Ecological Indicators 150 (2023) 110264

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Ecological network design based on optimizing ecosystem services:case study in the Huang-Huai-Hai region, China

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ARTICLE INFO

Keywords:
Agricultural landscape
Ecosystem service values
North-China Plain
Semi-natural habitat
Scenario planning

ABSTRACT

In modern agricultural landscapes, constructing 'ecological networks' is regarded as an efficient way to conserve biodiversity and maintain ecosystem services. Here we aimed to develop an approach to design ecological corridor by employing the ecological source - resistance surface - ecological corridor framework in combination with semi-natural habitat planning and ecosystem service trade-off assessment. 'Ecological source patches' were identified based on a 'Remote Sensing Ecological Index' (RSEI) to objectively classify ecological and environmental conditions. Our resulting spatial resistance surface was further modified used based on the 'Cultivated Land Use Intensity' index, to derive a high accuracy and rationality of ecological corridor extraction in agriculture landscape. While planning the ecological network, key nodes and resulting semi-natural habitat (SNH) distribution were identified using Linkage Mapper tools and circuit theory. We constructed ecological network scenarios with different amounts of semi-natural habitats and calculated resulting regional ecosystem service values (ESV) using an equivalence factor method to explore optimal spatial layouts. The results showed, while regional ecosystem service values generally increased in line with semi-natural habitat area contained within the ecological network, ecological networks with forests covering 10% of the total area were predicted as an optimal scenario balancing ecosystem services with agricultural yield in the study region. Networks with mixed forest and grassland cover totaling 20% of the area represented an alternative choice that strongly enhanced regional ecosystem services while may still allowing for high agricultural productivity. In constructing corridors, identifying, restoring and protecting key ecological nodes using targeted management and habitat restoration, while protecting existing wetlands and other water bodies that support regional water cycle and supply services, should be prioritized. Regional policy measures furthermore need to promote targeted ecological network planning to help improve the overall sustainability of agricultural production.

1. Introduction

Agricultural biodiversity and associated ecosystem services (ES) are critical elements of sustainable food production systems (Tamburini et al., 2020; Tscharntke et al., 2012). Nonetheless, they have faced massive declines due to loss and fragmentation of semi-natural habitats resulting from agricultural intensification (Brückmann et al., 2010; Foley et al., 2005; Stoate et al., 2009). Semi-natural habitats strongly promote both biodiversity (Šálek et al., 2022) and ES (Mestre et al., 2018; Raderschall et al., 2021) by providing refuge and source habitats, seasonal shelter and consistent food resources for many beneficial organisms (Holland et al., 2016). Re-establishing semi-natural habitats to form ecological networks connecting large existing semi-natural habitat patches in agricultural landscapes is therefore regarded as an effective practice to enhance landscape-scale biodiversity and ES (Blaschke, 2006; Shi et al., 2020; Tscharntke et al., 2021). Theoretically, ecological networks consist of ecological nodes that connect corridors between remaining, potentially protected natural and semi-natural habitat patches, potentially with additional buffer zones for both patches and corridors (Peng et al., 2017). These networks organically integrate farmland with woodland, grassland and other semi-natural habitats connected via corridors (Blaschke, 2006), hence providing

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https://doi.org/10.1016/j.ecolind.2023.110264
Received 26 December 2022; Received in revised form 3 April 2023; Accepted 13 April 2023
Available online 22 April 2023

habitat connectivity across regional landscapes that promotes migration, reduces habitat fragmentation, and in turn enhancing the ecological functioning and ES provisioning across the entire landscape (An et al., 2021).

Ecological network research commonly works on the principles of identifying ecological source areas and constructing relative resistance surfaces to identify 'low-resistance'-ecological corridors connecting the source areas (Peng et al., 2018b; Shi et al., 2020). Ecological source areas represent continuous ecological background structures of great significance for biodiversity, ecosystem services and therefore regional ecological security, or they contribute important radiation functions (An et al., 2021). Commonly, these are areas judged to be in good ecological conditions and/or producing high values of ecosystem services. The resistance surface is constructed based on an assumed difficulty degree for species to survive in, and migrate through, the respective space (Clergeau & Burel, 1997). This in turn is judged by the respective land-use types (Shi et al., 2020; Zhou et al., 2021). With regards to ecological corridors, previous research commonly selected rivers or others pre-exist semi-natural landscape features, but resulting corridor networks often performed poorly in improving overall landscape connectivity (Bhowmik et al., 2015) in failing to effectively connect existing high quality habitat patches. Alternatively, the minimum cumulative resistance (MCR) model, simulating spatial movement patterns across the landscape, can be used to identify ecological corridors and resulting networks (Peng et al., 2018a; Zhou et al., 2021). Nonetheless, this model, while allowing the generation of spatially explicit ecological corridors, fails to quantify corridor width. Circuit theory-based models address this shortcoming by quantifying multiple corridors with their respective width to identify key ecological nodes (McRae, 2006; McRae et al., 2008). These models have been widely employed in respective network studies (Breckheimer et al., 2014; Carroll et al., 2017; Jin et al., 2021).

Most studies investigating ecological networks tend to focus only on optimizing the construction of the network in terms of ecological source site selection and resistance surface construction (Dong et al., 2020). The evaluation of ecological networks post-construction is then chiefly limited to evaluating the effects on regional connectivity (Hofman et al., 2018), but ignores the impact on the different regional ecosystem types under different planning scenarios (Zhou et al., 2021). Nonetheless, the consideration of trade-offs relating for example to multiple ESs, including agricultural production, is important in a meaningful, applicable ecological network planning (Mach et al., 2015). The role of different semi-natural habitats in biodiversity conservation and ES maintenance furthermore varies according to habitat type and its amount in the landscape (Garibaldi et al., 2021; Mestre et al., 2018). A key challenge for ecological network planning in agricultural landscapes is therefore to identify a setting that optimizes the amount and type of semi-natural habitats to maximize biodiversity and ES outcomes while minimizing potential negative effects on agricultural productivity.

As one of the most densely populated and most important cereal production areas in China, the Huang-Huai-Hai region (Fig. 1) is currently characterized by a highly simplified homogenous landscape structure. Accordingly, the region harbors very low levels of biodiversity and associated ES, to a degree that is considered a threat to sustainable agricultural productivity and food security. Despite its crucial importance in sustainable production systems, the conservation of agricultural biodiversity also has long been neglected in China (Li et al., 2020). Although the re-establishment of semi-natural habitat networks is therefore urgently needed for both biodiversity conservation and sustainable agriculture, limited land resources in the region require highly efficient re-establishment scenarios that balance food production and biodiversity conservation.

In our paper, we aim to (1) explore approaches to identify optimal semi-natural habitat ecological network structures using the pathway of "ecological source selection - resistance surface construction - ecological corridor identification". (2) Find optimal corridor designs with most effective habitat distribution for different overall area cover-scenarios that provide a strong balance between the provision of ecosystem services provided by both, the ecological corridors and the remaining agricultural areas. These scenarios will be discussed in the context of

