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A new framework for identifying ecological conservation and restoration areas to enhance carbon storage

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ABSTRACT

Limited attention has been given to improving carbon storage by identifying ecological conservation and restoration areas (ECRAs). In this research, we proposed a new framework for identifying ECRAs by incorporating future carbon storage changes into ecological security patterns (ESPs), including several models of the Patch-generating Land Use Simulation (PLUS), Integrated Valuation of Ecosystem Service and Tradeoffs (InVEST), Minimum Cumulative Resistance (MCR) and circuit theory. This new framework was applied in Jiangsu Yangtze River Economic Belt, East China. To evaluate the effectiveness of this new framework, we compared two scenarios: an ecological priority scenario (EPS) where future carbon storage change was not considered and an ecosystem carbon sequestration scenario (ECSS) where future carbon storage change was explicitly incorporated. Under the EPS, ecological conservation areas and ecological restoration areas were 11169.87 km^2 and 221.11 km^2, respectively. Under the ECSS, the ecological conservation areas and ecological restoration areas were 14768.76 km^2 and 244.89 km^2, respectively. Carbon storage will be most likely to increase around lakes and the Yangtze River, and the identified key areas under the ECSS will be more adaptable to future environmental changes than the EPS. This new framework can effectively enhance both ecological function and carbon sequestration, providing effective support for policymakers in landscape management and low-carbon development in other regions facing similar challenges. In the meantime, more caution is needed for the possible limitations, such as without adequate consideration of uncertainties of changes in population, land use, and economy in the future.

1. Introduction

Terrestrial ecosystems have absorbed one-third of carbon emissions from burning fossil fuels and land use and cover change (LUCC), contributing significantly to climate change mitigation (Carvalhais et al., 2014; Lai et al., 2016; Yu et al., 2014). However, in recent decades, rapid global urban expansion has encroached on a large amount of ecological land, resulting in the degradation of approximately 60% of ecosystem function and a decrease in the carbon sinks of ecosystems (Assessment, 2005; Carpenter et al., 2009; Seto et al., 2012). Maintaining integrity and stability of ecosystem function has emerged as the focus of global environmental change research (Pecl et al., 2017; Tang et al., 2018). Ecosystem conservation and restoration have been regarded as an effective way to increase the carbon sink of terrestrial ecosystems by returning degraded ecosystems to their pre-degraded state and preserving habitat continuity (Strassburg et al., 2020; Su et al., 2021).

Ecological security patterns (ESPs) can be characterized by the key landscape elements, spatial positions and spatial connections (Kang et al., 2021; Li et al., 2020). These ESPs can provide a method for evaluating the significance of landscape patches in preserving ecosystem processes and functions (Li et al., 2023a; Wang et al., 2022c). This information can then be used to designate key regions as ecological conservation and restoration areas (ECRAs), ultimately ensuring the long-term ecological security and well-being of human (Fan et al., 2020; Peng et al., 2018a). Recently, the construction of ESPs has evolved to a widely accepted paradigm for determining ecological sources, establishing resistance surfaces, and identifying corridors and nodes

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(Beaujean et al., 2021; Dai et al., 2021; Zhang et al., 2017). In terms of sources determination, researchers are gradually committed to the quantitative assessment of ecological functions based on indicators, including ecological functional importance, landscape structure connectivity and ecological vulnerability (Jongman et al., 2011; Li et al., 2022a; Liang et al., 2018). In the process of resistance surface establishment, land use type, nighttime light data and slope have been extensively applied in the resistance coefficient calculation and correction to reflect the landscape heterogeneity within the same land type (Li et al., 2022a; Li et al., 2020). Ecological corridors can improve ecosystem connectivity and simulate the biological flows and have been generally extracted by circuit theory, Minimum Cumulative Resistance (MCR) and ant-colony algorithm (Peng et al., 2018a; Rinaldo et al., 2018; Zhou et al., 2021). Ecological sources and corridors and their buffer zones have been widely recognized as important areas for ecological conservation (Wang et al., 2022c). Ecological nodes, the potentially significant ecological restoration spaces, have been identified using the circuit theory (Smith et al., 2019a; Wang et al., 2022c). To sum up, previous studies on ESPs have focused on methodology optimization for improving the efficiency of biodiversity conservation, but few studies have constructed ESPs for increasing carbon stocks.

Some studies have found that implementing ecological restoration projects such as the Grain for Green Program and Grazing Exclosure have great carbon sink benefits, contributing significantly to reducing atmospheric CO_2 concentrations (Lu et al., 2018; Morsing et al., 2013; Zanini et al., 2021). The identification of ECRAs based on ESPs is the foundation for implementing ecological restoration projects (Zhang et al., 2022a). The process can accurately identify areas requiring ecological conservation and restoration, and it can provide essential data and support to execute restoration schemes with greater effectiveness, facilitating the implementation of targeted restoration measures (Li et al., 2022b; Ran et al., 2022). Thus, if carbon stocks can be incorporated into the process of ESPs construction, ecosystem restoration may have greater carbon sink benefits (Adame et al., 2015; Smith et al., 2019b). Currently, Peng et al. (2018b) and Xiao et al. (2020) have incorporated carbon storage assessment into ESPs, which mitigates the loss of carbon storage through some strict protection measures. However, the critical areas identified based on the current and past conditions do not reflect the possible impact of anthropogenic and natural factors on the landscape (Bellard et al., 2012). Even if the key areas are strictly protected and restored, without taking into account future changes in carbon storage induced by LUCC, they will be occupied by intensified human activities and expansion of construction land in the future, resulting in the decline of ecological protection effect and presenting additional challenges to the attainment of China’s carbon neutrality goals set for 2060 (Chausson et al., 2020; Sallustio et al., 2015; Yang et al., 2022; Yang et al., 2019).

Future carbon storage changes are frequently predicted by combining land use simulation with carbon storage estimates (Brovkin et al., 2013). The Patch-generating Land Use Simulation (PLUS) model has been increasingly applied for great potential for predicting future LUCC (Liang et al., 2021; Zhang et al., 2022b). It possesses an innovative multi-type random patch seeding mechanism based on threshold descent that can better integrate various spatial factors with geographic units and reach higher simulation accuracy (Liang et al., 2021). Studies on coupling the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model with the PLUS model to predict future carbon storage changes in ecosystems have gradually gained popularity (Wang et al., 2022a; Wang et al., 2022b). Few studies, however, have incorporated future carbon storage changes into ESPs, which is essential for adapting to future environmental changes and developing long-term effective measures for ecological conservation and restoration (Bellard et al., 2012; Gattuso et al., 2015).

To address this challenge, we proposed a new integrated framework for identifying ECRAs to increase carbon storage by combining future carbon storage dynamics with ESPs. In recent years, China has placed a greater emphasis on ecological conservation and restoration, particularly in the implementation of the Yangtze River protection strategy, which improves the Yangtze River’s environmental quality (Lu et al., 2020). However, the serious contradiction between anthropogenic activities and ecological conservation has been a significant challenge during rapid urbanization (Bardgett et al., 2021; Lee et al., 2014). Jiangsu Yangtze River Economic Belt (JYREB) has encroached on a large amount of ecological space, resulting in the degradation of ecosystem functions and the loss of carbon stocks (Xue et al., 2020). Therefore, JYREB was chosen as the case in the current study. The main aims of this research are to: (1) develop a new framework for identifying ECRAs to enhance carbon storage; and (2) evaluate the effectiveness of our framework by comparing two scenarios: an ecological priority scenario (EPS) where the carbon storage dynamic was not considered and an ecosystem carbon sequestration scenario (ECSS) where carbon storage dynamic was explicitly incorporated. In general, this study offers novel insights for identifying critical areas and serves as a useful reference for coordinating ecological security and low-carbon development objectives (hereafter referred to as dual objectives) in other regions facing the similar challenges.

2. Theoretical framework

The research developed two theory frameworks: (1) the interaction between ecological conservation and restoration and carbon balance; and (2) the harmonization of objectives, processes and results for ecological conservation and restoration.

