Conservation planning on China’s borders with Myanmar, Laos, and Vietnam

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Article impact statement: Species distribution pattern and connectivity change call for transboundary conservation on China’s borders with Myanmar, Laos, and Vietnam.

Abstract
Transboundary conservation is playing an increasingly important role in maintaining ecosystem integrity and halting biodiversity loss caused by anthropogenic activities. However, lack of information on species distributions in transboundary regions and understanding of the threats in these areas impairs conservation. We developed a spatial conservation plan for the transboundary areas between Yunnan province, southwestern China, and neighboring Myanmar, Laos, and Vietnam in the Indo-Burma biodiversity hotspot. To identify priority areas for conservation and restoration, we determined species distribution patterns and recent land-use changes and examined the spatiotemporal dynamics of the connected natural forest, which supports most species. We assessed connectivity with equivalent connected area (ECA), which is the amount of reachable habitat for a species. An ECA incorporates the presence of habitat in a patch and the amount of habitat in other patches within dispersal distance. We analyzed 197,845 locality records from specimen collections and monographs for 21,004 plant and vertebrate species. The region of Yunnan immediately adjacent to the international borders had the highest species richness, with 61% of recorded species and 56% of threatened vertebrates, which suggests high conservation value. Satellite imagery showed the area of natural forest in the border zone declined by 5.2% (13,255 km²) from 1995 to 2018 and monoculture plantations increased 92.4%, shrubland 10.1%, and other cropland 6.2%. The resulting decline in connected natural forest reduced the amount of habitat, especially for forest specialists with limited dispersal abilities. The most severe decline in connectivity was along the Sino-Vietnamese border. Many priority areas straddle international boundaries, indicating demand and potential for establishing transboundary protected areas. Our results illustrate the importance of bi- and multilateral cooperation to protect biodiversity in this region and provide guidance for future conservation planning and practice.

KEYWORDS
connectivity, land-cover change, land-use change, protected areas, species distribution, species richness, transboundary conservation

Planeación de la Conservación en las Fronteras de China con Myanmar, Laos y Vietnam

Resumen: La conservación transfronteriza cada vez juega un papel más importante en la preservación de la integridad del ecosistema y en el freno a la pérdida local de la biodiversidad causada por las actividades antropogénicas. Sin embargo, la falta de información sobre la distribución de las especies en las regiones transfronterizas y de la comprensión de las amenazas en estas áreas obstaculiza la conservación. Desarrollamos un plan de con-
INTRODUCTION

Earth’s biodiversity is essential to human well-being, but the expanding scale of human activities severely threatens it (Johnson et al., 2017). For geographical and historical reasons, transboundary regions often contain critical ecosystems that support rich biodiversity and play important roles in maintaining connectivity (Liu et al., 2020). More than half of terrestrial vertebrate species have ranges spanning international borders (Mason et al., 2020), yet transboundary conservation has so far focused on a few flagship species, such as mountain gorillas (Gorilla beringei beringei), Amur tigers (Panthera tigris altaica), and...
the eastern black crested gibbon (Nomascus nasutus), largely neglecting other species (Liu et al., 2020). Some species can disperse outside of existing protected areas (PAs) or shift their distributions by crossing international borders in response to climate change or human disturbances (Johnston et al., 2013; Urban, 2015). However, lack of transboundary planning has put many species in increasing peril through uncoordinated management among neighboring countries, which greatly impairs conservation effectiveness (Mason et al., 2020; Thornton et al., 2018). Transboundary conservation can also make a major contribution to current efforts to reduce future extinction risks by increasing the area protected, in accord with the zero draft of the Convention on Biological Diversities’s (CBD) post-2020 global biodiversity framework in which a target of 30% of land and oceans by 2030 is proposed (CBD, 2020). Appropriate spatial prioritization is crucial for both transboundary conservation and achieving the CBD’s proposed target because it can ensure that most important areas for biodiversity are included and PAs are well-connected within and across borders (Thornton et al., 2018; Hannah et al., 2020).