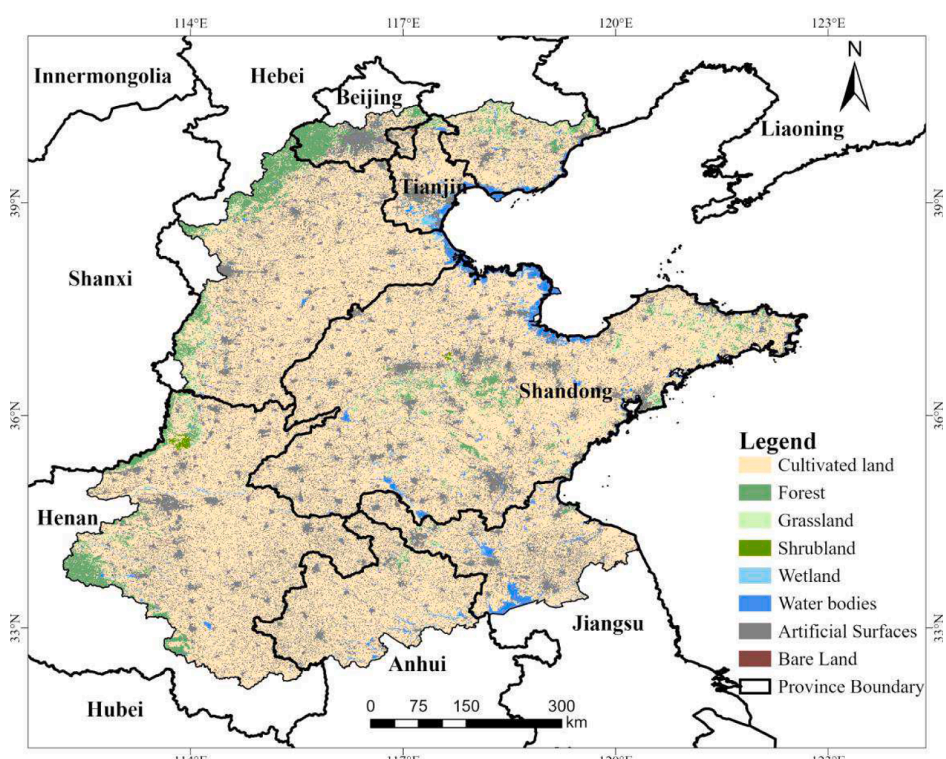

Fig. 1. Land use types of study area.

regional policy frameworks focused on biodiversity conservation and ES management. (3) Propose suggestions and measures for optimizing ecological networks in the research region.

2. Materials and methods

2.1. Study area

The Huang-Huai-Hai region (also called North China Plain, 32°10′N ~ 40°30′N, 112°10′E ~ 122°30′E, Fig. 1) is the second-largest plain in China and also one of the country's most densely populated areas (2.2 times the national average). It covers an area of about 400,000 km^2, distributed across five provinces (Hebei, Shandong, Henan, Jiangsu, and Anhui), and it includes the two major cities of Beijing and Tianjin. The region is mainly composed of landforms shaped by three main river systems - the Yellow (Huanghe) River, the Huaihe River, and the Haihe River, and it has an average elevation of <50 m. This area is characterized by a temperate monsoon climate, with a frost-free period of up to 230 days and an annual precipitation of 600–800 mm.

Based on its climate and landform, the region is one of the most important cereal crop production regions in China, with cultivated land accounting for about three-quarters of the total land area. In addition to arable land, artificial surfaces occupy 19% of the total area. Natural and semi-natural land, such as forest, shrubland and grassland, accounts for a relatively low percentage of only about 6.82% of the area. The lack of semi-natural habitats is one of the key issues affecting the sustainable development of the region's agriculture that needs to be addressed.

2.2. Research methodology

The primary target of constructing ecological networks in the Huang-Huai-Hai region is to strengthen regional connectivity between natural and semi-natural habitats in the predominantly agricultural landscape. We therefore identify potential ecological corridors based on the location of potential ecological source areas and the ecological resistance surfaces following the "ecological source selection - resistance surface construction - ecological corridor identification" pathway. We design semi-natural corridors for scenarios that differ in the percentages and types of semi-natural habitat in the landscape. An optimal design for large-scale semi-natural corridors connecting key source areas that also optimize ES provision are then computed based on the different scenarios.

2.2.1. Identification of potential ecological corridors

(1) Identification of core ecological areas

As cultivated land is such a dominant land-use type in the Huang-Huai-Hai region, it is problematic to identify ecological source areas solely depending on natural habitat patches provided by nature reserves, forest and wetland parks, as was done in previous studies (Teng et al., 2011). Instead, we used the Remote Sensing based Ecological Index (RSEI), an ecological status evaluation system widely employed (see e.g. Ariken et al., 2020; Xu et al., 2022; Yang et al., 2020) to quantify the quality of the environment (Formula 1), to identify key ecological source areas. In agricultural landscape lacking high quality natural and semi-natural habitats, this approach can identify potential areas with good habitat quality that could be considered for subsequent semi-natural habitat construction. For this index, higher values represent a higher 'ecological quality'. The RSEI is calculated as the function of four RS indices – the Normalized Differential Vegetation Index (NDVI), the Wetness Index (WET), the Normalized Differential Building-Soil Index (NDBSI) and the Land Surface Temperature Index (LST) (Xu et al., 2018). The NDVI is closely related to plant biomass, leaf area index, and vegetation cover as a representation of 'greenness'; while WET is derived from the third component of the tasseled cap transformation that represents 'local wetness' (Baig et al., 2014) as the overall moisture content of waterbodies, soil and vegetation. The NDBSI represents a dryness index that is calculated from the average bare soil index and the building index (Xu et al., 2018). It reflects the amount of impermeable surfaces that have replaced vegetated surface, resulting in the "drying out" of the ground surface. The LST is an index provided by MODIS (Zheng et al., 2021) that represents local heat conditions as an estimated land surface temperature. All four indices were standardized to eliminate dimensional differences, and a Principal Components Analysis (PCA) was used to calculate the main principal component representing the differentiation across the four indices as a fast, objective, quantitative evaluation model as follows:

$$RSEI = PCA1[f(NDVI, WET, NDBSI, LST)] \quad (1)$$

The "Natural Breaks" method computing an optimized hierarchy through continuous iterations that minimize intra-level variations and maximize inter-level variations in the data was then used to differentiate the RSEI values into five categories. Considering that ecological source patches will require a certain minimum area to play an effective role at the landscape scale (Balvanera et al., 2006), only coherent patches with an area > 10,000 ha (100 km^2) falling into the highest RSEI category were defined as ecological source areas.

(2) The Ecological Resistance Surface, modified by the Land-Use Intensity Index

The ecological resistance surface construction based entirely on land-use types commonly ignore the additional influence of land-use intensity on ecological resistance. Different methods have been trialed to correct the ecological resistance coefficient for specific land cover types (for example employing nighttime light data, surface curvature or the disaster disturbance risk index) to correct the resistance surface (Dong et al., 2020; Jiang et al., 2021; Li et al., 2021). In our study, we used the Cultivated Land-Use Intensity – Index (CLUI) as a correction factor to identify the differences between ecological resistance in the land use class "cropped area/agricultural land". We chose four indices to calculate the CLUI: the total power of agricultural machinery used per unit area, the amount of pesticides and chemical fertilizer application per unit area, and the cropping intensity as the number of crops planted and harvested per annum (Zhang et al., 2021b). The first three indicators were extracted for each county (as the smallest administrative unit for which this data is available) from the "China Statistical Yearbook", and they were further normalized to range between 0.1 and 0.9 using a range normalization method. The four normalized indices were superimposed to obtain the distribution map of cultivated land utilization degree across the study area. The larger the value, the higher the utilization intensity of cultivated land. The resulting ecological resistance value was calculated as:

$$R = R_0 + R_C \times \frac{CLUI_i}{CLUI_{mean}} + R_d + R_r$$

and $CLUI_i = M_i + C_i + F_i + P_i$

where R is the final ecological resistance, R_0 is the initial resistance value according to the respective land use type; R_c is the initial resistance value of cultivated land; R_d is the resistance value of roads; R_r is the resistance value of railroads; $CLUI_i$ is the land-use intensity of the respective grid cell i; $CLUI_{mean}$ is the average value of the land-use intensity of cultivated land; M_i is the normalized value of total power of agricultural machinery of grid cell i; C_i is the normalized value of Cropping intensity of grid cell i; F_i is the normalized value of fertilizer application amount of grid cell i; and P_i is the normalized value of pesticide application of grid cell i. The initial value of ecological resistance is defined according to different land-use types, with the respective values determined by referring to relevant literature and research (Dong et al., 2020; Peng et al., 2018a; Shi et al., 2020). Accordingly, we used values of 40, 5, 10, 15, 80, 80, 500, and 300, respectively, as the initial ecological resistance values for cultivated land, forest, grassland, shrubland, wetland, water bodies, artificial surface and bare land, respectively, with additional resistance values of 80 and 150, respectively, added for 500 m buffer area around roads and railroads.