2.1. *Interaction of ecological conservation and restoration with carbon balance*

It is widely acknowledged that ecological conservation and restoration can improve carbon storage by adjusting and optimizing ecosystem structure, function and local structure (Bustamante et al., 2019; Huang et al., 2022). Ecological conservation and restoration has altered the quantity and pattern of ecological sources, corridors and nodes, changing ecosystem functions, such as habitat maintenance and soil conservation (Feng et al., 2013; Smith et al., 2019c). Accordingly, the ecological process reacts positively or negatively, resulting in changes in carbon storage and carbon balance (Bottalico et al., 2016; Wang et al., 2021). Simultaneously, when carbon storage changes, important ecosystem elements, for example, soil, vegetation, and land change, affecting the ecosystem processes and functions and, ultimately, changing the structure of the ESP, location and quantity of ECRAs and restoration pathways (Metzger and Brancalion, 2013; Wang et al., 2022c) (Fig. 1).

2.2. *The harmonization of objectives, processes and results for ecological conservation and restoration*

This study proposed a theoretical framework of “objectives, processes and results harmonization” for ecological conservation and restoration based on the interaction between ESPs and carbon storage dynamics (Fig. 2). Dual-objective harmonization (ecological security and low-carbon development) guides the harmonization of two processes of ESPs construction and carbon stock adjustment. The goal of ecological security guides the process of ESPs construction, which includes the identification of ecological sources, the establishment of resistance surfaces, and the identification of corridors and nodes (Li et al., 2022a; Li et al., 2023a). The goal of low-carbon development guides the dynamic change process of carbon stocks by altering land use patterns and carbon density (Lai et al., 2016). By integrating carbon storage dynamics resulting from LUCC into the ESP construction process, the dynamic adjustment of ESPs becomes more adaptable to future LUCC and consistent with the process of carbon stock change (Brovkin et al., 2013; Yang et al., 2018). The harmonization of these two

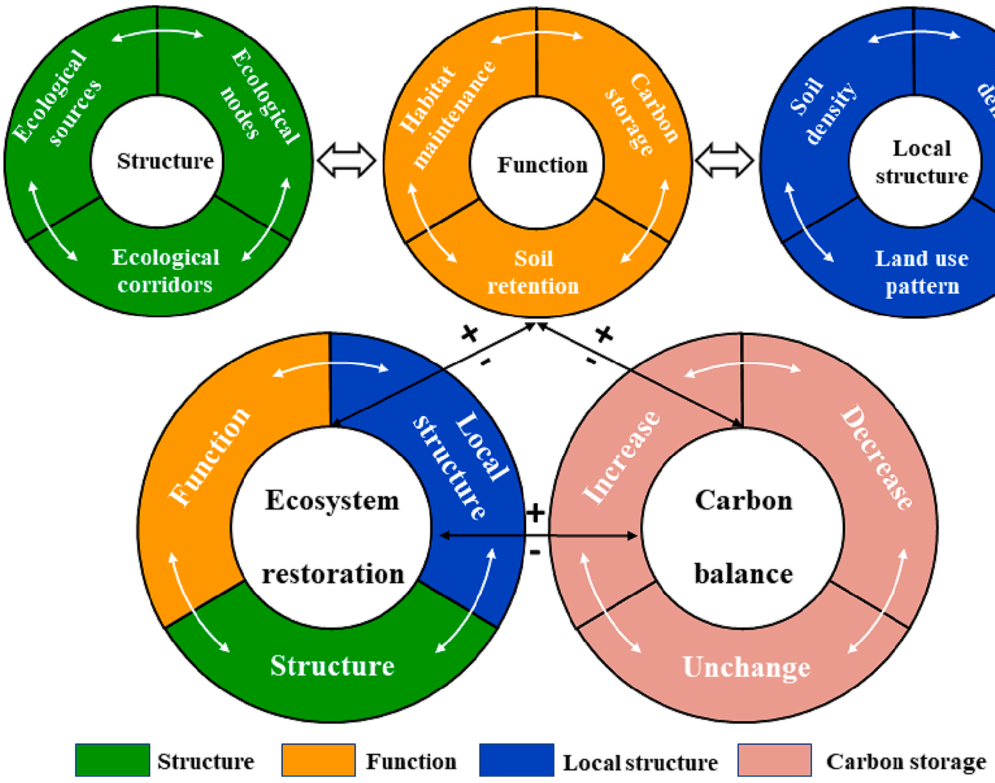

Fig. 1. Theoretical framework of interaction between ecological conservation and restoration and carbon balance.

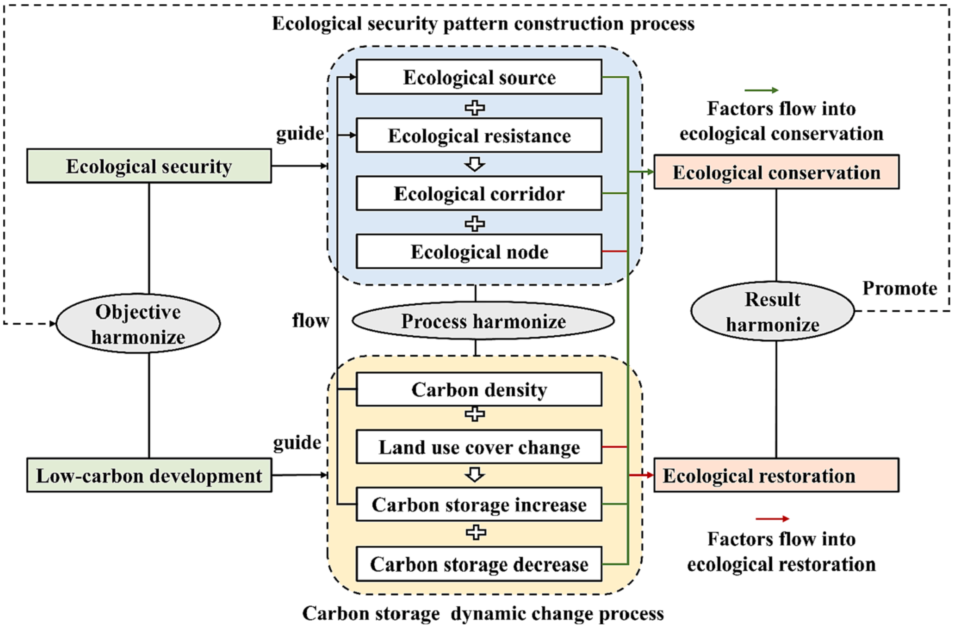

Fig. 2. Theoretical framework of "objectives, processes and results harmonization" for ecological conservation and restoration.

processes promotes the alignment of results, namely the harmonization of conservation areas and restoration areas. The protection of key elements, such as ecological sources and corridors, plays a crucial role in the conservation areas, enhancing the function and structure of ecosystems, while minimizing potential carbon storage loss (Liao et al., 2022; Zhao et al., 2021). Restoration areas require the restoration of potential barriers and pinch points, as well as areas with potential increases in carbon stocks (Wang et al., 2016; Zanini et al., 2021). The integration of results in ecological conservation and restoration facilitates dual-objective harmonization, effectively resolving conflicts between ecosystem conservation and land occupation while enhancing ecosystem function and increasing carbon storage.

3. Materials and methodology

3.1. Study area

Located in eastern China (30°43′-33°24′N; 118°19′-122°00′E), JYREB has eight cities along the Yangtze River and covers an area of 48463.85 km^2 (Fig. 3). This region is dominated by subtropical and temperate zones, with an average temperature of 13–16 °C and annual precipitation of around 1000 mm. It has flat topography and abundant water resources, as well as a high carbon storage capacity (Xiao et al., 2020).

As the Yangtze River Economic Belt's densest area, JYREB underwent rapid population growth and economic development. From 2010 to 2020, the urban population and gross domestic production (GDP) increased by 25.14% and 110.32%, respectively. Rapid economic development and urban sprawl have brought about serious environmental issues, such as over-use of ecological land, degradation of ecosystem function and a continuous loss of carbon storage (Han et al., 2021). For sustainable development, therefore, it is critical to improve carbon storage and ecosystem quality through ecological conservation and restoration.

