Impacts of onshore wind power projects on ecological corridor and landscape connectivity in Shanxi, China

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Abstract: Wind power industry has developed rapidly in China, however the effect of wind power projects on ecosystem is far from clearly understood. The objective of the current study is to evaluate the negative impact of wind power plants on ecosystem. In this research, Least-cost distance (LCD) and Least-cost path (LCP) models were employed to establish potential ecological corridors based on the resistance at the site of the wind power projects, which is located in the ecological function area in Qinyuan, South Shanxi Province, China. Landscape connectivity was evaluated using a set of connectivity indices. In addition, the impacts on corridor patency, length and connectivity between ecological corridors were analyzed. The results showed that the wind power projects could not only significantly increase the migration resistance that hampers the formation of ecological corridors of the species at landscape scale, but also have an obvious cutting effect on the landscape, resulting in the increase in the length of the ecological corridors and the decrease in corridor patency and landscape connectivity. The average increased corridor length was 95 km. There was also a positive relationship between length increase and the distance between source patches. In addition, the connectivity was enhanced with the increase in distance threshold. This study evaluated the ecological impacts of onshore wind power projects at the landscape level, filling the gap in such research on landscape ecology, especially in the key ecological function protected area. Meanwhile, the results are beneficial to guide the selection of wind power projects location and minimize the negative impact on the key ecological corridors.

Key words: Wind power project; Ecological corridor; Landscape connectivity; Migration resistance

1. Introduction

China's economy has developed rapidly in the last four decades with cost of degradation of ecology and environment (Yang et al., 2012; Yang et al., 2014a). The root cause for the ecosystem degradation is the heavily relying on fossil energy, particularly coal (Han et al., 2018). At present, China is still in the process of rapid urbanization and industrialization, and the demand for energy continues to grow. How to maintain the balance between rapid economic growth and environmental protection has been a big challenge for China (Yang, 2014; Yang et al., 2013). In the last decade, China has made great efforts to reverse the environment degradation. One of the most important measures is to gradually reduce coal consumption and increase the use of nonfossil energy, reshaping the energy structure of China (Dai et al., 2016; Yang et al., 2016; Yang et al., 2017).

Wind power is one of important renewable energies. With the increasing demand of energy, wind power is considered to be a promising renewable energy as a result of its technical maturity, low cost, flexible installation, simple operation, less land occupation and little pollution (Hepbasli et al., 2004). In China, wind power industry has developed rapidly duo to technological progress, power guiding policies, and improved energy price mechanism (Feng et al., 2015; Sun et al., 2015). Along with the expansion of wind power industry, there are many researches on wind power technology (Khosravi et al., 2018; Zhao et al., 2015; Zhou et al., 2010), industrial development (Alexandre et al., 2012; Luo et al., 2016; Zhao et al., 2013), policy recommendations (Kang et al., 2012; Liu et al., 2010; Wolsink, 2010), and economic analysis on the investment and operation (Li et al., 2013).

However, there are potentially adverse environmental and ecological impacts of wind power projects, which should not be overlooked (Leung et al., 2013). The low frequency noise generated by the turbine rotation can cause detrimental impacts on human and other organisms (Laratro et al., 2014; Wasala et al., 2015). The lights and shadows have visual impacts on the local communities (Juan et al., 2004). The turbine blades can cause interference to radio signals (Mroziński et al., 2015). Researches on the ecological impacts of wind power projects mainly focused on the influence on animals and plants (Escobar et al., 2015; Welcker et al., 2016; Whang et al., 2015). The impacts may be direct, such as mortality caused by rotating turbines (Peste et al., 2015; Wang et al., 2015), or indirect, such as damage on foraging and breeding caused by habitat loss (Braunisch et al., 2015; Law et al., 2018; Madsen et al., 2008; Pescador et al., 2019). Moreover, the operation of the wind farm can affect vegetation species and biomass (Fagúndez, 2010).

In particular, it is worth noting that construction of wind power projects changed the original landscape. Landscape pattern determines the landscape characteristics, such as spatial heterogeneity, landscape diversity, landscape connectivity and so on (Cook, 2002; Peng et al., 2015). Landscape process refers to the circulation and migration of internal and external material, energy, information, as well as the evolution of landscape system (Klunder, 2004). The impacts of wind power projects stem from substance retrospection above the landscape scale, which is crucial for ecological corridor construction, the maintenance of ecosystem function and regional ecological security (Skarin et al., 2015). The fragmentation of the landscape pattern causes the material flow, the information flow and the species flow to be blocked, affecting the ecological process in the horizontal direction of the landscape and damaging landscape (Liu et al., 2005).

The environmental impact of wind power projects can be analyzed using Geographical Information System (GIS) methods. GIS-based spatial models have been applied to effectively assess the impact of wind farms on animal behavior and habitat (Roscioni et al., 2013). GIS-assisted approaches have also been developed and applied to predict and evaluate visual impact of wind farms (Molina-Ruiz, 2011). In addition, GIS-based approaches can be used for wind resource assessment as well as for its planning to support the decision-making process by taking into account comprehensive factors that covered geological characteristics, economic cost and environmental constraints (Haaren et al., 2011; Li, 2018; Siyal, et al., 2015). With the development of GIS technology, Least-cost distance (LCD) and Least-cost path (LCP) models have been increasing applied to quantitatively research the ecological corridors, landscape connectivity, ecological network construction, conservation planning and so on (Avon et al., 2016; Barrows et al., 2011; Rabinowitz et al. 2010). Ecological corridors are land linkages to facilitate wildlife migration between green spaces, and to enhance landscape connectivity to promote dispersal and other types of movement (Balbi et al., 2019; Zhu et al., 2005). The field observation has confirmed that migration corridor and habitat connectivity for some species have been disrupted owing to construction of onshore wind power projects (Francis et al., 2018; Roscioni et al., 2014; Skarin et al., 2015). However, little has been known about the potential effect on ecological processes caused by fragmentation at landscape scale. Therefore, it is still very important for a quantitative ecological impact analysis of wind power projects at a large scale, coupling ecological corridor with landscape connectivity, which would be necessary for the trade-off between wind power development and ecological conservation.

Shanxi Province, which is located in the eastern part of the Loess Plateau and borders on the southern part of Inner Mongolia with many hills, deep valleys and rugged terrain, has abundant wind energy resources due to its geomorphological conditions (He et al., 2014). As one of the largest energy bases in China (Cao, 2017), Shanxi Province has been aggressively pursuing optimization of energy structure to mitigate serious environmental pollution and ecological damages (Li et al., 2018; Wei et al., 2018; Yang et al., 2012) from high dependence on fossil energy. In recent years, large-scale centralized wind farms have been built in Shanxi (Wang et al., 2018). By the end of 2017, the total installed wind power capacity in Shanxi was 8.72×10^6 kW, accounting for 11% of electricity installed capacity. The target for wind power development in 2020 has been set to 16×10^6 kW, nearly double the amount in 2017 (Zhou et al., 2018). Although environmental impact assessment is required for the wind farm project, the impact on ecological corridor and landscape connectivity is largely over simplified or even ignored. Hence increasing understanding of the ecological corridor and landscape connectivity is still necessary to provide a macro-perspective ecological impact analysis at landscape scale.

This study made the effort to fill the gap of the impact of wind power projects on ecological corridor and landscape connectivity in Shanxi Province, especially in the key ecological function protected area. The main research aims of the current study are: (1) to estimate the effects of wind power projects on ecological corridor by simulating corridor construction process under multiple influence factors in the selected built-up wind power area; and (2) to explore the landscape connectivity affected by wind power projects based on estimating relevant connectivity indices by using resistance distance.

