“Mapping Conservation Priorities and Assessing Connectivity Pathways for Threatened Mammals under Future Climate Change in the Eastern Himalayan Biodiversity Hotspot of Bhutan”

Thesis submitted by

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in fulfillment of requirements for the degree of ‘Doctor of Philosophy’ to School of Environmental and Rural Science, University of New England, Armidale, NSW 2350, Australia.

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10 April 2019

Certification

Statement by the Candidate

I hereby state that the work embodied in this thesis titled "Mapping Conservation Priority Areas and Assessing Connectivity Pathways under Future Climate Change in the Eastern Himalayan Biodiversity Hotspot of Bhutan" forms my own contribution to the research work carried out. This work has not been submitted for any other degree or any other University. Whenever the references have been made to the previous work of others, it has been clearly indicated as such and included in the references.

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Please be advised that this thesis contains chapters which have been either published or submitted for publication.

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Thesis Abstract

High species diversity and endemism within a vast area of intact and unexplored landscapes, makes the Eastern Himalayas a unique global biodiversity hotspot. The region is home to 255 native terrestrial mammal species including 75 globally threatened species such as the iconic tiger *Panthera tigris*, snow leopard *Panthera uncia* and the greater one-horned rhinoceros *Rhinoceros unicornis*. To complement the IUCN Red List of Threatened Species, I assessed the current conservation status of native terrestrial mammal species in the Eastern Himalayas and identified the 50 most threatened species based on conservation status, endemism, range size, and evolutionary distinctiveness. Despite a mismatch between current distribution of protected areas and priority areas to conserve these threatened mammals, my findings on the extent of ecoregion protection suggests adequate remaining natural habitats to expand current Eastern Himalayan protected areas.

Between 2014 and 2015, I deployed 1858 camera traps within 1129 5-km x 5-km grids over 536 days to investigate richness and diversity of mammals between protected areas, biological corridors, and intervening areas (NPAs) along an elevational gradient in Bhutan. My study revealed 18 (32%) of 56 identified mammal species were IUCN-listed threatened species. Bhutan's network of protected area and biological corridors harbor a richer mammal community than NPAs. Vegetation zones at upper and lower elevation ranges had high species richness and diversity relative to mid-elevations which had higher human presence.

Finally, I assessed the ecological functionality, structural design, and management effectiveness of Bhutan's biological corridor network by integrating detailed climatic, ecological, and biological data with emphasis placed on meta-populations of threatened, wide ranging, and

umbrella mammal species. To capture areas known to support high diversity of threatened species and reconcile current land use impact and climate change on biodiversity, the top seven priority areas for expansion within this network were identified. My innovative study fills a gap in existing knowledge on current progress and future prospective toward the novel idea by E.O. Wilson of securing a half earth, to conserve biodiversity, address the species-extinction crisis, and prevent collapse of vital ecosystem services such as carbon sequestration and climate regulation. My work is also an important milestone in addressing knowledge gaps for conservation of threatened mammals in the Eastern Himalayas. Regional collaborative cooperation for effective transboundary research and management is necessary, and regional prioritizing of areas for biodiversity conservation is essential to prevent species extinction.

Chapter 1: General Introduction

The Eastern Himalayan region encompasses Bhutan, parts of China, India, Myanmar and Nepal (Figure 1.1). High species diversity and endemism, together with a vast area of intact and unexplored landscapes, makes the region a unique global biodiversity hotspot (CEPF, 2005, WWF, 2015, Myers *et al.*, 2000, Velho *et al.*, 2016, Olson *et al.*, 2001). There are an estimated 10,000 plant, 300 mammal, 977 bird, 176 reptile, 105 amphibian, and 269 freshwater fish species in the region. The biological richness in the Eastern Himalayan region stems from its location at the juncture of the Indo-Malayan and Palearctic biogeographic realms, with pronounced ecological and altitudinal gradients (Olson *et al.*, 2001, Olson and Dinerstein, 1998, Badgley, 2010, CEPF, 2005). Iconic mammal species in the tropical forests of the Indo-Malayan realm include the royal Bengal tiger *Panthera tigris tigris*, Asiatic elephant *Elephas maximus*, greater one-horned rhinoceros *Rhinoceros unicornis*, sloth bear *Melursus ursinus*, and gaur *Bos gaurus*. Other notable mammals include the wild dog *Cuon alpinus*, several species of langurs *Semenopithicus spp*. and deer such as the muntjac *Muntiacus muntjak* and sambar *Cervus unicolor*. Flagship mammals in the subalpine conifer and mixed forests of the Palearctic realm include the snow leopard *Panthera Uncia*, Asiatic black bear *Ursus thibetinus*, blue sheep *Pseudois nayur*, takin *Budorcas taxicolor*, Himalayan thar *Hemitragus jemlahicus*, and red panda *Ailurus fulgens* (Dorji *et al.*, 2011, Dorji *et al.*, 2012). However, many floral and faunal taxonomic groups are understudied and the true extent of the region's biodiversity is undoubtedly underestimated (Li *et al.*, 2016, Chettri *et al.*, 2010b, Kandel *et al.*, 2016, CEPF, 2005, Chettri *et al.*, 2010a). New species are regularly discovered from within the region, and undescribed species even some from the higher taxonomic groups such as mammals, reptiles and amphibians, are very likely to occur in the more remote, heavily forested regions (WWF, 2015, CEPF, 2005). For instance, 211 new species comprising 133 plant, 39 invertebrate, 26 fish, 10 amphibian, and one reptile, bird, and mammal species each were discovered between 2009 and 2014. The newly discovered mammal species was the notable Myanmar snub-nosed monkey *Rhinopithecus strykeri* (WWF, 2015). Thirteen of the mammal species in the Eastern Himalayas do not have adequate data to determine their current conservation status under the IUCN Red List of threatened species (IUCN, 2018). The rugged and difficult to access landscape containing vast areas of intact and poorly explored areas makes biological surveys in the region extremely difficult.

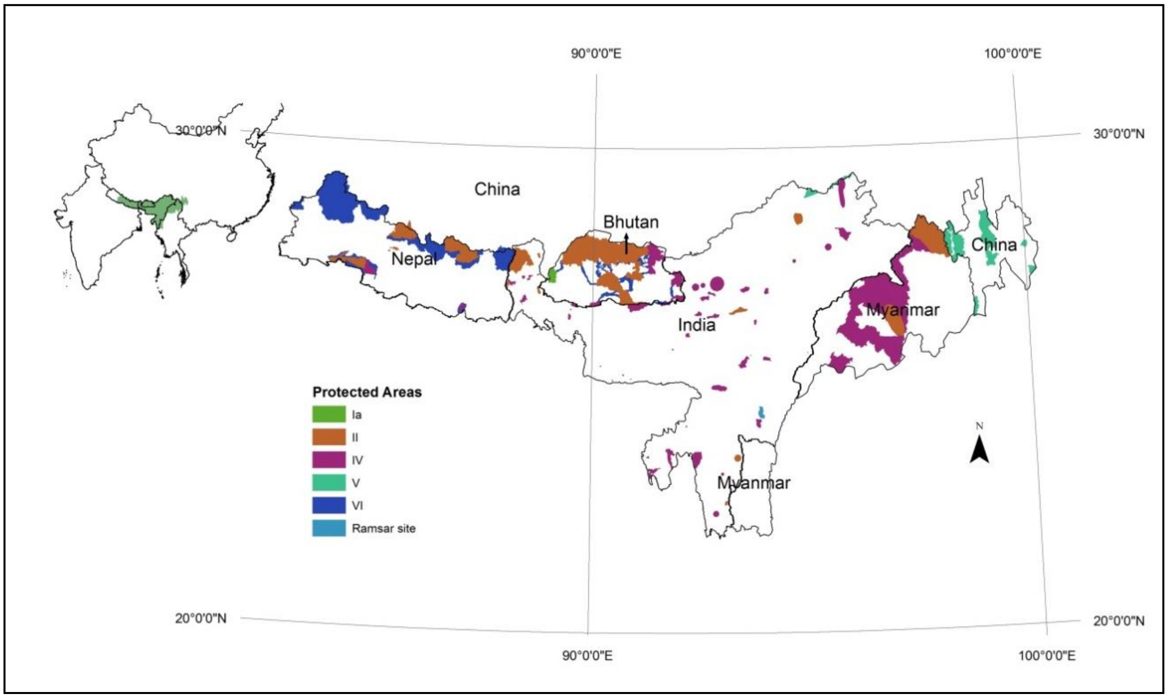

Figure 1.1 The eastern Himalayan region (study area) and six International Union for Conservation of Nature (IUCN) categories of Protected Areas (PA) and Ramsar sites designated by respective range countries. IUCN PA Category, I - Strict Nature Reserve or Wilderness areas, II – National Parks, III - Natural Monument, IV - Habitat/Species

Management Areas, V - Protected Landscape/Seascape, VI - Protected area with sustainable use of natural resources.

Covering an area of 38,394 km^2, Bhutan is located entirely within the Eastern Himalayan region (Figure 1.1). The country transitioned to the modern world with most of its ecosystems intact. This mainly stemmed from strong environmental conservation leadership of the monarchs, decades of self-imposed isolation from the outside world, an agrarian lifestyle, a sparse population, nature reverent traditional beliefs, rugged topography, and belated modernization (Thinley, 2014). The importance of environmental conservation is embedded in every aspect of Bhutanese culture, ranging from traditional beliefs, socio-cultural perspectives, and development philosophy. Bhutan has committed to maintain at least 60% of the country's area under permanent forest cover, which has been legislatively incorporated into the national constitution. Environmental conservation is one of the four pillars of Bhutan's tenet of Gross National Happiness (GNH), a philosophy and policy instrument that seeks to promote human development and manage environmental conservation within a sustainable strategy guided by Buddhist ethics (Ura *et al.*, 2012). As such, benefits from environmental conservation in Bhutan are widespread at the national, regional, and global level. For example, Kubiszewski *et al.* (2013) estimated that about 53% of the total benefits from Bhutan's ecosystem services are accrued to people outside Bhutan, and protection of Bhutan's forests makes it one of the few net-carbon sequestering countries in the world. Therefore, the intact forests and well-preserved watersheds in Bhutan contribute not only to positive socioeconomic development for the Bhutanese people, but also benefit innumerable downstream communities in neighboring India and

Bangladesh who subsist on agriculture, fisheries, and other water resource-based economic activities (Katel *et al.*, 2015, Dorji, 2016).

However, protected areas elsewhere in the Eastern Himalayan region are becoming isolated pockets as unrelenting habitat conversion is causing irreversible damage to the landscape and the region's biodiversity (Dorji *et al.*, 2018, Chettri *et al.*, 2008, Sharma *et al.*, 2008). Bhutan is one of the few global countries which has achieved the novel idea of securing at least half of the earth, as suggested by E.O. Wilson (2016) to address the species-extinction crisis, conserve biodiversity, and prevent collapse of vital services provided by ecosystems, such as carbon sequestration and climate regulation (Dinerstein *et al.*, 2017, Locke, 2014). The Royal Government of Bhutan has made a strong commitment and placed high priority on conserving its forests through a network of protected areas, which currently constitutes 51.4% of its territory; including 9.5% designated as biological corridors. These biological corridors were declared in 1999 as a "gift to the earth from people of Bhutan", and Bhutan is attempting to become the world leader in the use of biological corridors to create a durable network of protected areas (Wildlife Conservation Division, 2010). However, detailed scientific understanding on the functionality and efficacy of Bhutan's protected areas is still lacking. As such, it is critical that biodiversity conservation in the country is guided by data-driven meta-analysis on the diversity and distribution of different taxa, most notably terrestrial mammals.

My study addresses the aforementioned issues by proposing a comprehensive and multi-scaled approach that ensures adequate protection of rich Eastern Himalayan biodiversity while simultaneously considering the needs of 1.5 billion people dependent on natural resources in the landscape. My study's main emphasis was on terrestrial mammal species because they play an important role in the maintenance and regeneration of forests. Mammals perform essential ecological functions and can be considered key taxa in structuring biological communities. Evaluating the mammal community on a regular basis in the context of Bhutan's development activities such as road development will help to evaluate the effectiveness of measures, if they are taken, to increase protection and maintain connectivity between the Eastern Himalayan protected area networks. This in turn should prevent protected areas from becoming fragmented and disconnected landscape units and allow them to facilitate the movement of animals.

This thesis can be divided into three parts. In Part 1 (Chapter 2), I identified key knowledge gaps and future priorities for the expansion of protected areas in the Eastern Himalayas based on spatial analyses on the distribution of 255 mammalian species. I then conducted a comprehensive synthesis of available data to address this aim, including field verifications, perusal of published literature, and comprehensive investigation of online data on protected areas and species distribution maps available on the World Database of Protected Areas, and the IUCN website. Further re-validation of information was drawn from national geoportals of respective range countries of the Eastern Himalayas and the International Centre for Integrated Mountain Development (ICIMOD), and from interviews and personal communication with experts in the region. Through this approach, the work provided new insights on prioritizing mammal species for conservation by emphasizing threatened and evolutionarily distinct small and medium sized mammal species which face certain extinction if adequate protection is afforded in the near future. I subsequently identified new priority Eastern Himalayan areas for protection and/or integration with current transboundary reserves, and also provide appropriate management and scientific recommendations for the expansion of current regional protected areas to combat species extinction.

In Part 2 (Chapter 3 & 4), I collected, processed and analyzed an enormous camera trapping dataset from a nationwide camera trapping program in Bhutan that I coordinated. This rigorous field study involving the first ever nation-wide comprehensive wildlife camera trapping exercise in Bhutan, utilized 1,858 camera traps over 148,598 trap-nights between 2014 and 2015. I sorted and identified around 10 million photos of mammal, bird, human and other pictures to species level. I identified at least 65 mammal species representing 18 families within seven orders, of which, 18 (32.16%) are listed as threatened by the International Union for Conservation of Nature (IUCN). I then compared mammal species richness and diversity between Bhutan's protected areas, biological corridors and non-protected areas (Chapter 3), and estimated and compared the species richness and functional diversity of mammal in various ecological zones along the altitudinal gradient in Bhutan (Chapter 4). These chapters provide an understanding on the functionality of the protected areas network in the Eastern Himalayas using real field data, and presented practical experiences and recommendation for the future of Bhutan's Protected Areas, and for implementation in other parts of the world.

In the Part 3 (Chapter 5), I assessed the ecological functionality, structural design and management effectiveness of the biological corridor network in Bhutan. I modelled species distribution and identified priority wildlife habitat outside five national parks, four wildlife sanctuaries, and a strict nature reserve (hereafter termed as protected areas); quantitatively assessed impact of land-use and climate change on the current biological corridor network; identified the optimal pathway between core priority areas; characterized how species moved between patches and identified pinch points and barriers to their potential movement; and made necessary policy and management recommendations on connectivity at the local and regional scale for a range of planning scenarios.

The final chapter (Chapter 6) synthesizes the research contained in this thesis, and provides policy recommendations for Bhutan's Biological Corridors Network. Because of diverse study approaches, my work represents the first comprehensive assessment of threatened mammal species and their habitat status in the Eastern Himalayan region, and the first rigorous description of issues that are impacting the conservation of these species in the region. Overall, this research provides practical support toward efforts to achieve the 'half-earth' ideal aimed at addressing the extinction crisis and preventing collapse of vital ecosystems services such carbon sequestration and climate regulation.

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Photo of "Mount Jomolhari" at 7326 m asl in Jigme Dorji National Park, Bhutan. It is part of the Eastern Himalayan Landscape, straddling the border between Tibet, China and Western Bhutan. The mountain is an important source of the head waters of two major rivers in Bhutan (Parochu and Amochu). Currently, mountain climbing is banned in Bhutan due to cultural restriction by the local communities living in the mountains.

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Chapter 2: Identifying Conservation Priorities for Threatened Eastern Himalayan Mammals

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Article Impact Statement: Spatial analysis of Eastern Himalayan mammal distribution identifies regional protected-area expansion toward conservation of half-earth.

Abstract

To augment mammal conservation in the Eastern Himalayan (EH) region, we assessed the resident 255 terrestrial mammal species and identified the 50 most threatened species based on conservation status, endemism, range size, and evolutionary distinctiveness. By using the spatial analysis package letsR and the complementarity core-area method in the conservation planning software Zonation, we assessed their current efficacy of protection and identified priority conservation areas by comparing protected area (PAs), land cover, and global ecoregion 2017 maps at a 100 × 100 m spatial scale. The 50 threatened species that were most threatened, geographically restricted, and evolutionarily distinct faced a greater extinction risk than globally non-threatened, wide-ranging and species with several close relatives. Small, medium-sized, and data-deficient species faced extinction from inadequate protection in PAs relative to wide-ranging charismatic species. There was a mismatch between current PA distribution and priority areas for conservation of the 50 most endangered species. To protect these species, the skewed regional PA distribution would require expansion. Where possible, new PAs and transboundary reserves in the 35 priority areas we identified should be established. There are adequate remaining natural areas in which to expand current EH PAs. Consolidation and expansion of PAs in the EH requires strengthening national and regional transboundary collaboration, formulating comprehensive regional land-use plans, diversifying conservation funding, and enhancing information sharing through a consolidated regional database.

Introduction

The Eastern Himalayan (EH) region encompasses Bhutan and parts of China, India, Myanmar, and Nepal and is recognised globally for its high biodiversity and endemism (Myers et al. 2000). Located at the juncture of the Indo-Malayan and Palearctic biogeographic realms, the EH supports iconic Indo-Malayan mammals, such as tigers (*Panthera tigris)*, Asiatic elephants (*Elephas maximus)*, greater one-horned rhinoceroses (*Rhinoceros unicornis)*, sloth bears (*Melursus ursinus)*, and red pandas (*Ailurus fulgens)*, as well as iconic Palearctic mammals, such as snow leopards (*Panthera Uncia)*, Asiatic black bears (*Ursus thibetinus)*, blue sheep (*Pseudois nayur)*, takins (*Budorcas taxicolor)*, and Himalayan thar (*Hemitragus jemlahicus)* (Dorji et al. 2012).

The EH contains 3 global biodiversity hotspots (Dinerstein et al. 2017), eight Global 200 Ecoregions (Olson & Dinerstein 1998), and two endemic bird areas (Stattersfield et al. 2005). Regional threatened species face extinction from habitat loss (Velho et al. 2016), inconsistent protection (Oldfield 2012), and inadequate protected area (PA) coverage (Kandel et al. 2016).

The Convention on Biological Diversity established Achi Target 11 to protect 17% of global terrestrial land and inland water areas by 2020. However, protecting this 17% is inadequate to effectively represent all species (Noss et al. 2012) and maintain ecosystem services (Perrings et al. 2010). Some biologists now advocate half-earth protection through networked PAs to halt biodiversity loss and prevent species extinction (Wilson 2016). Büscher et al. (2017) argue that half-earth protection is impractical and would have negative impacts on humans in underdeveloped countries, but Dinerstein et al. (2017) assert its achievability through habitat protection and restoration. Watson and Venter (2017) call for a realistic half-earth protection based on desirability, feasibility, and ecoregional representation of protected areas.

In terms of EH PA evaluation, Chettri et al. (2008) assessed bird areas and ecoregions within PAs in the Hindu Kush but did not cover mammal diversity. Li et al. (2016) evaluated conservation priorities for mammals, birds and amphibians in India, China, and Myanmar but excluded Bhutan and Nepal. To assess current EH PA efficacy, we mapped the distribution and representation of resident terrestrial mammal species in PAs and ecoregions. We selected terrestrial mammals because they are key indicators for measuring anthropogenic impacts on Earth's biota (Ceballos & Ehrlich 2002), require relatively large areas, and are functionally important for ecosystems (Ripple et al. 2015). We also identified priority areas for PA expansion to address species extinction. Our study is the first of its kind in this region.

Methods

Study Area

The EH region covers 524,190 km^2 (ICIMOD 2016) from central Nepal to northwest Yunnan in China and encompasses Bhutan; the northeastern Indian states of Arunachal Pradesh, Assam, North Bengal, and Sikkim; southeast Tibet; and Myanmar (Supporting Information). Elevation ranges from 300 m asl in the low plains to over 8800 m asl at Mount Everest. Tropical forest (below 1000 m asl), subtropical forest (1000 - 2000 m asl), warm temperate forest (2000 – 2500 m asl), cool temperate forest (2500 - 3000 m asl), subalpine forest (3000 - 4000 m asl), and alpine habitat (>4000 m asl) (ICIMOD 2016) comprise the vegetation.

Data on Spatial Distribution of Mammals

Environmental Systems Research Institute (ESRI) shapefiles on known ranges of each terrestrial mammal species in the EH was obtained from the International Union for Conservation of Nature Red List database on 16 September 2017 (IUCN 2017). We also extracted species name, taxonomic information, distribution, and threat status of mammals within EH boundaries. The original data set was projected using a WGS84 datum. We reprojected the data set into a Lambert azimuthal equal area (LAEA) projection to provide a more accurate estimate of polygon area in each planning unit (Jenkins et al. 2013). Species-range data sets were then dissolved based on species name and checked for geometric and topological errors, which were repaired to make the data set topologically correct for further processing. We extracted and used information on species classified as native under the origin field and extant under the presence field and removed other attributes such as possibly extant, extinct, presence uncertain, and non-native extant entries from the map to avoid overestimating degree of exposure (Ameca y Juarez et al. 2013; Venter et al. 2014). Final spatial data was processed using the IUCN Red List Toolbox for ArcMap in ArcGIS 10.4.1 (Environmental Systems Research Institute 2016) following guidelines by Ravilious and Thorley (2015), and a species richness map was generated with the R package letsR (Vilela & Villalobos 2015).

We categorized threatened, endemic, small-ranged, and evolutionarily distinctive mammals as species of high conservation priority. We considered threatened species those categorized by IUCN (2016) as critically endangered (CR), endangered (EN), and vulnerable (VU) and near threatened (NT) and least concern (LC) species as nonthreatened. Species with insufficient data were data deficient (DD). Following Jenkins et al. (2015), we considered a species was an EH endemic if >95% of its extant distributional range was within the region and that range did not extend >50 km beyond EH's border because EH boundaries (as defined by International Center for Integrated Mountain Development) and species distribution ranges (as defined by IUCN) were arbitrary. Species with range sizes smaller than their overall global median were considered small ranged, whereas wide-ranged species had range sizes greater than the global median (Jenkins et al. 2015). Evolutionarily distinct species were those on Isaac et al.'s (2007) list of evolutionarily distinct and globally endangered (EDGE) species.

Protected Area and Global Ecoregion Data

We downloaded PA spatial data from the World Database on Protected Areas (WDPA) on 26 September 2016, re-projected the data set into a LAEA projection for consistency, and followed Visconti et al.'s (2013) methods to avoid caveats of PA with point location. We considered only nationally gazetted PAs and classified them based on IUCN categories (IUCN 2016). We based species protection on the percentage of its geographic range within PAs, which ranged from 0 (no overlap) to 100 (100% overlap) (0%, species unprotected; <10%, very poor protection; 11 – 25%, poor protection; 26-50%, inadequate protection; >50%, adequate protection). Based on a half-earth policy, <50% protection overall was deemed under-protected and >50% as protected. Therefore, species we identified as of high conservation priority that had low levels of protection in current PAs were considered priority species because they faced a higher risk of extinction than wide-ranging and better-protected high-priority species in EH PAs. Ecoregion protection status followed the nature needs half (NNH) classifications by (Dinerstein et al. 2017).

Area Prioritization

We identified priority conservation areas with Zonation (Moilanen et al. 2009) by specifically using a complementarity core-area zonation method (Lehtomäki & Moilanen 2013) that hierarchically prioritized landscapes based on rare and threatened species. Species were weighted on a scale from 1 – 5 based on rarity, endemism, range size, and evolutionary distinctiveness. Rarity scores were 5 for CR, 4 for EN, 3 for VU, 3 for DD, 2 for NT, and 1 for LC (IUCN 2016). Data deficient species were scored (3) same as VU because DD species often become threatened when sufficient data is gathered (Bland et al. 2015). Endemism was based on species extant range in the EH (5, 100% extant; 4, 90 – 99%; 3, 80–89%; 2, 50 – 79%; 1, <50%). Evolutionary distinctiveness scores followed Isaac et al.'s (2007) EDGE list: 5, among 10% most evolutionarily distinct species; 4, 11 – 25%; 3, 26 – 50%; 2, 51 – 90%; 1, >90%. We scored small-ranged species 2 and wide-ranged species 1.

Land-cover classification was based on the assumption that a greater degree of natural vegetation cover confers a higher quality of habitat in general (FAO 2010): 5, natural forest and grassland; 3, grasslands, shrub, crops with low livestock density; 2, forest with agriculture activities and moderate to high livestock density; 1, unmanaged grasslands; 1, sparsely vegetated areas; 0 (lowest quality wildlife habitat), urban areas, agriculture, open water, bare areas, grasslands, shrub and crops with high livestock density.

We used Dinerstein et al.'s (2017) NNH classifications as the cost layer: 1, area half protected; 2, area could reach half protected; 3, nature could recover, and 5, nature imperiled. Because the EH include 5 range countries of different sizes and mammal conservation priorities, we used local administrative priorities (ADMU Mode 2) in our final zonation solution (Moilanen & Arponen 2011).

We identified threatened endemic and geographically restricted species that faced a higher extinction risk, due to a low level of protection in EH PAs, relative to threatened wide-ranging charismatic species. We based this focus on the relationship among species range size, protection level, and extinction risk (Pimm et al. 2014) and used the following priority-ranking index (pi) formula:

$$\text{pi} = \log(\sum x * r_j * s_j) \quad , \qquad (1)$$

where x is total weighting for each mammal species based on their conservation priority; r_j is ratio of species j's overall range within the EH; and s_j is proportion of species j's range outside current PAs. To identify priority areas, we compared the top 17% (Aichi Target 11) and 50% (half-earth protection) of constrained and unconstrained Zonation results to ascertain spatial overlap with existing PAs.

Results

Mammal Status

Of 255 EH terrestrial mammal species, 21% (n=53) were globally threatened of which 8% (n=4) were CR, 43% (n=23) were EN, and 49% (n=26) were VU (defined above). The remaining 202 (79%) were nonthreatened species of which 11% (n=21) were NT, 89% (n=168) were LC, and 5% (n=13) were DD (Table 2.1). The number of small-ranged (50.2%; n=128) and wide-ranged (49.8%; n=127) species nearly equal, but there were more threatened small-ranged (28.1%; n=36) than wide-ranged species (13.4%; n=17) (Table 2.1). There were 13 endemic EH mammal species almost equally distributed between threatened (53.9%; n = 7) and non-threatened (46.1%; n=6). Seven percent (n = 17) of EH mammal species were in the top 10% of EDGE species, but

more were nonthreatened (70.6%; n = 12) than threatened (29.4%; n = 5) (Table 2.1).

Table 2.1 Number of Eastern Himalayan small-ranged, wide-ranged, endemic, and evolutionarily distinct mammal species assigned to International Union for Conservation of Nature conservation status categories[a].

Species categories[b]	Threatened			Nonthreatened			Total
	CR	EN	VU	LC	NT	DD	
Small range [b]	3	20	13	68	11	13	128
Wide-range	1	3	13	100	10		127
Endemic	3	3	1	1	1	4	13
Top 10% evolutionarily distinct	1	3	1	9	2	1	17

[a]Categories: CR, critically endangered; EN, endangered; VU, vulnerable; LC, least Concern;, NT, near Threatened; DD, data Deficient.

[b]Small-ranged species, range size smaller than the global median (1,584,684 km^2) for overall mammal species; wide-ranged species, range size larger than the global median range; endemic species, those with >95% of their range in the Eastern Himalayan region and not extending >50 km beyond its border following criteria used by Jenkins et al.

(2015a); eevolutionarily distinct, species listed in the top 10% of evolutionarily distinct species by Isaac et al. (2007).

Mammal Protection

Eighteen percent (n = 47) of EH mammal species had <10% of their range protected, and 4% (n=9) had none of their range protected (Table 2.2). The majority (51%; n = 130) had 11 - 25% protected ranges. 18% (n = 47) had 26 – 50% of their range protected, and 9% (n = 22) had >50% of their range protected (Table 2.2). Among endemics, 23% (n = 3) were protected within the <10%, 10 – 25%, and 25 – 50% categories, and 31% (n = 4) had >50% of their range protected. However, 21% (n = 11) of threatened species had <10% of their range protected, whereas 47% (n = 25), 17% (n = 9), and 13% (n=7) had 11 – 25%, 26 – 50%, and >50% of their range within PAs, respectively (Table 2.2).

Table 2.2 Percentage of overall, endemic, and threatened mammalian species represented in Eastern Himalayan protected areas (PAs).

Species category[a]	Representation[b]					Total number
	0%	<10%	11-25%	26-50%	>50%	
Overall	4 (9)	18 (47)	51 (130)	18 (47)	9 (22)	255
Endemic	0 (0)	23 (3)	23 (3)	23 (3)	31 (4)	13
Threatened	2 (1)	21 (11)	47 (25)	17 (9)	13 (7)	53

[a]Endemic, species with >95% of their range in the Eastern Himalayan and not extending >50 km beyond EH border following criteria used by Jenkins et al. (2015a); threatened,

species classified as vulnerable, endangered, or critically endangered by the International Union for Conservation of Nature.

[b]Representation in protected areas: 0%, no representation; <10%, very poor representation; 11-25%, poor representation; 26-50%, inadequate representation; >50% , adequate representation. Numbers in parentheses denote species numbers.

Mammal Species Richness

Mammal species richness was highest between eastern Nepal and western Bhutan in the Indian state of Sikkim and north of West-Bengal and in areas in northern Myanmar and western Yunnan in China (Fig. 2.1). Very high small-ranged mammal species richness occurred in northern Myanmar, western Yunnan, and between eastern Nepal and western Bhutan (Fig. 2.1). Northern areas had low small-ranged mammal species richness as did Southern Nepal, central Arunanchal Pradesh, and the regions between Dubri, Goalpara, Barpeta, and Guwahati in the Indian states of Assam and Tripura. Mana, which borders India and Bhutan, areas around Hukaung, Namlang, and Bumhpabum in Myanmar and Garampani in Assam, India, had the highest concentration of threatened mammals (Fig. 2.1). Central and southern parts of the EH in India and Myanmar had moderate threatened mammal richness relative to the low richness in the northern EH. Endemic mammal richness was highest in Sikkim, India (Fig. 2.1). High endemicity also occurred in eastern Nepal, central Bhutan, Namdapha in Indian Arunachal Pradesh, and areas bordering northern Myanmar and eastern Yunnan in China (Fig. 2.1).

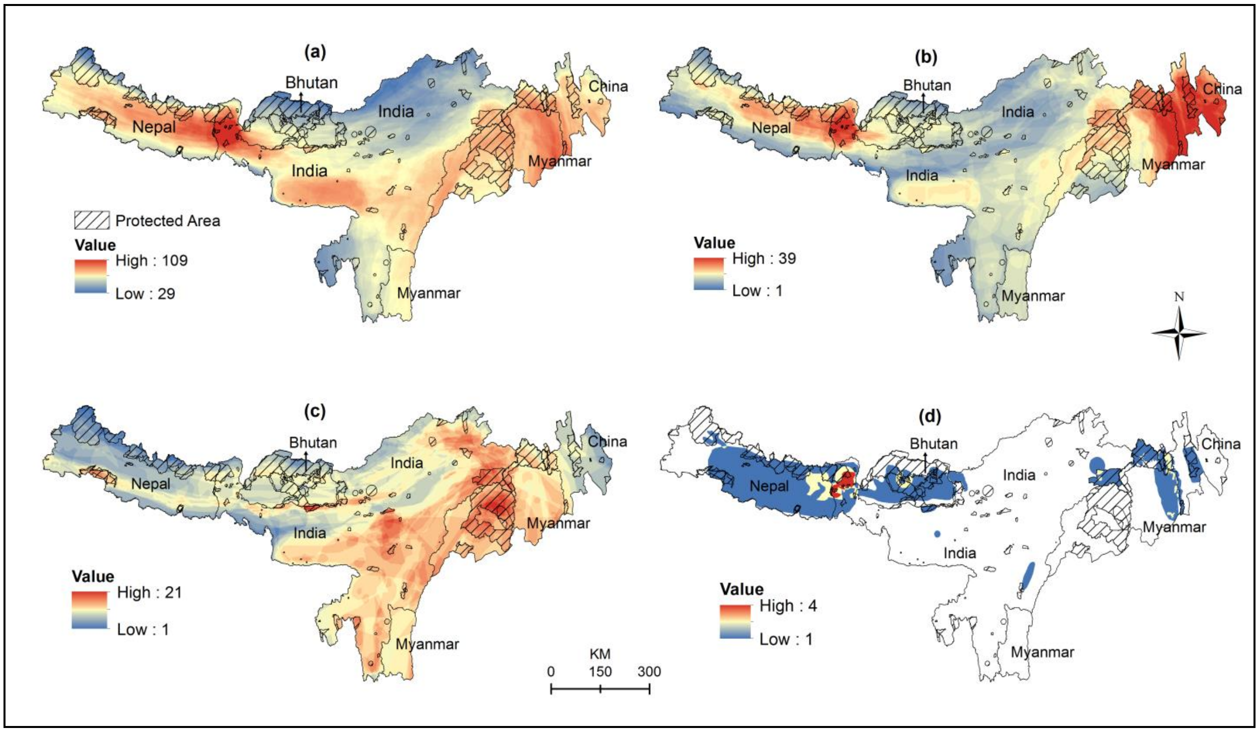

Figure 2.1 Mammal species richness in the Eastern Himalayan region (a) overall species; (b) small-ranged species (distribution range is lower than the median global distribution range for all mammal species relative to the Eastern Himalayan region); (c) threatened species (vulnerable, endangered, or critically endangered [IUCN, 2016]); and (d) endemic species (endemic if >90% of its range is within the Eastern Himalayan region and not extending >50 km beyond the border (Jenkins et al. 2015a).

Priority Areas

A minimum of 17% of land area was protected under constrained solutions, but these solutions did not protect a minimum 17% of habitat (Fig. 2.2a) for the 50 EH species we identified as of the highest conservation priority (hereafter 50 species) (Table 2.3). From unconstrained solutions, we identified 35 priority areas not captured by the constrained solutions (areas under current protected area system). These areas require readjustment or expansion of current PAs to conserve the top 17% of habitat for the 50 species (Fig. 2.2a). There were eight priority areas in Nepal (areas 1 – 8 in Fig. 2.2a), four in Bhutan (areas 9 – 12), 11 in India (areas 13 and 14 in Assam, areas 15 – 19 in Arunachal Pradesh, area 20 in Meghalaya, area 21 in Tripura, area 22 in Mizoram, and area 23 in Manipur), seven in Myanmar (areas 24 – 25 and 26 - 30) (map shows south and north), and five in China (areas 31 - 35). Protecting these priority areas in addition to current PAs protected a minimum 36% of the 50 species' ranges (Supporting Information) (see figure legend). A half-earth protection goal for the 50 species required an additional 14% protection in unconstrained 50% priority areas (Fig. 2.2a). An overall 50% EH regional protection of unconstrained solutions protected 75% of the current ranges of all resident mammal species, an increase from the current 20% protection (Supporting Information).

Priority areas based on respective range countries' administrative units in the final Zonation analysis (Fig. 2.2b) differed from overall regional priority areas (Fig. 2.2a). India had 4.15% of EH land area protected, but 11 priority areas were identified for India to achieve Aichi Target 11 (Fig. 2.2b). Other countries have achieved a minimal 17% terrestrial area protection (Fig. 2.2b). Protecting 50% country-level EH terrestrial areas protected 25% (based on species with the smallest ranges) (minimum proportion remaining) (Fig. 2.2b) to 76% (average and weighted proportion remaining) (Fig. 2.2b) of mammal ranges.

Seven (70%) of the 10 species of most conservation concern were small (top 3, Hume's rat [*Hadromys humei*], Namdapha flying squirrel [*Biswamoyopterus biswasi*], inquisitive shrew mole [*Uropsilus investigator*]) and 3 (30%) were medium sized (Table

2.3). Evolutionarily distinct species were 14% (n =7) of the 50 and included the number first ranked Hume's rat. Endemic medium-sized mammals (4th ranked Myanmar snub-nosed monkey [*Rhinopithecus strykeri*] and 5th ranked Arunachal macaque [*Macaca munzala*]) were in the top 5 of the 50 species. Evolutionarily distinct and iconic large-sized mammals, such as the great one-horned rhinoceros takin, and Asian elephant were ranked 12th, 40th, and 44th, respectively (Table 2.3).

