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The impact of onshore wind power projects on ecological corridors and landscape connectivity in Shanxi, China

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Abstract: The wind power industry has developed rapidly in China, but the effect of wind power projects on the ecosystem is far from being clearly understood. The objective of this study is to evaluate the negative impact of wind power plants on the ecosystem. In this research, least-cost distance and least-cost path 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. The landscape connectivity was evaluated using a set of connectivity indices. In addition, the impact on the corridor patency, length, and the 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 the landscape scale, but also have an obvious cutting effect on the landscape—resulting in an increase in the length of the ecological corridors and a decrease in corridor patency and landscape connectivity. There was also a positive relationship between the increase in length and the distance between the source patches. In addition, the connectivity was enhanced with the increase in distance threshold. This study evaluated the ecological impact of onshore wind power projects at the landscape level, filling the gap in research on landscape ecology, especially in the protected area with key ecological function. Meanwhile, the results are beneficial to guide the location selection for wind power projects and minimize their negative impact on the key ecological corridors.

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

42 **1. Introduction**

43 China's economy has developed rapidly in the last four decades at the cost of the degradation
44 of its ecology and environment (Yang et al., 2012; Yang et al., 2014a). The root cause for the
45 ecosystem degradation is the heavy reliance on fossil fuels, particularly coal (Han et al., 2018). At
46 present, China is still in the process of rapid urbanization and industrialization, and the demand for
47 energy continues to grow. Maintaining the balance between rapid economic growth and
48 environmental protection has been a big challenge for China (Yang, 2014; Yang et al., 2013). In the
49 last decade, China has made great efforts to reverse the environmental degradation. One of the most
50 important measures is to gradually reduce coal consumption and increase the use of renewable
51 energy—reshaping the energy structure of China (Dai et al., 2016; Yang et al., 2016; Yang et al.,
52 2017).

53 Wind power is an important form of renewable energy. With the increasing demand for energy,
54 wind power is considered to be a promising source of renewable energy as a result of its technical
55 maturity, low cost, flexible installation, simple operation, spatial efficiency, and minimal pollution
56 (Hepbasli et al., 2004). In China, the wind power industry has developed rapidly due to
57 technological progress, power guiding policies, and improved energy price mechanism (Feng et al.,
58 2015; Sun et al., 2015). Along with the expansion of wind power industry, there are many studies
59 on wind power technology (Khosravi et al., 2018; Zhao et al., 2015; Zhou et al., 2010), industrial
60 development (Alexandre et al., 2012; Luo et al., 2016; Zhao et al., 2013), policy recommendations
61 (Kang et al., 2012; Liu et al., 2010; Wolsink, 2010), and economic analyses on the investment and
62 operation (Li et al., 2013).

63 However, there are potentially adverse environmental and ecological impacts of wind power
64 projects, which should not be overlooked (Leung et al., 2013). The low frequency noise generated
65 by rotating turbines can detrimentally impact humans and other organisms (Laratro et al., 2014;
66 Wasala et al., 2015). The lights and shadows also visually impact the local communities (Juan et al.,
67 2004). Additionally, the turbine blades can interfere with radio signals (Mroziński et al., 2015).
68 Research on the ecological impact of wind power projects mainly focused on their influence on
69 animals and plants (Escobar et al., 2015; Welcker et al., 2016; Whang et al., 2015). The impact may
70 be direct, such as deaths caused by the rotating turbines (Peste et al., 2015; Wang et al., 2015); or
71 indirect, such as the damage caused to foraging and breeding by habitat loss (Braunisch et al., 2015;
72 Law et al., 2018; Madsen et al., 2008; Pescador et al., 2019). Moreover, the operation of the wind
73 farm can affect vegetation species and biomass (Fagúndez, 2010).

74 In particular, it is worth noting that the construction of wind power projects changed the
75 original landscape. The landscape pattern determines the landscape's characteristics, such as spatial
76 heterogeneity, landscape diversity, landscape connectivity, and so on (Cook, 2002; Peng et al., 2015).
77 Landscape process refers to the circulation and migration of internal and external material, energy,
78 information, as well as the evolution of the landscape system (Klunder, 2004). The effects of wind
79 power projects stem from substance retrospection above the landscape scale—which is crucial for
80 ecological corridor construction, the maintenance of ecosystem function, and regional ecological
81 security (Skarin et al., 2015). The fragmentation of the landscape pattern blocks the material flow,
82 the information flow, and the species flow—affecting the landscape's ecological processes and
83 damaging landscape (Liu et al., 2005).

84 The environmental impact of wind power projects can be analyzed using Geographical
85 Information System (GIS) methods. GIS-based spatial models have been applied to effectively

86 assess the impact of wind farms on animal behavior and habitats (Roscioni et al., 2013). GIS-
87 assisted approaches have also been developed and applied to predict and evaluate the visual impact
88 of wind farms (Molina-Ruiz, 2011). In addition, GIS-based approaches can be used for wind
89 resource assessment, and can also support the decision-making process by taking into account
90 comprehensive factors that address geological characteristics, economic cost, and environmental
91 constraints (Haaren et al., 2011; Li, 2018; Siyal, et al., 2015). With the development of GIS
92 technology, least-cost distance (LCD) and least-cost path (LCP) models have been increasingly
93 applied to quantitatively research ecological corridors, landscape connectivity, ecological network
94 construction, conservation planning, and so on (Avon et al., 2016; Barrows et al., 2011; Rabinowitz
95 et al., 2010). Ecological corridors are land linkages which facilitate wildlife migration between
96 green spaces, and enhance landscape connectivity to promote dispersal and other types of movement
97 (Balbi et al., 2019; Zhu et al., 2005). The field observation has confirmed that migration corridors
98 and habitat connectivity for some species have been disrupted owing to the construction of onshore
99 wind power projects (Francis et al., 2018; Roscioni et al., 2014; Skarin et al., 2015). However, little
100 has been known about their potential effect on ecological processes through the fragmentation that
101 they cause at the landscape scale. Therefore, it is paramount to conduct a large scale quantitative
102 ecological impact assessment of wind power projects—coupling ecological corridor with landscape
103 connectivity—which would be necessary for the trade-off between wind power development and
104 ecological conservation.

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

119 This study made the effort to fill the gap in research regarding the impact of wind power
120 projects on ecological corridor and landscape connectivity in Shanxi Province. The main research
121 aims of the study are: (1) to estimate the effects of wind power projects on ecological corridor by
122 simulating the corridor construction process under multiple influence factors in the selected
123 constructed wind power area; and (2) to explore how the landscape connectivity is affected by the
124 wind power projects by estimating relevant connectivity indices through the use of resistance
125 distance.

