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1.Full title

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

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

Abstract

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

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

1 Introduction

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

Ecological network planning is based largely on landscape-connectivity modelling. Landscape connectivity is usually defined as the degree to which the landscape facilitates or impedes movement among resource patches (Taylor, Fahrig et al., 1993). The most widely used landscape-connectivity model is the least-cost-distance model, which identifies the least-cost paths and least-cost corridors between core areas (Beier, Majka et al., 2008). In corridor design, focal-species-based methods are widely used since species of different taxa may have a degree of spatial overlap such that the requirements of certain species can be selected to represent wider species assemblages. This has proven to work well in certain regions (Breckheimer, Haddad et al., 2014). However, focal-species-based connectivity modelling has limitations. First, the focal species used may not be able to effectively represent other species (Chetkiewicz, Clair et al., 2006), and expert opinions may not necessarily represent the true characteristics of species movement (Pullinger and Johnson 2010). Second, data on habitat requirements and actual movement are available for only a few species, making it difficult to be applied in data-poor regions (Theobald, Reed et al., 2012). Third, it takes much time and investment in modelling multi-species connectivity (Beier, Spencer et al., 2011), making it difficult to be applied at a large scale (Krosby, Breckheimer et al., 2015).

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

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

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

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

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

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

2 Conceptual framework

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

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

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

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

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

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

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

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

3 Materials and methods

3.1 Study area

The study area is the Great Taihang Region (34°34′～40°47′N, 110°14′～116°34′E), which is located in the north China region (shown in Figure 1). The total area of the study region is 214,100 km^2, accounting for 2.2% of China's terrestrial area and covers the entire territory of Shanxi province, as well as some districts and counties in Beijing, Hebei and Henan provinces. The region has a temperate continental climate, with an annual average temperature between 8～13 °C, and annual precipitation between 400～1000mm. The study area is mainly mountainous and contains the most densely distributed population of north Chinese leopard (*Panthera pardus japonensis*) in China (Laguardia, Kamler et al., 2015).

Insert Fig.1.

3.2 Identification of core wild areas

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

3.2.1 Boolean wilderness patches

Spatial data on national scale wilderness areas in China (Cao, Carver et al., 2019) are extracted using the boundary of the study area. Wilderness patches are defined as areas with natural land cover and containing neither human settlements nor mechanized roads/railways. In addition, 100km^2 is used as the minimum threshold for patch size, which is in line with the medium-sized wilderness defined in Chinese wilderness maps and Platinum Wilderness areas defined in the European Wilderness Quality Standard and Audit System (Kun, Vancura et al., 2015; Radford, Senn et al., 2019). This size threshold is also comparable to the average size of the nature reserves in the study area.

3.2.2 Areas with the highest wilderness quality index

A wilderness quality index for China is used, which is a composite indicator reflecting human modification and combining six wilderness quality indicators including biophysical naturalness, population density, remoteness from settlements, remoteness from roads/railways, settlements density and roads/railways density (Cao, Carver et al., 2019). Here we identify the top 10% areas with the highest wilderness quality in the study region using the tool of *slice by equal area* (Carruthers-Jones, 2013; Radford, Senn et al., 2019), and patches meeting the minimum area threshold of 100km^2 are selected.

3.2.3 Nature reserves protecting habitat for north Chinese leopard

The north Chinese leopard is a top carnivore and a key umbrella and flagship species in the study region and is facing severe challenges in reduced range through habitat fragmentation (Laguardia, Kamler et al., 2015). To the best of our knowledge, GPS wildlife tracking has not been used to study the north Chinese leopard movement ecology in this region, so the leopard movement data is not available at this stage. While there are several protected areas have conducted wildlife survey using the camera trap technology, it is therefore reasonable to choose the north Chinese leopard's habitat reserves as source patches in connectivity modelling as a comparison with the wildland network. Data on nature reserves were downloaded from the World Database of Protected Areas (WDPA), and those reserves that north Chinese leopard inhabit are selected as the source patches according to the comprehensive information from a range of sources including official information provided by the nature reserves, peer-reviewed published literature and camera trap records (Laguardia, Kamler et al. 2015; Song, 2016), which is the best available data we could collect (see Table S1). To minimize the uncertainty of the data, experts from the Chinese Felid Conservation Alliance, who are familiar with the current status of the north Chinese leopard population in this region, were consulted to verify the collected information.

3.3 Creation of resistance surfaces

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

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

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

$$wqi\_std = \frac{\text{Max}\,(wqi) - wqi}{\text{Max}\,(wqi) - \text{Min}\,(wqi)} \qquad (1)$$

where *wqi* is the original wilderness quality index extracted for the study area, *wqi_std* refers to the standardized wilderness quality index.

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

$$R = 100 - 99 \times (wqi\_std) \qquad (2)$$

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

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

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

3.4 Creation of ecological corridors under different scenarios

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

Insert Table 1.

3.5 Identification of pinch-points in least-cost corridors

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

4 Results

4.1 Core wild areas

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

4.2 Resistance surfaces

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

4.3 Least-cost corridors

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

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

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

5.3 A methodological framework linking wilderness mapping and connectivity modelling

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

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

Insert Fig.4.

There are several potential advantages to building such a wildland network. First, the wildland network is mainly based on human impact data. The difficulty of data acquisition and calculation is lower than that of traditional species-based habitat networks, so it is much easier to be modelled and applied. Second, in many areas where there is no basic species survey at all, where modelling habitat networks is impossible, the wildland network could be used as an effective alternative method. Third, the wildland network connects the two knowledge domains of wilderness mapping and connectivity modelling, which can greatly enhance the application of wilderness maps. Fourth, as protecting core wilderness and strengthening the connectivity between them are the focus of rewilding, which has become an important strategy for nature conservation recently (Foreman, 2004; Lorimer, Sandom et al., 2015; Liang, He et al., 2018), the proposed methodology may be widely used for rewilding practices across different regions.