The rest of the paper is organized as follows. In Section 2, two important approaches – selecting origination of landscape process, and determining the distribution of resistance surface with multiple factors including wind farms – were used as the basis for applying LCD and LCP methods to assess the ecological corridor and landscape connectivity. In Section 3, the spatial distribution characteristics of research region were presented, and status of ecological corridor patency, corridor length and landscape connectivity in the area before and after the construction of wind power projects were compared, as a key criterion to assess the changes of the migration routes and landscape connectivity. In Section 4, the reasons for the adverse effect on landscape ecological indicators caused by onshore wind power were discussed, and some suggestions to mitigate the impacts were proposed.

2. Material and Methods

2.1 Study Area

The Taiyue Mountain Wind Power Project with a capacity of 250MW is located in the north of Qinyuan County of Shanxi Province, China (36°51′N, 112°3′E) (Fig. 1). The project was proposed in 2010 and went into operation in 2014. The study area, including turbines and roads and buffer area within 2 km, covers an area of 165.68 km^2 and reaches a height of around 2100 m above sea level (asl). The average annual wind speed is 7.2 m/s and the wind power density is 319 W/m^2, showing large potential for developing wind power plants. The study area is located in the warm temperate semi-arid and semi-humid continental monsoon climate zone, with annual mean temperature of 8.6℃ and annual average precipitation of 656.7 mm. The main soil type is mountain meadow soil and the main types of vegetation are short grasses and alpine plants (Zhang, 2016).

The Taiyue Mountain Wind Power Project is the first wind power project to be built and put into production in the southeast of Shanxi Province. The study area is located in the ecological function area for water conservation, which is one of the most typical subalpine meadows in Shanxi Province. In addition, the wind power project lies in the experimental area of Mianshan Nature Reserve (Fig. 2). Due to its ecological importance, this area was selected to assess the ecological impact of the wind power projects.

2.2 Data

Landsat TM images with a resolution of 30 m during the research period of 2005-2017 obtained from the Geospatial Data Cloud (http://www.gscloud.cn/search) were used to analyze the NDVI (Normalized Difference Vegetation Index). NDVI indicates the amount of green vegetation present in the pixel by measuring the difference between near-infrared which vegetation strongly reflects and red light which vegetation absorbs. Higher NDVI values denote more green vegetation in the pixel. The Landsat TM images in 2005 and 2017 were classified into different land use types. The locations of wind turbines and the distances from the turbine were obtained from the Landsat TM images in 2017. These images were processed using ENVI (The Environment for Visualizing Images) Version 5.0 (Esri, Redlands, CA). The slope and relief were obtained from GDEM Product (Global Digital Elevation Model) from the Geospatial Data Cloud (http://www.gscloud.cn/sources/?cdataid=302&pdataid=10), with a spatial resolution of 30 m. Daily precipitation data was provided by Shanxi Meteorological Station and calculated by using Kriging interpolation in ArcGIS 10.2 (Esri, Redlands, CA). The vegetation coverage was calculated based on NDVI as follows:

$$Vegetation\ coverage = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{1}$$

where $NDVI_{min}$ and $NDVI_{max}$ represent the minimum and maximum value of NDVI, respectively.

2.3 Methods

The methodology of this research is schematically illustrated in Fig. 3. Firstly, to identify the starting point of ecological expansion, the source patches were selected based on variation trend analysis of NDVI. Secondly, ArcGIS was applied to build a landscape resistance surface that synthesised the multiple factors affecting landscape process in the wind farms. Thirdly, LCD and LCP methods were used to establish the ecological corridors derived from source patches and the landscape resistance surface. A connectivity analysis was also performed using a set of connectivity indices based on resistance of corridors. Finally, the effects of the wind power projects on ecological corridor and landscape connectivity were assessed based on corridor patency, corridor length and connectivity indices.

2.3.1 Selection of source patches

In landscape ecology, the source patches are basic units that can promote the development of landscape ecological process (Leitao et al., 2002; Sun et al., 2018). In general, the high vegetation cover area can provide more suitable habitats which are important for wildlife survival (Jiménez-Alfaro, et al., 2016). In order to study species migration process in the areas with good vegetation cover which can be indicated by NDVI, the pixels with an increase trend in NDVI that linked up with each other to form a continuous area rather than emerged dispersedly, were selected as the sources by outlined with closed curve.

Monadic linear regression trend analysis can simulate the changing trend of each grid, reflecting the spatiotemporal variations of the whole area. The change trend of NDVI was evaluated by using the following Monadic linear regression equations (Stow et al. 2003):

$$\mathrm{S} = \frac{n \times \sum_{i=1}^{n}(i \times NDVI_i) - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} NDVI_i)}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \tag{2}$$

where S is pixel's NDVI change rate; n is total years, i is an annual sequence; $NDVI_i$ is NDVI value in the year of i. S can reflect the improvement or degradation of NDVI. $S > 0$ indicates the increase in NDVI with time; the larger the value is, the more apparent the improvement is. On the contrary, $S < 0$ indicates the decrease in NDVI with time.

2.3.2 Determination of resistance surface

Resistance surfaces are the basis for modeling connectivity and designing conservation initiatives (Zeller et al., 2012). Different methods can be used for quantifying resistance surface. In order to avoid the risk of oversimplification, a range of indicators were used to calculate migration resistance.

Land cover type and topography are two basic factors affecting the landscape (Diffendorfer et al., 2014). Slope and topography are the resistance factors affecting vegetation growth (Zhao et al., 2014). In addition to the direct impact on the natural environment, noise pollution and visual impact caused by the wind power projects affect species migration. The low frequency noise and shadow on the ground generated by the rotation of the turbines have negative impacts on ecosystem (Juan et al., 2004; Laratro et al., 2014; Wasala et al., 2015). The species needs to keep a certain distance far from the turbines to avoid the negative impacts. Based on these, the land use type, slope, relief, vegetation coverage, the impact on vegetation, noise pollution, and visual impact were selected as factors in the assessment of migration resistance.

Vegetation growth can be affected by climate change and human activity. Wind power projects, as a kind of human activity, has a certain level of impact on vegetation. In order to assess the impact of wind power projects on vegetation, the impact of climate change needs to be eliminated. The residual analysis method, proposed by Evans and Geerken (2015), was used to conduct regression analysis of the NDVI and climate indicators for each pixel for obtaining the prediction value of NDVI, which can be considered as the effect of climate factors on NDVI. Then, the vegetation influenced by human activities was calculated as the difference between the real NDVI value and predicted NDVI value as follows:

$$\varepsilon = NDVI_{real} - NDVI_{predicted} \tag{3}$$

where ε is residual value of NDVI for each pixel. $\varepsilon > 0$ indicates a positive impact of human activities; $\varepsilon = 0$ means no impact; and $\varepsilon < 0$ suggests a negative impact. $NDVI_{real}$ is the real NDVI value of the pixel, which was obtained from Landsat TM images. $NDVI_{predicted}$ is the NDVI value which was predicted by the linear regression equation between NDVI and climate indicators. Since the study area is located in mountain region with water limitation, the main factor reflecting climate characteristics is precipitation and NDVI change is largely correlated with precipitation (Zhao et al., 2011).

According to the *in situ* survey of the wind power projects, the blade length of the turbines is about 45 m. The shadows of different lengths are formed on sunny days. Considering the effect of the noise, a safe distance between the wind turbines and residential areas or roads should be at least 200 m (Wang, 2011). The attenuation effect of the turbines noise in the air is mainly related to the propagation distance. With attenuation, the noise contribution value at 500 m from the turbines is less than the minimum noise level in the night (Wang, 2011). Therefore, the noise pollution and visual impact can be calculated by the distance from the turbine.

For a landscape factor, the resistance value was determined according to the different degrees of impacts on migration. Table 1 summarizes the relative resistance values of different landscape factors. Within the resistance value range of 1-100, the species move freely when the resistance value is close to 1; however, they cannot move when the value is close to 100. The resistance value of forest was the smallest, followed by grassland, farmland, and construction land. The larger slope and relief are, the greater the resistance value is.

The comprehensive analysis was performed to synthesize the spatial layers of each factor by running ArcGIS. Each resistance factor was classified using the reclassify tool and the corresponding resistance value was assigned to each landscape unit for each factor layer. The resistance surface was determined by overlaying these factors layers together.

