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Cao, Y, Yang, R and Carver, S (2020) Linking wilderness mapping and connectivity modelling : A methodological framework for wildland network planning. *Biological Conservation*, 251. 108679. ISSN: 0006-3207

<https://doi.org/10.1016/j.biocon.2020.108679>

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Author Accepted Manuscript

Accepted by Biological Conservation on Jun 17, 2020

1. Full title

Linking wilderness mapping and connectivity modelling: A methodological framework for wildland network planning

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1 **Linking wilderness mapping and connectivity modelling : A** 2 **methodological framework for wildland network planning**

3 **Abstract**

4 Habitat fragmentation is one of the key drivers of global biodiversity loss. In this context,
5 connectivity modelling is increasingly important for effective conservation. Most previous
6 studies on connectivity modelling are based on focal species, while fewer studies focus on
7 models based on landscape naturalness or wildness. We propose a methodological framework
8 for wildland network planning, which utilizes the results from wilderness mapping as input
9 data for connectivity models. Here, the least-cost model and circuit model are applied using
10 Linkage Mapper and Circuitscape, with selected wilderness areas used as source patches
11 together with resistance values transformed from a wilderness quality index. Taking the Great
12 Taihang region of China as an example, wildland networks are created and pinch-points
13 identified. We show that the selection of core patches and resistance surfaces have a significant
14 impact on the resulting corridors. The wildland network could serve as an effective and efficient
15 alternative to habitat networks and supplement the protected areas networks, especially when
16 the species data are lacking, or a rapid assessment is required. This framework for wildland
17 planning could potentially be applied to fragmented landscapes across various countries to
18 eliminate or reduce the negative impacts of habitat fragmentation on biodiversity.

19

20 *Keywords:* habitat fragmentation; wilderness mapping; connectivity conservation; protected
21 areas; Circuitscape

22 **1 Introduction**

23 Fragmentation and the resulting reduction and degradation of natural habitats are key
24 drivers of the global biodiversity crisis (Fahrig 2003; Butchart, Walpole et al., 2010). Under
25 the dual threats of climate change and expansion of modified ecosystems, protecting and
26 restoring landscape connectivity by creating effective ecological networks have become core
27 strategies for nature conservation (Kanagaraj et al., 2013; Liu, Yang et al., 2015; Saura, Bertzky
28 et al., 2019; Yemshanov et al., 2019).

29 Ecological network planning is based largely on landscape-connectivity modelling.
30 Landscape connectivity is usually defined as the degree to which the landscape facilitates or
31 impedes movement among resource patches (Taylor, Fahrig et al., 1993). The most widely used
32 landscape-connectivity model is the least-cost-distance model, which identifies the least-cost
33 paths and least-cost corridors between core areas (Beier, Majka et al., 2008). In corridor design,
34 focal-species-based methods are widely used since species of different taxa may have a degree
35 of spatial overlap such that the requirements of certain species can be selected to represent
36 wider species assemblages. This has proven to work well in certain regions (Breckheimer,

37 Haddad et al., 2014). However, focal-species-based connectivity modelling has limitations.
38 First, the focal species used may not be able to effectively represent other species (Chetkiewicz,
39 Clair et al., 2006), and expert opinions may not necessarily represent the true characteristics of
40 species movement (Pullinger and Johnson 2010). Second, data on habitat requirements and
41 actual movement are available for only a few species, making it difficult to be applied in data-
42 poor regions (Theobald, Reed et al., 2012). Third, it takes much time and investment in
43 modelling multi-species connectivity (Beier, Spencer et al., 2011), making it difficult to be
44 applied at a large scale (Krosby, Breckheimer et al., 2015).

45 On the other hand, connectivity models based on landscape naturalness or ecological
46 integrity may be regarded as a more cost-efficient method (Theobald, Reed et al. 2012; Krosby,
47 Breckheimer et al. 2015). Compared to focal-species-based connectivity models, however,
48 there are fewer studies focusing on naturalness-based connectivity modelling (Theobald, Reed
49 et al. 2012; Krosby, Breckheimer et al. 2015; Belote, Dietz et al. 2016). At the same time,
50 wilderness mapping studies have been carried out at multiple scales, including global scale (e.g.
51 Lesslie and Taylor 1985; McCloskey and Spalding 1989; Allan, Venter et al. 2017), national
52 scale (e.g. Müller, Bøcher et al., 2015; Cao, Carver et al., 2019; Radford, Senn et al., 2019) and
53 local scale (e.g. Carver, Comber et al., 2012; Orsi, Geneletti et al., 2013; Lin, Wu et al., 2016).
54 These wilderness mapping studies have identified areas with high naturalness or ecological
55 integrity in those regions. However, these maps are principally used in wilderness inventory,
56 protected areas planning and monitoring, while few examples exist where these have been
57 applied to connectivity modelling (Carruthers-Jones, 2013). Therefore, it is valuable to link the
58 two knowledge domains of wilderness mapping and connectivity modelling, which could make
59 the wilderness maps more useful in connectivity conservation, especially in areas where species
60 data are not available and wilderness maps already exist.

61 Our research is based on previous studies which suggested landscape naturalness or
62 landscape integrity could be used in creating resistance surface (WHCWG, 2010; Theobald et
63 al., 2012; Belote et al., 2016), areas with the highest wilderness quality index could be used as
64 cores patches (Carruthers-Jones, 2013), and pointed out that naturalness-based corridor models
65 may offer an efficient proxy for focal-species models (Krosby et al., 2015). However, there is
66 still a lack of a comprehensive methodological framework for developing wildland networks
67 based on the latest research (especially how to identify core wild areas, how to create resistance
68 surfaces, and how to identify pinch-points in the wildland networks). To fill this knowledge
69 gap, we address key questions in modelling wildland networks. For example: What is the
70 difference between a wildland network and a commonly used habitat network or protected area
71 network? How best to identify core areas and resistance surfaces in wildland network planning
72 based on wilderness maps? How sensitive are wildland networks to core patches and resistance
73 values? The above questions are crucial to wildland network planning and will be explored in
74 this study. In summary, the objectives of this study are to:

75 (1) Establish a conceptual model and planning method for developing wildland networks,
76 using the results from wilderness mapping as the input data for connectivity modelling.

77 (2) Explore the differences between wildland networks under different source and
78 resistance scenarios.

79 (3) Identify the ecological corridors between wilderness areas and any pinch-points in
80 these corridors, using the case of the Great Taihang Mountains in China as an example.

81 The broader aim of the research is to provide guiding principles for wildland network
82 planning supported by sound spatial and ecological analysis.

83 2 Conceptual framework

84 A conceptual framework for the development of wildland networks at regional scales
85 needs to be established. In this paper, a wildland network is defined as a spatial network
86 consisting of core wilderness areas and the functional ecological corridors between them. The
87 principal elements include:

88 (1) Core wilderness areas, which refer to large unmodified or slightly modified areas,
89 retaining their natural character and influence. This definition corresponds with the IUCN
90 wilderness protected areas guidelines (Casson, Martin et al., 2016), stressing how wilderness
91 areas are characterized by low degree of human modification or impact. Wilderness areas are
92 the main habitats of those species which are sensitive to human disturbance and that cannot
93 live in areas with high levels of human modification, such as towns, farmlands, and road-effect
94 zones. In this study, core wilderness areas are defined from wilderness maps including the
95 Boolean wilderness patches and areas with the highest wilderness quality index (Cao, Carver
96 et al., 2019).

97 (2) Ecological corridors between core wilderness areas, which maintain relatively low
98 human impact and provide functional connectivity between core wilderness areas, thus
99 providing the biophysical conditions necessary for ecosystems and populations to survive in
100 human-dominated landscapes (Catchpole, 2016). From the perspective of movement ecology,
101 wilderness-dependent species may move and migrate through the ecological corridors between
102 core wilderness areas to meet their survival requirements or adapt to climate change. This is
103 especially important for those species with large home ranges such as large carnivores or those
104 that migrate long distances. In this study, ecological corridors are identified as linkages between
105 core wild areas based on connectivity modelling.

106 A wildland network can be considered as a type of ecological network both in concept and
107 in practice, such as the wildland network in North America and the Yellowstone to Yukon
108 Initiative (Foreman, 1998; Soule and Noss, 1998; Soulé and Terborgh, 1999; Locke and Heuer
109 2015). To further clarify this concept, wildland networks are compared with protected area
110 networks and habitat networks, which are commonly used in conservation. The three types of
111 networks are not mutually exclusive and due to the potential spatial overlap between wild areas,
112 protected areas, and habitats for certain species, the ecological corridors between them could
113 exhibit a certain degree of spatial overlap. However, there are differences between them:

114 (1) Differences between wildland networks and protected-area networks. As wilderness
115 areas are key components of protected areas (Casson, Martin et al., 2016), the protected-area
116 network usually covers many of those wilderness areas in the region of concern. However,
117 many studies have pointed out that there are many *de facto* wilderness areas with important
118 conservation values but are not covered by existing protected areas (Lin, Wu et al. 2016; Cao,

119 [Carver et al., 2019](#)). By connecting core wild areas, wildland networks cover those wilderness
120 areas that are not included within many protected area networks. Therefore, wildland networks
121 may be of great significance for building resilience into regional ecological security patterns
122 ([Belote, Dietz et al., 2017](#)), by adding additional values and linkages into protected-area
123 networks. While it should be noted that protected-area networks may include non-wild regions
124 that are valuable for species or regions having potential to be restored to a wilderness state,
125 although protected areas may be protected for wrong reasons or that they were once wild but
126 now have been degraded by human activity and so are declining rapidly.

127 (2) Difference between wildland networks and habitat networks. The wildland networks
128 and habitat networks can be seen as landscape-oriented and species-oriented methods,
129 respectively. Habitat networks are concerned with habitat connectivity and are usually
130 modelled using focal species ([Fischer and Lindenmayer, 2007](#)), while the wildland networks
131 target are modelled for connectivity between core wild areas supporting wilderness-dependent
132 species. Therefore, there may be inconsistency in the areas represented between the two types
133 of networks.

134 In summary, in addition to the commonly used protected-area networks and habitat
135 networks, it is valuable to explore wildland network planning as an alternative and efficient
136 method. In fact, wildland network planning is urgently needed by policymakers and local
137 practitioners in addressing concerns over habitat fragmentation, isolation and species decline.
138 Taking China as an example, the fragmentation of wilderness areas in the eastern half of the
139 country may be some of the worst in the world due to intensified agriculture, settlement and
140 infrastructure construction, which can be seen clearly from the Chinese wilderness maps ([Cao,
141 Carver et al., 2019](#)). This study uses China's Great Taihang Mountains as a case study and
142 explores how the conceptual framework of wildland network can be applied in conservation.