3.2. *Data sources and processing*

Table 1 shows the data types, sources, time, and spatial resolution used in this study. Land use data were classified into six categories: farmland, woodland, grassland, water area, built-up land and unused land, which were used for ecosystem function assessment, carbon storage evaluation and resistance surfaces establishment. Digital elevation model (DEM) data were used for slope calculation, resistance surface correction and land use simulation. Soil data were used to calculate soil retention. Normalized difference vegetation index (NDVI) data were used to obtain the fractional vegetation cover (FVC). Net primary productivity (NPP) and FVC were used to correct the habitat quality. Precipitation and temperature data were used to revise the carbon storage and simulate future land use patterns. Population density, economic density, road, ecological protection red line and farmland protection red line were used for land use simulation. Nighttime light data were used to correct the resistance coefficient. Socio-economic data, including population and economic statistical data, were used to analyze the local conditions. Using the nearest neighbor method, all data were resampled to 100 m and projected into Albers' equal-area projection.

3.3. *Methodology*

The methodological framework in this study includes four parts (Fig. 4). First, the PLUS and InVEST models were used to predict future land use and carbon storage. Second, the InVEST and revised universal soil loss equation (RUSLE) models were applied to evaluate habitat quality, soil retention and carbon storage to quantify ecological functional importance (EFI). Third, circuit theory and the MCR model were used to construct ESPs in two scenarios, which included determining ecological sources, corridors and nodes. Fourth, ECRAs were identified based on the above results. Each detailed process is described in the following sections.

3.3.1. *Prediction of carbon storage change*

3.3.1.1. Simulation of land use pattern. Land use simulation is the foundation of future carbon storage assessments. PLUS is a new land use simulation model composed of two components: a land expansion analysis strategy (LEAS) and a CA based on multiple random seeds

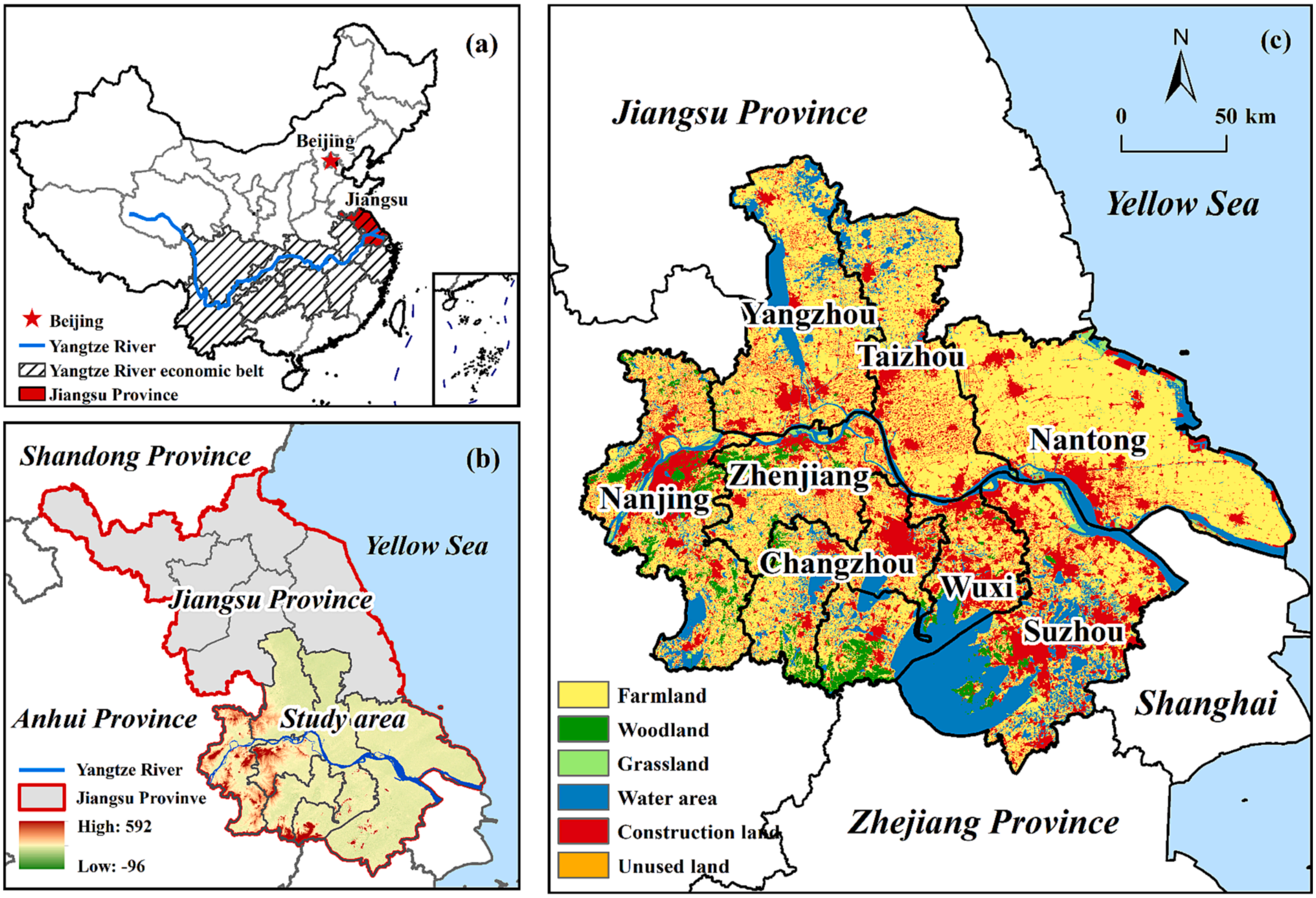

Fig. 3. Location and environment of Jiangsu Yangtze River Economic Belt (JYREB). (a) Jiangsu Province in the Yangtze River Economic Belt, East China; (b) JYREB in Jiangsu Province and digital elevation model (DEM); (c) land use in JYREB in 2020.

Table 1
Description of the data.

Data type	Data sources	Time	Spatial resolution	Use
Land use data	https://www.resdc.cn/	2015, 2020	30 *m*	Land use simulation; resistance factor; ecosystem function assessment
Digital elevation model (DEM)	https://www.gscloud.cn/	2009	30 *m*	Driving factor; resistance factor modification; ecosystem function assessment
Soil data	The Harmonized World Soil Database (HWSD V1.2)	1995	1:1 000,000	Ecosystem function assessment
Normalized difference vegetation index (NDVI)	https: / /https://www.resdc.cn	2019	1 km	Ecosystem function modification
Net primary productivity (NPP)	https://www.usgs.gov/	2020	500 *m*	Ecosystem function modification
Precipitation	https://www.resdc.cn/	2015	1 km	Driving factor
Temperature	https://www.resdc.cn/	2015	1 km	Driving factor
Economic density	https://www.geodata.cn	2015	1 km	Driving factor
Population density	https://www.worldpop.org/	2015	100 *m*	Driving factor
Road	https://www.openstreetmap.org/	2015	$1{:}25 \times 10^4$	Driving factor
Basic Farmland vector data	Permanent Basic Farmland Designation Dataset of Jiangsu province	2018	1:10,000	Restriction factor
Ecological Redline vector data	Jiangsu Province's National Ecological Protection Red Line Plan	2018	1:100,000	Restriction factor
Nighttime light data	https://www.ngdc.noaa.gov/	2013	1 km	Resistance factor modification
Socio-economic data	Statistical Yearbook of Jiangsu province	2010——2020	City	Local conditions analysis