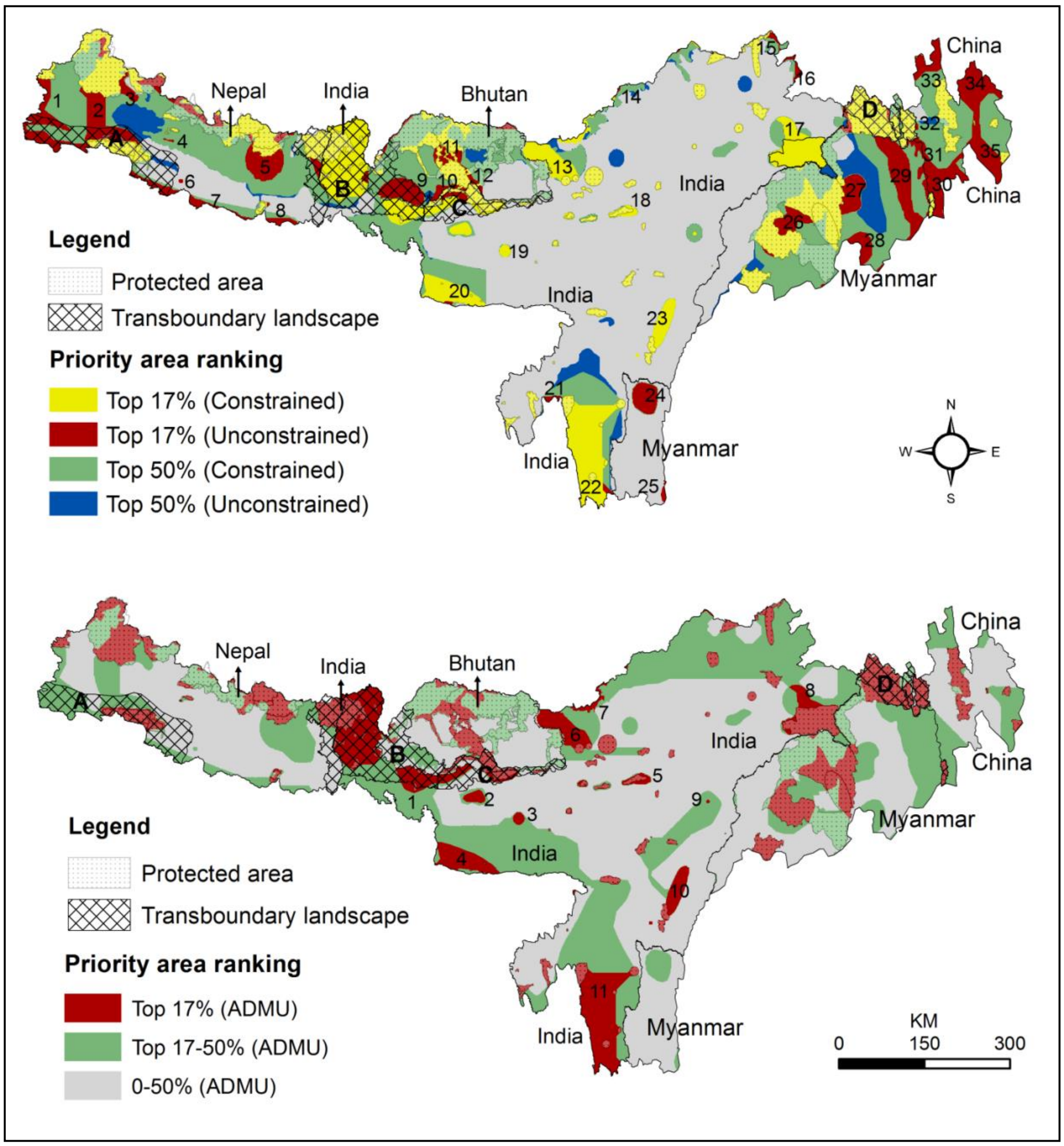

Figure 2.2 (a) Overall priority areas for mammal conservation in the Eastern Himalayas (Fig. 2a) and (b) priority areas identified for respective range countries when country borders are incorporated as an Administrative Unit (ADMU) in the Zonation analysis (Figure 2.2b) (constrained, a priority rank map when an existing protected area network has been forcibly included in the highest ranked fraction of the solution using as a mask file; unconstrained, showing what would have been selected as a priority area based on 255 mammal species if no areas were already protected). The following weightings were applied to 255 EH mammal species: presence of categorized species (critically endangered, endangered, vulnerable, data deficient, other) (IUCN, 2016); presence of evolutionarily distinctive species; presence of endemic species; existing land use; and Nature Needs Half categories (Dinerstein et al. 2017) as the cost layer. Current nationally designated protected areas and existing transboundary conservation landscapes are overlaid with priority areas (A, Terai-Arc Landscape; B, Kangchenjunga Conservation Landscape; C, Transboundary Manas Conservation Area; D, Brahmaputra-Salween Landscape).

Table 2.3 Fifty most endangered mammals in Eastern Himalayan ranked on the risk of extinction based on endemism[a], conservation status, range size[b], and evolutionary distinctiveness.

Rank	Common name[c]	Scientific Name	Conservation status[d]	Priority area[e]
1	Hume's rat*†	*Hadromys humei*	EN	12; 18
2	Namdapha flying	*Biswamoyopterus*	CR	20

	squirrel*	*biswasi*		
3	Inquisitive shrew mole*	*Uropsilus investigator*	DD	24
4	^Myanmar's snub-nosed monkey	*Rhinopithecus strykeri*	CR	24
5	^Arunachal macaque	*Macaca munzala*	EN	10
6	^Shortridge's langur	*Trachypithecus shortridgei*	EN	24; 25
7	Forrest's mountain vole*	*Neodon forresti*	DD	26; 28; D
8	Joffre's pipistrelle*	*Pipistrellus joffrei*	DD	22; 16
9	Sombre bat*	*Eptesicus tatei*	DD	B
10	Himalayan field mouse*	*Apodemus Gurkha*	LC	2
11	Giant mole shrew*	*Anourosorex schmidi*	DD	7; 20; B
12	Greater one-horned rhinoceros†#	*Rhinoceros unicornis*	VU	19; A; B; C
13	Himalayan white-	*Niviventer*	LC	1; 2; 5; 7;8; 9; 12; 14;

	bellied rat*	*niviventer*		15; 18; 19; 20; B
14	Bhutan giant flying squirrel*	*Petaurista nobilis*	NT	7; 8; 9
15	Himalayan mole*	*Euroscaptor micrura*	LC	7; 8;12; 14; 15; B
16	Csorba's mouse-eared bat*	*Myotis csorbai*	DD	1; 2
17	^Gee's golden langur	*Trachypithecus geei*	EN	7; 8;9; C
18	Ward's red-backed vole*	*Eothenomys wardi*	NT	27; 28; 29; 30
19	Hoary-bellied squirrel*	*Callosciurus pygerythrus*	LC	5; 8; 9; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21; B; C
20	^Pygmy hog†	*Porcula salvania*	CR	C
21	Forrest's pika*	*Ochotona forresti*	LC	7; 8; 9; 10; 11; 20; 21; 24; 25; 26; 27; 28; 30; C
22	Wild water buffalo#	*Bubalus arnee*	EN	6; 19; 21; 20; C
23	Crump's mouse*	*Diomys crumpi*	DD	3

24	^Western Hoolock gibbon†	*Hoolock hoolock*	EN	13; 14; 15; 16; 17; 18; 21
25	^Red panda†	*Ailurus fulgens*	EN	1; 2
26	Little Nepalese horseshoe bat*	*Rhinolophus subbadius*	LC	2; 10; 11; 13
27	Surat serotine*	*Eptesicus dimissus*	DD	A
28	Little Himalayan rat*	*Niviventer eha*	LC	2; 5; B
29	^Capped langur	*Trachypithecus pileatus*	VU	9; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21; C
30	Hodgson's giant flying squirrel*	*Petaurista magnificus*	LC	5; 7; 8; 9; 16; 17; 20; 21
31	Orange-bellied Himalayan squirrel*	*Dremomys lokriah*	LC	5; 8; 9; 10; 11; 13; 16; 17; 20; 21; 22; 23; 24; 25; 26; B; D
32	Millard's rat*	*Dacnomys millardi*	DD	20; B
33	^Himalayanmuskdeer	*Moschus leucogaster*	EN	1; 2; 5; 7; 8; B

34	Bronze sprite*	*Arielulus circumdatus*	LC	5; 6; 12; 13; B; C;
35	^Hog deer	*Axis porcinus*	EN	3; 4; 5; 6; 12; 18; 19; 20; 21; A; B; C
36	Hispid hare*†	*Caprolagus hispidus*	EN	3; 4; 5; 6; A; B; C;
37	^Black musk deer	*Moschus fuscus*	EN	10; 11; ; 24; 25
38	^Tarai gray langur	*Semnopithecus hector*	NT	1; 2; 5; A; B
39	^Himalayan serow	*Capricornis thar*	NT	1; 2; 5; 7; 8; 9; 10; 11; 13; 14; 15; 16; 17; 18; B
40	Takin†#	*Budorcas taxicolor*	VU	7; 10; 11; 24; 25; 26; 27; 28; 29; 31
41	^Himalayan goral	*Naemorhedus goral*	NT	1; 2; 5; 7; 8; 9; 10; 11; B
42	Blandford's fruit bat*	*Sphaerias blanfordi*	LC	5; 6; 7; 8; 9; B; C
43	Sikkim vole*	*Neodon sikimensis*	LC	2; 5; B

44	Asian elephant†#	*Elephas maximus*	EN	13; 19; 20; 21; B; C
45	Anderson's squirrel*	*Callosciurus quinquestriatus*	NT	24; 25
46	Cook's mouse*	*Mus cookie*	LC	2 – 24; B; C
47	Himalayan shrew*	*Soriculus nigrescens*	LC	11; B
48	^Golden cat	*Catopuma temminckii*	NT	7; 9; 10; 11; 14; 15; 20; 21; 25; 27; 28; 29; 31; B; C
49	Long-tailed brown-toothed shrew*	*Episoriculus leucops*	LC	2; 5; 24; 25; D
50	^Red goral	*Naemorhedus baileyi*	VU	20; 25 – 30; D

[a]Endemism is weighted based on the proportion of the species' range in the Eastern Himalayan region (Score of 5 ,100%; 4, 90 - 99%; 3, 80 – 89%; 2, 50 – 79%; 1, <50%).

[b]Small-ranged species have a range-size smaller than the overall global median range for mammal species (1,584,684 km^2) while wide-ranged species have a range-size larger than the median range, both relative to the eastern Himalayas.

[d]International Union for Conservation of Nature categories: CR, critically endangered; EN, endangered ; VU, vulnerable; NT, near threatened ; LC, least concern; DD, data deficient.

[c]Codes: *, small-sized mammal; †, evolutionarily distinct species listed in the top 10% of evolutionarily distinct species by Isaac et al. (2007); ^, medium-sized mammal; #, large-sized mammal.

[e]Numbers, priority areas in Fig 2.3a,b; letters, represent transboundary landscapes: A, Terai-Arc Landscape; B, Kangchenjunga Conservation Landscape; C, Transboundary Manas Conservation Area; D, Brahmaputra-Salween Landscape.

Ecoregions

No EH area was under Dinerstein et al.'s (2017) class 1 (half protected) category, and 56.6% (293,945 km^2) were class 2 (nature could reach half), 22.97% (123,749.7 km^2) were class 3 (nature could recover), 18.6% (96,535.60 km^2) were class 4 (nature imperilled), and 1.9% (138,730.20 km^2) consisted of rock and ice (Fig. 2.3). Seventy-three percent (65,663.90 km^2) of EH PAs were class 2; 12.5% (11,216.40 km^2) were class 3; 5.7% (5,063 km^2) were class 4; and 8.4% (7,486 km^2) were unclassified rock and ice (Fig. 2.3). Eighty-two percent (31,723.69 km^2) of Bhutan, 52.7% (143,829.35 km^2) of India, 93.1% (87,531 km^2) of Myanmar, and 36.6% (30,837.36 km^2) of Nepal were class 2 (Fig. 2.3). Twelve percent (4670 km^2) of Bhutan, 100% (34,783 km^2) of China, 18% (49,291 km^2) of India, 4.1% (3,889.71 km^2) of Myanmar, and 36.9% (31,139.26 km^2) of Nepal were class 3. Class 4 covered 0.8% (303.39 km^2) of Bhutan, 28% (76,519 km^2) of India, 2.7% (2,566 km^2) of Myanmar, and 20.3% (17,146.85 km^2) of Nepal. A small percentage of Bhutan (4.4%, 1,698 km^2), India (1.1%, 3,095 km^2), and Myanmar (6.1%; 5,167 km^2) were under rock and ice (Fig. 2.3).

In unconstrained zonation solutions, 64.8% (57,322 km^2) of the top 17% (88,502 km^2) priority areas were class 2; 28% (24,781 km^2) were class 3; and 7.2% (6,399 km^2) were class 4 (Fig. 2.3). Similarly, 55.7% (145,034 km^2) of the top 50% of priority areas (260,845 km^2) were class 2, 31% (81,073 km^2) were class 3, and 13.3% (34,738.5 km^2) were class 4 (Fig. 2.3). When using NNH categories as a cost layer, 63.2% (164,906 km^2) of the top 50% of priority areas were class 2, 27.3% (71,236.8 km^2) were class 3, and 9.5% (247,020.30 km^2) were class 4 (Fig. 2.3).

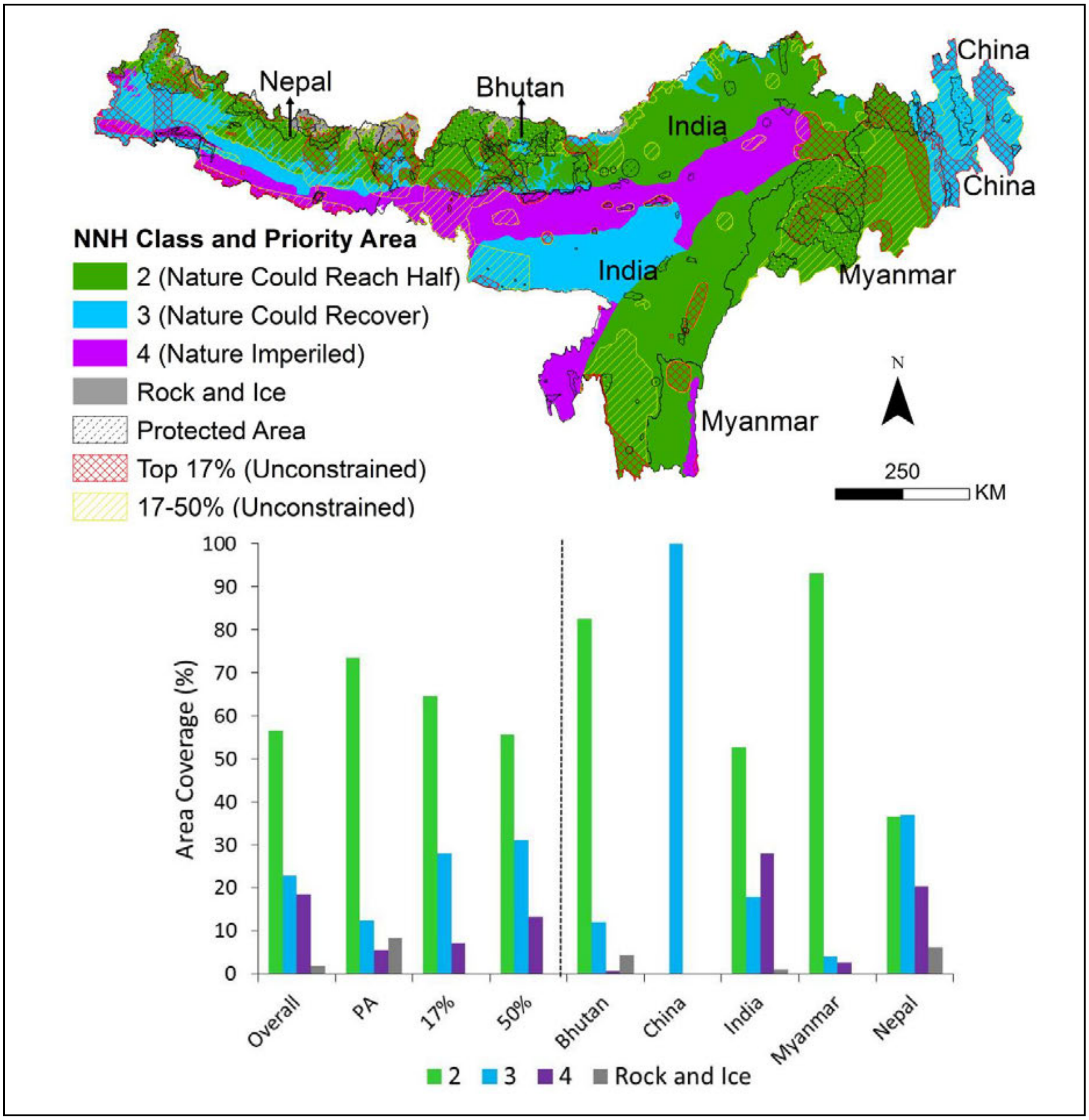

Figure 2.3 (a) Representation of range countries, their protected areas, and priority conservation areas for mammalian species in the Eastern Himalayas under the Nature Needs Half (NNH) categories (numbers 2-4) (Dinerstein et al. 2017) (b) Overall representation of the Eastern Himalayas, range countries, their current protected areas, and if we protect 17% and 50% of the Eastern Himalayas respectively under the Nature Needs Half (NNH) categories (numbers 2-4). Coverage, percent area of EH, respective range countries, their current protected areas, and if we protect 17% and 50% of the EH under the NNH categories (number 2-4).

Discussion

Protecting threatened species and reducing extinction risk has mostly targeted charismatic large mammals (Andelman & Fagan 2000). However, the 50 species we identified as of the highest conservation priority in EH highlight a greater extinction threat to small, geographically restricted, endemic, and evolutionarily distinct species (Crooks et al. 2017; Pimm et al. 2014; Williams & Isaac 2008). Our list differs from the IUCN Red List because we prioritized threatened endemic and geographical restricted species facing a higher extinction risk due to a low level of protection in EH PAs over threatened wide-ranging charismatic species. Our consideration of these 50 species (this said “very important priority species for biodiversity conservation") is proactive, rather than reactive, because we did not consider only threatened species.

The top ranked Hume’s rat is restricted to a 5,000 km^2 range in five isolated forest pockets in northeastern India; 82% of its range is unprotected. Already extinct in Bangladesh and Nepal (IUCN 2016), the CR pygmy hog (*Porcula salvania*) is confined to 881 km^2 of alluvial grassland habitat in Manas National Park, India, and is at risk of global extinction through habitat loss, agricultural encroachment, hunting, and burning (Narayan & Oliver 2015). The Namdapha flying squirrel is endemic to northeastern India and has an estimated unprotected habitat of <100 km^2 in Namdapha National Park (Molur 2016). The Myanmar snub-nosed monkey's population of only 300 individuals is unprotected within an area of <270 km^2 along the Sino-Myanmar border (Long et al. 2012). Although, not featured in our top 50 species, both the critically endangered Chinese pangolin and endangered Indian Pangolin (*Manis crassicaudata)* are heavily poached for meat and scales (Mohapatra et al. 2015; Thapa et al. 2014; Zhang et al. 2017), further highlighting the plight of small-sized terrestrial mammal species. Only 31% (4,510 km^2) and 22% (72,870 km^2) of their estimated ranges in the EH are protected, respectively, making them especially vulnerable to extinction.

Due to protection in and outside EH PAs, large wide-ranging iconic mammals, such as the greater one-horned rhinoceros (ranked 12th) and Asiatic elephant (ranked 44th), were not in the top 10 of our 50 species, and the Bengal tiger (ranked 84th) and snow leopard (ranked 201st) were not among the 50 species. They are, however, regionally threatened through habitat loss, poaching, persecution, and human-wildlife conflict (Rajaratnam et al. 2016; Sangay & Vernes 2008; Velho et al. 2012). Although conserving large wide-ranging species protects co-occurring species (Andelman & Fagan 2000), rhinoceros populations are disjunctly protected across several PAs in India and Nepal (Aryal et al. 2017). Fifty percent of the Asiatic elephant's EH range is protected, but this may be inadequate due to their long-distance migration (Koirala et al. 2016). Tigers and snow leopards are apex predators well represented in EH PAs. However, only 13% of the EH geographic range of the sambar deer (*Rusa unicolor*), the tiger's principal prey, is protected. The blue sheep, among the 50 species and a key prey species for snow leopards, have <25% of their range within EH PAs. Conservation of EH mammals can be enhanced by extending protection to the 50 species we identified in addition to protecting large, wide-ranging species.

Eastern Himalayan PAs have been integral in conserving species, maintaining habitat integrity, and improving human socioeconomic conditions (Watson et al. 2014). Since the inception of India's Manas Wildlife Sanctuary as the first EH PA in 1928, the number and coverage of regional PAs have increased and PAs have gone from conserving iconic landscapes and wildlife to meeting a complex set of conservation, social, and economic goals (Reddy et al. 2016). With the exception of India, all range countries have individually protected more than 17% of their EH land. However, extending current PAs in the 11 priority areas we identified would enable India to achieve Aichi Target 11 for the Indian EH region.

The EH region has achieved the Aichi Target 11 of 17% protection, but coverage is underestimated because of inconsistent reporting to the WDPA (UNEP-WCMC 2016). For instance, the WDPA spatial data on China is still incomplete and assigned inconsistent IUCN categories (Wu et al. 2017; Wu et al. 2011). Coverage of EH PAs would be higher if transboundary conservation landscapes, community-managed forests, and other forms of habitat protection were considered. For example, 50% of Nepal's land is somewhat protected through PAs and community-managed forest schemes (Dinerstein et al. 2017), but WDPA data indicate that only 27.6% of Nepal's land is protected. Additionally, 14 sites covering 2.9% (14,958 km^2) of the EH region are currently listed as proposed PAs in the WDPA. These PAs play a crucial role in biodiversity conservation in the area, despite inconsistent information on current status and coverage. For instance, Namdapha National Park (1,985 km^2) in Arunachal Pradesh, which was captured in our priority areas 19 and 7 (Fig. 2.3a and 2.3b, respectively), is a nationally designated PA and one of the largest nature reserves in northeastern India (Arunachalam et al. 2004). However, it is only shown as a point location and its current status is not reported in the WDPA database. Namdapha Sanctuary (200 km^2) is reported as a proposed PA, although there is a management plan in place (Areendran et al. 2012), and the area of the sanctuary is inflated to 3,841 km^2 in the WDPA database (Table 2.2 in the database's appendix). This priority site (site 19 in Fig. 2.2) provides an important refuge to 7 priority species (Table 2.3).

In line with Dinerstein et al. (2017), most ecoregions and our priority areas were class 2 and thus had adequate habitat for a >50% expansion of PA. However, >31% of priority areas in India, Nepal, and China were class 3, which requires habitat restoration to meet and exceed the Achi target. Of our priority areas in class 4, 13.3% may be impossible to protect or restore due to high anthropogenic pressure (<4% of natural habitat remaining) (Dinerstein et al. 2017). For example the Terai-Duar Savannah and Grassland Ecoregion has is only 8.7% protected, less than the global average for protected ecoregions of 15.8% (Dinerstein et al. 2017). However, this ecoregion critically supports endangered Asiatic elephant and tiger populations, including the vulnerable rhinoceroses (Dhakal 2002). Similarly, the Brahmaputra Valley Semi Evergreen Forest Ecoregion supports an extant population of Asiatic elephants, tigers, and rhinoceroses (Koirala et al. 2016), but 28% of this ecoregion is class 4 because only 9.4% is protected regionally.

The Zonation output of unweighted biodiversity features showed a pattern similar to our species richness map (Fig. 2.1); thus, using overall species richness to identify priority conservation areas is misleading (Chao et al. 2014; Jenkins et al. 2015a; Veach et al. 2017). We therefore used weighted biodiversity features to identify priority areas for the 50 EH species we identified as of the highest conservation priority. However, there was a mismatch between EH PA distribution and our priority areas. Despite our finding that the EH region has achieved the Aichi 17% protection target and that it has the potential to meet Wilson's (2016) call to protect half -earth, only 9% of EH mammal species have >50% of their range inside PAs. Because of a growing recognition of the importance of ecological features to conserve biodiversity hotspots (Jenkins & Joppa 2009; Veach et al. 2017), PA network modification should strategically target areas that contribute most to biodiversity conservation and that need urgent conservation action (Butchart et al. 2015). Accordingly, our priority areas ensured optimum representation of the 50 species because most areas were outside current PAs. However, remote human communities in biodiversity-rich areas needing conservation are often economically, physically, and socially susceptible to negative effects of PA expansion (Büscher et al. 2017; Karanth & Nepal 2012). In return, PAs are subject to anthropogenic pressure from resource extraction, grazing, and poaching (Zheng & Cao 2015). Therefore, EH PA expansion in all classes is unrealistic unless the socioeconomic needs of resident people are addressed.

Several priority areas we identified are transboundary and thus require regional cooperation to maintain environmental integrity (Kandel et al. 2016) and promote PA security (Stolton et al. 2015). Cooperative transboundary initiatives will further enhance survival of the 50 species Successful regional examples include the Manas Conservation Area (India and Bhutan) and Terai Arc Landscape (India and Nepal) (WWF-Bhutan 2013) and improved information sharing, capacity building, and community participation in protected area management (Kiran et al. 2011). Other successful EH transboundary conservation areas include Kangchenjunga (Bhutan, India, and Nepal), Kailash (China, India, and Nepal) and the Brahmaputra-Salween (China, India, and Myanmar) (ICIMOD 2016).

The large negative effects the expanding EH human population is having on biodiversity (Bawa et al. 2010; Rao et al. 2002; Zhang et al. 2016) can be addressed through incentive-based community involvement in PA management, regional information exchange, enforcement of anti-poaching legislation, capacity building, and development of a comprehensive regional land-use plan. Finally, realignment of existing EH regional PAs based on the priority areas we identified will help in protecting the 50 species we identified as of the highest conservation priority in EH and achieving the Aichi Target 11 of 17% protection in EH region.

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Bhutan city bus painting showcasing Bhutan's biodiversity.

University of New England

STATEMENT OF AUTHORS' CONTRIBUTION

(To appear at the end of each thesis chapter submitted as an article/paper)

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Chapter 2: Identifying Conservation Priorities for Threatened Eastern Himalayan Mammals	**19-50**

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Principal Supervisor

10/04/2019
Date

Training survey team in 2014






Photos of my survey teams during Bhutan's nationwide camera trapping survey in 2014 and 2015

This chapter titled **Mammal Richness and Diversity in a Himalayan Hotspot: the role of Protected Areas in the Conserving Bhutan's Mammals** has been accepted as an original research paper, pending minor changes on 8 April 2019 by the international journal *Biodiversity and Conservation*.

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N.B. We adapted the referencing style of Biodiversity and Conservation for this chapter.

Royal Bengal tiger *Panthera tigris* (a mother tigress and three cubs) captured at 3000 m asl during Bhutan's nationwide camera trapping exercise in 2014 and 2015. The cubs are at the front and rear towards the right; tigress is at the centre. Only right ear of one cub can be seen on the picture but all three cubs are visible in the video record of the same animals.

Chapter 3: Mammal Richness and Diversity in a Himalayan Hotspot: the role of Protected Areas in the Conservation of Bhutan's Mammals.

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Abstract

More than 51% of Bhutan is in a Protected Area (PA) network and our study demonstrates its effectiveness in conserving large and medium mammal species. We conducted camera trapping in Bhutan's PAs, biological corridors (BCs) and intervening non-protected areas (NPAs) to investigate the richness and diversity of mammals, and assess the network's efficacy in protecting mammals. 1858 camera traps were deployed within 1129 5-km x 5-km grids over 536 days between 2014 and 2015, resulting in 148,598 trap-nights (mean = 80 traps-nights/camera) which yielded nearly 10 million photos (mean = 5,368 photos/camera trap). Fifty-six mammal species (65% of Bhutan's 86 medium and large terrestrial mammal species) representing 18 families within seven orders were identified, of which, 18 (32.16%) are listed as threatened by the

International Union for Conservation of Nature (IUCN). There was a significant difference in mammal diversity between PAs, BCs, and NPAs (PERMANOVA test; $p < 0.001$; Pseudo-F = 6.40; unique perms = 9921), with the strongest difference between PAs and NPAs. Additionally, Hill's numbers $q = 0$ (species richness), $q = 1$ (Shannon's entropy index) and $q = 2$ (Simpson's concentration index) revealed a higher mammal diversity in PAs compared to BCs and NPAs. Higher mammal diversity in PAs can be attributed to the added presence of threatened species, including the tiger *Panthera tigris*, red panda *Ailurus fulgens*, Asian elephant *Elephas maximus*, and golden langur *Trachypithecus geei*. However, BCs and NPAs share similar pattern of mammal diversity and globally threatened species such as the Chinese pangolin *Manis pentadactyla* and Indian pangolin *Manis crassicaudata* were only detected in NPAs. Although Bhutan's PA network is effective in conserving much of the country's mammal diversity, realignment of some protected areas and biological corridors would ensure the long-term protection of several threatened mammal species.

Keywords

Mammals, Eastern Himalayas, protected areas, camera trapping, species richness and diversity, Bhutan

Introduction

To prevent mass species extinction, halt global biodiversity loss, slow earth's rising temperature, and ensure continued provision of essential ecosystem services, scientists advocate the protection of 50% of earth's land and seas through inter-connected protected areas (Dinerstein et al. 2017; Wilson 2016; Wuerthner et al. 2015)., However, Buscher et al. (2016) argued that half-earth protection is impractical and would result in widespread negative consequences for human populations, especially in under developing countries. Bhutan achieved the Half-Earth target by setting aside 51.44% of the country's area in a protected area (PA) and biological corridor (BC) network, including a commitment to protect 17% of global terrestrial land and inland water areas by 2020 through Achi Target 11 (Convention on Biological Diversity 2010). Although Bhutan's PAs are well managed in partnership with local communities, they are experiencing increased pressure from infrastructure development, grazing, resource collection, human-wildlife conflict, and climate change (Dorji et al. 2012; Dorji 2016; Sangay and Vernes 2008; Thinley et al. 2018; Wang and Macdonald 2006). Previous studies on the nation's PA management effectiveness indicated that scientific data on PA functionality and effectiveness is lacking which, in turn, hinders adaptive management to changing land use pressures and climate (Choden 2016; Lham et al. 2018; Tshering 2003).

Mammals are key indicators for measuring anthropogenic impacts on biota (Ceballos & Ehrlich, 2002), and important for the maintenance and functionality of ecosystems through seed and fruit dispersal, pollination, nutrient recycling, and plant succession (Davidson *et al.*, 2012; Ripple *et al.*, 2015). Mammals also benefit people through the provision of food, recreation, and income (Naidoo *et al.*, 2016; Velho *et al.*, 2016). Therefore, knowledge on presence and distribution of mammals is crucial for planning and evaluating conservation strategies for a region or country (Tobler *et al.*, 2008). Despite their importance, detailed understanding of mammal diversity, distribution, and abundance are lacking in many regions including the Eastern Himalayas (Dorji *et al.*, 2018), and several efforts made in the past to inventory the mammal diversity in Bhutan mainly used sign surveys, direct observation and interviews, (Chakraborty 1975, Rawat and Wangchuck 2000, Sathyakumar and Adhikari 2005, Dorji, Vernes et al. 2011, Dorji, Rajaratnam et al. 2012). Most of these methods were poorly suited for rugged Himalayan terrain of Bhutan because of dense vegetation, rugged topography, high precipitation, animal behavior and logistical constraints often affected the effectiveness and consistent observation of animal or their signs (Sangay, Rajaratnam et al. 2014). Moreover, these methods have detected mostly the common and large mammals and missed elusive and rare species. The use of camera traps has overcome many of these issues and now has widespread applications (Tobler, Carrillo-Percastegui et al. 2008, McCallum 2013).

In Bhutan, only camera trap works published so far were Tempa, Hebblewhite et al. (2013) and (Wang and Macdonald 2009) and their focus were mainly on the charismatic species like felids like tiger in the biodiversity rich areas. We summarize the results of a nation-wide camera trapping survey between 2014 and 2015, and compare the richness and diversity of mammals in Bhutan's protected areas, biological corridors, and intervening non-protected areas. We further ascertain the adequateness of Bhutan's protected area and corridor network in conserving large and medium sized mammals.

Study area and methods

Altitude in Bhutan ranges from 150 – 7,570 meters above sea level (m asl) and there are three distinct eco-floristic zones: Alpine (>4000 m asl), Temperate (2000 – 4000 m asl) and Sub-tropical (150 – 2000 m asl) (Ministry of Agriculture and Forests 2014). This study was conducted across Bhutan's ten PAs, nine BCs that link PAs, and the intervening landscape comprising 14 Territorial Divisions ('non-protected areas' hereafter called 'NPAs'). Our study area covered 33,909 km^2 (88.30% of the country's area) from 150 m asl to approximately 4,500 m asl, and was divided into 5km x 5km survey grids. It was segregated into two blocks (Southern and Northern; Figure 3.1) which were sampled in two consecutive phases because of human resource constraints, camera trap availability, weather conditions, and funding availability. In each grid, we set up a camera station consisting of a pair of opposing un-baited cameras set 10-30 m apart at a height of 30-60 cm from the ground, and maintained a minimum distance of two kilometres between any two camera stations, for independence. Cameras were deployed along trails in areas with pronounced animal signs (tracks, scrapes, etc.) (Aung et al. 2017; Meyer et al. 2015; Moo et al. 2018; Tobler et al. 2008). Our cameras was specifically aimed at studying large and medium size mammals such as tigers and their prey, and our survey design have limitations of capturing small and aboreal mammals.

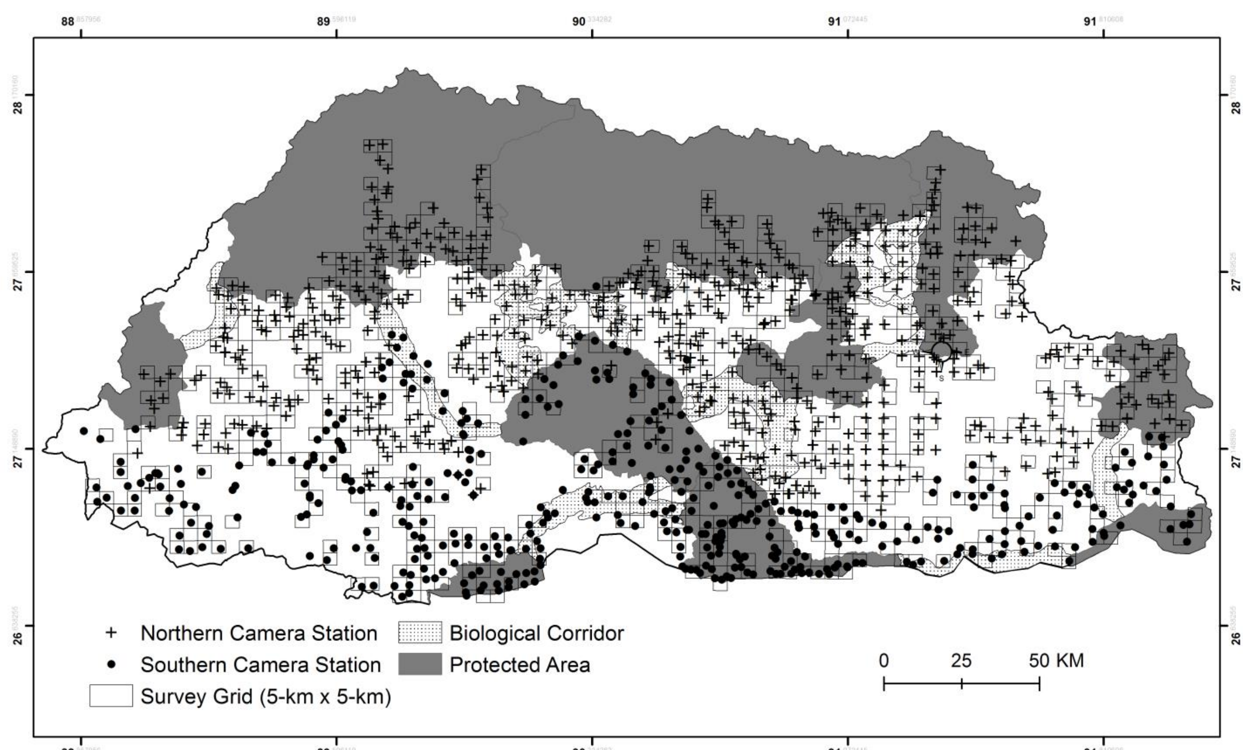


Fig. 3.1 Distribution of camera traps within 5-km x 5-km survey grids (square boxes) in this camera trap study of mammals in Bhutan from 2014 to 2015. Black circles indicate a camera station in the southern block and crosses indicate a camera station in the northern block

We compiled data over 536 days between January 2014 and June 2015, from 1,129 camera stations comprising 1,858 cameras (excluding malfunctioned cameras, stolen cameras, and cameras destroyed by elephants, rain, and windstorm). Image files were re-labeled according to their time and date using the Program 'Renamer' (http://www.snapfiles.com); sorted manually into species folders; and processed using 'Camerasweet' software (Sanderson and Harris 2014). Sampling effort at a station was calculated as the number of days a camera trap was operational at the location i.e. duration between installation of the last camera and retrieval of the first camera in each location. We assumed images of an individual species taken at least 30 minutes apart at a camera station to be independent events, and photographic rates or Relative Abundance Index (RAI) were obtained by dividing total events by the number of trap nights and multiplied by 100 (Rovero and Marshall 2009; Tobler et al. 2008). Species identification and conservation status were adapted from the International Union for Conservation of Nature and Natural Resources (IUCN) (IUCN 2018). We broadly characterized the community structure of mammals based on body mass (Smith et al. 2003) as follows: up to 1 kilogram = small sized mammal; 1-10 kilograms = medium sized mammal; and >10 kilograms = large sized mammal. We further categorized mammals into general trophic categories i.e. carnivore, herbivore, insectivore and omnivore based on dietary literature (Lambert 2014; Nowak and Walker 1999; Wilson et al. 2017). There were only three records of two species of insectivores (Chinese Pangolin *Manis pentadactyla* and Indian pangolin *Manis crassicaudata*) in the NPAs. As such, we excluded them from any analysis.