Species distribution mapping and land-use change analysis are widely used in conservation planning. Spatially explicit maps can help identify priority areas for biodiversity conservation (Zhang et al., 2012). Land-use change caused by human activities alters landscape structure, which may hinder or promote dispersal and migration of species and ultimately influence population viability (Hanski, 2011; Saura et al., 2014; Martensen et al., 2017). Landscape connectivity is determined by the dispersal abilities of species and the spatial configuration of habitat patches in the landscape (Saura & Rubio, 2010; Saura et al., 2011). Changes in connectivity over time as a consequence of land-use change may determine whether a species can persist in a landscape in the long term (Metzger et al., 2009). Generally, specialist forest-inhabiting species, such as small mammals and insectivorous birds, disperse poorly across unforest areas and are thus expected to be at increased risk of extinction when connectivity decreases (Martensen et al., 2012). Differing land-use policies between adjacent countries can reduce connectivity in transboundary regions, leading to weakened conservation effort. Therefore, assessing changes in connectivity is essential for strengthening biodiversity conservation in transboundary areas.

China’s Yunnan province borders Myanmar, Laos, and Vietnam; the total border length is 4060 km. This region is largely in the Indo-Burma biodiversity hotspot, yet habitat destruction and hunting have caused declines in wildlife populations (Myers et al., 2000; Xu & Wilkes, 2004; Harrison, 2011; Hughes, 2017). Despite forceful appeals for transboundary conservation, the spatial distributions of biodiversity and threats to landscape connectivity in the transboundary region remain unknown because there have been few biodiversity surveys and little transboundary sharing of data (Wang et al., 2016; Basnet et al., 2019; Liu et al., 2020). We integrated species distribution patterns and recent land-use change and determined the change of landscape connectivity for natural forest in the transboundary region to identify priority transboundary areas for conservation and restoration.

METHODS
Study area
Our study area was between 20°−29.5°N and 96°−107°E. It covered all of Yunnan and a transboundary region, including 100-km-wide strips on both sides of the international borders between China and Myanmar, Laos, and Vietnam (Figure 1). The total areas of Yunnan (394,100 km²) and the transboundary region (395,227 km²) are very similar. The transboundary region contains 4 subregions: southwestern China, northeastern Myanmar, northern Laos, and northern Vietnam. This region hosts one of the largest remaining contiguous natural forest blocks in Southeast Asia, supporting numerous species, and has been recognized as a global hotspot for biodiversity conservation (Myers et al., 2000). However, losses of natural forest are now occurring at an unprecedented rate due to the expansion of cash-crop plantations, other croplands, and logging (Stibig et al., 2014; Zhang et al., 2019).

Methodological framework
We identified priority areas for conservation and restoration in the transboundary area through an analysis of species richness patterns to assess the importance of the transboundary region for biodiversity conservation and an assessment of land-use change in the transboundary region based on satellite imagery. We divided the transboundary region into 4151 equal-area planning units (landscapes) and quantified the connectivity change for natural forest in each landscape. We defined landscape connectivity as the degree to which habitat amount and spatial configuration of habitat patches facilitate or impede movements of species (Saura et al., 2011; Martensen et al., 2017). Following Margules and Pressey (2000), we then identified conservation and restoration priorities using both the irreversibility of a site (i.e., its importance in maintaining species persistence) and its vulnerability (i.e., urgency of the threats to connectivity). A map for the methodological framework is in Appendix S1.

Data collection
We compiled a comprehensive new data set of species distributions for vascular plants and vertebrates in Yunnan from specimen collections and monographs (Appendix S2). Most records were from 1980 to 2005, but we also included new plant species discoveries up to 2017. Similar data were not available for Myanmar, Laos, and Vietnam, so we also downloaded the species range polygons (most vertebrate and a few plant species) from the International Union for Conservation of Nature (IUCN) (https://www.iucncatalogue.org/resources/spatial-data-download). These are based on an expert assessment of available data and are expected to be at least partly independent of our Yunnan data set (Appendix S3). To
analyze the land-use change, we obtained satellite imagery from the Landsat Thematic Mapper (TM) (level-1 data products) in 1995 and the Landsat 8 Operational Land Imager (OLI) (level-1 data products) in 2018 via EarthExplorer (Appendix S4 [https://earthexplorer.usgs.gov]). We downloaded PA data from the World Database on Protected Areas (https://www.protectedplanet.net) and added some new boundary polygons for nature reserves in Yunnan. Administrative boundaries of Yunnan province came from the National Geomatics Center of China (https://www.webmap.cn) and country boundaries for Myanmar, Laos, and Vietnam from the Database of Global Administrative Areas (https://gdam.org).