126 The rest of the paper is organized as follows. In Section 2, two important approaches—
127 selecting the origination of landscape process, and determining the distribution of the resistance
128 surface with multiple factors including wind farms—were used as the basis for applying LCD and
129 LCP methods to assess ecological corridor and landscape connectivity. In Section 3, the spatial

distribution characteristics of the research region were presented, and the status of ecological corridor patency, corridor length, and landscape connectivity in the area before and after the construction of wind power projects were compared to assess changes in the migration routes and the landscape connectivity. In Section 4, the reasons for onshore wind power's adverse effects on landscape's ecological indicators were discussed, and some suggestions to mitigate the effects were proposed.

2. Material and Methods

2.1 Study Area

The Taiyue Mountain Wind Power Project—possessing a capacity of 250MW—is located north of Qinyuan County within 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—which includes the turbines, roads, and a buffer area of 2 km—covers an area of 165.68 km² 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/m², showing significant potential for developing wind power plants. The study area is located in a warm temperate semi-arid and semi-humid continental monsoon climate zone, with an annual mean temperature of 8.6 °C and an 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 southeastern region 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—spanning the research period of 2005-2017—were obtained from the Geospatial Data Cloud (<http://www.gscloud.cn/search>). These images were used to analyze the Normalized Difference Vegetation Index (NDVI). NDVI indicates the amount of green vegetation present in the pixel by measuring the difference between near-infrared—which is strongly reflected by vegetation—and the absorbed red light. 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 the wind turbines and the distances from the turbine were obtained from the Landsat TM images in 2017. These images were processed using the Environment for Visualizing Images (ENVI) Version 5.0 (Esri, Redlands, CA). The slope and relief were obtained using the Global Digital Elevation Model (GDEM) 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 the NDVI as follows:

$$\text{Vegetation coverage} = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (1)$$

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

175 2.3 Methods

176 The methodology of this research is schematically illustrated in Figure 3. First, to identify the
177 starting point of ecological changes, the source patches were selected based on a variation trend
178 analysis of the NDVI. Second, ArcGIS was applied to build a landscape resistance surface that
179 synthesized the multiple factors affecting the landscape process in the wind farms. Third, LCD and
180 LCP methods were used to establish the ecological corridors derived from the source patches and
181 the landscape resistance surface. A connectivity analysis was performed using a set of connectivity
182 indices based on the resistance of corridors. Finally, the effects of the wind power projects on the
183 ecological corridor and the landscape connectivity were assessed based on corridor patency, corridor
184 length, and connectivity indices.

186 2.3.1 Selection of source patches

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

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

$$198 \quad S = \frac{n \times \sum_{i=1}^n (i \times NDVI_i) - (\sum_{i=1}^n i)(\sum_{i=1}^n NDVI_i)}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (2)$$

199
200 where S is pixel's NDVI change rate; n is total years, i is an annual sequence; $NDVI_i$ is the
201 NDVI value in the year of i . S can reflect the improvement or degradation of the NDVI. $S > 0$
202 indicates an increase in the NDVI with time. The larger the value is, the more apparent the
203 improvement is. On the contrary, $S < 0$ indicates a decrease in NDVI with time.

205 2.3.2 Determination of resistance surface

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

210 Land cover type and topography are two basic factors affecting the landscape (Diffendorfer et
211 al., 2014). Slope and topography are the resistance factors affecting vegetation growth (Zhao et al.,
212 2014). In addition to the direct impact on the natural environment, noise pollution and visual impact
213 caused by the wind power projects also affect the migration of species. The low frequency noise

214 and the shadows on the ground generated by the rotation of the turbines negatively impact the
215 ecosystem (Juan et al., 2004; Laratro et al., 2014; Wasala et al., 2015). The species need to keep a
216 certain distance away from the turbines to avoid its negative effects. Based on these, the land use
217 type, slope, relief, vegetation coverage, the impact on vegetation, noise pollution, and visual impact
218 were selected as factors in the assessment of the migration resistance.

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

$$\varepsilon = NDVI_{real} - NDVI_{predicted} \quad (3)$$

227
228
229
230 where ε is the residual value of NDVI for each pixel. $\varepsilon > 0$ indicates a positive impact caused
231 by human activities; $\varepsilon = 0$ means no impact; and $\varepsilon < 0$ suggests a negative impact. $NDVI_{real}$ is the
232 real NDVI value of the pixel, which was obtained from Landsat TM images. $NDVI_{predicted}$ is the
233 NDVI value which was predicted by the linear regression equation between NDVI and climate
234 indicators. Since the study area is located in a mountainous region with limited water, the main
235 factor reflecting climate characteristics is precipitation, and the NDVI change is largely correlated
236 with precipitation (Zhao et al., 2011).

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

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

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

255 2.3.3 Establishment of ecological corridors by Least-cost distance and Least-cost path

256 The relationship between the landscape pattern and the ecological process is the core of
257 landscape ecology (Fu et al., 2011). The landscape pattern and the spatial combination

258 characteristics of different landscape elements are relatively static in a given period of time, but the
 259 real ecological process can be dynamic during the same period. Source-sink landscape theory breaks
 260 through this limitation in the traditional sense—making the landscape pattern dynamic and
 261 reflecting both the influence of the pattern on the process and the effect of the process on the pattern
 262 (Chen et al., 2003; Chen et al., 2008). The approaches for regulating the ecological process were
 263 analyzed based on the spatial balance of the "source" landscape. The extension of species to the
 264 surroundings is a process of competitive control of land use, which must be achieved by overcoming
 265 the resistance, so the resistance surface can reflect the spatial trend of species migration. With the
 266 advantage of evaluating the landscape spatial patterns by analyzing the effects of different landscape
 267 types on the target species, the LCD and the LCP have been applied to evaluate the impact of
 268 different land use types on the ecological flow (Balbi et al., 2019; Chetkiewicz et al., 2009).
 269 Similarly, the LCD and the LCP models were used to establish ecological corridors based on the
 270 resistance surface in this study (Walker et al., 1997).

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

281 Both the LCD and the LCP methods were performed in ArcGIS 10.2. In the LCD model,
 282 cumulative cost from each pixel to the nearest source was obtained by inputting the previously
 283 derived source patches and resistance surface. As a further calculation based on the LCD, the LCP
 284 identified a singular least cost path connecting every two source patches based on cumulative cost.
 285 These paths were the potentially ecological corridors.

286

287 2.3.4 Assessment of landscape connectivity

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

291

$$292 \quad IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n \frac{a_i \times a_j}{1 + nl_{ij}}}{A_L^2} \quad (4)$$

$$293 \quad PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i \times a_j \times P_{ij}}{A_L^2} \quad (5)$$

294

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

300 stepping stone patches.