We assessed the completeness of our sampling by computing the sample size and coverage-based accumulation curves among three treatments (PA, BC & NPA; hereafter called sites) based on the C.hat estimator with 95% confidence intervals as proposed by Chao and Jost (2012). This yields the expected number of species in a community by normalizing bias due to sample size (Chao and Jost 2012; Rovero et al. 2017). We compared species richness and diversity of mammals between the three sites using integrated sample size and coverage-based rarefaction and extrapolation methods, for both abundance and incidence matrices at the 95% confidence interval (Chao et al. 2014; Chao and Jost 2012; Colwell et al. 2012). This allowed a fair comparison of species richness and diversity across sites despite differences in sampling effort (Chao et al. 2014; Hsieh et al. 2016). All the analyses were performed using R package iNEXT (Hsieh et al. 2016). We also performed a one-factor design, SS Type III (partial) Permutational Multivariate Analysis of Variance (PERMANOVA) test with 9999 permutations to compare significant differences between site-associated mammal communities using Primer 6 (Primer-E 2008).

Results

Trapping Effort, Species Composition, and Species Detection Rate

From 536 days of camera trapping, 9,975,258 photographs were obtained over 148,598 trap-nights (mean = 80 trap-nights/camera). Pooling data from multiple cameras in a grid returned a total sampling effort of 59,551 trap-nights in 751 survey grids (PA = 248; BC = 116; NPA = 387), from which, 51,017 independent photographs were obtained (20,496 in PAs; 8,098 in BCs; 22,423 in NPAs). This comprised 19,448 trap-nights in PAs, 9,787 trap-nights in BCs, and 30,316 trap-nights in NPAs (Table 3.1).

Table 3.1 Summary of camera trapping data of mammals in protected areas (PA), biological corridors (BC), and non-protected areas (NPA) of Bhutan between 2014 & 2015.

Sites	**Camera station**	**Total trap-night**	**Mean trap-night per camera station**	**Total event**	**Mean event**
PA	248	19448	78.4±3.45	20496	79.4±2.41
BC	116	9787	84.4±4.18	8098	66.4±2.44
NPA	387	30316	78.1±2.29	22423	55.5±2.54
Total	751	59551	80.0±1.77	51017	67.9±7.13

Fifty-six terrestrial mammal species representing 18 families within seven orders were recorded, of which, 18 (32.14%) are listed as threatened by IUCN. Threatened species included one Critically Endangered (CR) mammal (1.79%; Chinese Pangolin), eight Endangered (EN) mammal species (14.29%; including tiger *Panthera tigris*, red panda *Ailurus fulgens*, golden langur *Trachypithecus geei* and Asian elephant *Elephas maximus*), and nine Vulnerable (VU) mammal species (16.07%; including clouded leopard *Neofelis nebulosi*, Takin *Budorcas taxicolor*, and Binturong *Arctictis binturong*) (Table 2). The remaining 38 mammal species comprised eight Near Threatened (NT) species (14.29%) and 30 species (53.57%) of Least Concern (LC) (Table 3.2). Carnivores were the most diverse group, represented by 28 species (50%). There were nine (16.07%) rodent species, nine (16.07%) cetartiodactyl species, five (8.93%) primate species, two (3.57%) pholidota species, two (3.57%) lagomorph species, and one (1.79%) proboscid species (Table 3.2). Eighteen (32.14%) of the 56 mammal species recorded were totally protected under the Forest and Nature Conservation Rule of Bhutan, 2017 (Table 2). In terms of trophic categories, there were 26 (46.43%) carnivore, 24 (42.86%) herbivore, two (3.57%) insectivore, and 4 (17.14%) omnivore species.

Overall naïve occupancy of people captured on camera was 0.52 comprising 8,155 photos (15.98% of the total independent photographs excluding survey team members). The naïve occupancy of people was 0.38, 0.52, and 0.54 in the PAs, BCs, and NPAs, respectively. However, mean RAI of people was higher in BCs (mean ± SE photos per period = 1,310 ± 300) compared to PAs (mean ± SE photos per period = 1,227 ± 298) and NPAs (mean ± SE photos per period = 910 ± 120). Livestock (cattle, horse, yak, goat, sheep, and domestic dog) was captured in 14.35% of total independent photographs from 55.7% of camera stations. The naïve occupancy of livestock was 0.56, 0.62, and 0.54 in the PAs, BCs, and NPAs, respectively. Mean RAI of livestock was higher in PAs (mean ± SE photos per period = 1,363 ± 208) and BCs (mean ± SE photos per period = 1,333 ± 175) compared to NPAs (mean ± SE photos per period = 1,066 ± 92). Some cameras stationed along the Indian border in the south also recorded Indian poachers carrying rifles (5 stations), forest fires (6 stations), and a vehicle (one station).

Commonly detected mammal species were barking deer *Muntiacus muntjak*, Sambar deer *Rusa unicolor*, wild-pig *Sus scrofa*, Asiatic black bear *Ursus thibetanus*, Himalayan serow *Capricornis thar*, and gaur *Bos gaurus* (Table 3.2). The Asian elephant was also recorded in 91 camera stations (Table 3.2). Amongst the carnivores, commonly detected species were yellow-throated marten *Martes flavigula*, Asiatic golden cat *Catopuma temminckii*, leopard cat *Prionailurus bengalensis*, common leopard *Panthera pardus*, and marbled cat *Pardofelis marmorata* (Table 3.2).

Uncommon species, recorded at just one camera station each, were small-toothed ferret badger *Melogale moschata*, small Indian mongoose *Herpestes javanicus*, Asian small-clawed otter *Aonyx cinereus*, golden langur, and Chinese pangolin (Table 3.2).

Table 3.2 Summary of mammal species recorded during the nationwide camera trapping exercise in Bhutan from 2014 to 2015, and their current conservation status as per International Union for Conservation of Nature (IUCN) red list criteria (CR = Critically Endangered; EN = Endangered; VUL =Vulnerable; NT = Near Threatened & LC = Least Concerned). * = totally protected species under Forests and Nature Conservation Rule (FNCR), 2017; N = number of camera stations that captured the species; PA = Protected Area; BC = Biological Corridor; NPA = Non-Protected Area; Relative Abundance Index = the number of events divided by the sampling effort per 100 trap-nights; Trophic level (C = Carnivore, H = Herbivore, O = Omnivore, I = Insectivore).

Order\Family	Common name	IUCN	Trophic	Size	N	Mean Relative Abundance Index			
Scientific name						Overall	PA	BC	NPA
CARNIVORA						31.14	34.61	24.95	12.46
Ailuridae						0.44	0.71	0.25	0.33
*Ailurus fulgens**	Red Panda	EN	H	M	54	0.44	0.71	0.25	0.33
Canidae						1.74	2.36	1.78	1.35
Cuon alpinus	Dhole	EN	C	L	196	1.08	1.15	1.35	0.95
Vulpes ferrilata	Tibetan fox	LC	C	M	8	0.26	0.84	0.00	0.00
Vulpes vulpes	Red fox	LC	C	M	28	0.39	0.37	0.43	0.39
Canis aureus	Asiatic jackal	LC	C	L	1	0.01	0.00	0.00	0.01
Felidae						9.94	14.74	12.52	6.29

*Panthera tigris**	Tiger	EN	C	L	122	0.97	1.24	2.01	0.49
P. bengalensis	Leopard cat	LC	C	M	243	2.49	3.67	2.56	1.77
Felis chaus	Jungle cat	LC	C	M	7	0.01	0.00	0.02	0.01
Catopuma temminckii	Asiatic golden cat	NT	C	L	261	2.56	4.35	2.36	1.57
Pardofelis marmorata	Marbled cat	NT	C	M	148	1.70	2.35	2.32	1.12
*Panthera pardus**	Common leopard	VU	C	L	187	1.86	2.53	2.75	1.19
*Neofelis nebulosi**	Clouded leopard	VU	C	L	79	0.34	0.61	0.50	0.14
Herpestidae						0.24	0.52	0.11	0.12
Herpestes urva	Crab-eating mongoose	LC	C	M	39	0.23	0.47	0.11	0.12
Herpestes edwardsii	Common Mongoose	LC	C	M	2	0.01	0.04	0.00	0.00
Herpestes javanicus	Small Indian mongoose	LC	C	S	1	0.002	0.000	0.000	0.003
Mustelidae						2.60	2.42	4.26	2.19
Martes flavigula	Yellow-throated	LC	C	M	293	2.57	2.39	4.20	2.17

	marten								
Mustela kathiah	Yellow-bellied weasel	LC	C	S	2	0.01	0.02	0.00	0.01
Mustela sibirica	Siberian weasel	LC	C	S	1	0.01	0.00	0.06	0.00
Melogale moschata	Small-toothed ferret badger	LC	C	S	1	0.001	0.000	0.00	0.002
Mustela altaica	Pale weasel	NT	C	S	2	0.005	0.004	0.00	0.007
Aonyx cinereus	Asian Small-clawed otter	VU	C	M	1	0.002	0.006	0.00	0.000
Prionodontidae						0.06	2.42	4.26	2.19
Prionodon pardicolor	Spotted linsang	LC	C	S	22	0.06	0.03	0.09	0.07
Ursidae						3.93	9.48	2.54	1.05
*Ursus thibetanus**	Asiatic black bear	VU	O	L	278	3.92	9.46	2.54	1.05
Arctictis binturong	Binturong	VU	C	L	2	0.01	0.03	0.00	0.00
Viverridae						2.46	4.34	3.40	1.06
P. hermaphroditus	Common palm	LC	C	M	37	0.64	1.62	0.38	0.13

	civet								
Paguma larvata	Himalayan palm civet	LC	C	M	147	1.24	1.49	2.24	0.79
Viverra zibetha	Large Indian civet	LC	C	M	43	0.47	0.92	0.76	0.12
Viverricula indica	Small Indian civet	LC	C	M	18	0.11	0.31	0.01	0.02
CETARTIODACTYLA						45.57	65.60	57.07	30.13
Bovidae						7.72	14.35	8.87	3.42
*Bubalus arnee**	Asiatic water buffalo	EN	H	L	6	0.22	0.70	0.00	0.00
*Capricornis thar**	Himalayan serow	NT	H	L	294	3.03	4.07	3.70	2.21
Naemorhaedus goral	Himalayan goral	NT	H	L	130	1.58	2.42	3.14	0.60
*Bos gaurus**	Gaur	VU	H	L	102	2.83	6.98	2.03	0.60
*Budorcas taxicolor**	Takin	VU	H	L	3	0.06	0.18	0.00	0.01
Cervidae						28.50	40.38	31.76	20.43
Muntiacus muntjak	Barking deer	LC	H	L	528	19.53	23.80	24.22	15.54
*Rusa unicolor**	Sambar deer	VU	H	L	363	8.97	16.57	7.54	4.89

Moschidae						0.48	0.66	0.83	0.27
*Moschus species**	Musk deer	EN	H	L	39	0.48	0.66	0.83	0.27
Suidae						8.87	10.21	15.61	6.01
Sus scrofa	Wild boar	LC	O	L	465	8.87	10.21	15.61	6.01
LAGOMORPHA						0.14	0.35	0.11	0.03
Ochotonidae						0.14	0.35	0.11	0.03
Ochotona roylei	Common pika	LC	H	S	6	0.10	0.21	0.11	0.03
Lepus nigricollis	Indian hare	LC	H	M	2	0.05	0.15	0.00	0.00
PHOLIDOTA						0.01	0.00	0.00	0.02
Manidae						0.01	0.00	0.00	0.02
*Manis pentadactyla**	Chinese pangolin	CR	C	M	1	0.004	0.00	0.00	0.008
*Manis crassicaudata**	Indian pangolin	EN	C	M	2	0.01	0.00	0.00	0.01
PRIMATES						1.39	1.56	1.16	1.36
Cercopithecidae						1.39	1.56	1.16	1.36
*Trachypithecus geei**	Golden langur	EN	H	M	1	0.00	0.01	0.00	0.00
Semnopithecus entellus	Grey langur	LC	H	L	9	0.04	0.08	0.04	0.01

Macaca mulatta	Rhesus macaque	LC	O	M	11	0.24	0.01	0.28	0.36
Macaca assamensis	Assamese macaque	NT	O	L	125	1.03	1.42	0.73	0.89
Trachypithecus pileatus	Capped langur	VU	H	L	12	0.08	0.03	0.10	0.11
PROBOSCIDEA						2.71	7.50	0.82	0.45
Elephantidae						2.71	7.50	0.82	0.45
*Elephas maximus**	Asian elephant	EN	H	L	91	2.71	7.50	0.82	0.45
RODENTIA						2.92	3.94	3.39	2.17
Hystricidae						2.55	3.27	2.94	2.00
Hystrix brachyuran	Himalayan crestless porcupine	LC	H	M	164	2.27	2.99	2.39	1.81
Atherurus macrourus	Asiatic brush-tailed porcupine	LC	H	M	34	0.27	0.28	0.56	0.18
Hystrix indica	Indian crested porcupine	LC	H	L	1	0.00	0.00	0.00	0.01

Sciuridae						0.37	0.66	0.44	0.18
C. pygerythrus	Hoary-bellied Himalayan squirrel	LC	H	S	14	0.18	0.43	0.10	0.05
Dremomys lokriah	Orange-bellied Himalayan squirrel	LC	H	S	12	0.08	0.10	0.20	0.04
Callosciurus erythraeus	Pallas's squirrel	LC	H	S	8	0.06	0.06	0.05	0.07
*Petaurista magnificus**	Hodgson’s Giant flying squirrel	LC	H	M	1	0.01	0.00	0.02	0.00
*Ratufa bicolor**	Malayan giant squirrel	NT	H	M	7	0.03	0.04	0.06	0.01
*Petaurista nobilis**	Bhutan giant flying squirrel	NT	H	M	7	0.01	0.02	0.02	0.01

Sample Completeness, Species Richness, and Species Diversity

Forty-one (73.21%) species were found at all three sites, while the remaining 15 (29.82%) occurred only in one or two sites (Table 3.2). A total of 47, 39 and 48 each were observed in PAs, BCs and NPAs (Table 3.2). Similarly, eight (14.03%) species occurred only in PAs, six (10.52%) occurred only in NPAs, and one (1.75%) species occurred only in BCs. Forty one (73.21%) species each overlapped between PAs and BCs, PAs and NPAs, and BCs and NPAs (Table 3.2). Overall detection rate was higher in PAs compared to BCs and NPAs (Table 3.2). Detection rates of Bovidae (mean ± SE photos per period = 14.35 ± 1.23), Cervidae (mean ± SE photos per period = 40.37 ± 2.23), Ochotonidae (mean ± SE photos per period = 0.35 ± 0.07), Elephantidae (mean ± SE photos per period = 7.49 ± 0.78), Hystricidae (mean ± SE photos per period = 3.27 ± 0.23), Cercopithecidae (mean ± SE photos per period = 1.56±0.115, and Sciuridae (mean ± SE photos per period = 0.66 ± 0.13) families were higher in PAs compared to BCs and NPAs (Figure 3.2).

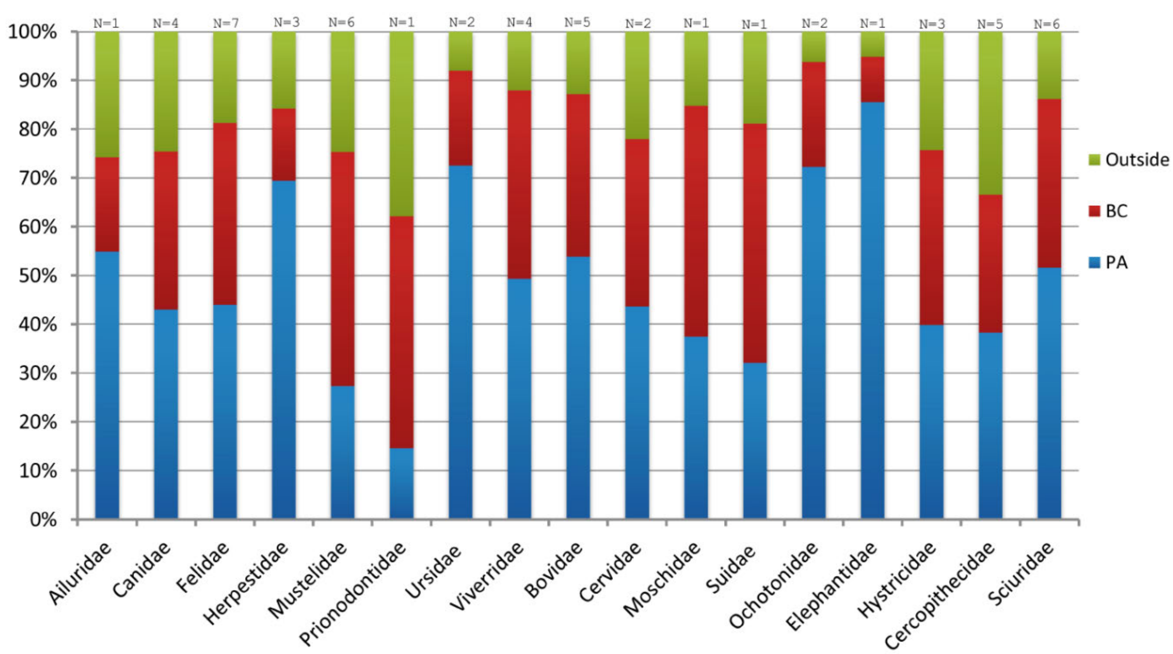


Figure 3.2 Mean detection rate with standard error of terrestrial mammal family in the protected areas (PA), biological corridors (BC) and non-protected areas of Bhutan based on the nationwide camera trapping data between 2014 and 2015. N = number of species in each family.

Although PAs showed higher RAIs in terms of overall mammal species diversity compared to BCs and NPAs, mean RAI for tiger and common leopard was highest in the BCs (Table 3.2). Similarly, mean RAI for their favored prey species such as barking deer, wild-pig *Sus scrofa*, and musk deer *Moschus spp*. was also higher in BCs compared to PAs and NPAs (Table 3.2). However, mean RAI for sambar deer was higher in PAs (Table 3.2). BCs also had a higher RAI for the Mustelidae family and the RAI of one species from the Prionodontidae family, the spotted lingsang *Prionodon pardicolor,* was highest in BCs (Table 3.2). However, both pangolin species (*Manis pentadactyla and Manis crassicaudata*) was recorded only in the NPAs. Overall RAI of mammal species was lowest in NPAs compared to PAs and BCs (Table 3.2).

Sample size of unstandardized raw abundance data (number of individuals) combined for all mammal species was 23,131 for PAs, 8,280 for BCs, and 12,689 for NPAs (Table 3.3). Observed species richness, Shannon diversity index, and Simpson diversity index (Hill’s numbers for q = 0, 1, 2) was 47, 16, and 11 for PAs, respectively; 39, 12, and 6 for BCs, respectively; and 48, 12, and 6 for NPAs, respectively (Table 3.3). Estimated species richness, Shannon diversity, and Simpson diversity (Hill’s numbers for q = 0, 1, 2) was 47, 16, and 11 for PAs, respectively; 39, 12, and 6 for BCs, respectively; and 52, 12, and 6 for NPAs, respectively (Table 3.3).

Table 3.3(a) Summary information of incidence data from a nationwide camera trapping exercise in Bhutan between 2014 and 2015 including site name (PA = protected area; BC = biological corridor; NPA = non-protected area or areas outside PA and BC); T = number of observed sampling units in the reference sample (sample size for incidence data); S.obs = observed species richness; SC = sample coverage estimate;

	Site	T	S.obs	SC	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
1	NPA	12689	48	0.99	4	2	2	3	2	1	0	1	0	1
2	BC	8280	39	1.00	0	3	0	2	0	1	0	3	0	1
3	PA	23131	47	1.00	0	3	0	1	1	2	0	2	0	2

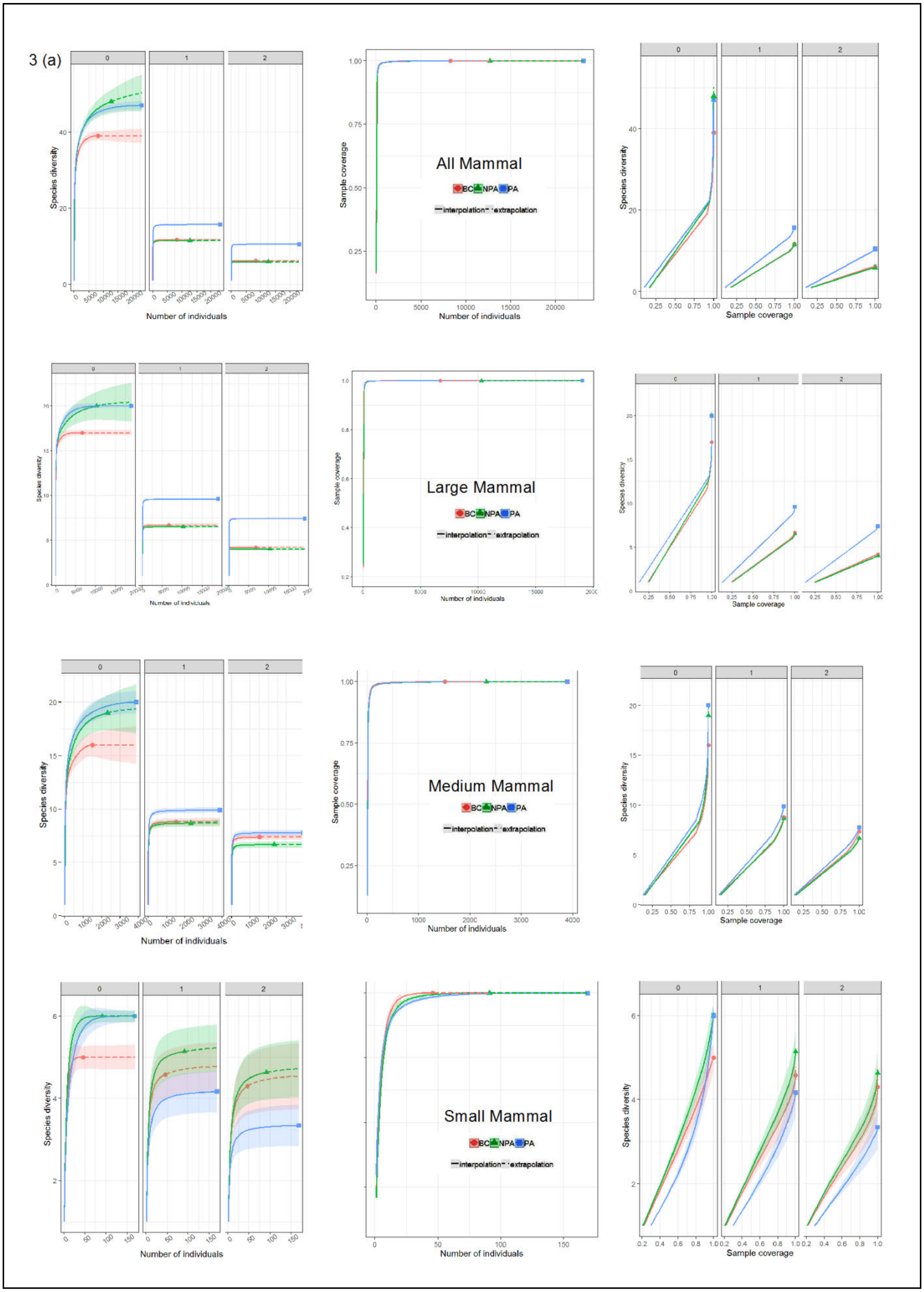
Table 3.3 (b) Asymptotic diversity estimates along with related statistics for a series of rarefied and extrapolated samples for nationwide camera trapping data along with related statistics on species richness (0), Shannon Diversity Index(1), and Simpson Diversity Index(1), and Simpson Diversity Index (2) in PAs, BCs and NPAs of Bhutan. SE = standard error; LCL = lower confidence level; UCL = upper confidence level. F1-F10 = the first ten species incidence frequency counts in the reference sample; Observed = number of species observed; Estimator = estimator of the sample coverage suggested by Chao et al. (2013).

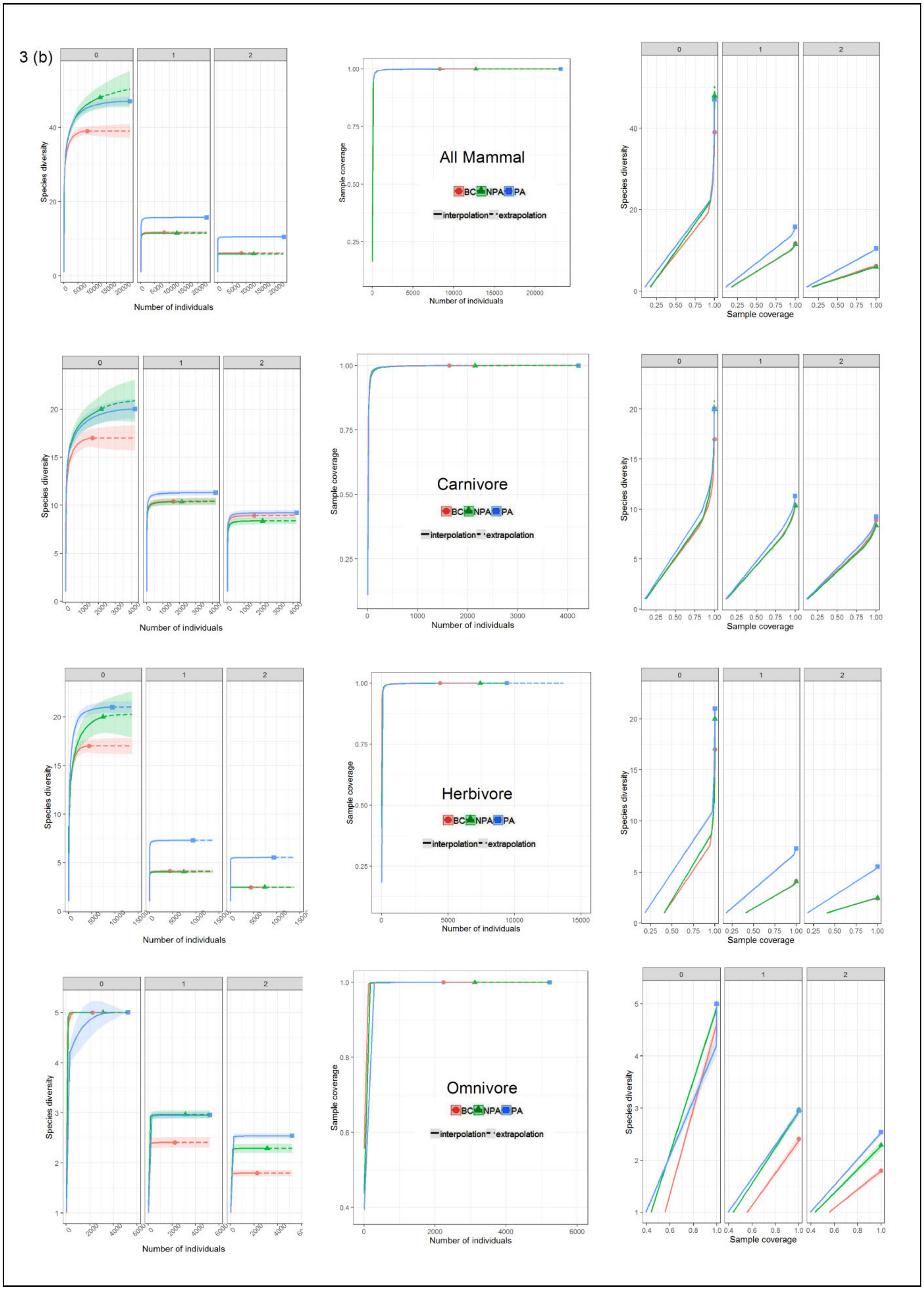
Site	Diversity	Observed	Estimator	SE	LCL	UCL
PA	Species richness	47	47	0.62	47.00	48.66
PA	Shannon diversity	16	16	0.11	15.73	15.95

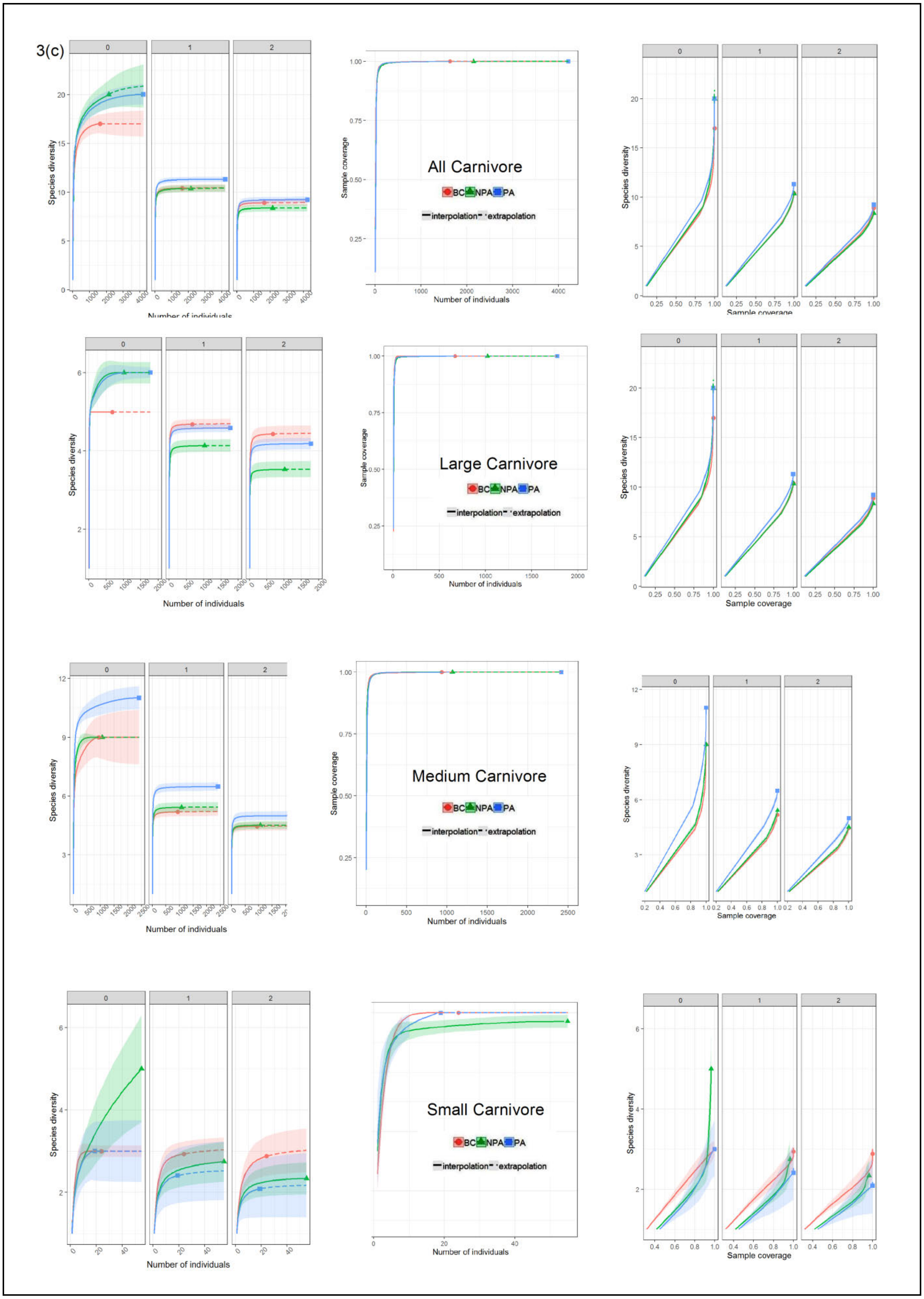
PA	Simpson diversity	11	11	0.10	10.49	10.69
BC	Species richness	39	39	0.63	39.00	40.69
BC	Shannon diversity	12	12	0.18	11.73	12.10
BC	Simpson diversity	6	6	0.10	6.21	6.41
NPA	Species richness	48	52	5.29	48.56	76.72
NPA	Shannon diversity	12	12	0.13	11.51	11.79
NPA	Simpson diversity	6	6	0.09	5.92	6.10

Although integrated sample size-based extrapolation curves at 95% confidence intervals for species richness (q = 0) showed that overall species richness was significantly higher in PAs and NPAs compared to BCs (Figure 3.3a), confidence intervals for PAs and NPAs overlapped, suggesting there were no significant differences in species richness between PAs and NPAs. Sample coverage for the three sites was estimated at 100%, 100%, and 99% respectively, indicating that sampling was nearly complete for all sites (Figure 3.3b). Curves reached their asymptote at a sample size of 4,500 sampling units (i.e. number of individuals) for all three sites. Both PAs and NPAs achieved their sampling asymptote well ahead of the sample reference point of 23,131 and 12,689, respectively (Figure 3.3a). Similarly, both sample size and coverage-based sampling curves showed that overall species diversity was significantly higher in PAs compared to BCs and NPAs (top panel of Figure 3.3a & 3.3b) for any fixed sample-size up to 23,131 and 0.99 in all orders of Hill's numbers ($q = 0$, 1 and 2). Diversity of species in BCs and NPAs was almost similar in all cases except that species richness was higher in NPAs between 30-90% coverage (left panel in Figure 3.3a and 3.3b for all mammals). PERMANOVA test results on mammal abundance data also showed a strong significant difference between the three sites ($p < 0.001$; Pseudo-F = 6.40; unique perms = 9921). Further pair-wise test results also showed similar results, with strong effects between PAs and NPAs, and BCs and NPAs.

Diversity of large and medium sized mammals was significantly higher in PAs compared to BCs and NPAs (Figure 3.3a). There was no significant difference in small mammal diversity between all three sites. Some differences were also observed at the general trophic level (carnivore, herbivore, and omnivore; Figure 3.3b). However, species richness was significantly lower in BCs for carnivores, herbivores, large-sized, and small-sized mammal species compared to PAs and NPAs (Figure 3.3a & 3.3b). There were no significant differences in species richness between PAs and NPAs at all levels. In terms of specific tropic levels, species diversity of large-sized carnivores and medium-sized carnivores was significantly higher in PAs compared to BCs and NPAs (Figure 3.3c). But species richness and diversity of small carnivores, medium-sized herbivores, and small herbivores was similar in all three sites (Figure 3.3c & 3.3d). Similarly, the diversity of large herbivores was significantly higher in PAs compared to BCs and NPAs, despite no significant differences in species richness among three sites (Figures 3.3c and 3.3d).


3 (a)
All Mammal
Large Mammal
Medium Mammal
Small Mammal
BC NPA PA
interpolation extrapolation
Species diversity
Sample coverage
Number of individuals


3 (b)
All Mammal
Carnivore
Herbivore
Omnivore
BC NPA PA
interpolation extrapolation
Species diversity
Number of individuals
Sample coverage


3(c)
All Carnivore
Large Carnivore
Medium Carnivore
Small Carnivore
BC NPA PA
interpolation extrapolation
Species diversity
Sample coverage
Number of individuals

3(d)

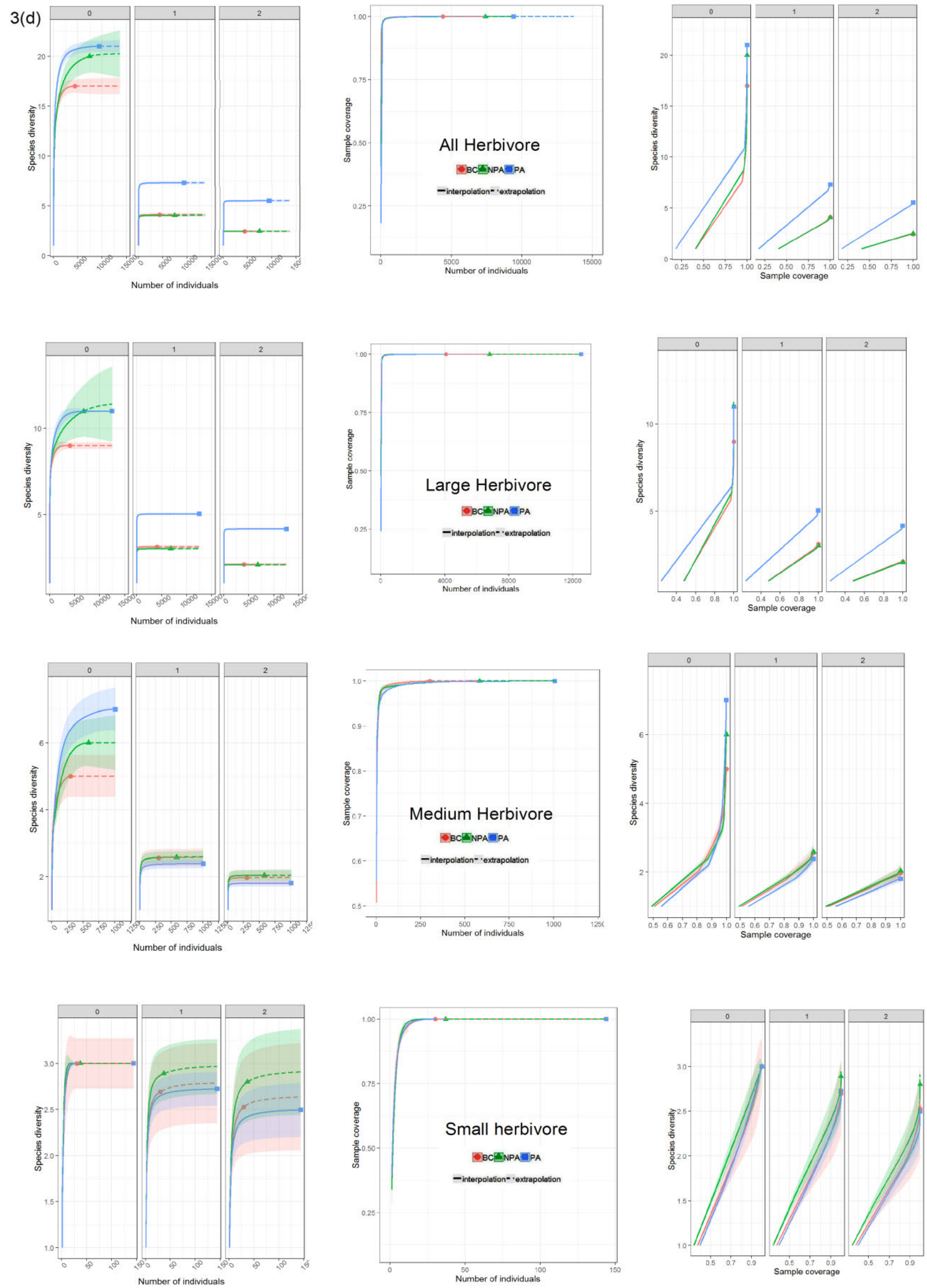

All Herbivore
BC NPA PA
interpolation extrapolation
Large Herbivore
Medium Herbivore
Small herbivore
Species diversity
Number of individuals
Sample coverage

Fig 3.3 Sample size and coverage-based rarefaction (solid line segment) and extrapolation (dotted line segments up to largest reference sample size) curves with 95% confidence intervals (shaded areas) using Hill numbers (q = 0, 1, 2) comparing mammal species richness and diversity from camera trapping data in the protected areas (PA), biological corridors (BC), and non-protected areas (NPA; outside the PA and BC). 95% confidence intervals were obtained by a bootstrap method based on 200 replications. Left panel = sample size-based rarefaction and extrapolation curves; Middle panel = sample completeness curves; Right panel = coverage-based rarefaction and extrapolation curves (All curves are based on the Hill's numbers for Q0= Species richness; Q1 = Shannon diversity index, Q2 = Simpson diversity index). Mammals were arbitrarily categorized based on their body mass (small mammal = <1 kgs; medium mammal = 1-10 kgs; large mammal = >10 kgs; Fig 3.3(a) and trophic level (carnivores, herbivores, omnivores); Fig 3.3(b). Fig 3.3(c) denotes species richness and diversity of carnivore species. Fig 3(d) denotes species richness and diversity of herbivore species.