(3) Ecological corridor identification

Potential ecological corridors were defined as the least-cost corridors between identified core source areas using the Linkage Pathways module in the Linkage Mapper tool (McRae and Kavanagh, 2011). Using ecological source locations and resistance surfaces, this tool calculates cost-weighted distances from all pixels on the ecological resistance surface to each ecological source to obtain a cumulative minimum cost path, with the cost-weighted distance threshold to use in truncating corridors being set to 200,000 units. For the generated ecological corridors, a small ratio of the cost-weighted distance (CWD) in relation to the least-cost path (LCP) distance indicates a small relative resistance of that pathway for species migration, in turn indicating a strong connectivity of the ecological corridor (Kong et al., 2021). We again used the "Natural breaks" method to split the ratio values (CWD: LCP) into 5 classes and selected the minimum level as identifying key ecological corridors.

Our approach also allows for the identification of pinch or corridor bottleneck points as areas of the corridor with highest current flow densities intersecting surrounding hostile landscape sections characterized by a high resistance to species movements. Protecting the SNH in these sections is therefore a particular priority in network management. We used the Pinchpoint Mapper module in the Linkage Mapper tool (McRae, 2012a) and chose the "raster centrality" mode to identify these pinch point sections. Subsequently, a series of iterative operations was performed between all paired patches using the "pairwise" method. Finally, remaining corridor sections with high current values were extracted as corridor pinch points. We also identified barrier points that indicate the location of important barriers affecting the quality of corridors. Barrier points are identified as areas of existing high resistance to species movement between source sites, where SNH need to be restored or re-established to locally reduce the resistance of corridor sections to species' movements, greatly enhancing the overall connectivity between source areas. Barrier points were identified using the Barrier Mapper module in the Linkage Mapper tool (McRae, 2012b). We chose the "maximum" method, iterated with a radius of 500 m, and replaced the center pixel of the search window with the minimum cost distance value between the sources using a moving window approach, with the area with a large improvement value representing a barrier or obstacle point in the respective corridor.

2.2.2. *Designing and optimizing the ecological network*

(1) Designing the ecological network

Ecological corridor construction and arable land conservation are in direct competition and due to the great demands on food production and the strongly limited arable land area in China, this competition is quite severe. Therefore, the creation of an optimal ecological corridor needs to consider trade-offs between area required and ES provision. Traditionally, conservation organizations have argued for at least 10–12% of each ecosystem type to be protected (James et al., 2001), and for a protection of at least 10% of a landscape, which are also values widely applied by policy makers (Soulé & Sanjayan, 1998). Other researchers have suggested for at least 15–30% of a landscape to be protected (Shaffer et al., 2002; Stein et al., 2000), which, depending on the habitats in protected areas, is regarded as a proportion suitable to effectively conserve wider biodiversity (James et al., 2001; Shaffer et al., 2002). Based on these debates, we modelled three distinct scenarios for the proportional land area covered by ecological corridors across our study region, generating a total SNH cover of 10%, 15%, or 20% of the total land area, balancing essential productive ES requirements for sustained agricultural yields with the limited arable land that realistically could be set aside for SNHs without impeding on the region's nationally important contribution towards food security, and aligning with arable land protection policies (MARA, 2015). As SNH in corridors could be composed of varied combinations of forest, grassland and shrubland habitats, we additionally created three simplified corridor vegetation coverage scenarios for 100% cover of idealized forest, grassland and shrubland, respectively, for each corridor area scenario. According to the nature and social settings of the study region, we set "mixed conifer - broad leaved" as forest type, "dry land" as cultivation land type, "bush" as shrubland type and "shrub and grass" as grassland type in our ESV calculations. While 100% cover of a single habitat type is not realistic, it is nonetheless regarded as helpful in generating a general understanding of the effects of different corridor habitat coverage on regional ES provisioning and can inform the general, appropriately prioritized design of corridor vegetation further amended and tailored according to local condition (local precipitation regimes, soils and their irrigation, but also preferences of local communities). We therefore generated a total of nine ecological network scenarios for further analysis (Table 1).

According to these total cover values, we generated corridors of uniform widths for each scenario with the Pinchpoint Mapper tool using circuit theory, setting different cost-weighted distances as cutoff values, to create the respective corridor structures. Ecological networks resulted from the combination of the corridors that connected large patches of existing forest, grassland and shrubland, respectively. Finally, the additional areas taken up by the different land use types under each network scenario were calculated to generate totals for each land-use type.

(2) Optimization of the ecological networks in terms of ecosystem service delivery

Changes in the ecosystem services in the study area under different ecological network scenarios were calculated using the equivalence factor method proposed by Costanza (Costanza et al., 1997). This method determines the equivalent factors of ecosystem services through expert knowledge based on an ecosystem-specific standard unit ES, then quantifying the area contributions of different ecosystems to these standard ESs. Xie et al. (2003) adapted these equivalent factors of ESs to the situation in China. Following Xie et al. (2008), a value of 1/7 of the market value of the current national grain yield in that year was taken as a standard equivalence factor. The value of grain output is calculated based on average yields for the three major grain crops, rice, wheat and corn, using the formula:

$$D = (S_r \times P_r + S_w \times P_w + S_c \times P_c)/7$$

where D represents 1 standard equivalence factor for the value of ESs (Yuan/ha), S_r, S_w and S_c represent the average yield of 1 ha of rice, wheat and corn (kg/ha), respectively, P_r, P_w and P_c represents the average unit price of rice, wheat and corn (Yuan/kg), respectively. The average unit price, sown area and grain yield of rice, wheat, and corn were collected from the statistical yearbook. The resulting values of the equivalent factor for ES per unit in 2018, 2019, and 2020 was 1,945.45 CNY, 1,869.21 CNY, and 2,167.31 CNY, respectively. To avoid the impact of economic fluctuations on food prices, the average value of the 3-years equivalent factor was calculated as a final equivalent factor value for further analysis, with this value equating to ~1994 CNY.

According to the equivalent coefficients of China's ecological service values (Xie et al., 2017), we used the area of each ecosystem type to calculate the total ES value (TESV) of each ecosystem type based on the aforementioned scenarios. A total of 11 ecosystem services (food

Table 1
The planning of different SNH scenarios.

Label	Scenario	Percentage of SNH	Land coverage
F1	10% SNH -Forest	10%	Forest
S1	10% SNH -Shrubland	10%	Shrubland
G1	10% SNH -Grassland	10%	Grassland
F2	15% SNH -Forest	15%	Forest
S2	15% SNH -Shrubland	15%	Shrubland
G2	15% SNH -Grassland	15%	Grassland
F3	20% SNH -Forest	20%	Forest
S3	20% SNH -Shrubland	20%	Shrubland
G3	20% SNH -Grassland	20%	Grassland

production, material production, water supply, air quality regulation, climate regulation, waste treatment, regulation of water flows, erosion prevention, maintenance of soil fertility, habitat services, cultural and amenity services) in four categories were calculated as follows:

$$ESV_{ij} = D \times F_{ij} \times A_i$$

Where ESV_{ij} is the total value of ES j delivered by ecosystem i, D is 1 standard equivalence factor for the value of ESs, F_{ij} is the equivalent coefficients of ES j of ecosystem i suggested by Xie et al. (2017), and A_i is the area of ecosystem i.

In order to have a better evaluation on the trade-offs and synergies between different ESs, this study integrated the Ecosystem Services Trade-off Synergy Degree (ESTD) model for quantitative evaluations (Gao et al., 2019). The ESTD is based on the linear fitting of data, which reflects the direction and degree of interaction among various ecosystem services as:

$$ETSD_{ij} = \frac{ESV_{ia} - ESV_{ib}}{ESV_{ja} - ESV_{jb}}$$

where $ESTD_{ij}$ represents the trade-offs and synergies of ESs i and j; ESV_{ia} and ESV_{ja} are the change of ES i and j at scenario a, and ESV_{ib} and ESV_{jb} the change of ES i and j at scenario b, respectively. A negative ESTD reflects ES i and j being in a trade-off relationship while a positive ESTD value indicates synergistic relationships between the two. The absolute value of ESTD represents the degree of change in ES i in comparison with a change in ES j. ESTD values were calculated for the different scenarios to identify the effectiveness of ecological network scenarios in improving ES delivery. Scenarios with the lowest ESTD value were considered to be the most effective, with least trade-offs on the improvement of regional ES. We calculated the enhancement effect of each type of semi-natural habitat scenario on total regional ecosystem services by fitting the relationship between changes in food production and total ecosystem services under each scenario based on linear models. Besides, "Es value change rate" was calculated to describe the efficiency of corridor construction with different land use cover under different scenarios. It means the amount by which total ecosystem service value increases for each hectare of cultivated lost under different scenario (Unit: yuan/ha).