2.3.3 Establishment of ecological corridors by Least-cost distance and Least-cost path

The relationship between landscape pattern and ecological process is the core of landscape ecology (Fu et al., 2011). The landscape pattern and the spatial combination characteristics of different landscape elements are relatively static in the certain period of time, but the real ecological process can be dynamic in the same period. Source-sink landscape theory breaks through the limitation in the traditional sense, which makes the landscape pattern dynamic and reflects both the influence of the pattern on the process and the effect of the process on the pattern (Chen et al., 2003; Chen et al., 2008). The approaches for regulating the ecological process were analyzed based on the the spatial balance of the "source" landscape. The extension of species to the surrounding is the competitive control of land use, which must be achieved by overcoming the resistance, so the resistance surface can reflect the spatial trend of species migration. With the advantage of evaluating the landscape spatial patterns by analyzing the effects of different landscape types on the target species, LCD and LCP have been applied to evaluate the impact of different land use types on the ecological flow (Balbi et al., 2019; Chetkiewicz et al., 2009). Similarly, LCD and LCP models were used to establish ecological corridors based on resistance surface in this study (Walker et al., 1997).

LCD is the accumulated cost distance of the most likely route where an individual would take to move between two habitat patches (Walker et al., 1997). Since many factors affect species migration, a range of distances rather than only one is used, causing variation in species dispersal distances (Adriaensen et al., 2003). In the LCD model, a single path of the least resistance between two nodes is identified based on the resistance surface (Adriaensen et al., 2003). All paths between two habitat patches are used to calculate resistance distance, which represents the effective distance separating the two habitat patches for a species (Ayon et al., 2016). Resistance distance has been widely used to evaluate functional landscape connectivity between patches (Avon et al., 2016; Rabinowitz et al. 2010; Richard et al., 2010). In addition, LCP is the single path for a species to move between two source patches.

Both LCD and LCP methods were performed in ArcGIS 10.2. In LCD model, cumulative cost from each pixel to the nearest source was obtained by inputting source patches and resistance surface achieved before. As a further calculation based on LCD, LCP identified a single path of the least cost connecting every two source patches based on cumulative cost. The paths were the potentially ecological corridors.

2.3.4 Assessment of landscape connectivity

The connectivity of each habitat patch in the network was assessed using a measure of the relative change in the integral index of connectivity (IIC) and probability of connectivity (PC) (Pascual-Hortal and Saura 2006; Saura and Pascual-Hortal 2007) following the equations:

$$\mathrm{IIC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \times a_j}{1+nl_{ij}}}{A_L^2} \tag{4}$$

$$\mathrm{PC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \times a_j \times P_{ij}}{A_L^2} \tag{5}$$

where a_i and a_j are the area of each habitat patch; nl_{ij} is the number of links in the shortest path (topological distance) between patches i and j; A_L is total area; and P_{ij} is the maximum product probability of all paths between patches i and j. If patches i and j are close enough, the maximum probability path will simply be the step between nodes i and j. If patches i and j are more distant, the maximum probability path will probably be composed of several steps through intermediate stepping stone patches.

The impact of the wind power projects on landscape connectivity of core patches was evaluated by using equivalent connected area (ECA), including equivalent connected area of integral connectivity (EC(IIC)) and equivalent connected area of probability connectivity (EC(PC)) using Conefor 2.6 (Saura and Torne, 2009).

3. Results

3.1 Spatial patterns of NDVI variation trend and resistance surface

Fig. 4 and Table 2 show the statistical characteristics of NDVI changing trends during the period of 2005-2017. The variation trends were divided into serious degradation ($S \leqslant -0.01$), degradation ($-0.01 < S \leqslant -0.005$), unchanged ($-0.005 < S < 0.005$), increase ($0.005 < S < 0.01$), and significant increase ($S > 0.01$) according to S values. Approximately 59.35% of NDVI values remained basically unchanged, 26.69% of NDVI showed an increasing trend and 13.97% of NDVI showed a decreasing trend.

NDVI values in the northern part of the study area were less affected by human activities and were in the growth period, showing an increasing trend. Despite the effect of human activities and climate change, the NDVI of shrub and grassland in the central and southern parts of the study remained largely unchanged during the study period.

NDVI variation trend was related to the change of land use type. Table 3 and Fig. 5 show the different land use categories with and without the wind power projects. Forests, including deciduous broad-leaved forest, evergreen needle forest, and deciduous broad-leaved shrub, accounted 77.13% to the whole area in 2017. Grassland, including grass and meadow, accounted 14.10%. Farmland, residence land and industrial land areas accounted 3.04%, 0.09% and 5.64%, respectively. Compared with the pre-construction of the wind power projects in 2005, the area of the main patterns of land use in source patches, evergreen needle forest and deciduous broad-leaved forest increased in 2017, indicating the ecosystem in source patches was less impacted by the wind power projects.

Fig. 6 shows the spatial distribution of different landscape resistance with and without the wind power projects. The resistance distribution is continuous and low resistance dominated in the study area without wind power projects. When the wind power projects were built, the resistance values were obviously stratified, and the largest resistance values appeared in the wind power projects area.

3.2 Effects of wind power projects on ecological corridor and landscape connectivity

Based on NDVI evaluation results, seven sources were identified in the study area. Considering ecological corridors with the least cumulative resistance, potential ecological corridors connecting every two source patches with and without the wind power projects were created based on LCD values (Fig. 7). There seven sources in different locations throughout the study area. In order to maintain landscape connectivity and ensure that species can move smoothly between sources, every two source patches were connected by an ecological corridor. The overlap of ecological corridors with and without the wind power projects was small, indicating that the construction of wind power projects had changed the ecological corridors.

3.2.1 Effects on corridor patency

Fig. 8 shows the comparison of resistance increment resulting from with and without the wind power projects. The construction of the wind power projects reduced the corridor patency between source patches, which is reflected in the increase in LCD values. Although the LCD values of one corridor decreased, this corridor does not go through the region of the wind power projects, indicating little impact of the wind power projects on this corridor. The average, minimum and maximum of LCD increased to 1019.66, 71.35 and 3557.43, respectively. The high resistance corridors generally crossed over the wind power projects, resulting in the enhanced reduction effect on corridor patency.

3.2.2 Effects on corridor length

Fig. 9 shows the comparison of corridor length increment between with wind power projects and without the wind power projects. The wind power projects lengthened most of corridors, thus increasing the migration distance. The length of one corridor decreased, while the lengths of others increased by different levels, the average increase is 95 km. The increase was related to the distance between the source patches. The farther the distance was, the larger the increase was. The distance between the source patches of no.1 and no.7 was the largest, which made the length of corridors increase by 119.460 km. A thorough change in the route between source patches of no.3 and no.5 leaded to 6.5 times increase in the length.

The relationships between reduction rate of corridor patency and increase rate of corridor length were expressed as P=0.268 L-24.804 and L=3.499 P+125.726, where P is reduction rate of corridor patency (%) and L is increase rate of corridor length (%). The determination coefficient (R^2) is 0.937, indicating a well fitted linearly relationship.

3.2.3 Effects on landscape connectivity

Habitat network models were used to calculate a set of connectivity indices including EC(IIC) and EC(PC), using Conefor 2.6. Patch connectivity is related to the scales of different ecological processes, and the calculation of the connectivity index needs to specify the distance threshold for patch connectivity (Ramirez-Reyes et al., 2016). When the resistance distance exceeds the distance threshold, the two patches are not related; otherwise, they are related. According to the real LCD values, 1000, 3000, 5000 were set as the distance thresholds, representing weak, medium, and strong migration ability respectively (Table 4). Comparison between with and without wind power project indicates the construction of the wind power projects weakened the ecological processes of different migration abilities. The reduction rates of EC(IIC) under different distance thresholds were 25.09%, 0.85%, and 0, respectively. The reduction rates of EC(PC) under different distance thresholds were 11.06%, 3.91%, and 2.35%, respectively. The value of connectivity index increased gradually along with the growth of the distance threshold, indicating that the larger the scale of the ecological process was, the higher the connectivity of the same landscape was.