Species richness mapping

Most species distribution records from Yunnan were reported as occurrences in a county, of which there are 129 in Yunnan, with areas ranging from 438 to 11,421 km². To assess the conservation importance of the transboundary region, we therefore assigned each county to 1 of 5 concentric zones. The counties on the border form the first zone, the counties with their boundaries touching the first zone form the second zone, and so on, with adjustments to ensure that the zones were approximately the same size despite variation in the sizes of the counties (Figure 1). We implemented a data-cleaning process with the following steps: first, subspecies were merged to species level; second, records without distribution information at county level were excluded; and third, duplicate records for the same county were removed. The Yunnan data set for species richness analysis contained 18,991 plant species and 2013 vertebrate species. There were a total of 197,845 county-level records. We also identified threatened species from the IUCN Red List (https://www.iucnredlist.org), including species listed as vulnerable (VU), endangered (EN), and critically endangered (CR). A total of 158 vertebrate species from our data set were rated as threatened, but few plants were listed, reflecting the small proportion

FIGURE 1 Study area in Myanmar, Laos, Vietnam, and Yunnan province, China. The transboundary region contains 4 subregions: southwestern China (SWoC), northeastern Myanmar (NEoM), northern Laos (NoL), and northern Vietnam (NoV). Yunnan was divided into 5 zones with different colors.
of plant species in this region that have been assessed. We used an R package, iNEXT, to evaluate the representativeness of the data set for species richness in the 5 different zones (Hsieh et al., 2016). Processing of the IUCN range polygons is described in Appendix S3.

**Land-use classification**

We used satellite imagery with a spatial resolution of 30 m (from the Landsat Thematic Mapper from 1995 and the Landsat Operational Land Imager from 2018) to map the land uses for these 2 years in the transboundary region. We classified the region into 6 land-use types: natural forest, shrub, meadow, plantation, cropland, and other land covers (including urban, roads, waterbodies, bare lands, and glaciers) (Appendix S4). The training data for supervised classification and the validation data for assessing classification accuracies were collected by field surveys from 2012 to 2019 (Appendix S4) and by visual interpretation of high-resolution remote sensing images from Google Earth. The sampling protocol was based on geographic strata and designed to maximize the geographic spread of the samples. We conducted a supervised image classification in ENVI software. The assessment of classification accuracy showed the overall accuracies were 91.1% and 91.4% for the years 1995 and 2018, respectively. Producer and user accuracies for natural forest were ≥90.0% for the 2 study years (Appendix S4). For more information on satellite imagery and its processing, classification accuracies, and definitions of land use and land cover, see Appendix S4.

**Evaluation of changes in connectivity for natural forest**

Natural forest harbors the overwhelming majority of species in the Indo-Burma biodiversity hotspot (CEPF 2012). Connectivity in natural forest is closely associated with the spatial configuration of forest patches in a landscape and the dispersal ability of species. To evaluate the change in connectivity, we created maps of natural forest cover for 1995 and 2018 after land-use classification. We divided the transboundary region into 4151 hexagonal landscapes of 100 km² each (landscapes hereafter) (Ochoa-Quintero et al., 2015). For each landscape, we designated 3 dispersal distances (100, 1000 and 10,000 m) that represent broadly the dispersal abilities of different generic groups of forest-dwelling species (Wang et al., 2016). For each dispersal distance, we calculated the equivalent connected area (ECA) with the Conefor 2.6 command line version. The ECA is the amount of reachable habitat for a species and incorporates both the habitat in a patch (i.e., patch area) and the amount of habitat in other patches within dispersal distance (Saura & Torne, 2009; Saura et al., 2011):

