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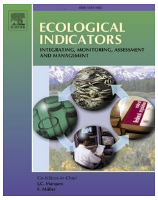

Original Articles

How to restore ecological impacts from wind energy? An assessment of Zhongying Wind Farm through MSPA-MCR model and circuit theory

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ABSTRACT

The wind energy industry is developing rapidly in China with a maximum capacity worldwide. Meanwhile, the stability of the ecological network is challenged by extensive renewable energy expansion. There are still research deficiencies in wind farm ecological impacts at project scale from an ecological restoration perspective. It is of great necessity to monitor the ecological impacts with time going and explore ecological restoration strategies for wind power development. The research case of Zhongying Wind Farm is selected based on investigation and interviews regarding its ecological impact in the prior study. It employs a comparative methodology by comparing the ecological quality before and after the construction of Zhongying Wind Farm. Raw data from Landsat 8, the Digital Elevation Model (DEM), the Normalized Difference Vegetation Index (NDVI), and wind turbine statistics originating from open data platforms are analyzed and visually represented with ArcGIS. This paper establishes an ecological network based on morphological spatial pattern analysis (MSPA) and the Minimum Cumulative Resistance (MCR) model to quantify wind farms' impacts on ecological corridors. The circuit theory and Pajek software are used to identify and categorize the ecological nodes into weak and obstacle points. The results reveal that ecological impacts on ecological corridors decay with distance, reflecting changes in length, connection strength and cumulative values of corridors. While the impacts on ecological nodes depend on nodes' attributes: the number of weak points increased by 18.5 %, and obstacle points increased by 350 %, with their locations shifting from the edges of urban construction sites to the edges of wind farm. Differentiated strategies are proposed according to the impact magnitude of each ecological corridor and node: such as dynamic inspection mechanism, construction prohibition for protection; corridor structure and function recovering, stepping stones addition for restoration; buffer belts, warning radar, and monetary schemes for compensation. This research fills the gap of ecological impact assessment under the challenges of wind energy expansion. It helps to balance wind energy development and ecological restoration at the regional level.

1. Introduction

With international commitments to carbon neutrality and climate change mitigation, the energy transition has been globally promoted. The concerns of the energy transition have broadened from technologies to political, social, environmental, and economic perspectives (Lazaro et al., 2022). The Chinese government has accounted for its carbon neutrality strategy, reaching carbon emissions peak before 2030 and carbon neutrality before 2060 (IREA, 2022). The announced pledge scenario expresses China's ambitions to shift towards innovation-driven growth and the socio-economic benefits it would bring beyond those associated with reducing the impact of climate change (IEA, 2021). The Chinese government promised that non-fossil fuels achieve 25 % of the national primary energy mix by 2030. It released great opportunities for renewable energies that emit low carbon during production. Wind energy has been recognized as the competitive substitute for fossil fuels with its characteristics of clean, renewable, and rich resource distributions. According to the annual report issued by the Global Wind Energy Council, the global wind energy capacity reached 906.2 GW, among which China accounts for over 40 % at the end of 2022 (GWEC, 2023). The wind industry witnessed the prosperity of the Chinese market with its explosive growth in the last decade. China has been widely accepted as the wind energy industry leader in both cumulative installation capacity and newly installed capacity of wind power.

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As wind energy capacity grows, a large amount of research focuses on the various environmental impacts of wind farms, such as noise (Freiberg et al., 2019), shadow flicker (Harding et al., 2008), visual impact (Manchado et al., 2019), and impairments to biodiversity (Siyal et al., 2015). Zhu et al. (2018) overviewed the noise prediction models for wind turbines under complex inflow conditions, including models based on the acoustic analogy, flow-acoustics splitting techniques, Amiet's model, and various engineering models. Cao et al. (2020) developed a numerical optimization framework for wind farms in an optimization algorithm to balance the noise emission and annual energy production. Guan (2022) proposed a Landscape Visual Impact Evaluation (LVIE) model with three dimensions of landscape sensitivity, visual impact of WTs, and viewer exposure to optimize the wind farm planning procedures. Bruinzeel et al. (2018) proposed a model for mortality estimation based on the specific characteristics of bird species to validate the impairment of wind turbines on wild birds. With more factors considered in the process of wind farm layout, multi-criteria decision-making approaches have been extensively explored to achieve sustainable development of society, economy, and environment (Baseer et al., 2017; Virtanen et al., 2022). However, existing research are mainly focused on site selection optimization to increase energy production efficiency, while the long-term potential ecological impacts caused by wind facilities are ignored.

Regarding the growing sizes and broad distribution of wind turbines, the ecosystems have been affected to various extents (Katzner et al., 2019). Some studies proved that the turbine blade rotation and cue lights could affect wild bird habitats and migration paths, further influencing the ecological structure and stability (Masden et al., 2009; Xu et al., 2021). Guo et al. (2020) quantified the impact of wind power plants on the ecosystem by the Least-cost distance and Least-cost path models. The indexes of landscape connectivity and ecological corridors were compared before and after the wind farm construction in Shanxi Province of China. Guan (2023) has compared the number and routes of ecological corridors affected by wind farms, aiming to illustrate the change in ecological quality in Ningbo City. Yang et al. (2023) have improved the evaluation process and indexes by introducing the length, connection strength, and cumulative values of ecological corridors, and utilized in the PV project site selection. The ecological approaches are gradually being applied in renewable energy site selection. Even so, the approaches for ecological network construction, such as morphological spatial pattern analysis (MSPA) and Minimum Cumulative Resistance (MCR) focus on the quantitative assessment methods of ecological impacts. There are still research gaps in restoration strategies after assessment. A solution-oriented assessment framework is of great necessity for wind farms to quantify and monitor the changes in ecological quality.

It is already a well-acknowledged consensus that renewable energy facilities, such as wind farms, do affect ecological quality. However, the solution-oriented ecological impact assessment by corridors and nodes are insufficient. This paper explores the assessment approach of ecological impacts from onshore wind farms by quantifying the ecological corridors and nodes with MSPA-MCR Model and circuit theory with comparison before and after the construction of wind farms. This research aims to: 1) develop a framework for quantifying the ecological impacts of wind farms; 2) propose restoration strategies based on the ecological impact assessment. The ecological impact assessment was conducted in four steps with the case of Zhongying Wind Farm: (i) collecting basic data of DEM, satellite images, NDVI, and landcover types for identifying the ecological sources through MSPA; (ii) constructing the ecological corridors and nodes through MCR model and circuit theory; (iii) quantifying the ecological quality through corridor length, connection strength, cumulative values, as well as the number, distribution, importance-level, and land cover of ecological nodes; (iv) proposing protection, restoration, and compensation recommendation based on the assessment results. This paper offers scientific and rational recommendations for ecological network stability while balancing wind power development and ecological security. Meanwhile, it can provide monition data based on regional ecological quality for wind energy repowering in the future.

2. Research methodology

2.1. Research area

Zhongying wind farm is chosen as the study area, which is an onshore wind farm located in Ningbo City, Zhejiang Province, China. The location is near the Donghai Sea, north of Xiangshan Port, south of Hangzhou Bay (Fig. 1). Zhongying wind farm was built and connected to the electricity network in 2012, with 18 WD103-2500T wind turbines on the peak of Fuquan Mountain, with the altitude between 120 and 450 m. The research area is made up of forest, shrubs, agricultural land, construction land, and water. There are 17 villages around the wind farm, with about 5800 residents.

Since installing wind turbines in the locality, ecological changes, such as forest encroachment, soil erosion, and reservoir water shortages, have been blamed by residents (Guan and Zepp, 2020). Therefore, the project received fierce resistance from residents who suffer from the above ecological impacts. Given the ecological sensitivity and local opposition, the site was selected as the case for the study of ecological network restoration near wind projects.

