Land-use changes conservation network of an endangered primate (*Rhinopithecus bieti*) in the past 30 years in China

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Abstract

Aim: This study aims to propose a conservation network that contains suitable habitat and connectivity corridors for mitigation due to habitat transformation and fragmentation of Yunnan snub-nosed monkeys (*Rhinopithecus bieti*). Further, we also aim to understand the effects of land-use changes on the conservation network of *R. bieti* from 1990 to 2020.

Location: Three Parallel Rivers Region (TPRR) on the Qinghai–Tibetan Plateau (QTP) of China.

Methods: We used a GIS-based niche model to predict habitat suitability and extracted highly suitable habitats with an area above 30 km\(^2\) as potential core habitats (PCH patches). We designed a normalized importance value index (NIVI) to select PCH patches with the top 5 NIVI values designated as priority protection habitats (PPHs), and we selected a circuit model to build connectivity corridors among PPHs and five protected areas (PAs) from 1990 to 2020.

Results: Unsuitable areas and lowly suitable habitats increased 69.3 and 46.8 km\(^2\), respectively, from 1990 to 2020. In particular, the area of PPHs dramatically decreased from 212.1 km\(^2\) in 1990 to 101.6 km\(^2\) in 2020. Average length of connectivity corridors among PCH patches and PPHs decreased from 75.9 km in 1990 to 56.8 km in 2020.

Main conclusion: Habitat loss and fragmentation are common phenomena as evidenced by decreasing in highly and moderately suitable habitats of *R. bieti* and increasing in lowly suitable habitats and unsuitable areas. Five PAs are central to build a conservation network and to protect populations and wild groups of *R. bieti*. Land use changes the conservation network of *R. bieti* in the past 30 years. Based on re-planning boundaries of PAs to incorporate all protection network of *R. bieti*, it has practical significance to re-adjust the system of PAs that conservation network of *R. bieti* should be as fundamental management unit for PA development.

Keywords: connectivity corridor, conservation network, habitat suitability, land-use change, protected areas (PAs), *Rhinopithecus bieti* (*R. bieti*), Three Parallel Rivers Region (TPRR)
1 | INTRODUCTION

Land-use change is a major threat to terrestrial ecosystems, including substantial declines in suitable habitats of wildlife (Díaz et al., 2019; Jung et al., 2020; Powers & Jetz, 2019). Due to the impact of land-use change alone, by 2070, approximately 1700 species of terrestrial vertebrates globally are predicted to be endangered, including species of high conservation value and functional importance (Penjor et al., 2021; Powers & Jetz, 2019). Recent projections of worldwide forest degradation or deforestation suggest a potentially substantial increase in the extinction risk of forest-associated vertebrate species (Betts et al., 2017). For millennia (7000–9000 years ago), China experienced significant changes in patterns of land use and food production associated with animal and plant domestication, sedentarization and a major expansion of its human population (Li et al., 2018). In moving from a largely agrarian economy to a highly industrial economy in recent decades, great changes have taken place in land-use patterns in China (Liu, 2010). China has transformed its natural environment in ways that have negatively impacted biodiversity and species survival (Li et al., 2018; Ren et al., 2015). Today, due to its large human population (1.42 billion, the seventh China National Census) (National Bureau of Statistics, 2021), long history of agricultural production, deforestation, and recent expansion of cities, China is facing significant environmental challenges in attempting to balance social development and biodiversity conservation (Li et al., 2018). Dozens of government forestry bureaus were established for purposes of logging and the expansion of the timber industry from the 1950s to 1980s that led to the loss of 1.5 × 10^8 km² of forest in addition to losses incurred by the activities of private companies and illegal loggers (Li et al., 2018; Sun et al., 2004). China's timber resources are distributed principally in three major regions: northeast, southwest and south China, which coincide with zones of high primate diversity (Liu, 2014). Deforestation and degradation lead to habitat transformation and fragmentation of wildlife. Habitat transformation and fragmentation are primary causes for ongoing biodiversity loss, such as negatively affecting species' distributions, population structures, genetic diversities and likelihoods of survival (Zhao, Ren, Li, Garber, et al., 2019). Habitat fragmentation transforms large tracts of continuous habitat into smaller and spatially distinct patches immersed within a dissimilar matrix (Wilson et al., 2016; Zhao, Ren, Li, Xiang, et al., 2019). It also may hinder gene exchange among groups, generating isolated populations that must increase feeding effort to consume more energy to support greater movements (Li et al., 2020).