Discussion

Efficacy of Bhutan's Protected Area Network

Over 21% of global mammal species including those in the Eastern Himalayas are currently threatened with extinction (Dorji et al. 2018; IUCN 2018) from habitat alteration (Crooks et al. 2017; Schipper et al. 2008). Protected areas are integral for biodiversity conservation and play a vital role in preventing species extinction, preserving habitat integrity, and conserving species diversity especially across the Eastern Himalayas (Chettri et al. 2008; Dorji et al. 2018). While protected areas elsewhere in the EH region are becoming isolated pockets as unrelenting habitat conversion is causing irreversible damage to the landscape and the region's biodiversity

, Bhutan is one of the few global countries which has achieved the novel idea of securing at least half of the earth, as suggested by E.O. Wilson (2016) to address the species-extinction crisis, conserve biodiversity, and prevent collapse of vital services provided by ecosystems, such as carbon sequestration and climate regulation (Dinerstein et al., 2017; Locke, 2014). Our study further shows that Bhutan's PAs are effectively conserving medium and large mammal species, as demonstrated through the significant difference in mammal diversity between PAs, BCs, and NPAs with the strongest difference between PAs and NPAs (Figure 3.3, Table 3.3). Furthermore, results from our sample size and coverage-based sampling curves established a greater diversity of mammals in PAs relative to BCs and NPAs, while BCs and NPAs shared an almost similar pattern of mammal diversity. PAs in Bhutan afford better habitat protection because consumptive uses (firewood, non-timber forest products and timber for rural house construction) are heavily regulated, and no commercial activities (such as mining, hydropower damming and commercial logging) are allowed (Wangchuk, 2007). PAs also effectively prevented up to 63% of net forest cover loss, with early established protected areas and the less fire-sensitive broadleaf forests showing higher effectiveness (e.g. Royal Manas and Jigme Dorji National Parks) (Bruggeman et al. 2018). However, confidence intervals in species diversity curves for BCs and NPAs eventually converge, indicating that these two landscape types share similar mammal species diversity. This can be possibly attributed to a land management perspective, as both BCs and NPAs are managed by Bhutan's various Territorial Divisions for multiple land-use purposes (Bruggeman et al. 2018; Katel and Schmidt-Vogt 2015; Lham et al. 2018). Moreover, only three of the eight BCs are currently operational and have conservation management plans in place (Dorji and Wangdi 2018). However, the resource uses in the BCs are more regulated with tighter rules than NPAs, once BCs are operationalized.

Previous studies from the region show that human disturbance adversely affects the abundance and conservation of small and large mammals (Dorji et al. 2012; Mishra et al. 2006; Panthi et al. 2017; Velho et al. 2016). Although forest cover in Bhutan increased between 1990 and 2010 with an annual net-gain of 0.22% (average annual growth rate of 59-km^2/year) (Gilani et al. 2015), habitat quality did degrade in some areas because of infrastructure development such as hydropower dams, road-network expansion, industrial development, urbanization, selective logging, and mining (Bruggeman et al. 2016; Watershed Management Division 2017). Greater forest cover loss was also observed along the periphery of PA boundaries compared to areas inside and further away (Bruggeman et al. 2018). Most developments were initiated in the last three decades and mainly occurred in the NPAs and BCs, since most of the BCs were not operationalized. For example, all nine of Bhutan's major hydropower dams, forest management units for logging, and district urban towns (except Gasa which has less than 500 residents) are in NPAs. Based on the study by Tshering (2003) and Wangchuk (2002), livestock grazing was once thought to be the main threat to biodiversity conservation in Bhutan's PAs but has now decreased due to change in livestock grazing patterns and the promotion of intensive livestock management practices (Samdup et al. 2010; Wangchuk et al. 2014). In particular, local free ranging breeds of cows were progressively replaced by improved dairy crossbred cattle, which are mainly stall-fed (Samdup et al. 2010). PAs and BCs also have a higher proportion of shrub lands and grasslands relative to NPAs (Gilani et al. 2015). Such habitats are important for herbivores (Gibson 2009; Sankaran 2009). Similarly, only 4% of agricultural and human inhabited areas in the country fall inside PAs including BCs (Dorji and Wangdi 2018). Furthermore, habitat degradation from agricultural activities has decreased in the last two decades due to agricultural intensification, a ban on shifting cultivation, and increased agricultural imports (Bruggeman et al. 2016; Phuntsho et al. 2015; Roder et al. 1992). Therefore, despite human presence in Bhutan’s protected area network (Dorji et al. 2012), anthropogenic impacts are relatively low compared to NPAs, thus delivering better efficacy in maintaining and conserving mammal diversity.

Mammal Species Diversity and Conservation

By virtue of adequate landscape protection, higher mammal diversity in PAs relative to BCs and NPAs is attributed to the presence of large and medium-sized carnivore species such as the tiger, dhole *Cuon alpinus,* Binturong, clouded leopard and Tibetan fox *Vulpes ferrilata*, along with large herbivore species such as Asiatic water buffalo *Bubalus arnee,* golden langur, musk deer and Asian elephant (Table 3.2 and Figure 3.3a, 3.3b). However, the presence of the critically endangered Chinese pangolin and endangered Indian Pangolin which are priority species for the Eastern Himalayas (Dorji et al. 2018), was only confirmed in NPAs (Table 3.2). NPAs also recorded higher diversity of omnivore species such as Asiatic black bear, wild pig *Sus scrofa*, Assamese macaque *Macaca assamensis*, Rhesus macaque *Macaca mulatta* and yellow-throated marten *Martes flavigula*. A realignment of PA and BC boundaries to capture areas of NPAs known to support these species is, therefore, warranted and feasible in Bhutan where the vast majority of the landscape still remains forested regardless of tenure. This will be especially crucial for the survival of the endangered Chinese and Indian pangolins. Furthermore, all the omnivorous species occurred on all three sites and are categorised as problematic species in the national human-wildlife conflict management strategy of Bhutan (Nature Conservation Division 2008), and thus, require immediate conservation and management intervention.

Bhutan has high carnivore diversity (39 species; Wangchuk et al. 2004) within large tracts of undisturbed habitat. Of the 56 terrestrial mammal species we detected, more than 50% were carnivores and about 16% were ungulates which are important prey (Wang and Macdonald 2009a, Table 3.1). This high carnivore diversity and associated prey can be largely attributed to the diverse array of habitats ranging from subtropical forests in the lowlands to temperate broadleaf and mixed conifer forests at higher elevations across two biogeographical realms (Dinerstein et al. 2017). We detected nine (81.8%) of Bhutan’s 11 resident felid species across this landscape, and consistent with results from previous studies (Tempa et al. 2013; Wang and Macdonald 2009b), our study also showcases the effectiveness of Bhutan’s PAs in conserving large carnivores and their prey. BCs, in particular, have a higher diversity of large carnivores like tigers, clouded leopard, dhole and common leopards, and prey species such as barking deer, sambar, wild-pig and musk deer. This clearly indicates that Bhutan’s BCs are currently functional and facilitating movement, breeding or range expansion of these big cats (Wangchuk 2007). Because our study area stopped at the tree line (4, 500 m asl), we did not record high elevation felids like the snow leopard and Pallas’s cat *Otocolobus manul*. However, >95% of areas above 4,500 m asl are in the protected area network, with guaranteed protection (Dorji and Wangdi 2018).

Our comprehensive landscape survey recorded the presence of some rare mammals previously only known from sporadic records. This included the Chinese pangolin, Indian pangolin, mountain weasel *Mustela altaica*, small-toothed ferret badger, Binturong, Asian small clawed otter, and Bhutan giant flying squirrel *Petaurista nobilis***.** However, we did not record the critically endangered pygmy hog *Porcula salnania* and vulnerable Indian rhinoceros *Rhinoceros unicornis*, previously recorded in the Royal Manas National Park (Wikramanayake and Wangchuk 1993) and only confirmed through anecdotal information in the last decade (Dorji 2014). This may be because of their relative low density which may be caused by reduction in grassland, shrubland, and barren areas (Gilani et al. 2015) which are key habitat requirements (Dinerstein and Price 1991; Mary et al. 2013)**.** Grassland cover reduction in Bhutan is due to poor or non-existent habitat management, and invasion by exotics such as *Lantana camara* and *Eupatorium odoratum* (Dorji 2014; Wangdi 2015).

Thirty-three percent (n = 19) of our detected mammal species are totally protected under the Forest and Nature Conservation Rules of Bhutan, and 31% (n = 18) are threatened under the IUCN category of threatened species. Despite stringent legislation, high mammal species diversity in PAs, and a strong political will for nature conservation, our detection of local people, domestic livestock, foreign poachers, and forest fires reveal inherent threats to resident mammals. This finding reinforces local and regional threats to mammals from agricultural activities, livestock grazing, timber collection, poaching and illegal trading of wildlife parts, forest fire, and human-wildlife conflict (Dendup and Lham 2018; Dorji et al. 2018; Velho et al. 2012). Despite these anthropogenic threats, Bhutan's network of PAs and BCs still harbor a rich mammal community through the government's ability to reconcile biodiversity conservation goals with social and economic issues. The importance of local communities within PAs and BCs is further recognized and integrated into PA conservation goals, and stewardship promoted through incentive-based conservation programs (Lham et al. 2018; Tshering 2003). This integration of landscape protection (PAs) and connectivity (BCs) along with harmonious coexistence with local communities will ensure the conservation of Bhutan's mammal diversity well into the future.

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Type of work	Page number/s
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Camera trap photos of the globally endangered Dhole *Cuon alpinus* at 3200 m asl in Gantey valley, captured during Bhutan’s nationwide camera trapping exercise in 2014 and 2015. The background Mountains depicts the black mountain in Jigme Singye Wangchuck National Park.

Selected camera trap photos of mammal species captured during Bhutan's nationwide camera trapping exercise in 2014 and 2015.

This chapter titled **Mammal Assemblages, species richness and diversity in an Eastern Himalayan Biodiversity Hotspot: Results from nationwide camera trapping in Bhutan** has been prepared as a manuscript for submission to the international journal *Animal Conservation* as a peer-reviewed research paper.

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Photo showing a mother and two cubs (one is melanistic) of the common leopard *Panthera pardus*. Photo captured during Bhutan's nationwide camera trapping exercise in 2014 and 2015.

Chapter 4: Mammal assemblages, species richness and diversity in an Eastern Himalayan Biodiversity Hotspot: Results from a nationwide camera trapping in Bhutan.

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Abstract

The Kingdom of Bhutan has high mammal species richness from largely intact forests geographically centered within a global biodiversity hotspot. Despite considerable advances in documenting the occurrence and distribution of mammal fauna in Bhutan, knowledge gaps remain on distribution, composition, and the functional role of mammal species along floristic zones within an altitudinal gradient in the landscape. To assess species richness, diversity, and mammal assemblages in Bhutan's seven major forest types, we conducted nationwide camera trapping from the southern lowlands (150m above sea level) to the approximate tree-line (at 4,500m above sea level), using 1858 camera traps stationed within 1129 5-km x 5-km grids over 536 days between 2014 and 2015. A total of 148,598 trap-nights (mean trap-night = 79.97/camera) were completed, yielding 9,975,258 photos and videos (mean = 5,368 photos/camera trap). We recorded 65 mammal species comprising 22 large, 24 medium, and 19 small mammal species, including nine species identifiable at the genus level only. The vegetation zones at lower (sub-tropical and warm broad leaved forests) and upper elevation ranges (Fir and mixed conifer forests) had higher species richness and diversity compared to mid-elevations (approximately 2000 – 3000 m asl) vegetation zones (blue pine, chirpine, cool broadleaved forests). Lower species richness and diversity at the mid-elevation is possibly due to higher density of human settlements and associated anthropogenic land use because more than 70% of Bhutan's human population live at this elevation range in sympatry with wild mammals. Regular monitoring of mammals in Bhutan during the current period of intense development activities amidst anthropogenic climate change can guide conservation measures aimed at protecting the mammal fauna, maintaining forest connectivity, and ensuring the integrity of the protected area network.

Introduction

Biodiversity loss can affect ecosystem processes, its functioning, and resulting ecosystem services, with negative consequences on humans (Pimm *et al.* 2014). Habitat alteration through anthropogenic activities like deforestation, fragmentation, and forest conversion into agricultural land are main causes of global biodiversity loss (Butchart *et al.* 2010). Understanding the effects of anthropogenic and habitat alterations on mammal diversity is, therefore, essential to guide conservation efforts beyond protecting species numbers, towards a more holistic approach prioritizing ecosystem function and stability (Myers *et al.* 2000; Pimm *et al.* 2014).

Within the Eastern Himalayan ecoregion, regional human population growth-rates and agricultural expansion coupled with impacts of climate change represent a threat to biodiversity and natural ecosystem function, with successful conservation outcomes becoming more reliant on well managed human-modified landscapes (Chettri *et al.* 2008; Gillison 2016). Terrestrial mammals perform essential ecological functions and, therefore, play an important role in the maintenance and regeneration of the forests. As such, mammals are considered key species in structuring biological communities (Sinclair 2003).

Bhutan is a key area for mammal biodiversity conservation within the Eastern Himalayan region with its variety of eco-zones from sub-tropical forests and temperate forests to high rocky mountains, pronounced variations in altitude (100–7800 metres above sea level), and presence of rare and endangered mammal species due to its location at the juncture of the Palearctic and Indo-Malayan realm (Dorji *et al.* 2019). Despite this, there is little information on the distribution of many mammal species, or an understanding of the factors that correlate with patterns of mammal species richness and diversity (Dorji *et al.* 2019). Most local mammal studies in the past have been largely confined to existing protected areas (Wang & Macdonald, 2009a; Tempa *et al.*, 2013; Thinley *et al.*, 2018). By contrast, there have been few scientific studies conducted on mammal distribution and diversity outside protected areas. Moreover, most of the past studies (Chakraborty 1975; Dorji *et al.* 2012; Dorji *et al.* 2011; Rawat & Wangchuck 2000; Sathyakumar & Adhikari 2005) investigated mammals in Bhutan through indirect sign surveys amidst constraints imposed by the country’s dense vegetation, rugged topography, and high precipitation. Such surveys typically detect common and large mammals, but miss elusive and rare species (Sangay *et al.* 2014).

Our study used non-invasive remote camera trapping (Tobler *et al.* 2008; Wang & Macdonald 2009) to ascertain mammal species richness and diversity in Bhutan's forest types along an altitudinal gradient. It aimed to establish baseline information for monitoring the condition of the Eastern Himalayan temperate broad leaved, conifer and sub-tropical forests over time, using mammals as indicators. We assessed species richness, diversity, composition and assemblages of terrestrial mammals in seven major habitat types of Bhutan (sub-tropical forest, warm broadleaved, cool broadleaved, chirpine, blue pine, mixed-conifer and fir) spanning a steep altitudinal gradient (150 – 4500 m asl). Because most of Bhutan's mammal species have widespread distributions (Wangchuk 1994) within extensive and largely contiguous forest types, we further hypothesized no differences in mammal richness, diversity and assemblages between forest types along the altitudinal gradient.

Material and Methods

Study Area

Bhutan is located in the eastern Himalayas (centred on 27.5142 N, 90.4336 E) covering a total area of 38,394 km^2. Altitude ranges from 150 – 7,570 metres above sea level (m asl) (Figure 4.1). The study area has varied climatic conditions with annual mean temperature varying between 12 ± 0.46 ºC in Fir forests to 41.9 ± 0.46 ºC in sub-tropical forests (Figure 4.2). Mean annual precipitation in the study area varied between 645 ± 14.4 mm in the Fir forest to 3410 ± 75 mm in the sub-tropical forest (Figure 4.2). The country's vegetation zones can be categorized into Alpine (>4000 m asl) mainly consisting of *Juniperus spp.*, *Rhododendron spp.* and alpine scrub; Temperate forest (2000 – 4000 m asl) comprising vegetation zones of fir *Abies densa*, mixed-conifer forest of spruce *Picea spinulosa* and hemlock *Tsuga dumosa*, blue pine *Pinus wallichiana*, and cool broad leaved forests dominated by *Quercus species, Magnolia species, Acer species and Betula species*; Warm broadleaf forest (700 – 2000 m asl,) dominated by *Castanopsis, Lithorcarpus and Quercus species*; Chirpine forest *Pinus roxburghii* (700 - 2000 m asl); and Sub-tropical lowland forest dominated by *Shorea robusta, Tectona grandis and Dalbergia sissoo* (<700 m asl,) (Ministry of Agriculture and Forests 2014). We sampled areas up-to 4,500 m asl covering all major vegetation types in Bhutan's ten National Park and Nature Reserves (hereafter called 'PAs'), nine Biological Corridors that link PAs (hereafter called 'BCs') and the intervening landscape comprising 12 Territorial Divisions ('non-protected areas'; hereafter called 'NPAs').

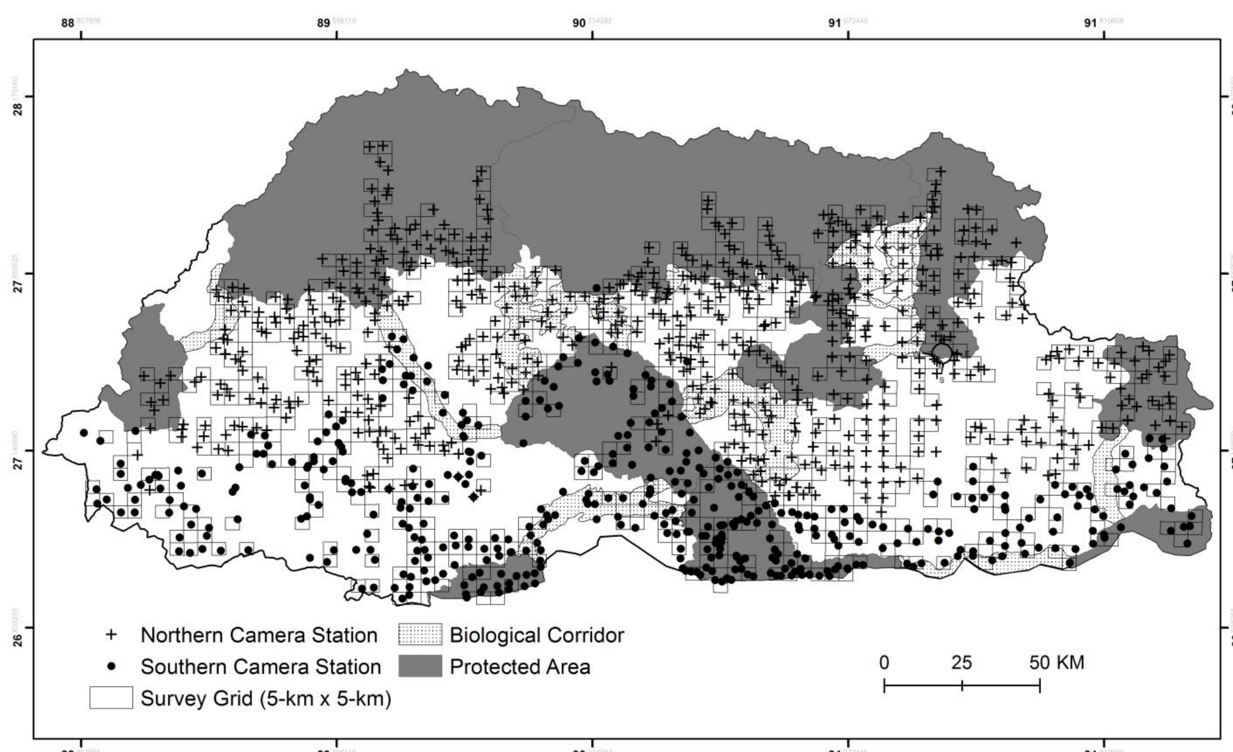


Figure 4.1 Map depicting survey grids and camera trap stationed in the protected area, biological corridor and intervening landscape during Bhutan's nationwide camera trapping exercise in 2014-2015. Black solid circles represent first-phase sampling period from February to September 2014 and cross-lines represent second-phase sampling period from September 2014 to May 2015.

Camera trapping

We surveyed the mammal community in Bhutan's seven major forest types (< 4000m asl) through 1,858 camera traps (Reconyx PC 900 Hyperfire–Reconyx, Inc, WI, USA; HCO Scoutguard SG565, Inc, GA, USA; and Cuddeback Capture IR® Cuddeback Digital, Non-Typical Inc., WI, USA) at 1,129 camera stations between January 2014 and June 2015. Sampling was conducted in two consecutive phases (Southern and Northern; Figure 4.1) due to limited personnel, camera trap availability, weather conditions, and funding constraints. The study area was divided systematically into 5km x 5km survey grids using ArcGIS 10.2 (ESRI 2016) and pair of opposing cameras was set in each grid, 10-30 m apart at a height 30-60 cm above the ground. We maintained a minimum distance of two-kilometres between each camera station to ensure independence. Image files were relabelled according to their time and date using Program 'Advanced Renamer' (Moran 2015), sorted manually into species folders and sub-folders based on the number of individuals in each photo, and processed using 'Camerasweet' software (Sanderson & Harris 2014). We broadly characterized the community structure of mammals based on feeding-guild and body size. For each species, we obtained estimates of body-size from a global mammal database (Smith *et* *al.* 2003) and categorized mammal body mass up-to 2kgs as small, 2-10kgs as medium, and >10kgs as large mammals. We assigned general feeding-guild categories based on dietary habits i.e. carnivore, herbivore, omnivore and insectivore (International Union for Conservation of Nature and Natural Resources (IUCN 2018; Wilson & Reeder 2005). The photographic event of each species was defined as independent when separated by more than 30 minutes (Meek *et al.* 2014; Rovero & Zimmermann 2016). Sampling effort was defined as the number of days the camera traps were in operation (per 24-hour period) at each location from the date the camera was set until the date it was retrieved or, if cameras malfunctioned, until the date stamped on the final exposure. We used capture rate as a proxy for abundance, qualified as the number of captures per unit time. Using these metrics, we calculated the relative abundance index (RAI) of each species using formula

$$\text{RAI} = \frac{\Sigma \text{i}}{tn} \text{ x } 100 \qquad (1)$$

where i = number of events and tn = sampling effort. *RAI* provides an estimate of abundance based on the total number of photographs and effort, for comparisons between different sites and studies (Meek *et al.* 2014).

Environmental Data

We used rainfall and temperature data (Fick & Hijmans 2017) downloaded from http://www.worldclim.org/. Human foot prints were defined as the capture rate of humans, livestock, and distance to road. Distance to the nearest road from each camera station was measured using a road shapefile data from the Bhutan geoportal (National Land Commission of Bhutan 2018). We scored road intensity from 0-5 (<0.1 km = 5; 0.1 - 0.5 km = 4; > 0.5 – 1 km = 3; >1-2 km = 2; >2-3 km = 1; and >3 km = 0).

Statistical Analysis

We estimated and compared asymptotic mammal species richness between study sites using the Jackknife1 species richness estimator in the R-package BiodiversityR (Kindt & Kindt 2019). Jacknife1 performs better for estimating species richness of mammals for camera trapping data (Tobler *et al.* 2008). To assess sample completeness, we computed integrated sample-size-based and coverage-based rarefaction and extrapolation curves for each trophic-level category and body size-group in the seven forest types in our study area, using the C.hat estimator with a 95% confidence interval (Chao *et al.* 2014; Chao & Jost 2012) in the R package iNEXT (Hsieh *et al.* 2016). We then compared mammal assemblages and species composition based on Hill's numbers: species richness (q=0), Shannon's Diversity Index (q=1, the exponential of Shannon entropy), and Simpson diversity (q=2, the inverse of Simpson concentration) (Chao *et al.* 2014; Chao & Jost 2012), with a 95% confidence interval.

To compare species composition between sites, we performed a cluster analysis and constructed a dendrogram using the Jaccard distance (Anderson *et al.* 2008). To investigate relationships between species diversity, richness and functional diversity, and the human foot print, we computed a linear model regression analysis using the R-package "vegan" (Oksanen *et al.* 2010).

Environmental data were normalized before performing a Principle Component Analysis (PCA) based on the Euclidean distance matrix (PRIMER-E 2008). Prior to Multi-dimensional scaling (MDS) ordination, mammal abundance data were Log(X+1) transformed and similarity matrices constructed using the Bray–Curtis similarity coefficient (Clarke & Warwick 1994). After transforming the variable that did not adjust to a normal distribution, Analysis of Similarity (ANOSIM) tests were used to assess differences in mammal assemblage attributes between forest types, using PRIMER (PRIMER-E 2008). Similarity percentages (SIMPER) were used to determine which species typified mammal groups in each site and were most responsible for any dissimilarity between groups (Clarke 1993). Because unconstrained coordination (i.e. MDS analysis) did not show clear separation among the mammal priori group due to high data variability, a Canonical Analysis of Principal Coordinates (CAP) analysis was performed to find the axis in the principal coordinate space that best discriminated a priori groups on observed assemblages.

Results

Environmental Variables and Mammal Species Encounter Rates

Mean annual temperature ranged between 12 ± 0.46 ºC in fir forests to 41.9 ± 0.46 ºC in sub-tropical forests (Figure 4.2a). Mean annual precipitation in the study area varied between 645 ± 14.4 mm in the Fir forest to 3410 ± 75 in the sub-tropical forests (Figure 4.2b). The elevation in the study area ranged from 75 to 4400 m asl with the highest mean elevation in the fir forests (mean = 3882 ± 27.8 m), and the lowest in the sub-tropical forests (mean = 389 ± 18.6 m) (Figure 4.2c).

A total of 9,975,258 photographs from 1,858 camera traps were accumulated in 148,598 trap-nights (mean = 80 trap-nights/camera station) over 536 days of camera trapping in seven major forest types. Pooled data from paired cameras (either side of the trail) yielded a total sampling effort of 59,551 trap-nights in 751 survey grids (Table 4.1), and generated a total of 65,918 events of fifty-six mammal species (mean RAI ± SE =

71.40 ± 3.66 individuals per camera station). We identified 22 large-sized mammal species (mean RAI ± SE = 149.8 ± 9.08 individuals per camera station; mean species richness ± SE = 4.68 ± 0.1 species per camera station), 24 medium-sized mammal species (mean abundance ± SE = 12.90 ± 0.8 individuals per camera station; mean species richness ± SE = 1.66 ± 0.6 species per camera station), and 10 small-sized mammal species (mean abundance ± SE = 0.98 ± 0.5 individuals per camera station; mean species richness ± SE = 0.09 ± 0.3 species per camera station) (Figure 4.2). We could not identify eight small mammal taxa and a bat species.

We detected 27 carnivore species (mean abundance ± SE = 16.33 ± 1.03 individuals per camera station; mean species richness ± SE = 2.4 ± 0.08 species per camera station) comprising seven large-sized (mean abundance ± SE = 6.53 ± 0.61 individuals per camera station; mean species richness ± SE = 1.09 ± 0.04 species per camera station), 13 medium-sized (mean abundance ± SE = 9.72 ± 0.70 individuals per camera station; mean species richness ± SE = 1.3 ± 0.05 species per camera station), and six small-sized species (mean abundance ± SE = 0.08 ± 0.02 individuals per camera station; mean species richness ± SE = 0.04 ± 0.01 species per camera station) (Table 4.1). Nineteen herbivore species were detected (mean abundance ± SE = 41.6 ± 2.96 individuals per camera station; mean species richness ± SE = 2.43 ± 0.06 species per camera station), of which, 12 were large-sized (mean abundance ± SE = 37.80 ± 2.8 individuals per camera station; mean species richness ± SE = 2.03 ± 0.05 species per camera station), eight were medium-sized (mean abundance ± SE = 2.94 ± 0.3 individuals per camera station; mean species richness ± SE = 0.35 ± 0.02 species per camera station), and four were small-sized (mean abundance ± SE = 0.90 ± 0.5 individuals per camera station;

mean species richness ± SE = 0.05 ± 0.01 species per camera station) (Table 4.1). All four detected omnivore species were large-sized (mean abundance ± SE = 30.4 ± 2.1 individuals per camera station; mean species richness ± SE = 1.15 ± 0.9 species per camera station). Only two insectivore species were detected in warm broad leaved forest (0.01 ± 0.004).

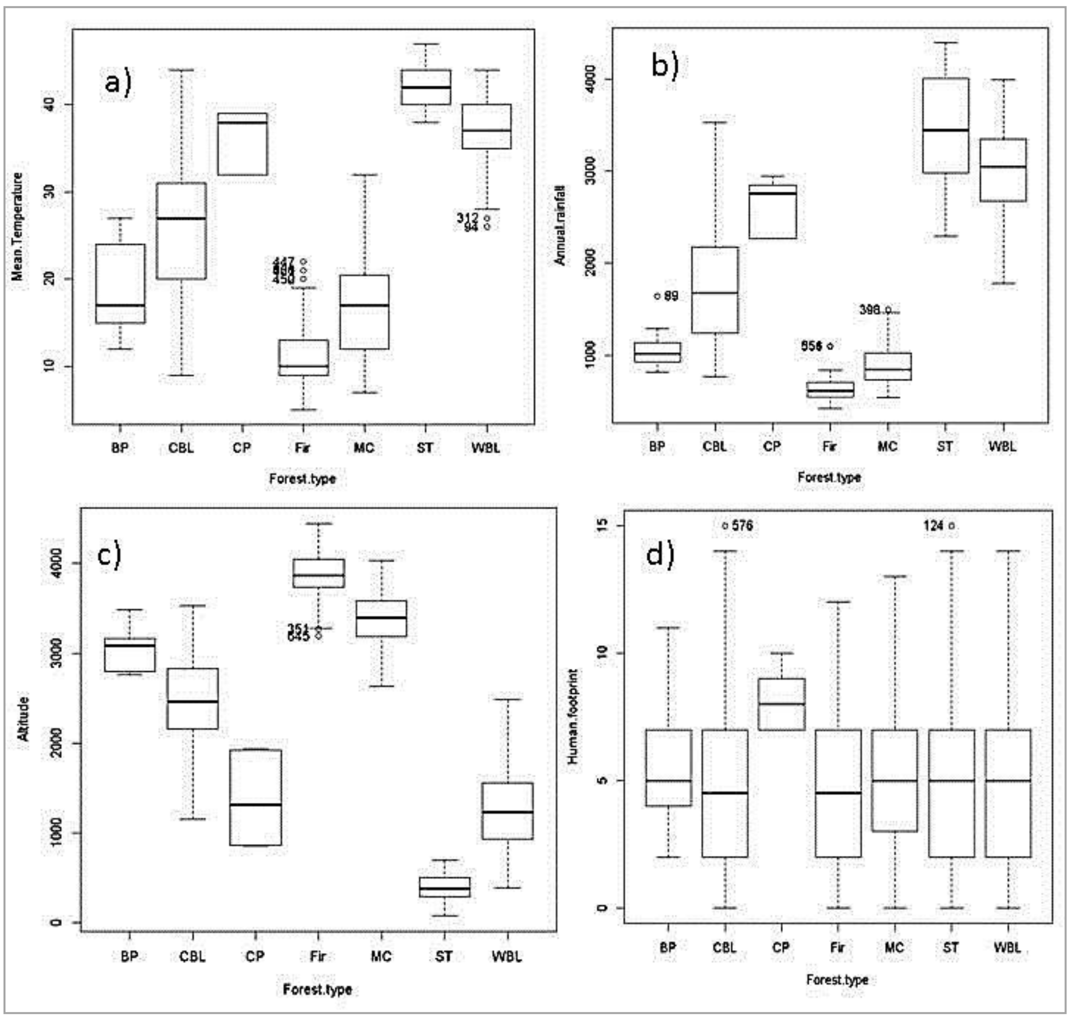


Figure 4.2 Box-plot showing mean, median, upper quartile and lower quartile of environmental variables; 4.2a (altitude), 4.2b (mean annual precipitation), 4.2c (altitude) and 4.2d (human footprint). The seven forest types are Blue-pine (BP), Cool broadleaved (CBL), Chirpine (CP), Fir, Mixed Conifer (MC), Sub-tropical (ST) and Warm broadleaved (WBL) forests.

Table 4.1 Mammal detection rate and capture frequency in seven major forest types of Bhutan from a nationwide camera trapping exercise in 2014 and 2015.