2.2. Data sources and processing

Data used in this research include remote sensing images, land cover, digital elevation model (DEM), vegetation coverage, and wind turbine statistics. Among them, the remote sensing images processed by Landsat 8 and DEM with 30 m spatial resolutions in 2010 and 2020 were obtained from the Geospatial Data Cloud (http://www.gscloud.cn/search). Referencing the availability of data during the study period and the influential factors such as cloud cover (below 5 %), Landsat 8 images from May to October were selected and preprocessed through ENVI (The Environment for Visualizing Images) for radiometric calibration and atmospheric correction. The location, height, and capacity of wind farms were obtained from the wind energy open data platform Vortex (https://interface.vortexfdc.com).

Landcover and vegetation coverage were processed through NDVI, which is introduced to represent the health status of vegetation. The value of NDVI is calculated through the bands in Landsat 8 as shown in Eq. (1):

$$NDVI = \frac{(Band5 - Band4)}{(Band5 + Band4)} \tag{1}$$

where Band 4 and Band 5 stand for the spectral reflectance measurements acquired in the red (visible) and near- infrared regions. The land cover was transferred from NDVI values, referencing the conversion range in Table 1 (Yin and Kong, 2014).

According to the Pixel Binary Model, the vegetation coverage (Fvc) can be illustrated by the information contributed by both green vegetation and barren land or area without vegetation cover processed through NDVI by Eq. (2):

$$Fvc = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{2}$$

The corresponding NDVI values of 0.5 % and 99.5 % are used as the values of $NDVI_{soil}$ and $NDVI_{veg.}$

2.3. Research method

A research framework is proposed to achieve the research target of assessing the ecological impacts of wind turbines. The length and connectivity of ecological corridors generated before and after the

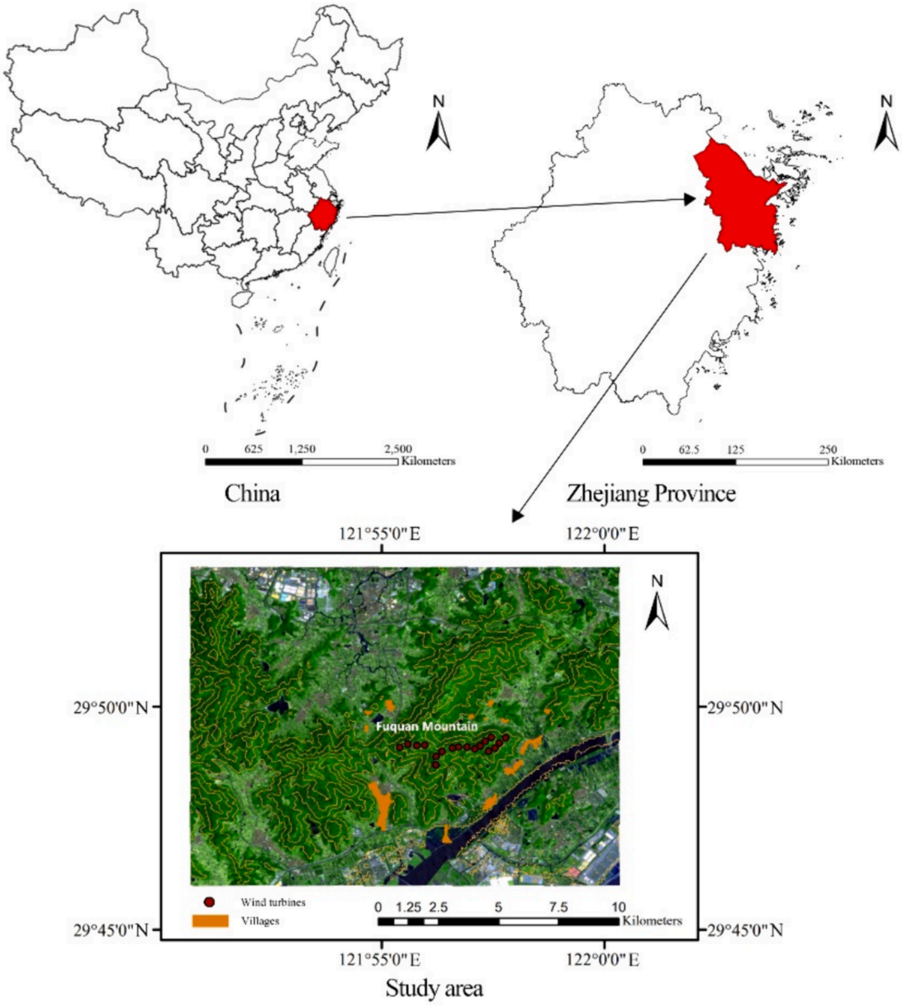


Fig. 1. Location of the study area.

Table 1
Conversion range of NDVI to Land cover.

NDVI value	Land cover
−0.028 to 0.015	Water
0.015 to 0.14	Built up area
0.14 to 0.18	Barren land
0.18 to 0.27	Shrub and farmland
0.27 to 0.36	Sparse vegetation
0.36 to 0.74	Dense vegetation

construction of Zhongying Wind Farm are compared to analyze the ecological network stability on a regional scale. According to the previous studies on the ecological impact (Guo et al., 2020; Ai et al., 2022; Wang et al., 2022), the quantification of ecological corridors and ecological nodes changes could be based on MSPA, MCR model, gravity model, and circuit theory. The ecological impact assessment is conducted through ArcGIS 10.8, Guidos Toolbox, Conefor 2.6, and Linkage Mapper (Fig. 2).

2.3.1. *Identification of ecological sources*

MSPA was introduced to destinate the ecological sources. It is a classification processing method based on mathematical morphology that helps to process the different spatial types of landscape patterns (Nie et al., 2021). The morphological spatial pattern analysis was conducted through the Guidos Toolbox to divide the landscape into eight types of landscape elements with clear ecological connotations: core, loos, islet, bridge, perforation, branch, edge, and background.

This study selected the forest based on land cover analysis as a suitable habitat for wild animals. In MSPA analysis, the forest was assigned as the foreground with an attribute of 2. Other land uses such as construction land, cropland, waters, shrubs, and grassland were assigned as background with the attribute value of 1. Since the area of selected patches is the key factor affecting the species immigration and information transition, patches in the core type over 5000 m^2 were selected. Additionally, the patch importance index (dPC) was calculated by Conefor 2.6 software to evaluate the connectivity between patches. Finally, the patches with an area over 5000 m^2 and dPC index over 0.1 were selected as ecological sources for constructing the MCR model.

2.3.2. *Construction of resistance surfaces*

The resistance surface represents how cost variations facilitate or hinder movement when species migrate from one source patch to another (Tang et al., 2020). This research proposes a comprehensive resistance index framework based on literature research and actual situations during fieldwork. Three resistance factors and their score assignments are listed in Table 2: natural conditions, human disturbance, and environmental response. Elevation, slope, and land cover are assigned to represent the natural condition. In the factor of human disturbance, wind turbines are selected as the variations. The environmental response index is represented by the vegetation coverage (FVC). Referencing expert opinions and related studies (Dai et al., 2021; Cui et al., 2022), the score of each resistance index was assigned to five