5.4 Recommendations for conservation action

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

5.5 Limitations and future research

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

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

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

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

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

6 Conclusions

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

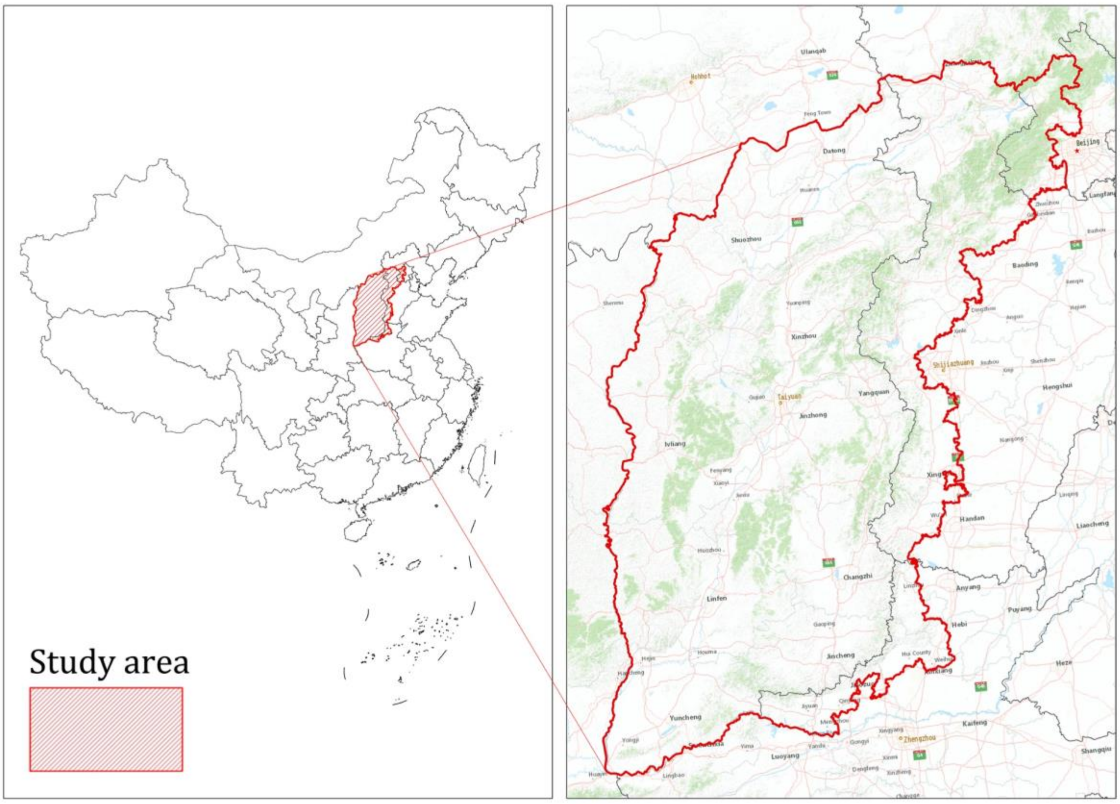


Fig.2. Least-cost corridors between the core patches (Scenario A, B and C).

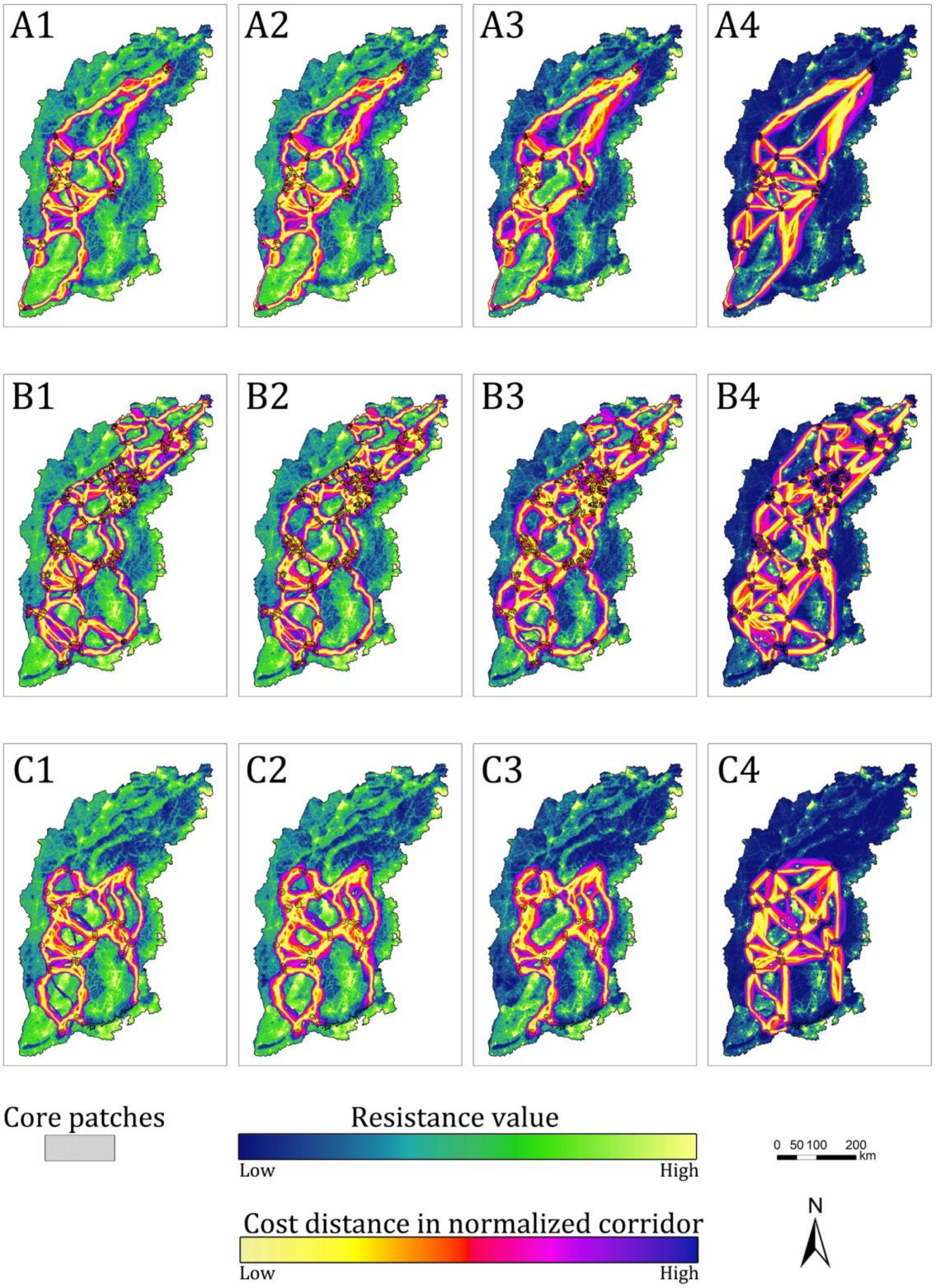


Fig.3. Pinch-points in resulting corridors (scenario B3). Pinch-points are areas with high cumulative current values and most important to connectivity conservation and restoration.