2.3. Data sources

This study is based on the following datasets: (1) land use and land cover data in 2020 was provided by Globeland30 (https://www.globallandcover.com), with a spatial resolution of 30 m, differentiating 10 land cover classes (cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surface, bare land, perennial snow, and ice). The total accuracy of GlobeLand30 2020 is given as 85.72%, with a Kappa coefficient of 0.82. (2) Digital elevation data was obtained from NASA's Shuttle Radar Topography Mission (https://earthexplorer.usgs.gov/) with a spatial resolution of 30 m; (3) sown area of rice, wheat, and corn, and the average net profit per unit area in 2018, 2019, 2020, were extracted from the "National Agricultural Product Cost and Benefit Data Compilation" (PDC, 2020), while data of the total power of agricultural machinery, the amount of fertilizer and pesticide application in 2020 were obtained from the "China Statistical Yearbook" (NBS, 2020) (www.stats.gov.cn); (4) cropping intensity was provided by the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (https://www.resdc.cn/); (5) the road and railroad data were extracted from the National Geographical Information Resource Directory Service System (https://www.webmap.cn/main.do?method=index), and (6) NDVI, LST, WET and NDBSI were derived from MODIS products MOD13A1, MOD11A2, MOD09A1, respectively. Considering the large scope of the study area and convenience for further analysis, all raster images were unified to a grid resolution of 1 km^2.

3. Results

3.1. Core ecological areas

The 5-category RSEI results for the Huang-Huai-Hai region (Fig. 2) showed that areas with very low, low-median, median and median-high RSEI values accounted for 11.23%, 21.63%, 27.12% and 21.63% of the total area in the region, respectively, while the area with high RSEI values accounted for only 7.09%. These latter, potential source areas were mainly distributed along the fringes of the study area, representing relatively high altitudes, and were mainly composed of forest, shrub land, and grassland. A total of 34 ecological source patches (high RSEI value and size >100 km^2, numbered ESP1 to ESP34, were identified. These accounted for 3.85% of the total area, with the largest patch area measuring 1252.4 km^2, and the smallest patch measuring 109.4 km^2 (Fig. 2 B).

3.2. Potential ecological corridors

A total of 71 potential ecological corridors (numbered EC1 to EC71) were generated by the Linkage Pathways tool, with an average corridor length of 160.92 km (Fig. 3). The longest corridor, connecting ecological source patches ESP2 and ESP14 along the eastern edge of the study region, has a total length of 834.89 km, while the shortest corridor, connecting ecological source patches ESP19 and ESP20, had total length of only 1 km. Based on the cost-weighted distances and least-cost path ratio (CWD:LCP) rankings, a total of 10 ecological corridors, which had the lowest CWD:LCP ratio indicating the lowest resistance for species migration, were identified as the key ecological corridors for prior protection(Fig. 3). These key corridors are mainly distributed along the western edge of the study area where they connect large forested source patches, with one exception distributed in the central of study area. In order to analyze the overall corridor land use type, we chose to use the 10% SNH scenario as an example for our analysis. To maintain the connectivity of the regional ecological network, the construction of these potential ecological corridors would require 3.19% of the land area. This area is currently dominated by cultivated land (53.73%) and hard surfaces (12.29%), with a further 19.29% representing forests and 7.29% grassland. Water bodies, wetlands, shrubland and bare land accounted for relatively small, additional proportions of 4.19%, 0.87%, 0.70%, and 0.1%, respectively. With increasing corridor width, 53% ~66% (10 %SNH scenario ~20% SNH scenario) of corridor area will take up formerly cultivated land. The construction of these ecological corridors in the study area therefore will inevitably lead to considerable decreases especially in cultivated land.

3.3. Pinch points and barrier points

Our investigations identified 87 ecological pinch points and 25 barriers points across the study area (Fig. 4). Ecological pinch points are mainly concentrated along the Ecological Corridors EC8, EC28, EC35, EC42 and EC48. Among these corridors, EC28, EC42 and EC48 were identified as key ecological corridors, while corridors EC8 and EC35 are long corridors lacking intermediate notes (existing SNH patches), highlighting the importance to protect these pinch point sections. The ecological pinch points are chiefly composed of cultivated land (49.57%) and artificial surfaces (17.09%), grassland (15.38%) and forest (10.26%), with a low percentage of good quality habitats, like high-quality forest and grassland. As ecological pinch points, they represent important pressure points that ensure the viability and functioning particularly of long-distance ecological corridors, as these cross areas vastly dominated by "hostile" habitats. The integrity of key ecological corridors such as EC28, EC42 and EC48 in this context is a clear priority.

Barrier points are mainly distributed along short corridors (such as EC11, EC33, EC70, EC71, EC80), set in areas mainly composed of cultivated land, forests and artificial surfaces, with an area ratio of

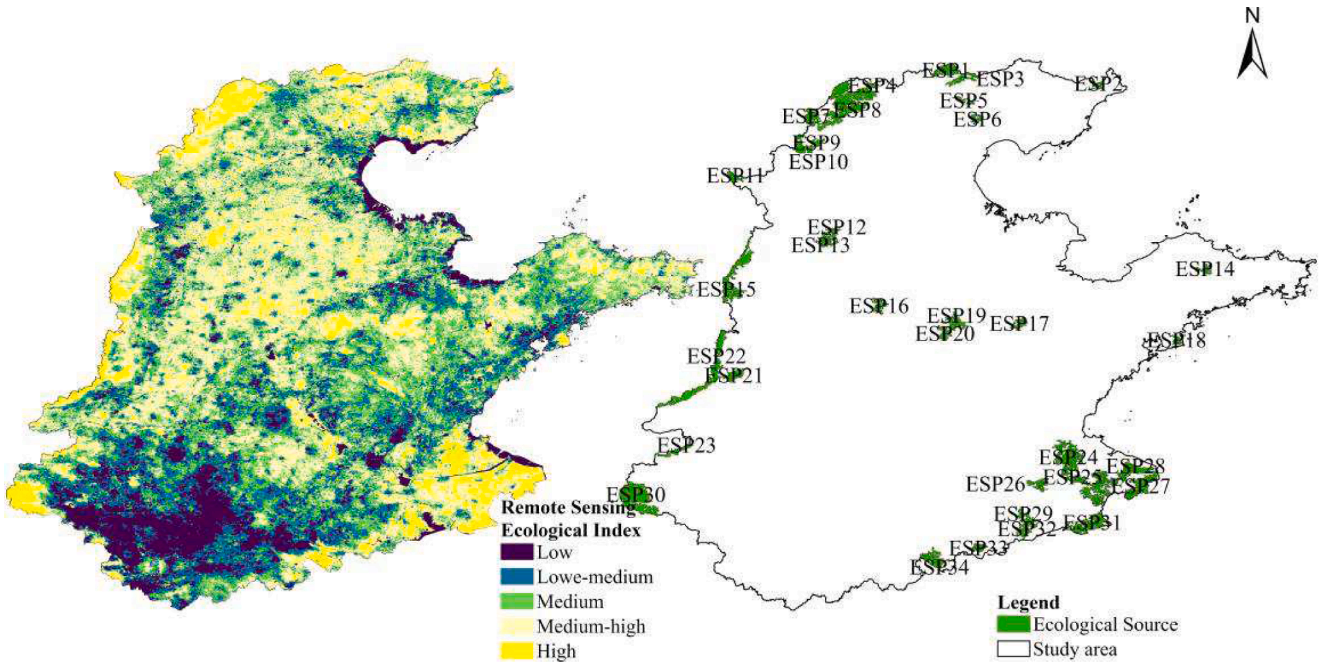

Fig. 2. Ecological quality grade (A) and ecological source patches (ESP) (B) in the Huang-Huai-Hai region based on Remote Sensing Based Ecological Index calculations (numbers indicating the respective ecological source label).