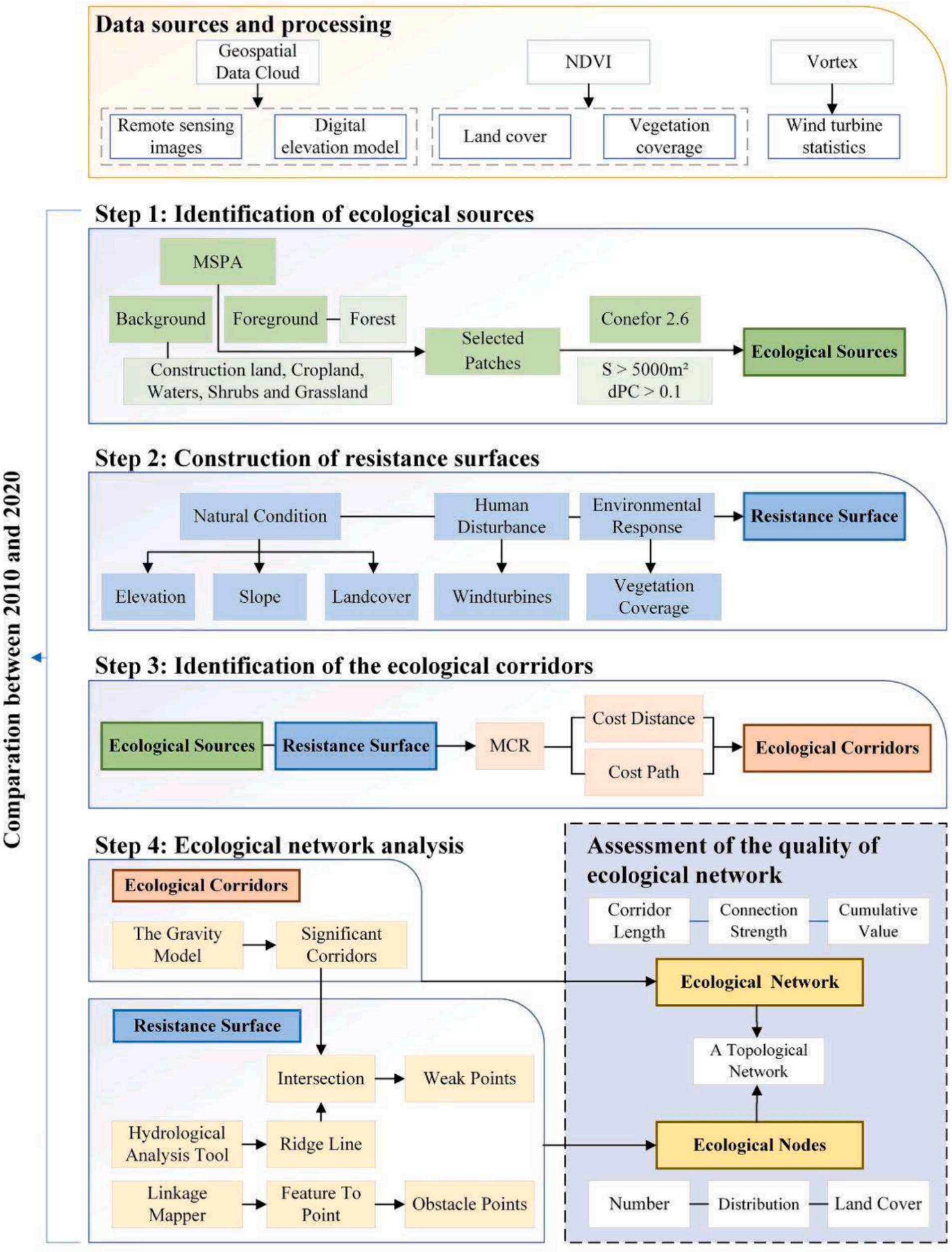


Fig. 2. Research structure.

Table 2
Composition of the resistance surface index framework.

Index		Resistance value				
		1	2	3	4	5
Natural condition	Elevation (m)	≤50	50–150	150–250	250–350	≥350
	Slope (°)	≤5	5–15	15–25	25–50	≥50
	Landcover	Forest	Shrub & Cropland	Grassland & Barren land	Waters	Construction land
Human disturbance	Wind turbines (H)	≥50	25–50	10–25	3–10	≤3
Environmental response	Vegetation coverage (%)	≥75	60–75	45–60	30–45	≤30

levels. The higher the score in each pixel, the higher the forces that hinder species exchange and spread in the ecosystems.

2.3.3. *Identification of the ecological corridors*

The MCR model is used to construct the ecological corridors with the ecological sources and resistance surface. This model is analyzed by the Cost Distance and Cost Path modules in ArcGIS, which aims to analyze the cumulative cost for animals' migration between two ecological sources (Guo et al., 2020). The MCR model can reflect the spatial trend of species migration and the flow of matter and energy (Pickett et al., 2017). Therefore, MCR is widely used to evaluate the ecological quality, landscape pattern, and corridor connectivity to illustrate the landscape spatial pattern. The calculation formula is defined as Eq. (3):

$$MCR = f_{min}\sum_{j=n}^{i=m} D_{ij} \times R_i \tag{3}$$

where *MCR* is the minimum cumulative resistance value of an ecological corridor; D_{ij} represents the distance between source i to source j; R_i means the total resistance values encountered during the migration process (Nie et al., 2021).

2.3.4. Ecological network analysis

Since the strength of source-to-source connection can characterize the effectiveness of corridor connectivity and the importance of connected patches (Yu et al., 2016), the significant corridors were subsequently selected with connection strength analysis through the Gravity Model. The priority of the corridors with interaction forces greater than a certain threshold was further extracted to generate the final significant ecological corridors in the study area. The Gravity Model can quantify the interaction force between sources, as shown by Eq. (4):

$$\begin{aligned} G_{ab} &= N_a N_b / D_{ab}^2 = \left[\frac{1}{P_a} \times \ln(S_a)\right]\left[\frac{1}{P_b} \times \ln(S_b)\right] \Big/ \left(\frac{L_{ab}}{L_{max}}\right)^2 \\ &= L_{max}^2 \ln(S_a)\ln(S_b) / L_{ab}^2 P_a P_b \end{aligned} \tag{4}$$

where G_{ab} represents the interaction force between sources a and b; N_a and N_b are the designated weight values of patches a and b; D_{ab} refers to the standard resistance value of the potential corridor between patches a and b; P_a is the assigned resistance value of patch a; S_a is the area of patch a; L_{ab} is the cumulative resistance value connecting patches a and b; L_{max} is the maximum resistance value of all corridors.

In the ecological network, the ecological nodes play a significant role in material and energy flow (Merrick and Koprowski, 2017). This study extracted ecological weak points and ecological obstacle points to assess the quality of the ecological network. The ecological weak points were defined as nodes with sensitive characteristics and exposed to ecological threats, which can be abstracted by the areas with the largest resistance values in the resistance surface analysis. The ridge line of the resistance surface generated in 2.3.2 was extracted through hydrological analysis tool in ArcGIS 10.8. The intersection of the ridge line and significant ecological corridors generated by the MCR model and Gravity Model were identified as the ecological weak points. The resistance of the eclogical network flows was simulated based on the circuit theory model in physics (Wang et al., 2022). The ecological obstacle points were therefore identified, which referred to the nodes located at the ecological corridors that influenced the ecological flows and functions. The Linkage Pathways – Build Network and Map Linkages and Barrier Map tools in the Linkage Mapper toolbox were used to identify the high-value areas of the layer. Then, the feature conversion tool Feature to Point was used to extract the ecological obstacle points.

A topological network was extracted based on the ecological corridors generated by the MCR model and ecological nodes identification in Arc GIS. The corridor length, connection strength, and cumulative value of the ecological corridors were selected as indicators to assess the quality of the ecological network after wind farm construction (Cui et al., 2022). In further research, recommendations for ecological restoration and compensations would be put forward according to the analysis of ecological corridors and nodes.

3. Results

3.1. Ecological sources identification

To assess the changes in the ecological network, the ecological sources are selected through the data of 2010. The outcomes of landscape pattern analysis through the MSPA methods are illustrated in Fig. 3. The core area is significant for biodiversity conservation and provides larger habitats for species. It covers an area of 78.69 km^2, accounting for 75.94 % of the ecological land and 38.17 % of the research area. Followed by the landscape types of edge, loop, and branch, with areas accounting for 11 %, 3.24 %, and 3.13 %, respectively (Table 3). The core patches with an area of over 5000 m^2 were selected as ecological sources for MCR model construction. Finally, a total of 8 patches were extracted as ecological sources.