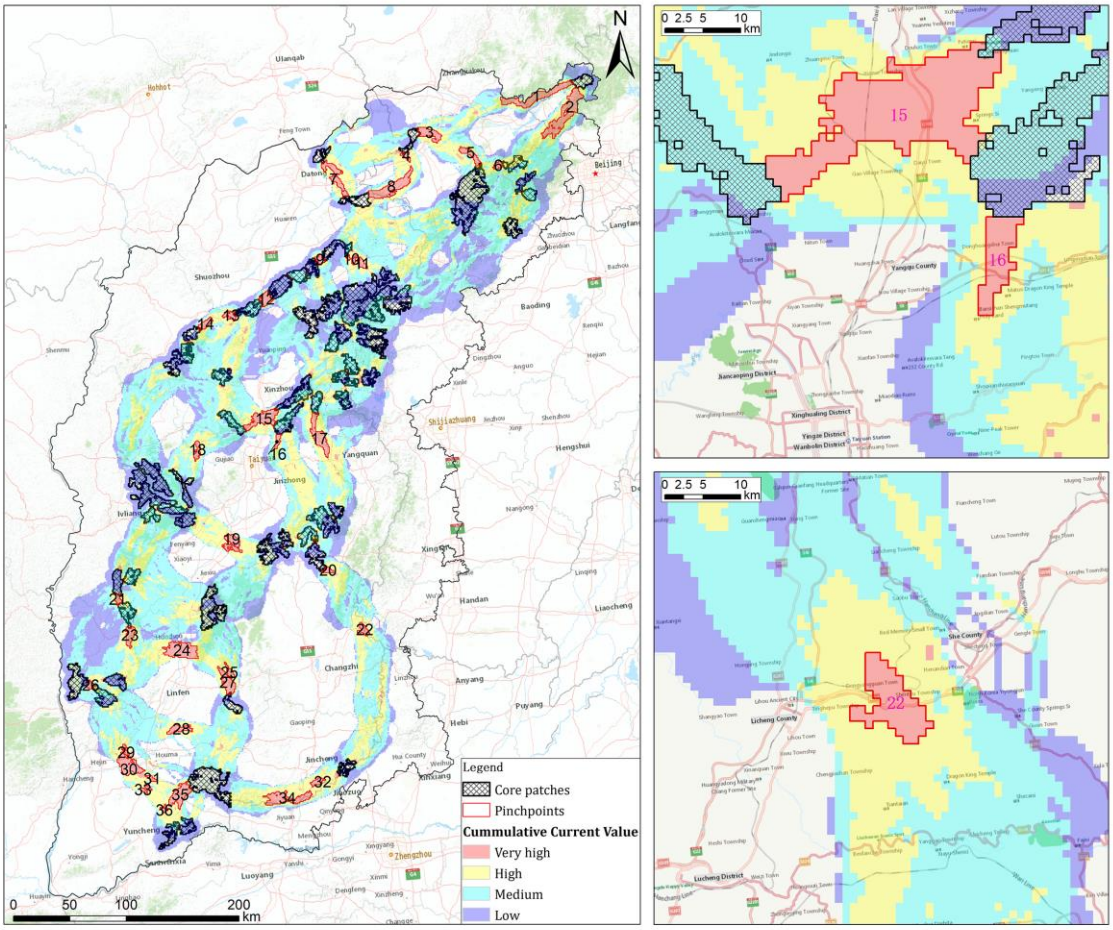
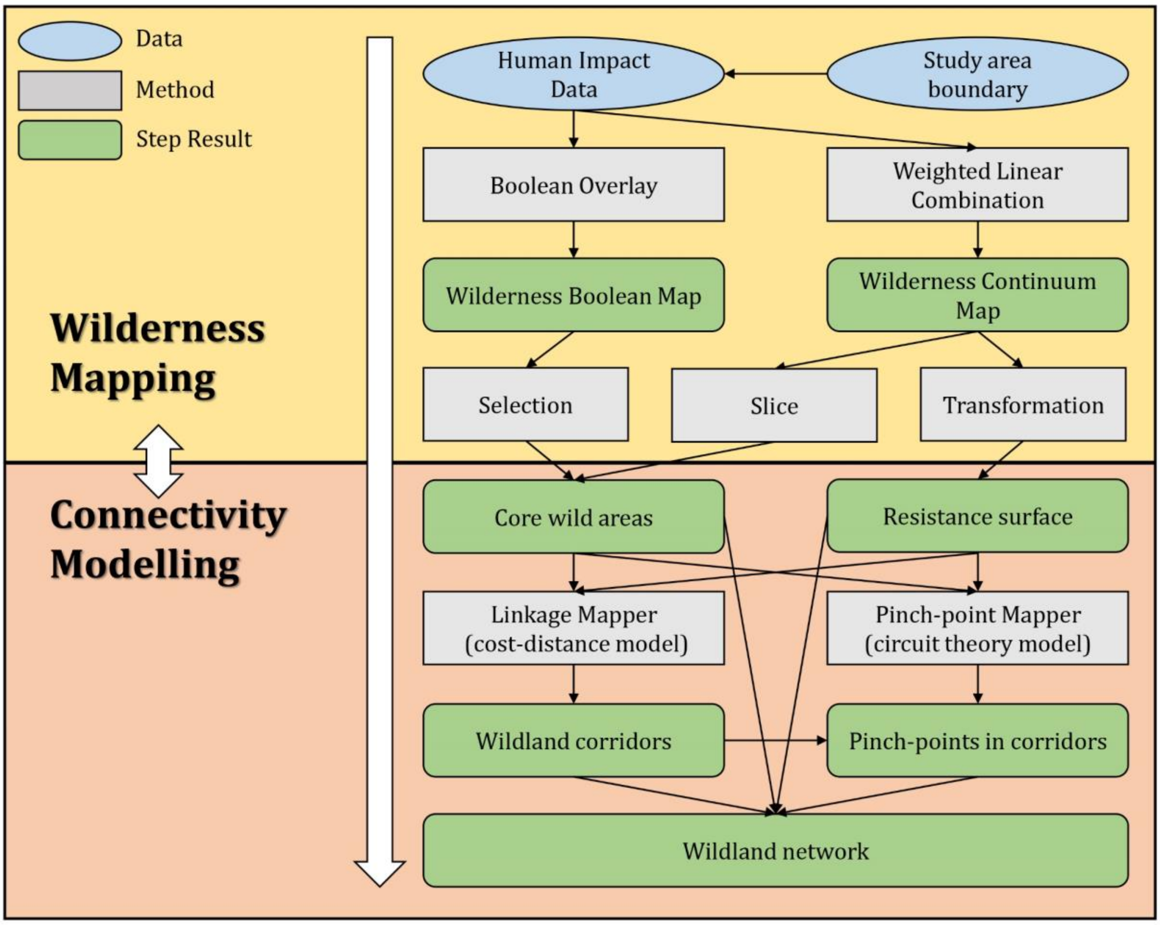


Fig.4. A methodological framework for wildland network planning, which links wilderness mapping and connectivity modelling.



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 Mountains	21312	National	Hebei	2001
2	Meng Xinnao		39047	Provincial	Shanxi	2002
3	Zhongyangshan		32671	Provincial	Shanxi	2002
4	Tieqiaoshan	Taiyue Mountains	35352	Provincial	Shanxi	2002
5	Bafuiling		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 Mountains and Wangwu Mountains	23947	Provincial	Shanxi	2002
11	Lishan		24800	National	Shanxi	1983
12	Taihangshan Macaque		56600	National	Henan	1998
13	Luyashan	Lüliang Mountains	21453	National	Shanxi	1980
14	Heichashan		25741	Provincial	Shanxi	2002
15	Lingjinggou		24920	Provincial	Shanxi	1993
16	Yundingshan		23029	Provincial	Shanxi	2002
17	Pangquangou		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; S335provincial 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).