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

305

306 **3. Results**

307 **3.1 Spatial patterns of the NDVI variation trend and the resistance surface**

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

314 The NDVI values in the northern part of the study area were less affected by human activities
315 and illustrated a period of growth through their increasing trend. Despite the effect of human
316 activities and climate change, the NDVI of shrub and grassland in the central and southern parts of
317 the study remained largely unchanged during the study period.

318 The NDVI variation trend was related to the change in the type of land use. Table 3 and Figure
319 5 show the different land use categories with and without the wind power projects. Forests—
320 including the deciduous broad-leaved forest, the evergreen needle forest, and the deciduous broad-
321 leaved shrub—accounted for 77.13% of the whole area in 2017. Grassland, which includes grass
322 and meadow, accounted for 14.10%. Farmland, residential land, and industrial land areas accounted
323 for 3.04%, 0.09% and 5.64% respectively. Compared to the period before the construction of the
324 wind power projects in 2005, the area of the main patterns of land use in the source patches—the
325 evergreen needle forest and the deciduous broad-leaved forest—increased in 2017. This indicates
326 that the ecosystem of the source patches was less impacted by the wind power projects.

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

332

333 **3.2 Effects of wind power projects on the ecological corridor and the landscape connectivity**

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

342

343 3.2.1 Effects on corridor patency

344 Figure 8 shows the before and after comparison of the resistance increment resulting from the
345 wind power projects. The construction of the wind power projects reduced the corridor patency
346 between the source patches, which is reflected in the increase in the LCD values. Although the LCD
347 values of one corridor decreased, this corridor does not go through the region of the wind power
348 projects—indicating minimal impact by the wind power projects on this corridor. The average,
349 minimum and maximum of the LCD increased to 1019.66, 71.35, and 3557.43 respectively. The
350 high resistance corridors generally crossed over the wind power projects, resulting in an enhanced
351 reduction effect on the corridor patency.

352

353 3.2.2 Effects on corridor length

354 Figure 9 shows the comparison of the corridor length increment between before and after the
355 wind power projects were built. The wind power projects lengthened most of the corridors, thus
356 increasing the migration distance. The length of one corridor decreased, while the lengths of others
357 increased by different levels—with the average increase being 95 km. The increase was related to
358 the distance between the source patches. The farther the distance was, the larger the increase was.
359 The distance between the source patches of no.1 and no.7 was the largest, which made the length of
360 the corridors increase by 119.460 km. A thorough change in the route between source patches of
361 no.3 and no.5 led to a 6.5-fold increase in the corridor length.

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

366

367 3.2.3 Effects on landscape connectivity

368 Habitat network models were used to calculate a set of connectivity indices—including EC(IIC)
369 and EC(PC)—using Conefor 2.6. The patch connectivity is related to the scales of different
370 ecological processes, and the calculation of the connectivity index needs to specify the distance
371 threshold for the patch connectivity (Ramirez-Reyes et al., 2016). When the resistance distance
372 exceeds the distance threshold, the two patches are not related. Otherwise, they are related.
373 According to the real LCD values, 1000, 3000, and 5000 were set as the distance thresholds—
374 representing weak, medium, and strong migration ability respectively (Table 4). Comparing the
375 before and after values indicates that the construction of the wind power projects weakened the
376 ecological processes of different migration abilities. The reduction rates of EC(IIC) under different
377 distance thresholds were 25.09%, 0.85%, and 0 respectively. The reduction rates of EC(PC) under
378 different distance thresholds were 11.06%, 3.91%, and 2.35% respectively. The value of the
379 connectivity index increased gradually along with the growth of the distance threshold, indicating
380 that the larger the scale of the ecological process was, the higher the connectivity of the same
381 landscape was.

382

383 4. Discussions

384 4.1 NDVI variation trend and resistance surface characteristics

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

389 Wind power projects not only include large sized turbines (point projects), but also additional
390 associated infrastructure required to support an array of turbines, such as roads and electrical
391 transmission lines (line projects). Although the turbine footing occupies marginal land, there are
392 numerous turbines and they span a wide range of area. The study area mainly consisted of high-
393 quality land conducive to the growth of forest and meadow, and the construction of the wind power
394 projects unavoidably destroyed the original vegetation. Meanwhile, the construction of turbines and
395 roads caused various levels of interference to the landscape structure, wildlife movement, and the
396 land use change in the surrounding areas (Fu et al., 2010; Loro et al., 2015; Obermeyer et al., 2011;
397 Shi et al., 2018). The range of interference may be further expanded with large scale development.
398 As shown in Table 1, the resistance value was negatively correlated with the vegetation coverage
399 and the distance from the turbine, so the construction of the wind power projects contributed
400 significantly to the increased resistance.

401

402 4.2 Effects of wind power projects on the ecological corridor and landscape connectivity

403 Ecological corridors can be the habitat of wildlife, and they can act as a channel, source, sink,
404 obstruction, and filter for biological movement—serving many functions such as biodiversity
405 conservation, contamination filtration, erosion prevention, and flood control (Forman, 1995; Zhu et
406 al., 2005). As an industrial zone with fully equipped infrastructure to support specific targeted
407 industries, the wind power projects are not conducive for the formation of ecological corridors due
408 to the lack of ecological function. In addition, the wind power projects—as pointed and linear
409 landscape units—have an obvious cutting effect on the landscape (Kuvlesky et al., 2007; Obermeyer
410 et al., 2011). It cut the entire landscape into isolated patches, causing an extensive fragmentation of
411 the landscape and the isolation of wildlife. Therefore, the wind power projects negatively impact
412 the ecological corridor patency, the ecological corridor length and the landscape connectivity—
413 through their construction of turbines and their development of infrastructure such as roads.

414 On the one hand, the construction of the wind power projects altered the direction of the
415 corridors between the source patches in the landscape—which hindered the migration and diffusion
416 of species (Kuvlesky et al., 2007)—leading to the reduction in corridor patency. On the other hand,
417 the construction of the wind power projects also changed the landscape structure and weakened the
418 species exchange among the patches. A species can move a larger geographical distance through
419 permeable landscapes than through high resistance landscapes (Avon and Berges, 2016). When the
420 species has to migrate over high resistance areas, the corridor length increases at the same time. Our
421 results confirm the significant relationship between the rate of increase of the corridor length and
422 rate of reduction of the corridor patency. The corridor length increased greatly due to corridor
423 change, leading to an increase in the resistance. Even though the distance in the source patches
424 between no.1 and no.2 decreased, the resistance still increased. Increased resistance means that the
425 ecological corridors with rich biodiversity and important ecological functions will play less

426 important roles. Clearly, the negative impact of wind power projects should not be ignored. Wildlife
427 are sensitive to human infrastructure and activity, and they have to adjust their migration routes to
428 avoid the low frequency noise and the shadows on the ground generated by the rotation of the
429 turbines (Cabrera-Cruz et al., 2016; Harrison et al., 2017).

