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Integrating priority areas and ecological corridors into national network for conservation planning in China

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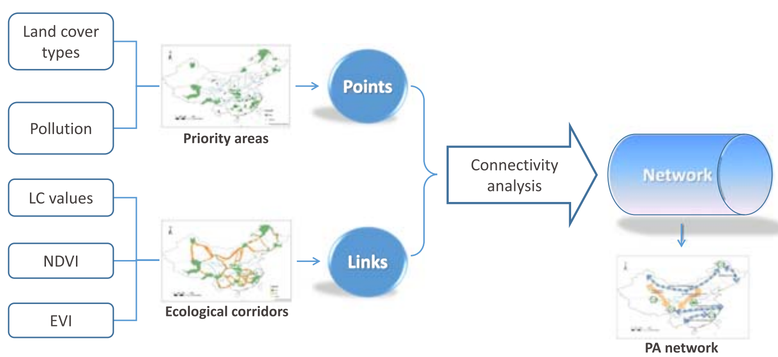
HIGHLIGHTS

- The method integrates priority areas and ecological corridors to the PA network.
- Spatial mismatch exists between nature reserves and priority areas.
- Patches with large areas, long boundaries contribute to high connectivity.
- Ecological network illuminates a strategy for strengthening PAs in China.

GRAPHICAL ABSTRACT



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ABSTRACT

Considering that urban expansion and increase of human activities represent important threats to biodiversity and ecological processes in short and long term, developing protected area (PA) network with high connectivity is considered as a valuable conservation strategy. However, conservation planning associated with the large-scale network in China involves important information loopholes about the land cover and landscape connectivity. In this paper, we made an integrative analysis for the identification of conservation priority areas and least-cost ecological corridors (ECs) in order to promote a more representative, connected and efficient ecological PA network for this country. First, we used Zonation, a spatial prioritization software, to achieve a hierarchical mask and selected the top priority conservation areas. Second, we identified optimal linkages between two patches as corridors based on least-cost path algorithm. Finally, we proposed a new framework of China's PA network composed of conservation priority and ECs in consideration of high connectivity between areas. We observed that priority areas identified here cover 12.9% of the region, distributed mainly in mountainous and plateau areas, and only reflect a spatial mismatch of 19% with the current China's nature reserves locations. From the perspective of conservation, our result provide the need to consider new PA categories, specially located in the south (e.g., the middle-lower Yangtze River area, Nanling and Min-Zhe-Gan Mountains) and north regions (e.g., Changbai Mountains), in order to construct an optimal and connected national network in China. This information allows us better opportunities to identify the relative high-quality patches and draft the best conservation plan for the China's biodiversity in the long-term run.

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1. Introduction

Protected areas (PAs) are regarded as one of main strategies for halting biodiversity loss resulted from land use change, habitat loss and fragmentation (Le Saout et al., 2013; Rodrigues et al., 2004; Thomas et al., 2012). The Aichi Biodiversity Targets accepted by the Convention on Biological Diversity (CBD; available in www.cbd.int/sp/targets/) proposed that global coverage of PAs should not be less than 17% of the total terrestrial surface by 2020. Well-designed PAs are essential for the conservation of both species and ecosystems (Bruner et al., 2001; Game et al., 2009), as well as, consequently, bringing benefit to society (Guerry et al., 2015). In fact, many authors showed that PAs carry out, in a medium and long term, a valuable role in developing reliable adaptation and mitigation strategies to conserve the biodiversity of focal ecosystems under future climate change scenarios (e.g., Ortega-Andrade et al., 2015; Prieto-Torres et al., 2016; Soares-Filho et al., 2010).

To effectively connect the key areas that may differ in shapes and sizes, and reduce the isolation of habitat fragments, both ecologists and conservation biologists recommended constructing ecological corridors (ECs; Peng et al., 2017). These corridors play an important role in providing routes and extended districts for the migratory species (Aars and Ims, 2008; Lynne et al., 2010); but at the same time they represent a valuable conservation tool promoting purify air pollutant, regulate climate and realize the movement of material, energy, and information in the ecosystem (Singh and Gokhale, 2015). Environmental protection organizations recognized the importance about the establishment of large-scale ECs for landscape connectivity, biodiversity restoration and, consequently, to maintain the ecological integrity of ecosystems (Bowers and Mcknight, 2012; Holland, 2012; Huang et al., 2008). Thus, in view of the scenarios mentioned above, some authors proposed an ecological network approach based on sustainability-related indicators into high-priority areas and their linkages (Théau et al., 2015).