It is worth noting that the areas and spatial distribution of selected ecological sources are uneven. The largest ecological source spreads across the Fuquan Mountains in Ningbo City, covering an area of 58.1 km^2. The second largest ecological source is located in Ritou Mountain, covering an area of only 5.9 km^2, followed by 4.3 km^2, 2.0 km^2, 1.5 km^2, and three sources with 0.8 km^2 area. In order to extract the topological model, the severely fragmented ecological sources below 5000 m^2 located in the northern part of the study area were eliminated.

3.2. Resistance surfaces

The resistance surfaces for the MCR model are built up under two hypotheses- with and without wind facilities- to compare the connectivity of ecological corridors (Guo et al., 2020). Fig. 4 illustrates the process of resistance surface construction with indexes of land cover, elevation, slope, vegetation coverage, and wind turbine disturbance in 2010 and 2020 as the comparison options. Fig. 4a presents the resistance surface without the index of wind turbine disturbance in 2010, which shows comparatively low scores. By contrast, the scores remained higher and stratified close to the wind facilities in Fig. 4b, including changes in landcover, vegetation coverage, and wind turbine allocation in 2020.

3.3. Ecological corridors

The MCR model is constructed based on sources and resistance surfaces to imitate potential ecological corridors with minimum resistance cost (Su et al., 2016; Zeller et al., 2012). It is supposed that at least one corridor between two ecological sources guarantees the flow of material, information, and species migration. Based on the ecological corridor identification by the MCR model, two groups of ecological networks before and after the construction of Zhongying Wind Farm are displayed in Fig. 5. It reveals the changes in ecological corridors distribution.

With the least-cost distance and least-cost path analysis in ArcGIS 10.8, a total of 28 ecological corridors were initially identified. The ecological impacts on ecological corridors decay with distance, reflecting on the changes on length, connection strength and cumulative values of corridors. Because the absolute values of corridor length, connection strength, and cumulative resistance values vary extremely from each other, Fig. 6 shows the rates of variation for the above indexes of the 28 ecological corridors. The variation rates of these three indexes were divided into five levels according to the natural breakpoint method. As shown in Tables A.1 and A.2, a threshold of the top 30 % was set to extract eight important corridors from 28 corridors by calculating the interaction matrix between pairwise ecological sources (Yin and Kong, 2014).

The comparison between ecological corridors with and without the impact of wind turbines revealed that the length of most corridors was reduced to different extents. Only the corridor between sources 7–8 increased by 5.23 %. The average reduction in corridor length remained at 15.06 %. The largest decline was in the corridor between sources 5 and 6, with 87.76 %. Eight important corridors present a stable decline, ranging from 0 % to 22.22 % (see Table A.3). The length of the corridor across the wind farm area changes significantly. As the distance from the wind farm increases, the corridor length change rate decreases.

The index connection strength can be introduced to characterize the effectiveness of potential ecological corridors and the importance of connecting sources (Yu et al., 2016). In the analysis of all the 28

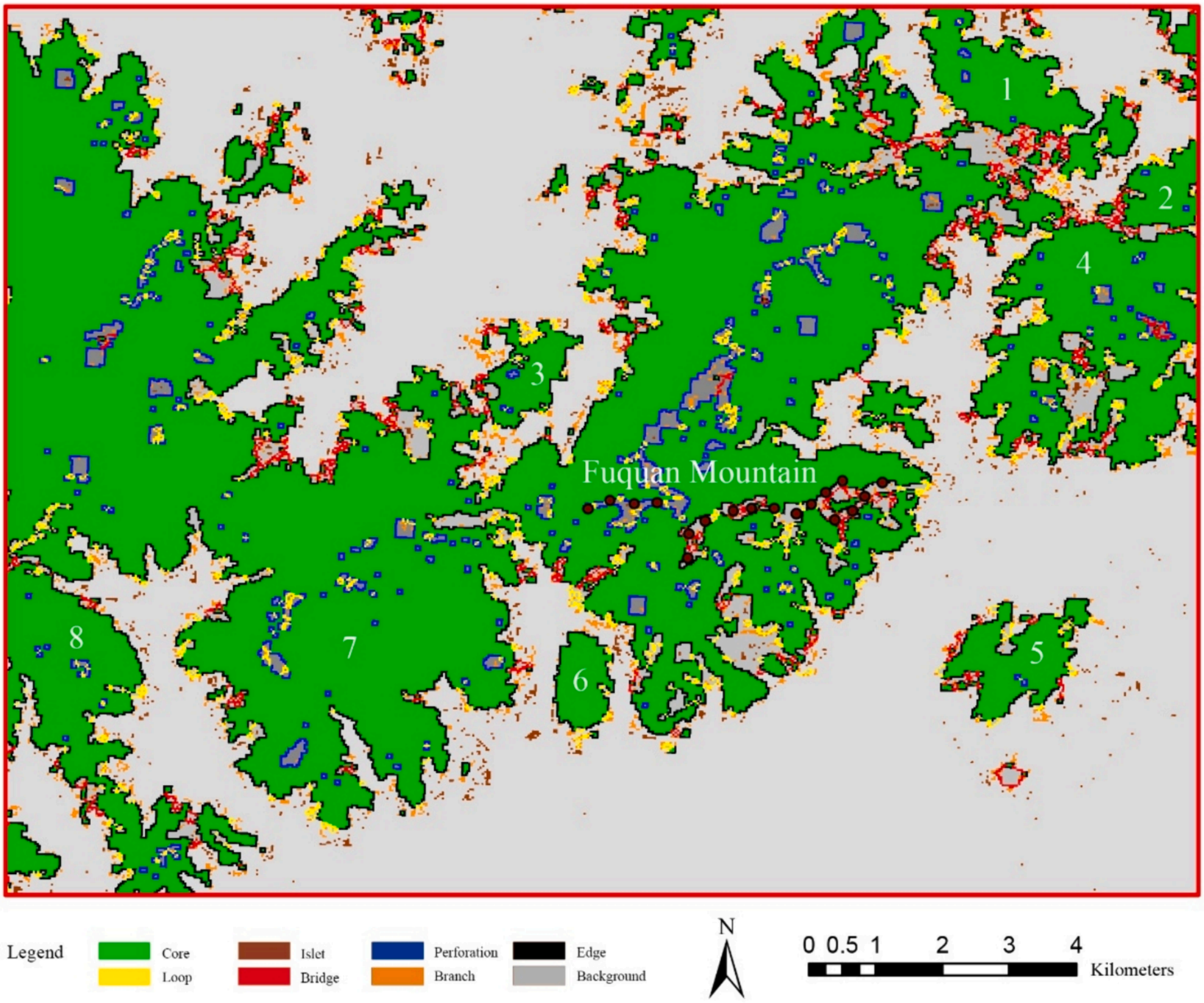


Fig. 3. Landscape classification and meaning based on MSPA.

Table 3
Statistics of landscape types through MSPA with the data of 2010.

Landscape types	Area (km^2)	Accounted for area of ecological land (%)	Accounted for area of the research area (%)
Core	78.69	75.94	38.17
Loop	3.36	3.24	1.63
Islet	1.31	1.26	0.64
Bridge	2.60	2.51	1.26
Perforation	3.02	2.91	1.46
Branch	3.25	3.13	1.58
Edge	11.40	11.00	5.53
Total	103.63	100.00	50.27

ecological corridors, only two corridors (Source 2–4, Source 2–5) increased in connection strength by 6.13 % and 5.29 %, respectively. The connection strength of other corridors showed different degrees of reduction, ranging from 0.69 % to 68.62 %. Among the eight important corridors, five corridors connected to Source 7 showed large declines, with an average value of 54.05 % (see Table A.4). At distances of 5 km from wind farms, connection strength decreases in a linear trend; at distances less than 5 km, it decreases exponentially.

The index cumulative value represents the sum of resistance values for each corridor, which showed small fluctuations with an average variation rate of 3.60 %, ranging from −16.70 % to 18.79 %. The resistance values of 9 corridors decreased, one remained unchanged, and the resistance values of the remaining 18 corridors showed an upward trend (see Table A.5). The resistance value of the corridor located within 5 km of the wind farm increases most significantly.