Identifying species and locations most at risk from habitat loss and fragmentation is key for prioritizing in management of biodiversity (Powers & Jetz, 2019). Three Parallel Rivers Region (TPRR) is a biodiversity hotspot in south Asia and a critical part of Asia’s water source and glacier ice repository of the ‘Third Pole’ in the Himalayas (Penjor et al., 2021). The extreme altitudinal variation and topographical complexity influence weather patterns and create a unique microclimate that harbours a wide assemblage of wildlife such as the endangered Yunnan snub-nosed monkey (Rhinopithecus bieti) (Li et al., 2013). Biodiversity in the TPRR is under siege from human-induced changes to the landscape (Li et al., 2018; Mahmoud et al., 2020). Habitat transformation and fragmentation, important forms of habitat degradation, are a consequence of forest degradation or deforestation. R. bieti is an endangered flagship and umbrella colobine species of the TPRR and leaf-eating primate endemic to China (Li et al., 2018, 2020). The range of R. bieti includes coniferous forests (such as Pinus yunnanensis) and alpine mixed broad-leaved coniferous forests (Grueter et al., 2013; Li et al., 2020). There are approximately 3500 individuals and 24 wild groups of R. bieti that inhabit the highest elevation (ranging up to 4500 m) of any non-human primate; the species’ population appears to have increased relative to IUCN estimates (Li et al., 2020; Long et al., 1994; Su et al., 2019). The primary factor contributing to the increase in population size of R. bieti is a decrease in anthropogenic disturbances including hunting and deforestation. For example, beginning in the late 1990s, China implemented large reforestation initiatives called ‘The Natural Forest Protection Program (NFP)’ and ‘National Nature Reserve Program’ (Li et al., 2018; Zhao et al., 2018). Despite the large amount of human and financial capital invested by China to increase forest cover, unless policies are specifically designed to expand the natural ecosystems required by R. bieti, the effectiveness of these policies for conservation is limited (Li et al., 2018). Most of these programmes are not aimed to regenerate native habitats that are crucial for R. bieti survival (Viña et al., 2016). Suitable habitat of R. bieti may decrease by 8.0%–22.4% by the year 2050 due to increased climate change and anthropogenic disturbances, such as forest products collection and the conversion of natural forest to pasture land for livestock grazing (Huang et al., 2017; Li et al., 2020; Zhao, Ren, Li, Xiang, et al., 2019).

Designing a conservation network will help to maintain population and wild groups of R. bieti. A conservation network contains suitable habitat and connectivity corridors among different habitats for mitigating habitat transformation and fragmentation of R. bieti. Establishing a conservation network is important for making robust conservation management decisions. The species distribution model, also commonly referred to as the ecological niche model, is a main tool used to derive spatially explicit predictions of environmental suitability for species (Guisan et al., 2013). Habitat suitability mapping is the first step in building a conservation network and often necessitates the integration of limited data from multiple sources, especially for R. bieti in remote mountainous regions of limited accessibility (Zhang et al., 2020). Information on occurrence sites of wildlife can be provided by predictions of species occurrences derived from environmental suitability models that combine biological records with spatial environmental data (Guisan et al., 2013). The second step to build a conservation network is the construction of connectivity corridors between the largest and the closest habitat fragments, which can provide one of the highest returns on investment for primate species (Newmark et al., 2017). In the short-term, human-made bridges or other constructed zones of safe passage and strips of non-native fast-growing tree species can be made as temporary...
connectivity corridors to achieve rapid recovery of *R. bieti* populations and wild groups (Li et al., 2018). However, in the long-term, these corridors should be comprised of native forest communities with the goal of expanding suitable habitat and ultimately increasing the size and genetic variability of *R. bieti* populations and wild groups (Li et al., 2018).

To understand the effects of land use on the conservation network of the endangered primate *R. bieti* from 1990 to 2020, we documented (1) shifts in habitat suitability, (2) construction of connectivity corridors among potential core habitat (PCH patches) and protected areas (PAs), and (3) proposes new conservation network and changes assessment within it.