Taxomic	**IUCN Status**	**Trophic guild**	**Size**	**Capture rate by forest type**							**Capture frequency**
				BP	**CBL**	**CP**	**Fir**	**MC**	**ST**	**WBL**	
Carnivora											
Ailuridae											
Ailurus fulgens†*	EN	H	M	3	85	0	71	154	0	0	54
Canidae											
Cuon alpinus	EN	C	L	11	256	5	92	187	61	156	196
Canis aureus	LC	C	L	0	0	0	0	5	0	0	1
Vulpes ferrilata	LC	C	M	0	0	0	209	13	0	0	8
Vulpes vulpes	LC	C	M	22	19	0	79	158	0	0	28
Felidae											
*Panthera pardus**	VU	C	L	7	520	1	40	200	316	242	187
Prionailurus bengalensis	LC	C	M	2	768	16	20	173	170	626	243
*Panthera tigris**	EN	C	L	17	241	0	88	185	112	50	122
Pardofelis marmorata	NT	C	M	0	792	89	45	65	42	177	148
*Neofelis nebulosi**	VU	C	L	0	97	2	8	13	28	96	79
Catopuma	NT	C	L	10	683	11	188	725	7	204	261

temminckii†											
Felis chaus	LC	C	M	0	1	0	1	2	0	2	7
Herpestidae											
Herpestes urva	LC	C	M	0	0	0	0	0	113	49	39
Herpestes edwardsii	LC	C	M	0	0	0	0	0	10	0	2
Herpestes javanicus	LC	C	S	0	0	0	0	0	0	1	1
Mustelidae											
Martes flavigula	LC	C	M	9	682	33	146	549	89	324	293
Mustela sibirica	LC	C	S	0	0	0	0	0	7	0	1
Aonyx cinereus	VU	C	M	0	0	0	0	0	1	0	1
Melogale moschata	LC	C	S	0	0	0	0	0	1	0	1
Mustela kathiah	LC	C	S	0	5	0	0	0	0	2	2
Mustela altaica	NT	C	S	0	0	0	0	3	0	0	2
Prionodontidae											
Prionodon pardicolor	LC	C	S	0	35	0	0	2	1	6	22
Ursidae											
*Ursus thibetanus**	VU	O	L	16	1390	0	418	628	131	212	278
Arctictis binturong	VU	C	L	0	0	0	0	0	0	6	2
Viverridae											
Viverra zibetha	LC	C	M	0	76	0	0	1	202	59	43
Paradoxurus hermaphroditus	LC	C	M	0	10	0	0	0	122	322	37

Viverricula indica	LC	C	M	0	5	0	0	0	52	22	18
Paguma larvata	LC	C	M	0	433	3	0	2	52	398	147
Cetartiodactyla											
Bovidae											
*Bos gaurus**	VU	H	L	0	100	0	0	8	1481	437	102
*Bubalus arnee**†	EN	H	L	0	0	0	0	0	132	25	6
*Capricornis thar**†	NT	H	L	3	869	1	176	665	81	366	294
Naemorhaedus goral†	NT	H	L	2	297	2	221	226	59	320	130
*Budorcas taxicolor**†	VU	H	L	0	0	0	11	32	0	0	3
Cervidae											
*Rusa unicolor**	VU	H	L	106	1704	28	299	560	2447	1252	363
Muntiacus muntjak	LC	H	L	92	7164	123	457	1327	1295	3464	528
Moschidae											
*Moschus chrysogaster**†	EN	H	L	6	84	0	91	161	0	0	39
Suidae											
Sus scrofa	LC	O	L	38	2911	12	310	969	1187	899	465
Lagomorpha											
Ochotonidae											
Lepus nigricollis	LC	H	M	0	0	0	0	0	33	0	2
Ochotona roylei	LC	H	S	0	365	0	30	42	0	0	6
Pholidota											

Manidae											
*Manis crassicaudata**	EN	I	M	0	0	0	0	0	0	5	2
*Manis pentadactyla**	CR	I	M	0	0	0	0	0	0	3	1
Primates											
Cercopithecidae											
Macaca assamensis	NT	O	L	0	245	1	39	59	220	168	125
Macaca mulatta	LC	O	M	0	13	0	0	2	34	122	11
Trachypithecus pileatus†	VU	H	L	0	7	4	0	0	14	33	12
Semnopithecus entellus	LC	H	L	0	3	0	9	14	0	0	9
Trachypithecus geei†*	EN	H	M	0	0	0	0	0	0	0	1
Proboscidea											
Elephantidae											
Elephas maximus†*	EN	H	L	0	37	0	0	0	1520	379	91
Rodentia											
Hystricidae											
Hystrix brachyura	LC	H	M	0	602	29	78	170	188	551	164
Atherurus macrourus	LC	H	M	0	109	0	0	0	17	70	34
Hystrix indica	LC	H	L	0	0	0	0	0	0	3	1
Sciuridae											
Dremomys lokriah†	LC	H	S	0	32	0	0	5	5	18	12

*Ratufa bicolor**	NT	H	M	0	3	0	0	0	3	14	7
Callosciurus erythraeus	LC	H	S	0	15	0	6	0	0	25	8
Callosciurus pygerythrus †	LC	H	S	0	75	0	42	2	0	7	14
Petaurista nobilis†*	NT	H	M	0	1	0	2	1	0	6	7
Petaurista magnificus†*	LC	H	M	0	2	0	2	0	0	0	1
RAI				196.8	95.3	64.3	48.9	55.1	196.8	96.7	
± SE (RAI)				18	4	84	7	6	18	7	

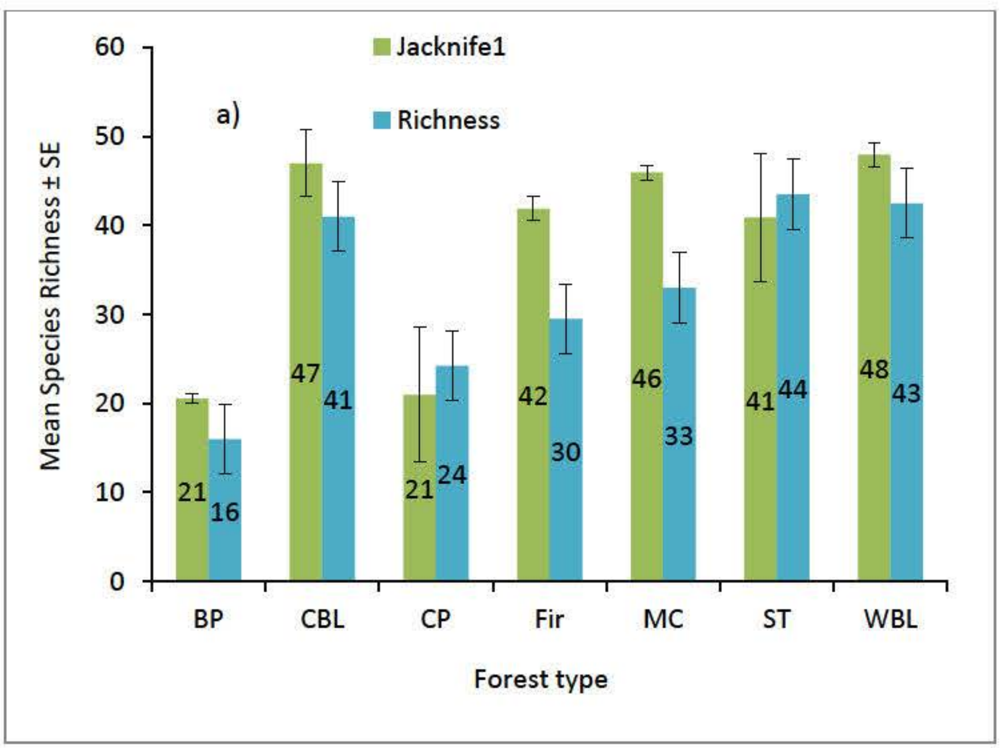
*Listed as protected species under Forests and Nature Conservation Rule of Bhutan 2017. † Listed as priority species for conservation in the Eastern Himalayas (Dorji *et al.* 2019). International Union for Conservation of Nature and Natural Resources (IUCN) status: CR = critically endangered, EN = endangered, VUL = vulnerable, NT = near threatened, LC = least concerned. Trophic guild: H = herbivore, c=Carnivore, o=omnivore, I = insectivore. Body size : up to <2kgs = small; 2-10kgs = medium; >10kgs = large. Forest-type: BP = Blue-pine, CBL = cool broadleaf, CP = Chirpine, Fir, MC = mixed conifer, ST = sub-tropical, WBL = warm broadleaf.

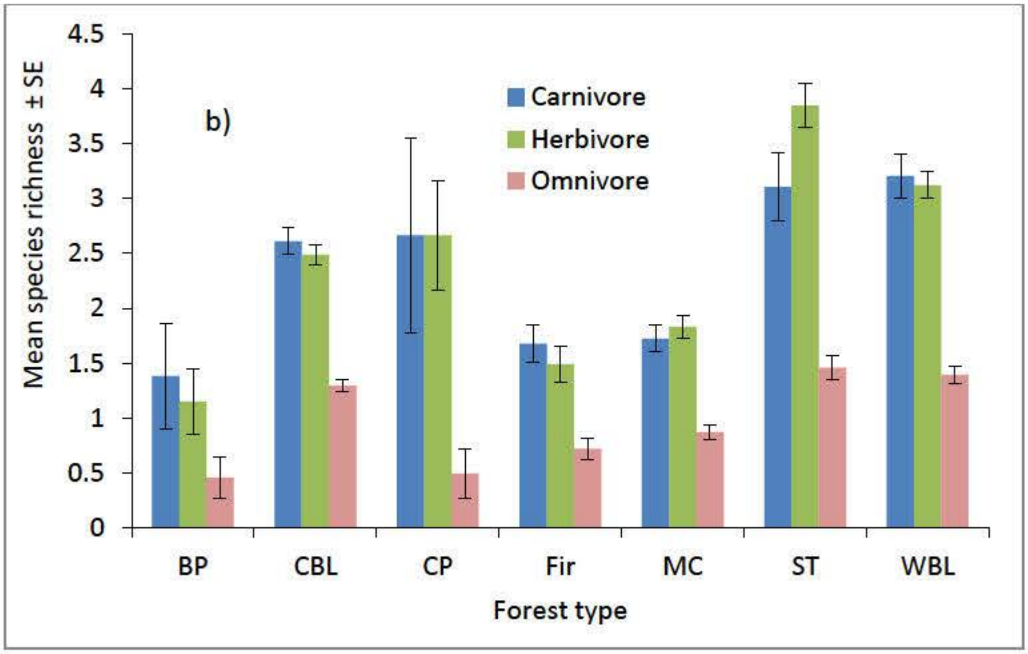
Species Richness and Composition

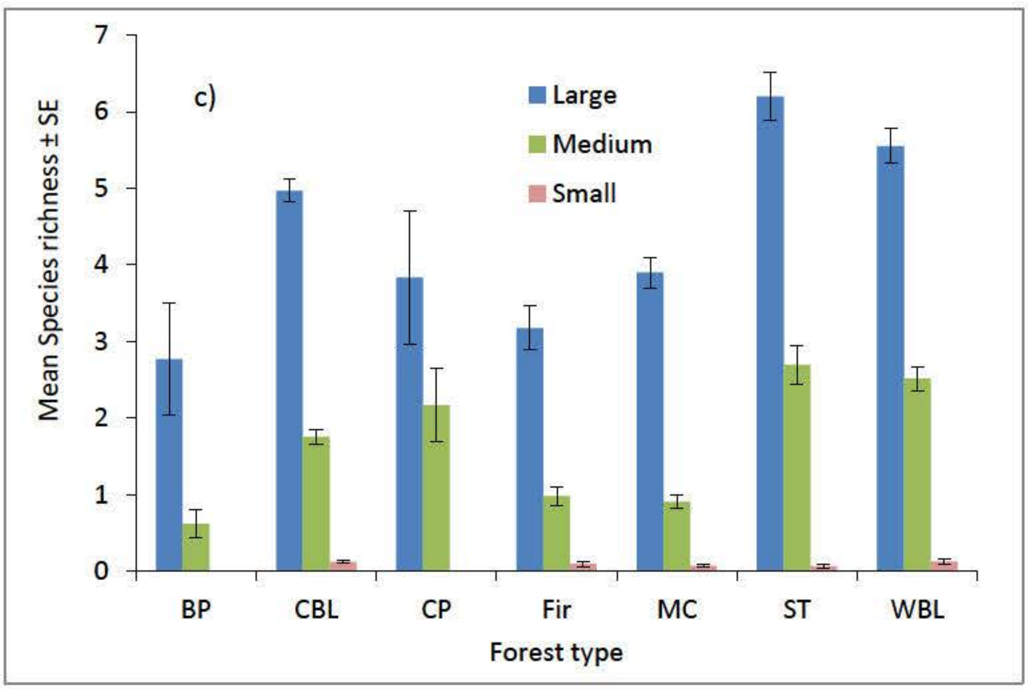
Estimated Jacknife1 species richness was higher in warm broad leaved (mean ± SE = 48 ± 1.3 species) and cool broad leaved forests (mean ± SE = 47 ± 3.7 species) compared to blue pine (mean ± SE = 20 ± 0.5 species) and Chirpine forests (mean ± SE = 21 ± 7.5 species; Figure 4.3a). Similarly, mean species richness per camera station ± SE for 41 mammal species detected in warm broad leaved forest was 7.78 ± 6.64 which included 18 carnivore (3.2 ± 0.2), 17 herbivore (3.12 ± 0.12), four omnivore (1.39 ± 0.07), and two insectivore species (0.01 ± 0.004) (Figure 4.3a-e). Thirty nine mammal species were captured in cool broad leaved forest (mean species richness ± SE = 6.54 ± 2.3 per camera station) comprising 16 carnivore (2.6 ± 0.12), 19 herbivore (2.49 ± 0.08), and four omnivore species (1.29 ± 0.05). Thirty-five mammal species were captured in sub-tropical forest (mean species richness per camera station ± SE = 8.43 ± 5.7) including 18 carnivore (3.1 ± 0.3), 13 herbivore (3.8 ± 0.2), and four omnivore species (1.46 ± 0.1, Figure 4.3a-e). Thirty four mammal species were observed in mixed conifer forest (mean species richness per camera station ± SE = 4.68 ± 5.7) comprising 16 carnivore (1.73 ± 0.12), 14 herbivore (1.8 ± 0.11), and four omnivore species (0.88 ± 0.06). There were 29 mammal species in Fir forest (mean species richness per camera station ± SE = 4.47 ± 6.0) which comprised 11 carnivore (1.70 ± 0.17), 15 herbivore (1.49 ± 0.2), and three omnivore species (0.72 ± 0.09, Figure 4.3a-e). Chirpine forest recorded 16 mammal species (mean species richness per camera station ± SE = 5.83 ± 94.4) comprising eight carnivore (2.67 ± 0.8), six herbivore (2.67 ± 0.5), and two omnivore species (0.5 ± 0.5, Figure 4.3a-e). Blue pine forest had the lowest species richness with only 15 mammal species captured (mean species richness per camera station ± SE = 3.9

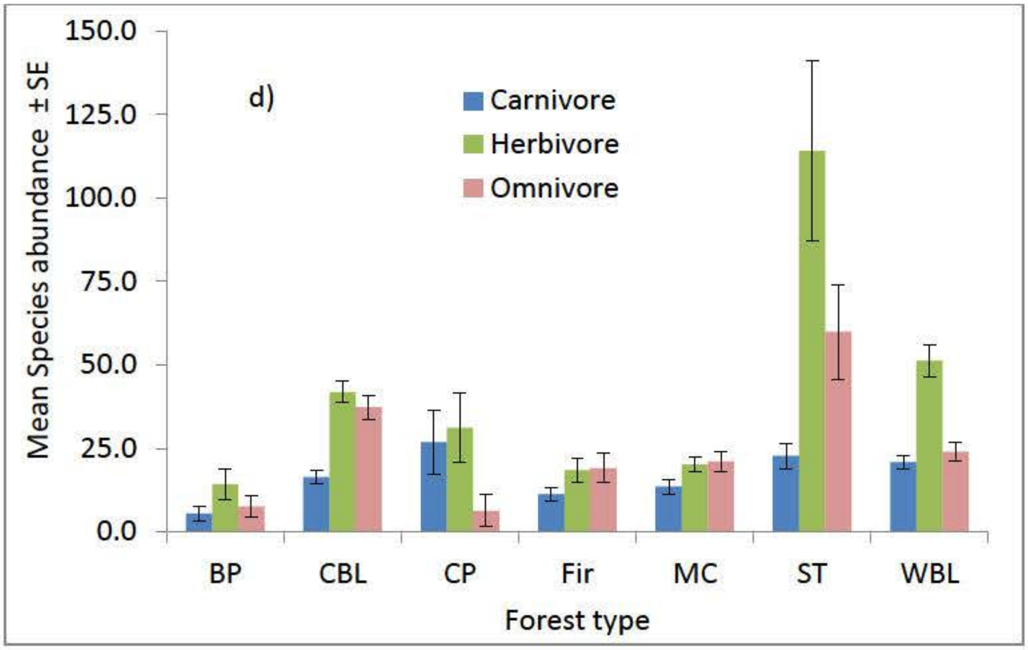
± 0.8) comprising seven carnivore (1.4 ± 0.5), seven herbivore (1.15 ± 0.3), and one omnivore species (0.46 ± 0.2, Figure 4.3a-e).

There were 11 globally threatened species recorded in cool broad leaved forest (mean species richness per camera station ± SE = 2.25 ± 0.08), 11 globally threatened species in sub-tropical forest (EN = 4, VUL = 7), and 10 globally threatened species in mixed conifer forest (mean species richness per camera station ± SE = 2 .1 ± 0.11). Ten mammal species recorded in fir forest were globally threatened (mean species richness per camera station ± SE = 2 ± 0.13), while five threatened species were recorded in Chirpine forest (mean species richness per camera station ± SE = 1.6 ± 0.57), along with seven threatened species in blue pine forest (mean species richness per camera station ± SE = 2 ± .33).




b)
Carnivore
Herbivore
Omnivore
Mean species richness ± SE
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
BP
CBL
CP
Fir
MC
ST
WBL
Forest type


c)
Large
Medium
Small
Mean Species richness ± SE
0
1
2
3
4
5
6
7
BP
CBL
CP
Fir
MC
ST
WBL
Forest type



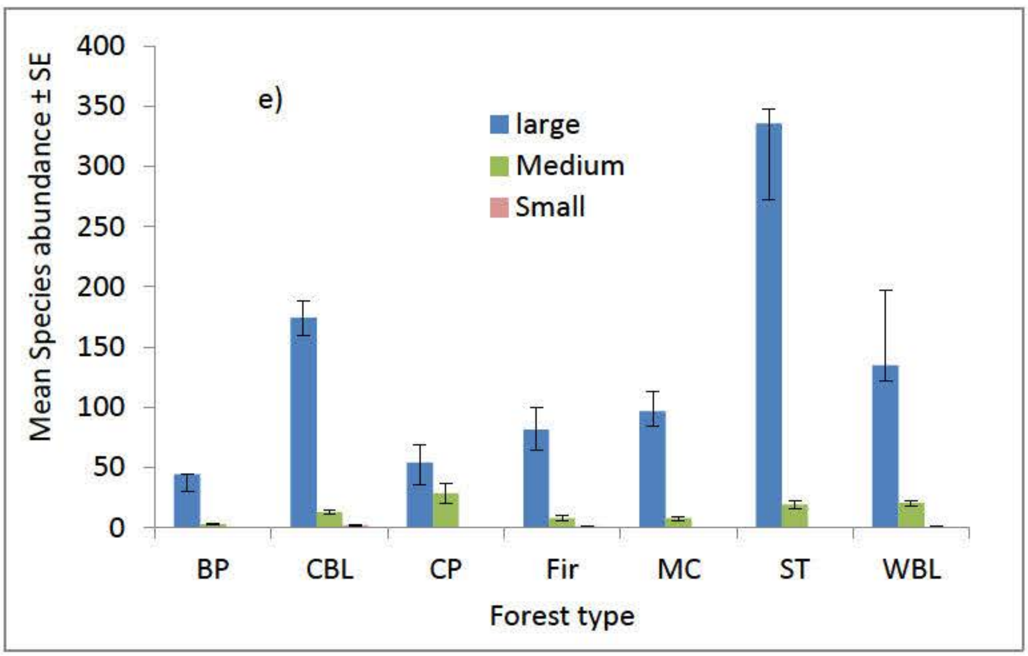


Figure 4.3 Estimated (Jacknife1) and observed mammal species richness (a), mean species richness of mammals categorised into feeding-guild (b) and body-size (c), mean abundance of mammals categorised into feeding-guild (d) and body-size (e), using sample-size and coverage-based sampling (Chao *et al.* 2014; Hsieh *et al.* 2016) results

from a nationwide camera trapping exercise in the seven major forest types of Bhutan in 2014 and 2015. Forest types: Blue-pine (BP), Cool broadleaved (CBL), Chirpine (CP), Fir, Mixed Conifer (MC), Sub-tropical (ST) and Warm broadleaved (WBL) forests. Tropic guild: Carnivore, Herbivore, Insectivore and Omnivore. Body-size categorised based on Smith *et al*. (2003); <2kgs = small, 2-10kgs = medium, >10kgs = large mammals.

Species Diversity

An ANOSIM based on Bray-Curtis similarity coefficients at 999 permutations established a significant difference in mammal abundance among these seven forest types (global R = 0.264, $p < 0.005$; Table 4.2). Further pairwise comparisons of ANOSIM determined highly significant differences in mammal abundance between Fir and cool broad leaved forests (global R = 0.23, $p < 0.005$), Fir and warm broad leaved forests (global R = 0.15, $p < 0.005$), chirpine and Sub Tropical forests (global R = 0.813, $P < 0.05$), blue pine and cool broad leaved forests (global R = 0.62, p ,< 0.05), blue pine and warm broad leaved forests (global R = 0.49, $p < 0.05$), blue pine and sub-tropical forests (global R = 0.58, $p < 0.01$), and cool broad leaved and mixed conifer forests (global R = 0.18, $p < 0.005$). Livestock detection showed a negative correlation with Shannon's mammal diversity (R^2=-0.65; p-value < 0.05), but there was no correlation with human detection rate (R^2=0.11; p-value > 0.1).

The SIMPER analysis further disentangled average species composition dissimilarity between the seven forest types and identified species that drive community-level differences (Table 4.2). The average dissimilarity ranged between 57 - 72% (Table 4.2). Dissimilarity was mainly influenced by abundant and large-sized mammal species such as wild pig *Sus scrofa* (RAI ± SE = 26.650 ± 2.09), barking deer *Muntiacus muntjak* (RAI ± SE = 19.5 ± 1.19), sambar deer *Rusa unicolor* (RAI ± SE = 8.99 ± 1.40), Asiatic golden cat *Catopuma temmincki* (RAI ± SE = 2.56 ± 0.44), common leopard (RAI ± SE = 1.85 ± 0.37), leopard cat *Prionailurus bengalensis* (RAI ± SE = 2.5 ± 0.35), yellow-throated marten *Martes flavigula* (2.6 ± 0.34), and Himalayan goral *Naemorhaedus goral* (RAI ± SE = 1.6 ± 0.37, Table 4.2).

Table 4.2 Analysis of similarity (ANOSIM) results based on Bray-Curtis similarity coefficients at 999 permutations and similarity percentage (SIMPER) analysis showing average mammal species composition dissimilarity between the seven forest types and species that drive community-level differences.

Forest type	ANOSIM Pairwise Global-R	p-value	SIMPER Overall dissimilarity	Five most influential species	Average dissimilarity (±SD)	Contribution (%)	Cumulative (%)	Higher Abundance
Fir & CBL	0.23	0.1	62.5	*Muntiacus muntjak*	8.58±1.33	13.72	13.72	CBL
				Sus scrofa	7.05±1.3	11.28	25	CBL
				Rusa unicolor	4±1.08	6.4	31.4	CBL
				Ursus thibetanus	3.94±0.73	6.3	37.71	CBL
				Pardofelis marmorata	2.86±0.91	4.57	42.27	CBL
Fir & WBL	0.15	0.3	66.3	*Muntiacus muntjak*	7.93±1.54	11.97	11.97	WBL
				Sus scrofa	6.46±1.3	9.74	21.71	WBL
				Rusa unicolor	4.18±1.12	6.31	28.02	WBL
				Naemorhaedus goral	4.14±0.38	6.25	34.27	WBL

				Ursus thibetanus	3.25±0.69	4.9	39.18	Fir
BP & CBL	0.62	0.6	71.2	*Muntiacus muntjak*	11.03±1.28	15.49	15.49	CBL
				Sus scrofa	8.31±1.28	11.66	27.15	CBL
				Rusa unicolor	4.87±1.16	6.83	33.98	CBL
				Ursus thibetanus	4.14±0.79	5.81	39.79	CBL
				Capricornis thar	4.07±1.42	5.71	45.5	CBL
BP & WBL	0.49	1.4	73	*Muntiacus muntjak*	10.25±1.38	14.03	14.03	WBL
				Sus scrofa	7.55±1.16	10.34	24.36	WBL
				Rusa unicolor	5.03±1.2	6.88	31.25	WBL
				Naemorhaedus goral	4.63±0.31	6.34	37.59	WBL
				Bos gaurus	3.27±0.76	4.47	42.06	WBL
BP & ST	0.58	0.5	74.6	*Sus scrofa*	7.8±1.2	10.45	10.45	ST
				Muntiacus muntjak	7.19±1.24	9.64	20.1	ST
				Bos gaurus	6.84±2.51	9.17	29.26	ST
				Rusa unicolor	6.3±1.46	8.45	37.71	ST
				Elephas maximus	5.5±1.78	7.37	45.08	ST
CBL & MC	0.18	0.1	56.8	*Muntiacus muntjak*	6.56±1.3	11.54	11.54	CBL

				Sus scrofa	6.42±1.31	11.3	22.85	CBL
				Ursus thibetanus	3.88±0.69	6.83	29.68	MC
				Rusa unicolor	3.07±1.3	5.41	35.09	CBL
				Catopuma temminckii	3.04±0.9	5.35	40.43	MC
MC & WBL	0.20	0.1	61.5	*Sus scrofa*	5.89±1.39	9.58	9.58	WBL
				Muntiacus muntjak	5.84±1.61	9.51	19.09	WBL
				Naemorhaedus goral	4.07±0.45	6.62	25.71	WBL
				Ursus thibetanus	3.35±0.63	5.45	31.16	WBL
				Rusa unicolor	3.27±1.34	5.33	36.49	WBL
CP & ST	0.81	3.6	60.3	*Sus scrofa*	7±1.33	11.61	11.61	ST
				Bos gaurus	5.52±2.42	9.15	20.76	ST
				Pardofelis marmorata	5.49±2.7	9.1	29.86	ST
				Elephas maximus	4.51±1.66	7.48	37.34	ST
				Muntiacus muntjak	4.29±2.14	7.11	44.46	CP

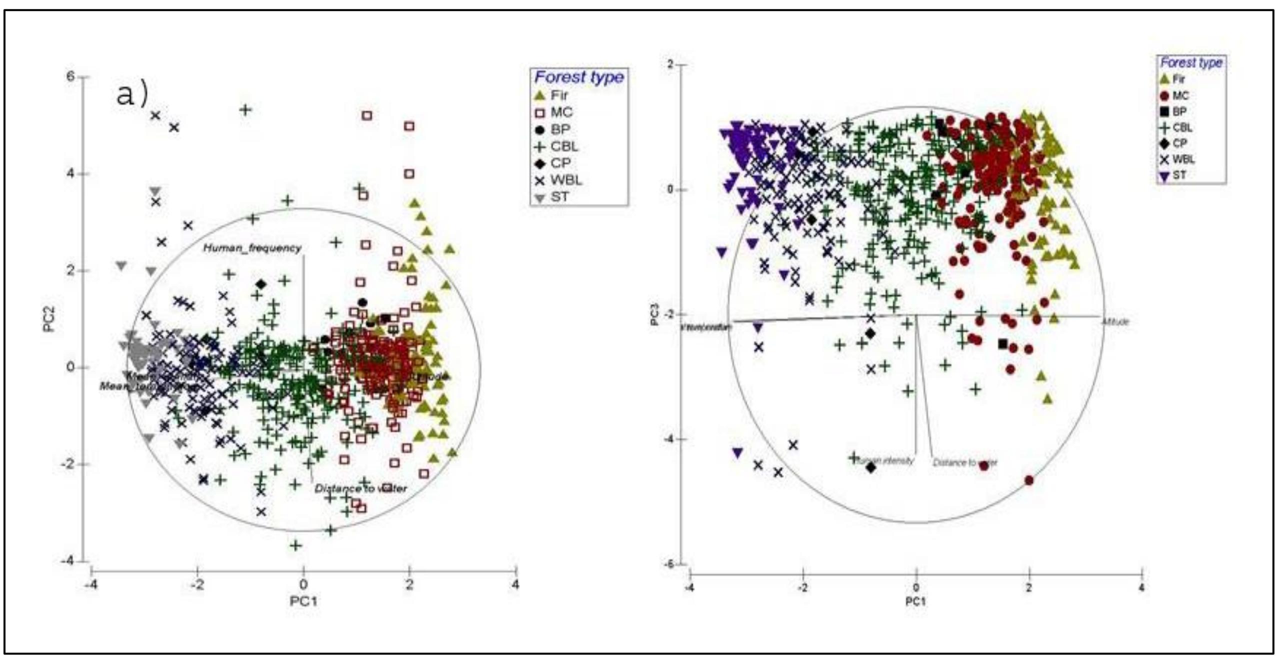
Multivariate analysis

Biota and environmental matching analysis ranked temperature, precipitation, elevation, detection rate of humans from camera traps, and distance to water as the best predictor of the biota (global r = 0.207; Table 4.3). Principle Component Analysis (PCA) narrowed environmental variables from seven forest types into three principle components that explained 98.9% of the total variance (Figure 4.4 a). PC1 explained 57.1% of the total variation, which was attributed to mean annual temperature, precipitation, and elevation; both temperature and precipitation decreased along the axis with altitude increasing along the positive end (Table 4.3, Figure 4.4a). This axis largely distinguishes sub-tropical and broadleaf forest plots at the negative end, and conifer forest plots at the positive end. Detection rate of humans from camera traps and distance to the nearest water source explained 21.4% of total variance along axis 2. Human detection rate increased along the positive end and distance to water increased along the negative end of axis 2 (Figure 4.4a). The third axis explained 18.5% of the total variation, mainly driven by distance to water and human detection rate, both on the negative end (Figure 4.4a).

The Bray Curtis Similarity cluster analysis further explained that species composition of mammals in cool broad leaved, warm broad leaved and sub-tropical forests are similar. Species composition in Chirpine forest was closely related to cool broad leaved, warm broad leaved and sub-tropical forests (Figure 4.4b). Similarly, species composition of blue pine forests was closely related to species composition in mixed conifer and Fir forests (Figure 4.4b). The Fir and mixed conifer forest shared the highest percentage of species composition similarity, followed by cool broad leaved and warm broad leaved forests (Figure 4.4b).

Table 4.3 Eigenvectors (Coefficients in the linear combination of variables making up PC's) of environmental variables from Bhutan’s nationwide camera trapping exercise in 2014 -2015. PC1 explained 57.1% and PC2 explained 21.4% of the variations.

Variable	**PC1**	**PC2**	**PC3**
Altitude	0.578	-0.002	-0.009
Human_frequency	-0.001	0.713	-0.701
Mean_rainfall	-0.58	-0.002	-0.032
Mean_temperature	-0.572	-0.063	-0.037
Distance to water	0.05	-0.699	-0.711



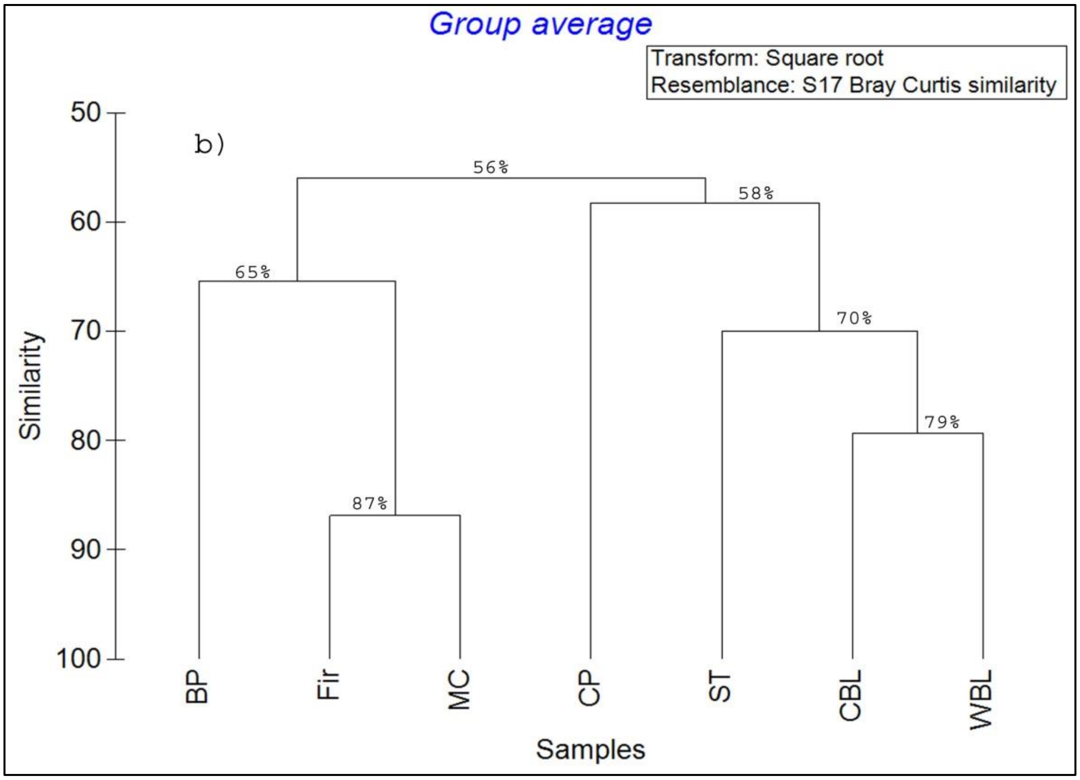


Figure 4.4(a) Principle Component Analysis (PCA) of environmental variables from data of Bhutan's nationwide camera trapping in 2014 -2015; 4.4(b) Dendrogram-tree showing mammal assemblages in seven forest types of Bhutan based on the cluster analysis using Bray-Curtis Similarity resemble data. Major forest types are Blue-pine (BP), Fir, Mixed conifer (MC), Chirpine (CP), Sub-tropical (ST), Cool-broadleaved (CBL) and Warm-broadleaved (WBL) forests. Percentage indicates similarity of species composition between forest types.

Discussion

The mammal community across the seven major forest types of Bhutan comprised 65 species (including nine unidentified species) of which 18 were globally threatened (IUCN 2018) and 14 listed as the most threatened species in the Eastern Himalayan region (Dorji *et al.*, 2018). Warm broad leaved forest recorded the highest number of threatened species (n = 14). Further, the presence of Chinese pangolin *Manis pentadactyla* (CR), Golden langur *Trachypithecus geei* (EN), Indian pangolin *Manis crassicaudata* (EN), Binturong *Arctictis binturong* (VUL) and Asian small-clawed Otter *Aonyx cinereus* (VUL) were confined to warm broad leaved forest. Threatened species such as red panda *Ailurus fulgens* (EN) and musk deer *Moschus chrysogaster* (EN) were also recorded mainly in blue pine, fir, mixed conifer and cool broad leaved forests. Although Chirpine forest had the least mammal diversity and mammal species richness, we also confirmed the presence of five globally threatened species (IUCN 2018) in the Chirpine Forests which were the dhole (EN), common leopard (VUL), capped-langur *Trachypithecus pileatu* (VUL), Asiatic black bear *Ursus thibetanus* (VUL), and sambar deer (VUL). This highlights the significance of the Eastern Himalayan temperate broadleaved and coniferous forests in Bhutan, recognized as a global conservation priority within the Himalayan biome (Dinerstein *et al.* 2017; Olson & Dinerstein 1998), in contributing to mammal species richness in the Eastern Himalayan region.

Our record of 65 terrestrial mammal species in the study area were comparable with studies in other parts of the Eastern Himalayan landscape such as Arunachal Pradesh (55 mammal species; Kumar, 2018), Myanmar (35 mammal species; Naing *et al.*, 2015), and Khangchendzonga Biosphere Reserve in Sikkim (42 mammal species; Sathyakumar *et al.*, 2011). However, some species would not have been detected, particularly arboreal species (such as squirrels), volant species (bats), or species occurring beyond the elevational range of our study (i.e. snow leopard and their prey) (DoFPS 2016), because these species either require specific habitat niches and/or camera placement did not capture micro-habitats likely to be used by these species. Some species expected to have occurred in some sites may not have been recorded during this survey because of their rarity, or because they migrated between habitats across the Indian border. For example, our study did not record globally endangered one-horned rhinoceros in the 2014-15 survey, but this species was photographed later in May 2018 during an annual camera trapping program in the Royal Manas National Park (Pokhrel 2018). Thus, non-detection of a particular species in this study cannot conclusively prove that this species was absent. There were also uncommon mammal species which were restricted to specific forest types. For example, the Indian hare *Lepus nigricollis*, Siberian weasel *Mustela sibirica*, small-toothed ferret badger *Melogale moschata*, small Indian mongoose *Herpestes javanicus*, and Asian small-clawed Otter (VUL) were captured only in the sub-tropical forest. Similarly, the pale weasel *Mustela altaica* and Asiatic jackal *Canis aureus* were recorded only after 90 days of camera trapping in the mixed conifer forests. However, in general, our camera trapping methods worked well in detecting medium-sized and large mammals, but missed small mammals and arboreal mammals. Accordingly, future surveys in Bhutan should be designed based on the species behavior and size as specifically recommended by Sangay *et al.*, (2014) for small mammals.

Elevation is a critical biogeographical variable in many parts of the world, and species richness patterns may be either linear or hump-shaped with respect to elevation gradients (McCain 2007; Paudel *et al.* 2018; Wilson & MacArthur 1967). Our study showed a high geographical variation in species richness and composition along an altitudinal gradient which was primarily driven by human impacts in conjunction with climatic variation, thereby influencing change in habitat conditions and food resource availability. Although we did not include the alpine zone above 4000 m asl, Fir and mixed conifer forest constituting the highest habitat in the study area (>3000 m asl), had equally high mammal species richness and diversity similar to moist sub-tropical and warm broad leaved forest in the lowlands. Fir and mixed conifer forests are important habitats for many mammal species of global and regional importance such as the red panda, musk deer, takin *Budorcas taxicolor*, Himalayan serow *Capricornis thar* and tiger (Dendup & Lham 2018; DoFPS 2015; Dorji *et al.* 2019; Dorji *et al.* 2011). Our study also showed greater species evenness and unique species composition in these two forest types, representative of mammal communities in Palearctic and Indo-Malayan zones (Corbet & Hill 1992; Olson & Dinerstein 1998). High mammal diversity in the Fir and mixed conifer forests may be also influenced by better representation of these forest types in Bhutan's protected area system compared to other forest types i.e. about 78% of fir and 58% of mixed conifer were captured by current protected areas (Dorji unpublished data).

Diversity of large herbivorous species were highest in the sub-tropical and warm broad leaved forests and large herbivore such as Asiatic elephant *Elephas maximus*, gaur and Asiatic water buffalo *Bubalus arnee* were only confined to these two forest types in the lower altitude. Because soil fertility and rainfall are primary determinants of plant diversity (Anderson *et al.* 2007; Yang *et al.* 2011), a higher plant diversity offering diverse forage may be the main contributor to higher large herbivore diversity in the lower altitude forests. The energy available to a particular herbivore species depends on its diet and energetic requirements of individuals depend largely on their body masses (Robinson & Redford 1986). Studies have shown that forests below 2600 m asl in the

Himalayas have higher plant biomass compared to areas above these elevation ranges (Bhattarai & Vetaas 2003; Rawat & Adhikari 2005; Singh *et al.* 1994).However, distribution of the human population is also influenced by the climatic conditions with population density decreasing rapidly as altitude increases (Hunter Jr & Yonzon 1993; Torres-Romero & Olalla-Tárraga 2015). Spatial overlap of humans and native mammals at the mid-altitude vegetation zones may be contributing to moderate mammal species diversity and richness at the mid-altitudes of Bhutan. This is because more than 70% of the country's population (0.734 million) are presently inhabiting an elevation zone ranging between 1000 – 3000 m asl due to favorable climatic conditions (Dorji 2011). In addition, some mid-elevation forest types are under-represented in the current protected area system. Only 25% of warm broad leaved, 40% of cool broad leaved, 0.7% of blue pine, and 1.3% of Chirpine forests are captured by current protected areas (Dorji, unpublished data). This could have implications for conservation planning in the face of climate change. For example, species that are shifting their elevation in response to changing abiotic conditions may be trapped in montane islands at intermediate elevations (Gonzalez *et al.* 2010). Reassessing the protected area system in Bhutan, particularly biological corridors, is thus critical to reducing the impact of human activities on biota and maintaining ecosystem resilience in the face of climate change. Our results also showed that blue pine forest, despite overall low mammal diversity, is an important refuge to globally threatened large mammal species, especially carnivore species like tiger, common leopard, Asiatic black bear, and dhole.