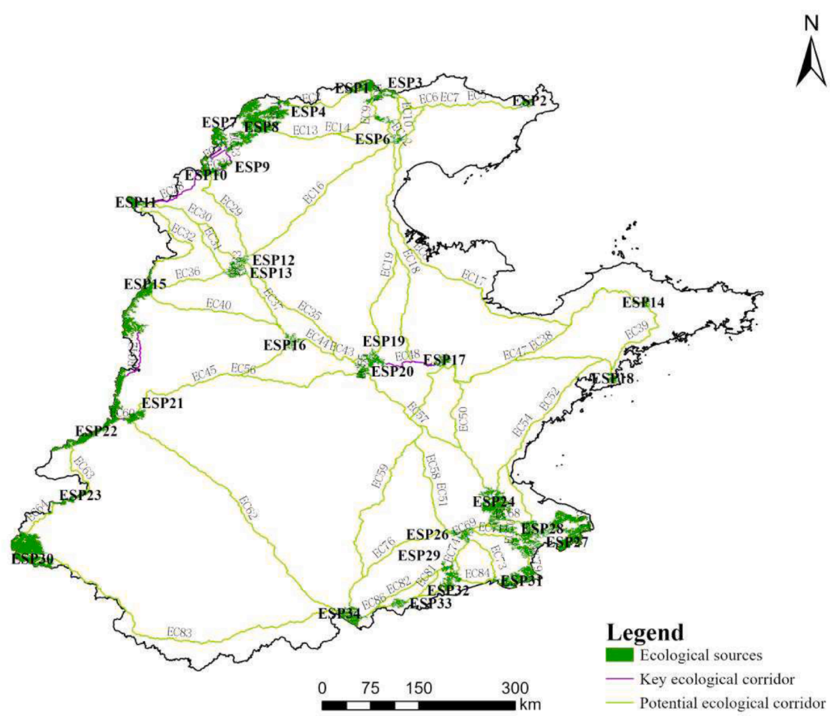

Fig. 3. Ecological corridors in the study area. (Ecological source patches were shown in boldface letters coding with ESP 1 to ESP 34, the ecological corridor was shown in black number coding with EC 1 to EC 71).

59.72%, 19.91% and 13.74% respectively. These points indicate weak pre-existing linkages caused of high resistance between neighboring ecological source patches, with the barrier points currently seriously hindering the migration and flow between the ecological sources. It is therefore difficult to combine ecological source patches even in close vicinity to each other, as they are broken up by these barrier sections. Restoring SNH at these sections has a very high potential to immediately significantly improve regional connectivity, or to even create large, coherent SNH patches that can provide significant ES for the wider surrounding landscape.

3.4. Land use types required for the ecological corridor creation under different scenarios

Our analysis showed that cost-weighted distance cutoff values of 45 k, 115 k, and 190 k, respectively, generated corridors resulting in semi-

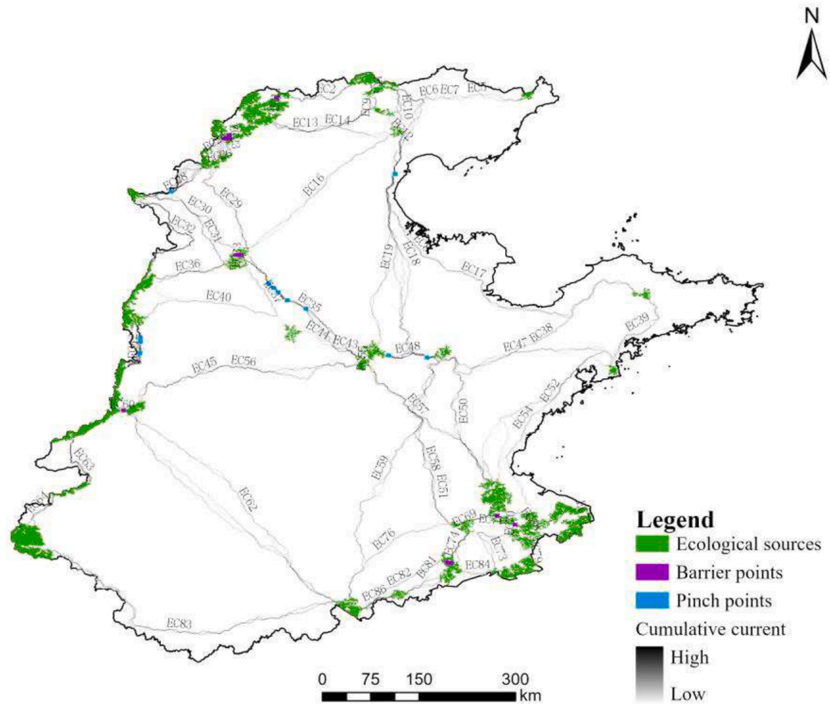

Fig. 4. Ecological pinch point and Barrier point in the study area.

natural habitats accounting to an overall of 10%, 15% and 20% of the total area (Fig. 5) in alignment with the three area scenarios. The resulting corridors themselves accounted for 4.76%, 10.52% and 16.11% of the total area in the study region, respectively, and they were chiefly located on existing cultivated land and on forests (Table 2). In line with the increased area covered by semi-natural habitat corridors, the proportion of cultivated land therefore decreased strongly from 70.43% to 59.94%, while the overall proportion of other land uses decreased much less (Table 2) or, depending on the SNH type of the corridor, increased in accordance to the corridor configuration.

3.5. Ecosystem services under different scenarios

Based on the ecological corridor plans, ES were calculated for the different habitat types, respectively (Table 3). As Table 4 shows, and with the exception of the 10% SNH-Shrubland scenario that resulted in a slightly lower overall ecosystem service value following corridor construction, the total value of ecosystem services across all remaining scenarios increased, indicating that the construction of the ecological corridors, despite the loss in arable land it causes, has an overall net positive effects on regional ecosystem services. Under the best-performing 20% SNH-Forest scenario, these services increased by nearly 22% (Table 4). In terms of ecosystem service enhancement alone, the models indicate that forest corridors are more effective in improving ecosystem services when compared to grassland and especially shrubland corridors. Based on the results, the most effective habitat combination, also taking into account the regional differences in climatic and soil parameters, appears to be a forest-grassland combination. Under all ecological corridor scenarios, food production, water supply and regulation of water flows were predicted to decrease since the corridors took up areas formerly covered by agricultural fields and wetland habitats that the model replaced with terrestrial SNHs, while remaining ecosystem services (air quality regulation, climate regulation, waste treatment, erosion prevention, maintenance of soil fertility, habitat

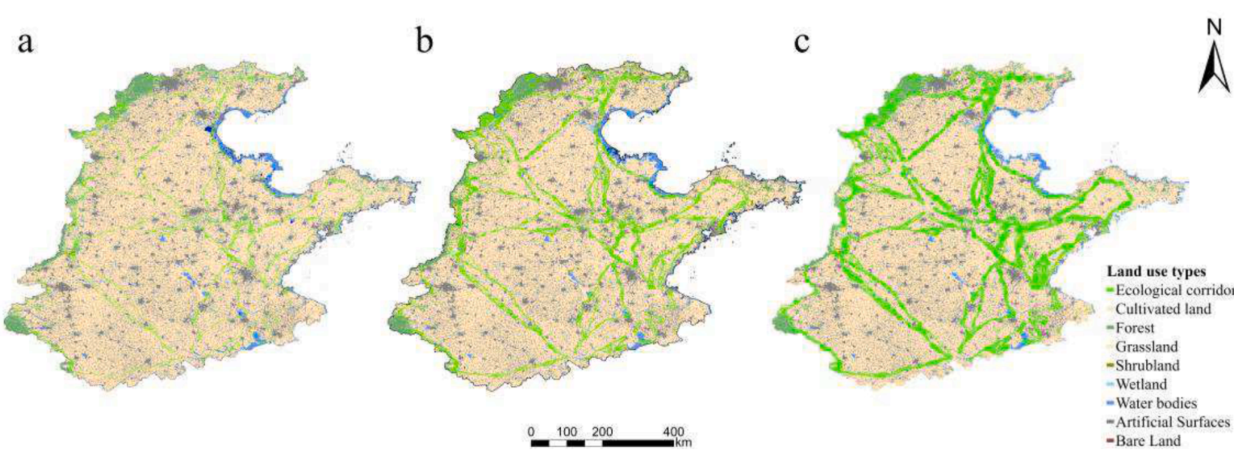

Fig. 5. Different planning scenario of Ecological corridors. Note: (a) is 10% SNH scenario, (b) is 15% SNH scenario, (c) is 20% SNH scenario of ecological corridors spatial distribution.