430 In addition, studies found that the landscape configuration became fragmented and the
431 connectivity of the natural landscape declined along with wind energy development (Kuvlesky et
432 al., 2007; Obermeyer et al., 2011). The wind power projects in the study area include 164 turbines
433 and 80 connecting roads. The construction has an obvious cutting effect on the landscape, causing
434 landscape fragmentation and a decline in connectivity. Fragmentation is detrimental to both the
435 integrity of the ecological systems and the long-term viability of associated wildlife, and may
436 magnify the deleterious effects on species and ecosystems by limiting the species' ability to adapt
437 or migrate (Ewers et al., 2006). Therefore, the protection of the current ecological corridors and the
438 construction of new ones in appropriate locations should be prioritized.

439

440 **4.3 Comparison between the current study with previous results**

441 This study focuses on ecological corridors and landscape connectivity to better reflect the
442 landscape pattern and the landscape ecological structure. In view of the ecological impact of onshore
443 wind power projects, there are some differences in research objectives, methods, and results between
444 this study and previous studies (Table 5). Unlike many previous studies—which focused on
445 particular species (especially birds)—this study instead focused primarily on the landscape ecology
446 to determine the potential ecological corridor—which provide the paths for wildlife migration and
447 plays an important role in connecting the isolated and dispersed ecosystem (Zhu et al., 2005). Our
448 purpose was to quantitatively evaluate the ecological impact of the wind power projects on the
449 ecological corridor and the landscape connectivity. Meanwhile, with the GIS technology, this study
450 took into account the specific elements of the wind power projects to accurately assess their impact
451 on the ecosystem. Previous studies showed that the construction of wind power projects altered the
452 migration corridors (Cabrera-Cruz et al., 2016; Harrison et al., 2017; Pocewicz et al., 2013; Skarin
453 et al., 2015)—reinforcing our results which depicted changes in the ecological corridors with respect
454 to wildlife migration.

455

456 **4.4 Implication and application of the results**

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

462 The construction of projects at different stages can have various effects on ecosystems (Hazem
463 et al., 2019; Lin, 2018). In order to reduce the negative impact of a wind power project on the
464 landscape ecology, an ecological impact assessment should be carried out strictly before the
465 construction, and ecological restoration should be carried out properly after construction. It is
466 necessary to scientifically plan and identify the optimal location for wind power projects. A
467 quantitative assessment of the impact of the wind power projects on the ecological corridor and the
468 landscape connectivity is the foundation of scientific planning in ecologically sensitive areas.

469 Figures 8 and 9 show a comparison of the impact on the ecological corridor with and without the
470 wind power projects, and Table 4 shows the comparison of the impact on landscape connectivity—
471 which can be used to evaluate the ecological impact of the proposed wind power projects before
472 their construction. Traditionally, the location selection of the wind power projects focuses on local
473 wind resources, but its negative effects on ecosystems should not be ignored. According to the
474 results in Figures 7, 8, and 9, and Table 4, in order to minimize the impact of the wind power projects
475 on the ecological system, the following steps need to be undertaken. First, attention must be given
476 to the ecological corridors that suffer significant changes due to wind farm construction. Second,
477 the wind farms that affect these corridors should be identified. Lastly, suitable locations for the wind
478 farms should be selected based on the degree of their impact on the ecosystem. In addition,
479 ecological restoration is mainly to improve the ecosystem service functions. In our study area, the
480 main aim of ecological restoration is to improve water conservation and maintain biodiversity.
481 Around the constructed area of the wind power projects, local dominant species of dwarf grass and
482 alpine plants—such as purple fescue, lanceola, and others—should be planted.

483 This study analyzed the ecological impact of the wind power projects at the landscape level in
484 Shanxi Province, filling the gap in research on the same. In addition, this study focused on the pre-
485 construction and the operational phase of the wind farms, thus beneficially guiding the selection of
486 locations for future wind power projects by avoiding the key ecological corridors in the area.
487 Reducing carbon emissions by replacing fossil fuels with renewable energy has received increasing
488 attention in most countries. In the meantime, measures are still needed to mitigate the environmental
489 and ecological impacts caused by the development of renewable energy (Yang et al., 2014b).

491 **4.5 Limitation and future study**

492 Similar to many existing studies, this study also has its limitations. The LCD method has been
493 widely used for landscape ecology evaluation (Avon et al. 2016; Chen et al. 2017), but it is difficult
494 to accurately set the resistance values. Due to a lack of observational data, the simulation results
495 were not able to be calibrated—possibly incorporating a certain level of bias within the results.
496 However, the performance evaluation is based on the comparative data, and is not informed by
497 direct simulations of the observed results. For this reason, the impact of bias on the calculated results
498 due to uncertainty regarding the resistance values is minor (Shi et al., 2018). In addition, this study
499 did not analyze the obstructed situation of different species such as flying birds, large animals, and
500 small animals—which could affect the pertinence of the calculation results. Even so, the ecological
501 influence of the wind power projects revealed in this study can facilitate sustainable wind power
502 development in the future (Francis et al., 2018; Skarin et al., 2015). In future studies, field
503 observations of the migration of different species can be applied to further improve the simulation
504 results.

506 **5. Conclusions**

507 This study evaluated the impact of onshore wind power projects on the ecological corridors
508 and the landscape connectivity in the Taiyue Mountain Wind Power Project in Qinyuan, Shanxi,
509 China.

510 The results showed that the wind power project not only significantly increased the resistance
511 to the formation of ecological corridors at the landscape level, but also had an obvious cutting effect

512 on the landscape—resulting in an increase in the length of the ecological corridors and a decrease
513 in the corridor patency and the landscape connectivity. The resistance distribution determines the
514 construction of corridors that are beneficial for species migration. When the wind power projects
515 were built, the resistance value was obviously stratified, and the largest resistance value appeared
516 in the area of wind power projects. The construction of the wind power projects reduced the corridor
517 patency between the source patches, which was reflected in the increase in the migration resistance.
518 The average increased value and rate were 1019.66 and 148.63% respectively. The construction of
519 the wind power projects altered the direction and length of the corridor between the source patches,
520 which hindered the migration and diffusion of species. The wind power projects caused most
521 corridors to grow in length, and the average length increased by 95 km. The further the distance was,
522 the larger the increased value was. The relationships between the rate of reduction in corridor
523 patency and the rate of increase in corridor length were expressed as $P=0.268 L-24.804$ and $L=3.499$
524 $P+125.726$ (P is the rate of reduction (%) in corridor patency and L is the rate of increase (%) in
525 corridor length). The construction of the wind power projects weakened the landscape connectivity,
526 which was illustrated by the reduction of the connectivity indices. In addition, the larger the scale
527 of the ecological process was, the higher the connectivity of the same landscape was. When
528 resistance thresholds were 1000 m, 3000 m, and 5000 m, the reduction rates of EC(IIC) were 25.09%,
529 0.85%, and 0 respectively; while the reduction rates of EC(PC) were 11.06%, 3.91%, and 2.35%
530 respectively.