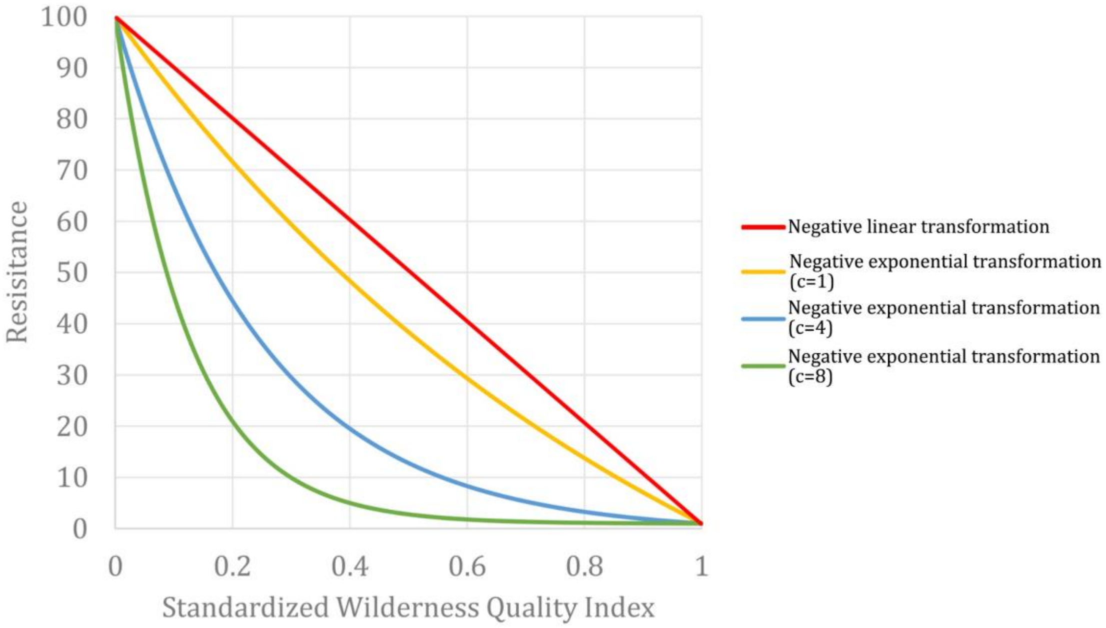


Figure S2. Core wild areas. In scenario A, core patches are wilderness patches derived from the wilderness Boolean map. In scenario B, core patches are areas with the highest wilderness quality index derived from the wilderness continuum map. In scenario C, core patches are nature reserves that north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

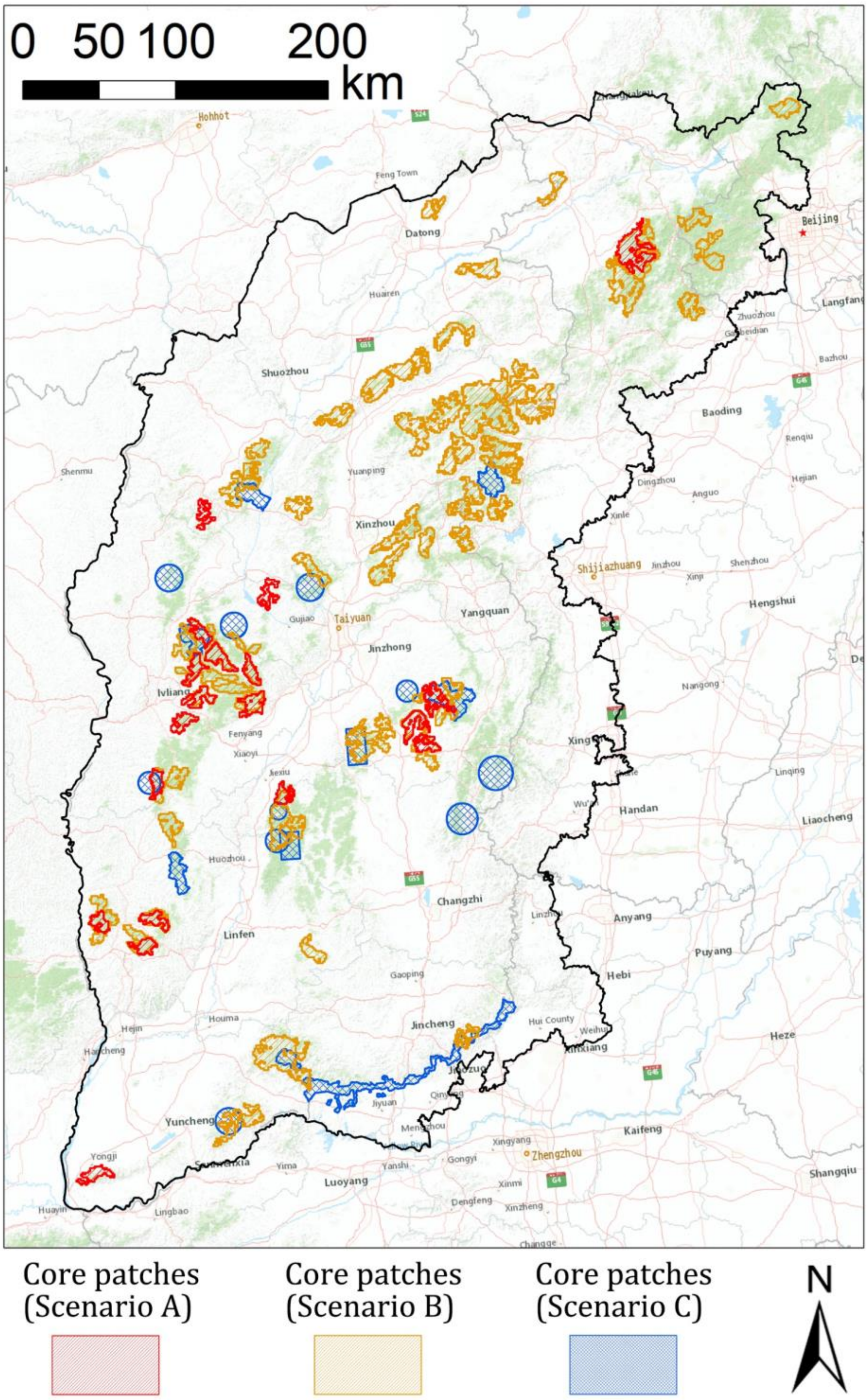


Figure S3.