## 2 | METHODS

### 2.1 | Study area

The study area, which is rich in biodiversity and mineral resources, is a part of the TPRR, named for the Nu-Salween, Lancang-Mekong and Jinsha Rivers. Bounded by the Lancang-Mekong River in the west and Jinsha River in the east, it contains Deqin, Weixi, Yunlong and Lanping Counties in Yunnan Province and Mangkang County in Tibet, with a total area of $3.3 \times 10^4$ km$^2$. Most wild groups of *R. bieti* are protected within 3 national nature reserves (NNR) (Honglaxueshan in Tibet, Baimaxueshan and Yunlontianchi in Yunnan Province) and 1 provincial nature reserve (PNR) (Yunling in Yunnan Province). Laojunshan scenic spot locates in the study area. Bamei wild group, which is located between Honglaxueshan NNR and Baimaxueshan NNR, is protected by an association organized spontaneously by people from Bamei Village. Covering an area of 2820 km$^2$, Baimaxueshan NNR is the biggest nature reserve with the endangered primate's range. Honglaxueshan NNR, Yunlontianchi NNR, Yunling PNR and Laojunshan scenic spots cover 1852, 145, 746 and 1107 km$^2$, respectively. Elevation ranges from 1300 m in the south to 5535 m in the north. The wet season is from May to October, and the dry season is from November to April.

### 2.2 | Data collection

We acquired eight variables including elevation, slope, aspect, distance to water, settlements and roads, vegetation type and land use and cover change (LUCC) for calculating habitat suitability of *R. bieti*. To survey forest ecosystem changes and to verify the accuracy of the LUCC surface as of 2020, we conducted a field investigation to collect 5342 GPS points with vegetation types along the route shown in the red line in Figure 1. LUCC data in 1990, 2000 and 2010 were provided by the ‘Environmental & Ecological Science Data Center for West China’ (http://westdc.westgis.ac.cn). LUCC data in 2020 were downloaded from GLOBELAND 30 (total accuracy was 85.72% and the Kappa coefficient was 0.82 tested by 5342 GPS points), which were provided by the Ministry of Natural Resources of the People’s Republic of China (http://www.globallandcover.com).

All LUCC data were raster with a resolution of 30 m × 30 m. We derived lakes from LUCC data in 1990, 2000, 2010 and 2020. We downloaded a Digital Elevation Model (DEM) data from the United States Geological Survey (USGS) (http://earthexplorer.usgs.gov/) at 30-m spatial resolution and derived the slope and aspect from those data. We obtained distribution data of settlements (locations of cities, counties and villages) and roads (national highways, provincial highways, county roads and village roads) in 1990, 2000, 2010 and 2020 and river data (vector) from ‘National Tibetan Plateau Data Center’ (http://westdc.westgis.ac.cn). Combining field survey results with occurrences from the literature, we identified 24 locations where *R. bieti* were known to occur to verify the accuracy of the GIS-based niche model (Su et al., 2019; Zhao, Ren, Li, Garber, et al., 2019; Zhao, Ren, Li, Xiang, et al., 2019).

### 2.3 | Habitat variables and GIS-based niche model

The GIS-based niche model incorporated eight environmental and biological variables that were deemed as potentially the most important factors based on ecological requirements and natural history of *R. bieti* (Huang et al., 2017; Su et al., 2015, 2019; Venne & Currie, 2021; Zhao, Ren, Li, Xiang, et al., 2019; Zhu et al., 2016). We tested for multicollinearity to avoid including highly correlated environmental variables. None of the variables were highly correlated ($r \geq 0.8$), and so, all were included in the models (Behdarvand et al., 2014; Cerqueira et al., 2021). For vegetation preferences, researchers have identified the main plant species in the diets of *R. bieti*, through analysing the mean relative density of plant fragments in faeces (Li, Peng, et al., 2006; Li et al., 2009, 2011, 2013; Su et al., 2019). The mean per cent of fragments was a proportion of different vegetation types indicating the main food of the *R. bieti* (Li et al., 2009, 2011, 2013; Su et al., 2019). Wild groups of *R. bieti* distributed in regions with elevation ranging from 2500 to 4700 m (Huang et al., 2017; Su et al., 2015, 2019; Zhao, Ren, Li, Xiang, et al., 2019; Zhu et al., 2016). There were no distributions of *R. bieti* wild groups with elevations above 4700 m. Because most of *R. bieti* wild groups distributed elevation ranged from 2800 to 3600 m, we used segmented assignment to identify suitability threshold values of elevation ranging from 2800 to 3600 m were one hundred (100). We assigned 75 with elevation ranging from 2701 to 2800 m and 3601 to 4300 m. From this, we normalized and assigned values from 0 to 100 to the eight variables with greater numbers indicating the preference by *R. bieti*, due to different values of eight variables. (Table 1) (Su et al., 2019). For example, if the value of slope was zero (0), it meant that *R. bieti* did not select this area as habitat, the same as vegetation, LUCC and so on. Firstly, we multiplied these eight normalized variables together to divide habitat suitability in the GIS-based niche model for yielding PCH patches for *R. bieti*. Second, the resulting maps from the GIS-based niche model were then reclassified with...
natural break into 4 kinds of potential habitats for *R. bieti*, in which 0 (zero) stood for unsuitable areas, 1–25 for lowly suitable habitats, 26–50 for moderately suitable habitats and 51–100 for highly suitable habitats (51–75 selected as PCH patches and 76–100 selected as PPHs) (Su et al., 2019). Finally, we used field survey data and references data to verify which suitability threshold values were more appropriate for *R. bieti*. Based on verification results, suitability threshold values (25, 50, 75 and 100) determined for dividing suitability levels can be used in this research. We defined all PAs as PPHs for *R. bieti*. Due to minimum requirements for habitat area of *R. bieti*, PCH patches with more than 30 km² were chosen to build connectivity corridors in the circuit model (Xiang et al., 2007, 2013).