An ecological network involves, usually, two parts during its development. One of them, named as “ecological points”, represents the priority areas distributed spatially in areas with high biodiversity and conservation values (Nitu et al., 2014), while, the other (called “ecological links”) is described as the narrow and linear (or near-linear) corridors that comprise the possible areas used directly by organisms to move from one patch to another (Beier and Noss, 1998). Hence this alternative conservation approach can be capable to maintain the protection challenges no matter the environmental and ecological (e.g., moves of species) changes at least in some extent. However, so as to maximize the efficiency of ecological network conservation, it is important to establish landscape connectivity among isolated biotope (Baranyi et al., 2011). This landscape connectivity (considered as the measure to describe the spatial connection and extension of areas) is very important because it ensures the possibility of dispersal and gene flow among populations of species, as well as other ecological functions of ecosystems (Haddad et al., 2003; Saura and Rubio, 2010; Tang et al., 2008). Maintaining or increasing connectivity denotes a better strategy to mitigate the adverse synergistic effects of habitat fragmentation and climate change (Prieto-Torres et al., 2016; Saura et al., 2011b).

Our case of study for ecological network construction is China, where a rapid economic development has produced a decrease in biodiversity and environmental degradation (Jia et al., 2011). The primary category within the China PA system involved the nature reserves (where anthropogenic activities are controlled and limited by the national laws to conserve nature), representing 80% of protected areas (Xu et al., 2017). Although these reserves can preserve some habitats and particular threatened species, it is important to objectively highlight that their current spatial delimitations are promoting the configuration of islands ecologically separated (Roedder et al., 2016; Zhang et al., 2016). Despite the increasing habitat fragmentation and global biodiversity crisis, the current application of ECs in China is limited only for local scale or in particular regions, without a global perspective for the landscape connectivity and ecological integrity (Dong et al., 2015; Kong et al., 2010). These cases mainly focused on urban greening (Yu et al., 2006). It represented an important problem and conservation gap for the country, especially if we considered that ecological network was changing from the micro to macroecology perspective to design efficient strategic planning (e.g., Ferretti and Pomarico, 2013; Samways and Pryke, 2016).

In this paper, we implemented an ecological network analysis for strengthening the PA system of China to identify and address the potential conservation gaps mentioned above. This methodological perspective allow us identify new potential conservation areas to promote the creation of a more representative, connected and efficient network for this country, maximizing the representation of biodiversity and improving the conservation of ecosystems in the medium and long term. This information is of great value because it can provide new and more accurate evidence that can guide current conservation decision-making processes.

2. Materials and methods

2.1. Environmental and spatial data

For our spatial analyses we used the information available in the land cover (from Global Land 180 Cover by National Mapping Organizations, http://www.iscgm.org/) and nature reserves (IUCN and UNEP-WCMC 2010; available at https://www.protectedplanet.net/) maps of China, as well as the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) from Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC, https://ladsweb.modaps.eosdis.nasa.gov/). In the first step, land cover types were classified into eight categories, including the broadleaf forest, coniferous forest, shrub, herbaceous plant, sparse vegetation, wetland, water body and urban area (Wang et al., 2009; Xiao et al., 2016). Then, we assessed the vegetation quality of the study area according to EVI and NDVI, which were obtained based on the data time series from January to December 2013, provided every 16 days at 500 m spatial resolution as a raster level-3 product. Finally, we downloaded the shapefiles for the 2158 China's nature reserves from World Database on Protected Areas (WDPA) provided by the United Nations Environment Programme (UNEP). All data were used in raster format with the same spatial resolution of NDVI maps (i.e., grid cell size corresponding to 500 m in each raster).