3.4. Ecological nodes

The ecological nodes were identified through ArcGIS 10.8 and the Linkage Mapper toolbox. The ecological nodes generated were compared in the number, spatial distribution, and importance level of ecological nodes before and after the construction of Zhongying Wind Farm, with data of 2010 and 2020. Through the assessment of the indexes of node centrality, node core degree, and node clustering degree, the importance of ecological nodes was ranked. The importance value was divided into five levels through the natural breakpoint method. The higher the level, the more important value the nodes have (Figs. 7 and 8).

Due to the construction of huge wind turbines, the number of weak points increased from 27 to 32. Moreover, the high-importance nodes in the study area increased obviously, especially 24 % of Level 4. Regarding spatial distribution, the weak points were evenly distributed around the wind farm, most located at the edge of ecological sources.

The number of ecological obstacle points increased obviously, from 8 to 36. Furthermore, the proportion of important nodes (Level 5) increased dramatically, from 6 % to 37.5 %. From 2010 to 2020, the spatial distribution of obstacle points gradually spread outward from the wind farm. The high-importance nodes are concentrated in the northwest of the wind farm, which is mainly located at the ridge of Fuquan

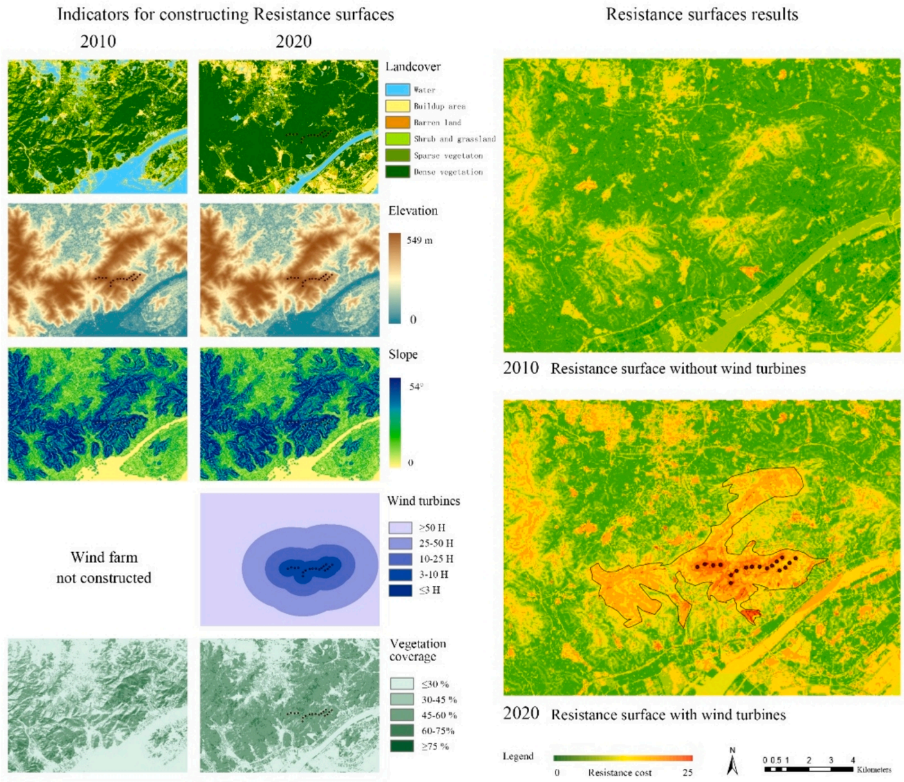


Fig. 4. Resistance surfaces with and without wind turbines.

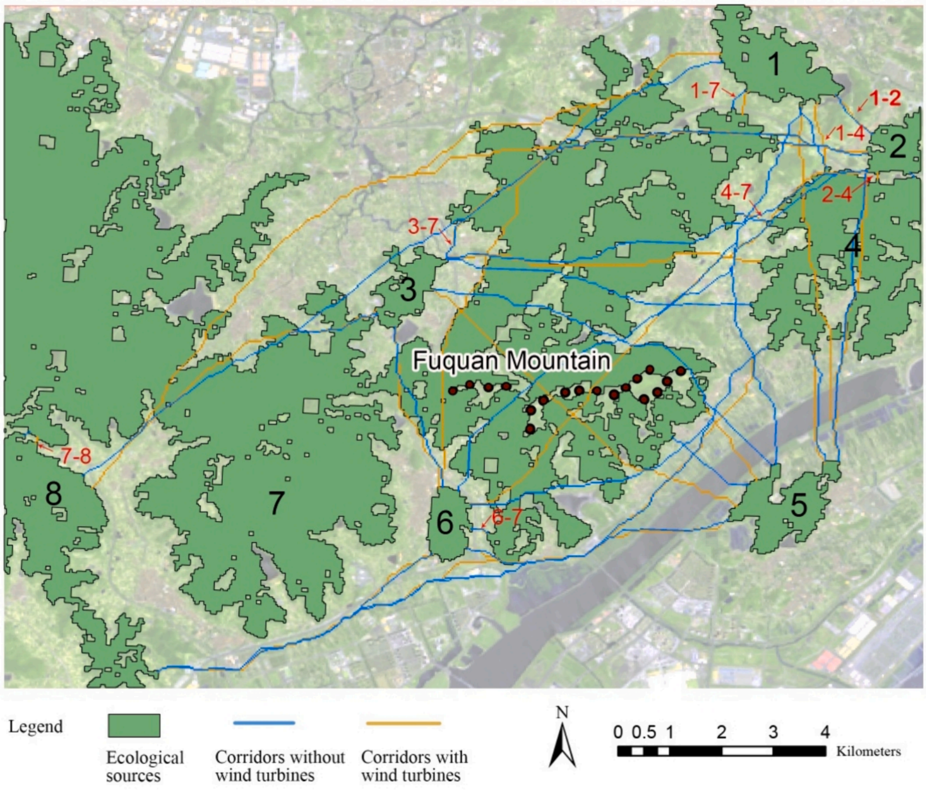


Fig. 5. Potential ecological corridors with and without Zhongying wind farm.

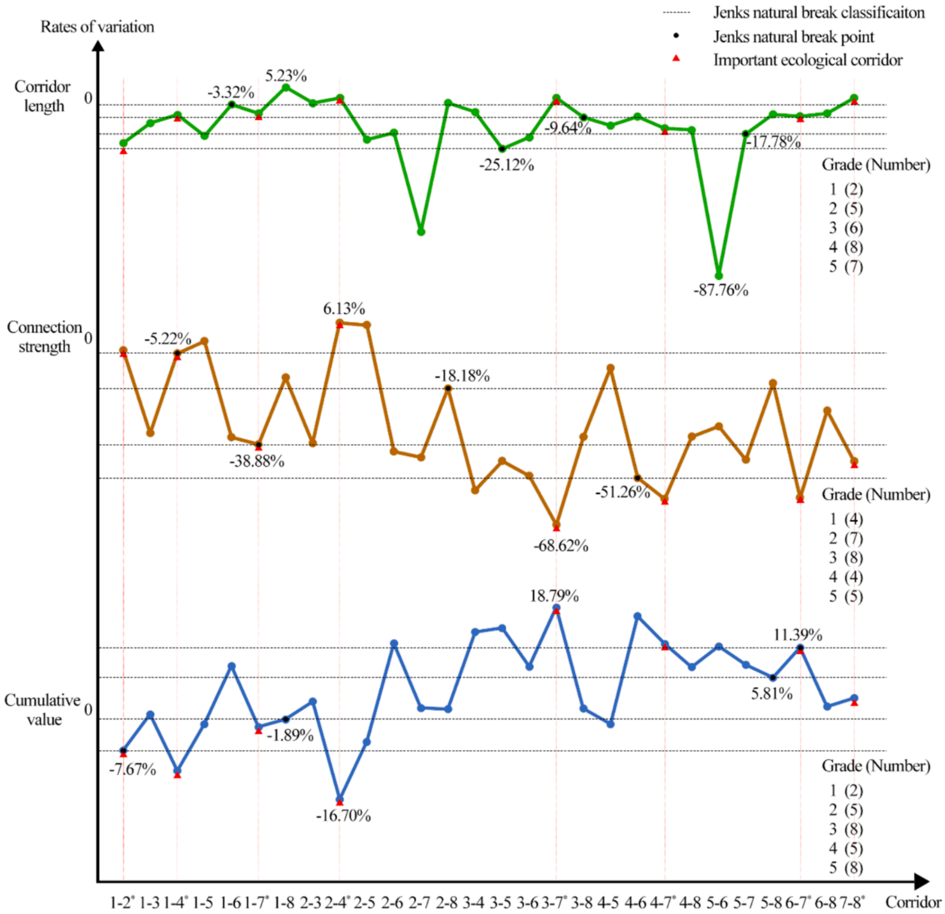


Fig. 6. The variation rates of corridor length, connection strength, and cumulative value of significant ecological corridors. (Note: Corridors with "*" represents the important ecological corridors.)