2.4 Analyses in the circuit model

Circuit models can be used as simple movement models to inform areas of ecology that deal with networks when data are limited or lacking (McRae et al., 2008). We used the Linkage Mapper GIS tool which was designed to simulate connectivity corridors to connect all PAs and suitable habitats (McRae et al., 2008, 2013).
| Classification                  | Value | Classification            | Value |
|--------------------------------|-------|---------------------------|-------|
| **Aspect**                     |       |                           |       |
| 0°                             | 0     | 136°–225°                 | 100   |
| 1°–45°                         | 25    | 226°–270°                 | 75    |
| 46°–90°                        | 50    | 271°–315°                 | 50    |
| 91°–135°                       | 75    | 316°–359°                 | 50    |
| **Slope**                      |       |                           |       |
| 0°                             | 0     | 21°–40°                   | 100   |
| 0°–15°                         | 25    | Above 40°                 | 0     |
| 16°–20°                        | 50    |                           |       |
| **Distance to water**          |       |                           |       |
| Water source                   | 0     | 3.5 km away from water source | 75  |
| More than 5 km away from water source | 25 | 1 km away from water source | 100 |
| 5 km away from water source    | 50    |                           |       |
| **Elevation**                  |       |                           |       |
| 1300 m–2600 m, 4501 m–4700 m   | 25    | 2801 m–3600 m             | 100   |
| 2601 m–2700 m, 4301 m–4500 m   | 50    | Above 4701 m              | 0     |
| 2701 m–2800 m, 3601 m–4300 m   | 75    |                           |       |
| **Distance to settlement**     |       |                           |       |
| Settlement                     | 0     | 5 km away from settlement | 75    |
| 1 km away from settlement      | 25    | More than 5 km away from settlement | 100 |
| 3.5 km away from settlement    | 50    |                           |       |
| **Distance to road**           |       |                           |       |
| 50 m away from road            | 0     | 3.5 km away from road     | 75    |
| 100 m away from road           | 25    | More than 3.5 km away from road | 100 |
| 1 km away from road            | 50    |                           |       |
| **Vegetation**                 |       |                           |       |
| Tsuga chinensis pritz, Betula alnoides | 100 | Cotinus nana          | 50    |
| Tsuga dumosa (D. Don) Eichler  | 100  | Sophora davidii          | 50    |
| Betula platyphylla Suk         | 75    | Imperata cylindrica      | 50    |
| Abies delavayi Franch          | 75    | Bothriochloa ischaemum (L.) Keng | 50 |
| Betula albo-sinensis Burk. var. septentrionalis Schneid | 75 | Rhododendron telageiun | 50 |
| Platycladus orientalis         | 75    | Arundinella setosa, Arundinella anomala | 50 |
| Quercus aquifoliiodes          | 75    | Rhododendron flavidiun Franch | 50 |
| bies forrestii                 | 75    | Salix cupularis          | 50    |
| Picea balfouriana              | 75    | Themeda triandra Forsk. Var. Japonica (Wild.)Makino, Miscanthus | 50 |
| Neosino calamus affinis        | 75    | Caragana jubata (Pall.) Poir. | 50    |
| Larix potaninii var. macrocarpa | 75 | Rosa sericea Lindl. | 50 |
| Sabina tibetica Kom            | 75    | Rhododendron heliolepis Franch. | 50 |
| Lithocarpus variolosus (Fr.) Chun | 75 | Rhododendron delavayi Franch. | 50 |
| Castanopsis delavayi Franch    | 75    | Rhododendron fastigium Franch. | 50 |
| Pinus densata                  | 75    | Vaccinium bracteatum Thumb. | 50 |
| Quercus pseudosemecarpifolia A. Camus | 75 | Heteropogon contortus | 50 |
| Betula albo-sinensis Burk      | 75    | Malus baccata (L.) Borkh, Prunus padus L. | 50 |
| Pinus armandii Franch          | 75    | Rhododendron adenogynum Diels | 50 |
| Quercus pannosa Hand.-Mazz.    | 75    | Sabina pingiivar.wilsonii, Sabina squamata | 50 |
2012; McRae & Kavanagh, 2011). As R. bieti moves among core habitats, cost-weighted distance analyses produce maps of total accumulated movement resistance (McRae et al., 2008; Su et al., 2019). Constructing resistance surfaces is the first and key step to simulate connectivity corridors of R. bieti. Usually, cell values of resistance surfaces are given to reflect energetic cost, difficulty or mortality risk of moving across that cell (Su et al., 2019). It is typically determined by cell characteristics, such as topography (e.g., elevation, aspect and slope) or human disturbances (e.g., settlement/urban area and road), combined with species-specific landscape resistance models (Roever et al., 2013). Based on existing researches, we derived the elevation, slope and aspect preferred by R. bieti to draw the resistance map (Huang et al., 2017; Li, Grueter, et al., 2006; Xia et al., 2016). We used buffer analysis to obtain the spatial distribution of the effective range from settlement/urban area and roads and selected 1, 3.5 and 5 km from human activities as buffer distances in 1990, 2000, 2010 and 2020 (Xiang et al., 2013). The cell value of the resistance surfaces ranged from zero (minimum resistance value) to 100 (maximum resistance value).