Our findings suggest that the human footprint including livestock abundance and its accessibility to natural forests, were negatively correlated with mammal species richness and diversity. Areas where human populations are more dependent on the exploitation of natural resources for their livelihoods often show a negative relationship between human impacts and species richness (Ceballos & Ehrlich 2002; Crooks *et al.* 2017; Torres‐Romero & Olalla‐Tárraga 2015). About 69% of the Bhutanese population still reside in rural villages and practice agro-pastoralism (Thinley *et al.* 2018), with cattle supporting cropping through manure fertilization and draught power (Renewable Natural Resource Statistic Division 2017). This agricultural system thus depends on forests where cattle usually graze (Samdup *et al.* 2013). While the impact of agriculture and grazing pressure on deforestation in the country has decreased in the last decade (Gilani *et al.* 2015; Samdup *et al.* 2010; Wangchuk *et al.* 2014), habitat quality continues to degrade in some areas because of major infrastructure development such as hydropower dams, road-network expansion, industrial development, urbanization, selective logging, and mining (Bruggeman *et al.* 2016; Watershed Management Division 2017). Relatively high rates of gross forest loss observed at the mid-altitude zone (1000 m – 3000 m asl) in the western and southern districts during the last two decades can be partly explained by these infrastructure expansion given rapid urbanization (Gilani *et al.* 2015; Gillison 2016). Additionally, Torres-Romero and Olalla-Tárraga (2015) suggest that observed anthropogenic effects on mammal richness and diversity do not only depend on disturbance levels that currently take place in each site, but are also mediated through patterns of intensive land use in the past, and historical location of human settlements. Livestock overgrazing was once thought to be the main threat to biodiversity conservation in Bhutan (Tshering 2003; Wangchuk 2002) but free ranging livestock populations are now decreasing because they are progressively being replaced by improved dairy crossbred cattle, which are mainly stall-fed (Samdup *et al.* 2010; Wangchuk *et al.* 2014). This may have reduced the impact on natural forest. However, Bhutan government's effort to phase-out traditional prescribed burning of pastures may have caused net-decrease in grass and shrub land in temperate forest meadows over the last two decades (Gilani *et al.* 2015). As such, this has negative consequences on wild herbivores because such areas are critical wildlife habitat (Gibson 2009; Sankaran 2009). It has also been argued that the complete phasing out of shifting cultivation in the country may in certain cases; contribute to an overall loss of biodiversity and species habitat degradation (Gillison 2016; Namgyel *et al.* 2008).

Bhutan is one of the few countries in the world with negative carbon emissions (Banerjee & Bandopadhyay 2016). But Bhutan's status as a negative carbon emitter does not make it immune to the impacts of climate change. In fact, its location in the Himalayas renders it more vulnerable to the impacts of climate change because warming trends are higher and impacts are magnified by the extreme changes in altitude over small distances (Shrestha & Eriksson, 2009). Identification and understanding of key ecological and socio-economic parameters of mountain ecosystems, including their sensitivities and vulnerabilities to climate changes, have become crucial for planning and policy-making for environmental management and sustainable development. Bhutan's commitment to perpetually maintaining 60% of forest cover in an extensive protected area network, connected by biological corridors across more than 51.4% of the country, offers a great opportunity to maintain ecosystem resilience (Wangchuk 2007). However, resilience can only be maintained if contiguous forest types along the environmental gradient across the country can provide compatible conservation measures. Evaluating the mammal community on a regular basis amidst increasing development activities will help determine effectiveness of measures to increase protection and maintain connectivity between different vegetation zones. This will prevent Bhutan's protected area network from becoming fragmented and hinder the movement of animals (Ceballos & Ehrlich 2002; Schipper *et al.* 2008). We also recommend reassessing the functionality of protected area system of Bhutan and realigning the boundaries, especially the current biological corridors. This will conserve meta-populations of wide ranging species, increase the resilience of reserve networks, and allow species to adapt to potential threats associated with climate change.

Most of the tool to study wildlife such as aerial surveys, live-trapping, spotlighting and radio telemetry are expensive, logistically demanding and often have associated ethical limitations (Noss et al., 2003; Sutherland, 2006). The transect sampling with direct sighting of an animal is an efficient and relatively inexpensive for surveying many natural populations (Anderson, Laake, Crain, & Burnham, 1979; Buckland, Rexstad, Marques, & Oedekoven, 2015), but this method is not applicable in Bhutan due to ruggedness and thick vegetation cover of the country. And the indirect sign survey methods is the cheapest but inaccurate due to seasonal variation in animal behavior and environmental factors that influences animal signs (Munari, Keller, & Venticinque, 2011; Sutherland, 2006). Therefore, non-invasive camera trapping method is found to be the most efficient field techniques for surveying terrestrial mammals (Tobler *et al*. 2008; Wang & Macdonald 2009). However, our experiences from this study showed that efficiency of such methods and outcome of the survey could be influenced by resources availability such budget, time-frame and human involvement. Therefore, we recommend similar studies in future to follow a cost effective method of stratified random sampling along the altitudinal gradient with minimum 30% representation of the each habitat types, and each site should be monitored seasonally for an operational period of two to four weeks (installation of last camera until retrieval of the first camera). We also recommend using of occupancy modelling in the subsequent future studies to account for the effects of season, weather, and vegetation on both detectability and likelihood of species presence (MacKenzie et al., 2017; O'Connell, Nichols, & Karanth, 2010).

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Habitat of the critically endangered white-bellied heron *Ardea insignis* along the Punastangchu river basin

A photo of a cow killed by tiger captured during the nationwide camera trapping in 2014

This chapter titled **Mapping conservation priorities and connectivity pathways under climate change in the Eastern Himalayan biodiversity hotspot of Bhutan** has been prepared as a manuscript for submission to the international journal *Conservation Letters.*

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Camera trap photos of mammal species chosen as focal species for the delineation of biological corridors in Bhutan. Snow leopard photo copy right ©WCNP.

Chapter 5: Mapping conservation priorities and connectivity pathways under climate change in the Eastern Himalayan biodiversity hotspot of Bhutan.

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Abstract

Bhutan's network of protected area and biological corridors within the Eastern Himalayan region still harbor a rich mammal community through Bhutan's government's ability to reconcile biodiversity conservation goals with social and economic issues. However, further realignment of Bhutan's protected and biological corridor boundaries to capture areas known to support high diversity of threatened species has been proposed to reconcile impact of current land use and climate change on biodiversity distribution. We used a combination of species distribution modelling, complementarity zonation algorithms, least cost path analysis, SDMtoolbox, and ArcGIS tools to redefine the existing corridors of Bhutan. Specific emphasis was placed on meta-populations of threatened wide ranging umbrella species like the tiger

Panthera tigris, snow leopard *Panthera uncia,* Asiatic elephant *Elephas maximus,* red panda *Ailurus fulgens*, musk deer *Monchas spp.*, Asiatic black bear *Ursus thibetanus*, golden langur *Trachypithecus geei* and takin *Budorcas taxicolor*. Occurrence data on these keystone species were incorporated into developing a predictive model of animal usage against available habitat within protected areas and outside of protected areas, and juxtaposed with spatial data on human settlements and its environs, land use patterns, the proposed and current road network, townships, urban plans, and hydropower dams. Least cost categories were reassigned to reflect major wildlife habitats and discard private registered land and anthropogenic factors, with an aim to establish a durable network of protected areas and minimize conflict of interest with development partners and local people living in and around protected areas. Resultant models integrated the most detailed climatic, ecological, and biological data ever applied to predict the changing distribution and conservation status of these species in response to climate change in Bhutan. Finally, we identified and recommended the seven most important priority areas outside the current protected area system for expansion of the current network of biological corridors, and formulated appropriate policy recommendations regarding the effectiveness, potential realignment of Bhutan's biological corridors, and the future management of this ecological and climatically resilient corridor system, without compromising the livelihood needs of the local communities living in and around the protected areas.

Introduction

A diverse and interconnected landscape is important to support plant and animal movement, ensure safe passage and the resource needs of migrating animals, maintain genetic flow between populations and sub-populations, and allow animal dispersal and geographic range shifts of species responding to climate change (Beier & Brost 2010; Bennett 1999a; MacKinnon 1999; Rosenberg *et al.* 1997). However, landscape modification by humans coupled with anthropogenic climate change has displaced many species from their native ranges, forcing individuals to traverse great distances through intensively human-modified landscapes to find suitable habitat (Aryal *et al.* 2016; Loucks *et al.* 2010; Morueta-Holme *et al.* 2010; Williams & Blois 2018). Wildlife corridors are designed to maintain habitat linkages and facilitate movement of individuals between habitats, through both dispersal and range-shift. They also provide a cost-effective, reliable strategy to conserve meta-populations of wide ranging species, increase the resilience of reserve networks, and allow species to adapt to potential threats associated with climate change (Beier & Brost 2010; Bennett 1999b; Hoffmann *et al.* 2019). While some species are better adapted to move between high-quality habitats through modified landscapes, others with limited tolerance for disturbance and fragmentation may require wide unbroken corridors. Long-term persistence of these species relies upon their capacity to respond to human-induced landscape modification and habitat transformation (Hansson 1991; Hoffmann *et al.* 2019; Noss 1991). In countering global issues of habitat degradation and climate change, Bhutan is one of the few countries to achieve the half earth protection goal (Locke 2014; Wilson 2016). Additionally, Bhutan’s effort to maintain at least 51% of its surface area in a protected area system connected by a network of biological corridors is being consistently acknowledged by many scientists (Beier *et al.* 2011a; Dinerstein *et al.* 2017). Nevertheless, integrating conservation and sustainable development strategies at the landscape scale are pressing issues in the country, and the value of Bhutan's protected areas network cannot be assured into the future unless these issues are carefully addressed (Banerjee & Bandopadhyay 2016; Gillison 2016; Wangchuk 2007).

The biological corridors in Bhutan were declared in 1999 as a "gift to the earth from people of Bhutan" (Figure 1), but they continue to be un-operational and their past and present effectiveness for conservation is unknown. Corridors were designed using the Landsat satellite imagery and land-use maps to identify habitat links between the protected areas, primarily based on nine key mammal species, the level of human land-use, and the potential for avoiding future habitat conversion based on terrain and accessibility (Mackinnon 1999; Figure 1). Although a pioneering effort in its heyday, biological corridor theory has evolved globally in the last two decades. As such, Bhutan's current corridor network may not have adequately captured the ecological processes and dynamics of Bhutan's ecosystem, as originally intended (Gyeltshen *et al.* 2012; Thinley 2010; Wildlife Conservation Division 2010). Many corridors traverse steep and inaccessible terrain mainly comprising ridge lines with low potential for human use; the logic being that these areas would better survive future human impacts and habitat conversion. However, studies have proven that areas which make corridors inaccessible and unsuitable for human use, also often make them sub-optimal for wildlife movement (Dickson & Beier 2007; Graham *et al.* 2009; Koirala *et al.* 2016; Roy 2010). Furthermore, the original corridor design did not include any substantial riparian habitat and important river catchments, and as a result, the economic transformation that has occurred in Bhutan over the last two decades has changed land-use patterns in the country (Gilani *et al.* 2015). The conservation of watershed and wetlands are paramount for both wildlife conservation as well as socio-economic development because Bhutan's economy is mainly dependent on agriculture and the export of hydropower energy. As such, corridor-based landscape connectivity in Bhutan should not be considered solely for movement of particular species, but should also integrate with the current land use pattern and sustainable development plans of the country (Beier & Brost 2010; Beier *et al.* 2011b; Bennett 1999b; Wildlife Conservation Division 2010). The regulatory framework for Bhutan's network of corridors, prepared by Paul Beier (Wildlife Conservation Division 2010), also recommended reassessing the corridors using current knowledge and ecological principles such least cost path analysis and circuitscape theory (Beier & Brost 2010; Beier *et al.* 2011b; Bennett 1999b).

In this paper, we assessed the ecological functionality, structural design, and management effectiveness of the biological corridor network in Bhutan. We modelled species distribution and identified priority wildlife habitat outside national parks, wildlife sanctuaries, and strict nature reserves; quantitatively assessed impact of land-use and climate change on the current biological corridor network; identified the optimal pathway between core priority areas; and characterized how species move between patches to identify pinch points and barriers. Based on our results, we offer a series of policy and management recommendations on connectivity at the local and regional scale for a range of planning scenarios.

Methods

Study Area

The study was conducted in the Eastern Himalayan country of Bhutan (Figure 1). Altitude ranges from 150 – 7,570 meters above sea level (m asl), the annual temperature ranges between -20 and 42 ºC, and mean annual precipitation ranges between 645 and 3410 mm (Dorji *et al.* 2019a). The country can be categorized into three distinct eco-floristic zones: Alpine (>4000 m asl), Temperate (2000 – 4000 m asl), and Sub-tropical (150 – 2000 masl) (Ministry of Agriculture and Forests 2014). There are currently five national parks (NP), four wildlife sanctuaries (WS) and one strict nature reserve (hereafter collectively termed 'protected areas'; 'PAs'), and eight biological corridors (BCs; Figure 5.1).

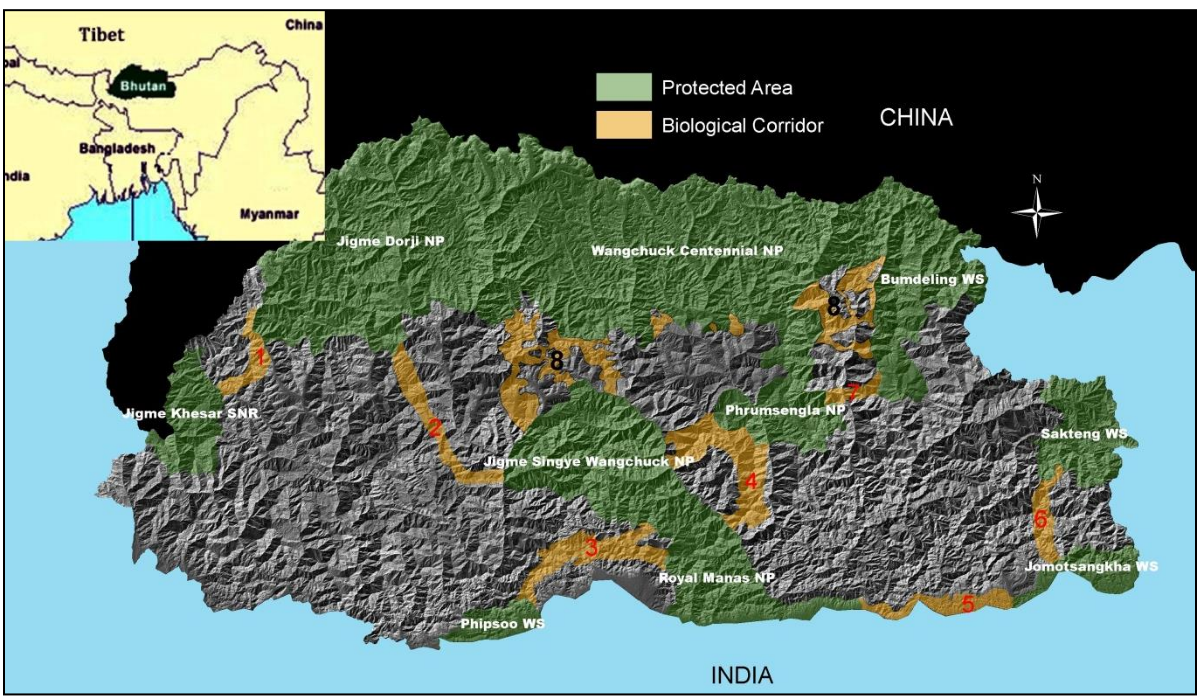


Figure 5.1 Study area map showing current protected areas and the biological corridor network of Bhutan.

Focal species identification and occurrence

The concept of a focal species has been proposed as a tool for determining minimum size for conservation areas, selecting sites to be included in reserve networks, and setting minimum standards for the composition, structure, and processes of ecosystems (Barua 2011; Lambeck 1997). During the biological corridor consultative workshop facilitated by Paul Beier in 2010 (Wildlife Conservation Division 2010), biodiversity experts from Bhutan identified a suite of species that can be used as focal species for corridor revision. Eight mammal species, and one fish and bird species each, were shortlisted as being important focal species for corridor delineation (Table 5.1). Among the mammals, the Asiatic black bear *Ursus thibetanus* and takin *Budorcas taxicolor* were not considered in the final zonation analysis, because their distribution and habitat overlapped considerably with tigers, with predicted minor range contraction under future climate scenarios. Thus, the black bear was not considered in the corridor delineation process beyond the creation of initial habitat suitability and climate models. Additionally, takin range falls entirely within the Northern PAs. As such, it does not need additional corridors outside the Northern PAs (annexure 3, Figure 1). The golden Mahseer *Tor putitora* and the critically endangered white bellied heron *Ardea insignis* were the identified fish and bird focal species, respectively. Because of data limitations, it was not possible to generate habitat suitability maps for these species, but we attempted to include include critical watershed areas, riparian habitats, and wetlands as linear habitat within the proposed corridors for future sustenance of any important riparian species.

Table 5.1 Focal species used for a habitat suitability model and zonation analysis to assess and realign the biological corridor network in Bhutan. 1 – Jigme Kesar Strict Nature Reserve (JKSNR) to Jigme Dorji National Park (JDNP); 2 – JDNP to Jigme Singye Wangchuck NP (JSWNP); 3 – Phibsoo Wildlife Sanctuary (PWS) to JSWNP and Royal Manas NP (RMNP); 4 – Phrumsengla NP (PNP) to JSWNP and RMNP; 5 – RMNP to Jomotshangkha WS (JWS); 6 – JWS to Sakteng WS (SWS); 7 – PNP to Bumdeling WS (BWS); 8 - Wangchuck Centennial NP (WCNP) to JSWNP and JDNP; and 9 – WCNP to PNP and BWS.

Species	**Focal corridor number**	**Reason for connectivity**	**Zonation analysis**
Tiger *Panthera tigris*	All	Dispersal from natal areas	Yes
Elephant *Elephas maximus*	3	Probable seasonal movements	Yes
Snow leopard *Panthera uncia*	1 and 8	Dispersal and large home ranges	Yes
Red Panda *Ailurus fulgens*	1, 2, 4, 6, 7 and 8	Habitat specialist requiring access to climate refugia	Yes
Takin *Budorcas taxicolor*	All habitats inside protected areas. No corridor required outside	Seasonal migrations	No. All habitat inside PAs
Golden Langur *Trachypithecus geei*	3 and 6	Genetic connectivity through habitat connectivity	Yes
Musk Deer *Monchas spp.*	1, 2, 4, 6, 7 and 8	Habitat specialist	Yes

Black bear *Ursus thibetanus*	All	Habitat generalist	Yes, but not a priority for zonation analysis

Maxent Habitat Modelling

We modelled species environmental niches of nine focal mammal species using the most reliable occurrence data from nationwide tiger *Panthera tigris* and snow leopard *Panthera uncia* camera trapping surveys (DoFPS 2015, 2016), aggregated at a 0.01 degree (~1-km) resolution. To avoid spatial autocorrelation of occurrence points, we eliminated spatial clusters of localities at a 1-km resolution for model calibration and evaluation (Dormann 2007). Current and future climatic variables comprising eight precipitations and eleven temperatures at a 30 arc-sec resolution were downloaded from www.worldclim.org and clipped to the boundary of the study area. The 2016 land cover map (National Land Commission of Bhutan 2018) and digital elevation model (Muane 2007) were combined with species data to create correlative models of species distribution, using a combination of Maxent (Elith *et al.* 2011; Phillips *et al.* 2006; Phillips & Dudík 2008), SDMtoolbox 2.0 (Brown 2014; Brown *et al.* 2017), and ArcGIS 10.3 (ESRI 2016). Individual species models were fitted using a maximum of 10,000 iterations, and a convergence threshold set to 0.00001 and 0.5 as prevalence of the species. For background sites (“absences”), we used a set of all gridded occurrence records surveyed for other species in the area (target group background). There were two reasons for this background approach: first, to avoid inflation of AUC values due to contrast between few species records and a large number of background points

(Yackulic *et al.* 2013); and second, to minimize the effect of biased sampling (Elith *et al.* 2011; Phillips & Dudík 2008) which is inherent in incidence species records (Elith *et al.* 2006; Elith *et al.* 2011; Phillips & Dudík 2008). The regularization parameter was set to linear, quadratic, product, threshold, and hinge feature classes using Maxent default parameters for number of samples at which features were first used (Young *et al.* 2011). Additionally, we used 10-fold sub-sample partitioning species occurrences in 80% for training data and 20% for testing models. To avoid model over-parameterization, we removed redundant variables within each ecological category that were highly correlated with others in that category (Pearson's correlation index above 0.70), and retaining those with more physiological importance in controlling growth, reproduction, morphology, and behavior during the SDMtoolbox (Hernandez *et al.* 2006). Remaining relatively independent variables were then submitted to manual selection strategies, including forward selection, backward elimination, and stepwise procedures using Maxent (Phillips 2005). Variables contributing the least information based on their permutation importance (less than 2% via jackknife tests were successively dropped (Williams *et al.* 2012). We finally selected Annual Mean Temperature (bio1), Mean Temperature of Warmest Quarter (bio10), Mean Temperature of Coldest Quarter (bio11), Annual Precipitation (bio12), Precipitation of Wettest Quarter (bio16), land cover map of Bhutan 2016, and a digital elevation model to run the final model. Suitable habitat for each species was generated using a 10 percentile training presence logistic threshold value (i.e. probability of the minimum value for suitable habitat) from the final Maxent output (Young *et al.* 2011).

To measure the predicted distribution changes for each species, binary SDMs were projected to Asia North Albers Equal-Area Cylindrical projection in ArcMap 10.3 (ESRI 2016) at a spatial resolution of 0.0083 degree or 1-km^2 grids. We used Model for Interdisciplinary Research on Climate (MIROC5) (Watanabe, Suzuki et al. 2010), the latest version of global climate change (GCM) to predict the distribution of nine focal species. The MIROC5 captures various observed features of future climate very well, especially for the South Asian region, and previous studies in the Eastern Himalayan region (Sharmila, Joseph et al. 2015, Aryal, Shrestha et al. 2016, Lamsal, Kumar et al. 2018, Su, Aryal et al. 2018) have used it to predict species distribution for Nepal Himalaya. Two medium and extreme future climate scenarios for two representative concentration pathways (RCPs) for carbon dioxide, namely RCP4.5 and RCP8.5, for two periods for 2050 (average of predictions for 2041–2060) and 2070 (average of predictions for 2061–2080) were used (www.worldclim.org). These were the most recent GCM climate projections that are used in the Fifth Assessment IPCC report. RCP4.5 is supposed to be a medium carbon emission scenario that peaks around 2040 – total radiative forcing could reach +4.5 W/m2 (~650 ppm CO2 equivalent) by the end of the 21st century and stabilizes thereafter, whereas RCP8.5 is an extreme carbon emission scenario that continue to rise throughout the 21st century with radiative forcing reaching +8.5 W/m2 (~935 ppm CO2 equivalent) (Stocker, Qin et al. 2013). We calculated and connected geographic centroids of the current and future binary SDMs in ArcGIS 10.3 using SDMtoolbox v2.4 to examine whether range shifts were predicted to occur (Brown 2014; Brown *et al.* 2017). Future and current SDMs were then subtracted from each other, and areas of contraction, expansion, and stability were calculated. Each of these individual classes was summed separately for all species, generating a map displaying the intensity of contraction, expansion, and stability throughout Bhutan. Expansion was classified as a species that expanded its future range to more than 125% of its current predicted range, whereas contraction was classified as a species with a future range of 75% or less of its current predicted distribution. Stable species are those with future range areas between 75 and 125% of their current predicted distributions.

Zonation analysis

To characterize conservation priority areas or habitat patches we ran 'Zonation' (Moilanen *et al.* 2009a), a reserve selection software designed to identify networks of areas necessary for retaining high habitat quality for multiple biodiversity features (Franco *et al.* 2009; Lehtomäki & Moilanen 2013; Moilanen *et al.* 2009b). Zonation's algorithm produces a hierarchical prioritization of the landscape based on the occurrence level of biodiversity features in sites by retaining high quality habitats for multiple biodiversity features (Kremen *et al.* 2008; Lehtomäki & Moilanen 2013). We used the core area zonation method, a complementarity which minimizes biological loss by retaining the most valuable and rare feature over other biodiversity features that have high occurrences (Lehtomäki & Moilanen 2013; Moilanen 2007; Moilanen *et al.* 2011; Moilanen *et al.* 2005). Zonation determines the relative contribution of the total amount of each biodiversity feature in a given cell and then iteratively discards grid cells of lowest proportional value across all features, maximizing the retention of more highly weighted features. Weighting biodiversity features is a critical component of the Zonation algorithm and features can be assigned different weights based on factors such as perceived threat, endemism, rarity, ecological importance, economic value, or population trend (Lehtomäki & Moilanen 2013; Moilanen *et al.* 2009b). We weighted 5 points each for all the focal species. Land-use types were weighted as natural forest and grassland = 5; forest with agriculture activities and moderate to higher livestock density = 2; grasslands, shrub, crops with low livestock density = 3; unmanaged grasslands = 1; sparsely vegetated areas = 1; grasslands, shrub, crops with high livestock density, agriculture, open water, bare areas, urban areas = 0. We also took into consideration, the dispersal capability of each focal species to ensure reduction of edge effects and connectivity of habitat niches of each species into the corridor system. In order to approximate the aggregate response of a species to edge effects, we used Boundary Quality Penalty curves based on the dispersal range (home range size) and log-body mass data (Smith *et al.* 2003). We computed priority ranking of the same biodiversity feature data twice (with and without weighting and mask file) for both current and future time points in order to determine how much of the maximum possible conservation value is protected in PAs, and how much will be contracted in by comparing the constrained and unconstrained curves at the same proportion of landscape lost (Cabeza & Moilanen 2006). Reliable data from a cadastral survey of Bhutan depicting accurate coverage of privately registered land and forest areas (National Land Commission), road networks including farm roads (Ministry of Works and Human Settlement), current and planned hydro-power project data (Ministry of Economic Affairs), community forests maps (Social Forestry and Extension Division, DoFPS), critical watersheds and wetlands (Watershed Management Division, DoFPS), Forest Management Units and Forest (Forest Resources Management Division, DoFPS), and critical habitat of white bellied heron (Royal Society of Protection of Nature and Natural Resources), allowed us to plan a reliable corridor network.

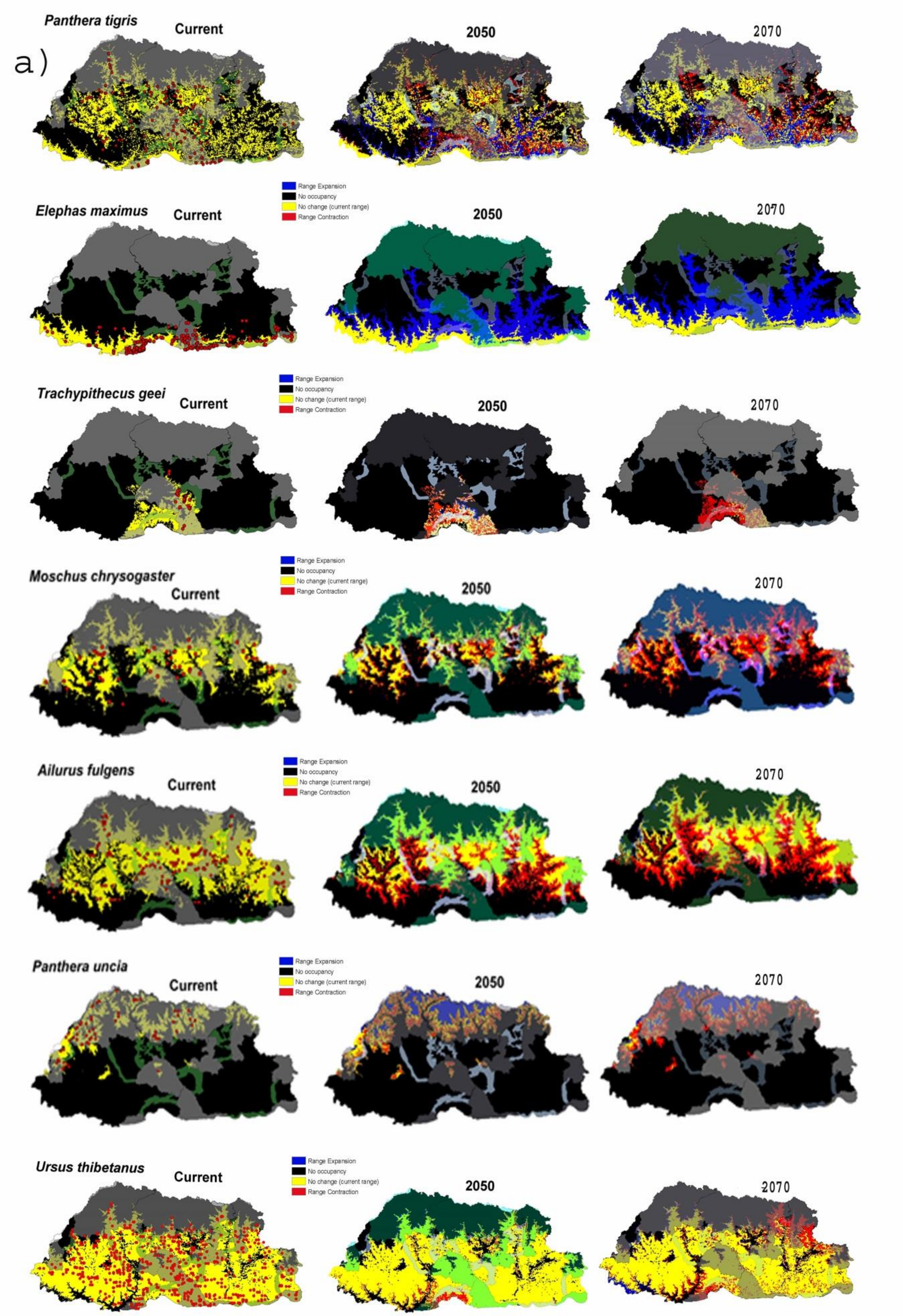
Corridor delineation, barriers and choke points

The aim of the corridor delineation was to meet the ecological needs of focal species used in the analysis to be able to persist in natural habitats, especially given Bhutan's development plans (Wildlife Conservation Division 2010). We first compared constrained and unconstrained solutions of Zonation to check the proportion of landscape conserved by current PAs and remaining valuable and rare features outside PAs. Based on areas of high ecological integrity resulting from zonation analysis, we calculated the least cost path analysis (categories of paths that include paths with slightly less suitable habitats relative to the optimum path) between highly suitable habitat patches outside PAs to refine the existing corridors of Bhutan. We mainly focused outside PAs because habitats inside PAs have adequate and better protection compared to areas outside (Dorji *et al.* 2019b). As a friction layer (the layer used to depict the site-by-site connectivity cost in least-cost corridor analyses), we inverted the final zonation output layer and standardized it from 0 to 1, placing a friction value of 1 on unsuitable habitat areas such as settlements, agricultural land, rock, ice, and water bodies. We made several field visits between 2011 and 2018 to identify barriers and choke points. Common barriers and choke points in Bhutan are mainly agricultural land, human settlements, hydropower dams, roads, and rivers. We also incorporated human settlements and agricultural land as the mask layer in zonation analysis and tried to exclude them into the corridor system to minimize the conflict of interest between conservation and future development. We initially tried using the Corridor (Majka *et al.* 2007) and LinkMapper (McRae & Shah 2009), but these programs failed due to windows compatibility or software mechanical problems. Final corridors were delineated via least-cost pathway analysis estimated using SDMtoolbox v2.4 in ArcGIS 10.3 based on the default settings (Brown 2014). We then realigned boundaries to follow obvious terrain contours and to include critical watershed boundaries, riparian areas, and habitat of the critically endangered white bellied heron and golden Masheer. We overlaid individual focal species distribution maps to ensure adequate representation of focal species habitat into the protected area system.

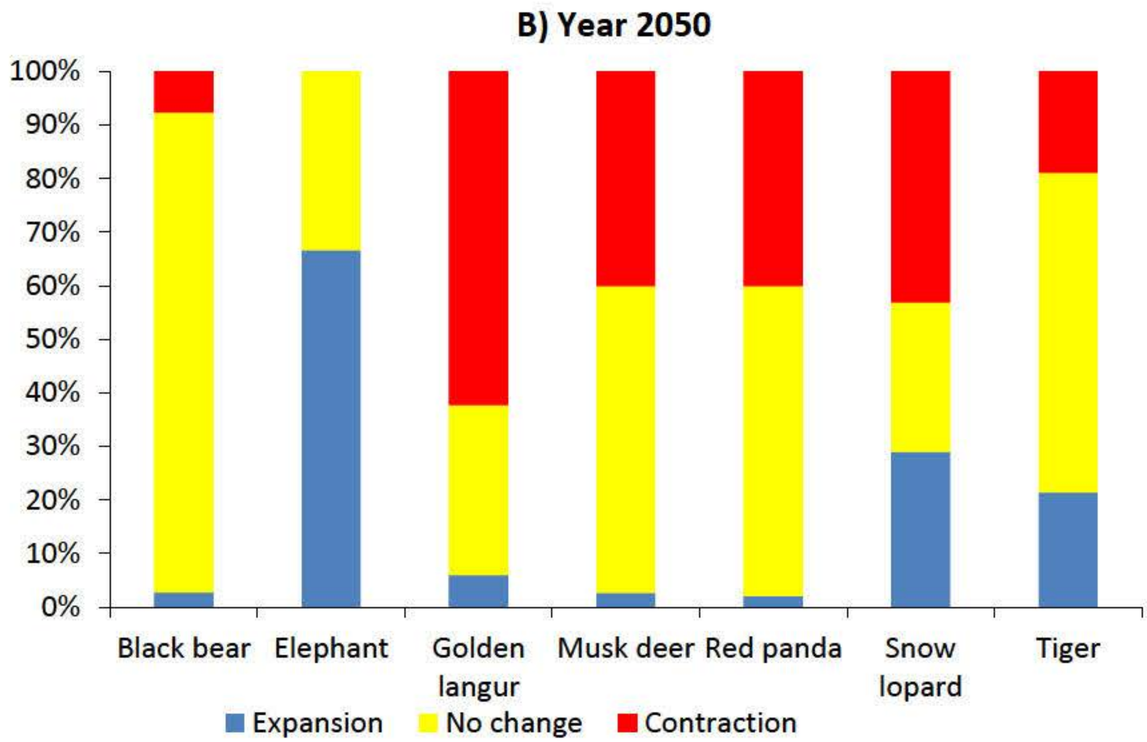
Results

Current status and future prediction of focal species

Our results predicted an array of species-specific range contractions and expansions under future climate scenarios (Figure 2). From an estimated area of 17,754 km^2 of suitable habitat in Bhutan, the tiger's range is predicted to expand by 21% and 25% in the next 30 and 50 years, respectively, mainly towards the mid-elevation zone of the country. However, the tiger's range along the southern part of the country is predicted to contract by 19% and 18%, respectively, in the same period, thus forcing it to higher elevations. From 6504 km^2 of suitable habitat predicted in the country, the snow leopard's range is predicted to expand by 29% and 27% in next 30 and 50 years, respectively, and experience contraction of its habitat by about 43% and 59% in the same period. This may, in particular, cause contraction of snow leopard habitat in Jigme Kesar Strict Nature Reserve (JKSNR) and Jigme Singye Wangchuck National Park (JSWNP) by 50% in the next 50 years. Similarly, the estimated suitable habitat of the Asiatic black bear was 33,037 km^2, Asiatic elephant *Elephas maximus* was 4904 km^2, golden langur *Trachypithecus geei* was 10,989 km^2, musk deer *Moschus* spp. was 14467 km^2, and red panda *Ailurus fulgens* was 22,402 km^2. The other focal species were expected to experience contraction of their current range between 7-78% in the next 30 and 50 years - musk deer (40%, 78%), golden langur (62%, 76%), Asiatic black bear (7.6%, 16.5%) and red panda (40%, 46%). However, the Asiatic elephant was predicted to expand its current range northwards by 67% and 71% after 2050 and 2080, respectively, without any range contraction (Figure 5.2).



a)
Panthera tigris
Current
2050
2070
Range Expansion
No occupancy
No change (current range)
Range Contraction
Elephas maximus
Trachypithecus geei
Moschus chrysogaster
Ailurus fulgens
Panthera uncia
Ursus thibetanus


B) Year 2050
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Black bear
Elephant
Golden langur
Musk deer
Red panda
Snow lopard
Tiger
Expansion
No change
Contraction

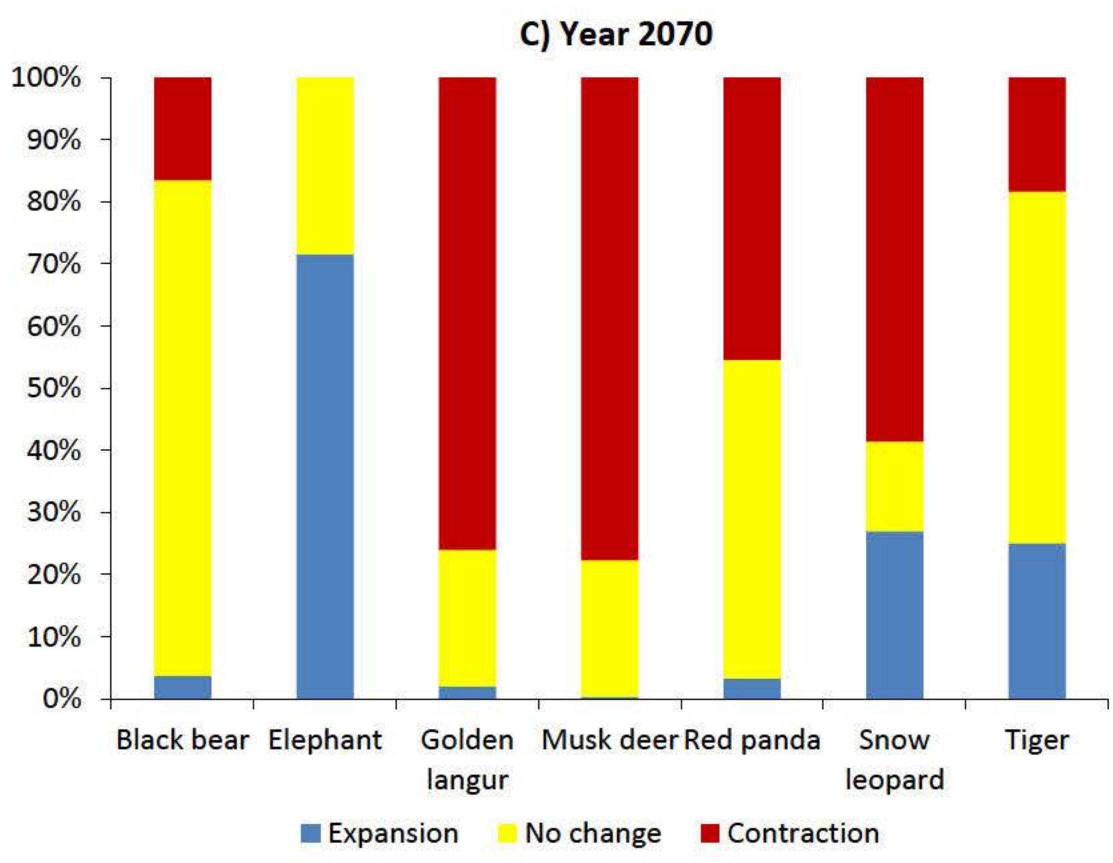

C) Year 2070
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Black bear
Elephant
Golden langur
Musk deer
Red panda
Snow leopard
Tiger
Expansion
No change
Contraction

Figure 5.2 a) Predicted range expansion and contraction by 2050 and 2070 for seven focal mammal species nominated for Bhutan's biological corridor network delineation; b) graph showing percent of range expansion, contraction and no change by 2050; c) graph showing percent of range expansion, contraction and no change by 2070.