143 **3 Materials and methods**

144 **3.1 Study area**

145 The study area is the Great Taihang Region (34 ° 34 ' ~ 40 ° 47 ' N, 110 ° 14 ' ~ 116 ° 34 '
146 E), which is located in the north China region (shown in [Figure 1](#)). The total area of the study
147 region is 214,100 km², accounting for 2.2% of China's terrestrial area and covers the entire
148 territory of Shanxi province, as well as some districts and counties in Beijing, Hebei and Henan
149 provinces. The region has a temperate continental climate, with an annual average temperature
150 between 8 ~ 13 °C, and annual precipitation between 400 ~ 1000mm. The study area is mainly
151 mountainous and contains the most densely distributed population of north Chinese leopard
152 (*Panthera pardus japonensis*) in China ([Laguardia, Kamler et al., 2015](#)).

153 [Insert Fig.1.](#)

154

3.2 Identification of core wild areas

155 The principal components of any wildland network are the core wilderness areas. In
156 previous studies, there are usually two methods for identifying wilderness areas, Boolean
157 overlay (McCloskey and Spalding, 1989; Cao, Carver et al., 2019) and weighted linear
158 combination (Carver, Comber et al., 2012; Lin, Wu et al. 2016; Allan, Venter et al., 2017;
159 Radford, Senn et al., 2019). Although the wilderness areas identified by these two methods
160 may overlap, they differ both conceptually and in the final results (Cao, Carver et al., 2019).
161 Such differences will likely cause uncertainty in connectivity modelling. To explore the impact
162 of source selection on wildland network, it is necessary to compare the two methods. In
163 addition, to better understand the relationship between wildland networks and the habitat
164 networks, designated nature reserves are also used as a reference (Belote, Dietz et al., 2016).

165

3.2.1 Boolean wilderness patches

166 Spatial data on national scale wilderness areas in China (Cao, Carver et al., 2019) are
167 extracted using the boundary of the study area. Wilderness patches are defined as areas with
168 natural land cover and containing neither human settlements nor mechanized roads/railways.
169 In addition, 100km² is used as the minimum threshold for patch size, which is in line with the
170 medium-sized wilderness defined in Chinese wilderness maps and Platinum Wilderness areas
171 defined in the European Wilderness Quality Standard and Audit System (Kun, Vancura et al.,
172 2015; Radford, Senn et al., 2019). This size threshold is also comparable to the average size of
173 the nature reserves in the study area.

174

3.2.2 Areas with the highest wilderness quality index

175 A wilderness quality index for China is used, which is a composite indicator reflecting
176 human modification and combining six wilderness quality indicators including biophysical
177 naturalness, population density, remoteness from settlements, remoteness from roads/railways,
178 settlements density and roads/railways density (Cao, Carver et al., 2019). Here we identify the
179 top 10% areas with the highest wilderness quality in the study region using the tool of *slice by*
180 *equal area* (Carruthers-Jones, 2013; Radford, Senn et al., 2019), and patches meeting the
181 minimum area threshold of 100km² are selected.

182

3.2.3 Nature reserves protecting habitat for north Chinese leopard

183 The north Chinese leopard is a top carnivore and a key umbrella and flagship species in
184 the study region and is facing severe challenges in reduced range through habitat fragmentation
185 (Laguardia, Kamler et al., 2015). To the best of our knowledge, GPS wildlife tracking has not
186 been used to study the north Chinese leopard movement ecology in this region, so the leopard
187 movement data is not available at this stage. While there are several protected areas have
188 conducted wildlife survey using the camera trap technology, it is therefore reasonable to choose
189 the north Chinese leopard's habitat reserves as source patches in connectivity modelling as a
190 comparison with the wildland network. Data on nature reserves were downloaded from the
191 World Database of Protected Areas (WDPA), and those reserves that north Chinese leopard

192 inhabit are selected as the source patches according to the comprehensive information from a
 193 range of sources including official information provided by the nature reserves, peer-reviewed
 194 published literature and camera trap records (Laguardia, Kamler et al. 2015; Song, 2016),
 195 which is the best available data we could collect (see Table S1). To minimize the uncertainty
 196 of the data, experts from the Chinese Felid Conservation Alliance, who are familiar with the
 197 current status of the north Chinese leopard population in this region, were consulted to verify
 198 the collected information.

199 3.3 Creation of resistance surfaces

200 In naturalness-based models, resistance values are usually estimated based on human
 201 footprint or similar indexes (Leu, Hanser et al., 2008; Theobald, 2010; Theobald, Reed et al.,
 202 2012). The sensitivity of wildlife to human disturbance implies that the higher the intensity of
 203 human activity, the higher the degree of resistance for species migration. Using the degree of
 204 human modification to estimate the resistance value is therefore deemed a reasonable approach
 205 (Hand, Cushman et al., 2014; Zeller, McGarigal et al., 2014; Belote, Dietz et al., 2016; Correa
 206 Ayram, Mendoza et al., 2017). A human modification map (Belote, Dietz et al., 2017), a human
 207 footprint index (Correa Ayram, Mendoza et al., 2017) or a wilderness quality index (Theobald,
 208 Reed et al., 2012; Krosby, Breckheimer et al., 2015; Belote, Dietz et al., 2016) could be used
 209 to create the resistance surface.

210 However, simply using the reciprocal of the wilderness as the resistance value may have
 211 uncertainties described below, and it is necessary to further optimize the resistance surface. The
 212 discussion of resistance values in the habitat network modelling literature is useful here. Many
 213 previous studies have simply equated resistance to the inverse of habitat suitability, but some
 214 research has questioned this hypothesis because species are usually more tolerant of landscapes
 215 in movement corridors compared with the core habitats (Beier, Majka et al., 2008). Based on
 216 the analysis of actual species movement data, several studies have shown that there is a negative
 217 exponential relationship between the resistance value of heterogeneous landscapes and the
 218 habitat suitability, rather than a simple negative linear relationship (Trainor, Walters et al., 2013;
 219 Mateo-Sanchez, Balkenhol et al., 2015; Keeley, Beier et al., 2016). According to this,
 220 wilderness-dependent species may not have the same requirements for the wildland corridors
 221 as the core wild areas, so it is necessary to explore the use of negative exponential
 222 transformations when creating resistance surfaces.

223 We use multiple transformations to determine resistance values as the basis for sensitivity
 224 analysis and generation of multiple scenarios (Belote, Dietz et al., 2016; Zeller, Jennings et al.,
 225 2018). We extract the original wilderness quality index data for the study area, which can
 226 comprehensively reflect the degree of human impact on natural habitats (Cao, Carver et al.,
 227 2019). The higher the wilderness quality index, the lower the degree of human impact and the
 228 lower the resistance to species migration. The data are then rescaled using equation (1):

$$229 \quad wqi_std = \frac{\text{Max}(wqi) - wqi}{\text{Max}(wqi) - \text{Min}(wqi)} \quad (1)$$

230 where wqi is the original wilderness quality index extracted for the study area, wqi_std refers

231 to the standardized wilderness quality index.

232 Four resistance surfaces are obtained by applying different transformation functions. The
 233 first is a negative linear transformation using [equation \(2\)](#). The second, third and fourth are
 234 negative exponential transformations, using the formula proposed by Keeley et al. (see
 235 [equation 3](#))

$$236 \quad R = 100 - 99 \times (wqi_std) \quad (2)$$

$$237 \quad R = 100 - 99 \times \frac{1 - e^{-c \times H}}{1 - e^{-c}} \quad (3)$$

238 where R is the resistance value, H is the habitat suitability, and parameter c determines the
 239 curve shape of the function (here $c = 1$, $c = 4$ and $c = 8$ are used respectively) ([Keeley, Beier et](#)
 240 [al., 2016](#); [Keeley, Beier et al., 2017](#)).

241 The above four transformation curves are shown in [Figure S1](#). Among them, the negative
 242 exponential transformation strengthens the difference between the resistance values in areas
 243 with greater human influence and those in lower areas. After transformation, the final resistance
 244 value ranges from 1 to 100, which is suitable for further calculation in Linkage Mapper. The
 245 area with a value of 1 has the lowest resistance value, while the area with a value of 100 has
 246 the highest resistance value.

247 **3.4 Creation of ecological corridors under different** 248 **scenarios**

249 After the source and resistance values are determined, the ecological corridors between
 250 core patches are created based on the minimum resistance model using the Linkage Pathways
 251 Tool in Linkage Mapper ([Adriaensen, Chardon et al., 2003](#)). A total of 12 types of ecological
 252 networks are obtained using different types of core patches and different resistance surfaces
 253 (see [Table 1](#)). Groups A and B are wildland networks, while Group C is the habitat network for
 254 north Chinese leopards. Differences between these 12 networks are further analyzed.
 255 [Insert Table 1.](#)

256 **3.5 Identification of pinch-points in least-cost corridors**

257 To identify key areas for wilderness protection and rewilding/ecological restoration,
 258 especially areas to protect and enhance as wildlife corridors, key bottlenecks or pinch-points
 259 are identified in the resulting corridors using Circuitscape and the Pinchpoint Mapper tool in
 260 Linkage Mapper ([McRae, Dickson et al., 2008](#); [Dickson, Albano et al., 2019](#); [Li, Weckworth](#)
 261 [et al., 2020](#)). Areas with high accumulated current density are identified as the key pinch-points,
 262 which significantly affect the connectivity in the network.

263 4 Results

264 4.1 Core wild areas

265 The three types (Group A, B and C) of core wild areas are located in the mountainous
266 regions where settlements and agriculture are minimal. The basic information is shown in [Table](#)
267 [S2](#). Although many overlaps exist among three types of core areas, there are also significant
268 differences, as shown in [Figure S2](#).

269 4.2 Resistance surfaces

270 The four resistance surfaces are shown in [Figure S3](#). Areas with high resistance values are
271 mainly located in cities, towns and farmlands in the basin region, while areas with low
272 resistance values are mainly located in mountainous regions. The overall pattern of the four
273 resistance surfaces are similar but differ in their local scale details. The type one resistance
274 (negative linear transformation) and the type two resistance (negative transformation when $c =$
275 1) are quite similar, while the type three (negative transformation when $c = 4$) and four
276 (negative transformation when $c = 8$) resistance appear significantly different from the first two.
277 The higher the c value, the smaller the resistance value of each pixel will be. When $c = 8$, the
278 difference of the resistance values is the largest between areas with the highest wilderness
279 quality and those with the lowest wilderness quality.