2.5 | Design the NIVI index

We designed a normalized importance value index (NIVI) to describe the importance value of all PAs and PCH patches recognized from the GIS-based niche model in 1990, 2000, 2010 and 2020. We calculated the importance value index (IVI) of all PCH patches or PAs. To compare among the PCH patches or PAs, the IVI needs to be normalized between zero (no importance) and 1 (the most important) by the following formulas (Su et al., 2015, 2019):

\[
IVI = \frac{A}{T_L} \times T_N
\]

\[
NIVI = \frac{IVI - \text{Min}_{IVI}}{\text{Max}_{IVI} - \text{Min}_{IVI}}
\]

where IVI is the importance value index of the PCH patches or PAs in different years; A is the area of PCH patches or PAs; T_L is the total length of all connectivity corridors that connect one
FIGURE 2  Habitat suitability distributions of *R. bieti* in (a) 1990, (b) 2000, (c) 2010 and (d) 2020
TABLE 2 Areas of habitat, PCH patches and PPHs, and length of connectivity corridors among PCH patches, PPHs and protected areas

| Name                                   | 1990     | 2000     | 2010     | 2020     |
|----------------------------------------|----------|----------|----------|----------|
| Unsuitable area (km²)                  | 4425.2   | 4444.8   | 4453.6   | 4494.5   |
| Low suitable habitat (km²)             | 1273.1   | 1381.4   | 1379.8   | 1319.8   |
| Moderate suitable habitat (km²)        | 707.3    | 719.0    | 719.7    | 687.7    |
| High suitable habitat (km²)            | 901.5    | 761.9    | 753.9    | 805.1    |
| PCH patches (km²)                      | 1663.2   | 988.2    | 959.6    | 1048.2   |
| PPHs (km²)                             | 424.2    | 328.2    | 541.1    | 203.2    |
| Corridor length among PCH patches and PPHs (km) | 1593.3   | 821.1    | 1059.7   | 1363.1   |
| Corridor length among protected areas (km) | 673.2    | 584.9    | 885.6    | 696.0    |

Note: PCH patches—potential core habitats; PPHs—priority protection habitats.

PCH patch or PA; $N$ is the total number of connectivity corridors that connect one PCH patch or PA; $\text{Min}_{i,j}$ is the IVI minimum of one PCH patch or PA; and $\text{Max}_{i,j}$ is the IVI maximum of one PCH patch or PA.

We used the NIVI index to describe the protection importance and priority of all PCH patches and PAs. We selected the PCH patches with top 5 NIVI value and five PAs to propose a conservation network of *R. bieti*.

