSS* low functional sustainable sources, *MFSS* medium functional sustainable sources, *HFSS* high functional sustainable sources. **b** Land use composition of the sources

Table 3 The decreases of EN structural stability after different nodes are removed

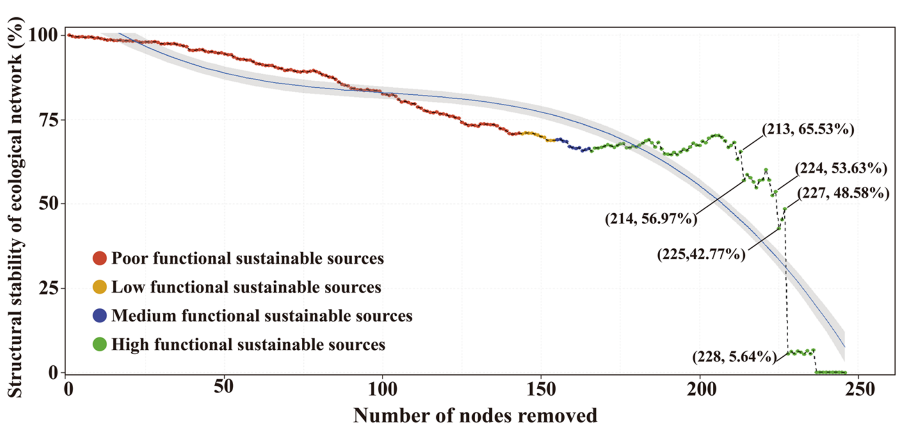
Source	Number of the nodes removed	Decrease of EN structural stability (%)
PFSS	143	28.98
LFSS	11	2.22
MFSS	10	2.35
HFSS	82	66.45

2050 because of the ecosystem service degradation of lakes in the central and northern regions. These degradations tend to expand from lake margins to lake shallow areas and remain a perennial concern of ecological managers. Therefore, to ensure the integrity of lake regions, in addition to incorporating the lakes into protected areas, existing protected areas should establish corresponding buffers around the lakes (Portela et al. 2021).

Development of function and structure integrated assessment

Currently, studies have discussed the development and application of landscape sustainability, and a few of them have explored the necessity of EN functional sustainability and structural stability integrated

Fig. 7 Structural stability assessment of the EN in YRDUA



assessment (Gonzalez et al. 2017; Thompson et al. 2017; Wang et al. 2021). For example, Gonzalez et al. (2017) pointed out that topological connections between habitats can have non-linear effects on ecosystem function. In contrast, our study stresses the understanding of differences and linkages in the response of functional sustainability and structural stability of EN when influenced by ongoing climate and land use change disturbances. Furthermore, we provide an integrated approach to analyzing the future development of EN function and structure based on a case study, which can inform effective information for ecological conservation.

Previous studies usually used only functional sustainability to analyze the future development of EN. However, the degradation of ecological source function is accompanied with the fragmentation of local landscape patterns and the turbulence of the overall EN topology, which indicates the necessity of combining structural stability metrics to comprehensively describe EN dynamics. Our results show that approximately 6.23% of ecological sources within the current EN are projected to experience a decline in their capacity to efficiently provide ecosystem services by 2050 (Fig. 6a), while the overall structural stability of the EN is expected to decline by 33.55% (Table 3). These findings suggest the difference in the responses of EN's function and structure when EN is disturbed under climate change scenarios. These differences could lead researchers to underestimate the potential impact of future risks on EN and thereby interfere with the prioritization of ecological restoration implementation.

Moreover, we developed a deterministic attack approach based on EN functional sustainability and human footprint to assess EN structural stability. In previous studies, the development of deterministic attack often relied on the node (ecological source) importance evaluation, for example, removing the node in descending order of the node importance. However, this deterministic approach is not well aligned with the real disturbances suffered by EN, because nodes with high importance (typically large and well-protected areas) are usually not the first to be disturbed and face the risk of disappearance. This issue is commonly overlooked, which weakens the potential of structural stability assessment in guiding EN planning. Our study proposed a removal order that can represent the future disturbances suffered by EN under multiple climate scenarios, which is more consistent with the real disturbances experienced by EN. The results show that the structural stability of the EN decays with a slow pace when PFSS, LFSS and MFSS are facing the risk of disappearance, however, the structural stability will rapidly collapse when HFSS are gradually disappearing. Therefore, it is imperative to comprehensively understand the changes in EN function and structure, and ensure the long-term integrity of regional ecosystems when effectively managing EN (Keyes et al. 2021; McDonald-Madden et al. 2016).

Limitations

Although multiple GCMs under different SSP scenarios are considered in this study, high-resolution data on future climate and land use are difficult to completely collect, and these data can only reflect the general trend of future climate changes (Ummenhofer and Meehl 2017; Young et al. 2006). In future studies, it is necessary to gather more climate informations to support refined EN construction and evaluate their capacity to adapt to different climate change scenarios. Furthermore, we used three structural metrics to assess the structural stability of the EN, which could be further complemented by more other feasible metrics. Finally, limited by the precision of experimental data, minimal amounts of built-up land (0.2%) and unused land (0.01%) were identified, while in fact, they are not suitable as sources due to the low ecological value.

Conclusions

Under the impact of accelerating climate change, prospective integrated assessment of EN is increasingly important for ecological strategy development and long-term landscape management. Taking YRDUA as a study case, we used climate scenario construction, ecosystem service evaluation, EN identification, and complex network analysis to integrally assess the functional sustainability and structural stability of the current EN. Our results indicate that the capacity of 6.23% of the CESs is projected to decline in efficiently providing ecosystem services by 2050 under the selected nine future climate scenarios. These functional degradations will also lead to a

33.55% decrease in the overall EN structural stability. PFSS, LFSS, and MFSS will be fragmented and mostly located in forests and water bodies of the central YRDUA, while HFSS will mainly be distributed in the southwestern mountainous regions and water areas in the north-central region with a larger average patch area.

In general, we provide an integrated assessment methodology to help address the potential ecological risks to EN under multiple climate change scenarios. Hence, policymakers and planners can detect warning signals of future crises that the EN may face and decide whether ecological restoration needs to be undertaken in advance, thereby effectively maintaining the long-term development of EN. The framework and methodology can also be applied to other areas to guide managing EN and implementing ecological conservation.

Author contributions HS, HY, FK, and JS contributed to the study's conception and design. Material preparation, data collection and analysis were performed by HS, JS and ZS. The initial draft was written by HS. All authors provided comments on previous versions of the manuscript and have read and approved the final version.

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Data availability The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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