280 4.3 Least-cost corridors

281 Twelve ecological networks are obtained by using combinations of three types of core
282 patches and four resistance surfaces, which are shown in [Figure 2](#). There are many identical
283 corridors between the A, B, and C ecological networks, indicating that some key corridors can
284 be identified by multiple methods and as such may be regarded as robust solutions. At the same
285 time, there are some obvious differences between these groups. For example, group A network
286 lacks corridors distributed in the southeast part of the study area, while the group C network
287 lacks corridors distributed in the north of the study area. Group B network contains the most
288 corridors and covers Group A and C very well. This shows that choosing different identification
289 methods for core wild areas has a significant impact on the spatial distribution of resulting
290 corridors. In group A networks, A1, A2, A3, and A4 are similar, but there are significant
291 differences at the local scale. The obvious difference between the A4 network and the other
292 three is that the corridors are more inclined to be straight, and less curved and tortuous, which
293 may not be in line with reality. This may be caused by the large c value, which has led to the
294 oversimplification of the corridor shape. This shows that the choice of resistance value has a
295 significant impact on the wildland network as well.
296 [Insert Fig.2.](#)

4.4 Pinch-points in resulting corridors

Figure 3 shows a cumulative current density map taking the B3 network as an example, indicating the probability of species moving through in the least-cost corridors. B3 network is chosen as it is the most comprehensive network and covers networks A and C very well. The red areas are with very high cumulative current density value and thus identified as pinch-points. To maintain or improve connectivity, ecological protection and restoration (e.g. building eco-bridges across major road barriers, promoting compatible land uses, reducing human impacts, rewilding landscapes) should be carried out in these pinch-points. To guide the conservation actions and highlight areas requiring urgent ecological protection and restoration, basic information for the 34 pinch-points is provided in Table S3, including the location of pinch-points and main barriers within them. Detailed maps for each pinch-point are shown in Fig. S4.

Insert Fig.3.

5 Discussion

5.1 Effects of core areas and resistance selection in wildland networks

This study shows that in developing robust wildland networks, the selection of core wild areas and the resistance values can have significant impacts on the resulting networks and so must be carefully determined using scenario analysis. In particular:

(1) In the selection of core wild areas, there are usually two methods. One is to identify discrete wilderness patches from the Boolean wilderness map, and the other is to select areas with the highest wilderness quality index from the wilderness continuum map (Cao et al., 2019). As the source areas obtained by these two methods may be different, the resulting wildland network may be different as well, which can be seen from the comparison between scenarios A, B and C.

(2) In the creation of resistance surfaces, the use of negative exponential transformation may better reflect the movement requirements of the species, as stated in previous studies. However, when the value of the parameter c is large, the corridor shape may be oversimplified.

5.2 Comparison of wildland networks to habitat networks

Wildland networks can be seen as efficient and effective alternatives to habitat networks. It can be seen that the wildland networks (scenario B) mostly cover the north Chinese leopards' habitats network (scenario C). This is because suitable habitats for the leopards are mostly located in wilderness areas, so building a wildland network can effectively cover the habitats network. This may also be true for other wilderness-dependent species, especially the large

331 carnivores. Although wildland networks could not replace habitat networks, they could be used
332 as an efficient and effective alternative, especially when the species data are lacking, or a rapid
333 assessment is needed. This is because habitat networks can better reflect the movement needs
334 of different species, yet modelling these can lead to higher computing costs and research
335 investment (e.g. fieldwork and genetics). While creating wildland networks is more efficient
336 because data on human impact is relatively easy to obtain.

337 From the perspectives of rewilding and restoration, wildland networks can show the
338 direction in which habitat networks can expand in the future. The network of Group C is
339 concentrated in the south of the study area, while the network of Group B involves not only the
340 south, but also the northern part of the study area. The Xiaowutai National Nature Reserve in
341 the northern part of the study area is covered by Group B but not covered by Group C, which
342 is a historical habitat for the leopards and has the potential to be rewilded by building better
343 connections with other core habitats. This shows that the wildland network can cover some
344 potential habitats where key species are not currently present but were there before and so helps
345 identify areas still worth protecting and developing as potential target areas for rewilding and
346 ecological restoration.

347 **5.3 A methodological framework linking wilderness** 348 **mapping and connectivity modelling**

349 This study develops an ecological connectivity model that links wilderness mapping and
350 connectivity modelling to create wildland networks that are different from the protected-area
351 networks and the focal-species-based habitat networks. In addition, compared to previous
352 studies on models based on landscape naturalness, we differentiated two types of core wild
353 areas (based on [Cao et al., 2019](#)), applied negative exponential transformations in the creation
354 of resistance surfaces (based on [Keeley et al., 2017](#)) and identified pinch-points in wildland
355 networks (based on [McRae et al., 2016](#)).

356 The framework is developed outlining the steps required for wildland network planning,
357 as shown in [Figure 4](#). Boolean and wilderness continuum maps are used as input data for
358 connectivity modelling. Through the application of the cost-distance model and circuit model,
359 the ecological corridors between core wild areas can be identified, as well as pinch-points in
360 the resulting corridors which are critical to landscape connectivity.

361 **Insert Fig.4.**

362 There are several potential advantages to building such a wildland network. First, the
363 wildland network is mainly based on human impact data. The difficulty of data acquisition and
364 calculation is lower than that of traditional species-based habitat networks, so it is much easier
365 to be modelled and applied. Second, in many areas where there is no basic species survey at
366 all, where modelling habitat networks is impossible, the wildland network could be used as an
367 effective alternative method. Third, the wildland network connects the two knowledge domains
368 of wilderness mapping and connectivity modelling, which can greatly enhance the application
369 of wilderness maps. Fourth, as protecting core wilderness and strengthening the connectivity

370 between them are the focus of rewilding, which has become an important strategy for nature
371 conservation recently (Foreman, 2004; Lorimer, Sandom et al., 2015; Liang, He et al., 2018),
372 the proposed methodology may be widely used for rewilding practices across different regions.

373 **5.4 Recommendations for conservation action**

374 Wildland network planning is important for conservation for several reasons. First, for the
375 identified wilderness areas and ecological corridors, measures including designating,
376 upgrading, expanding, and strengthening management of protected areas should be considered.
377 Second, for connectivity conservation, in areas identified as pinch-points, consideration should
378 be given to the establishment of built infrastructure such as wildlife bridges or underpasses,
379 especially at the intersections with major highways. Third, for areas in corridors that are not
380 suitable for establishing protected areas, sustainable management of land use, and ecological
381 restoration should be considered to enhance connectivity.

382 **5.5 Limitations and future research**

383 (1) Identification of core wild areas. First, although we identified core wilderness areas
384 by segmenting wilderness continuum, multiple thresholds (e.g., 1%, 5%, 10%, 20%) could be
385 used, which also provides flexibility in defining core wild areas and the impact of these
386 thresholds should be further explored. Second, it may be helpful to combine the two types of
387 core wild areas so that both types of high-value lands are included simultaneously to create a
388 more comprehensive network. Similarly, it is worth exploring the integration of protected-areas
389 networks, habitat networks and wildland networks. Third, previous studies have shown that
390 historic and prehistoric human-driven extinctions have reshaped global mammal diversity
391 patterns (Faurby & Svenning, 2015), and global human footprint is not always strongly
392 correlated with mammal community intactness (Belote, Faurby et al., 2020). These indicate
393 that the relationship between human footprint and species richness/species intactness is
394 complicated, which may vary across scales, regions and taxa. Thus, this issue should be
395 recognized and further addressed in the selection of wilderness patches at finer scales, by
396 incorporating on-the-ground species data. Fourth, as the majority of the world's terrestrial large
397 carnivores have undergone substantial range contractions (Wolf & Ripple, 2017; Wolf & Ripple,
398 2018), target areas for rewilding ecological integrity should also be considered in defining
399 potential core wild areas.

400 (2) Creation of resistance surfaces. First, human impact data itself may cause uncertainties.
401 For example, the resolution of the wilderness data, and the weights used in combining wildness
402 indicators, may also affect the wildland networks by affecting the resistance values. Second,
403 the latest studies point out that it is better to discern two different sources of resistance, namely
404 movement behavior and mortality (Fletcher et al., 2019). Our study mainly focused on the
405 resistance to movement while not fully considering the mortality risk, which could be further
406 refined by incorporating mortality data (Marx et al., 2020).

407 (3) Applicability to different regions. Connectivity modelling should be context-specific

408 by considering the overall human modification conditions. It may be useful to reference the
409 “*Implementation framework of three global conditions for biodiversity conservation and*
410 *sustainable use*” which was developed for the post-2020 biodiversity framework (Locke, Ellis
411 et al., 2019). In this framework, all landscapes are divided into three categories based on human
412 footprint and land use data, including C1 (Cities and Farms), C2 (Shared Lands), and C3 (Large
413 Wild Areas). To take this a step further, condition-specific connectivity targets for the three
414 conditions were proposed (Belote, Beier et al., 2020). This illustrates that connectivity
415 conservation is important in all three conditions but have different targets and indicators. It is
416 therefore necessary to explore the applicability of the proposed wildland network modelling
417 approach in the three conditions as wilderness patches exist in all three conditions (Cao et al.,
418 2019). In addition, it is valuable to further explore the relationship between wildland networks,
419 habitat networks and protected-area networks, which may vary across regions, species and
420 protected areas categories.

421 (4) Validation and ground-truthing. Like most regional-scale connectivity modelling
422 projects which lack of evaluation or ground-truthing at the local level (Osipova et al., 2019),
423 the wildland network needs to be validated in the future using local knowledge and on-the-
424 ground movement data (McClure et al., 2016). In this process, a design charrette, which is a
425 commonly used approach in landscape architecture and urban planning, could also be applied
426 to review the accuracy of the modelling results which offers the benefits of improving accuracy
427 and enhancing the potential for implementation (Kilbane et al., 2019).