2.2. Conservation areas prioritization

We identified priority areas using the Zonation v4 software tool which is particularly well suited for large-scale high-resolution datasets (Moilanen et al., 2011). It starts from the entire landscape and then iteratively removes the least important site, considering distributions and weights of biodiversity features. Though using a set of species' distribution features could be considered as a better approach than biodiversity features based on ecosystem maps (e.g., Fajardo et al., 2014; Lessmann et al., 2014; Prieto-Torres and Rojas-Soto, 2016), we performed the analysis to define priority areas to protect by using the reclassified land cover map due to the fact that China involves a long species list and the individual biological information is difficult to obtain (e.g., Songer et al., 2012; Wan et al., 2017). In this sense, we considered the first seven established categories (see above) as important Chinese habitat types to protect (Wang et al., 2009; Xiao et al., 2016). For each of these habitats we assigned weights values (Table 1) according their priority and ecological importance (Liu et al., 1999; Shen et al., 2008). Contrarily, the remaining last one, namely urban area, was considered as the source of pollution that might cause future degradation of habitat quality; accordingly, we assigned negative weights (i.e. “penalization”) to pixels covered by these areas.

Table 1
Basic parameters used in Zonation V4 for the analysis conservation areas prioritization, which were based on the priority and ecological importance of habitat type (see Liu et al., 1999; Shen et al., 2008).

Habitat type	Weight	α-Value
Broadleaf forest	2.0	0.5
Coniferous forest	2.0	1.0
Shrub	1.0	1.5
Herbaceous plant	1.0	0.75
Sparse vegetation	1.0	0.5
Wetland	2.0	0.25
Water body	1.0	1.0
Urban area	−2.0	1.0

Zonation is an iterative removal of all cells one by one from the landscape, using minimization of marginal loss as the criterion to decide which cell is removed next and the sequence of cell removal is archived (Moilanen, 2007). It can be used to select any given top fraction of the landscape, like best 20% is used here, and make simply overlay analysis later (Kukkala et al., 2016; Nori et al., 2016). For this analysis, we used the removal rule of core-area Zonation (CAZ), to minimize the loss of conservation value accounting for weights given to them (Lehtomäki and Moilanen, 2013). In addition, we specified the values for α parameter (Table 1), which corresponded to a dispersal kernel and it had an inverse relationship with the scale of connectivity of features (e.g., range sizes of the surrounding landscape that species use (Moilanen et al., 2014)). For the final run-model, we implemented a warp factor equal to 1 in order to reduce computation times by orders of magnitude, allowing to apply Zonation to extremely large landscapes with high spatial resolution within practical time-frames (Moilanen et al., 2005). It is important to note that, because Zonation output typically represents one of several sources of information for decisions (Carlos et al., 2010), here we referred to our results as a possible solution, but not as the final decision, for the gaps into the current Chinese PAs network.

2.3. Least-cost corridors identification

We applied a modified graph-theoretic algorithm to calculate the cost of movement between patches for the species, identified as optimal linkages or corridors the areas with the lowest values (Pinto and Keitt, 2009). For this analysis, the algorithm needed to establish an adjacency matrix of all the points (Rayfield et al., 2010), regarding the whole landscape as the cost raster. As shown in the equations, the cost of movement between patches is calculated based on the cumulative resistance values (Eq. (1)) of species on the surface of a continuous grid, which is obtained from two scenarios: (1) cost from grid “a” to the vertically-adjacent grid “b” (Eq. (2)); and (2) cost that grid “a” moves to the diagonally-adjacent grid “c” (Eq. (3)). Detailed methods for obtaining the landscape resistance surface's map and ECs are provided in Supporting Information (see Appendix 1).

$$accum\_Cost = \sum_{i=1}^{n} A_i \tag{1}$$

$$A_1 = \frac{1}{2}[Cost(a) + Cost(b)] \tag{2}$$

$$A_2 = \frac{\sqrt{2}}{2}[Cost(a) + Cost(c)] \tag{3}$$

2.4. Landscape connectivity analysis

To construct an ecological network considering the highest connectivity possible, we calculated two landscape connectivity indices: (1) Integral index of connectivity (IIC; Eq. (4)), based on the binary connections model in which two points are directly linked if the distance between them is less than a given value (Pascual-Hortal and Saura, 2006); and (2) the Probability of connectivity (PC; Eq. (5)), which involves a probabilistic connections model without being influenced by adjacent patches or elements in the analyzed datasets (Saura and Pascual-Hortal, 2007). These values are given by the following expressions:

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

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \cdot a_j \cdot {p^*}_{ij}}{{A_L}^2} \tag{5}$$

where n is the total number of patches in the landscape; a_i and a_j are the attributions of patches i and j, respectively; A_L represents maximum landscape attribution; nl_{ij} is the number of links in the shortest path between i and j; and ${p^*}_{ij}$ is the maximum product probability of all paths between i and j.