$$ECA = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j p_{ij}^\delta},$$  

(1)

where \(a_i\) and \(a_j\) denote sizes of natural forest patches \(i\) and \(j\), respectively; \(n\) is the number of patches in a hexagonal landscape; and \(p_{ij}^\delta\) is the maximum product probability for all possible paths between patches \(i\) and \(j\). A path with maximum product probability has the highest connection probability among all the paths between 2 patches. The interpatch dispersal probabilities \(p_{ij}\) were calculated as:

$$p_{ij} = e^{-d_{ij}},$$  

(2)

where \(d_{ij}\) is the edge-to-edge distance between patches \(i\) and \(j\) and \(k\) is a constant (Saura & Pascual-Hortal, 2007).

The ECA is influenced by the dispersal capacity of a species and the landscape structure and has the advantages of area units and a straightforward interpretation, so it can be compared directly with the natural forest cover. For example, for a species with strong dispersal ability, such as the great hornbill (Buceros bicornis), which can disperse seeds 13 km from the breeding site (Naniwadekar et al., 2019), the reachable habitat coincides with the natural forest area in our defined landscape (because each hexagon landscape is approximately 12.4 km between the farthest vertices). In contrast, forest-inhabiting small mammals are more likely to be confined to certain forest fragments due to their limited dispersal abilities, so their ECA is less than the natural forest area in the landscape. We used the difference between the ECA (ΔECA) for the 2 study years to reflect the changes in connectivity (i.e., the habitat available) for each landscape, and the annual change rate of ECA was calculated by dividing by 23 years (from 1995 to 2018). The ECA for 1995 and 2018 are in Appendix S5.

**Identification of priority areas for conservation and restoration**

Recent studies suggest that retaining 30–50% forest cover is necessary to safeguard native biodiversity in a landscape (Martensen et al., 2012; Ochoa-Quintero et al., 2015). Moreover, landscapes with the intermediate level of forest cover and connectivity, such as our 30–50% ECA coverage, are considered intermediate resilience landscapes, where biodiversity is still high but vulnerable to local extinctions and the potential of biodiversity gains is greater via restoration (Tambosi et al., 2014; Grouzilles et al., 2016). Although forest cover is widely used to evaluate priority, we adopted ECA to rank the priorities for all the landscapes because it can reflect habitat availability for forest-dependent species (i.e., habitat that is reachable). For any of the dispersal distances we specified, we assumed the ECA would maintain a constant annual change rate in the respective landscape into the future. Based on this assumption and the ECA in 2018 (ECA2018), we calculated the ECA for the future 10, 20, and 30 years (ECA2028, ECA2038, and ECA2048, respectively). If ECA2018 was > 50 km² and ECA2028 was < 50 km² in a landscape, meaning that expected deforestation reduced habitat availability below the 50% threshold (because each landscape is 100 km²) in the next 10 years, then a high priority for conservation was assigned. If the ECA dropped below the
TABLE 1  Transition matrix for the areas (km²) of land-cover types in the transboundary region of southwestern China, Myanmar, Laos, and Vietnam

| From          | Natural forest | Shrub | Meadow | Plantation | Cropland | Other | Totala | Gross lossc |
|---------------|----------------|-------|--------|------------|----------|-------|--------|-------------|
| Natural forest| 206,662        | 36,887| 2796   | 5080       | 4698     | 992   | 257,115| 50,453      |
| Shrub         | 29,503         | 39,331| 4719   | 4100       | 7837     | 900   | 86,390| 47,059      |
| Meadow        | 2416           | 6957  | 4851   | 334        | 2448     | 370   | 17,376| 12,525      |
| Plantation    | 2341           | 1787  | 45     | 1070       | 797      | 145   | 6185   | 5,115       |
| Cropland      | 2620           | 9522  | 710    | 1199       | 8867     | 802   | 23,720| 14,853      |
| Other         | 318            | 628   | 1408   | 117        | 552      | 1416  | 4439   | 3,023       |
| Totald        | 243,860        | 95,112| 14,529 | 25,199     | 4625     | 395,225| 133,028|
| Gross gaind   | 37,198         | 55,781| 9678   | 10,830     | 3209     | 133,028|

a The diagonal indicates the areas persisting as each land-cover type.

b Area of each land-cover type in 1995.

c Gross loss and gross gain indicate, respectively, the total losses and gains for each land-cover type from 1995 to 2018.

d The area of each land-cover type in 2018.