428 **6 Conclusions**

429 This research proposes a methodological framework that links wilderness mapping and
430 connectivity modelling for developing a wildland network. Within this framework, wilderness
431 areas are used as source patches, and resistance surfaces are created based on the wilderness
432 continuum map. By using cost-distance and circuit models, ecological corridors between core
433 wild areas are identified, as well as the pinch-points in the resulting corridors. As the source
434 and resistance selection have significant impacts on the resulting network, scenario analysis
435 may be required according to the research purpose and application requirements. This
436 methodology could be extremely useful in areas where species data are lacking and where the
437 wilderness maps have already been created. The method proposed in this study has important
438 implications for connectivity conservation and spatial planning at regional scales, which could
439 be modified and applied to other fragmented landscapes worldwide to conserve and restore
440 connectivity.

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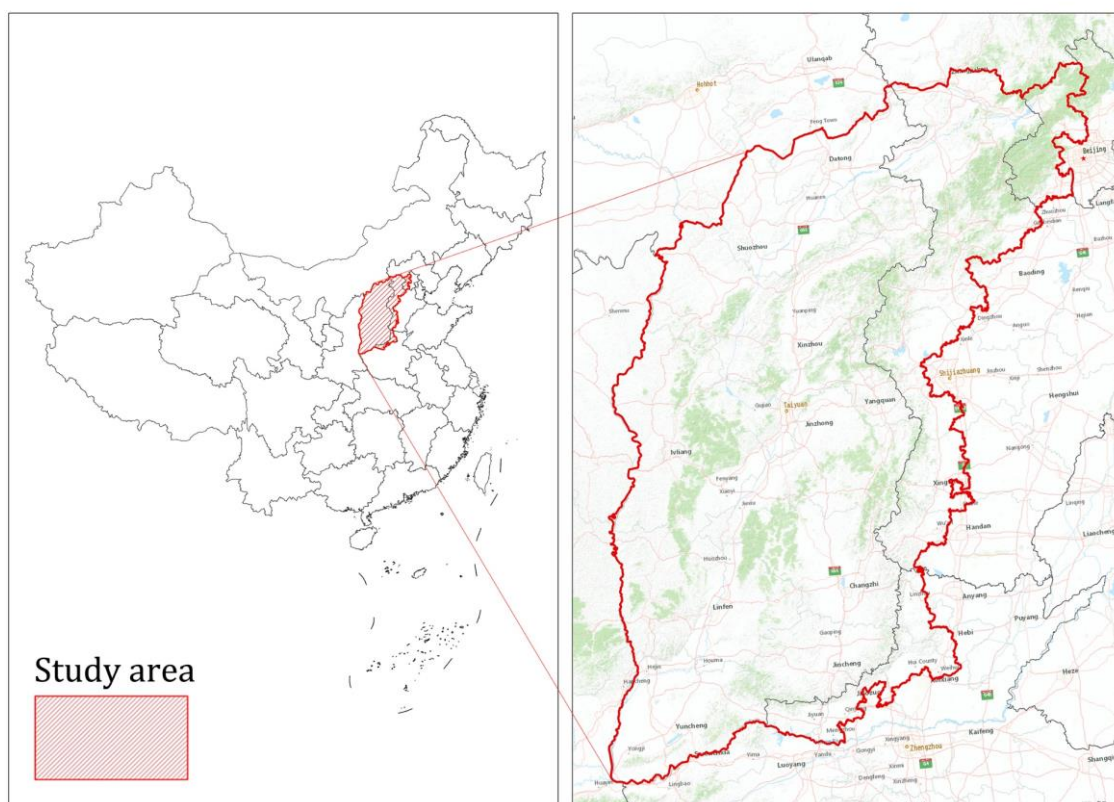
List of tables

Table 1. The code of 12 networks (A1-A4, B1-B4, C1-C4). Core patches type A, B, C represent Boolean wilderness patches, areas with highest wilderness quality index, and nature reserves protecting habitat for leopard, respectively. Resistance type 1 represents negative linear transformation and resistance type 2,3,4 represent negative exponential transformation when $c=1,4,8$ respectively.

	Resistance type 1	Resistance type 2	Resistance type 3	Resistance type 4
Core patches type A	A1	A2	A3	A4
Core patches type B	B1	B2	B3	B4
Core patches type C	C1	C2	C3	C4

Figures

Fig.1. Location of the study area.



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Fig.2. Least-cost corridors between the core patches (Scenario A, B and C).

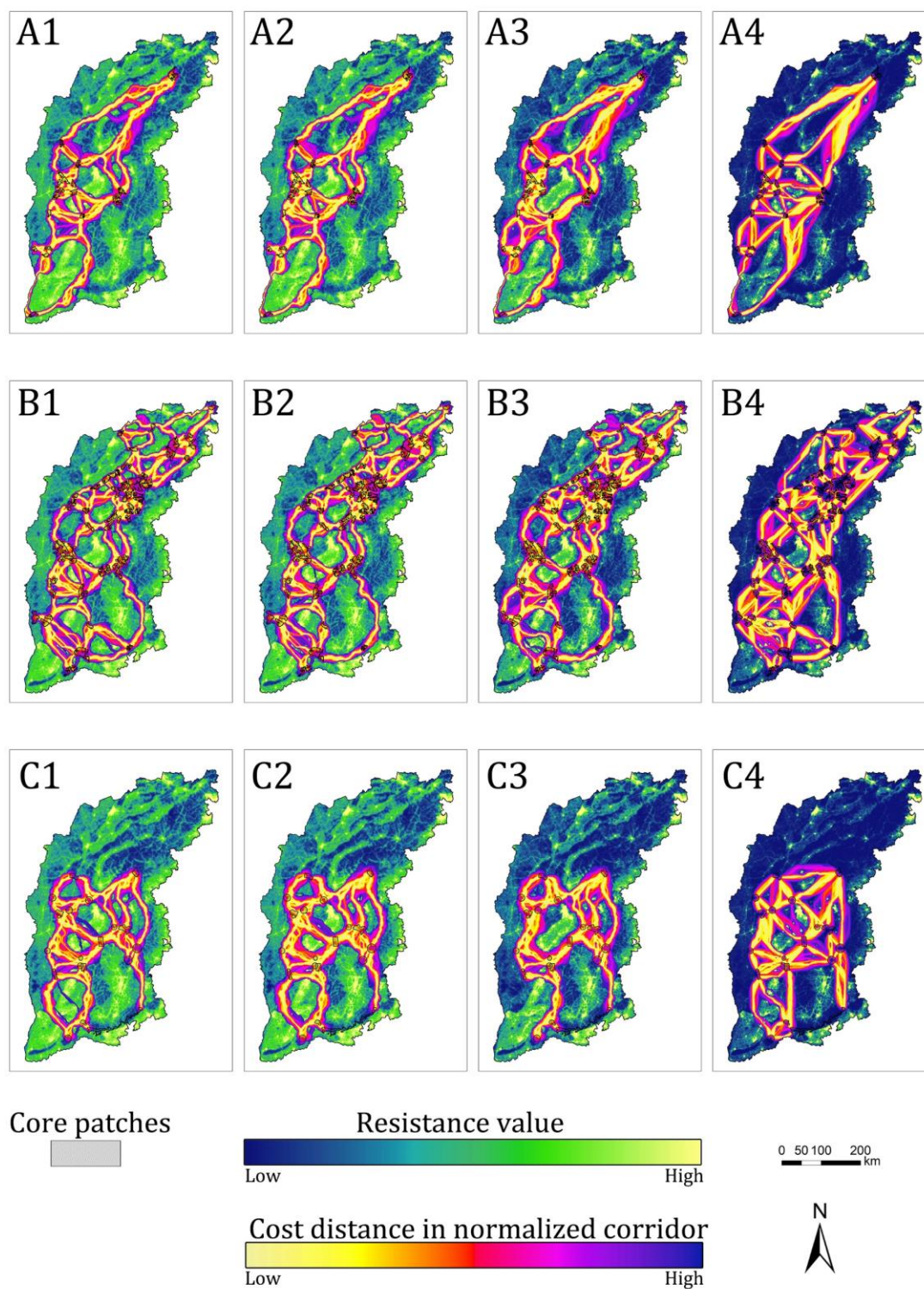


Fig.3. Pinch-points in resulting corridors (scenario B3). Pinch-points are areas with high cumulative current values and most important to connectivity conservation and restoration.