The relative ranking of patches by their contribution to overall connectivity, namely the change in landscape connectivity of the whole area when this point is broken (or removed), is most useful in evaluating biotope patch significance (Bodin and Saura, 2010). The importance of a patch according to a given connectivity index M can be expressed in relative terms:

$$dM(\%) = 100 \cdot \frac{M - M_{after}}{M} \tag{6}$$

where M is the total connectivity index when all patches exist in the landscape and M_{after} represents the value after the removal of single patch from the landscape.

Finally, we calculated the Equivalent Connected Area (ECA) index which is defined as the size of a single biotope patch providing the same value of PC instead of actual landscape pattern (Saura et al., 2011a). The value of ECA maintains all the desirable properties of PC index, avoiding the extremely low values when the amount of patches is very small compared to the total extent of the analyzed landscape. It is an overall index value, calculated as the square root of the numerator of PC as follows:

$$ECA = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \cdot a_j \cdot {p^*}_{ij}} \tag{7}$$

Landscape connectivity in this study was computed with p_{ij} set at 0.5 (assuming the distance is in accord with species average dispersal distance under analysis) when the distance thresholds were 2, 8, 16 and 30 km, respectively (Liu et al., 2014). It was important to highlight that we considered two patches are linked when the resistance distance is less than or equal to the threshold value. All connectivity indices were calculated using the Conefor Sensinode v2.6 software (available at http://www.conefor.org/) proposed by Saura and Torne (2009).

3. Results

Our result for the prioritization analysis showed that high-priority areas to conserve were distributed mainly in mountainous and plateau areas of China, including the Great Khingan, Changbai, Qinling, and Hengduan Mountains, as well as the Mount Wuyi and Tibetan plateau (Fig. 1). Designated top 20% priority conservation areas covered 12.9% of the country, which were distributed in four main regions: the south (38.6%), the Qinghai-Tibet (27.8%), the north (24.3%) and the northwestern (9.3%). In addition, we observed a spatial mismatch of 19% between these priority areas and the current Chinese's nature reserves