4. Discussions

4.1 NDVI variation trend and resistance surface characteristics

LCD model was used to identify the ecological corridors in this study. In the application of a concrete model, source patches and resistance surface should be considered. The source patches were identified based on NDVI variation trend. Potential ecological corridors connecting source patches were calculated based on the resistance surface value.

Wind power projects not only include the large size of turbines (point projects), but also the associated infrastructure required to support an array of turbines, such as roads and electrical transmission lines (line projects). Although the land occupation of a turbine footing is small, the number of turbines is large and they span a wide range of area. The study area was located mainly in high-quality land for the growth of forest and meadow, the construction of the wind power projects unavoidably destroyed the original vegetation. Meanwhile, the construction of turbines and roads caused various levels of interference on the landscape structure, wildlife movement, and land use change in the surrounding areas (Fu et al., 2010; Loro et al., 2015; Obermeye et al., 2011; Shi et al., 2018). The range of interference may be further expanded with a large scale of development. As shown in Table 1, the resistance value was negatively correlated with vegetation coverage and distance from the turbine, so the construction of the wind power projects contributed significantly to the increased resistance.

4.2 Effects of wind power projects on ecological corridor and landscape connectivity

Ecological corridors can be the habitat of the wildlife, and they can act as a channel, source, sink, obstruction, and filter for biological movement with many functions such as biodiversity conservation, contamination filtration, erosion prevention and flood control (Forman, 1995; Zhu et al., 2005). As an industrial zone with fully-equipped infrastructure to support specified targeted industries, the wind power projects are not conducive for the formation of ecological corridors due to the lack of ecological function. In addition, the wind power projects, as point and linear landscape units, have an obvious cutting effect on the landscape (Kuvlesky et al., 2007; Obermeye et al., 2011). It cut the entire landscape into isolated patches, causing the extensive fragmentation of landscape and isolation of wildlife. Therefore, the wind power projects have negative impacts on ecological corridor patency, ecological corridor length and landscape connectivity resulting from the construction of turbines as well as infrastructure development, such as roads.

On the one hand, the construction of the wind power projects altered the direction of the corridors between the source patches in the landscape, which hindered the migration and diffusion of the species (Kuvlesky et al., 2007), leading to the reduction in corridor patency. On the other hand, the construction of the wind power projects also changed the landscape structure and weakened the species exchange among the patches. A species can move a larger geographical distance through permeable landscapes than through high resistance landscapes (Avon and Berges, 2016). When the species has to migrate over high resistance areas, the corridor length increases at the same time. Our results confirm the significant relationship between increase rate of corridor length and reduction rate of corridor patency. The corridor length caused by corridor change increased greatly, leading to increase in resistance. Even though the distance in the source patches between no.1 and no.2 decreased, the resistance still increased. Increased resistance means that ecological corridors with rich biodiversity and important ecological functions will play less important roles. Clearly, the negative impacts of wind power projects should not be ignored. Wildlife are sensitive to human infrastructure and activity, and they have to adjust their migration routes to avoid the low frequency noise and shadow on the ground generated by the rotation of the turbines (Cabrera-Cruz et al., 2016; Harrison et al., 2017).

In addition, studies found the landscape configuration became fragmented and the connectivity of the natural landscape declined along with wind energy development (Kuvlesky et al., 2007;

Obermeye et al., 2011). The wind power projects in the study area include 164 turbines and 80 connecting roads. The construction has an obvious cutting effect on the landscape, causing landscape fragmentation and decline in connectivity. Fragmentation is detrimental to both the integrity of ecological systems and the long-term viability of associated wildlife, and may magnify deleterious effects to species and ecosystems by limiting the species ability to adapt or migrate (Ewers et al., 2006). Therefore, more attention should be paid to protect the current ecological corridors and construct new ones in the proper locations.

4.3 Comparison between the current study with previous results

This study focuses on ecological corridors and landscape connectivity to better reflect landscape pattern and landscape ecological structure. In view of the ecological impacts of onshore wind power projects, there are some differences in research objectives, methods and results between this study and previous studies (Table 5). Different from many researches which focus on certain species, especially birds, this study did not take the migration corridors of a specific species, but take the landscape ecology as the prime importance to determine the potential ecological corridor, which can provide the paths for wildlife migration and plays an important role in connecting the isolated and dispersed ecosystem (Zhu et al., 2005). Our purpose is to quantitatively evaluate the ecological impacts of the wind power projects on ecological corridor and landscape connectivity. Meanwhile, with the GIS technology, this study took into account the specific factors of the wind power projects to accurately assess the impacts on ecosystem. Previous studies showed that the construction of wind power projects altered the migration corridors (Cabrera-Cruz et al., 2016; Harrison et al., 2017; Pocewicz et al., 2013; Skarin et al., 2015), reinforcing our results of ecological corridors change from the aspect of wildlife migration.

4.4 Implication and application of the results

Landscape planning for species of concern requires detailed knowledge of the amount and quality of habitat as well as the connectivity or spatial configuration of the habitat (Fahrig, 2001). The construction of ecological corridor is beneficial for biodiversity conservation. Landscape connectivity is an important factor for considering during the decision-making process. The wind power projects can be routed optimally so that the disturbance can be minimized.

The construction of projects at different stages can have various impacts on ecosystems (Hazem et al., 2019; Lin, 2018). In order to reduce the negative impact of a wind power project on landscape ecology, ecological impact assessment should be carried out strictly before the construction and ecological restoration should be carried out properly afterwards. It is necessary to make scientific planning and identify the optimal location for wind power projects. Quantitative assessment of the impact of the wind power projects on ecological corridor and landscape connectivity is the foundation of scientific planning in ecological sensitive areas. Figs. 8 and 9 show the comparison of impacts on ecological corridor with and without the wind power projects, and Table 4 show the comparison of impacts on landscape connectivity, which can be used to evaluate the ecological impact of the proposed wind power projects before the construction. Traditionally, the location selection of the wind power projects focuses on local wind resource, but the negative impacts on ecosystems should not be ignored. According to the results in Figures. 7, 8, 9 and Table 4, in order to minimize the impact of the wind power projects on the ecological system, it is necessary to pay attention to the ecological corridors with large changes after the wind farm construction, find out the wind farms that cause corridor changes, and select the suitable location for wind farms with minimal impact on ecosystem. In addition, ecological restoration is mainly to improve the local ecosystem services functions. In our study area, the main aim of ecological restoration is to improve water conservation and maintain biodiversity. Around the built-up area of the wind power projects, local dominant species of dwarf grass alpine plants, such as purple fescue, lanceola, and others, should be planted.

This study analyzed the ecological impact of the wind power projects at the landscape level, filling the gap in the research on the impact of the wind power projects on the landscape process in Shanxi Province. In addition, this study focused on the pre-construction and operational phase of the wind farms, so it is beneficial to guide the location selection of future wind power projects and avoid the key ecological corridors in the area. Reducing carbon emission by replacing fossil energy with renewable energy, such as wind energy, has received increasing attentions in most countries. In the meantime, the measures are also still needed to mitigate the environmental and ecological impacts of the renewable energy development (Yang et al., 2014b).

4.5 Limitation and future study

Similar as many studies, there are some limitation of the current study. LCD method has been widely used for landscape ecology evaluation (Avon et al. 2016; Chen et al. 2017), but it is difficult to accurately set the resistance values. Due to the lack of observation data, the simulation results were not able to be calibrated, probably resulting in a certain level of biases in the results. However, performance evaluation is based on the comparison, not directly simulating the observed results. For this reason, the impact of the biases on the calculated results due to uncertainties of resistance values is minor (Shi et al., 2018). In addition, this study did not analyze the obstructed situation of different species such as flying birds, large animals and small animals, which could affect the pertinence of the calculation results. Even so, the ecological influence of the wind power projects revealed in this study is helpful for the sustainable wind power development (Francis et al., 2018; Skarin et al., 2015). In the future studies, the field observation of different species migration can be applied to further improve the simulation results.