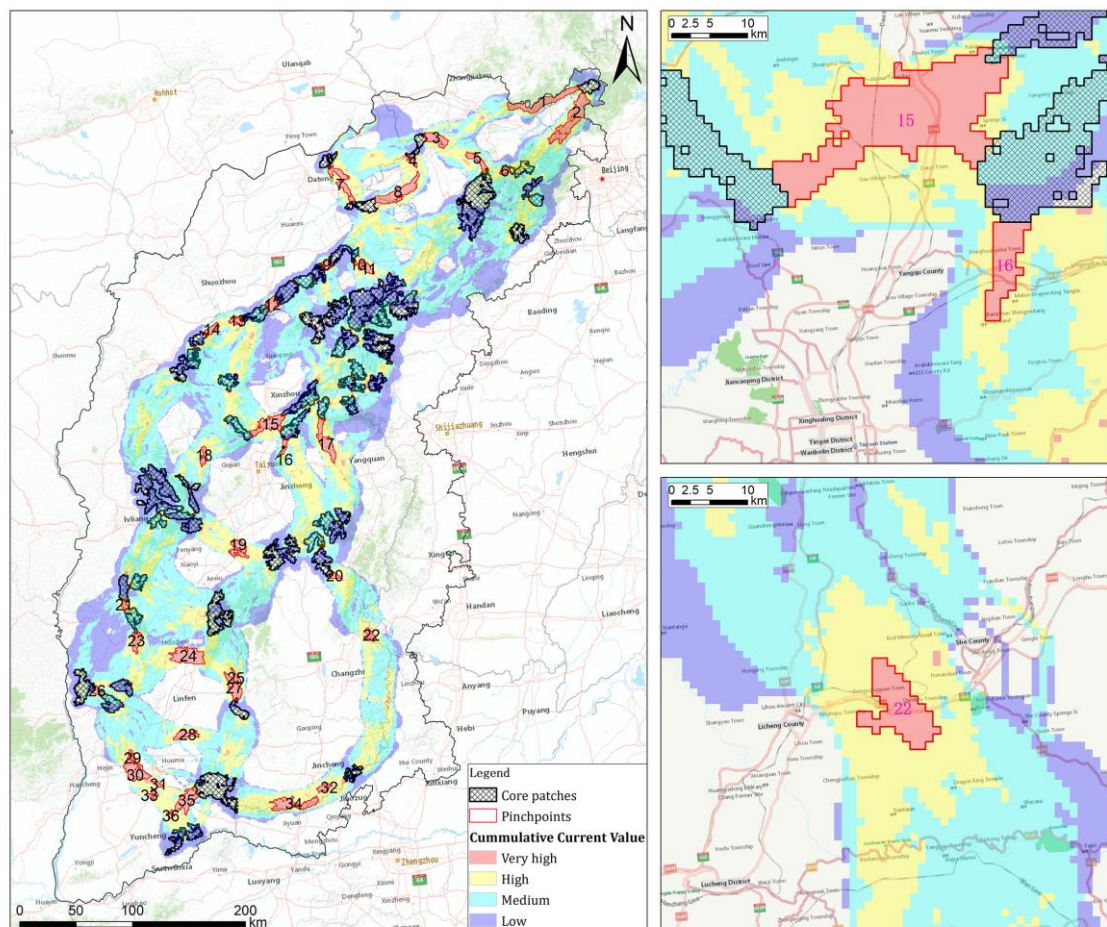
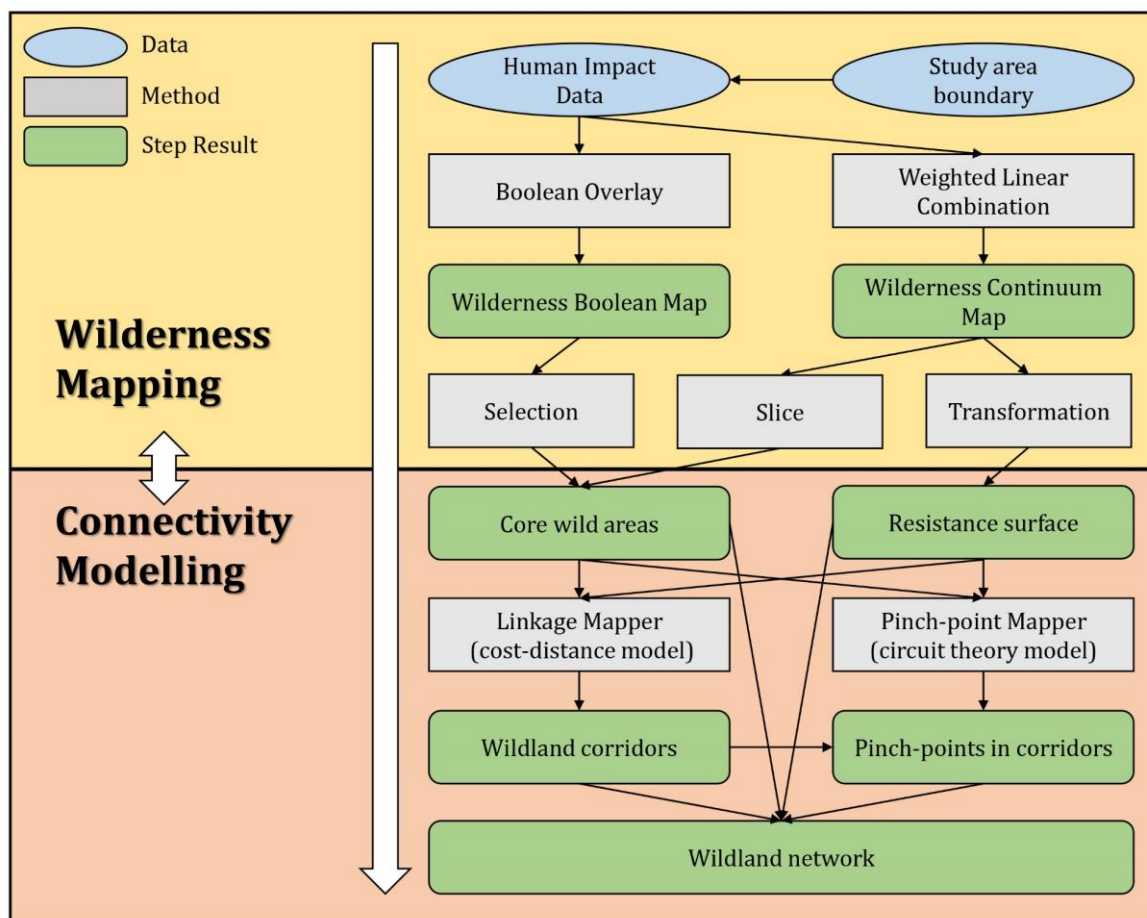


Fig.4. A methodological framework for wildland network planning, which links wilderness mapping and connectivity modelling.



Appendix A. Supplementary Data

Table S1. Basic information of nature reserves that north Chinese leopards inhabit.

Number	Nature reserve	Region	Area (Hectare)	Level	Province	Year designated
1	Tuoliang	Taihang	21312	National	Hebei	2001
2	Meng Xinnao	Mountains	39047	Provincial	Shanxi	2002
3	Zhongyangshan		32671	Provincial	Shanxi	2002
4	Tieqiaoshan	Taiyue	35352	Provincial	Shanxi	2002
5	Bafuiling	Mountains	15267	Provincial	Shanxi	2002
6	Sixiannao		16000	Provincial	Shanxi	2002
7	Mianshan		17827	Provincial	Shanxi	1993
8	Huoshan		17852	Provincial	Shanxi	2002
9	Lingkongshan		10117	National	Shanxi	1993
10	Taikuanhe	Zhongtiao	23947	Provincial	Shanxi	2002
11	Lishan	Mountains	24800	National	Shanxi	1983
12	Taihangshan Macaque	and Wangwu Mountains	56600	National	Henan	1998
13	Luyashan	Lüliang	21453	National	Shanxi	1980
14	Heichashan	Mountains	25741	Provincial	Shanxi	2002
15	Lingjinggou		24920	Provincial	Shanxi	1993
16	Yundingshan		23029	Provincial	Shanxi	2002
17	Panguangou		10466	National	Shanxi	1980
18	Tuanyuanshan		16477	Provincial	Shanxi	2002
19	Wulushan		20617	National	Shanxi	1993

Table S2. Basic information of core wild areas in scenarios A, B and C.

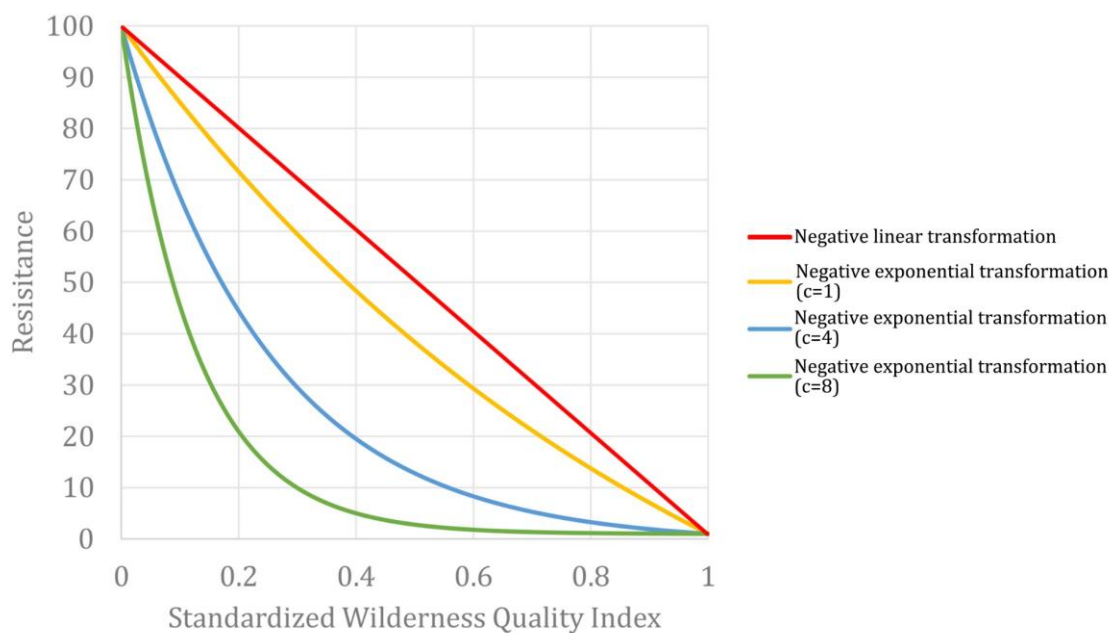
Scenarios	Number of core patches	Total area of core patches (km ²)	Proportion of the study area (%)	Minimum patch size (km ²)	Maximum patch size (km ²)	Average patch size (km ²)	Distribution
A	19	2548	1.2	100	351	134.1	Mainly distributed in the middle of the study area.
B	53	12688	5.9	100	1177	239.4	Distributed throughout the study area.
C	19	4983	2.3	94	811	262.3	Distributed throughout the study area.

Table S3. Basic information for the 34 pinch-points in the resulting corridors.

Code	Location (County or District)	Main barriers in the corridor
1	Yanqing and Huailai	S241 provincial road; S212 provincial road
2	Yanqing and Changping	S323 provincial road; S212 provincial road; G110 national road; G6 highway
3	Huai'an, Xuanhua and Yangyuan	G207 national road; G112 national road
4	Yangyuan	G109 national road
5	Zhuolu	G109 national road
6	Zhuolu	G95 highway; S241 provincial road
7	Datong and Yanggao	S45 highway; G109 national road
8	Yangyuan, Guangling and Yu	S243 provincial road
9	Ying	S205 provincial road
10	Hunyuan	S45 highway; S240 provincial road
11	Hunyuan	S45 highway; S240 provincial road
12	Dai and Shanyin	G55 highway; G208 highway
13	Ningwu	None
14	Ningwu and Shenchi	None
15	Xinfu and Yangqu	G108 national road; G55 highway
16	Yangqu	G5 highway; S314 provincial road
17	Yu and Shouyang	G5 highway; S216 provincial road
18	Loufan and Gujiao	S252 provincial road
19	Qi and Pingyao	Farmlands
20	Zuoquan	None
21	Jiaokou	G209 national road
22	She and Licheng	G22 highway
23	Xi an Pu	S70 highway
24	Fenxi, Huozhou and Hongtong	G5 highway
25	An'ze	None
26	Ji	G209 national road
27	Anz'ze and Gu	G22 national road
28	Xiangfen, Quwo, Yicheng and Fushan	Farmlands
29	Xinjiang	Farmlands; G040 national road; G108 national road
30	Xinjiang and Jishan	Farmlands; G040 national road; G108 national road
31	Wenxi	Farmlands; S75 highway; S236 provincial road
32	Zezhou	None
33	Wenxi	Farmlands; S75 highway; S236 provincial road
34	Zezhou and Yangcheng	S229 provincial road; G207 national road; G55 highway
35	Wenxi, Jiang and Yuanqu	S88 highway; S335 provincial road
36	Wenxi	S88 highway; S335 provincial road

Figure S1

Four functions transforming standardized wilderness quality index into resistance values. These include negative linear transformation and negative exponential transformation (when $c=1, 4$ and 8).