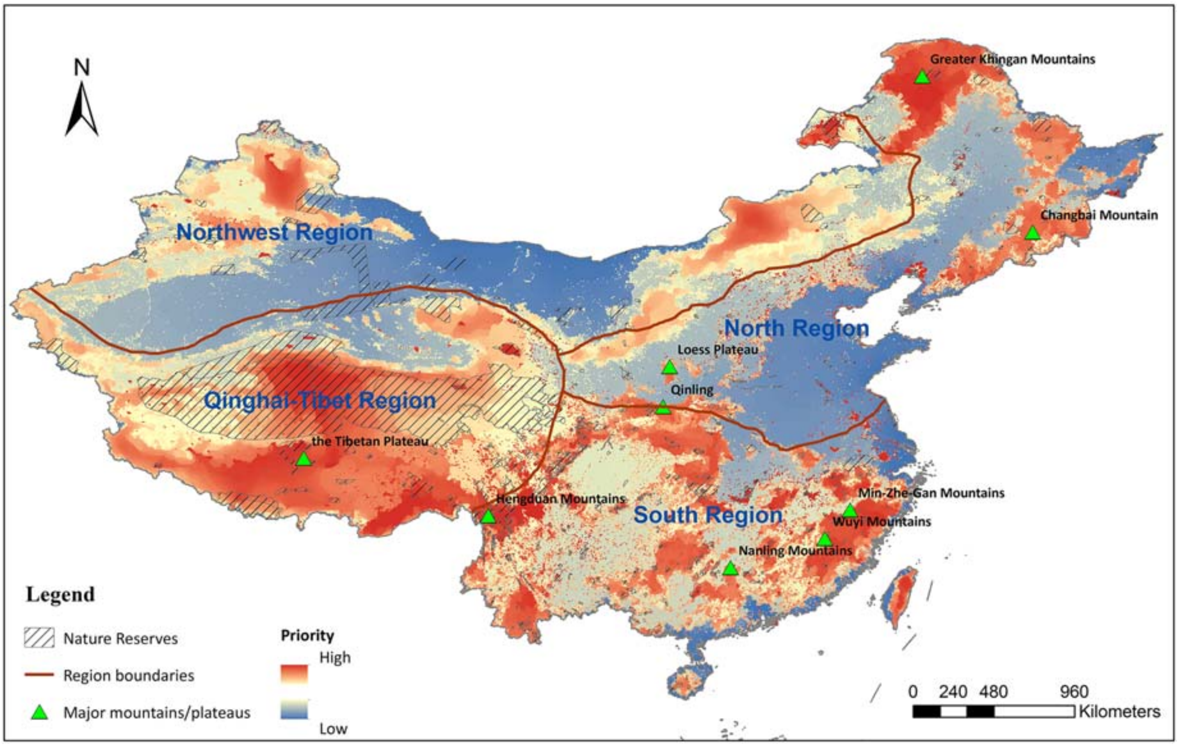

Fig. 1. Output priority rank map for the spatial conservation prioritization. The blue shows low conservation priority which grids are removed first, while the red shows high priority retained till the end. Here, areas have been zoned to graded colors based on their priority rank, with highest priorities (top 20% of total area) shown in red. Black shaded polygons correspond to the current nature reserves in China. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

locations. As shown in Fig. 1, overlapping areas were predominantly located in Tibetan Plateau (66%).

Our result indicated that distributions of ECs based on least-cost pathway method were distributed to avoid the optimal development areas in China such as Beijing-Tianjin-Hebei Economic Circle, Yangtze River Delta, and the Pearl River Delta (Fig. 2). It is important to note that development of cities leads to deviation from the shortest straight line between two patches, instead of enforcing a circuitous route to other patches. Thus, these corridors have no choice but to keep away from high-density buildings in residential areas and distributed along the urban boundaries.