Table 2
Composition of land use types under different scenarios.

		Corridor scenarios EXCLUDING the habitats covering the corridors themselves		
	Initial proportion	10% SNH (F1, G1, S1)	15% SNH (F2, G2, S2)	20% SNH (F3, G3, S3)
Ecological corridor	0	4.76%	10.52%	16.11%
Cultivated land	70.43%	68.14%	64.19%	59.94%
Original* forest	4.67%	3.70%	3.12%	2.79%
Original* grassland	2.05%	1.67%	1.34%	1.16%
Original* shrubland	0.10%	0.07%	0.05%	0.04%
Wetland	0.34%	0.29%	0.25%	0.22%
Water bodies	3.20%	2.99%	2.77%	2.61%
Artificial surface	19.16%	18.34%	17.72%	17.09%
Bare land	0.04%	0.04%	0.04%	0.03%

* "original" indicating here that the areas exclude corridor areas potentially covered by the respective habitat type.

services, cultural and amenity services, as well as potentially timber (forest) or fodder production (grassland)) showed increasing trends, with the most notable increases in climate regulation, habitat services and cultural and amenity services (Table 4).

There was therefore a clear trade-off between food production services and total regional ecosystem services in all scenarios, except for the 10% SNH-Shrubland scenario (net decrease to 99.79% of original service provision) (Table 4). That is, change in overall regional total ecosystem services increased as food production services decreased and vice versa. The general trend in trade-offs between ecosystem services were not significantly different in the forest (ETSD from −0.0269 to −0.0294) and grassland (ETSD from −0.0312 to −0.0338) scenarios, while trade-offs between ecosystem services in the shrub scenario (ETSD from −0.1634 to −0.3120) were significantly higher. In terms of the degree of trade-off, the 10% SNH-forest scenario showed the smallest trade-off between food production services and total regional ecosystem services (ETSD = -0.0269), favoring synergistic development of regional ecosystem services. Nonetheless, compared with 10% SNH scenarios, the 20% SNH-forest and 20% SNH-grassland scenarios were more effective in enhancing total regional ecosystem services (TESV increased by 21.98% and 15.56%, respectively) and also showed relatively small trade-offs (ETSD of −0.0285 and −0.0318, respectively). According to Es value change rate (Table 5), the loss of one hectare of cultivated land in the 10% SNH-forest and 20% SNH-forest scenarios can result in an increase in ecosystem service value of 35,867 yuan and 35,774 yuan, respectively which are better than 15% SNH-forest scenario. The 15% SNH-grassland and 20% SNH-grassland scenarios have a higher potential for improving ecosystem service value compared to the 10% SNH-grassland scenario. Meanwhile, the ecosystem service value obtained by converting one hectare of cultivated land to shrubland is significantly lower than that of forest or grassland. Overall modelled results indicated that 10% and 20% SNH scenarios were preferable compared to the 15% SNH scenario, which had a slightly higher trade-off (ETSD = −0.0294 ~ −0.3120) (Fig. 6), and lower ES value change rate. In contrast to grassland forest scenarios, all shrub scenarios showed much more limited improvements and efficiency in net ecosystem services (TESV increased from −0.21% to 5.23%, ES value change rate is lower). The

Table 3
Total ecosystem service value (ESV) of the eight ecosystems and four ecosystem services $\times 10^7$ CNY.

Ecosystem	Provisioning services			Regulating services						Habitat Services	Cultural & amenity services
	Food Production	Materials production	Water Supply	Air quality regulation	Climate regulation	Waste treatment	Regulation of water flows	Erosion prevention	Maintenance of soil fertility	Habitat Services	Cultural and amenity services
Cultivated land	5260.71	2475.63	123.78	4146.68	2228.07	618.91	1671.05	6374.74	742.69	804.58	371.34
Forest	127.81	292.72	152.54	968.85	2898.31	820.43	1447.09	1179.11	90.70	1071.92	470.00
Grassland	68.71	101.26	56.05	356.21	942.05	311.00	690.71	433.96	32.55	394.18	173.58
Shrubland	1.77	4.01	2.05	3.83	39.47	11.94	31.26	16.05	1.21	14.65	6.44
Wetland	14.78	14.49	75.04	55.05	104.30	104.30	702.01	66.93	5.22	228.02	137.04
Water bodies	225.72	64.89	2339.02	217.26	646.12	1565.93	28846.99	262.40	19.75	719.48	533.26
Artificial surface	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bare land	0.00	0.00	0.00	0.08	0.00	0.40	0.12	0.08	0.00	0.08	0.04
Total	5699.49	2953.00	2748.49	5747.95	6858.32	3432.92	33389.24	8333.27	892.11	3232.91	1691.71

Table 4
Changes in ecosystem service value under different scenarios in comparison with before the construction of ecological corridor.

	10% SNH -Forest	10% SNH -Grassland	10% SNH -Shrub	15% SNH -Forest	15% SNH -Grassland	15% SNH -Shrub	20% SNH -Forest	20% SNH -Grassland	20% SNH -Shrub
Food Production	−1.68%	−1.17%	−2.56%	−4.88%	−3.74%	−6.83%	−8.27%	−6.53%	−11.25%
Materials production	4.40%	2.27%	0.43%	9.87%	5.17%	1.09%	15.46%	8.27%	2.03%
Water Supply	−2.21%	−3.13%	−4.50%	−2.89%	−4.91%	−7.94%	−1.44%	−4.53%	−9.17%
Air quality regulation	9.69%	6.92%	−4.43%	22.89%	16.77%	−8.34%	36.63%	27.27%	−11.17%
Climate regulation	29.35%	18.25%	12.28%	71.09%	46.54%	33.31%	114.71%	77.13%	56.89%
Waste treatment	13.35%	10.06%	4.70%	33.71%	26.43%	14.57%	56.17%	45.03%	26.88%
Regulation of water flows	−3.23%	−2.84%	−3.43%	−5.30%	−4.44%	−5.74%	−5.26%	−3.95%	−5.94%
Erosion prevention	7.58%	5.27%	1.86%	17.75%	12.64%	5.09%	28.31%	20.49%	8.93%
Maintenance of soil fertility	4.57%	2.69%	0.35%	10.30%	6.15%	0.97%	16.19%	9.84%	1.90%
Habitat Services	21.04%	15.61%	7.72%	51.84%	39.82%	22.36%	84.83%	66.43%	39.70%
Cultural and amenity services	16.44%	11.99%	5.31%	41.01%	31.17%	16.40%	67.80%	52.73%	30.13%
Total ecosystem services Value	4.74%	2.84%	−0.21%	12.61%	8.41%	1.66%	21.98%	15.56%	5.23%

Table 5
The ETSD and Es value change rate of food production services and regional ecosystem services under each scenario.