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Figure S2. Core wild areas. In scenario A, core patches are wilderness patches derived from the wilderness Boolean map. In scenario B, core patches are areas with the highest wilderness quality index derived from the wilderness continuum map. In scenario C, core patches are nature reserves that north Chinese leopards inhabit.

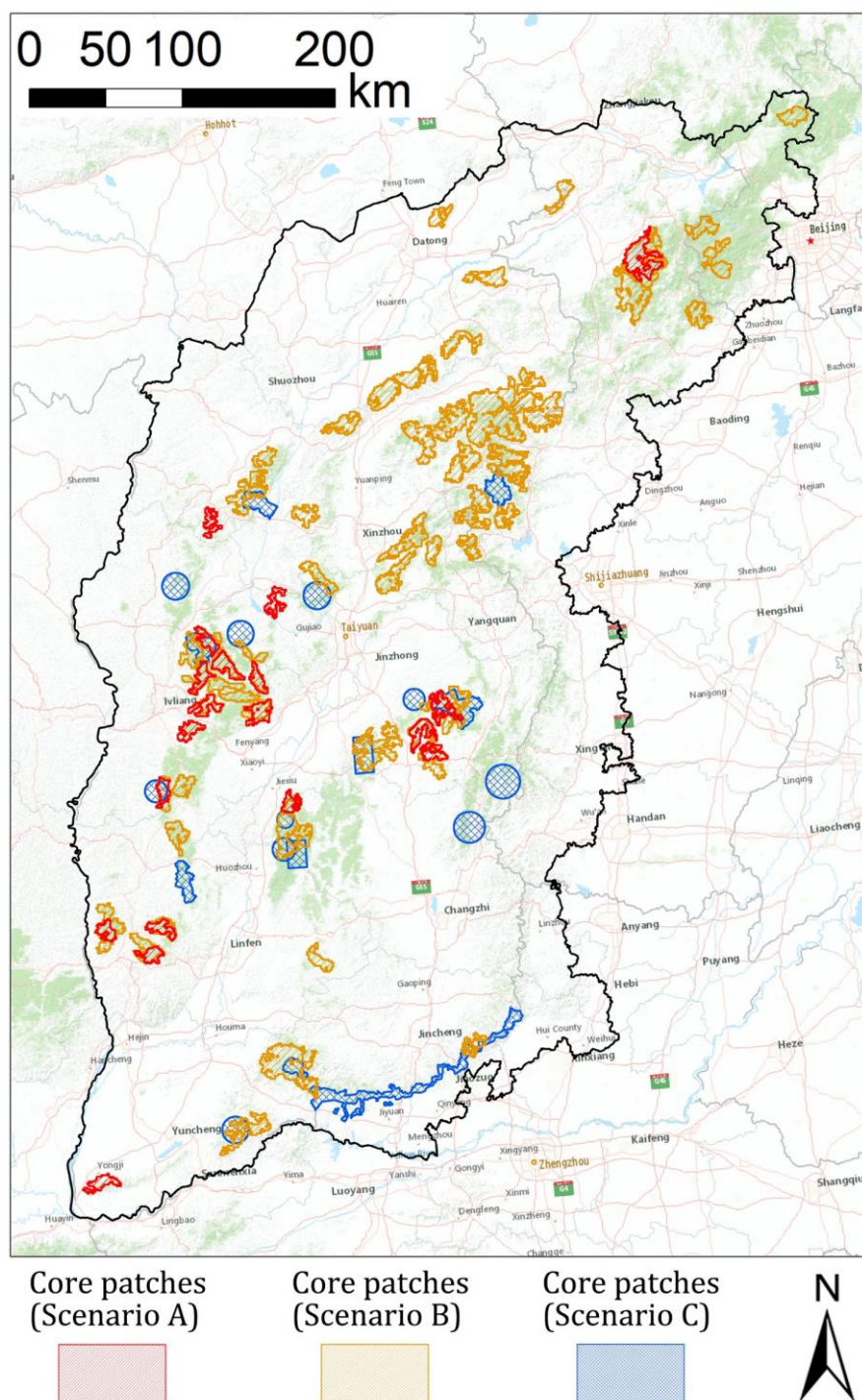


Figure S3.

Resistance surfaces. Resistance values range from 0 (dark blue) to 100 (yellow).