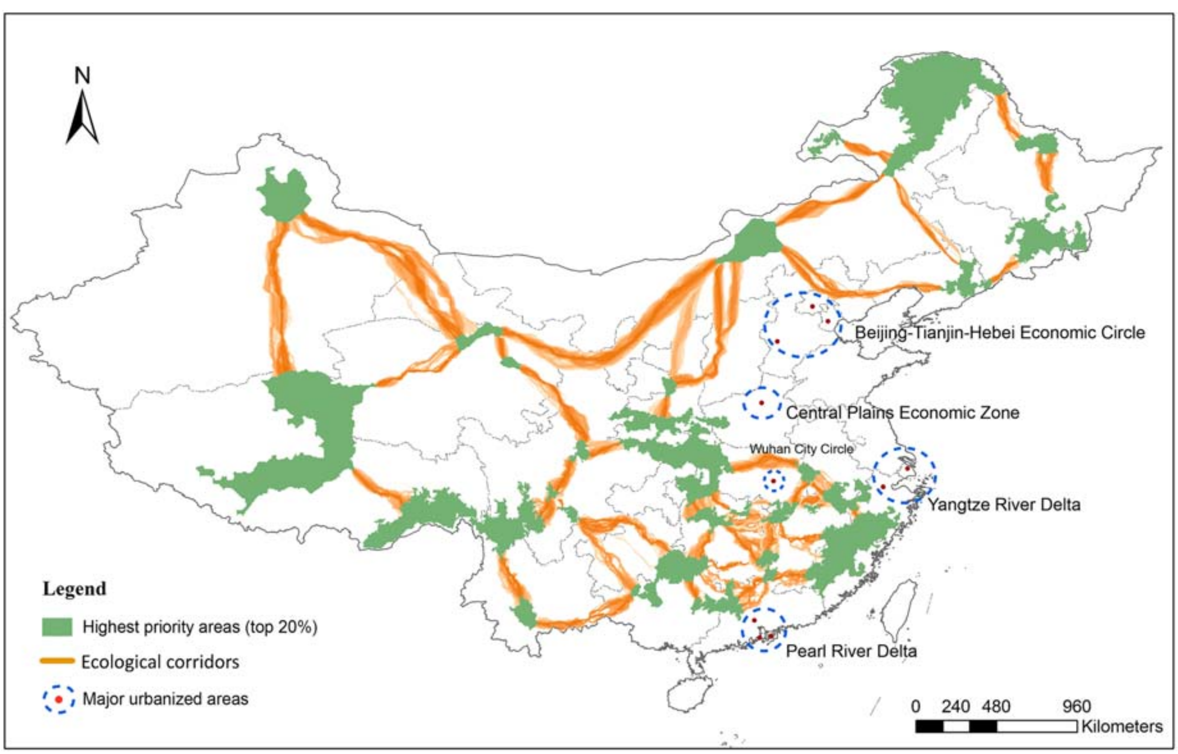

Fig. 2. Distributions of ecological corridors in the major urbanized areas of China. Color depth (orange) of potential corridors represents the resistant value. The deepest path is the optimal path between two priority areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

According our connectivity analysis, there is a high correlation between overall connectivity change and dispersal distance ranging from ECA = 55.4104 for d = 2 km up to ECA = 107.4766 for d = 30 km (Table S1). Taking 30 km as an example, priority areas were classified into seven grades on the basis of the results of *d*IIC and *d*PC value (Fig. S2). Thus, based on selected priority areas and highly important ECs, and considering national terrain factor and multi-use demand, a new PA network framework as "one center, two wings, four belts, and four cores" was proposed for China in this study (Fig. 3). "The center" (the Qinling-ba Mountains) is located in central China, preferably connecting the north and south protected areas, while the two wings correspond to the ecological barriers of Qinghai-Tibet Plateau and the Loess Plateau-Sichuan Yunnan, respectively. These wing-shaped corridors were proposed to ensure ecological safety on the basis of landscape ecology principles, physical geographical conditions and historical context (China's National Development and Reform Commission, 2015). In addition, four belts (the northeast China forest, northern China sand prevention, central Yangtze River, and southern hills and mountain) are identified as potential ECs making it possible to form an ecological outline of green development, which connects core priority areas in the fragile district of ecology (Fig. 3). Finally, four cores (Three-river Region, Greater Khingan Mountains, the southeast Tibetan Plateau, and Min-Zhe-Gan Mountains) are defined as important priority areas based on the relevance of patches in this study. These key ecological areas and sensitive areas (e.g., nature reserves, scenic spots, forest parks, and geological parks) have a major influence on the regional environment, and should be well protected and strictly regulated (Fig. 3).

4. Discussion

4.1. The current nature reserve system and priority areas

The primary PAs in China are nature reserves (the most strictly protected PAs, chiefly for biodiversity conservation), covering 15% of the country (Ministry of Environmental Protection of the People's Republic of China, 2015). They are concentrated mainly in the Qinghai-Tibetan region (78.35%) while there is lack of adequate attention to the important areas in other provinces, such as Nanling and Min-Zhe-Gan Mountains, in the southern China, Changbai Mountains and Loess Plateau, in the northern China. The proportion of overlap between areas of priority areas identified here and China's nature reserves (19.08%) suggests that the current nature reserves are not well delineated. The majority of China's nature reserves were established without a clear planning framework, and couldn't maximize efficiency of conservation targets (Wu et al., 2011). This is a notable gap, which means that China may be establishing "paper parks" rather than achieving sustainable conservation outcomes (Liu et al., 2003).

According to the spatial prioritization analysis, the representativeness of the PA network would substantially increase by protecting the remaining priority areas. This standpoint is important because these important zones for species migration are not considered as conservation goals in the current nature reserve system (Xu et al., 2017). Thus, based on the results we recommend promoting new PAs (considering ECs as new categories) or enlarging the current nature reserves in the country to encompass these important areas, like the middle-lower Yangtze River area, the Min-Zhe-Gan and Wuyi Mountains and Nanling. A change in ecological construction is needed to enable us to face the future uncertainties such as climate change and land use change, and to improve resistance and resilience properties in the biodiversity features to these challenges (Kostyack et al., 2011; Prieto-Torres et al., 2016). Therefore, in view of the pollution problems and the environmental changes (such as global climate), it is necessary to increase the complementary areas in the current nature reserve system for maximizing the conservation efforts in China.