50% threshold by 2038 (i.e., ECA_{2018} > 50 km² and ECA_{2028} > 50 km², but ECA_{2038} < 50 km²), then it was assigned an intermediate conservation priority. If ECA_{2018-2038} > 50 km² and ECA_{2048} < 50 km², meaning it took 30 years for the ECA to drop below the 50% threshold, then the landscape was assigned a low conservation priority. If a landscape had >1 rank, the higher rank was assigned. In addition, we assigned high restoration priority to those landscapes when ECA_{2018} was 30–50% and the expected ECA was below 30% in the following 10 years, which means urgent human intervention is necessary. For each dispersal distance (100, 1000, and 10,000 m), we identified conservation and restoration priorities for all landscapes following the above rules. If high conservation priority was assigned to a landscape at all 3 dispersal distances, then it was given a final high conservation priority. Final intermediate and low priorities were determined in the same way. We also conducted a sensitivity analysis for ECA thresholds (Appendix S5). Using an ECA threshold of 50% to identify the conservation priority area, we considered the degree of threat in landscapes, the numbers of landscapes that need protection (associated with conservation costs), and the potential for transboundary conservation (i.e., the distribution of prioritized landscapes) (details are in Appendix S5).

RESULTS

Species richness pattern

Our Yunnan data set included 97% of the vertebrate and plant species known from Yunnan and 47% of those from China. For Yunnan, the range of completeness was 70% (amphibia) to 98% (ray-finned fish) (Appendix S2). The rarefaction curves showed the Yunnan data set gave a reasonable representation of species richness in all the 5 zones (Appendix S2). In zone 1, there were 11,297 plant species (59% of all plants in the Yunnan data set) and 1467 vertebrates (73%), and the species richness decreased gradually from zone 1 to zone 5 (Figure 2a & b). Maps based on the IUCN range maps showed similar patterns for Yunnan and confirmed that high richness continued across the borders (Appendix S3). Of the new plant species described in Yunnan in the past 2 decades, 59% were found in zone 1 (Figure 2c). In addition, 56% of the threatened vertebrates occurred in zone 1 (Figure 2d).

Land-use change in the transboundary region

From 1995 to 2018, the net losses in natural forest and meadow in the transboundary zone were 5.2% (13,255 km²) and 16.4%, respectively, whereas the net gains in plantation, shrub, cropland, and other were 92.4%, 10.1%, 6.2%, and 4.2% (Table 1 & Appendix S4). During this period, 50,453 km² of natural forest was converted to other land uses. The gains in plantations and croplands mainly came from the loss of natural forest and shrub (Table 1), accounting for 77.1% and 49.7% of their respective gross gains.

From 1995 to 2018, the net loss of natural forest in northern Vietnam (NoV) was 22.6%, which was much higher than other subregions. Plantations increased dramatically in NoV (net gain of 378.1%) followed by southwestern China (SWoC) (93.9%) and northern Laos (NoL) (61.3%). Other cropland expanded rapidly in NoV and NoL, but declined in SWoC (Appendix S4).

Change in landscape connectivity in the transboundary region

In more than half of the landscapes, the area of connected natural forest declined (∆ECA < 0) from 1995 to 2018 at all 3 dispersal distances (Figure 3b). Exceptionally high declines occurred in 3.6% of landscapes (Figure 3 148 red hexagons) (∆ECA < −50 km² at 100-m dispersal distance). The proportions were 2.6% and 2.1% (Figure 3 106 and 88 red hexagons, respectively) at dispersal distances of 1000 and 10,000 m, respectively. Overall, ECA declined by 14,894, 13,506, and 13,258 km² at the
3 dispersal distances, from small to large, respectively, despite increasing ECA in some landscapes. A paired sample \( t \) test showed that the changes in ECA at the 3 dispersal distances were significantly different (all \( p < 0.027 \)).