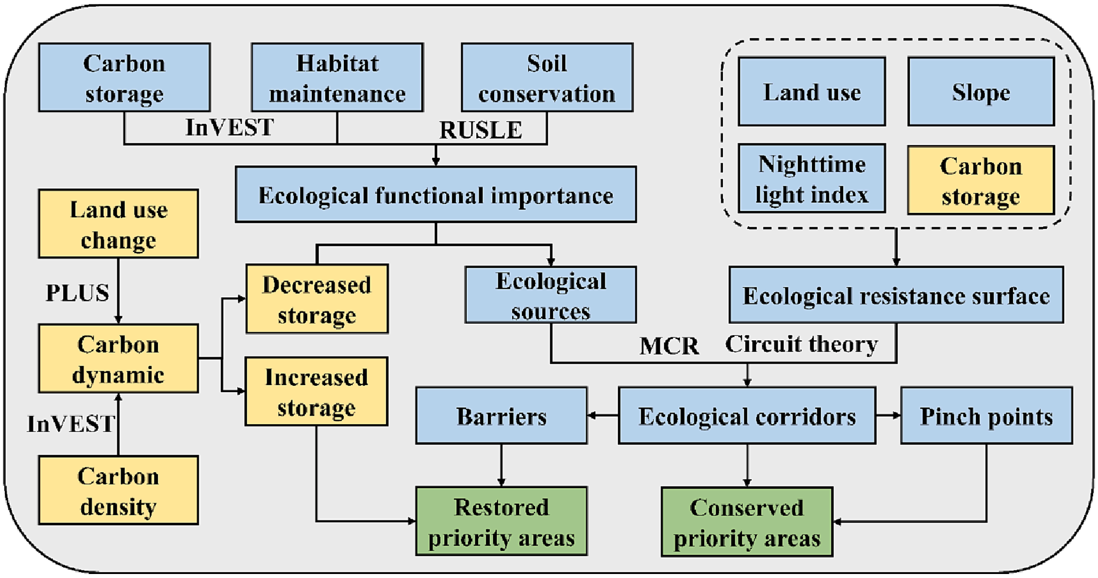

Fig. 4. The methodological framework for identifying ecological conservation and restoration areas.

(CARS) (Liang et al., 2021).

In the LEAS module, based on the LUCC in 2010 and 2020, the random forest classification (RFC) algorithm was used to examine the interrelationship between LUCC and nine drivers, i.e., elevation, slope, temperature, precipitation, population density, GDP, distance from highway, distance from railway and distance from the city center (Clarke et al., 1997; Liang et al., 2021; Liu et al., 2017). Based on the quantified interrelationship, the occurrence probability of various types of land was calculated.

In the CARS module, local land use competition was simulated using the probability of occurrence, neighbor effects and conversion cost matrices to ensure that the number of different types of land meets future development demands (Kurnia et al., 2022; Liu et al., 2017). Referring to Liang et al. (2021), this study quantified the neighbor effects using 3 × 3 M and set patches generation and expansion coefficients to 0.1 and 0.9, respectively.

Taking the land use pattern in 2010 as a baseline, the PLUS model was used to simulate the land use pattern in 2020, and the simulation accuracy was measured using the Kappa coefficient (Clarke et al., 1997). The Markov and PLUS models were used to predict the land use pattern in 2060 with sufficient accuracy.

3.3.1.2. Assessment of carbon storage. The InVEST has been widely used to assess carbon storage. Referring to the carbon density parameters from published papers (Chuai et al., 2014; Lai et al., 2016), the carbon storage was calculated as follows:

$$C_{ij} = \left(D_{j-above} + D_{j-below} + D_{j-soil} + D_{j-dead}\right) \times S_{ij} \quad (1)$$

where C_{ij} is the carbon storage of land type *j* on unit *i* (t), $D_{j\text{-}above}$ is carbon density in the aboveground biomass of land type *j* (t/hm^2), $D_{j\text{-}below}$ is carbon density in the belowground biomass of land type *j* (t/hm^2), $D_{j\text{-}soil}$ is carbon density in the soil of land type *j* (t/hm^2), $D_{j\text{-}dead}$ is carbon density of in the dead matter of land type *j* (t/hm^2), and S_{ij} is the area of land type *j* on unit *i* (hm^2).

Carbon storage is correlated positively with precipitation but negatively with temperature (Zhou et al., 2020). Therefore, the carbon storage was corrected as follows:

$$C_i^{'} = C_{ij} \times \frac{\lg(PR_i)}{\lg(PR_j)} \times \frac{\lg(TE_j)}{\lg(TE_i)} \tag{2}$$

where C_i' is the corrected carbon storage on unit i (t), PR_i is annual precipitation on unit i (mm), PR_j is the average annual precipitation of land type j (mm), TE_i is the annual temperature on unit i (℃), and TE_j is the average annual temperature of land type j (℃).

The future carbon storage changes from 2020 to 2060 were calculated using equations (1) and (2) based on the land use data in 2020 and 2060. Grids with a carbon storage change value of less than 0 were considered vulnerable to carbon sink reduction, with a likelihood of carbon storage loss. Conversely, grids with a carbon storage change value of greater than 0 were considered important for carbon sink gain, with a potential increase in carbon storage (Yang et al., 2020; Zhu et al., 2020).

3.3.2. Quantification of ecological functional importance

JYREB has experienced serious environmental issues such as increased carbon emissions, biodiversity loss and soil erosion (Han et al., 2021). Therefore, the EFI was quantified by evaluating ecosystem functions such as carbon storage, habitat quality and soil conservation as follows:

$$EFI = (\overline{C^{'}} + \overline{Q^{'}} + \overline{A})/3 \tag{3}$$

where EFI represents the ecological functional importance, $\overline{C^{'}}$, $\overline{Q^{'}}$ and $\overline{A}$ represent the normalized value of the modified carbon storage, corrected habitat quality and soil conservation, respectively. Based on the natural breakpoint classification method, the EFI was divided into five grades: not important (1), general (2), important (3), very important (4), and most important (5) (Li et al., 2022a). Equations 4–6 show the methods for assessing habitat quality and soil retention.

(1) Evaluation of habitat quality

Using the InVEST model and the parameters from the published papers (Chuai et al., 2016; Xiao et al., 2020), the habitat quality was calculated as follows:

$$Q_{ij} = H_j \times \left(1 - \frac{D_{ij}^z}{D_{ij}^z + k^z}\right) \tag{4}$$

where Q_{ij} is the habitat quality of land type j on unit i, H_j is the habitat suitability of land type j, D_{ij} is habitat threat of land type j on unit i, and z and k are half-saturation constants, set to 2.5 and 0.5, respectively (Yohannes et al., 2021).

To differentiate the value of the same type of land, the habitat quality was corrected using the NPP and FVC (Li et al., 2022a):

$$Q_i^{'} = Q_{ij} \times \left[1 + f_{\text{normal}}\left(\frac{NPP_i}{NPP_j} \times \frac{FVC_i}{FVC_j}\right)\right] \tag{5}$$

where Q_i' is revised habitat quality on unit i, f_{normal} is a normalized function with a range of 0 to 1, NPP_i is net primary production on unit i, NPP_j is average net primary production of land type j, FVC_i is the fractional vegetation cover on unit i, and FVC_j is the average fractional vegetation cover of land type j.

(2) Assessment of soil retention

Soil retention has been widely defined as the difference between potential and actual soil erosion, as determined by the RUSLE model (Benavidez et al., 2018):

$$A = R \times K \times LS \times (1 - C \times P) \tag{6}$$

where A represents soil retention (t), R represents rainfall erosion, K is soil erodibility, LS is slope length and gradient, C represents vegetation cover and management, and P represents soil conservation practice.

3.3.3. Construction of ecological security pattern under different scenarios

3.3.3.1. Determination of ecological sources. At a certain scale, ecological sources are effective in maintaining the stability of ecosystem structure and function (Li et al., 2023a; Peng et al., 2018b). Therefore, the first 60 large patches within the most important patches were determined as ecological sources in the EPS. Prioritizing the protection of vulnerable carbon sink reduction areas and patches with high EFI benefits ecological security and low-carbon development (Lu et al., 2018; Yang et al., 2019). Therefore, under the ECSS, the most vulnerable and important patches were merged using the elimination tool in ArcGIS 10.5 (ESRI, Redlands, California, USA), and the first 60 large patches within those merged patches were identified as ecological sources.