531 Our results indicate the ecological impact of wind power plants, and therefore it is crucial for
532 strict ecological impact assessments to be conducted before the construction of wind power plants.
533 Afterwards, its ecological damage should be minimized by undertaking comprehensive ecological
534 restoration.

535

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542

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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	NDVI residual	<30	100
	8-15	10		<-0.05	1
	15-25	50		-0.05-0.05	50
	25-35	75		>0.05	100
Relief	>35	100	Distance from the turbine (m)	>500	1
	<25	1		200-500	50
	25-50	10		<200	100
	50-75	50			

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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

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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

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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

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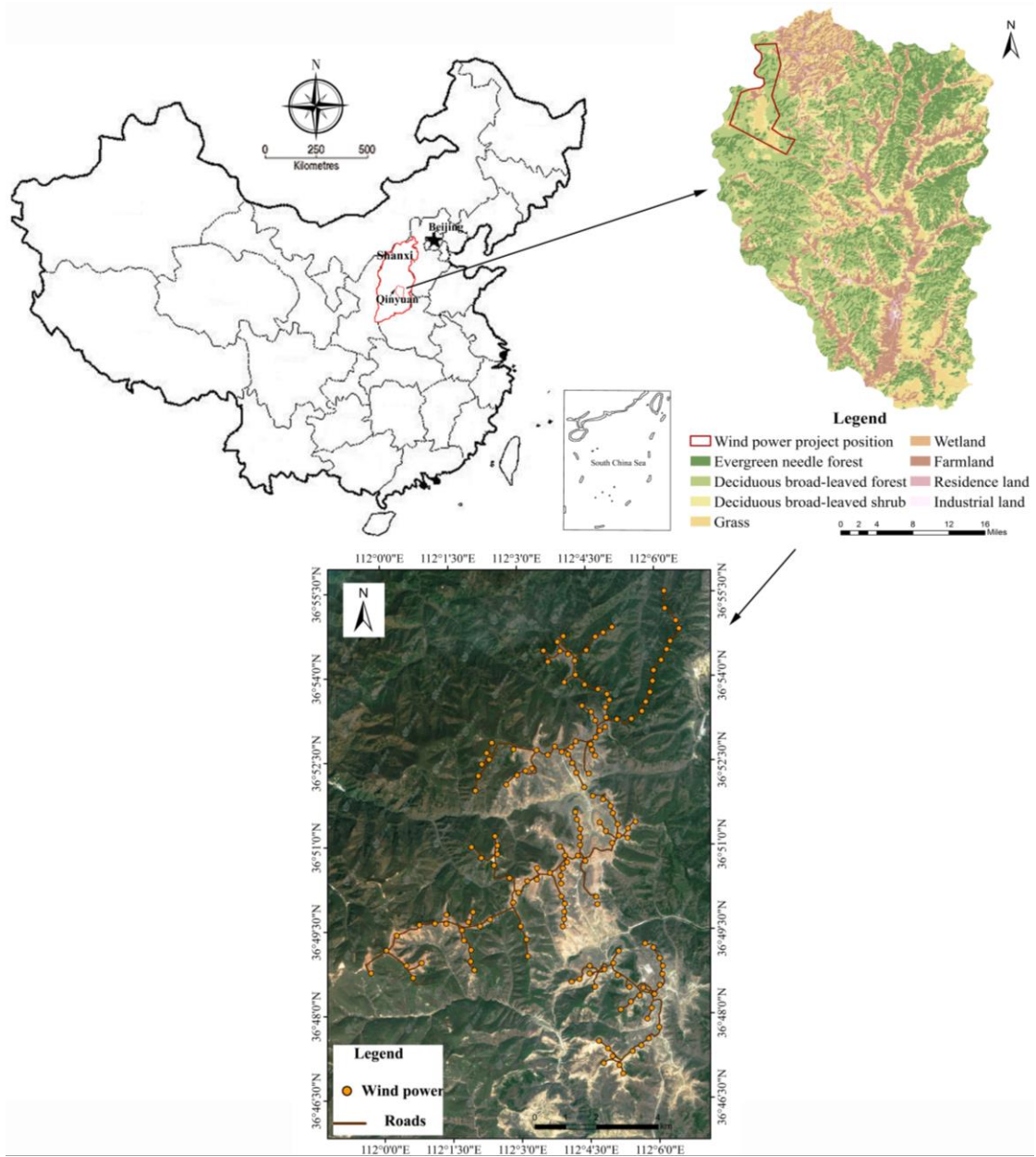
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Table 5 Comparison between this study with previous studies

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 America.	Mojica et al., 2016
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

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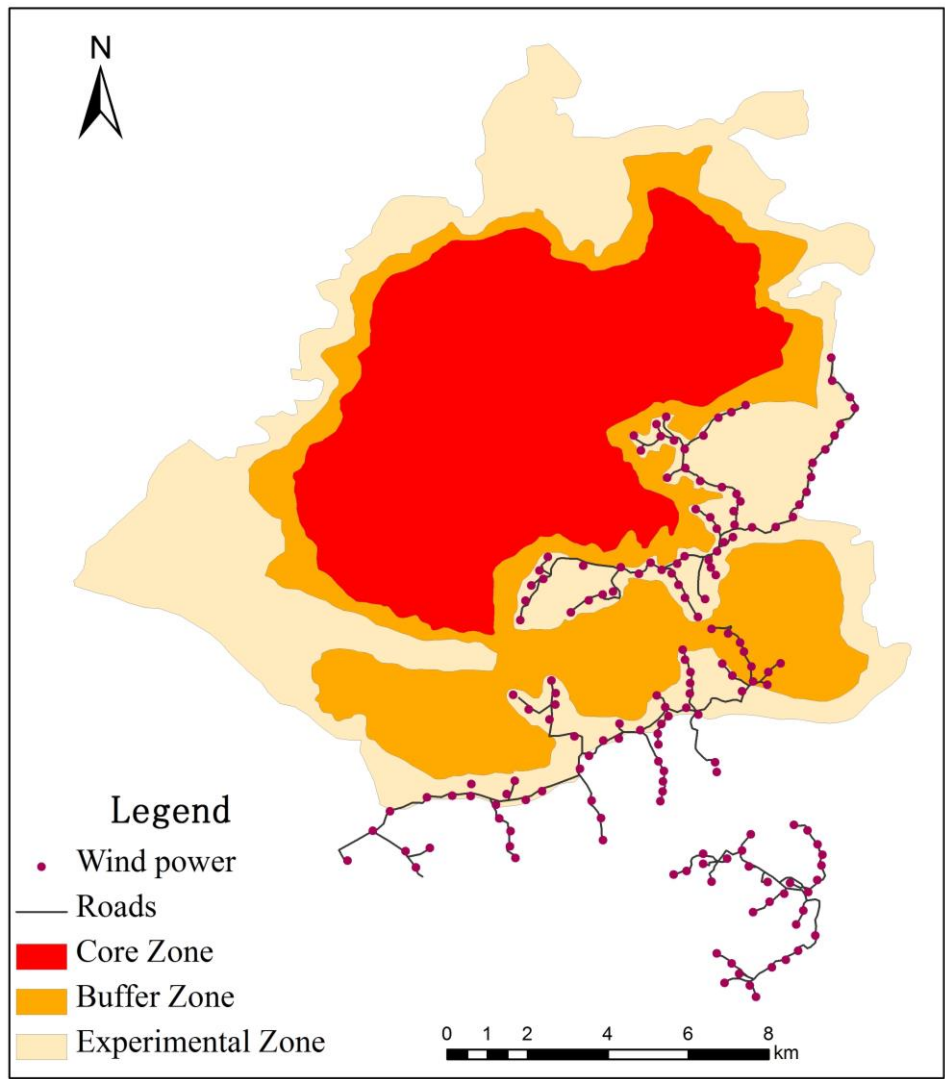