3 | RESULTS

3.1 | Habitat suitability changes from 1990 to 2020

There were 13 wild groups of *R. bieti* located in highly suitable habitats, 3 in moderately suitable habitats and 8 in lowly suitable habitats in 1990 (Figure 2a); 14 wild groups in highly suitable habitats, 4 in moderately suitable habitats and 6 in lowly suitable habitats in 2000 (Figure 2b); 13 wild groups in highly suitable habitats, 4 in moderately suitable habitats and 7 in lowly suitable habitats in 2010 (Figure 2c); 12 wild groups in highly suitable habitats, 3 in moderately suitable habitats and 9 in lowly suitable habitats in 2020 (Figure 2d). Areas of lowly suitable habitats and unsuitable areas increased 46.7 and 69.3 km², and areas of moderately suitable habitats and highly suitable habitats decreased 19.6 and 96.4 km² from 1990 to 2020 (Table 2).

3.2 | Spatio-temporal distributions of PCH patches and PPHs

Areas of PCH patches and PPHs decreased 615.1 and 221.0 km² from 1990 to 2020 (Table 2). There were 20 PCH patches with a total area of 1663.2 km² in 1990, 14 PCH patches with a total area of 988.2 km² in 2000, 12 PCH patches with a total area of 959.6 km² in 2010 and 13 PCH patches with a total area of 1048.2 km² in 2020. There were 2 PPHs with a total area of 424.2 km² in 1990, 3 PPHs with a total area of 328.2 km² in 2000, 7 PPHs with a total area of 541.1 km² in 2010 and 2 PPHs with a total area of 203.2 km² in 2020. Most of PPHs were around Baimaxueshan NNR and Laojunshan scenic spots from 1990 to 2020 (Figure 3a–d). None of PCH patches and PPHs were located inside or around Yunlingtianchi NNR from 1990 to 2020.

3.3 | Spatio-temporal changes of conservation network

There were 21 corridors with a total length of 1593.3 km among PCH patches and PPHs, and 6 corridors with a total length of 673.2 km among PAs in 1990; 15 corridors with a total length of 821.1 km among PCH patches and PPHs, and 6 corridors with a total length of 584.9 km among PAs in 2000; 20 corridors with a total length of 1059.7 km among PCH patches and PPHs, and 6 corridors with a total length of 885.6 km among PAs in 2010; and 24 corridors with a total length of 1363.1 km among PCH patches and PPHs, and 6 corridors with a total length of 696.0 km among PAs in 2020 (Figure 4). The average length of corridors among PCH patches and PPHs showed a decreasing trend during the study period, which was 75.9 km in 1990, 54.7 km in 2000, 53.0 km in 2010 and 56.80 km in 2020 (Table 2). The average length of corridor among PAs was 112.2 km in 1990, 97.5 km in 2000, 147.6 km in 2010 and 116.0 km in 2020. The total number of corridors among PAs did not change from 1990 to 2020.

4 | DISCUSSION

4.1 | Habitat transformation and fragmentation

Habitat transformation and fragmentation are widely regarded as among the greatest near-term threats to biodiversity survival, which causes reductions in population sizes of wild species and leads to greater likelihoods of extinctions and the collapse of ecosystems (Fletcher et al., 2018; Haddad et al., 2017). Meanwhile, habitat transformation can affect populations of wildlife through well-known effects on connectivity (i.e., the degree to which landscapes alter movement among habitats) and habitat edge to cause extinction (Fletcher, Didham, et al., 2018). To address the extinction of wildlife species, biodiversity conservation often...
FIGURE 3  PCH patches and PPHs distributions of *R. bieti* in (a) 1990, (b) 2000, (c) 2010 and (d) 2020.
**Figure 4** Conservation network of *R. bieti* in (a) 1990, (b) 2000, (c) 2010 and (d) 2020.
focuses on protecting species' populations, wild groups and habitats through a variety of legal and policy mechanisms such as the establishment of PAs (Evans & Malcom, 2021; UNEP-WCMC & IUCN, 2017). Understanding the roles of habitat transformation is highly relevant for decision-making regarding biodiversity conservation. Populations and wild groups of *R. bieti* are strictly protected by PAs and local governments that have overseen a stable rise to 3500 individuals and 24 groups during the past 30 years (Li et al., 2020). In the case study, land-use change has negative environmental impacts on the species' habitats that have become degraded and fragmented due to land-use changes, which result in an expansion of unsuitable areas and slowly suitable habitats and shrinkage of highly and moderately suitable habitats. As the main land-use change in the study area, forest degradation and deforestation are leading to a reduction in food availability, increasing habitat fragmentation and subpopulation isolation of *R. bieti* (Li et al., 2017). It is the main anthropogenic challenge that populations and wild groups of *R. bieti* face in the future. Fragmentation has led to a decrease in the total number of PCH patches from 20 in 1990 to 13 in 2020, and the number of corridors among PCH patches increased from 21 in 1900 to 24 in 2020. Most highly suitable habitats were located around Baimaxueshan NNR, Laojunshan scenic spots and Yunling PNR, and no highly suitable habitats were near Yunlongtianchi NNR. Several PCH patches and PPHs were around Laojunshan scenic spots from 1990 to 2020. As a scenic spot, there are intense human activities such as tourists and tourism infrastructure construction in Laojunshan, which may have negative effects on the survival of *R. bieti*. The PCH patches in the northern of Honglaxueshan NNR disappeared, and there was none of PCH patches and PPHs around Honglaxueshan NNR from 1990 to 2020. We found that land-use change used the conservation network of *R. bieti*, due to corridor length decreasing among PCH patches and PPHs, among PAs, and areas decreasing of PCH patches and PPHs during the study period.