Mountain and the junction of forests and built-up areas. In summarize, the number of weak points increased by 18.5 %, and obstacle points increased by 350 %, with their locations shifting from the edges of urban construction sites to the edges of wind farm. According to the priority of nodes, protection, restoration, and compensation strategies were adopted for nodes of high importance.

4. Discussion

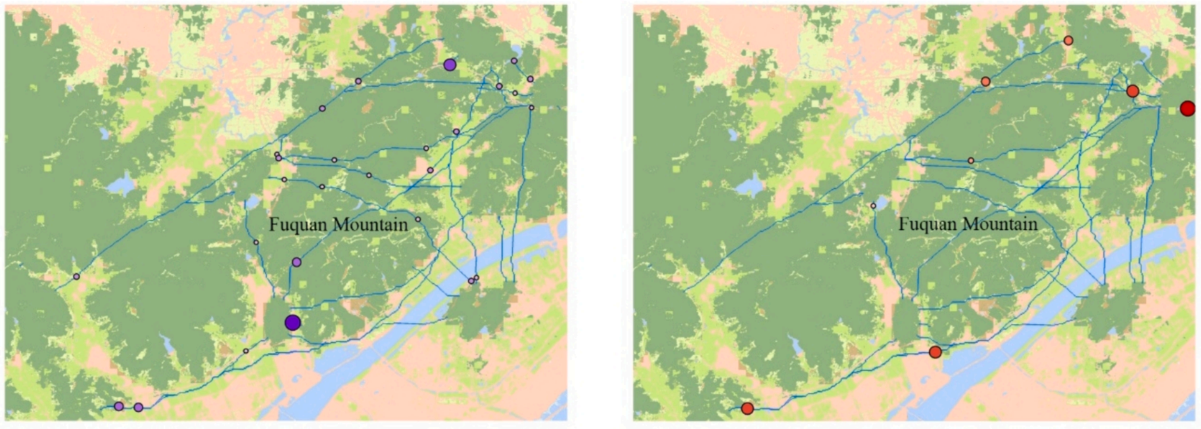
4.1. Ecological protection, restoration, and compensation strategies

In this study, the evaluation approaches of both ecological corridors and ecological nodes were restoration-oriented, and obeyed the protection, restoration, and compensation sequence. The strategies are proposed based on the results of ecological impact assessment for ecological corridors and ecological nodes (Table 4). For ecological corridors, the average variation rates of corridor length, connection strength, and cumulative values are calculated and classified into three categories: 1) slight recession, the variation rates below 10 %; 2) moderate recession, the variation rates from 10 to 20 %; 3) serious recession, the variation rates over 20 %. The strategies for ecological nodes are according to their importance value as explained in Section 3.4.

Protection strategies for avoiding ecological impacts from wind facilities contain two connotations. First, before the site selection of wind farm, large-scale wind farms and huge-size wind turbines should be avoided in ecologically sensitive areas to ensure the stability of the ecosystem. The wind farms should also be sited to avoid conflicts with ecological corridors and nodes. Second, after the construction of wind farm, a dynamic inspection mechanism is necessary to monitor the function of ecological corridors and maintain biodiversity (Cui et al., 2022). For instance, the ecological assessment framework in this paper could be promoted to detect changes in ecological corridors and nodes before and after the construction of renewable energy facilities. For detailed implementation, the corridors with slight recession and ecological nodes of Level 1 should be protected by prohibiting any artificial construction and development within 5 km.

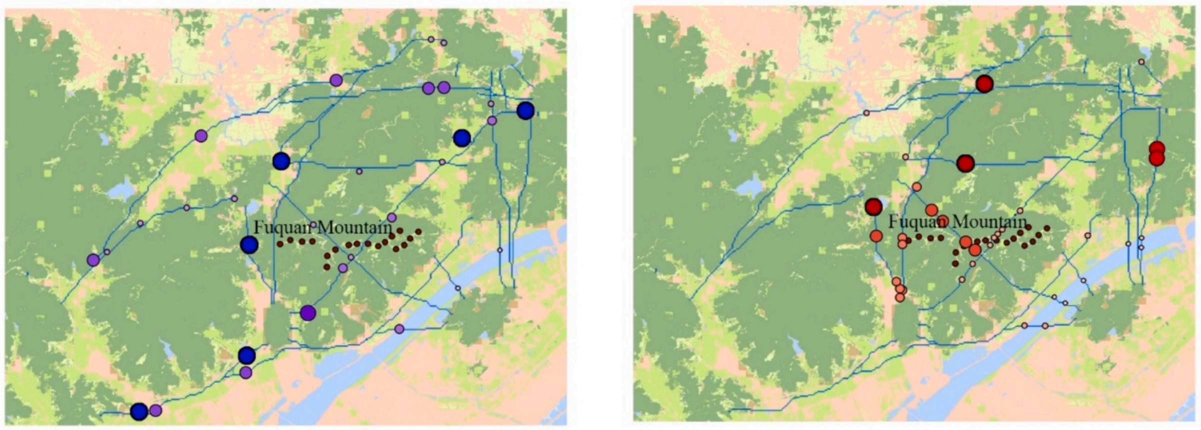
As defined by Martin (2017), "ecological restoration refers to the process of managing or assisting the recovery of an ecosystem that has been degraded, damaged or destroyed." To achieve the restoration targets of minimizing ecological impacts from wind energy, strategies are proposed for both ecological corridors suffering from moderate impact and ecological nodes of Levels 2 and 3. It is suggested to add stepping stones along the corridor to mitigate ecological fragmentation and increase the number of ecological sources. From a long-term perspective, establishing a dynamic inspection mechanism to ensure the stability of ecological network. To reduce the cumulative value of corridors, any artificial construction and ecological destruction around the potential corridors are prohibited. Additionally, it is encouraged to restore the ecological quality by recover the structure and function of corridors.