Label	Scenario	Percentage of SNH	Land coverage	ETSD	Es value change rate
F1	10% SNH -Forest	10%	Forest	−0.0269	35,867
S1	10% SNH -Shrubland	10%	Shrub	0.9369	/
G1	10% SNH -Grassland	10%	Grass	−0.0312	21,516
F2	15% SNH -Forest	15%	Forest	−0.0294	34,632
S2	15% SNH -Shrubland	15%	Shrub	−0.3120	4,568
G2	15% SNH -Grassland	15%	Grass	−0.0338	23,108
F3	20% SNH -Forest	20%	Forest	−0.0285	35,774
S3	20% SNH -Shrubland	20%	Shrub	−0.1634	8,510
G3	20% SNH -Grassland	20%	Grass	−0.0318	25,323

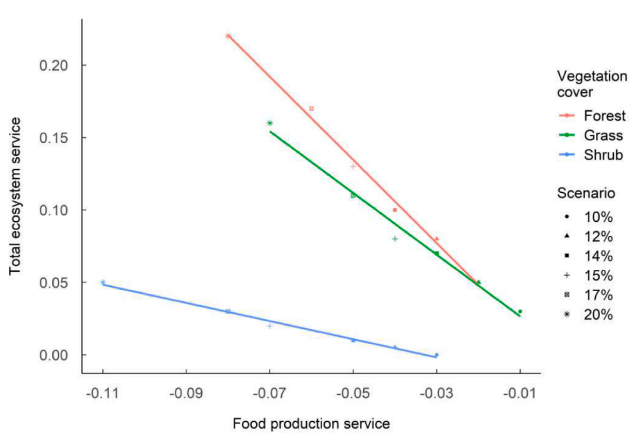

Fig. 6. Linear relationship between food production service and total ecosystem service.

synergistic relationships between decreased food production and total ecosystem service delivery (Fig. 6) further emphasized the similarity in benefits of grassland and forest scenarios, indicating that mosaics or mixtures of these two habitats across the corridor network is likely to create the highest overall benefits to the agricultural landscape.

With the increase of the proportion of semi-natural habitats, ecosystem services in the region all showed increasing trends. Change of vegetation coverage had much stronger effects on ES delivery and rate of increase. The tree forest corridor scenarios (F1, F2, F3) showed the most significant enhancement on regional total ecosystem services, followed closely by the grassland scenarios (G1, G2, G3), while shrubland scenarios again showed a much lower delivery of ES (S1, S2, S3) (Fig. 6).

4. Discussion

4.1. Ecological sources and corridors

As key step in ecological network planning, the identification of ecological source areas revealed that in our study region, about 50.11% of the core ecological source patches represented large woodland patches. Cropland accounts for a large portion of the remaining ecological resources, comprising approximately 43.16% of the total. Artificial surfaces make up 5.77% of ecological sources, while water, wetlands, and bare land occupy the remaining areas, about 0.07%, 0.87%, 0.02% respectively. This shows that forests formed the dominant habitat type in good habitat quality in this region. Surprisingly, the remaining ecological source patches were dominated by cultivated land. This classification may be chiefly contributable by irrigated cropland that, through consistently high water availability when compared to other land use types, was categorized as high quality in the remotely sensed imagery. Geographically, forest and grassland source areas mainly occurred in the mountainous areas distributed on the northern and western edges of the study area, as well as at more isolated mountain ranges chiefly in Shandong province, while the generally wetter (WET) and greener (NDVI) south-eastern ecological source areas were regularly dominated by agricultural land (Fig. 2).

To contextualize the ecological source area distribution further, the total amount of land classed under this category accounted for only ~3.85%, and therefore for ≪5% as the semi-natural habitat minimum threshold commonly set in the context of agro-biodiversity conservation and maintenance of landscape-scale ecosystem services (Cole et al., 2020; Nilsson et al., 2019), even before taking into account that not all ‘source areas’ actually represent semi-natural habitats in the first place. This further emphasizes the poor ecological quality of the environment across the Huang-Huai-Hai region – and the urgent need to establish new, and restore remaining, natural and semi-natural habitats across the region. The suggested ecological corridors in our view form an incredibly effective potential way forward in this regard, although its creation, as indicated by our models, will lead to substantial decreases in arable land, given that 53% ~ 66% (10 %SNH scenario ~20% SNH scenario) of the newly constructed corridors are situated on current arable land, which means that there might be policy restrictions, but also a lack of farmers’ willingness to transfer their agricultural fields towards semi-natural habitats particularly if adequate compensation schemes are not in place. On the other hand, existing natural and semi-natural habitats are currently chiefly distributed along the fringes of the study region, resulting in the most intensively cultivated areas across the region severely depleted of any ‘ecological infrastructure’ and associated ecosystem services required for the long-term sustainability and ecological intensification of the agricultural landscape. This indicates that keeping the status quo, particularly considering increasing pressures related to climate change and the associated ongoing environmental degradation, for example through topsoil being relatively susceptible to erosion (Yu & Deng, 2022), is nonetheless not an option.

Because of the large size of our study area and the scarcity of identified source areas in its center, potential ecological corridors connecting source areas are commonly very long (Fig. 3). Compared with shorter corridors, these long ecological corridors may not be very effective in promoting species migration particularly if migration is not further supported by large, newly created SNH patches acting as stepping stones (Saura et al., 2014). Therefore, such transit nodes, spaced at relatively regular intervals along particularly the long-distance corridors, might need to be created in addition to the main corridors (Yu et al., 2022). With the identified key corridors mainly located in forest and mountain areas at the edge of the study area, they will likely not use up large amounts of highly productive agricultural land, while potentially providing high biodiversity conservation value once connecting the existing high-value SNHs in this region.

4.2. Ecological networks design

4.2.1. Ecological networks selection and optimization

The ecological network covering with semi-natural habitats could provide migration routes and habitats for animals (Luo et al., 2021; Zhang et al., 2021a), and so that improve ecosystem services such as pollination and pest control(Holland et al., 2017; Mestre et al., 2018) . Additionally, an ecological network constructed primarily of woodland and grassland may not only enhance landscape aesthetics but also serve as a windbreak and sand stabilization measure, creating a microclimate to improve agricultural production (Schüpbach et al., 2021; Liu et al., 2020; Liu et al., 2021). This multifunctionality could favor the practical implement of this semi-natural habitats based ecological network designing. However, the Chinese government has legislated for a minimum threshold of 12 million ha of cultivated land to be preserved to ensure national food security, (Weiguo & Axmacher, 2016; MLR, 2016), an increase in the area of semi-natural habitat for ecological corridors would inevitably linked to the loss of arable land. An ideal ecological corridor scenario should optimize ES provisioning while occupying a minimal amount of formerly cultivated land area. From the point of prevention of arable land losses, the 10% SNH scenario hence appears to be the most realistic and compliant with policy requirements for the study area. the limited loss of cultivated land under this scenario will also be more in line with farmers' willingness to support the construction of the ecological infrastructure as a critical determinant for the effective implementation of the corridor network (Sauer & Fischer, 2010). However, we have demonstrated that the ES gains linked to the 10% SNH scenario remain somewhat limited, given the overall increase in ES with increasing corridor area up to at least the 20% scenario even where loss of yields are accounted for. A 20% threshold for semi-natural habitat has furthermore been suggested as crucial in the maintenance of biodiversity by recent studies (Garibaldi et al., 2021), with such a relatively large areal extend of ecological infrastructure also believed to greatly enhance the resulting connectivity between the currently isolated patches across the landscape (Tscharntke et al., 2021). Overall, we recommend to preserve this higher proportion of semi-natural habitats across the landscape wherever possible, particularly since this will be highly instrumental to shift towards an ecological intensification of production, with higher per unit area-productivity that has not been included in our models allowing for a potential partial offset of the overall yield decreases inherently linked to the loss of cropped area. Additionally, food production can be increased by changing agricultural practices in general, too, for example by increasing the diversity of crop species and improving crop heterogeneity (Renard & Tilman, 2019), which not only guarantees the stability of food production, but also further contributes towards the targeted increase in biodiversity across the agricultural landscape (Sirami et al., 2019). Agricultural biotechnology will also be an essential part to solve conflicts between food production and ecosystem services by further enhancing productivity levels per unit area (Varshney et al., 2011).