5. Conclusions

This study evaluated the impacts of onshore wind power projects on ecological corridor and landscape connectivity in the Taiyue Mountain Wind Power Project in Qinyuan, Shanxi, China.

The results showed that the wind power projects not only significantly increased the resistance that is not conducive to the formation of ecological corridors at the landscape level, but also had an obvious cutting effect on the landscape, resulting in the increase of the length of the ecological corridors and the decrease of corridor patency and landscape connectivity. The resistance distribution determines the construction of corridors that are beneficial for species migration. When the wind power projects were built, the resistance value was obviously stratified, and the largest resistance value appeared in the wind power projects area. The construction of the wind power projects reduced corridor patency between source patches, which was reflected in the increase in migration resistance. The average increased value and rate were 1019.66 and 148.63%, respectively. The construction of the wind power projects altered the direction and length of the corridor between the source patches, which hindered the migration and diffusion of species. The wind power projects made the growth of most corridors' length, and the average length increased by 95 km. The further the distance was, the larger the increased value was. The relationships between reduction rate of corridor patency and increase rate of corridor length were expressed as P=0.268 L-24.804 and L=3.499 P+125.726 (P is reduction rate of corridor patency (%) and L is increase rate of corridor length (%)). The construction of the wind power projects weakened the landscape connectivity, which was displayed in the reduction of connectivity indices. In addition, the larger the scale of the ecological process was, the higher the connectivity of the same landscape was. When resistance thresholds were 1000, 3000, 5000 m, the reduction rates of EC(IIC) were 25.09%, 0.85%, and 0, respectively, while the reduction rates of EC(PC) were 11.06%, 3.91%, and 2.35%, respectively.

Our results indicate the ecological impact of wind power plants, and therefore it is crucial for strict ecological impact assessment before the construction of a wind power plant and proper ecological restoration afterwards to minimize its ecological damages.

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Table 1 The relative resistance values of different landscape factors

Factors	Classification	Value	Factors	Classification	Value
The land use type	Forest	1	Vegetation coverage (%)	>75	1
	Grassland	10		60-75	10
	Farmland	50		45-60	50
	Construction land	100		30-45	75
Slope (°)	<8	1		<30	100
	8-15	10	NDVI residual	<-0.05	1
	15-25	50		-0.05-0.05	50
	25-35	75		>0.05	100
	>35	100			
Relief	<25	1	Distance from the turbine (m)	>500	1
	25-50	10		200-500	50
	50-75	50		<200	100

Table 2 Statistical summary of NDVI variation trends

Variation trend	Serious degradation	Degradation	Unchanged	Increase	Significant increase
Area (m^2)	3.48	19.66	98.32	41.20	3.02
Percent (%)	2.10	11.87	59.35	24.87	1.82

Table 3 Land use categories

Type	Area (km^2)		
	2005	2017	Change between 2005 and 2017
Evergreen needle forest	25.92	27.21	1.30
Deciduous broad-leaved forest	78.11	86.74	8.63
Deciduous broad-leaved shrub	23.93	13.82	-10.11
Grass	8.33	4.98	-3.35
Meadow	23.54	18.20	-5.34
Farmland	5.37	5.00	-0.37
Residence land	0.45	0.41	-0.03
Wind power projects land	0.00	9.27	9.27

Table 4 Landscape connectivity indices under different distance thresholds

Distance threshold (m)	Without wind power project		With wind power project	
	EC(IIC)	EC(PC)	EC(IIC)	EC(PC)
1000	19.41	22.51	14.54	20.02
3000	22.41	24.02	22.22	23.08
5000	22.41	24.29	22.41	23.72

Table 5 Comparison between this study with previous studies

Objective	Methods	Results	Data sources
Eagles and other raptors along migratory routes	GPS-data	The frequency of collisions or displacement of raptors away from their usual migratory pathways increased as wind energy projects grow.	Katzner et al., 2012
Distribution of migratory bird stopovers	Migratory concentration models	73% of high potential wind development area intersects the important bird migration concentration areas in Wyoming.	Pocewicz et al., 2013
Landscape connectivity for bats	Species Distribution Model	54% of the existing and 72% of planned wind farms interfere with important corridors connecting western and eastern parts of the study areas.	Roscioni et al., 2014
Reindeer migration and movement corridors	GPS-data	During construction of the wind farms, use of original migration routes and movement corridors declined by 76 %.	Skarin et al., 2015
Migratory bald eagles	Dynamic Brownian bridge movement model	There was small overlap between bald eagle migration corridors and viable wind power areas in northeastern North	Mojica et al., 2016

		America.	
Migratory raptor	Radar and hawk-watch monitoring observations	Migratory raptors adjusted their flight trajectories to avoid wind farms.	Cabrera-Cruz et al., 2016
Habitat selection by wintering geese	Linear models	Geese strongly avoided power-lines, and wind turbines.	Harrison et al., 2017
Migration corridor of white storks	Multi-criterial evaluation model	Approximately 60% of the patches in the predicted migration corridor had either a moderate or high potential for wind energy generation.	Francis et al., 2018
Ecological corridor and landscape connectivity	LCD and LCP	Wind power projects reduced corridor patency, lengthened most of corridors, and weakened landscape connectivity.	This study