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

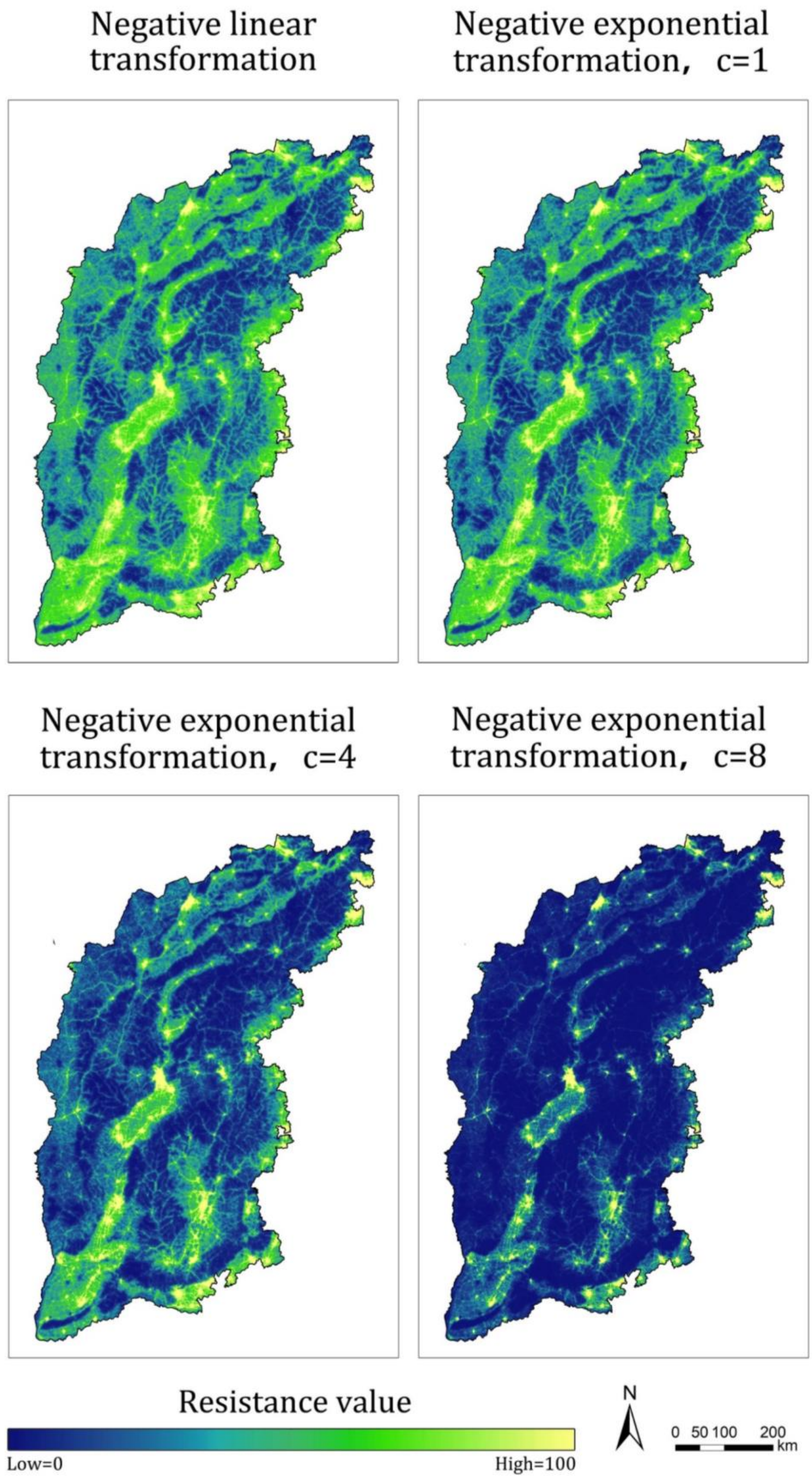
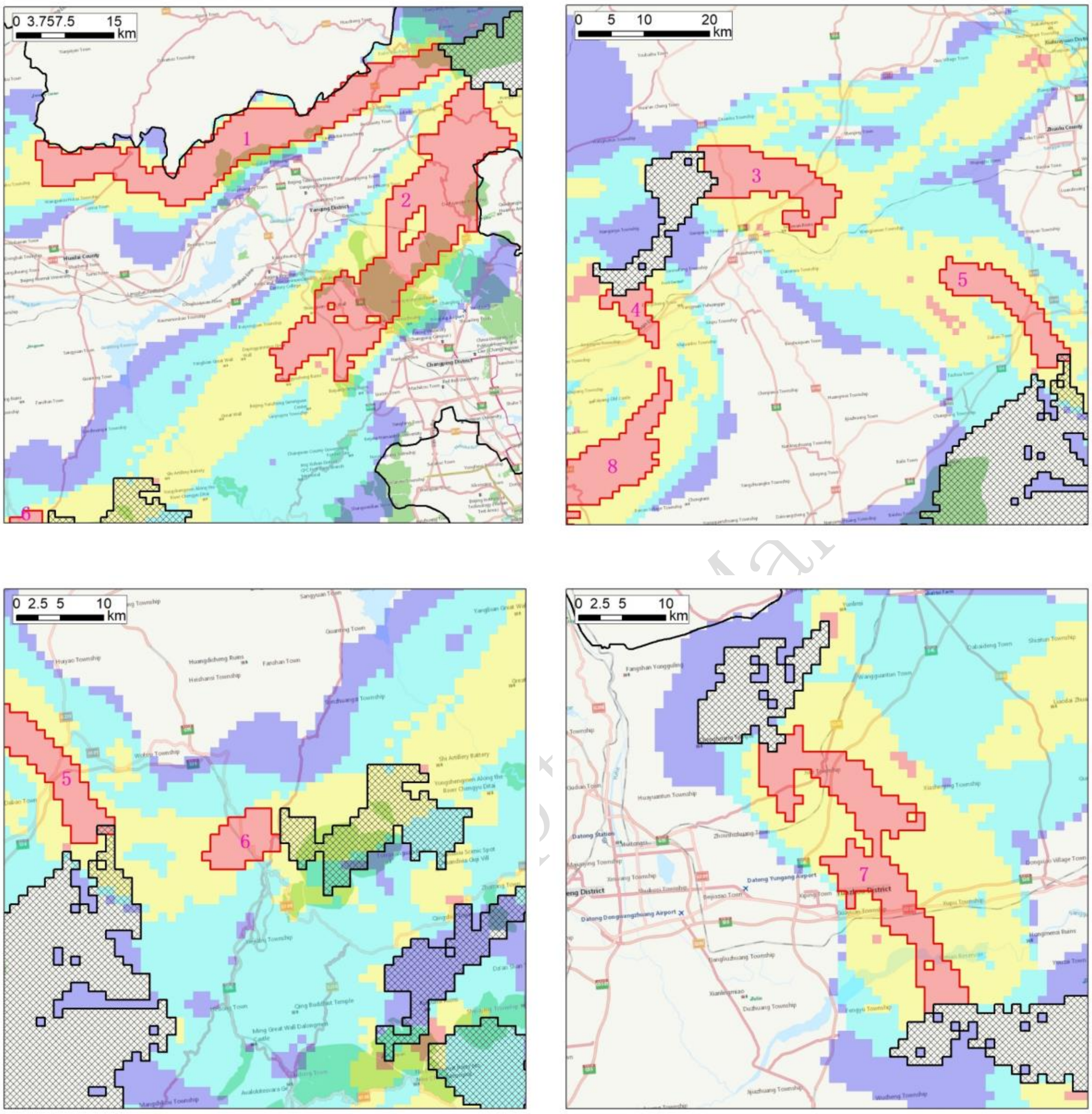
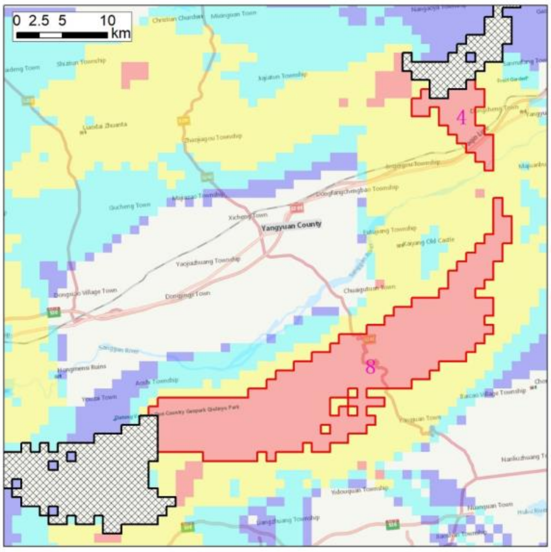