Optimizing the ES provision by semi-natural habitats will also encompass optimizing the vegetation composition or configuration in these habitats, as well as in the wider agricultural landscape. Forest coverage was indicated to enabling the greatest regional ES increases, followed closely by grassland – an ecological network containing large proportions of both forest and grassland cover will hence likely optimize ES provisioning if created with ES optimization in mind. Many planted forests in China currently consist of monodominant stands of single tree species like pines or poplar, resulting potentially in high timber production, but a low overall provision of ecosystem services and small contributions to biodiversity conservation. Improving the habitat quality of these plantation forest by increasing tree species diversity and restoring flowering herbaceous ground cover would greatly improve biodiversity-associated services (Wu et al., 2019). In this context, and despite model predictions, complex structural mosaics of forest and grassland with additional shrubland elements might be the ecologically optimal design supporting the highest levels of biodiversity and enhance creating optimal overall habitat stability (Cai et al., 2021; Marais et al., 2022; Murgueitio and Calle,1999). The creation and management of these habitat mosaics needs to account for multiple factors ranging from soil property, irrigation, aesthetics to construction and management costs and the potential impact and pressures from climate change. An alternative, highly cost-effective way to create the corridors could be to trial "hands off" approaches where local vegetation development is left widely to natural succession dynamics. Nonetheless, to guarantee ecosystem services linked for example to timber extraction and fodder quality provided by forest and grassland ecosystems respective, we believe that some targeted interventions like planting or supporting the establishment of plant species that are expected to greatly enhance local ecosystem services (including also e.g. legumes to improve local soil fertility, or nectar-rich late summer-flowering plants for sustaining local pollinator assemblages) would create a significantly improved outcome. Climate change-suitability should also be a determining factor in any interventions for example when consider enrichment planting in naturally regenerating SNH types within the ecological corridors.

Due to climatic conditions and other environmental factors in the study area, broadleaf forests dominated by fast-growing species like *Populus simonii Carr* (Liu et al., 2020) dominate in regional forest shelterbelt construction. Nonetheless, due to the relatively low overall precipitation that also exhibits strong seasonal and inter-annual variations in study area, *P. simonii* may not be the most suitable and sustainable species to plant, having already been linked to woodland degradation (Liu et al., 2020). Instead, mixed conifer-broadleaved forests that also more closely resemble the natural regional forest type should be promoted, showing not only better adaptations to local microclimatic variations, but also supporting high levels of biodiversity, and enhancing overall ecosystem service provisions (Felton et al., 2021). Ecological corridors with forests dominated by trees better adapted to low precipitation (such as locally native *Prunus* spp., *Pinus tabuliformis*, potentially accompanied by non-native species like *Robinia pseudoacacia*), shrubs (for example *Caragana korshinskii*) and herbs (*Chrysanthemum* spp., *Orychophragmus violaceus*) will likely result in more sustainable vegetation cover following corridor construction. However, given the large area covered by our investigations, these species are just for providing an initial reference point, while planting "native species" according to local conditions will optimize performance of ecological corridor construction, with particularly herbaceous species potentially naturally recruiting from the local flora.

4.2.2. Key node protection

In line with observations from earlier studies, our results show that the spatial distribution of corridors, and particularly the locations of associated nodes, remained widely unaffected by changes to the overall percentage of areal corridor extend (Peng et al., 2018b). Ecological pinch points on the long corridors that highlight sections of maximum corridor weakness for species migration therefore require crucial attention in all scenarios we created. Their key role in supporting species' movement means that they will require special protection (Harbaugh et al., 2009). Strengthening their effectiveness by potentially increasing corridor width in these sections, or even creating larger 'stepping stone' patches in their vicinity through reforestation and grassland restoration might be particularly beneficial to facilitate long-distance movement of species along the corridor between the remnant source habitat patches (Saura et al., 2014). Similarly, enhancing corridor width at barrier points that are found along short corridors, and targeting the wider areas with "grain for green" or other semi-natural habitat restoration measures, might allow for distinct patches to combine and transform into one large ecological source patch. This could also greatly enhance ecosystem stability and ecological functioning (Balvanera et al., 2006).

The extensive land area currently used for settlements and human infrastructure, and particularly the dense traffic networks in the study area, will render ecological corridors vulnerable to human disturbance and extremely difficult to create. Stepping stones rather than coherent linear corridors will hence likely have to be established in areas affected by major roads and construction infrastructure as transit points for migration, even though they are considered less efficient in creating connectivity and promoting biodiversity conservation. Stepping stones are nonetheless more flexible in their spatial distribution, indicating their great potential value as potential alternative, or supplementary, measure (Lynch, 2019; Wu et al., 2022).

Ecological corridors may also intersect wetlands and other water bodies that make important contributions towards the regional water supply and provide flow regulation services. Even small losses of water bodies and wetlands in this context can lead to significant adverse impacts for humans and biodiversity, alike. Any wetlands and other water bodies should hence be protected across the landscape, and, crucially, wherever they intersect with a corridor. Furthermore, and also in response to the predicted increase in drought conditions in the wider study area linked to climate change, plant species with low water demand should be selected in semi-natural habitat construction (Liu et al., 2020).

4.3. Limitations

There are a number of limitations associated with our study. Firstly, corridors with different width are derived by setting different cumulative resistance cutoff thresholds. Determination of ecological corridor width in practice should consider the effects of other factors such as conservation objectives, local and regional vegetation composition, surrounding land use and corridor length, as well as existing small patches of SNH, and particular wetland habitat of strong concern in the provision of water-related ES in this relatively dry region. Secondly, although the equivalence factor method can effectively model ESVs, it simplifies and therefore ignores potential spatial heterogeneity of ESs, such as the difference between ESs of the same land use type category for different plant species communities, and the impact of different land use intensity on ESVs (Gaglio et al., 2020). Our study only continued three general types of simplified corridor vegetation cover scenarios, while the vegetation configuration of all three habitats – shrubland, grassland, and particularly forest, in reality is highly complex, with strong implications for specific, local ecosystem service provisioning. Therefore, the equivalence factor method may ignore that simple addition of services might over-, but more likely underestimate the true provision of services, following the idea that "$1 + 1 > 2$" linked for example to understory herbaceous species in forest corridors and grassland habitats creating additional and non-linear responses for example in view of pollination or pest control offsetting locally reduced food production services due to higher yields in surrounding landscapes following the increase in the proportion of semi-natural habitats (Garibaldi et al., 2021). A finer classification of land-use types and the additive effects linked to mosaic-configurations of different land-use and vegetation types would therefore allow for a more realistic evaluation of the true ES-associated impacts of the corridor creation and allow a finer tuning of the construction of these corridors throughout the study region.

5. Conclusion

The construction of ecological corridors and networks can be used to connect remaining ecological source areas across cultivated land, allowing the migration of species that might be beneficial or of conservation concern throughout the wider landscape, while simultaneously increasing overall ecosystem service provisioning and potentially offsetting loss of agricultural land by increasing area-based productivity via ecological intensification. Although our study provides a approach for the establishment of semi-natural ecological networks in agricultural landscapes with the consideration for ecosystem services tradeoff, the methods could be further improved in the future with more consideration on the specific configuration of landscape elements within the corridor to maximize its impact and provision of regional ecosystem services (Li et al., 2020). At the same time, construction costs and ecological benefits need to be balanced with policy goals regarding conservation as well as food production to improve the feasibility of the urgently required establishment of ecological corridors in the heavily ecologically degraded agricultural landscapes, providing a more sustainable, ecologically intensified mode of food production.

Our study also indicated ecological networks accounting for 10% area of the region seems the most feasible scenario to achieve realistic trad-offs in the overall enhancement of regional ecosystem services and loss of food production under China's current national arable and production protection policies in the Huang-Huai-Hai region. For a further enhancement of regional ecosystem services, we suggested that the ecological network can be gradually extended to cover a total of 20 % of the region, at least where per-unit productivity enhancements allow for such an expansion. Diversification of vegetation structure and composition, and optimized spatial configurations of the corridor network could further improve regional ecosystem services and requires more detailed, additional modelling. Meanwhile, pinch points and barrier points along the corridors require special attention to ensure their protection and restoration, respectively, for example using "grain for green"- or similar programs, to strengthen the connectivity between ecological source patches. Additionally, wetlands and water bodies that play an important role in regional water circulation and supply services, should be preserved in priority to reduce the trade-offs of various ecosystem services.

CRediT authorship contribution statement

Shunxiang Fan: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Jan C. Axmacher:** Methodology, Writing – review & editing. **Hanjun Shu:** Methodology, Software. **Yunhui Liu:** Conceptualization, Writing – review & editing, Resources, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

Acknowledgements

We thank to the National Natural Science Foundation of China (NO. 41871186) and National Key R&D Program of China (NO. 2018YFC0507204).

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