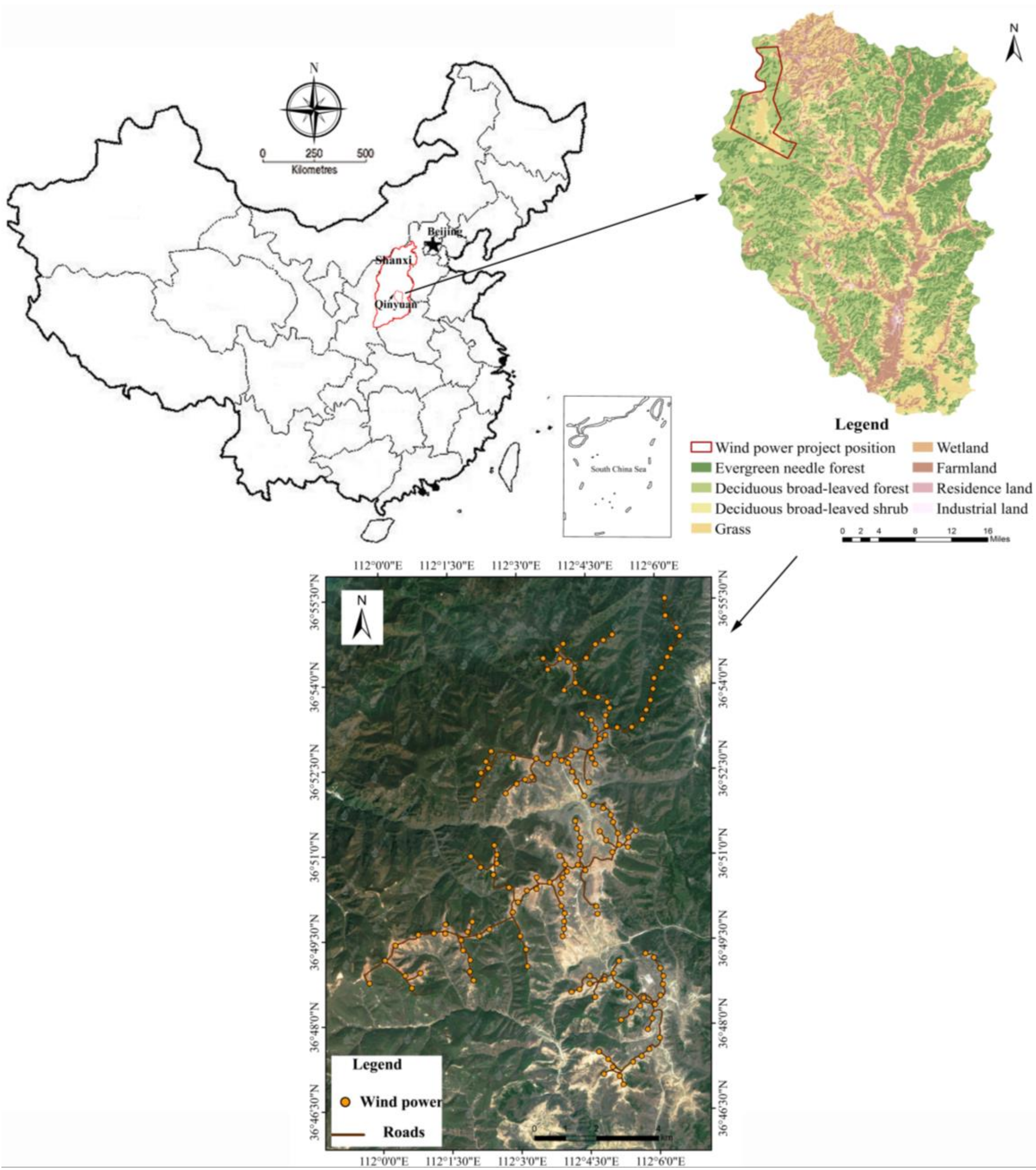

Fig.1. Location of the study area in Qinyuan, Shanxi Province, China.

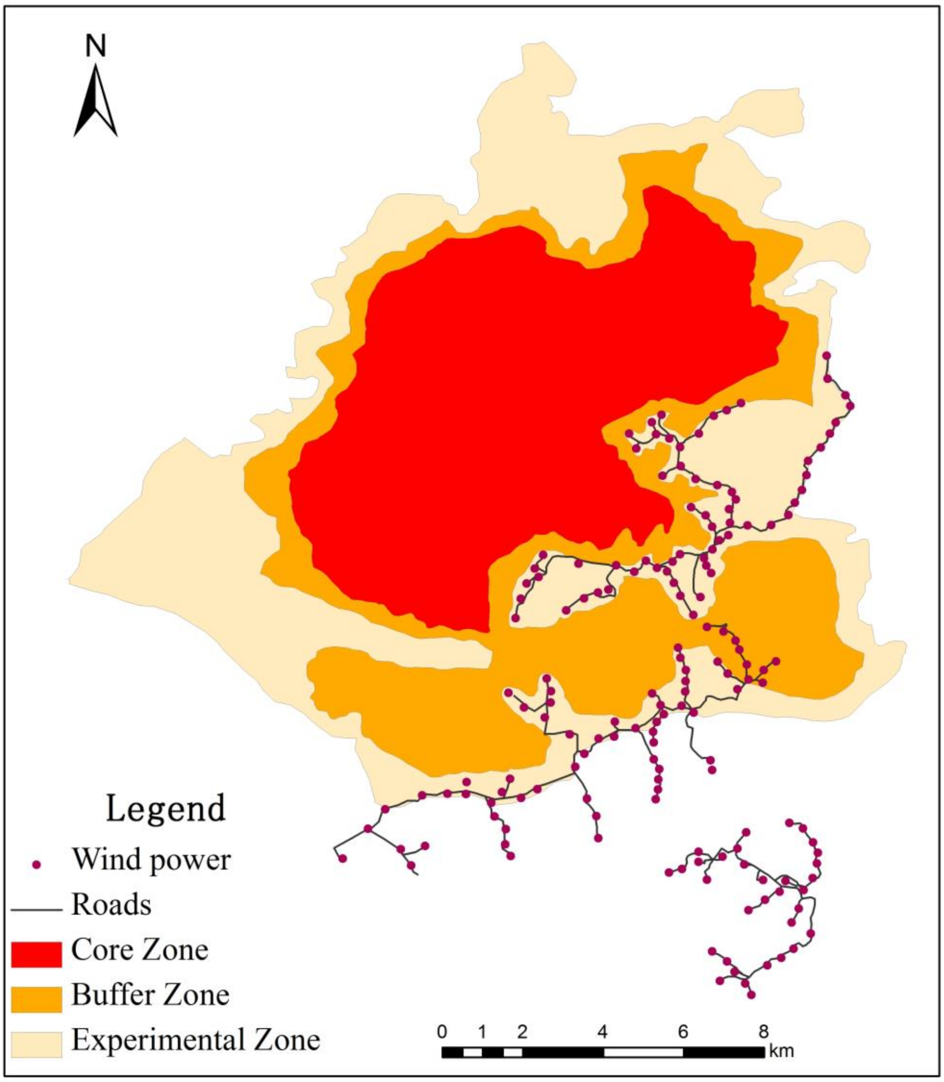

Fig.2. Wind power project, the road, and core, buffer and experimental zones of Mianshan Nature Reserve in the study area.

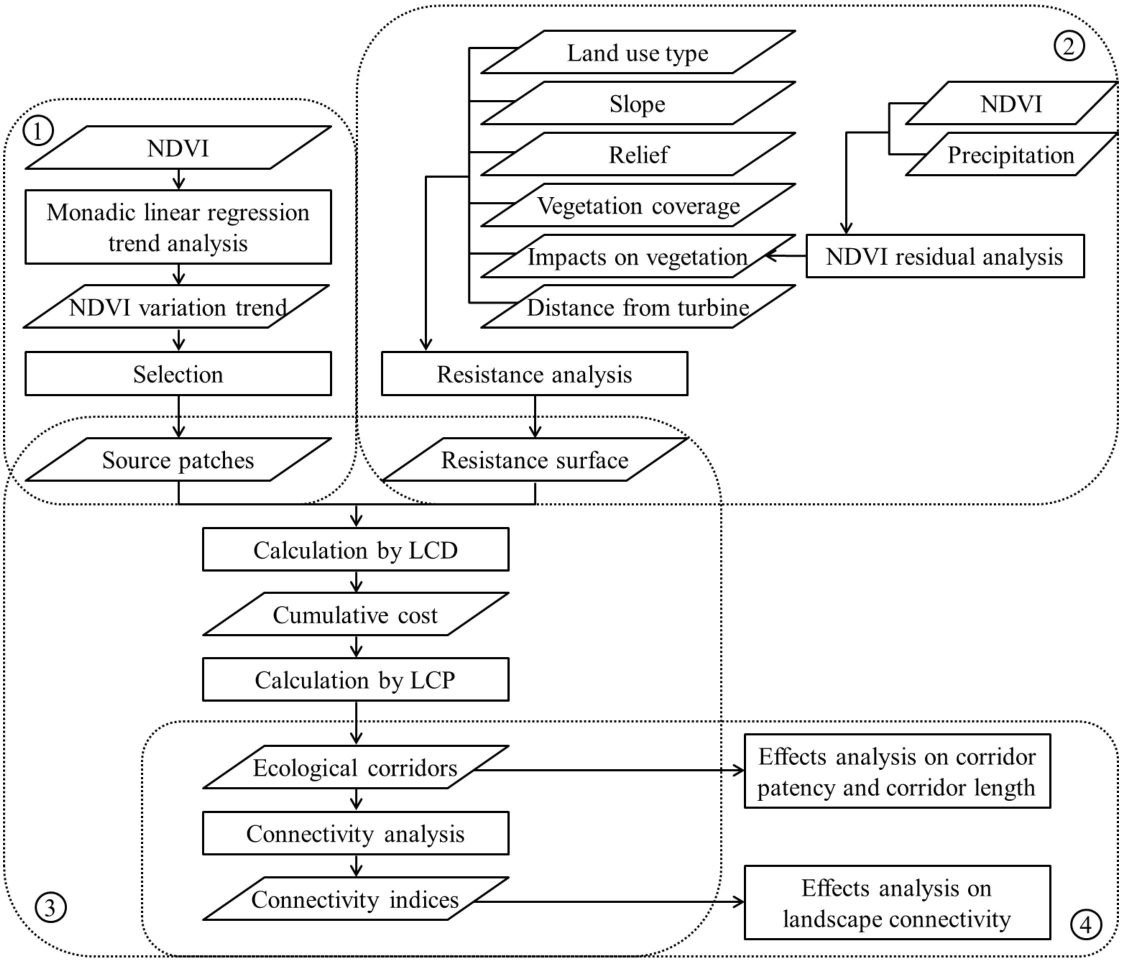

Fig. 3. Methodology of the study.