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Fig.1. Location of the study area in Qinyuan, Shanxi Province, China.



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

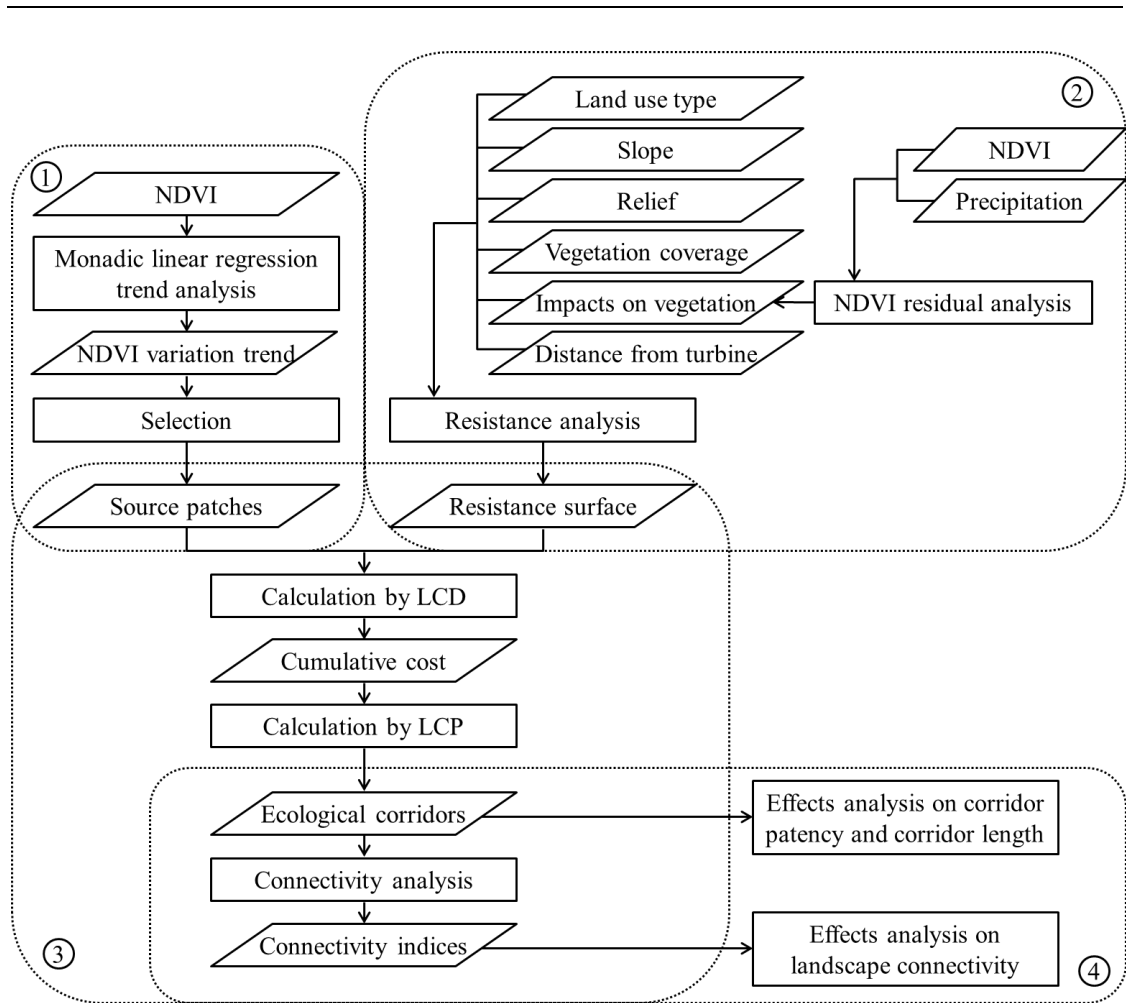
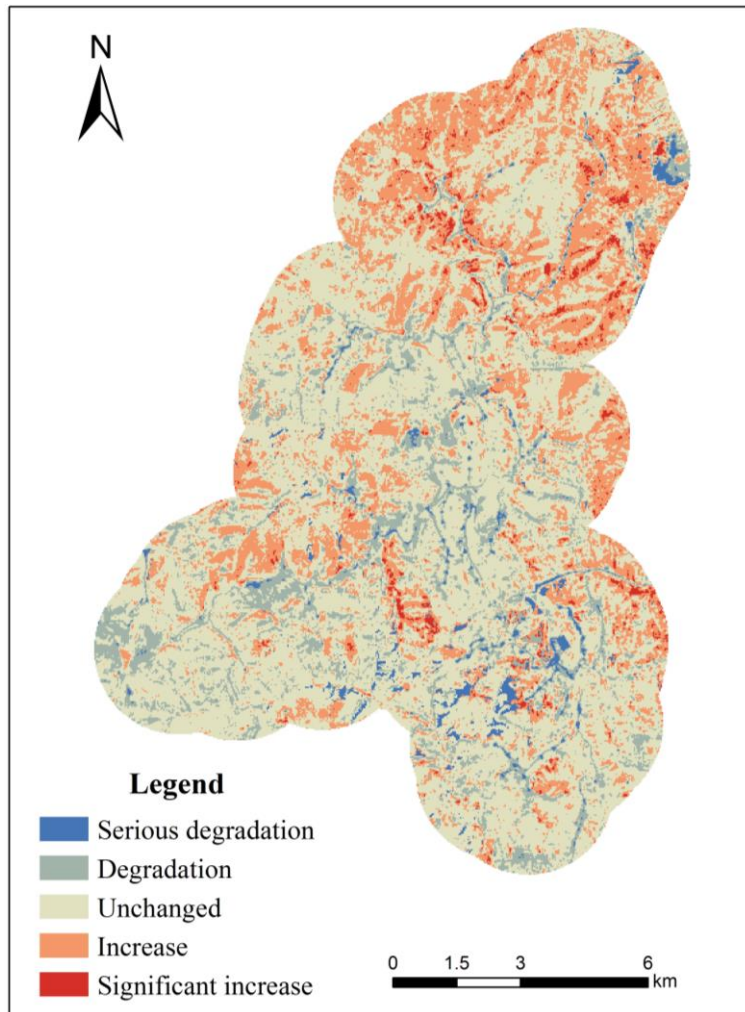


Fig. 3. Methodology of the study.