We suggest that all connectivity corridors should be protected by PAs and re-built through restoration of native forest and construction of artificial forests (such as *Pinus yunnanensis*), which can increase movements of *R. bieti* between habitats and across PAs. Simultaneously, the restoration of native forest and construction of artificial forest communities also benefit the livelihoods of people in the local human communities, who collect and use a variety of forest products (Dosen et al., 2017; Li et al., 2018; Newmark et al., 2017).

## 4.2 Strong protective effect of protected areas

Human activities have both positive and negative effects on biodiversity conservation. As a negative human activity, illegal hunting was one of the greatest threats to the survival of *R. bieti*, due to local villagers hunting it for meat and fur and as traditional medicine from the 1960s to 1990s (Zhao, Ren, Li, Garber, et al., 2019). Due to the enactment by the Chinese government in 1988 of the Wildlife Protection Act that listed *R. bieti* within the first class of key protected primates in China, it is protected strictly and illegal hunting has a limited effect on survival (Zhao et al., 2018; Zhao, Ren, Li, Garber, et al., 2019). Land-use change is impacting biodiversity across the earth, which directly causes habitat transformation and fragmentation of wildlife (Fletcher, Didham, et al., 2018). As a positive human activity, PA policies can mitigate this negative impact to a certain extent at a local scale. The establishment of PAs is essential to local biodiversity conservation (Estrada & Real, 2018). PAs are designed to safeguard and protect all environmental components that maintain biodiversity and ecosystem services, including populations, habitats of wild species and natural ecosystems (Frederico et al., 2018; Margules & Pressey, 2000). The establishment and improvement of PAs have protected subpopulations of *R. bieti* residing inside these PAs, and in some areas, this has resulted in an increase in the size of the remaining local populations of *R. bieti* (Su et al., 2019; Zhao, Ren, Li, Garber, et al., 2019). However, people and governments only focus on protecting the population of *R. bieti* and wild groups but ignore the strict protection of its habitats and connectivity corridors that are affected directly by land-use change, such as large areas of primary forest have been converted into pastures for cattle grazing (Xiao et al., 2003). In general, the wildlife inhabiting PAs enjoy higher protection and lower disturbance by human activities (land-use change) than populations living outside the areas (Estrada & Real, 2018). The evaluation of protective effect of PAs on their capacity to preserve species distributions and their habitats is a key topic in conservation biology (Estrada & Real, 2018). In this research, the length and number of connectivity corridors among 5 PAs have changed little during the study period. Land-use change has a limited effect on the PA conservation network, which contains all PAs and connectivity corridors from 1990 to 2020. PAs have strong protective effect on *R. bieti* conservation due to limiting effects of land-use change.