The compensation for wind farm construction can be classified as direct compensation and alternative compensation (offset ecological compensation or monetary compensation schemes). Based on the ecological equivalence principle, a pure ecological compensation can reduce the damage to social welfare (Hubbell, 2006). However, it is difficult to achieve by the constraints of land availability and price. According to the spatial decay of environmental costs and benefits, Gastineau et al. (2021) proposed a spatial theoretical framework for ecological compensation. It suggests to compensate in less populated



a) Ecological weak points in 2010

c) Ecological obstacle points in 2010



b) Ecological weak points in 2020

d) Ecological obstacle points in 2020

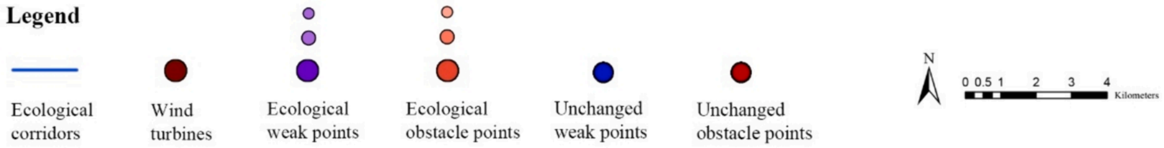
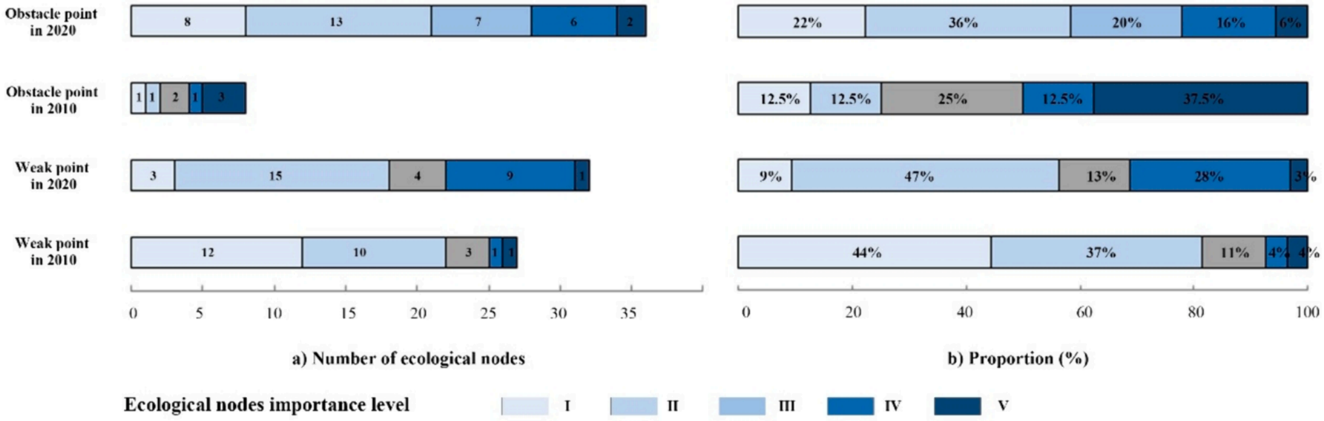


Fig. 7. The spatial distribution of ecological node.



a) Number of ecological nodes

b) Proportion (%)

Fig. 8. The number of ecological nodes at each level from 2010 to 2020.

Table 4
Protection, restoration, and compensation strategies for ecological corridors and nodes.

Strategy	Corridors and nodes		Concrete measures
Protection Strategy	Slight recession (<10 %)	Corridors: 1–4, 2–4, 1–5, 2–5, 4–5, 1–8, 2–8, 5–8	Precautions before site selection; dynamic inspection mechanism; prohibition of artificial construction and development
	Ecological nodes in Level 1		
Restoration Strategy	Moderate recession (10–20 %)	Corridors: 1–2, 1–3, 2–3, 3–4, 3–5, 1–6, 2–6, 4–6, 5–7, 6–7, 3–8, 4–8, 6–8	Adding stepping stones along the corridor; recovering the structure and function of corridors; artificial construction and ecological destruction are prohibited; establishing a dynamic inspection mechanism
	Ecological nodes in Levels 2 and 3		
Compensation Strategy	Serious recession (>20 %)	Corridors: 3–6, 5–6, 1–7, 2–7, 3–7, 4–7, 7–8	Ecological and monetary compensation schemes; planting buffer forest belts; erecting culvert for wile animal migration; installing radar or warning lights to avoid collisions; increasing vegetation coverage
	Ecological nodes in Levels 4 and 5		

areas in an effective spatial scale. In the compensation strategies for wind energy impact, both ecological and monetary schemes are required for mitigating ecological damage and improving residents' welfare. Detailed solutions such as planting buffer forest belts around wind farm, erecting culvert for wild animal migration, installing radar or warning lights to avoid collisions, increasing vegetation coverage are feasible for wind farm impacts.

In ecological node restoration, the strategies and solutions are highly related to the research scale. Therefore, the land cover types in ecological nodes were identified at different scales to analyze the precise implementation of restoration and protection. Buffer distances of 50, 100, and 150 m were set to obtain the land cover type composition of important ecological nodes (Fig. 9). Regarding ecological weak points, the forest (38 %), cropland (35 %), and construction land (20 %) occupy the largest proportion within 50 m. With the continuous expansion of buffer distances, the proportion of forest in the region gradually increases to 49 %, while the proportions of cropland and construction land gradually decrease to 23 % and 18 %, respectively. From the perspective of obstacle points, the forest maintains the highest proportion of over 80 % at different research scales, followed by cropland. However, the proportion of other land use around obstacle points is extremely small, all below 5 %.

It is obvious that the ecological functions of the weak points were highly related to the proportion of land cover with apparent changes at different scales. Subsequently, the restoration strategies could adjust the proportion of land use, control the total amount and type of construction land and improve the quantity and quality of ecological land. However, the important obstacle points are not directly related to the proportion change of land cover, reflected in the stable proportion in Fig. 9b. Restoration solutions could focus on the ecological functions, structures, and connections of the obstacle points.

In categorizing the ecological nodes, there are ten important weak points and eight important obstacle points (Levels 4 and 5), which need to be compensated. The important weak points are mainly located at the edge of green space and built-up areas. The changes in land use should be strictly prohibited within the 150-meter buffer distance for weak points. Near these nodes, urban sprawl and construction, especially industrial land use, need to be strictly prohibited. The important obstacle points are primarily distributed near wind turbines. Ecological compensation is encouraged to be an important tool to restore the function of ecological nodes. For instance, the biodiversity and ecosystem service near obstacle points should be compensated due to the ecological impact caused by wind turbines (Blicharska et al., 2022). However, the general ecological nodes (Levels 1, 2 and 3) are in the category of supervision and conservation. New facilities require strict approval and evaluation of impacts on ecological network stability.

4.2. Innovations in this study

Previously, governments and scholars from various countries and organizations have done a lot of research on the environmental impact of wind farms, including optimization of the environmental impact assessment procedures (Phylip-Jones and Fischer, 2013), developing approach for balancing wildlife habitats and renewable energy expansion (Copping et al., 2020), hard taboo and soft taboo for wind farm site selection (Guan, 2020), as well as the sustainable roadmap of wind farms based on eco-friendly scenarios (Eichhorn et al., 2019).

Current research focuses on the application of comprehensive evaluation frameworks and site selection optimization strategies. Göke et al. utilized the decision support tool Marxan for offshore wind siting decisions within the framework of Marine Spatial Planning (MSP) based on the principles of ecological, economic, social, and habitat space protection (Weinand et al., 2022). Virtanen et al. have developed a visual wind farm site selection system based on chromatographic identification theory, combining over 150 ecological, social, and economic evaluation indexes in the multidimensional decision-making software Zonation (Virtanen et al., 2022). Pınarbaşı et al. have established a modeling approach for offshore wind farm feasibility under technical, environmental impact, and feasibility constraints based on the Bayesian belief

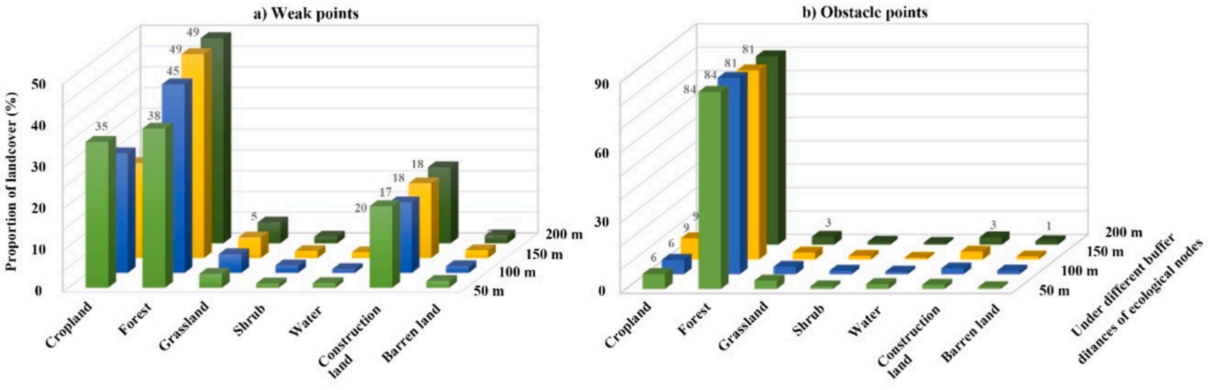


Fig. 9. Land cover composition of different buffer distances for ecological nodes.

network (Pınarbaşı et al., 2019).