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

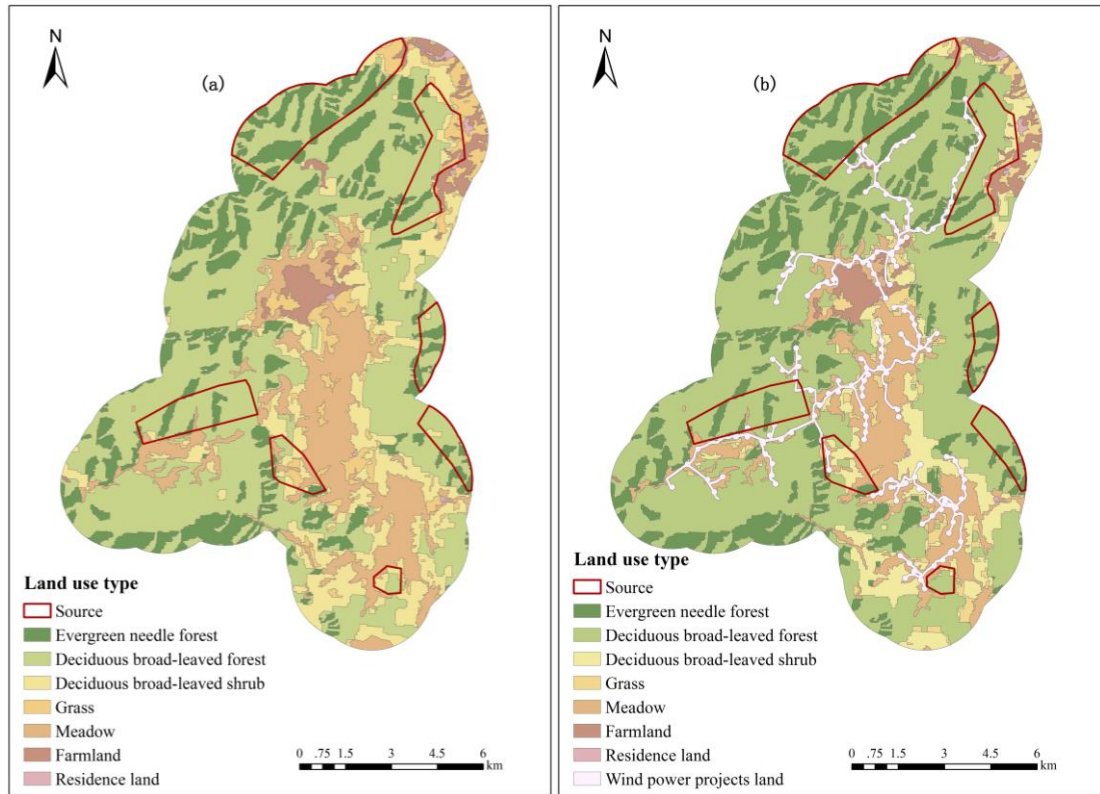
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Fig.4. The spatial distribution of the change rates of pixel's NDVI.

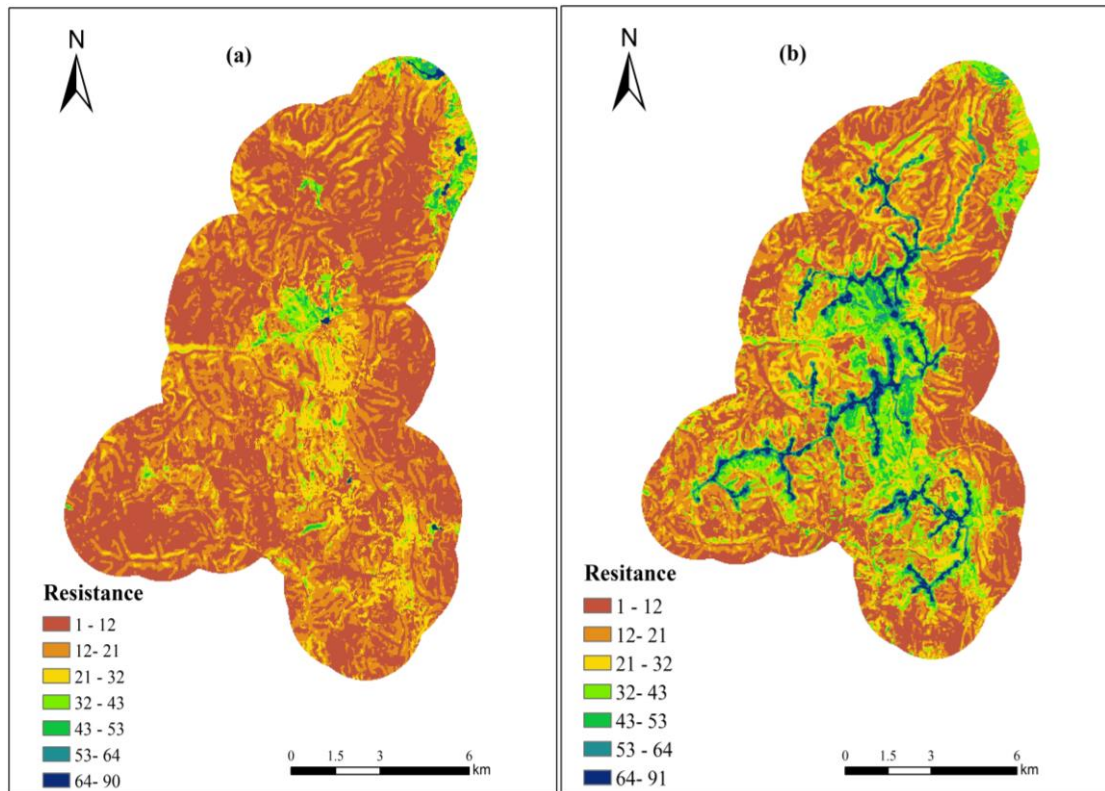


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Fig.5. Land use categories: (a) without the wind power projects; and (b) with the wind power projects.