3.3.3.2. Establishment of resistance surfaces. (1) Establishment of resistance surfaces in the ecological priority scenario.

The most common method for establishing resistance surfaces has been to assign values based on land types (McRae, 2006). Referring to other studies (Li et al., 2022a; Xiao et al., 2020), the resistance coefficients for woodland, water area, grassland, farmland, and built-up land/unused land were assigned to1, 3, 50, 100, and 300, respectively. To differentiate the coefficient within the same type of land even further, the slope and nighttime light index were applied to correct the values (Li et al., 2022a; Peng et al., 2018a):

$$R_i^{'} = R_i \times \left[1 + f_{\text{normal}}\left(\frac{NLI_i}{NLI_j} \times \frac{SL_i}{SL_j}\right)\right] \tag{7}$$

where R_i' denotes the corrected resistance coefficient on unit i, f_{normal} denotes the normalized function with a range of 0 to 1, R_i is the basic resistance coefficient on unit i, NLI_i is the nighttime light index on unit i, NLI_j is the average nighttime light index of land type j, SL_i is the slope on unit i, and SL_j is the average slope of land type j.

(2) Establishment of resistance surfaces in the ecosystem carbon sequestration scenario

Areas with high carbon storage tend to have high EFI and a low degree of species diffusion hindrance (Wang et al., 2022c). To emphasize the role of carbon storage in the establishment of resistance surfaces, the resistance coefficient was corrected using carbon storage based on the correction with slope and nighttime light index under the ECSS as follows:

$$R_i^{'} = R_i \times \left[1 + f_{\text{normal}}\left(\frac{NLI_i}{NLI_j} \times \frac{SL_i}{SL_j} \times \frac{C_j^{'}}{C_i^{'}}\right)\right] \tag{8}$$

where R_i' is the corrected resistance coefficient on unit i, C_i'is the revised carbon storage on unit i, and C_j' is the average revised carbon storage of land type j.

3.3.3.3. Extraction of ecological corridors and nodes. The MCR model has been the most commonly used method for extracting ecological corridors (Dai et al., 2021; Li et al., 2020):

$$MCR = f_{\min} \sum (D_{ai} \times R_i^{'}) \tag{9}$$

where MCR denotes the minimum cumulative resistance value of species migration from sources to targets, f denotes the positive correlation function between MCR and ecological process, and D_{ai} denotes the spatial distance traversed from the source a to unit i. Circuit theory models the movement of species and energy in a landscape based on the random walk characteristic of electrons in a circuit (Dickson et al., 2019). Therefore, ecological corridors were extracted using the Linkage Mapper tool in ArcGIS 10.5 based on circuit theory and the MCR model.

Ecological nodes include pinch points and barrier points. The Pinchpoint Mapper tool was used to calculate the cumulative current value in ecological corridors, and areas with a high value were identified as pinch points (Dickson et al., 2019). After removing barrier zones, the cumulative current recovery value was calculated using the Barrier

Mapper tool, and areas with a high value were identified as barrier points (Smith et al., 2019a).

3.3.4. Identification of ecological conservation and restoration areas

Based on the determined ESPs and areas of future carbon storage changes, ECRAs for two scenarios were identified. The specific classification criteria are shown in Table 2.

Table 2
The classification criteria of ecological conservation and restoration areas.

Key areas	Ecological priority scenario	Ecosystem carbon sequestration scenario
Conservation areas	Ecological sources, 1-km corridor buffer zones	Ecological sources, 1-km corridor buffer zones, and carbon storage reduction zones
Restoration areas	Pinch points and barriers points	Pinch points, barriers points, and carbon storage growth zones

4. Results

4.1. Spatio-temporal characteristics of carbon storage

4.1.1. Land use pattern changes from 2010 to 2060

Farmland, built-up land, and water area were the most common land types between 2010 and 2020, followed by woodland, grassland, and unused land (Fig. 5**a-b**). They covered 55.95%, 22.18%, 17.14%, 3.89%, 0.66% and 17.14% of the territory in 2020, respectively. In general, JYREB experienced large-scale urban expansion and significant changes in land use patterns from 2010 to 2020. Built-up land and grassland increased by 14.26% and 55.48%, respectively. It expanded in a “ring” mode with built-up land as the center, and it expanded in an “axis” mode along rivers and roads. Farmland, water area, woodland, and unused land decreased by 4.03%, 3.30%, 1.29% and 11.47%, respectively.

The actual land use pattern in 2020 and simulated results tended to be consistent (Fig. 5**b-c**). The Kappa coefficient was 90.65% and greater than 80%, indicating that the simulation accuracy was sufficient to meet the subsequent prediction requirement.

The land use structure in 2060 will be consistent with that in 2020 (Fig. 5**d**). From 2020 to 2060, the built-up land along the Yangtze River will grow at an expansion rate of 14.67%, from 10750.60 km^2 to 14896.03 km^2. Farmland in flat areas along the Yangtze River will be the most occupied, declining by 14.67%. Water area will increase by 2.04 km^2, while woodland, grassland and unused land will shrink by 95.06 km^2, 52.97 km^2 and 20.90 km^2, respectively.

4.1.2. Carbon storage changes in 2020–2060

Overall, JYREB provided high carbon storage in 2020, with 408.84 Tg of carbon storage and an average carbon density of 84.36 t/ha. High average carbon density values were concentrated in hilly mountain areas with relatively higher elevations in Changzhou City and Wuxi City, while low values were primarily distributed in lakes in Suzhou City, Yangzhou City and Wuxi City, as well as built-up land in each city (Fig. 6**a**).

Carbon storage and average carbon density in 2060 were 393.41 Tg and 81.18 t/ha, respectively, which were consistent with spatial characteristics in 2020 (Fig. 6**b**). From 2020 to 2060, the carbon storage and average carbon density will decrease by 15.43 Tg and 3.18 t/ha, respectively (Fig. 6**c**). The area with the reduced average carbon density will be concentrated in the expansion area of built-up land along the Yangtze River. The area with the increased average carbon density will be found in lakes and along the Yangtze River.

4.2. Ecological functional importance

The EFI was generally high, with significant spatial heterogeneity (Fig. 7**a**). The most important areas and very important areas covered 7960.39 km^2 and 23643.31 km^2, accounting for 16.43% and 48.79% of the total area, respectively. The most important areas, including water area, farmland, and woodland, were primarily distributed in Suzhou city, Wuxi city and Changzhou city in the south, as well as Yangzhou city in the north.

The three types of ecosystem functions had significant spatial heterogeneity. The overall low importance of soil retention was associated with flat topographic conditions (Fig. 7**b**). High values of soil retention were mainly located in relatively high-altitude areas with erosion problems and dense vegetation. The habitat quality was positively correlated with distance to built-up land but negatively with distance to the water area and woodland (Fig. 7**c**). High habitat quality values were found in the southwestern hilly mountain areas and the Yangtze River in the middle, as well as in lakes such as Taihu Lake, Gaoyou Lake, Shijiu Lake and Yangcheng Lake, which are highly protected with limited human interference. High values of carbon storage were concentrated in the woodland in hilly mountain areas and wetlands around the Yangtze River and Taihu Lake, which were characterized by high rainfall, vegetation cover and soil carbon density (Fig. 7**d**).