Note: Rhombuses represent data sources or products, and rectangles represent processes or methods.

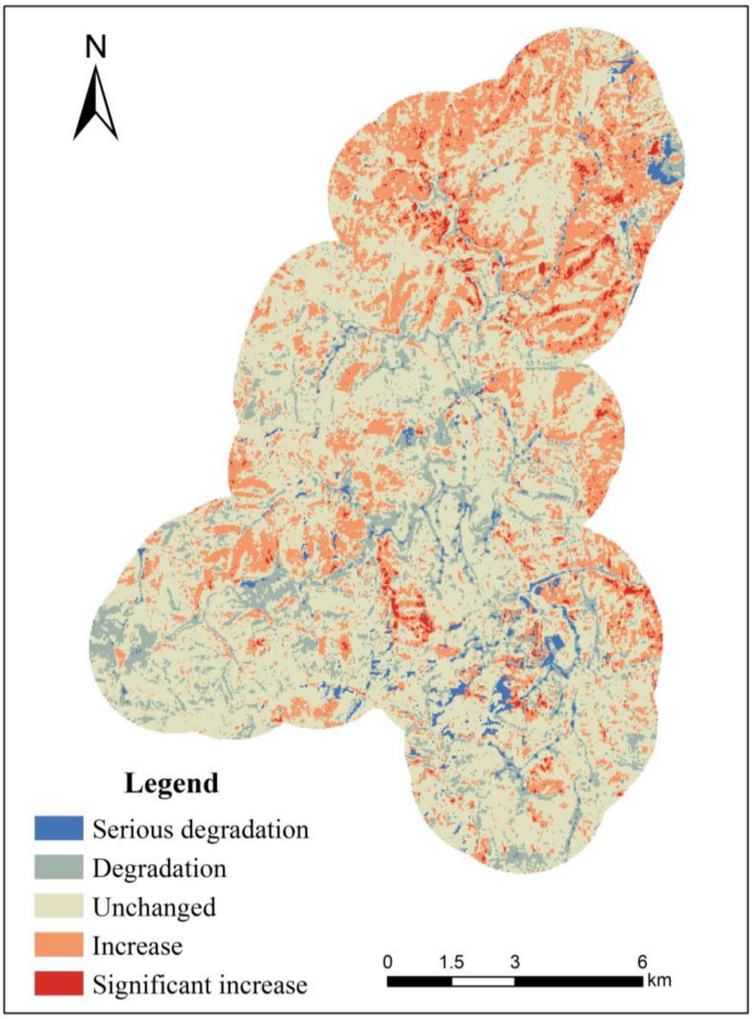

Fig.4. The spatial distribution of the change rates of pixel's NDVI.

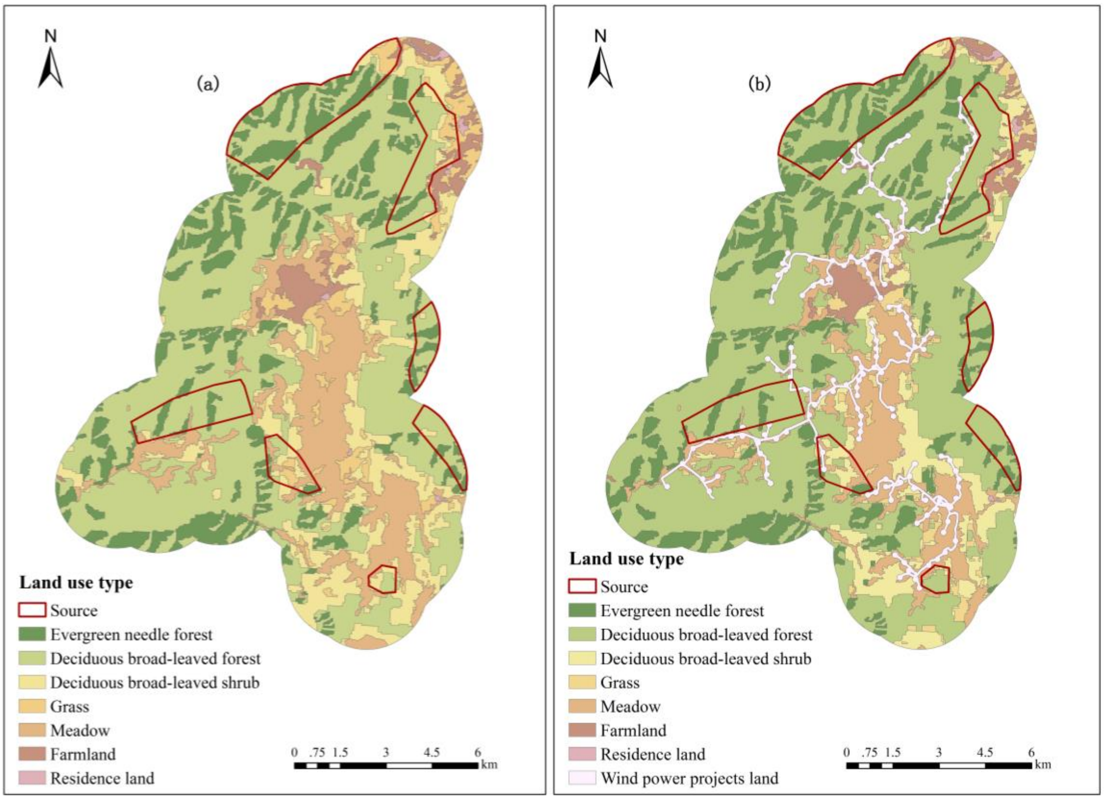

Fig.5. Land use categories: (a) without the wind power projects; and (b) with the wind power projects.

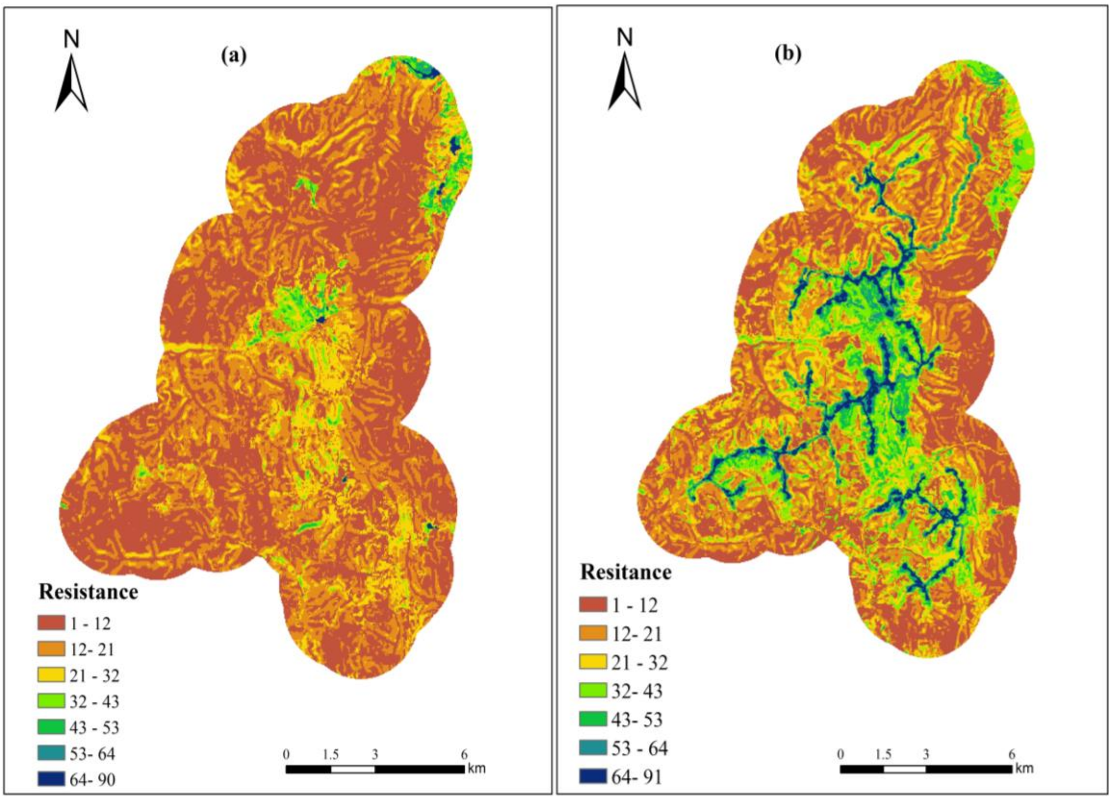

Fig.6. The spatial distribution of resistance: (a) without the wind power project; and (b) with the wind power project.