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

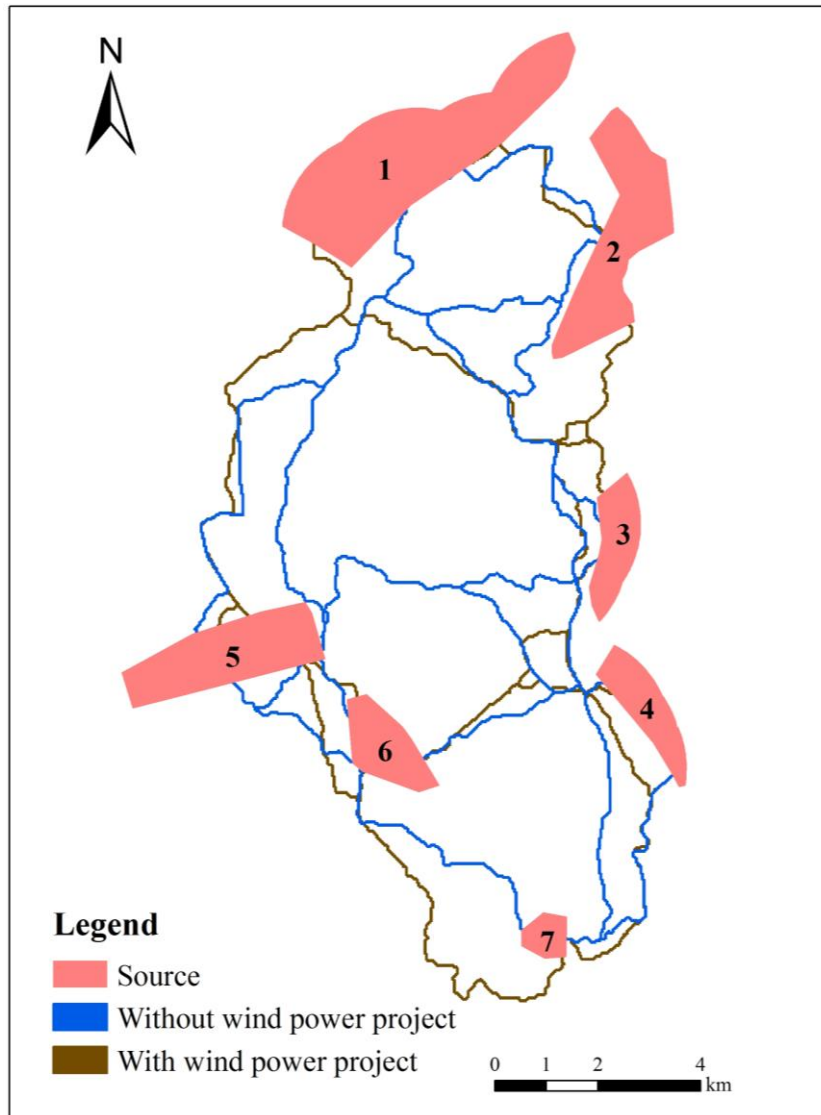
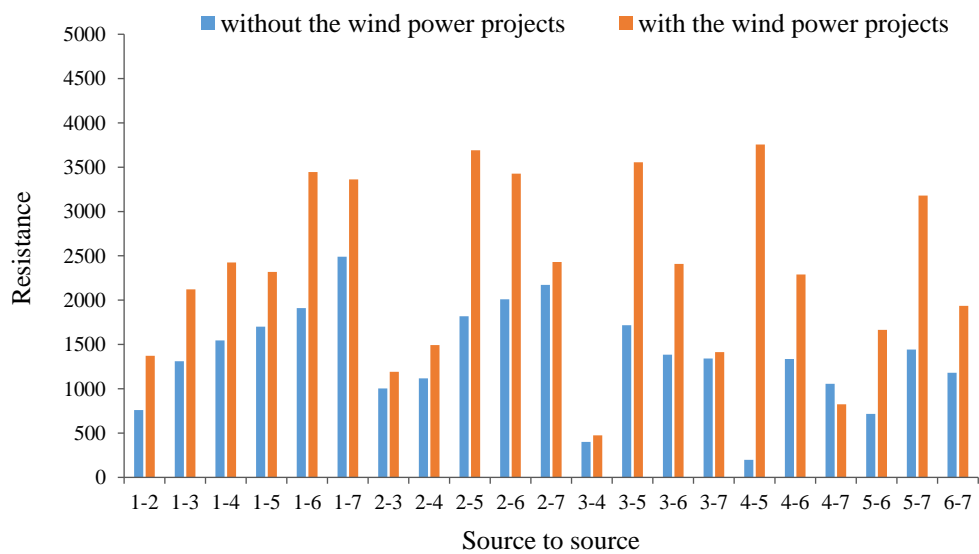


Fig.7. Potential ecological corridors with and without the wind power projects.

Note: Numbers 1-7 represents different sources.

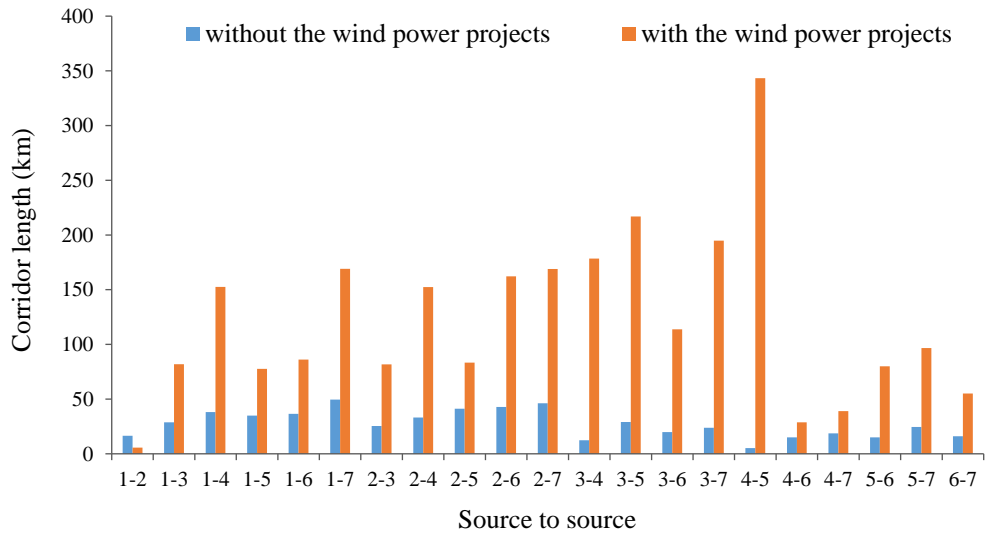
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Fig.8. The impact of the wind power project on corridor patency.



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