The most severe decline in landscape connectivity occurred in NoV; mean values of \( \Delta \text{ECA} \) ranged from \(-18\) to \(-15\) km\(^2\) at the 3 dispersal distances, followed by NoL, SWoC, and northeastern Myanmar. Most landscapes where ECA decreased more than 50 km\(^2\) (red hexagons) were in NoV and SWoC (Figure 3b).

**Conservation and restoration priorities in the transboundary region**

In the transboundary region, 6.9% of the landscapes (286 hexagons with orange and green colors [Figure 4]) were identified as candidates for further conservation and restoration, of which 1.9% (79 dark green hexagons) had high conservation priority and 0.8% (33 orange hexagons) had high restoration priority. The existing PAs covered only 7.7% of the transboundary region and 9.7% of the priority areas (Figure 4a). Many
candidates were distributed contiguously across international borders, such as the China-Myanmar border (Figure 4b) and China-Laos-Vietnam border (Figure 4c). Some candidates appeared among isolated PAs (Figure 4d).
FIGURE 4  Conservation and restoration priorities ranked by the predicted future rate of change in landscape connectivity: (a) the 286 landscapes chosen as priority candidates for further conservation and restoration and (b–d) representative areas highlighting transboundary conservation and potential protected-area connections

DISCUSSION

Conservation implications from species richness pattern in Yunnan

Spatially explicit maps are particularly useful for identifying areas where conservation efforts should be intensified. Previous studies of species distribution patterns provided valuable insights into plant conservation priorities for Yunnan (Zhang et al., 2012; Zhang et al., 2014), but our results are based on many more location records and provide a wider selection of taxa, including mammals, birds, amphibians, reptiles, and fishes (Appendix S2). Maps generated from 2 partly independent data sets (ours and the IUCN range maps) both showed the
highest richness of vertebrates in the transboundary region (Figure 2b & Figure 5a). Most species had transboundary ranges, including the recently discovered black snub-nosed monkey (Rhinopithecus strykeri), on the northern Sino-Myanmar border, the Asian elephant (Elephas maximus), distributed in Southeast Asia and southern Yunnan, and the great hornbill (Buceros bicornis) and green peafowl (Pavo muticus), distributed in south-central Yunnan, Myanmar, Laos, and Vietnam (IUCN 2020). These results underline the importance of transboundary conservation in this region. The high species richness in this region has been attributed to the high environmental heterogeneity, as a result of the uplift of the Himalaya-Tibetan Plateau and extrusion of the Indochina block, and to the tropical climate (Liu et al., 2017). The same factors have reduced accessibility and thus human impacts, until recent decades. The current incompleteness of knowledge is highlighted by the 39 new plant species per year discovered in Yunnan from 2000 to 2017; 59% occur the border area (Figure 2c). Completing the species inventory on both sides of these borders is essential for effective conservation planning and to prevent species from becoming extinct before they are recognized (Liu et al., 2019).

### Threats to biodiversity in the transboundary region

In Southeast Asia, logging, expansion of cropland and plantations, such as rubber, tea, and oil palm, have been the main causes of natural forest loss (Stibig et al., 2014; Zeng et al., 2018). As accessibility has increased, natural forests in the transboundary region have been subjected to logging and replacement by monoculture plantations and cropland. The annual net rate of loss was 0.2% (576 km$^2$) from 1995 to 2018. More rapid expansion of plantations and croplands has occurred in the border region of Vietnam (Figure 3a) (annual increase of 16.4% and 12.7%, respectively) (Appendix S4), which probably reflects the rapid economic growth in Vietnam in over this period (Vu et al., 2014). On the other side of the border, in southwestern China, the annual net loss rate of 0.1% for natural forest was much lower, which can be attributed to 2 nationwide forestry policies enacted in 2000, the National Forest Protection Program and the Grain-for-Green Program. But the decline of natural forest is still alarming in some areas, such as Xishuangbanna (Zhang et al., 2019).