Fig.S4. Pinch-points(red) in resulting corridors highlighting areas requiring ecological protection and restoration.

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4
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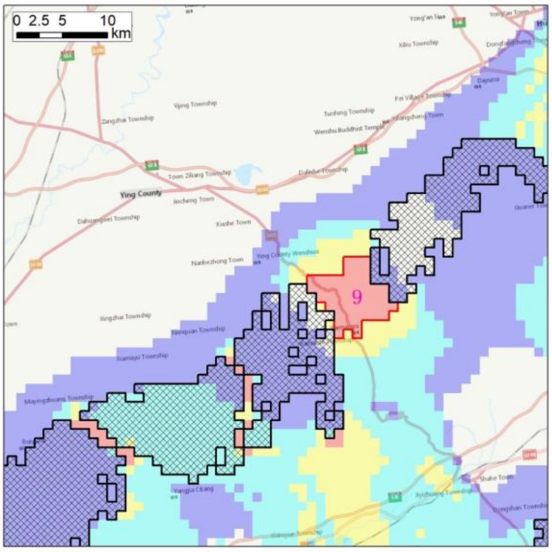
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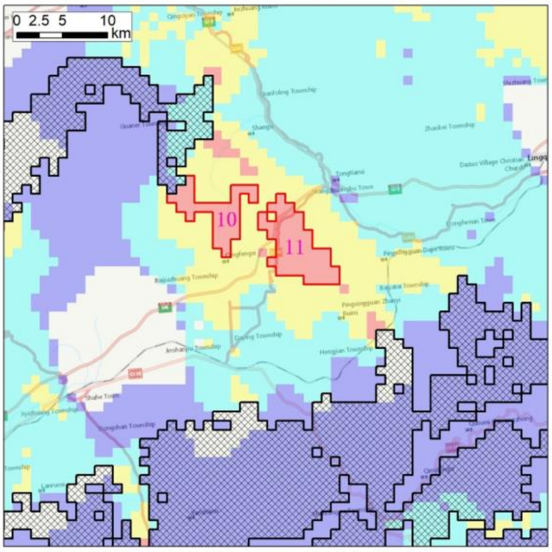
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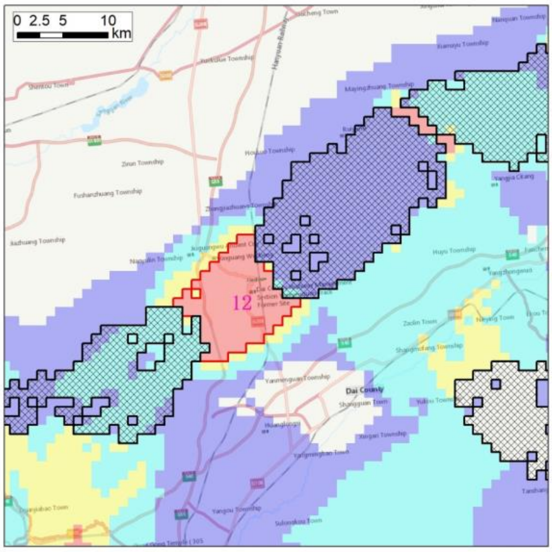
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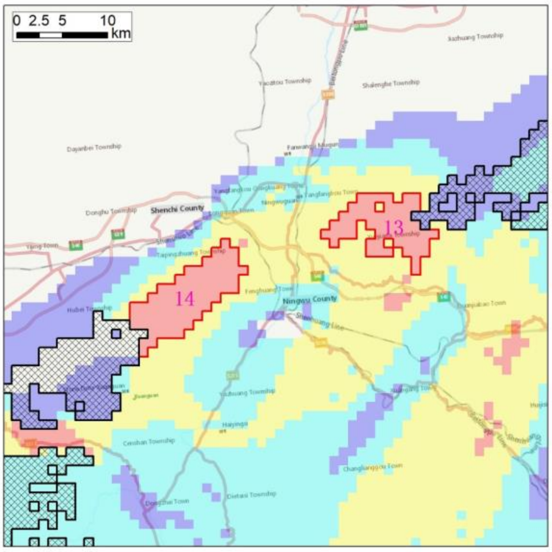
km
12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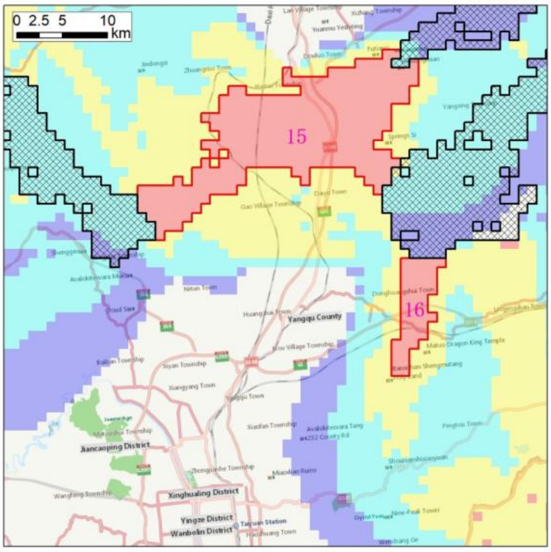
13
14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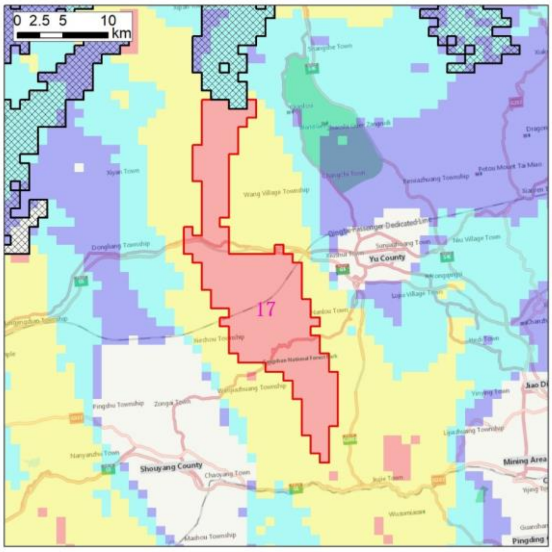