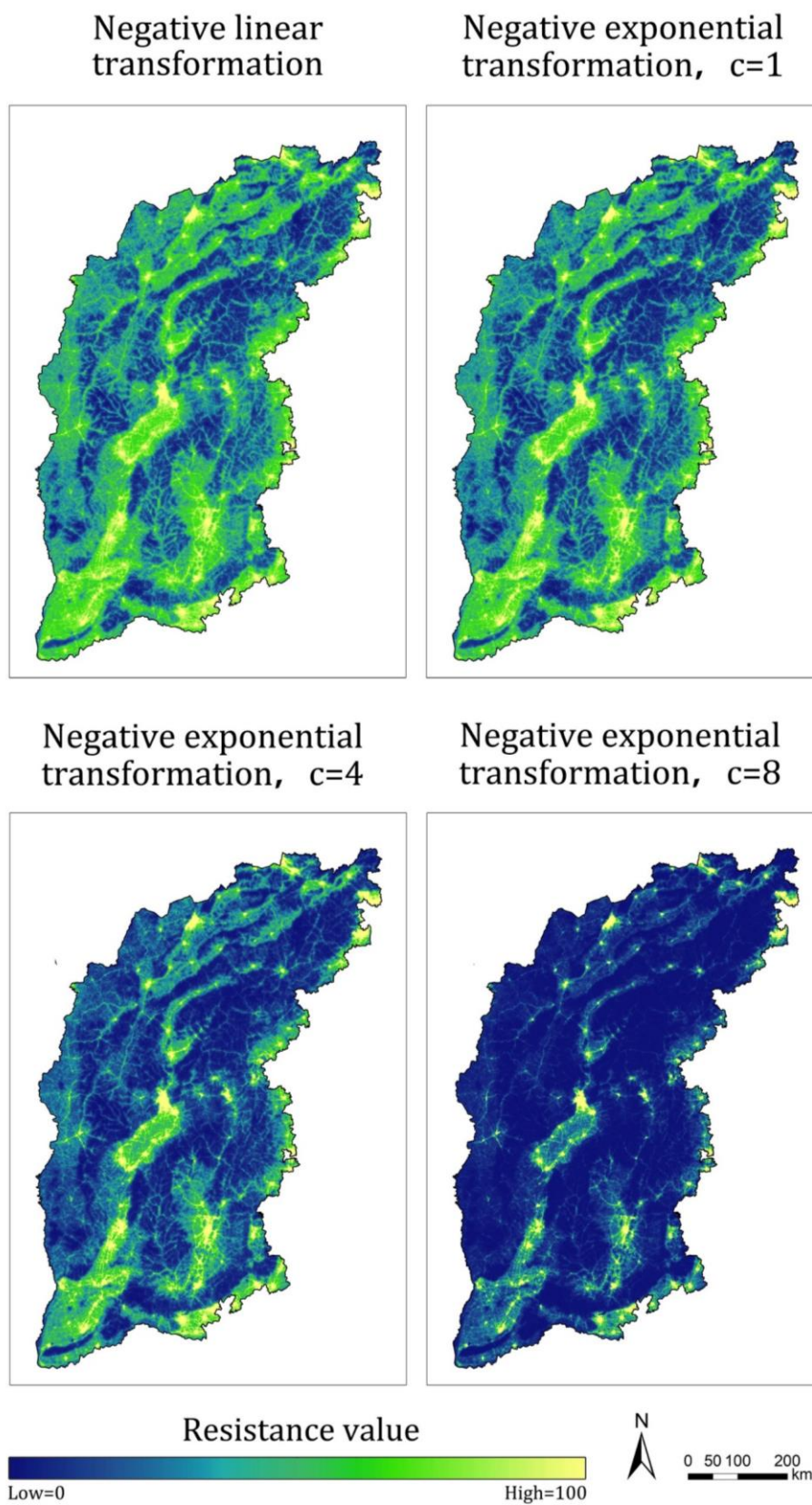
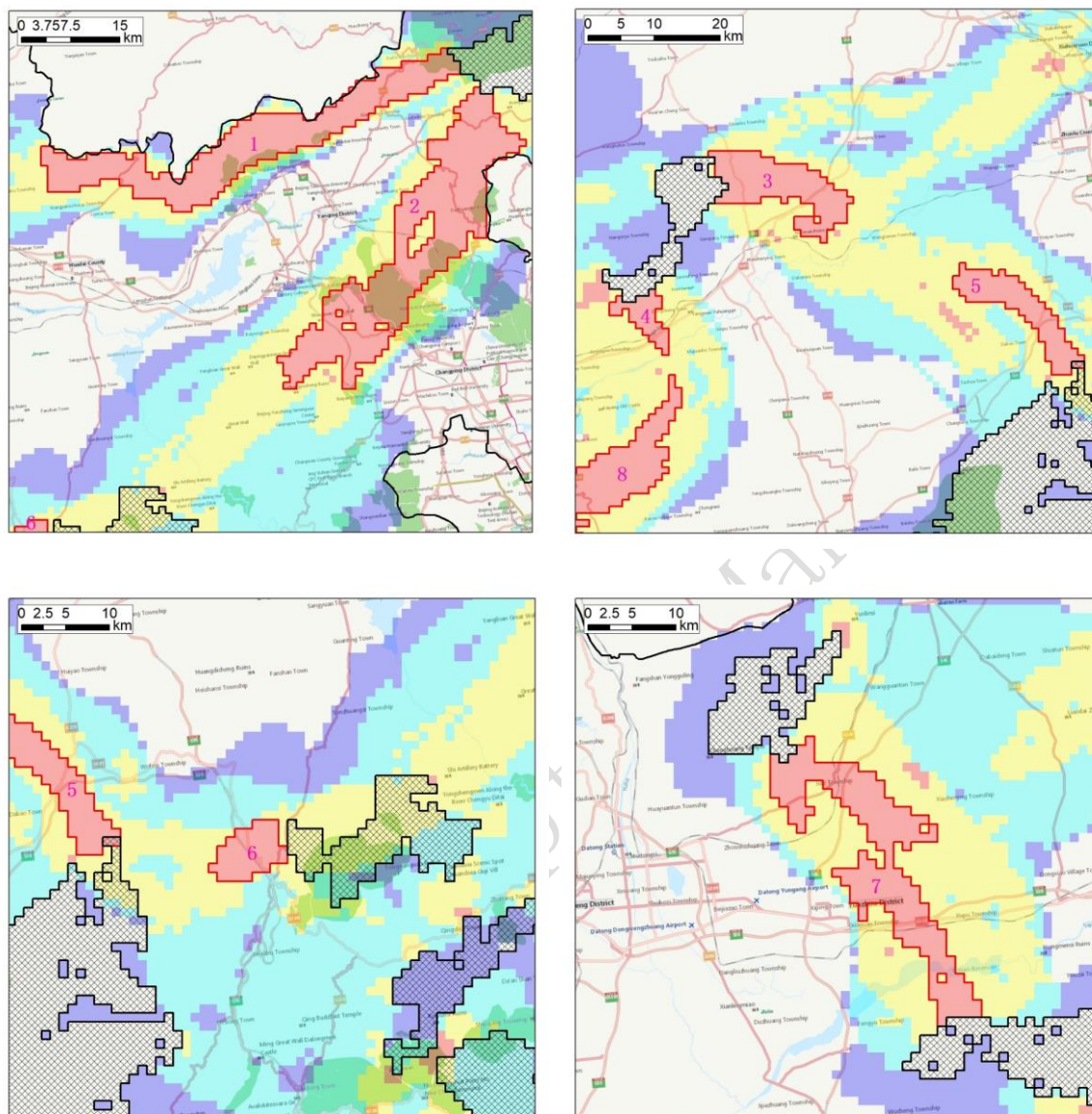
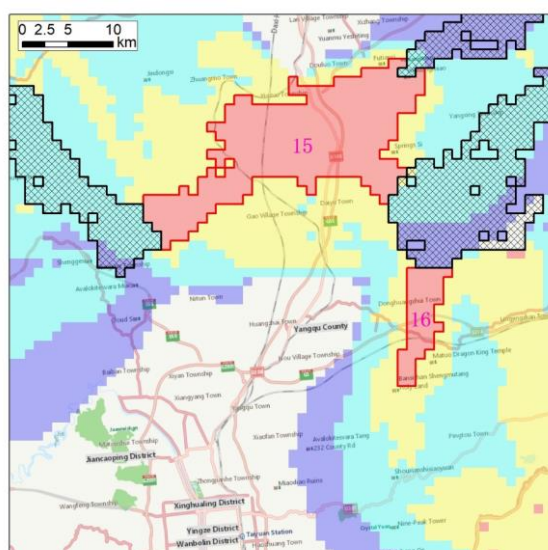
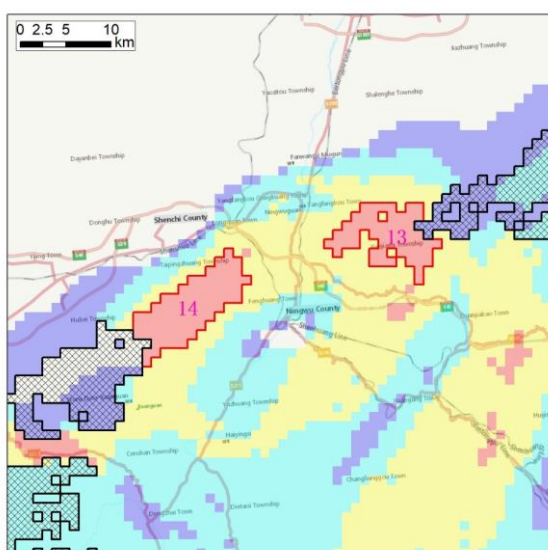
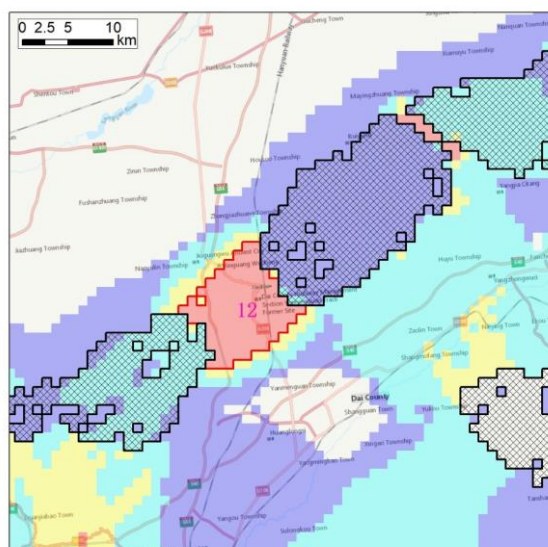
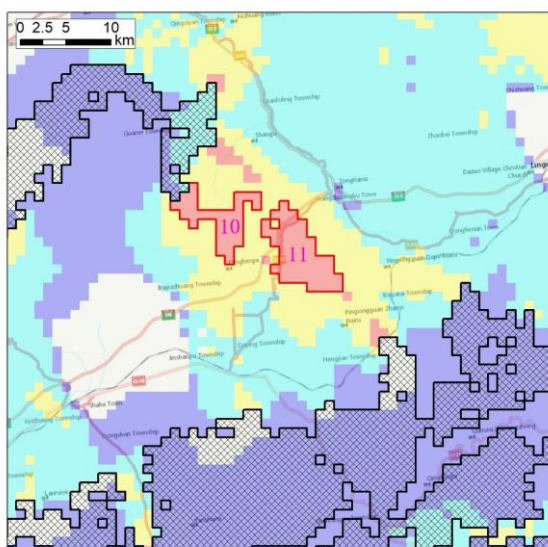
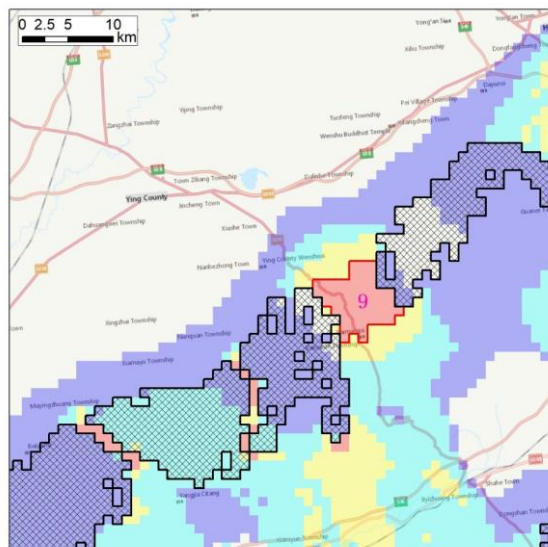
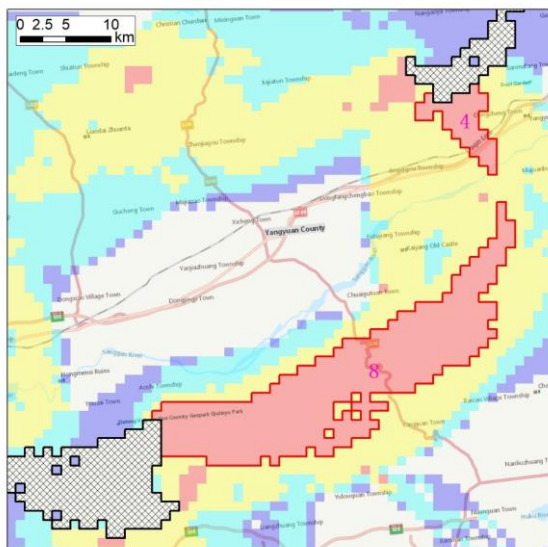
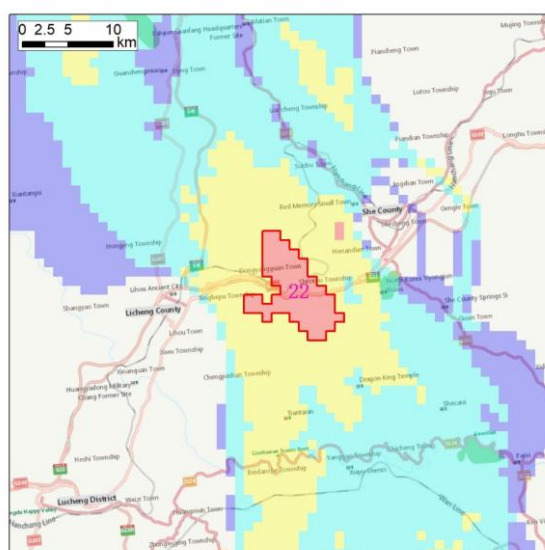
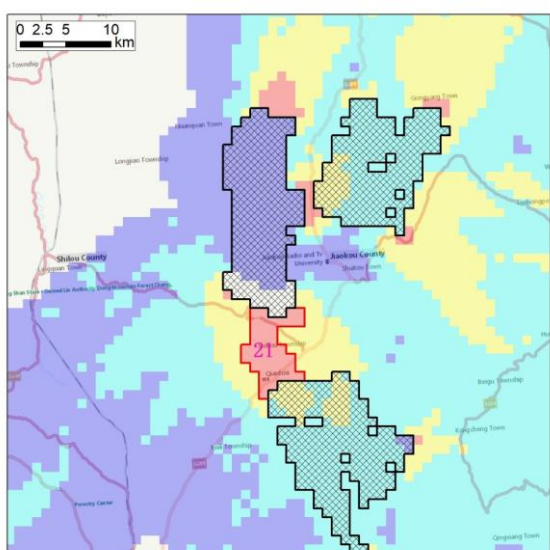
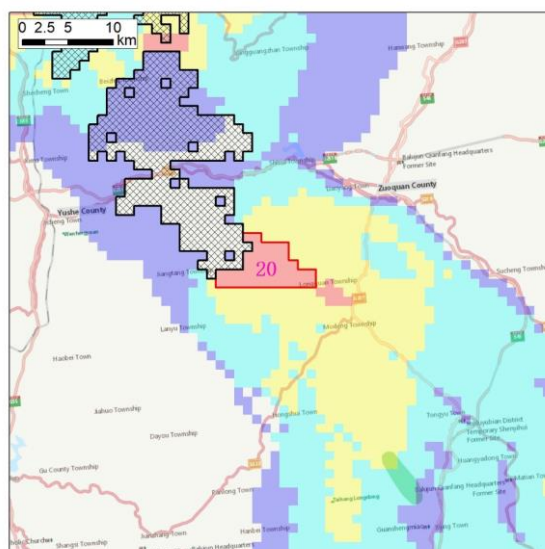
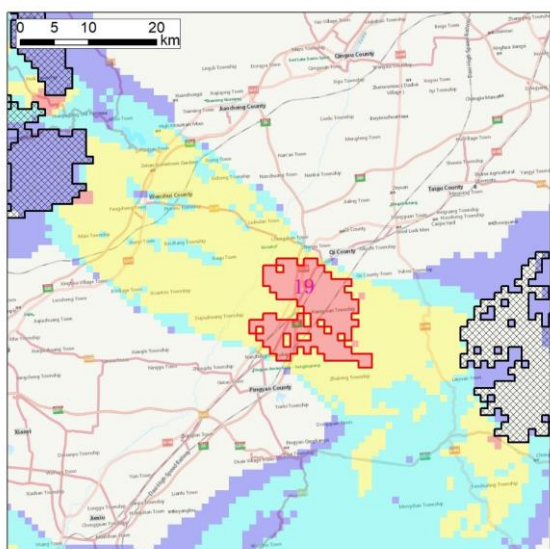
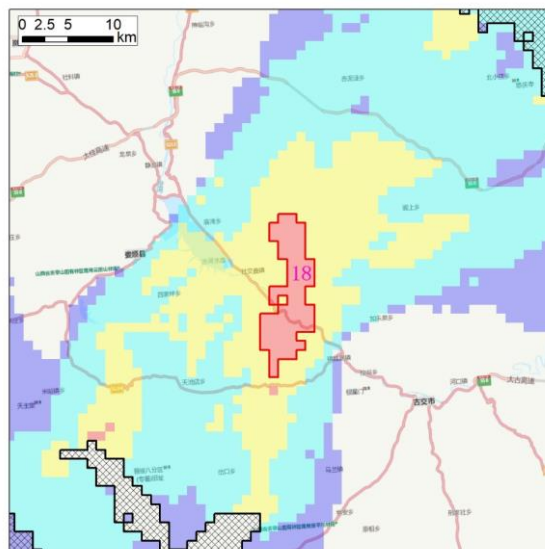