From the perspective of ecological impact assessment, a large amount of research focuses on ecological changes in and around urban construction areas, including urban ecological comfort assessment (Zhang et al., 2023), ecosystem services optimization (Tang et al., 2020), and ecological fragmentation mitigation from various spatial scales (Nie et al., 2021). For the ecological assessment of infrastructure facilities, Shang et al. (2022) compared the ecological status with the presence or absence of the reservoir.

With the rapid expansion of renewable energies under the carbon neutrality strategy, the ecological changes around renewable energy facilities should be quantified to propose ecological restoration solutions. Compared with previous quantitative studies, the innovation here fundamentally lies in identifying change patterns of ecological corridors and nodes. The results reveal that: 1) the corridor length change rates decrease with the distance raise from the wind farms. 2) The decrease of corridors' connection strength accelerates within 5 km of wind farms. 3) The cumulative resistance surface value of corridors also changed dramatically within the distance of 5 km. 4) Weak points and obstacle points grew by 18.5 % and 350 %, respectively, and were located on the outskirts of wind farms instead of the periphery of urban construction sites. Specific measures are recommended within the distance of 150 m of ecological nodes to differentiate ecological management around wind farms.

4.3. Limitation and future study

Oriented by the global carbon neutrality goals, renewable energies are recognized as substitutes for fossil fuels to reduce carbon emissions by various countries. It is anticipated that China will soon host a significant number of large-scale renewable energy installations. Meanwhile, the ecological impact of renewable energies should be paid more attention. Evaluation approaches for ecosystem stability, ecological functions, and structure have proliferated. This paper revealed the quantitative assessment of ecological corridors and nodes, and proposed targeted protection, restoration, and compensation strategies. It is innovative in the differentiated management of ecological quality around wind farms. It is no longer a one-size-fits-all decision whether forests are suitable for wind farm construction, but rather a case-by-case discussion about the location of wind farms in areas with intensive land use. This approach could even be extended to other renewable energy facilities and accelerate the energy transition process.

There are also limits in this study. The research scope is project-scale, focusing on micro-regional ecological impacts, and is not involved in the study of regional-level ecological networks. This study can be recognized as a pilot. Regional ecological networks will be established to achieve synergy between ecological security and renewable energies. Furthermore, only the land use of ecological nodes is analyzed, lacking consideration of land use along the corridors, as well as other ecological indicators, such as ecological network stability and biodiversity. Nevertheless, the assessment results could be inaccurate or inconsistent with reality, which needs to be validated in future empirical studies.

5. Conclusion

With the expansion of renewable energies worldwide, their long-term ecological impact cannot be neglected. This study assessed the ecological impact of Zhongying Wind Farm in Ningbo, Zhejiang Province, China. A comparison between the status of ecological quality before and after the construction of Zhongying Wind Farm in 2010 and 2020 was conducted. The ecological impacts caused by wind farms reflect in the changes in length, connection strength, and cumulative values of corridors, as well as the number, spatial distribution, importance-value, and land cover of ecological nodes. Sources with long distances suffered more critical challenges from ecological degradation in the perspective of route and corridor function. The important weak points were distributed at the edge between built-up areas and ecological regions, while the obstacle points were dramatically increased and located around the wind turbines. Differentiated management for protection, restoration and compensation are proposed according to the extent of ecological impacts to enhance the structure and function of ecological network and avoid human interference. This research clarifies the intensity and extent of wind farm impacts on the ecosystem, which aims to balance the relationship among ecological protection, wind energy development, and urbanization in the context of East China.

CRediT authorship contribution statement

Jinjin Guan: Writing – review & editing, Writing – original draft, Software, Investigation, Conceptualization. **Jiameng Hu:** Writing – review & editing, Resources, Project administration. **Beining Li:** Software, Formal analysis.

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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Appendix

Table A.1. Interaction matrix between pairwise ecological patches without wind turbines

Source	1	2	3	4	5	6	7	8
1		344.02 %*	8.18 %	232.03 %*	5.65 %	3.72 %	1772.92 %*	1.73 %
2			6.02 %	29007.85 %*	9.46 %	5.05 %	174.93 %	1.69 %
3				12.45 %	4.98 %	31.79 %	20495.92 %*	8.20 %
4					66.19 %	12.30 %	1357.08 %*	2.87 %
5						17.25 %	110.63 %	3.03 %
6							4256.75 %*	16.01 %
7								24364.50 %*

Note: * represents the selected corridors with the top 30 % connection strength in the Gravity Model.

Table A.2. Interaction matrix between pairwise ecological patches with wind turbines

Source	1	2	3	4	5	6	7	8
1		330.15 %*	5.34 %	219.91 %*	5.61 %	2.38 %	1083.66 %*	1.48 %
2			3.71 %	30786.64 %*	9.96 %	2.95 %	98.59 %	1.39 %
3				5.50 %	2.74 %	15.74 %	6430.97 %*	5.24 %
4					59.17 %	5.99 %	555.71 %*	1.84 %
5						11.70 %	61.35 %	2.54 %
6							1764.24 %*	11.79 %
7								13367.76 %*

Note: * represents the selected corridors with the top 30 % connection strength in the Gravity Model.

Table A.3. The rates of variation of potential ecological corridor length

source	1	2	3	4	5	6	7	8
1		−22.22 %*	−12.43 %	−8.33 %*	−18.75 %	−3.32 %	−7.69 %*	5.23 %
2			−2.58 %	0.00 %*	−20.63 %	−17.16 %	−66.04 %	−2.51 %
3				−6.94 %	−25.12 %	−19.42 %	0.00 %*	−9.64 %
4					−13.64 %	−9.23 %	−15.00 %*	−15.83 %
5						−87.76 %	−17.78 %	−8.15 %
6							−9.09 %*	−7.64 %
7								0.00 %*

Note: * represents the selected corridors with the top 30 % connection strength in the Gravity Model.

Table A.4. The rates of variation of the connection strength of each corridor

Source	1	2	3	4	5	6	7	8
1		−4.03 %*	−34.72 %	−5.22 %*	−0.69 %	−36.22 %	−38.88 %*	−14.14 %
2			−38.36 %	6.13 %*	5.29 %	−41.47 %	−43.64 %	−18.18 %
3				−55.86 %	−44.99 %	−50.48 %	−68.62 %*	−36.13 %
4					−10.61 %	−51.26 %	−59.05 %*	−35.97 %
5						−32.17 %	−44.55 %	−16.15 %
6							−58.55 %*	−26.33 %
7								−45.13 %*

Note: * represents the selected corridors with the top 30 % connection strength in the Gravity Model.

Table A.5. The rates of variation of the cumulative value of each corridor

Source	1	2	3	4	5	6	7	8
1		−7.67 %*	−0.96 %	−11.41 %*	−2.78 %	7.99 %	−3.31 %*	−1.89 %
2			1.41 %	−16.70 %*	−6.05 %	12.17 %	0.19 %	0.00 %
3				14.26 %	14.99 %	7.87 %	18.79 %*	0.12 %
4					−2.78 %	17.20 %	12.07 %*	7.78 %
5						11.61 %	8.19 %	5.81 %
6							11.39 %*	0.48 %
7								2.05 %*

Note: * represents the selected corridors with the top 30 % connection strength in the Gravity Model.

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