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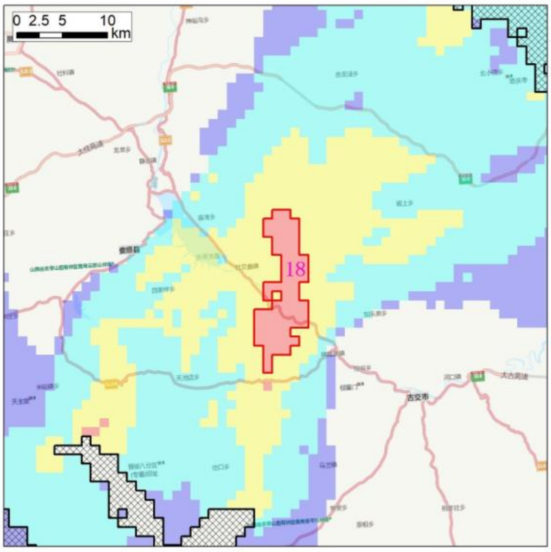
17
Yu County
Shouyang County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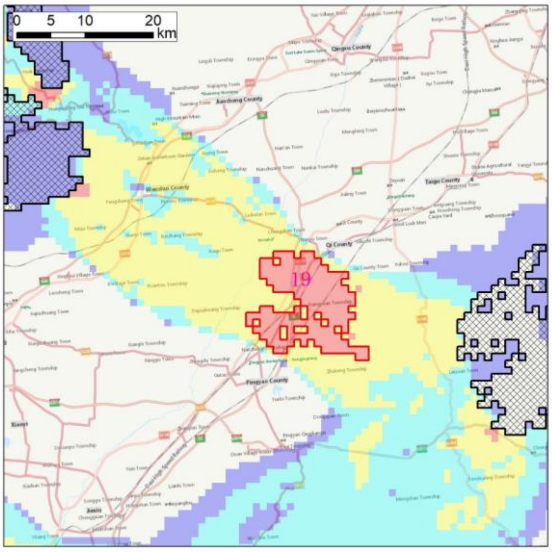
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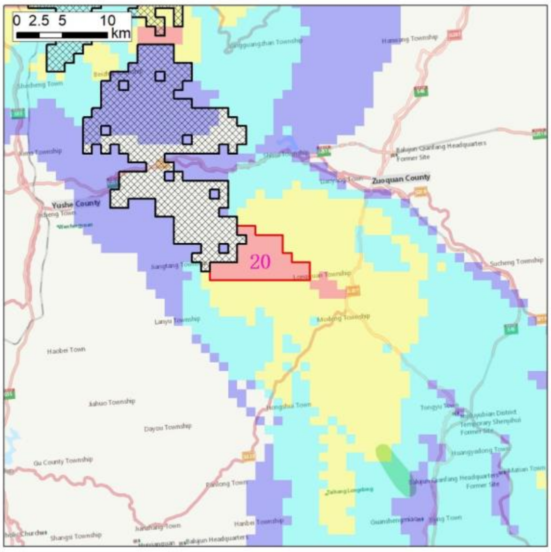
19
Qi County
Pingyao County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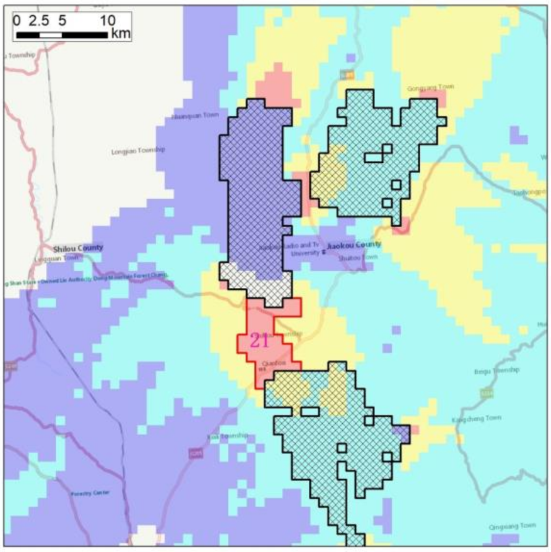
20
Yushe County
Zuoquan County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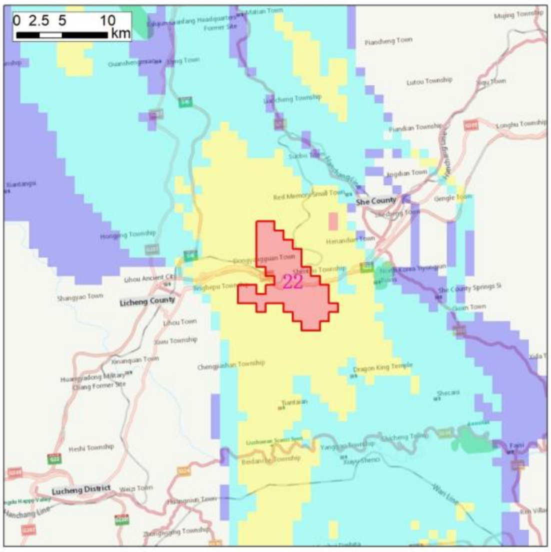
21
Shilou County
Jiaokou County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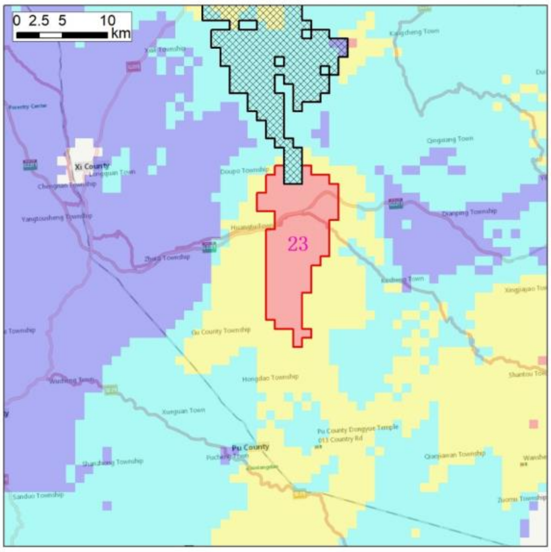
22
She County
Licheng County