From this perspective, our results showed that most important priority areas where future conservation efforts must be focused were located in the Khingan Mountains and Three-river Region. These areas are not only the vital ecological barrier that could reserve timber and response to climate change, but also an essential area for soil and water conservation (China Preparatory Committee for United Nations

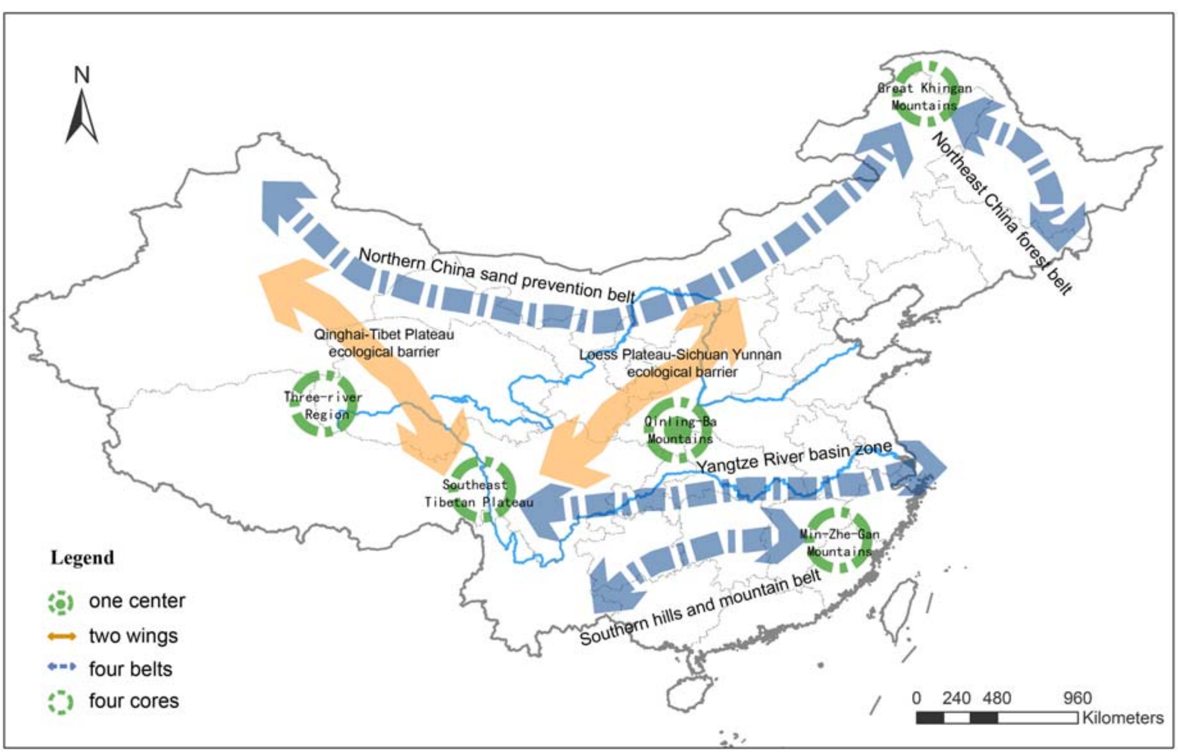

Fig. 3. China's PA network framework featuring "one center, two wings, four belts and four cores". "Center" and "cores" represent highly important priority areas. "Wings" and "belts" represent ecological corridors.

Conference on Sustainable Development, 2012). In fact, they represent one of the most concentrated areas of biodiversity and had great significance to network connectivity (Jiang and Zhang, 2016), whit a great many forests reduced the landscape resistance of species migration and were conducive to the flow of material energy.

4.2. The framework for a more representative and connected PA network in China

Compared with previous studies, the proposal for the national ecological network in this study is more systematic and multidimensional on a larger scale. In previous works, Jim and Chen (2003) applied landscape ecological principles to the green space planning of Nanjing City (China), however, they mainly focused on the whole metropolis with more details in planning and design. On the other hand, Xu et al. (2011) proposed future space patterns at both the city and regional level, based on existing patterns and changes of green spaces in Beijing, but they particularly focused on the relationship of landscape structure and function.