Previous land uses and policies have led to a decline in connectivity in the transboundary region, which is shown in the ECA index. The decline of connectivity means increased distances between habitat patches, which may result in higher mortality when species try to disperse among these habitat patches. This decline also sharply decreases reachable habitat, which may impede gene flow and lead to genetic isolation and ultimately influence population viability (Hanski, 2011; Saura et al., 2011). Although connectivity in some landscapes has improved in southwestern China (Figure 3b), protection on only one side of the border may not reduce the extinction risk for species with transboundary ranges because overall connectivity across the international boundary has decreased (Thornton et al., 2018).

The transboundary region is also a hotspot of poaching and illegal timber and wildlife trade due to limited government enforcement. These illegal activities have affected many species, causing a rapid decline in biodiversity (Liu et al., 2020). Collaborative transboundary conservation enforcement is urgently needed.

### Future conservation in the transboundary region

Projected further declines of ECA suggest an urgent need for conservation and restoration efforts because the time lag in biological responses to landscape change may be short (Metzger et al., 2009; Gibson et al., 2013). The landscapes with high conservation priorities are concentrated on the borders. Combining these landscapes with the existing PAs to form 2 large transboundary PAs (Figure 4b & c) would help protect biodiversity and maintain connectivity of forest ecosystems while directly benefiting some flagship species with small populations and transboundary ranges, such as the black snub-nosed monkey, hoolock gibbon (Hoolock hoolock), and gongshan muntjac (Muntiacus gongshantis). According to our long-term monitoring, some species, such as the green peafowl and northern white-cheeked gibbon (Nomascus leucogenys), have disappeared from Xishuangbanna prefecture in Yunnan. Bilateral or multilateral cooperation in biodiversity conservation and habitat restoration may help natural recovery.

The Chinese government is planning to establish a national park for China’s last Asian elephant populations in Xishuangbanna and adjacent prefectures. Elephants often move across the border between China and Laos. Maintaining or promoting connectivity to ensure movement of species between the extant PAs can also be achieved by protecting or restoring the landscapes with high priorities (Figure 4d). Whether establishing transboundary PAs or preserving connectivity between the extant PAs, conserving more lands for facilitating species dispersal and movement will be crucial to coping with the challenges posed by climate change and human disturbance (Hannah et al., 2020).

In addition to transboundary PAs, coordinated management across international borders is required to curb illegal logging and wildlife trade. These activities have been prevalent on the borders between Myanmar and China and Laos and China and have resulted in substantial losses of natural forest and biodiversity.

Challenges to transboundary conservation have also emerged. In Myanmar, civil unrest and armed conflicts have posed a critical threat to wildlife and habitat. Armed groups that do not recognize central government authority control most of the border areas of Myanmar, including Kachin State, bordering China in northernmost Myanmar, and Shan State, to the south of the Kachin State and bordering China, Laos, and Thailand. In these conflict zones, PAs have a low priority, and those proposed by the central government may not be recognized locally. Biodiversity surveys have not been possible. Transboundary conservation in contested borderlands requires a peace process, strong rule of law, and, even more than elsewhere, collaborative...
management. There is also a complicated political relationship between China and Vietnam for historical reasons, although scientific exchanges have continued. We believe, however, that strengthening comprehensive cooperation is conducive to improving the bilateral relations and that transboundary conservation can play an important role in this and benefit from it.

Research limitations and future applications

The species distribution patterns we found confirm the importance of transboundary conservation, and the recent land-use changes highlight its urgency. Our study is a first step in future conservation planning and action for the area. Our prioritization considered the importance of an area and the degree of threat, so some landscapes with high ECA values but low threat were not chosen. However, these low-threat landscapes are also important in maintaining biodiversity. Most are concentrated in northeastern Myanmar and are not close to the international boundary (Appendix S5), so they can be considered potential targets for domestic extension of PAs. We did not account for poaching in our prioritization because data are not available. Further research aimed at the design and establishment of transboundary PAs should integrate more information, such as costs, poaching pressure, distributions of settlements and roads, needs of stakeholders, and the provision of ecosystem services.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.