Lucheng District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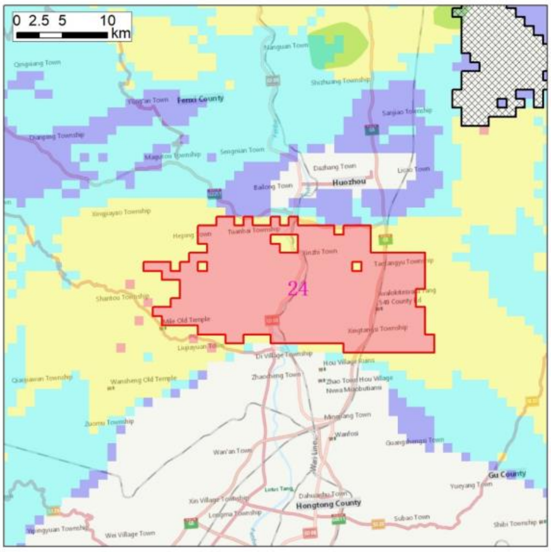
km
23
Xi County
Pu County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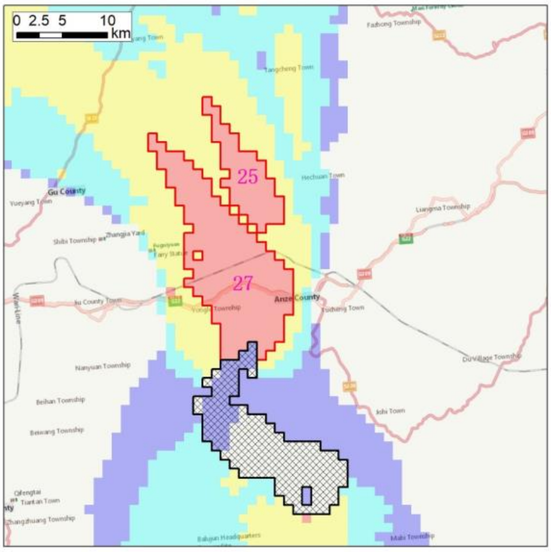
24
Fenxi County
Huozhou
Hongtong County
Gu County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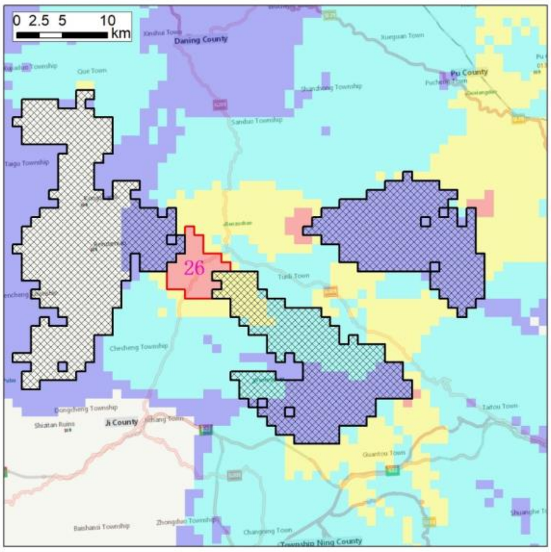
km
25
27
Gu County
Anze County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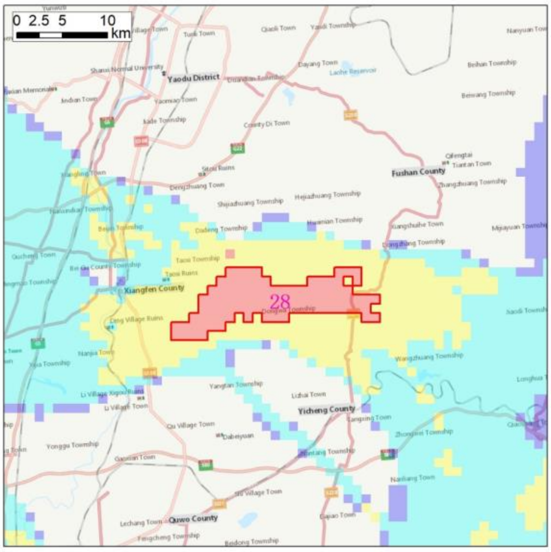
km
26
Daning County
Pu County
Ji County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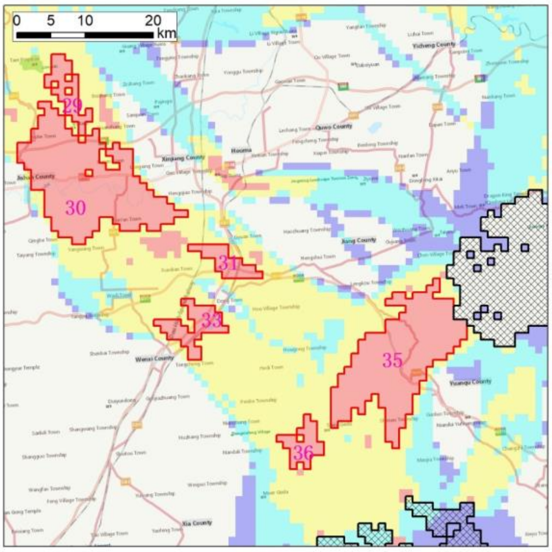
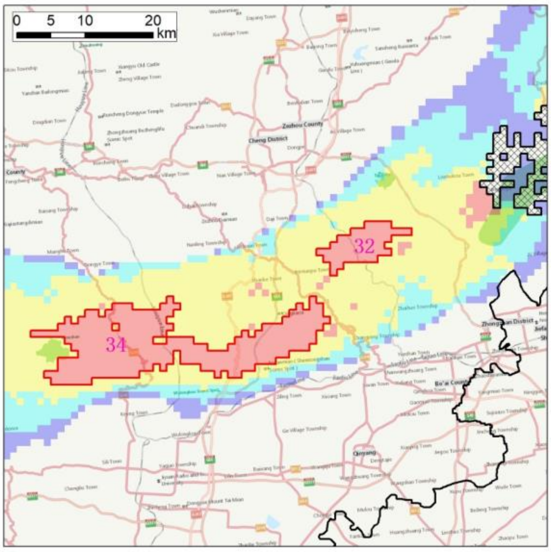
km
28
Yaodu District
Fushan County
Xiangfen County
Yicheng County
Quwo County


0 5 10 20
km
29
30
31
33
35
36


0 5 10 20
km
32
34