4.3. Comparison of ecological conservation and restoration areas between two scenarios

Ecological conservation areas under the EPS and ECSS covered 11169.87 km^2 and 14768.76 km^2, accounting for 23.05% and 30.47% of the entire area, respectively. They were mostly concentrated in the periphery and along the Yangtze River (Fig. 8**A and 8a**). Different from the EPS, some ecological conservation areas were scattered in farmland along the Yangtze River. The spatial distribution of ecological sources, corridors and their buffer zones were generally consistent with that of EPS, but their areas differed slightly. Ecological sources under the EPS and ECSS were 6009.93 km^2 and 6010.52 km^2, representing 53.80% and 40.70% of ecological conservation areas, respectively, and they were concentrated in the southwest and northeast of Jiangsu Province (Fig. 8**B and 8b**). The numbers of ecological corridors under the EPS and ECSS were 93, with a total length of 2565.51 km and 2567.12 km, respectively, and they were distributed evenly and can effectively improve ecosystem connectivity (Fig. 8**B and 8b**). Ecological corridor buffer zones under the EPS and ECSS covered 5159.94 km^2 and 5163.63 km^2, contributing 46.20% and 34.96% to ecological conservation areas, respectively. Carbon storage reduction zones under the ECSS covered 3594.61 km^2, contributing 24.34% to the ecological conservation areas (Fig. 8**e**).

Ecological restoration areas under the EPS and ECSS covered 221.11 km^2 and 244.89 km^2, contributing 0.46% and 0.51% to the entire area, respectively, and they were concentrated among ecological sources in the southwestern hilly mountainous region (Fig. 8**A and 8a**). The spatial distribution of pinch points and barrier points was similar to that of EPS, but their area differed slightly. Pinch points under the EPS and ECSS covered 10.88 km^2 and 10.96 km^2, representing 4.92% and 4.47% of the ecological restoration areas, respectively, and they were distributed throughout the ecological corridors in the southwest, northwest and southeast of Jiangsu Province (Fig. 8**C and 8c**). Barrier points under the EPS and ECSS covered 210.23 km^2 and 219.02 km^2, accounting for 95.08% and 89.43% of the ecological restoration areas, respectively, and they were distributed throughout the southern and northern ecological corridors (Fig. 8**D and 8d**). Carbon storage increase zones were 14.92 km^2, accounting for 6.09% of the ecological restoration areas, which were found around lakes and the Yangtze River (Fig. 8**e**).

5. Discussion

5.1. Novelty and rationality

Despite recent studies on the identification of key areas (Li et al.,

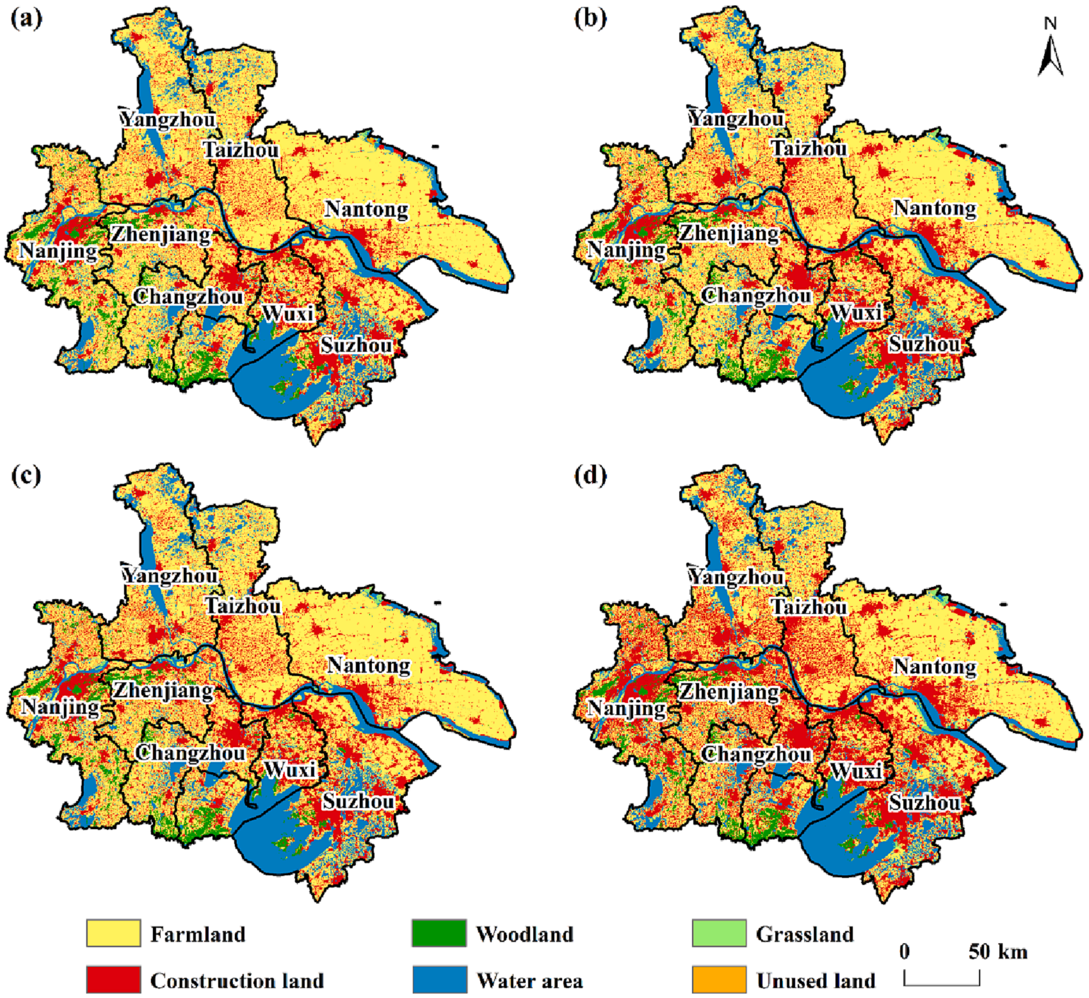

Fig. 5. Spatio-temporal changes in land use patterns. (a) in 2010, (b) the actual pattern in 2020, (c) the simulated pattern in 2020 and (d) in 2060.

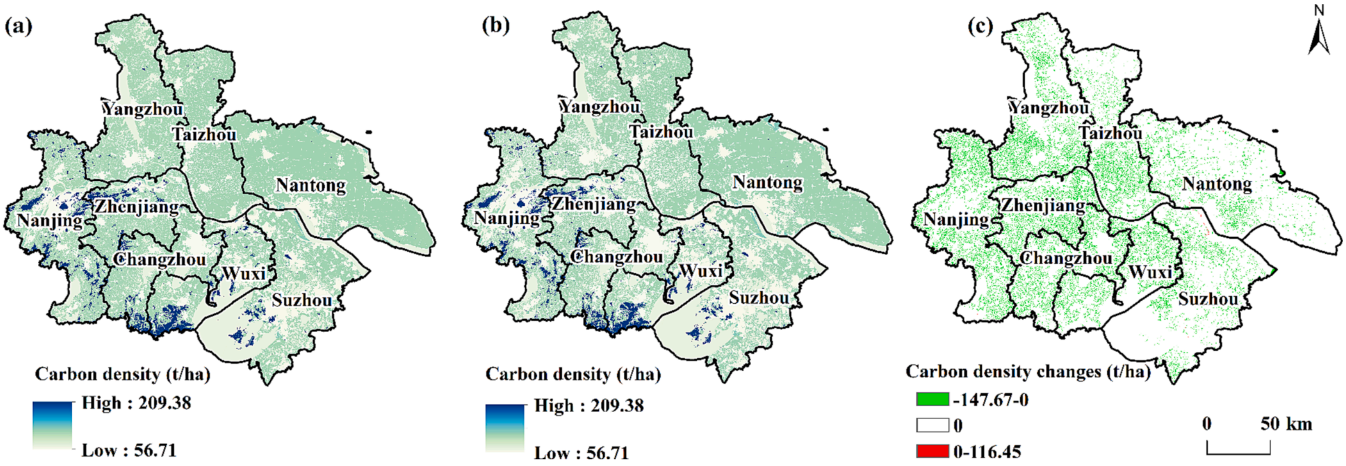

Fig. 6. Spatio-temporal changes in carbon storage in 2020–2060. (a) spatial variation in carbon storage in 2020, (b) spatial variation in carbon storage in 2060, and (c) changes in carbon storage in 2020–2060.