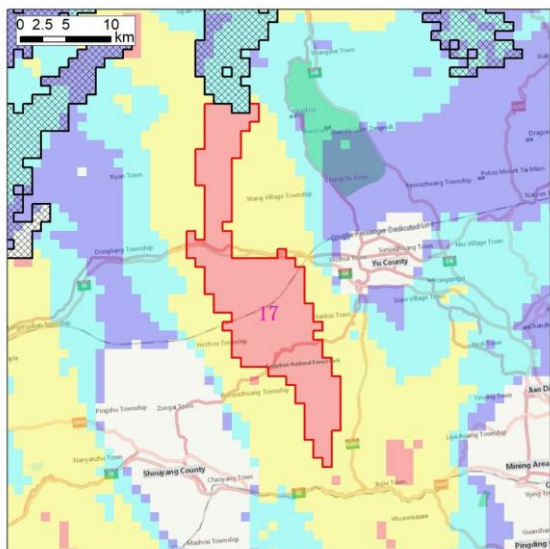
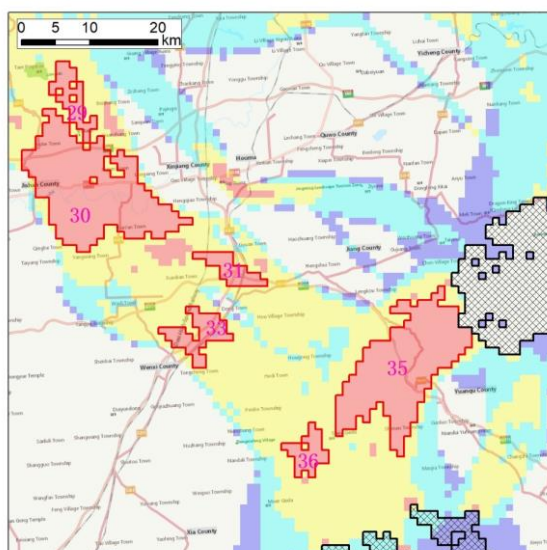
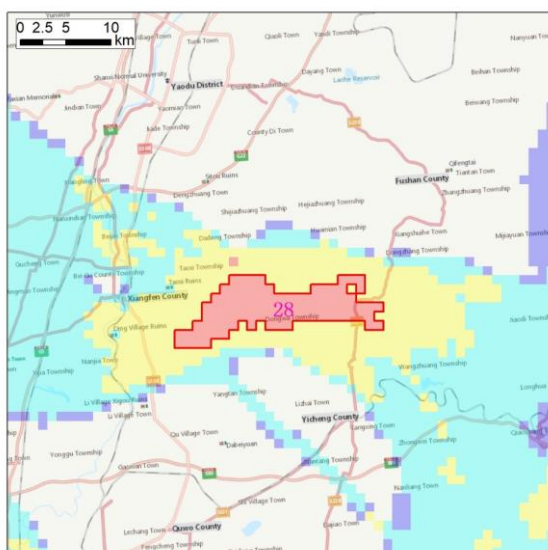
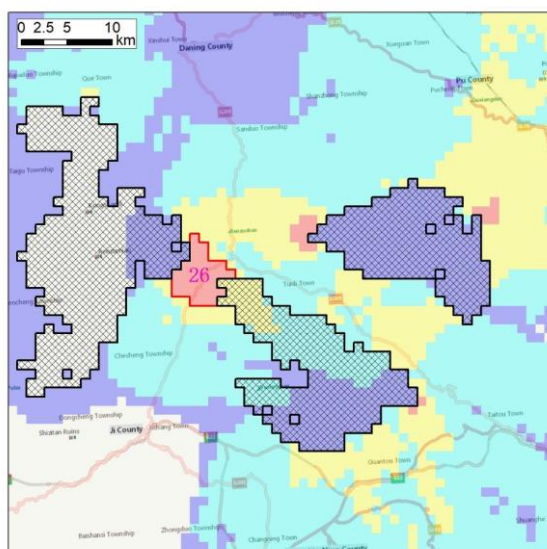
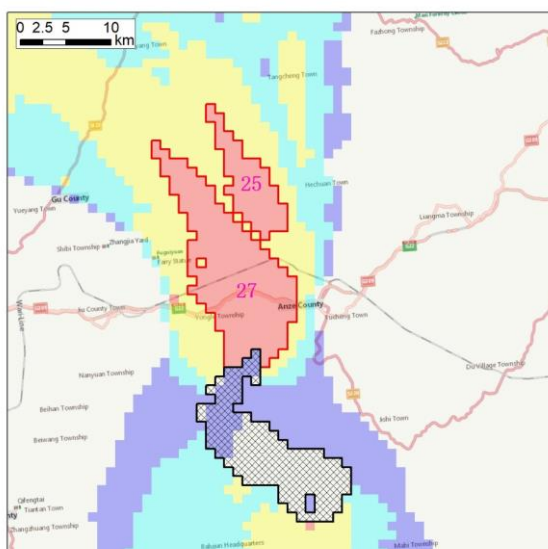
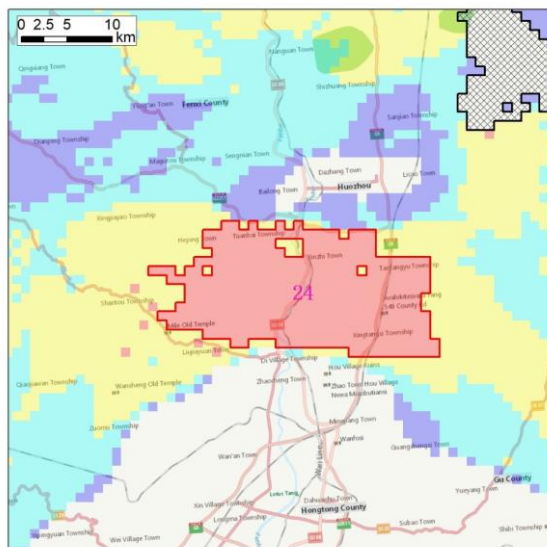
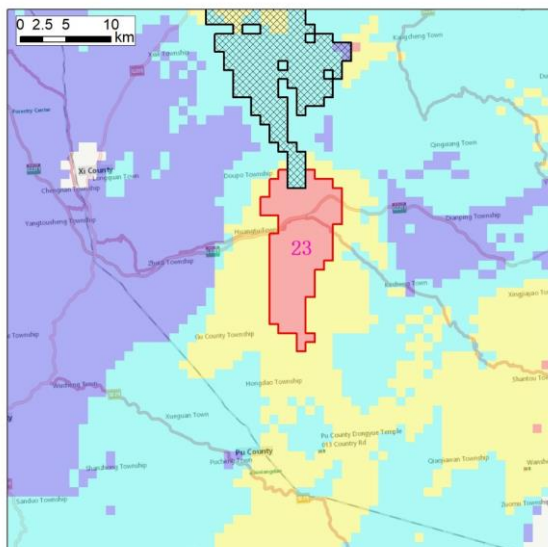


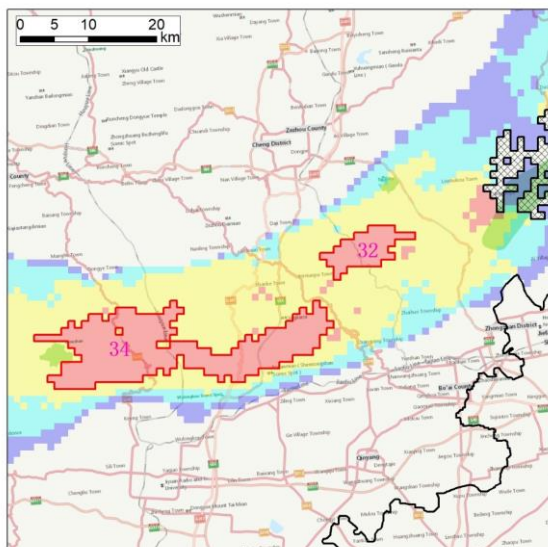
Fig.S4. Pinch-points(red) in resulting corridors highlighting areas requiring ecological protection and restoration.











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