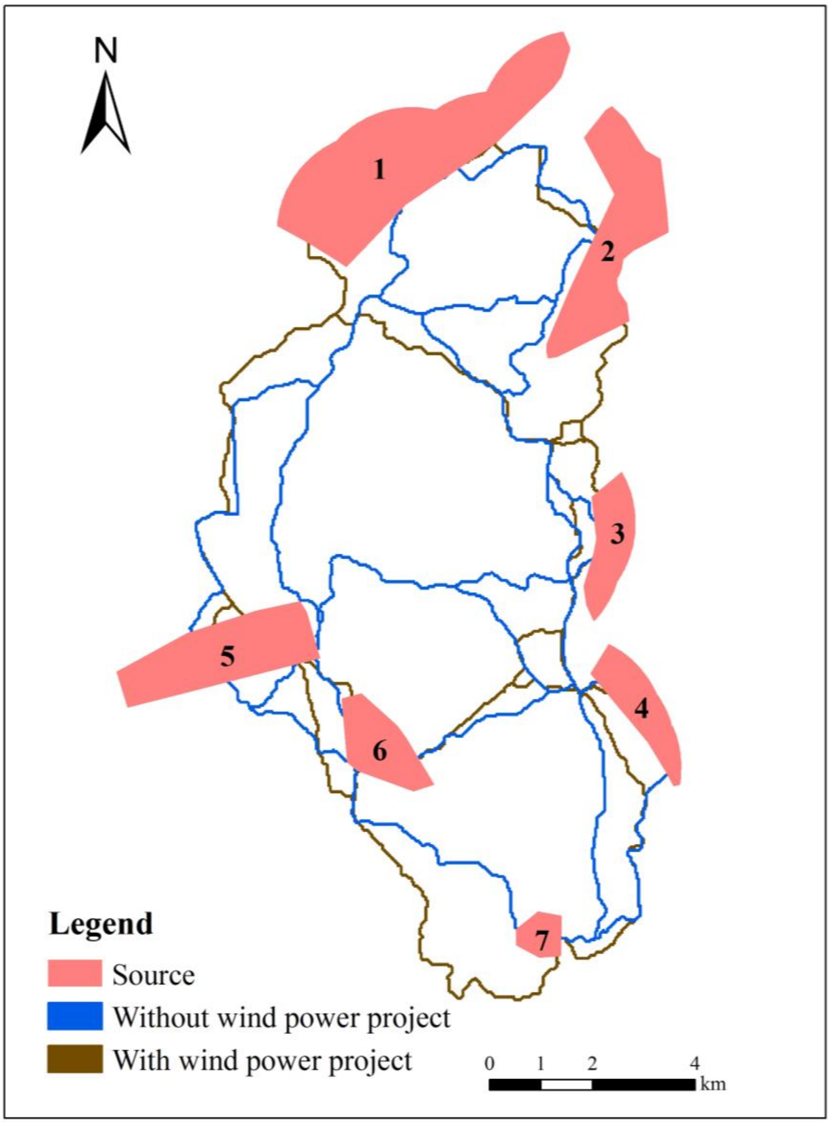

Fig.7. Potential ecological corridors with and without the wind power projects.

Note: Numbers 1-7 represents different sources.

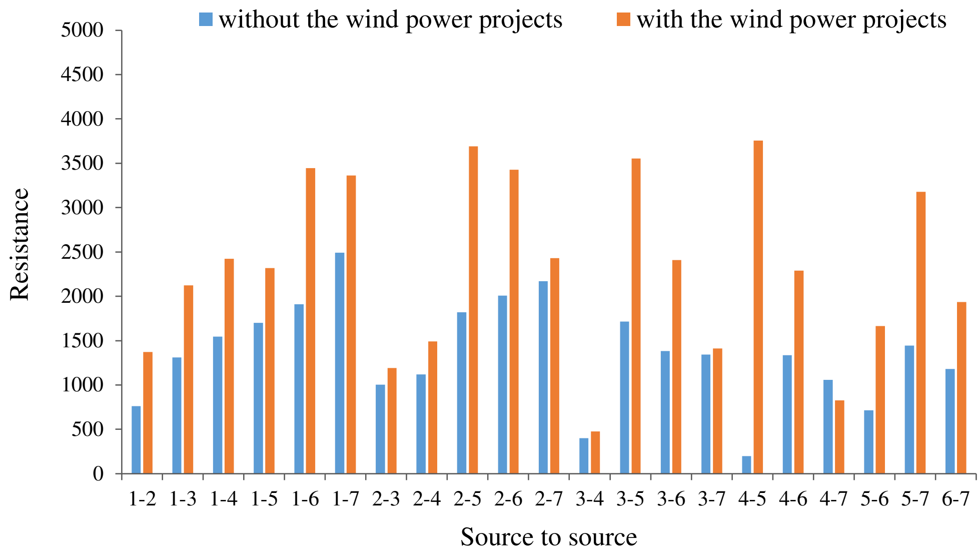

Fig.8. The impact of the wind power project on corridor patency.

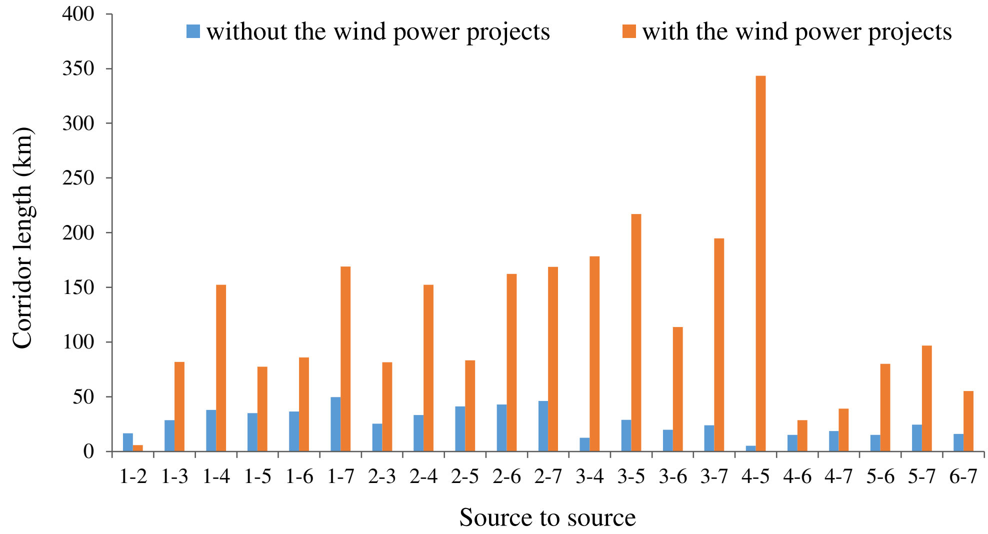

Fig.9. The impact of the wind power project on corridor length.