## 4.3 Framework adjustment and optimization of PAs

With an aim to optimize PA frameworks and enhance protective effects, the central government of China launched ‘Guidelines on establishing a system of PAs with national parks as the mainstay’ in 2019. It is important to reorganize the structure of PAs, which may include the following: merger of adjacent similar PAs, boundary adjustments and administrative level adjustments. In this case study, there are Honglaxueshan NNR in Tibet, Baimaxueshan NNR and Yunlongtianchi NNR in Yunnan Province and Yunling PNR in Yunnan Province designed and built to protect *R. bieti* and its habitats. These PAs are located in Yunling Mountain and distances between them are <50 km. Some wild groups of *R. bieti* are outside of PAs and locate among PAs, such as the Bamei wild group that is located between Honglaxueshan NNR and Baimaxueshan NNR and some wild groups are located in Laojunshan scenic spot. Because there are no corridors to connect with other PAs or PCH patches and PPHs, Yunlongtianchi NNR, located in the southern part of the study area, has no corridors to connect with other PAs or PCH patches and PPHs.
area, has become an isolated island. It may make it more difficult for populations and wild groups of *R. bieti* inside Yunlongtianchi NNR to exchange genes with other populations. In our opinion, PA boundaries should be re-planned and re-shaped based on the locations of populations and wild groups of *R. bieti* and to maximize the number of PCH patches and PPHs protected inside PAs.

An alternative is to design a national park (NP) that protects all populations and wild groups of *R. bieti*, its habitats, all PCH patches, PPHs and connectivity corridors. To build a new conservation network of *R. bieti*, all PAs should be listed as conservation mainstays, all PCH patches and PPHs as key nodes and all connectivity corridors (among PCH patches, PPHs and PAs) in the conservation framework of the NP. We suggest that the NP should be managed under a unified administration framework and uniform administration departments that can be across different PAs, provinces and autonomous regions. Conservation policies are likely to become obsolete and useless unless the management of NP is suitable for wildlife survival and local biodiversity protection (Trivino et al., 2018). Management of the NP for *R. bieti* conservation is a coupled ecological–social system linking the local human–ecosystem–wildlife. One key issue of NP management is how to protect populations and wild groups of *R. bieti* while maintaining sustainable development, to protect local ecosystems and also can provide for human well-being. A NP may be expanded to balance the social benefits of economic growth and the negative costs of the human impact on ecosystem health and biodiversity. Effective management of NPs can promote human–wildlife harmony and development that can benefit biodiversity conservation, ecosystem function and society sustainability.

Therefore, this NP conservation framework should give full consideration to local human well-being and biodiversity conservation, which aim to protect biodiversity and maintain sustainable development for society. Another key issue of NP management is the effective implementation of laws and regulations that protect populations and habitats of wildlife from degradation caused by land-use change (Evans & Malcom, 2021). A significant limitation in biodiversity conservation has been the ineffective implementation of laws and regulations. It needs flexible, efficient and effective monitoring and enforcement methods to help conservation policies (laws and regulations) realize their full benefit (Evans & Malcom, 2021).

5 | CONCLUSIONS

In conclusion, using the GIS-based niche model and circuit model to re-build conservation network of *R. bieti*, we clarify that land-use change lead to habitat transformation and fragmentation of *R. bieti* (Zhao, Ren, Li, Garber, et al., 2019; Zhao, Ren, Li, Xiang, et al., 2019), which directly affect wild groups’ distributions and threat population structures, genetic diversities and likelihoods of survival in the past 30 years. Due to land-use change, habitat loss and fragmentation are common phenomena as evidenced by decreasing in highly and moderately suitable habitats of *R. bieti* and increasing in lowly suitable habitats and unsuitable areas.

We have shown that PAs are central to protect populations and wild groups of *R. bieti*. Especially, Baimaxueshan NNR, as the cornerstone to construct conservation network of the endangered primate, can connect other PAs together through corridors. Nevertheless, distribution patterns of Honglaxueshan NNR, Baimaxueshan NNR, Yunlongtianchi NNR and Yunling PNR are failure to protect all wild groups of *R. bieti* and to cover all PCH patches and PPHs. Several wild groups locate at Laojunshan scenic spot which is a tourist area instead of the *R. bieti* protection. Therefore, based on re-planning boundaries of PAs to incorporate all conservation network of *R. bieti*, it has practical significance to re-adjust the system of PAs that conservation network of *R. bieti* should be as fundamental management unit for PA development.

Here, we propose that expectations to find parallel patterns between endangered species protection and natural resources utility, especially in the TPRR which is a biodiversity hotspot. It may be an alternative way to design a NP which should completely protect all populations and wild groups of *R. bieti*, its habitats, all PCH patches, PPHs and connectivity corridors. For full consideration of local human well-being and biodiversity conservation, the management framework of this NP should be a coupled ecological–social system linking human–ecosystem–wildlife in local.

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CONFLICTS OF INTEREST

The authors declare there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.ftdz08tr.

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