Current and future prediction of focal species and their protection

Results from the Zonation analysis showed that 39.8% of current focal species ranges fell within current PAs comprising five National Parks, four Wildlife Sanctuaries and one Strict Nature Reserve (Figure 5.4a). In terms of individual species protection, PAs captured 84% of the globally endangered snow leopard's current range, 40% of musk deer, 40% of red panda, and 36% of the tiger's current range in Bhutan. However, current PAs captured only 27% of Asiatic black bear, 22% of elephant, and 21% of the golden langur's current range in Bhutan (Figure 5.3).

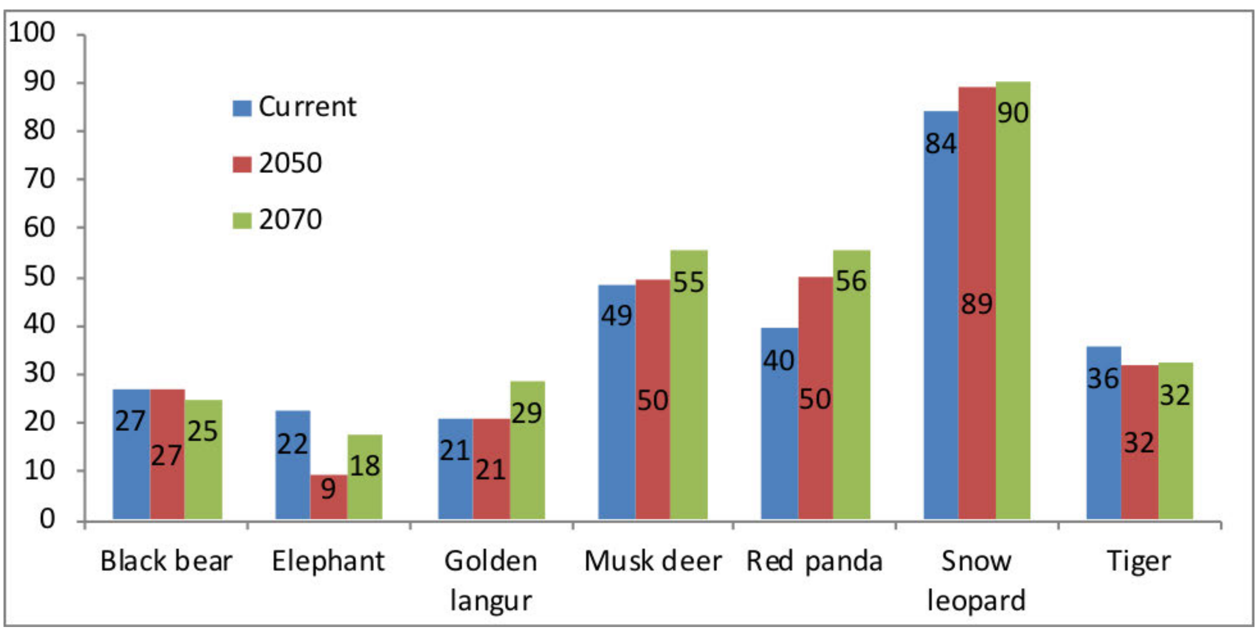


Figure 5.3 Graph showing percentage of current and predicted ranges (2050 and 2070) of focal mammal species nominated for biological corridor delineation captured by the current protected area system of Bhutan.

Priority conservation sites and connectivity network

In the context of current land use, biodiversity distribution patterns, and future climate scenarios, our Zonation model using a combination of different focal species grouping as follows: combination of tiger, snow leopard, musk deer and red panda only identified four priority sites outside PAs (annexure 3, Figure 2); combination of tiger, musk deer and red panda only identified four priority sites outside Pas (annexure 3, Figure 3), and six priority sites were identified for a combination of tiger, golden langur and elephant (annexure 3, Figure 4). The final zonation output from all focal species combined, generated seven priority areas outside current PAs (Figure 5.4a) and we validated the areas with expert opinion through consultation with the Department of Forests and Park Services and several field visits.

Priority Site 1 - The linkage between Jigme Khesar Strict Nature Reserve and Jigme Dorji NP (Corridor 1, Figure 5.1) was designed to facilitate movement of snow leopard, takin, blue sheep, musk deer and red panda (Wildlife Conservation Division 2010). However, these species will not remain within the margin of the current narrow corridor. Our results showed that snow leopard and musk deer habitat in Jigme Khesar Strict Nature Reserve is expected to shrink in the next 50 years and their range is expected to shift towards the northern border (Figure 5.2a). Similarly, tiger and red panda ranges are predicted to expand to higher elevations toward these areas (Figure 2a). Our final zonation solution identified priority area 1 for red panda, snow leopard, tiger and musk deer (Figure 5.4a & b). The area also provides protection to the river catchments of the Haachu and Pachu (Figure 5.4d)

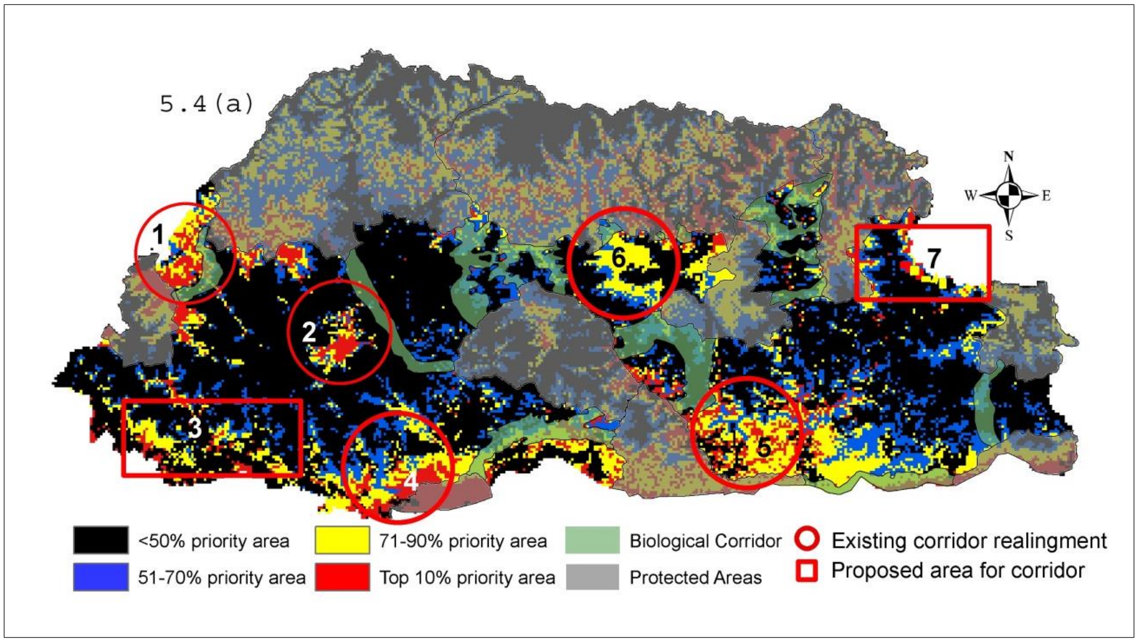
Priority Site 2 – This site lies outside the corridor between Jigme Singye Wangchuck NP and Jigme Dorji NP (Corridor 2, Figure 5.1). Corridor 2 is too narrow and does not serve any discernible function because most of the habitat area of focal species (red panda, tiger, and musk deer for this corridor) falls outside the boundaries of this corridor (Figure 5.4b & d). Priority site 2 will provide connectivity between tiger, red panda and musk deer core habitats and provide protection to some part of Wangchu, Punatsangchu, Dagachu and Basochu river catchments, and riverine habitat along these river tributaries.

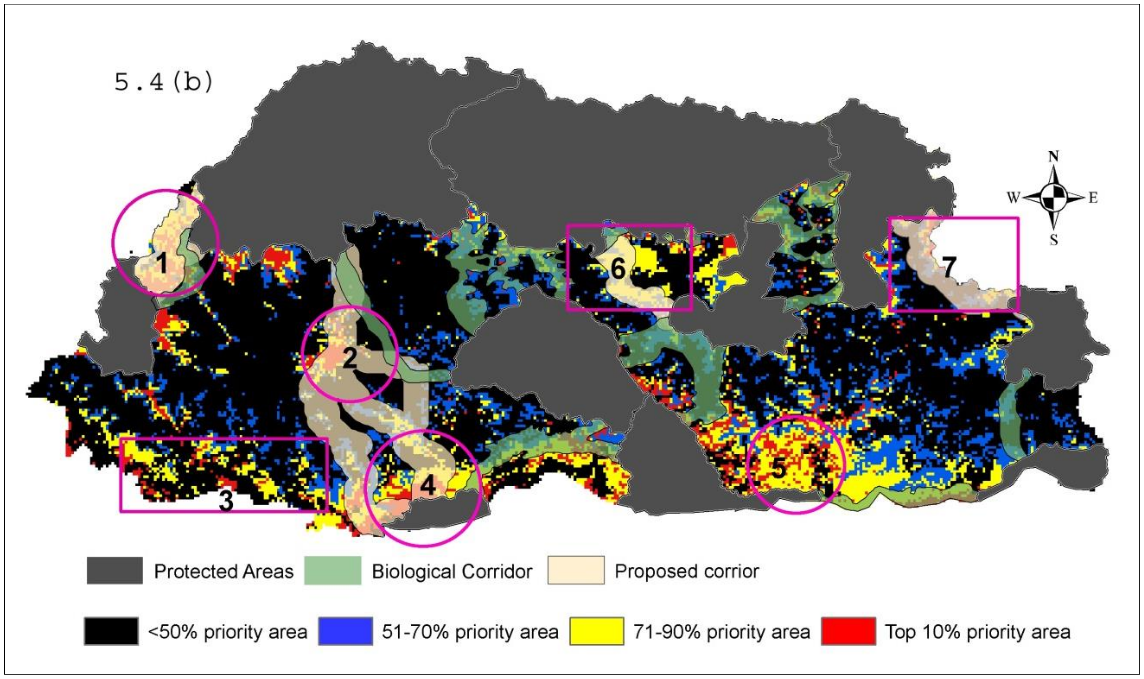
Priority Sites 3 & 4 – these sites are outside the Phibsoo WS and are central for facilitating the dispersal of many species from southern ecotones to Jigme Dorji NP and Jigme Kesar Strict Nature Reserve in the north. As more than 78% of the current estimated elephant range lies outside PAs, it is also predicted to act as a sanctuary for this species. Because elephants and tigers are both wide ranging species, this corridor does not need to be a continuous corridor, but can consist of adjacent stepping stone patches to supplement species dispersal through Corridor 2. Therefore, we propose for park boundary revision and also invest on community managed forest and habitat restoration in the area. We did not propose additional corridor here because the area is already under Kangchenjunga transboundary landscape (Chettri et al. 2007).

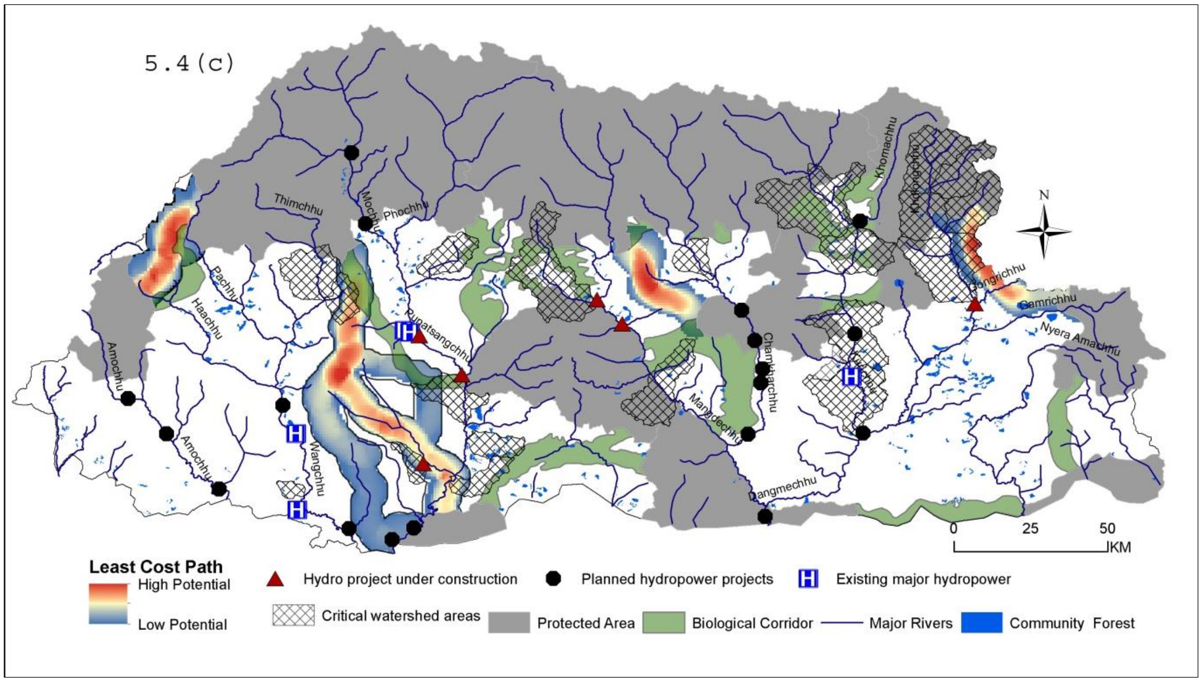
Priority site 5 - This site lies adjacent to the eastern boundary of Royal Manas NP and the corridor connecting Phrumsengla NP in the north. These areas are central to facilitating species dispersal from southern ecotones to east and central Bhutan, especially for the tiger, golden langur, and elephant. Priority Site 5 encompasses core golden langur habitat which is predicted to contract by 70% in the next 50 years (Figure 5.2a & b). However, these areas are currently under the Transboundary Manas Conservation Area (TraMCA) corridor which includes all the corridors and parks of Bhutan's southern border and Manas Park in India (WWF-Bhutan 2015).

Priority Site 6 – Some part of this site was part of corridor 8 (northern corridor) which got submerged into Wangchuck Centennial NP in 2008 when the park was first designated. It is key habitat for the tiger, musk deer, and red panda, providing contiguous linkage between Wangchuck Centennial, Phrumsengla, Jigme Singye Wangchuk and Royal Manas NPs in the south. The narrow threads that form Corridors 7 and 8 along the border of Wangchuck Centennial NP can now be redefined to better encompass tiger, red panda, and musk deer habitat. A tigress with three cubs was captured by a camera within this landscape during the nationwide camera trapping survey in 2015 (DoFPS 2015), demonstrating the value of this site to breeding tigers.

Priority Site 7 - This is one of the most important priority areas for maintaining a resilient and interconnected PA system in the country, in the face of changes predicted to occur under future climate change scenarios. Currently Bumdeling WS and Sakteng WS in eastern Bhutan have no connectivity between them. Our results showed that forest patches between these two protected areas provide key habitat linkages for the red panda, musk deer, Asiatic black bear, and tiger. These species are predicted to experience more than 40% of habitat contraction in the next 50 years especially in the areas under priority site 7 (Figure 5.2a & b). Recent biodiversity surveys also confirmed the presence of tigers in both Sakteng WS and Bumdeling WS. This area forms an important part of a regional tiger conservation landscape (Northern Forest Complex – Namdapha – Manas Landscape) in the Eastern Himalayas, connecting tiger habitats in Bhutan to habitats in eastern Assam and Arunachal Pradesh (India) which are linked to Myanmar (Wikramanayake *et al*. 2011). The area also protects significant water catchments of the Dangmechu and Kulong chu in eastern Bhutan (Figure 5.4d).







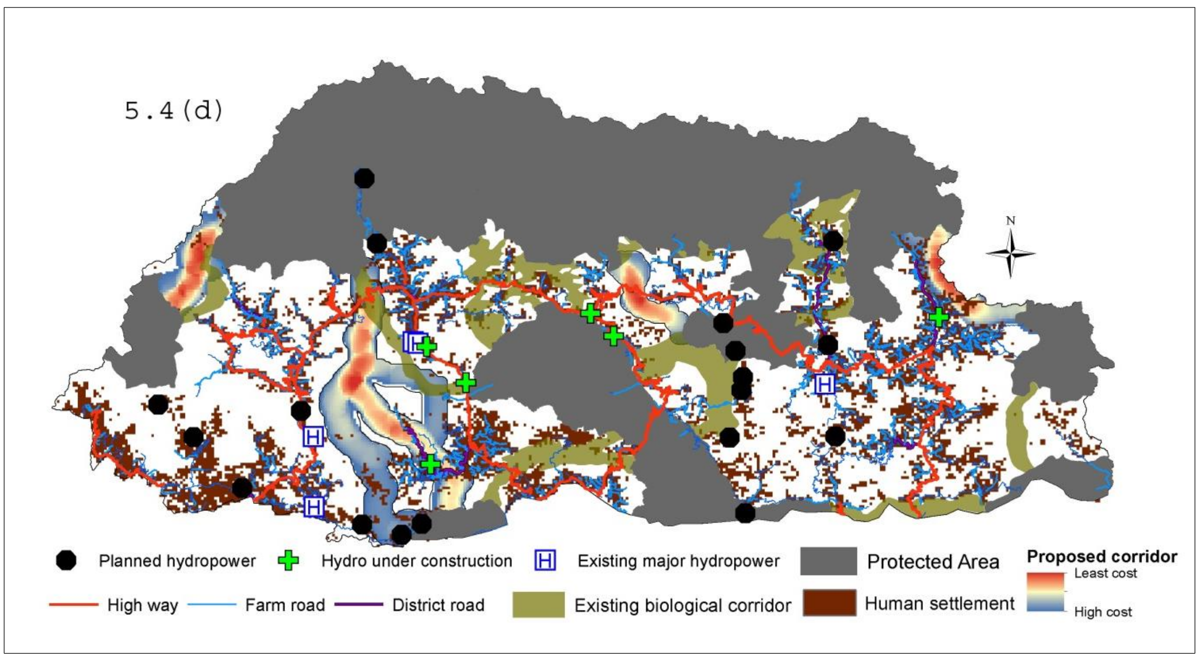


Figure 5.4(a) Core area zonation outputs of focal mammal species designated for biological corridor delineation and priority areas (outside current protected areas) recommended for readjustment of current corridor boundaries (circle) and new linkages (box). 5.4(b) zonation output and proposed biological corridor boundary in seven

priority areas identified for all focal species combined – tiger, snow leopard, musk deer, red panda, elephant, golden langur and Asiatic black bear; 5.4(c) map showing existing biological corridors and proposed corridors overlaid on the critical watershed areas, tributaries of major rivers, community forests and existing and planned hydro project in Bhutan. 5.4(d) map showing existing biological corridors and proposed corridors overlaid on the human settlement including agriculture land, road network and hydropower projects of Bhutan.

Discussion

In his review of the corridor network of Bhutan, Beier (2010) recommended that a corridor revision be conducted using the latest corridor-design software and ecological principles (Wildlife Conservation Division 2010). Different spatial arrangements of conservation priority areas resulting from the inclusion of different land use components and species representations have significant implications for conservation investment (Cabeza & Moilanen 2006; Kremen *et al.* 2008). We used a combination of species distribution modelling, complementarity zonation algorithms, least cost path analysis, SDMtoolbox, and ArcGIS tools to redefine the existing corridors of Bhutan. In addition to commonly used temperature and precipitation climate data, we also incorporated the most recent land use and infrastructure development data in Bhutan (National Land Commission of Bhutan 2018). Species locality data from the national tiger and snow leopard surveys (DoFPS 2015, 2016) allowed us to accurately model the distributions of our focal species. Our resultant models integrate the most detailed climatic, ecological, and biological data ever applied to predict the changing distribution and conservation status of these species in response to climate change in

Bhutan. Least cost categories were reassigned to reflect major wildlife habitats and discard private registered land and anthropogenic factors into the protected area system, with an aim to establish a durable network of protected areas, and minimize conflict of interest with development partners and local people living in and around the protected areas. These data are critical for making informed decisions pertaining to habitat protection with the goal of maintaining an ecologically and climatically resilient network of protected areas in Bhutan. The results of this study have significant practical implications for conservation agencies and policy makers to make a firm decision on conservation investment. Our results further emphasize the need for agencies to have clear objectives when targeting areas for nature conservation and developmental activities.

As per the IUCN Red List (IUCN 2018), all focal species including the takin and Asiatic black bear are currently threatened (6 Endangered and 2 Vulnerable) and 50% of them (musk deer, red panda, Asiatic elephant, and takin) were listed among the 50 most threatened species in the Eastern Himalayan region (Dorji *et al.* 2018). Our study predicts that 86% (n = 7) of these species will experience considerable range reductions in the next 50 years entirely due to future climate change (Figure 5.2). Range expansion may be limited by ecological or anthropogenic factors despite maintenance of seemingly suitable habitat linkages (Bennett 1999a; Wolf & Ripple 2017), and the conservation impacts of our predictions should be considered highly conservative in that they ignore the progressive and ongoing effects of anthropogenic activities associated with habitat reduction and degradation. For instance, global tiger habitat declined by 7.7% from 2001-2014 mainly due to habitat conversion and tiger landscape such as Russian Far East China, the Tenasserims and Northern Forest Complex - Namdapha Royal – Manas which includes Bhutan's tiger habitat, lost a combined 24,798 ± 7050 km of forest habitat in this period, accounting about 4% of the total landscape area (Joshi *et al.* 2016). However, situations are different for Bhutan as the country experienced high overall forest cover in the last two decades (Bruggeman *et al.* 2016; Gilani *et al.* 2015). If Bhutan's PAs are interconnected and remain representative habitat, short-distance and long-distance shifts in the range of species in response to future climate can be achieved through a combination of short movements with large, topographically and climatically diverse natural landscape blocks (Beier 2012). Recent reliable studies have used similar climate-based model predictions to demonstrate species range-shift and predict impact of future climate change scenarios on their population viability (Aryal *et al.* 2016; Williams & Blois 2018). Failing to include such specific elements of climate change in the conservation planning process will fail to prioritize those areas that will facilitate species dispersal, migration, and adaptation to climate change, and can result in priority areas requiring future expensive conservation measures (Cabeza & Moilanen 2006; Fernandes *et al.* 2015). For instance, the southern habitat of the snow leopard, especially in Jigme Kesar Strict Nature Reserve (JKSNR), Jigme Dorji National Park (JDNP) and Jigme Singye Wangchuck National Park (JSWNP), was predicted to contract by about 58% in the next fifty years, and its habitat predicted to expand further towards the northern border of the country (Figure 5.2). Previous analyses have also demonstrated potential impact of climate change on snow leopard habitat and provided recommendations on maintaining transboundary connectivity as an adaptive strategy against climate vulnerability in alpine habitats

(Aryal *et al.* 2016; Forrest *et al.* 2012; Riordan *et al.* 2016). Therefore, realigning the boundary of the corridor between JSKNR and JDNP within Priority Site 1, will enhance the resilience of the corridor between JKSNR and JDNP, and increase population viability of snow leopards and associated wildlife in the northern protected area network (Figure 5.4). The entire habitat of takin falls within the northern PAs. Maintaining habitat integrity of takin and snow leopard will, therefore, mostly come under the domain of PA management, not corridor management. However, Bhutan's legislation allows local communities to live within protected areas and enjoy access to natural resources, making takin habitat and seasonal migratory routes inside protected areas highly prone to habitat degradation and fragmentation (Sangay *et al.* 2016). Therefore, key wildlife habitat inside PAs should be appropriately mapped, zoned, and conservation measures undertaken as part of the park zoning and management plan implementation, especially in northern protected areas. Mapping should also ensure adequate provision of habitat connectivity between each core zones inside PAs.

Wild animals regularly traverse boundaries of PAs, and conservation planning and management must extend beyond such boundaries to encompass the whole landscape (Margules & Pressey 2000). Although Bhutan's mammal diversity is higher inside than outside PAs (Dorji *et al.* 2019a), forested areas adjacent to PAs have experienced greater habitat degradation in the last two decades, compared to areas away from PAs (Bruggeman *et al.* 2016; Gilani *et al.* 2015). Similar trends were also observed in other parts of the region (Tang *et al.* 2010). This can possibly lead to habitat fragmentation around PAs, thus impacting the capacity of organisms to disperse across the landscape, prevent gene flow, and prevent range shifts, thereby affecting the long-term viability of wildlife populations (Crooks *et al.* 2017; Tilman *et al.* 1994). Currently, Bhutan is a largely forested country with mostly intact and contiguous forest cover. As such, landscape connectivity is not currently threatened. However, exceptions were revealed in this study, with the weakest link observed along the southern belt and in the east. Furthermore, current landscape forest cover does not necessarily imply that Bhutan's protected areas are safe from habitat fragmentation into the future. Therefore, protecting important landscapes now while they remain intact should be a priority. For example, our study identified the area between Bumdeling Wildlife Sanctuary (BWS) and Sakteng Wildlife Sanctuary (SWS) as one of the important priority sites (Priority Site 7, Figure 4). There is currently no designated corridor to connect these two protected areas in Eastern Bhutan, and recent camera trap surveys (DoFPS 2015) confirmed the presence of tigers in both protected areas. Apart from tigers, the PAs also harbor many globally and regionally significant species such as the endangered musk deer, red panda, and Arunachal Pradesh macaque *Macaca munzala*. Furthermore, recent work by (Wangdi *et al.* 2019) in the area identified a risk of habitat loss due to high anthropogenic pressure such as agriculture, grazing, and infrastructural development. To avert negative ecological impacts from such development, we propose the establishment of an additional corridor between BWS and SWS. This corridor is anticipated to provide continuous tiger habitat linkage along the Northern Forest Complex – Namdapha –Manas Landscape (Wikramanayake *et al.* 2011), that would connect with habitats in eastern Assam, Arunachal Pradesh, and Myanmar.

Wildlife movement barriers are complete, partial, natural (e.g., rivers, cliffs), or human-made (e.g., urban areas, highways, some types of agriculture) where landscape features impede wildlife movement between habitat patches (Bennett 1999a). The most common barriers in Bhutan are roads, agriculture, human settlements, hydropower dams, and rivers. For instance, the most fertile and accessible parts of the landscape along the southern belt have been greatly transformed and only 22% of the predicted suitable habitat for the Asiatic elephant, tiger and golden langur combined, is captured by the current PA system (Figure 4c). Buying back land tenure rights from private owners is near to impossible, and one way of enhancing habitat connectivity in human dominated landscapes outside protected areas is to partner with local communities by incorporating community forestry plans as part of strategic conservation landscape planning. Local residents in and around Bhutan's PAs have been considered as conservation partners since the inception of its first PA in the 1960s, and traditionally, these people protected many natural sacred groves and represent the oldest form of habitat protection in the country (Wangchuk 2007). This would provide some form of habitat protection in Priority Areas 3, 4, 5, and 7 (Figure 5.4). Community forests deliver multiple outcomes by contributing substantially to the livelihoods of rural people, increase carbon storage, and promote ecosystem services and biodiversity conservation (Baral *et al.* 2018; Belsky 2015; Temphel & Beukeboom 2007). They serve the dual purpose of providing shelter to resident wildlife and act as stepping stones for migratory species. Further support from the government to promote income generation and recreational activities in community forests such as payment of environmental services schemes and ecotourism activities, can result in efficient, cost-effective, and equitable conservation. Recent studies in the country have also shown that gross forest cover changes inside Forest Management Units (FMU) are lower than other disturbed land facets (Gilani *et* *al.* 2015), and realigning the corridor boundary through FMU (for example Corridor 2) can potentially improve the effectiveness and efficacy of biological corridors. We didn't include the electrical transmission line as barrier to wildlife. Although, the transmission lines may cause some environmental damage during the initial installation, they do not block the mammal movement after installation (personal observations). At the outset we emphasize that corridor can be managed through multiple land-uses which include community forestry, Forest Management Units with sustainable harvest protocols, and other non-conversion land uses (thus, the forests in the corridors should not be cleared for development). Any infrastructure plans within these corridors should be subjected to a Strategic Environmental Impact Assessment and unavoidable infrastructure (e.g., roads) should follow Smart Green Infrastructure Development standards and park zonation guidelines.

Integrating conservation and development in the PAs of Bhutan are expensive and need to be spatially integrated to achieve efficient outcomes (Karst & Nepal 2019; Lham *et al.* 2018). Biodiversity and human communities along the mid elevational gradient in Bhutan are likely to be altered as lower elevation species move upslope. There is also a possible disruption to the range shift and migration of species at the mid elevational range due to anthropogenic activities because more than 68% of Bhutan's population resides in these mid-elevations (1000-3000 masl). Therefore, conservation management plans for biological corridors must integrate human community needs, and incorporate measures for climate change adaptation. We recommend that management zones are defined and delineated into core areas and buffer zones for protection and conservation of focal species, and multiple use zones from where local communities can collect forest products based on prescribed management plans. The core zone should include at least 75% of core priority sites, with the remaining 25% surrounding the core priority sites designated as buffer zones. We further suggest that multiple use zones should be established at least 500-1000 m away from the boundary around the core zone and allocated to the local community as a community forest. In the case of Forest Management Units falling inside new biological corridors, no felling should be allowed in designated core areas and any forest management outside the core zone should be strictly monitored as per the management plans prescribed by the Forest Resource Management Division under the Department of Forests and Park Services. In terms of afforestation and social forestry programs, restoration of disjoint corridors should be prioritized as a local mechanism to integrate conservation with community needs in order to maintain ecosystem resilience. Annual afforestation and plantation programs should focus on degraded habitat patches between priority sites to provide optimum stepping stones or linear habitat for wildlife movement. Corridor management plans should capitalize on provision of agroforestry and organic farming-based livelihoods for communities living in or adjacent to corridors. Forest-based enterprises such as medicinal plant cultivation, agroforestry, and ecotourism should be emphasized for local economic development and poverty alleviation, mainly to restore and maintain multi-functionality and minimize further impacts of biological corridors (Figure 5.4). For example, many successful community based biodiversity conservation and livelihood development projects have been implemented in PAs across Bhutan (Choden 2016; Wangchuk 2005) and Kangchenjunga transboundary landscape (Chettri *et al.* 2008), and this could be replicated in the corridors.

Bhutan has a tremendous amount of inland freshwater resources including glaciers, rivers, streams, wetlands, and lakes across the country. Rivers and associated wetlands support biodiversity and healthy functioning of many ecosystems in the catchments through which they flow (Allen 2010; Dorji 2016). There are at least 126,000 species of organisms living in fresh water, representing up to 12% of all known species on Earth (Garcia-Moreno *et al*. 2014). There is also clear evidence that the Himalayan glaciers are melting at an alarming rate in recent decades (Eriksson *et al*. 2009), resulting in major changes in freshwater flow. This has major implications for biodiversity as well as water security for household supply, hydropower, and agriculture. Accordingly, the golden masheer and the Critically Endangered white bellied heron were identified as focal species and indicators of the health of Bhutan's riverine ecosystems (Wildlife Conservation Division 2010). We therefore, recommend embedding important river tributaries like Punatsangchu, Drangmechu, Wangchu, Kulongchu and Dagachu into our biological corridor system. We, however, did not specifically create a habitat suitability map for the mahseer and white bellied heron. Instead, we recognize both as proxy species for aquatic connectivity including for hydrological flow, which is an important ecological service for sustaining biodiversity as well as human livelihoods and Bhutan's economy. Further, we recommend that instream development projects such as hydropower plants recognize the importance of maintaining connectivity for migrations of aquatic species and provide necessary access.

The new biological corridors we propose comprise about 6.55% of Bhutan's land area. Therefore, protected area coverage in Bhutan would increase to 57.86% if our recommendations are adopted. This represents a small investment of land for a potentially large benefit to biodiversity and threatened mammal species. In light of the present uncertainty about the nature and management of future climate change and its potential impacts, intact and unique biodiversity in Bhutan offer unique opportunities to bench mark scientific research and monitoring. Our study forms a baseline to monitor the efficacy and functionality of biological corridors in Bhutan and biodiversity monitoring in the Eastern Himalayan region. Since our evaluation was largely based on a connectivity analysis on large mammal distributions and habitat requirements, subsequent work should be directed at testing connectivity for smaller mammal and other taxa that may utilize the landscape differently.

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STATEMENT OF AUTHORS' CONTRIBUTION

(To appear at the end of each thesis chapter submitted as an article/paper)

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Photo showing Fir forests in Phrumsengla National Park, Bhutan (altitude between 3000 – 4300 m asl). These forests have high ecological and economically values. The meadows are equally important both for livestock and herbivorous mammal grazing. The forest here harbors globally threatened red panda *Ailurus fulgens*, musk deer *Moschus chrysogaster*, and tigers *Panthera tigris*. The areas also protect critical watersheds of Bhutan which are imperative for sustenance of downstream anthropogenic activities and hydropower production.

Photos showing three important habitat mosaics (stepping stones, culturally significant sacred grooves, and traditional agriculture farm land) captured within the protected area system of Bhutan. The riparian habitats (top left) are important for aquatic species and also acts as stepping stones; heritage sites with intact forests around them (top-right photo) are culturally significant with high biodiversity values as many such sites are protected through local ethos and beliefs; and traditionally, people of Bhutan practice organic farming in harmony with nature (bottom photo). Agricultural farm land also has high ecological significance, both for migratory and resident wildlife species. For example, flowering mustard plants in these agricultural landscapes provides important habitat linkage or act as stepping stones to migrating native bees and other wildlife in winter.

Camera trap covered with elephant dung to protect them from elephant damage. This method invented during the field work of Bhutan's nationwide camera trapping in 2014 has worked.

Chapter 6: Research synthesis and general recommendations

Protection of threatened species and expansion of protected areas (PAs) in the Eastern Himalayas

Given current regional human population growth-rate and agricultural expansion coupled with impact of climate change, the Eastern Himalayan (EH) ecoregion has become more threatened. As a result, conservation success here will progressively become dependent on appropriately managed human-modified landscapes (Chettri et al. 2008; Dorji et al. 2018; Gillison 2016). Although PAs in the Eastern Himalayas have increased significantly over the last four decades, there is a mismatch between their current distribution and priority areas for conservation of the 50 most threatened mammal species in the region, because current regional PAs are not adequately protecting them (Sangay et al. 2018; Chapter 2). This skewed regional distribution of protected areas requires expansion of existing protected areas and, where possible, the establishment of new parks and transboundary reserves based on 35 newly identified priority areas at the regional level, and 11 priority areas at country level.

To complement the IUCN Red List of threatened species, my top 50 most threatened species list placed a higher priority on endemic, geographically restricted, and evolutionary distinctive species facing a higher risk of extinction because their current level of protection in the PAs is lesser than wide-ranging charismatic species (Sangay et al. 2018; Chapter 2). Furthermore, my priority listing ensures protection of remaining habitat for EH mammal species that will become extinct if these habitats are lost. Similarly, small-sized, medium sized, and Data Deficient (DD) mammal species should also be equally emphasized to address the current crisis of species extinction. Finally, a major proportion of the region's ecoregions and my priority areas for PA expansion is under the Nature Needs Half Category 2 (Nature Could Reach Half) approach by

Dinerstein et al. (2017) to protect half of global terrestrial ecoregions. My findings on the extent of ecoregion protection suggests that there are adequate remaining natural habitats to expand current EH PAs by strengthening national and regional transboundary collaboration to develop and implement a comprehensive regional land use plan, and enhancing information sharing through a consolidated regional database. I demonstrate that respective countries in the region should take responsibility to increase their current area of PAs to achieve the goal of ‘half earth protection”.