2022a; Peng et al., 2019), an integrated framework for identifying key areas with synergistic low-carbon development goals remains lacking. Unlike previous research (Boerema et al., 2016; Lu et al., 2018) that evaluated the carbon sink benefits of ecosystem restoration, this study developed a new framework for identifying ECRAs to enhance carbon storage. Furthermore, future LUCC and carbon storage changes were incorporated into the entire process of ESP construction in this research. These key areas identified within the ECSS will be protected as much as possible from future urban sprawl by anticipating future environmental changes, and thus can provide long-term effective ecosystem services and have a greater carbon sink (Ning et al., 2021; Yang et al., 2018), which is important for decision makers developing policies to maintain

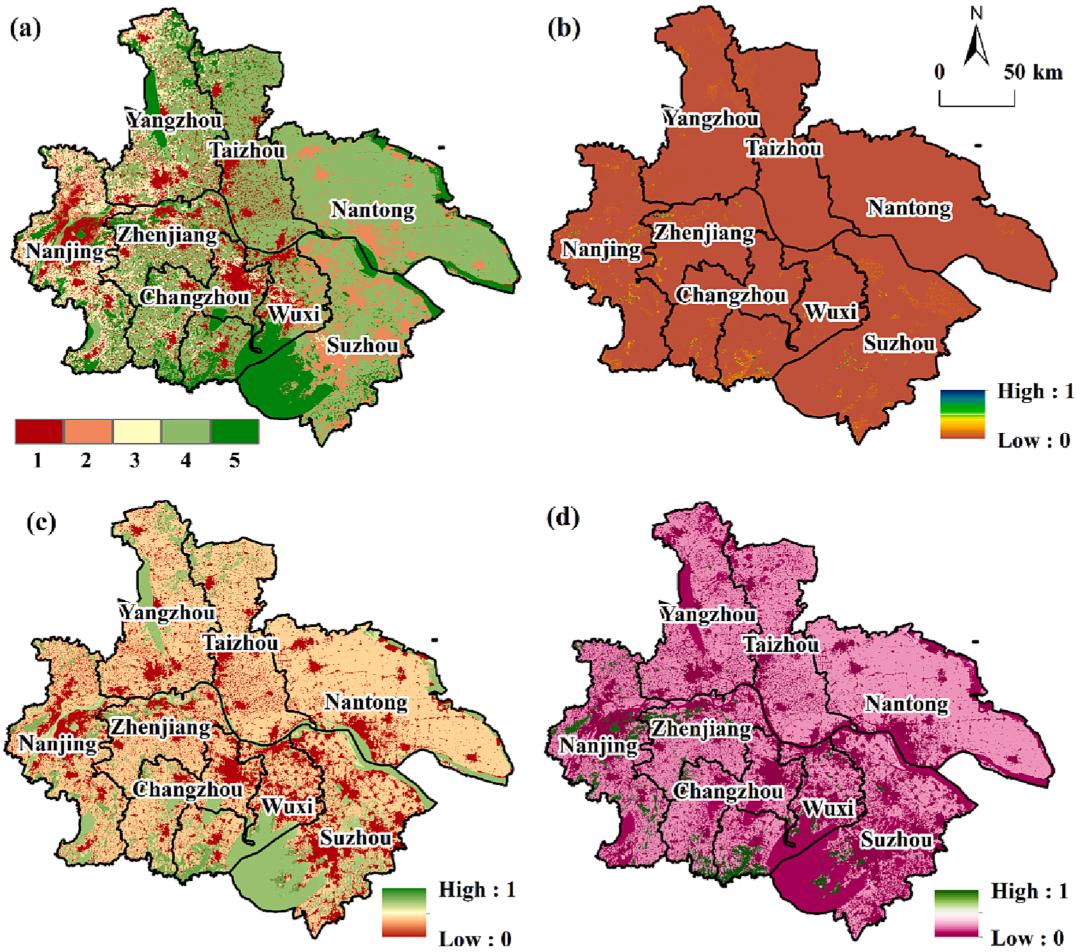

Fig. 7. Spatial variation in ecological functional importance. (a) ecological functional importance, (b) soil retention, (c) habitat quality and (d) carbon storage.

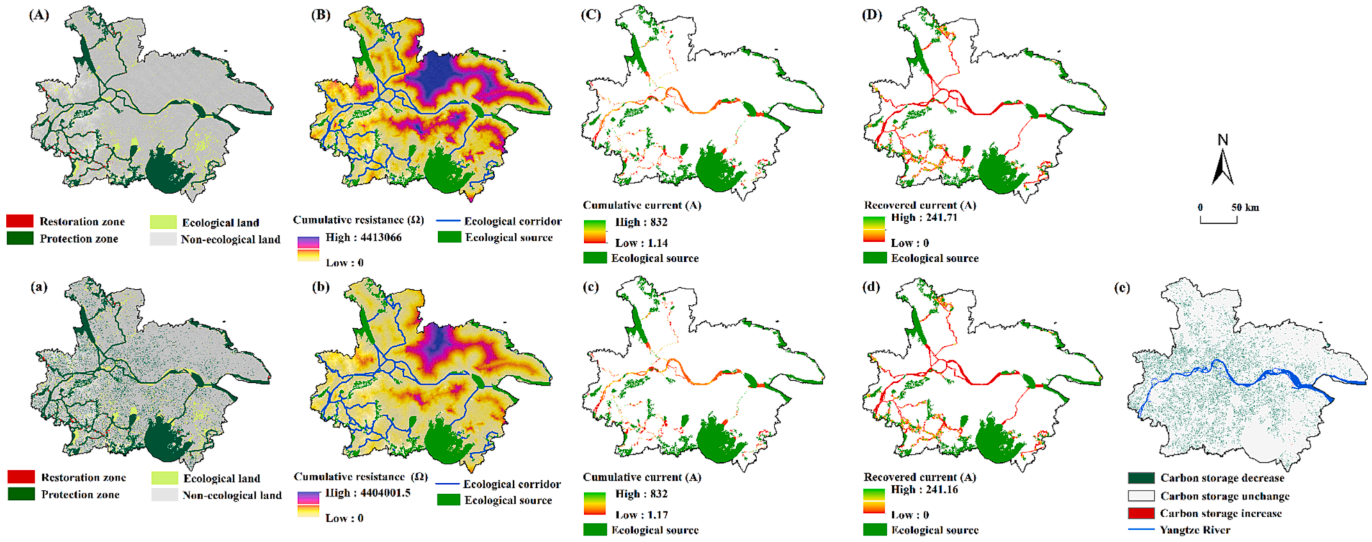

Fig. 8. Identification process and results of ecological conservation and restoration areas. Ecological priority scenario: (A) ecological conservation and restoration areas, (B) ecological sources and corridors, (C) pinch points and (D) barrier points. Ecosystem carbon sequestration scenario: (a) ecological conservation and restoration areas, (b) ecological sources and corridors, (c) pinch points, (d) barrier points, and (e) changes in carbon storage.

sustainable development and ecological security of cities.

The identification of ECRAs was performed with a high level of rationality and accuracy. The number and spatial distribution of ecological sources identified in the ECSS (6010.52 km^2 of ecological sources and 2567.12 km of corridors) were largely consistent with those found by Han et al. (2021) (5620.0 km^2 of ecological sources and 2209.0 km of corridors). This consistency highlights the accuracy of the framework employed for identifying ecological sources. The identified ecological conservation areas were concentrated in lakes and the Yangtze River, and their spatial distribution corresponded to the ecological pattern of Jiangsu Province's Territorial Spatial Planning (2021–2035) (https://www.jiangsu.gov.cn/). These results indicate that future ecological conservation and restoration will be supported by policies to facilitate implementation. Moreover, areas with increased carbon storage were primarily found in wetlands around the Yangtze River and lakes, supporting the conclusion and demonstrating the benefits of wetland restoration in increasing carbon sinks (Baustian et al., 2021; Mao et al., 2022; Mei et al., 2022). Other researchers can apply the methodology developed in this research and replicate our study in other areas. Additionally, the findings obtained in this paper are robust enough to be supported by the subsequent application.