It is important to note that conservation of ECs between priority areas requires balancing the relationship between ecological protection and economic development. However, considering the prominent contradiction between them, it is common that ECs construction has been interrupted by urbanization (Scudo, 2006; Toccolini et al., 2006). In fact, our analysis shows that roads within or surrounding biotope islands are usually regarded as serious barriers to connectivity and served to fragmented biotope, so they are not preferred ecological corridors (Figs. 2 and 3). As cities continue to expand, it can be predicted that corridor will be further stressed (Turner, 2006).

In order to mitigate this negative effect, decision-makers should leave some space and designate it as a reserved area in the future urban expansion. A few corridors existing in the areas of importance for new infrastructure facilities, roads and other lines of communication had high impedance value (Kautz et al., 2006; Mui et al., 2017). When it was unable to avoid traffic routes, a certain kind of biological channel should be set up in the vicinity of the intersection of the corridor and the traffic line. At the same time, setting the isolation belt on both sides of the road may induce species migrating from the biological channel. Stepping stone area refers to small temporary-stay block in the place of two larger patches, which may improve the resilience of fragmented patches and promote dispersal among fragmented populations (Baum et al., 2004; Liang et al., 2017). In fact, the quantity, quality and spatial configuration of corridor intersections determined the time, frequency and success rate of species migration (Fan et al., 2017), especially for those threatened species.

The potential ECs obtained in our study not only include the optimum path, but also contain several sub-optimum routes (some corridors showed braches), which is more in coincidence with the theory about migration of species. This is important because animals may not travel along a single pathway repeatedly, nor would they always traverse the shortest route possible in the complex environment (Liira and Paal, 2013). The spatial pattern of natural reserve fragments can be improved by the combination of corridors (proposed by "two barriers and four belts"). As is shown in Fig. 3, Tibetan Plateau ecological barrier has abundant natural resources, and aims at maintaining ecological equilibrium and regulating climate change in China; while the Loess Plateau-Sichuan Yunnan ecological barrier is located in areas of soil erosion and natural disaster caused by both natural and anthropogenic factors (Ministry of Environmental Protection of the People's Republic of China, 2011). Equally, four belts played an important role in biodiversity maintenance, soil and water conservation, disaster abatement, and economic development. For example, the northeast forest belt focused on the protection of forest resources and ecological diversity, while the northern sand prevention belt strengthened shelter forest construction, grassland protection, wind prevention and sand fixation (Yang et al., 2018). Central Yangtze River belt was extremely significant to ecological condition of the middle and lower Yangtze River Basin, which experienced intensive land use changes and impacted the local and regional climate (Wang et al., 2017).

4.3. Final considerations

From a long-term conservation perspective, in view of the rapid habitat loss and biodiversity reduction, the ecological network represents a valuable tool to protect the biotope and their ecological functions in China. In this regard, our results show the importance and need to develop a national protection network maintaining connectivity among them in order to achieve high cost efficiency. Definitely, our analyses imply that biodiversity, ecosystem services, and land use change should be incorporated into decision making (Liang et al., 2016).

In China, most habitats are highly fragmented and scattered, which are reflected in a great deal of small nature reserves. Corridors with both ecological and cultural functions can help connect fragmented patches of nature reserve system. Constructing a PA network composed of conservation priority and ECs is therefore particularly important, and can support the integration of ecological sustainability with human activities. Our approach provides a practical, transparent solution to the problem of maintaining high connectivity through the whole landscape that can be used to develop national strategies. However, one potential limitation is that future scenarios of climate change and land use are not considered, which may make the optimal solution identified here have a certain deviation in the future. Different climate scenarios may affect directly in the definition of conservation areas and future protection actions (e.g., Prieto-Torres et al., 2016; Rojas-Soto et al., 2012).

Since future scenarios are complex and act in a long run (Hua et al., 2015), the further studies should include methods to optimize the future ecological conservation under different future environmental changes scenarios (Prieto-Torres et al., 2016; Rojas-Soto et al., 2012). Furthermore, considerations of spatial scale are central to the process of designing an ecological network (Rouget et al., 2006). This is an important step in the process of making an effective national policy for ecological conservation. It is wise to strengthen cooperation between China and other neighboring countries in establishing or managing multinational ecological protection and construction (Bawa et al., 2010).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.01.086.

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