5.2. *Interpretation of results*

Our results indicate that urban sprawl remains the main cause of the decline in carbon stocks from 2020 to 2060. Increased population and anthropogenic activities in Jiangsu Province have resulted in uncontrolled sprawl of built-up land, which has occupied farmland and ecological land, resulting in a decline in carbon storage (Chuai et al., 2016; Xiao et al., 2020). It is critical to limit urban sprawl and protect areas at risk of carbon stock loss in the process of ecosystem restoration. Different from previous findings (Ran et al., 2022; Wang et al., 2022c; Zhang et al., 2022a), the areas with reduced carbon storage were included in the scope of ecological conservation areas, accounting for 24.34% of the total ecological conservation areas. The majority of these areas consist of croplands scattered along the Yangtze River. As a result, this study encompasses the protection of cultivated land within the scope of ecological conservation and restoration, as it can help prevent the loss of carbon storage. While prior studies mainly focused on ecological land as the subject of ecological conservation and restoration (Li et al., 2022b; Wortley et al., 2013; Zhou et al., 2020), this study also includes cultivated land, thus advancing our understanding of existing ecological conservation and restoration research.

There were differences in the number and spatial distribution of ECRAs identified in the two scenarios, indicating that the low-carbon development goal affected ecological conservation and restoration, and emphasizing the importance of identifying ECRAs that combine dual objectives (Wortley et al., 2013). In contrast to the EPS, the ECSS had a larger area of ecological sources because it contained some areas with decreased carbon storage. The ECSS had longer ecological corridors than the EPS to ensure the stability of ecosystem structure, which not only carried the flows of species and ecosystem information, but also improved the connectivity of patches with high carbon storage (Li et al., 2017). The connectivity of key elements of an ecosystem plays a significant role in the optimization of the ecosystem function (Smith et al., 2019a).

The area of ecological restoration areas under the ECSS was larger than the EPS, which not only restored the ecosystem to a healthy state, but also improved the ecosystem's carbon sink. The restoration of the areas characterized by an increase in carbon storage caused by LUCC will be better adapted for future land use management policies aiming at improving low-carbon benefits (Ning et al., 2021). There were minor differences in pinch points and barrier points between the EPS and ECSS, most probably due to the impact of changes in carbon storage on ecosystem structure, function, and process (Griscom et al., 2017).

5.3. *Policy implications*

In recent years, increasing urbanization along the Yangtze River caused many problems, including an increase in carbon emissions, a loss of carbon storage and a decline in ecosystem quality (Han et al., 2021; Mei et al., 2022). Therefore, preserving ecological security and low-carbon development through a "win-win" ecological conservation and restoration scheme is a long-term goal of territorial spatial planning currently (de Oliveira et al., 2013; Phelps et al., 2012). The identification of ECRAs under various scenarios can provide policy insights for coordinating regional objectives.

As a part of ecological restoration areas, the majority of the areas with reduced carbon storage were farmland along the north and south sides of the Yangtze River, where the conflict between ecological conservation and economic development will be the most visible. If the farmland is located within concentrated and continuous farmland, it could be assigned to farmland protection red lines and agricultural management measures such as improved fertilization, crop variety selection and fallowing can be implemented to reduce agricultural carbon emissions (Arneth et al., 2017; Liu et al., 2021). If farmland is close to ecological sources, it can be returned to forest and included in the ecological conservation red line to improve vegetation's carbon sink ability and ecosystem quality (Wang et al., 2020). Furthermore, key ESP elements such as ecological sources, pinch points and barrier points can be included in ecological conservation red lines for strict protection to limit uncontrolled urban sprawl (Li et al., 2022a; Li et al., 2023b).

Areas with rising carbon storage were found around lakes and the Yangtze River, which were the best restoration areas for increasing carbon sink. The current local policy defines that the areas within 1 to 10 km from the rivers and lake should be conserved. Some carbon-cutting measures, such as ceasing illegal housing construction and polluting business, should be recommended (Yang et al., 2012; Ye et al., 2018). Furthermore, policies and techniques, such as land remediation and farmland reclamation can be developed to restore vegetation and soil to increase the benefits of carbon sink (Chartin et al., 2013; Kolis et al., 2017). Environmental conservation and ecological restoration have received increased attention in China over the last decade, so stricter ecological conservation policies and the selection of locally appropriate ecological restoration modes are the keys to promoting long-term sustainability (Li et al., 2021; Yang et al., 2015).

5.4. *Limitations and future research*

This study makes an essential contribution to promoting low-carbon urban development and ensuring regional ecological security, but further research is still needed.

First, identifying ECRAs is the foundation of ecosystem restoration, while the subsequent program implementation is critical to ensuring the effectiveness of ecosystem restoration (Lu et al., 2018). Thus, specific restoration modes and construction subsequences of the restoration program can be determined to ensure feasible program implementation by taking into account the cost in the process of ecological conservation and restoration, the benefits after restoration, the local natural conditions and the needs of residents.

Second, marine ecosystem protection and coastal zone restoration are beneficial for increasing carbon sinks and preserving ecosystem function integrity (Duarte et al., 2013). As a result, marine and terrestrial ecosystems can be integrated for ecological conservation and restoration at the same time.

Third, this research used the past trends in land use change to predict future changes, providing support for the implementation of ecological restoration programs. Notably, however, population, land use, economy, and cities are dynamic and constantly changing, particularly in China which has a large and dynamic population (Liang et al., 2021; Liu et al., 2017; Yang et al., 2020). To better account for these changes and improve the accuracy of future prediction, further studies should incorporate dynamic changes of population, land use, economy, and cities into the projection of land use.

Fourth, due to data constraints, we can only select some socio-economic data with varying spatial resolutions to maintain data integrity, which may cause some deviation. To minimize bias, future advances in data collection can yield more detailed data with the same spatial resolution. Moreover, the determination of corridor width based on various geospatial data warrants more attention in the future studies.

Despite these limitations, this research expands the theory of ecological conservation and restoration, and our findings and framework can be applied to ecological conservation planning and carbon–neutral policy formulation in Jiangsu Province and other urbanized regions.

6. Conclusions

Different from the previous studies, this study appears to be the first attempt to propose a framework for identifying ECRAs for enhancing carbon storage, using several models including the PLUS, InVEST, MCR and circuit theory. Furthermore, we compared EPS and ECSS to evaluate the effectiveness of the proposed framework.

From 2010 to 2020, there was a significant shift in land use patterns, particularly along the Yangtze River where built-up land expanded the most in an "axis" pattern, resulting in a 14.26% increase over the decade. The continued expansion of built-up land into farmland will lead to a significant decline in carbon storage, resulting in an estimated decrease of 15.43 Tg between 2020 and 2060.

The distribution of both ecological conservation areas and ecological restoration areas in the ECSS exhibited a general similarity to that of EPS, albeit some differences in the areas. Notably, ecological conservation areas occupied a larger area within the ECSS (14768.76 km^2) than within the EPS (11169.87 km^2), accounting for 30.47% and 23.05% of the entire area, respectively, with concentrations primarily observed in the periphery and along the Yangtze River. The ecological conservation areas established within the ECSS serve a dual purpose, promoting the ecosystem restoration to a healthy state and preventing the loss of carbon storage. 24.34% (3594.61 km^2) of the ecological conservation areas can effectively prevent the loss of carbon storage throughout farmland along the Yangtze River.

Additionally, ecological restoration areas within the ECSS (244.89 km^2) occupied a larger area than the EPS (221.11 km^2), contributing 0.51% and 0.46% to the entire area, respectively, with concentrations primarily observed in the southwestern hilly mountainous region. Approximately 6.09% (14.92 km^2) of the ecological restoration areas located around lakes and the Yangtze River are projected to result in an enhancement in carbon storage.

This study expands the knowledge of ecosystem conservation and restoration, and provided recommendations for environmental management and carbon neutrality strategies in other regions facing the similar challenges.

CRediT authorship contribution statement

Long Li: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Validation. **Xianjin Huang:** Project administration, Funding acquisition, Writing – review & editing. **Hong Yang:** Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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