Protecting threatened mammals of Bhutan

Among the Eastern Himalayan range countries, Bhutan has placed sustainable development (locally called the “middle path approach”) as its central government policy and vision for long term development (Thinley 2014). Because the country’s philosophies are deeply rooted through Buddhist principles and belief, Bhutan has taken proactive measures to balance nature and culture conservation with development. Thirty-three percent (n = 19) of Bhutan’s known mammal species are totally protected under the Forest and Nature Conservation Act of Bhutan, 31% (n = 18) are categorized as threatened under the IUCN’s threatened species categories (IUCN 2018), and 28% (n = 14) listed as the most threatened species in the Eastern Himalayan region (Dorji et al. 2018). Despite stringent legislation, high mammal species diversity in protected areas, and a strong political will for nature conservation, my research results reinforces local and regional threats to mammals from agricultural activities, livestock grazing, timber collection, poaching and illegal trading of wildlife parts, forest fire, and human-wildlife conflict (Dendup & Lham 2018; Dorji et al. 2018; Rajaratnam et al. 2016; Velho et al. 2012). I recommend capacity-building, institutional coordination, human-wildlife conflict management, research, and financial resource mobilization to mitigate such threats.

Bhutan's network of protected areas and biological corridors still harbor a rich mammal community through the government's ability to reconcile biodiversity conservation goals with social and economic issues. The importance of local communities within protected areas and biological corridors is further recognized and integrated into protected area conservation goals, and local stewardship promoted through incentive-based conservation programs. This integration of landscape protection (PAs) and connectivity (BCs) along with harmonious coexistence with local communities will ensure the conservation of Bhutan's mammal diversity well into the future. Strengthening the management of the protected area network and the biological corridors are also crucial to ensure long-term persistence of the country's diverse ecosystems and habitats which support globally significant mammal species.

Realigning the conservation priorities in Bhutan

The realignment of corridors was carried out not solely for movement of specific species, but as habitat corridors which will also facilitate movement of other associated species, and act as climate refuges for migrating and small-ranged species. If Bhutan's protected areas are to remain interconnected representative habitats for the country's biodiversity, short-distance and long-distance range shifts of species in response to future climate change, can be achieved through a combination of short movements through large, topographically and climatically diverse natural landscape blocks. Failing to include specific elements of climate change in the conservation planning process will not prioritize areas which facilitate species dispersal, migration and adaptation to climate change, resulting in priority areas requiring expensive conservation measures in the future. I, therefore, recommended adjusting the boundary of corridor between Jigme Kesar Strict Nature Reserve and Jigme Dorji National Park (Priority Area 1), and including a new priority area between Wangchuck Centennial National Park, Phrumsengla National Park and Jigme Singye Wangchuck National Park (Priority Area 6). With these realignments, I expect to increase the resilience of the northern protected area network, and increase population viability of snow leopards and associated wildlife in the area.

Further results revealed a weak link between protected areas along the southern belt and in the east. In Priority Areas 2, 3, 4 and 5 (Figure number 4, Chapter 5), I recommend partnering with local communities living in and around the biological corridors to incorporate community forestry plans as part of strategic conservation landscape planning to enhance habitat connectivity in human dominated landscapes outside protected areas. These communal forests can serve the dual purpose of providing shelter to resident wildlife and act as stepping stones for migratory species. Further support from the government to promote income generation from recreational activities in community forests through environmental services schemes and ecotourism activities, can result in efficient, cost-effective and equitable conservation. In the east (Priority Area 7, Figure 5.4), there is currently no designated corridor to connect Bumdeling and Sakteng Wildlife Sanctuaries, and recent camera trap surveys (DoFPS 2015) confirmed the presence of tigers in both protected areas. Apart from tigers, the PAs also harbor several globally and regionally significant species such as the endangered musk deer, red panda, and Arunachal Pradesh macaque. Furthermore, recent work by Wangdi et al. (2019) in the area identified a risk of habitat loss due to high anthropogenic pressure from agriculture, grazing, and infrastructural development. To avert negative ecological impacts from such development, I propose the establishment of an additional corridor between Bumdeling and Sakteng Wildlife Sanctuaries. This corridor will also provide continuous trans-frontier tiger habitat linkage along the Northern Forest Complex – Namdapha – Manas Landscape (Wikramanayake et al. 2011), by connecting with habitats in eastern Assam, Arunachal Pradesh, and Myanmar. In conjunction, I strongly recommend the Bhutan government and conservation partners to initiate transboundary conservation collaboration with the Indian state of Arunachal Pradesh. This will help to maintain an interconnected landscape for conservation of global keystone species such as tigers, red panda, musk deer, snow leopard, and Arunachal Pradesh macaque between the Indian state of Arunachal Pradesh and Bhutan through Priority Area 7 (Figure 5.4, Figure 2.6; Figure 2.13). The areas also possess unique transhumant pastoralism culture among the local residents living along the border of the two countries.

Corridor number 2 connecting Jigme Dorji National Park and Jigme Singye Wangchuck National Park is affected by existing barriers comprising agricultural land, roads, hydropower dams, human settlements, and rivers. Moreover, the corridor does not capture prime habitat for focal threatened species in the area, principally the tiger, red panda, and musk deer. I recommend a realignment of this corridor to inclusively capture key habitats for these focal species, and recommend integrated conservation planning and land management approaches in corridor 2's management plan.

Conservation management plan and zoning of corridors

My results emphasized the need for conservation agencies to have clear objectives when targeting areas for nature conservation and developmental activities. Conservation management plans for biological corridors must integrate human community needs, and incorporate measures for climate change adaptation. I recommend that corridors are delineated into core areas and buffer zones for protection and conservation of focal species, and multiple use zones from where local communities can collect forest products based on prescribed management plans. Corridor management plans should capitalize on provision for agroforestry and organic farming-based livelihoods for communities living in or adjacent to corridors. Forest-based enterprises such as medicinal plant cultivation, agroforestry, and ecotourism should be emphasized for local economic development and poverty alleviation, to restore and maintain multi-functionality, and minimize further impacts from biological corridors. Annual afforestation and plantation programs should focus on degraded habitat patches between priority sites to provide optimum stepping stones or linear habitat for wildlife movement. Further, I recommend that instream development projects such as hydropower plants recognize the important of maintaining connectivity for migration of aquatic species and provide necessary access. Additionally, recent studies in the country have confirmed minimum gross changes to forest cover inside Forest Management Units (FMU) compared to other disturbed land facets (Gilani et al. 2015), and as such, FMUs should not be considered as barriers in corridors. Periodic forest management activities undertaken in FMUs may cause some disturbance to the wildlife but will not create permanent fragmentation. Therefore, realigning corridor boundaries through FMUs, for example, Corridor 2 (Jigme Dorji - Jigme Singye Wangchuck NPs), 8 (Jigme Dorji - Wangchuck Centennial-Jigme Singye Wangchuck NPs) and new priority area 6 (Phrumsengla - Wangchuck Centennial-Jigme Singye Wangchuck NPs), can potentially improve the effectiveness and efficacy of biological corridors, provided protected area zonation guidelines shaped and trailed in Bhutan's protected areas as key outcomes of this study, are implemented appropriately.

Policy Recommendations

The main aim of identifying and realigning connectivity was to establish a durable network of protected areas with minimum conflict of interest with development and local people living in and around PAs. I also took into consideration, a holistic approach through integrated landscape conservation at the spatial scale which will also contribute to Bhutan's socio-economic development, and provide habitat linkages that capture ecological processes and services i.e. hydrological processes, that is of paramount economic importance to Bhutan. The results of my study have significant practical implications for conservation agencies and policy makers to make firm decisions on conservation investment. As an outcome of this study, the protected area zonation guidelines (see annexure 3) has been accepted and trailed for implementation in Phrumsengla National Park. My zonation guidelines and the revised protected area system of Bhutan (see revised maps of Bhutan's protected area network in annexure 3 have been presented to the Department of Forests and Park Services, and relevant stakeholders in several rounds of meetings. The documents are now submitted for government approval and will be used as guiding documents for effectively managing Bhutan's protected area. My results further emphasize the need for agencies to have clear objectives when targeting areas for nature conservation and developmental activities. Accordingly, I make the following specific recommendations:

1. Integrate PA revision plans and zonation guidelines with an overall hydropower development strategy that takes into account sensitive environmental areas, including core tiger breeding zones. Such strategies should build on the Strategic Environmental Assessment of the hydropower sector, and make informed choices on what projects should be developed spatially and temporally;

2. Expedite the official definition, delineation, and designation of core habitats for focal/target species in the biological corridors to have clear-cut definition and management objectives for each corridor;

3. Establish and implement a framework for establishing baseline environmental status and regular monitoring processes for biological corridors;

4. Expedite the endorsement of zonation guidelines to standardize zonation in all PAs and BCs;

5. Establish adequate institutional arrangements involving national and subnational entities, and between sectors for planning of specific conservation projects, managing social and environmental risks, and promoting adaptive management during the implementation of the corridor management plan projects;

6. Accelerate skill enhancement and capacity building (human resources) in order to enable the development and implementation of smart green infrastructure in the hydropower sector;

7. Initiate a national level zoning program to integrate conservation objectives with development programs. The government's Nature Conservation Division must participate and play a pivotal role in integrating conservation into the national land-use planning program;

8. Develop tools and guidelines to include Smart Green Infrastructure (SGI) principles in park management planning and environmental legislations;

9. Share the responsibility for SGI across public agencies, the private sector, and the civil society. Conservation is not the sole responsibility of the Department of Forests and Park Services but a shared responsibility. Human capital and technical capacity to design, implement and supervise smart green infrastructure must be incorporated in infrastructure project planning, and corporate and financial institutions. All sectors must contribute to the necessary resources;

10. Identify and map remaining critical wildlife areas outside the protected area network and initiate sustainable livelihoods and smart green infrastructure programs for human residents in these areas;

11. Through strict compliance with land use and zoning, regulate the unplanned urban sprawl adjoining the protected area network and critical wildlife habitat to prevent encroachment into sensitive and important biodiversity rich habitats, and to contain the ecological footprint of expanding urban and rural settlements;

12. Department of Forests and Park Services should use and enhance existing park road guidelines in all PAs to apply minimum standards (in line with SGI – for example, core areas are inviolate and all road construction is prohibited) to all road construction, maintenance, and operations in PAs and BCs;

13. Liaise with the Ministry of Finance to develop bidding documents that capture the unit cost of environmental mitigation and monitoring as part of the submitted bids for new infrastructural development (cost estimate/km);

14. Map existing and proposed infrastructure in the country to mitigate pressure on PAs and integrate zonation guidelines and PA management plans with National Infrastructural Development Master Plans;

15. Develop social innovations at a community level to manage tourism and financial flows which would benefit grass-root level communities living in and around the PAs from ecotourism activities.

16. Initiate policy changes to channel direct monetary benefits from the tourism industry to local communities living in and around PAs.

Research recommendations

My camera trapping method worked well in detecting medium-sized and large mammals, but missed small mammals and arboreal mammals. Accordingly, future surveys in Bhutan should be designed based on species behaviour and size as specifically recommended by Sangay *et al.*, (2014) particularly for small mammals. Regular monitoring of mammals in Bhutan during the current period of intense development activities amidst anthropogenic climate change can guide conservation measures aimed at protecting mammals, maintaining forest connectivity, and ensuring the integrity of the protected area network. I recommend establishing permanent biodiversity monitoring plots along an elevational gradient within all ecological zones in Bhutan, to monitor the impact of climate change on the biodiversity of the Eastern Himalayas.

For better researcher access to current data and improve information sharing system at the national and regional level, it is recommended that national and regional educational institutions, government organizations, and non-governmental organizations develop an online, readily accessible database of all wildlife species. This should be well coordinated with established protocols for data management, data sharing, and user benefits among individuals and institutions, specifically in Bhutan.

Finally, my study forms a baseline to monitor the efficacy and functionality of biological corridors in Bhutan, and biodiversity monitoring in the Eastern Himalayan region. Since my evaluation was largely based on a connectivity analysis of large mammal distributions and habitat requirements, subsequent future research should be directed at testing connectivity for smaller mammals and other taxa that may utilize the landscape differently.

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Photos from field work in 2015 with my Supervisors Dr. Raj (left) and Associate Professor Karl (right)

Abandoned house in the middle of the forests, on the way to one of our survey plots

Supervisor Karl and survey team members identifying the animal scats during the 2015 field work in Bhutan.

Supervisor Karl and Raj during the field work in Bhutan

Survey team members transporting food and survey equipment to a base camp in Royal Manas National Park during the nationwide camera trapping.

Annexure 1

Supplementary material for Chapter 2: Identifying Conservation Priorities for Threatened Eastern Himalayan Mammals.

Demographic Representation, Chronology and IUCN Categories of PAs in the Eastern Himalayas

There were 105 PAs, covering 16.95% (88,855 km^2) of the region's terrestrial land, designated under six IUCN categories of PA. The first officially gazetted PA in the region was Manas WS, Assam, India in 1928. There were only three PAs until 1970 covering 0.31% of region's terrestrial area. The number of PAs increased to 26 in 1980 covering 3.16% of region's total are. The number of PA in the region increased to 70 between 1985-2005 covering 15% (78,928 km^2) of region's land surface. Only 2 PAs and 3 Ramsar sites were designated between 2005-2015 (7071 km^2, Figure 2). We couldn't establish year of designation of four PAs (Yading and Yaluzangbudaxiagu in China, Nam Lang NP in Myanmar, Pabha WS in India), we summed their coverage to overall cover in 2015.

Under the IUCN category of PAs, there were 1 Strict Nature Reserve (IUCN category - I), 22 NP (IUCN category - II), 53 WS (IUCN category - IV), 12 protected landscapes (IUCN category V), 20 biological corridors and buffer zones (IUCN category VI), 5 World Heritage sites and 6 Ramsar sites in the region Table 1)

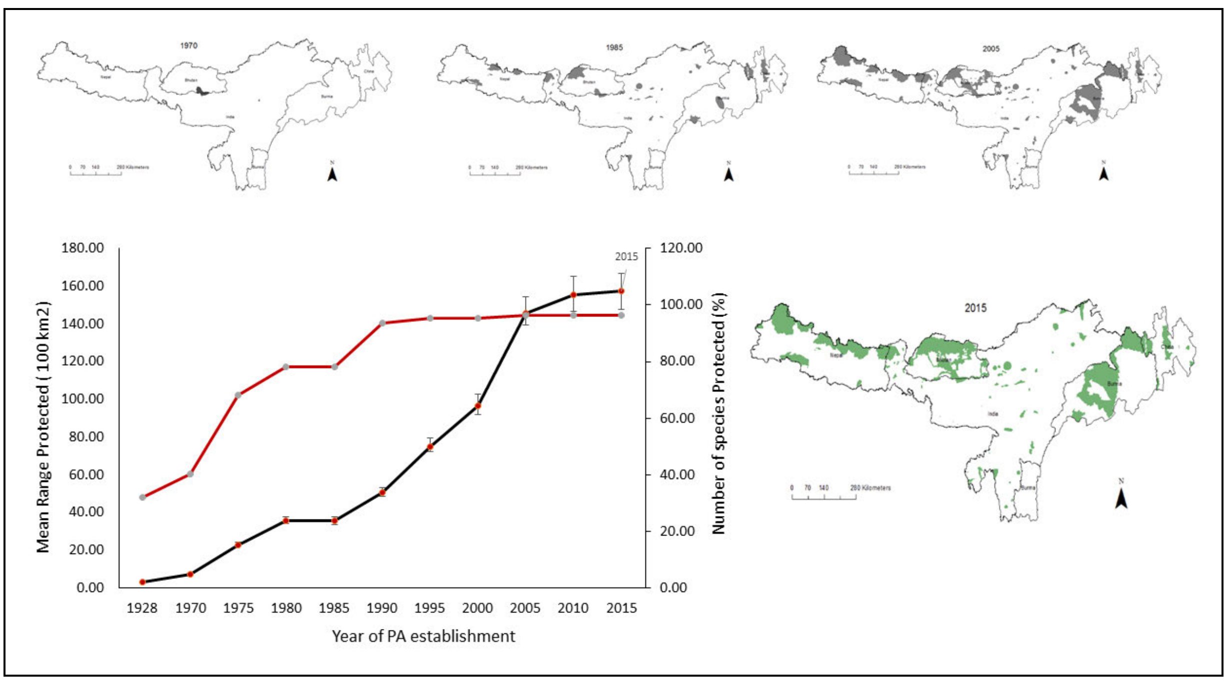

Figure 1 The chronology and growth of protected areas in the eastern Himalayas. 14 sites with their current status reported as proposed PA (14,959 km^2) in World Database of Protected Areas was excluded from analysis and thus in the cumulative graph.

Table 1 The land and protected area (PA) coverage, number of PA under six IUCN categories, Ramsar and world heritage site of respective range countries in the eastern Himalayan region (Figure in the bracket refers to percentage of respective range country's land surface in EH and under PA cover). The world heritage sites polygon overlapped with the PAs and thus dissolved together for aerial calculation.

Country	Area in EH km^2	PA cover km^2 (%)	World Heritage Site	Number of PA under IUCN category						
				IA	II	IV	V	VI	Ramsar Site	Total
Bhutan	38395 *(7.6)*	19676 *(51.24%)*	0	1	5	4		8	3	21
China	34783 *(6.39)*	6923 *(19.90%)*	1				12	1	1	14
India	272736 *(52.03)*	11336 *(4.15%)*	2		11	43			1	55
Myanmar	93987 *(17.90)*	28406 *(30.22)*	0		1	4				5
Nepal	84290 *(16.08)*	23263 *(27.59)*	2		5	2		11	1	19
Total	524191	88855	5	1	22	53	12	20	6	114

PA, Protected areas; EH, eastern Himalayas; IUCN, International Convention for Conservation of Nature. IUCN PA Category, I - Strict Nature Reserve or Wilderness areas, II – National Parks, III - Natural Monument, IV - Habitat/Species Management Areas, V - Protected Landscape/Seascape, VI - Protected area with sustainable use of natural resources.

Proposed protected areas and protected areas reported as point locations

We had to report the centroid (northing-easting) data of some protected areas (PAs) only presented as point locations, and their current status as proposed PAs under the World Database on Protected Areas (WDPA). Despite their crucial role in biodiversity conservation, they represent an unquantifiable proportion of the total extent of PAs, given common errors in reporting coverage and current IUCN status (Visconti et al. 2013). Some of these PAs overlapped with 35 new priority areas we identified through expansion of current PAs to conserve globally threatened, evolutionarily distinct and geographically restricted range and endemic mammal species of the Eastern Himalayas.

Table 1 List of proposed protected areas in the Eastern Himalayan region and their x,y centroid. The area is estimated based on the ESRI shapefile data of World Database of Protected Areas downloaded on September 26, 2016.

SN	Protected Area	Status	Country	Area (km2)	X - centroid	Y - centroid
1	Bumhpabum Wildlife Sanctuary	Proposed	Myanmar	2927	97.389	26.520
2	Bara Conservation Area	Proposed	Nepal	189	85.002	27.002
3	Phulchoki Conservation Area	Proposed	Nepal	149	85.267	27.617
4	Walong National Park	Proposed	India	1064	96.582	28.148
5	Lado Sanctuary	Proposed	India	223	92.891	27.634
6	Lado National Park	Proposed	India	991	92.906	27.641
7	Kalaktang Sanctuary	Proposed	India	298	92.152	27.182
8	Poba Sanctuary	Proposed	India	91	94.083	27.023
9	Kyongnosla Sanctuary (extension)	Proposed	India	21	88.682	27.379
10	Dibang Valley National Park	Proposed	India	1814	95.798	28.935
11	Walong Sanctuary	Proposed	India	690	96.654	28.278
12	Namdapha Sanctuary	Proposed	India	3761	96.528	27.513
13	Dibru Sanctuary	Proposed	India	490	95.186	27.602
14	Moiling Sanctuary	Proposed	India	1980	94.723	28.617
15	Namdapha National Park	Proposed	India	0	96.533	27.434

1.3 R-script for developing mammalian species richness map using r-package letsR.

The letsR package is being developed by Vilela and Villalobos (2015) to help researchers in the handling, processing, and analyzing macro-ecological data. It allows users to build presence-absence matrices (the basic analytical tool in macroecology) from species' geographical distributions and merge them with species' traits, conservation information (downloadable using functions from this package) and spatial environmental layers. Additionally, the package also enables users to summarize and visualize information from presence-absence matrices. We applied the letsR package to develop a terrestrial mammal species richness map of the Eastern Himalayan region using the IUCN spatial data on mammalian species.

r-code for species richness mapping using r-package letsR.

```
>mam <- readShapePoly("all_mam_eh", delete_null_obj = TRUE) ## Importing mammal shapefile into r console

> colors <- rainbow(length(levels(mam@data$binomial)), alpha = 0.5) ##Plotting species distribution range polygon

> position <- match(mam@data$binomial, levels(mam@data$binomial)) ## Defining attribute for generating spatial polygon map of mammals

> colors <- colors[position] ## Adding colour to the map

> plot(mam, col = colors, lty = 0, main = "Spatial polygons of mammals of the eastern Himalayas") #Plotting legend on the map

> pam <- lets.presab(mam, xmn = 82.70, xmx = 100.31, ymn = 21.95, ymx = 29.45, resol = .25) # Defining study area extent

> plot(pam, xlab = "longitude", ylab = "latitude", main = "EH Mammals Species Richness") # Plotting species richness map

> plot(pam, xlab = "longitude", ylab = "latitude", col_rich = matlab.like2, main = "Mammal Species Richness in EH") # Species richness map with colour index in the legend.
```

Reference

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Annexure 2

Supplementary material for chapter 4: Community structure, species richness and diversity of forest mammals in an Eastern Himalayan Biodiversity Hotspot: Results from nationwide camera trapping in Bhutan.

2.1 Mammal diversity comparison among seven forest types

Integrated sample-size-based and extrapolation curves at 95% confidence intervals for q = 1 (Shannon's entropy index) and q = 2 (Simpson's concentration index) revealed a significantly highest overall species diversity (higher evenness and lesser dominance of abundant species) in Fir forest (Figure 4.5). Amongst other forest types, mixed conifer and sub-tropical forests also showed an equally high diversity comparable to Fir forest. At the feeding guild level, diversity of carnivores was higher in warm broad leaved and cool broad leaved. Blue pine forests also hold greater evenness of large carnivore species like tiger *Panthera tigris,* common leopard *Panthera pardus* and dhole *Cuon alpinus*. Although sub-tropical and fir forests have an equally high overall herbivore species divesity, medium-sized herbivore species diversity was significantly lower in sub-tropical forests compared to Fir forests (Figur 4.1). warm broad leaved , Fir, mixed conifer and cool broad leaved had a significantly higher diversity of omnivore species compared to sub-tropical, blue pine and

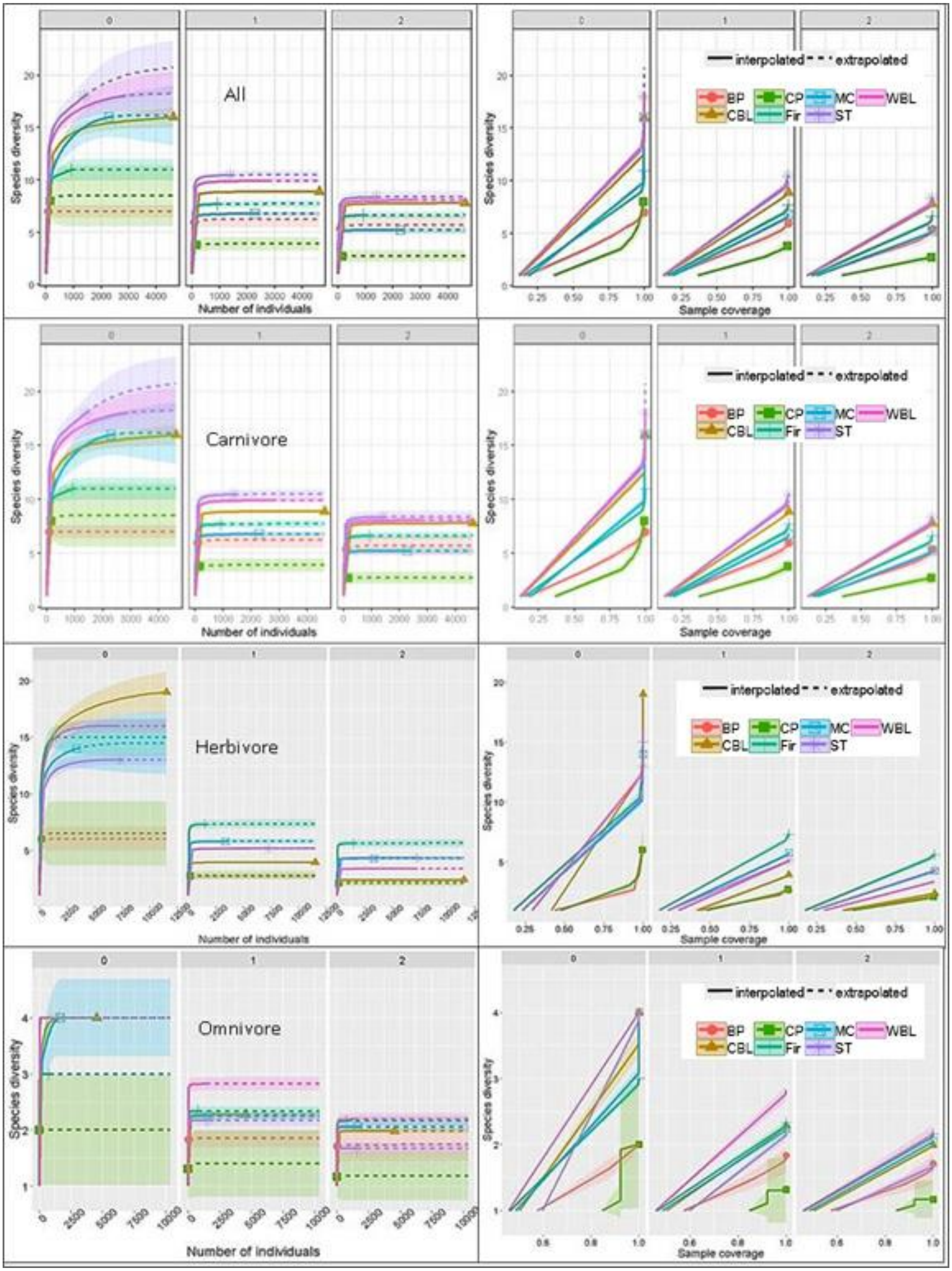

All
Carnivore
Herbivore
Omnivore
Species diversity
Number of individuals
Sample coverage
interpolated
extrapolated
BP
CP
MC
WBL
CBL
Fir
ST

Figure 2.1 Comparison of mammal diversity using sample-sized and coverage-based sampling (Chao et al., 2014Chao et al., 2014; Hsieh et al., 2016). Forest types: Blue-pine (BP), Cool broadleaved (CBL), Chirpine (CP), Fir, Mixed Conifer (MC), Sub-tropical (ST) and Warm broadleaved (WBL). Tropic-guild: Carnivore, Herbivore, Insectivore and Omnivore. Body-size based on individual body mass (Smith et al., 2003): <2kgs = small, 2-10kgs = medium, >10kgs = large mammals.

Annexure 3

Supplementary documents for chapter 5. The species zonation output and priority areas identified for the different combination of focal species based on their distribution and habitat overlap.

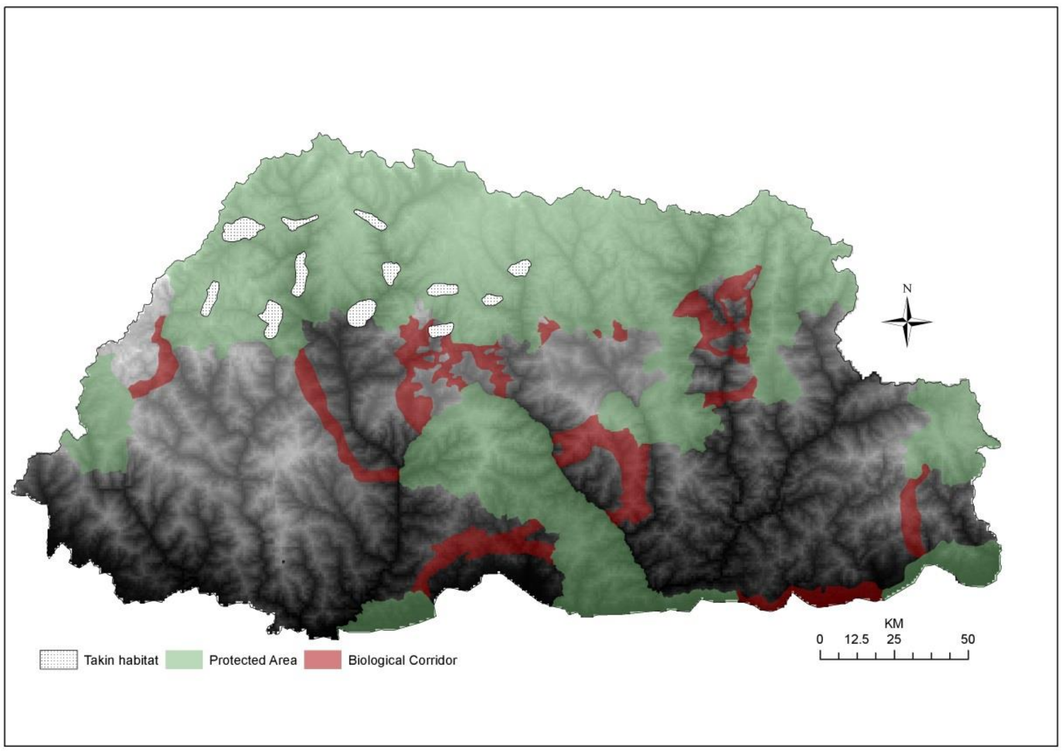


Figure 1 Mapping showing habitat of takin *Budorcas taxicolar* in Bhutan.

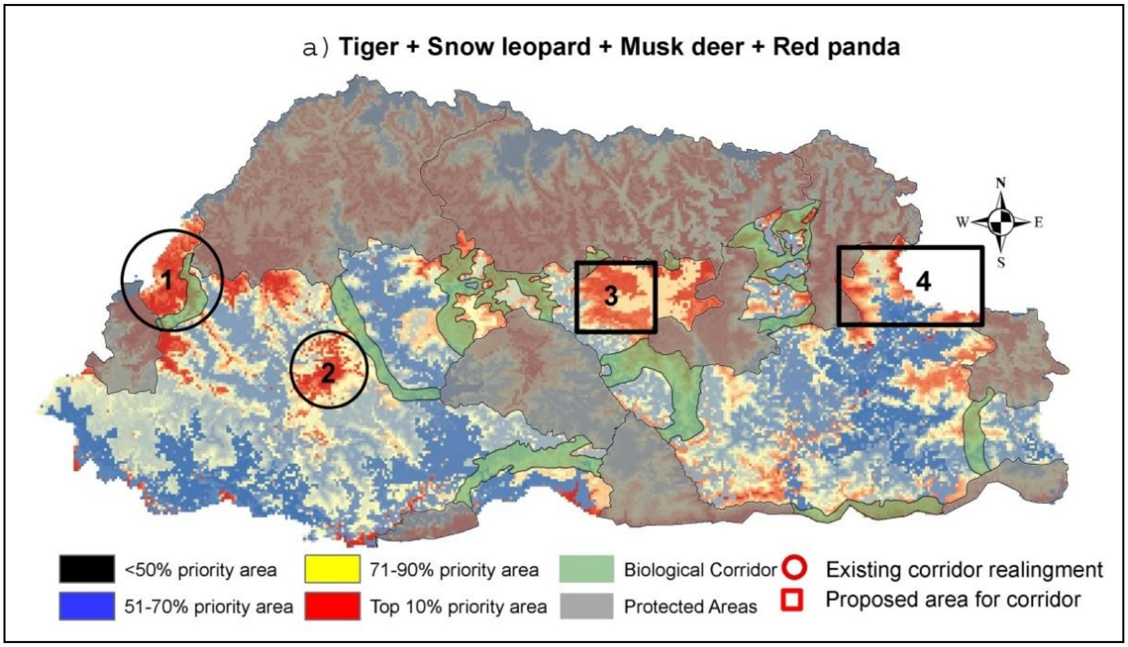


Figure 2 Zonation output and four priority areas identified for the combination of snow leopard, tiger, musk deer, and red panda input. The areas marked in circles indicate priority areas requiring readjustment of current corridor boundaries and boxes indicate new priority areas proposed for connectivity.

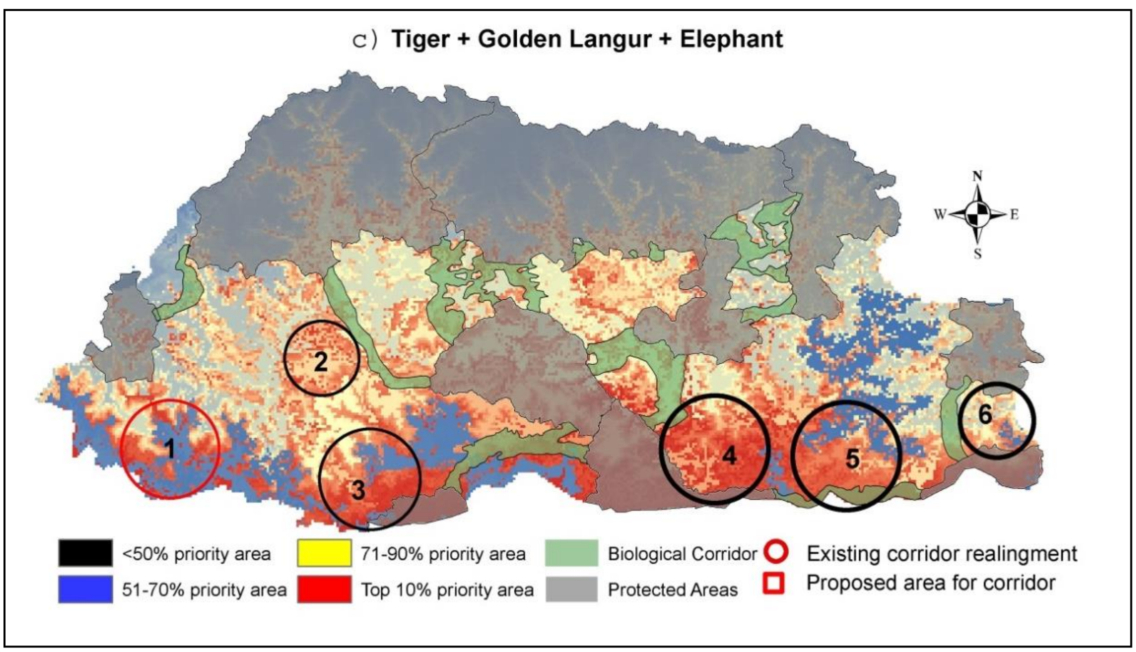


Figure 3 Zonation output and four priority areas identified for the combination of tiger, red panda, and musk deer. The areas marked in circles indicate priority areas requiring readjustment of current corridor boundaries and boxes indicate new priority areas proposed for connectivity.

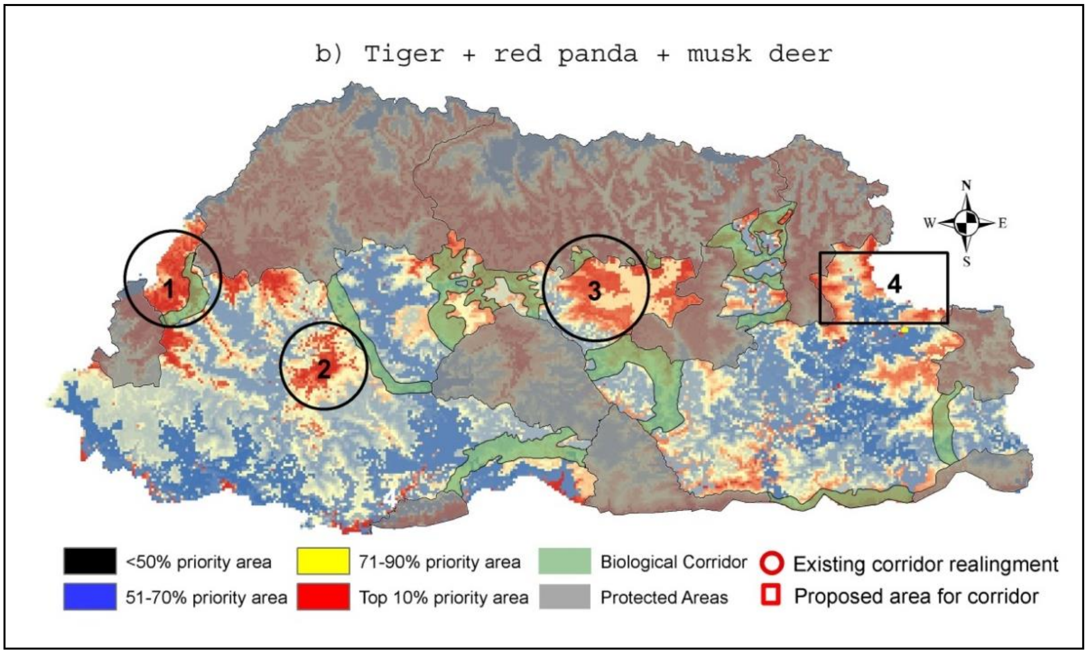


Figure 4 Zonation output and six priority areas identified for the combination of tiger, elephant, and golden langur. The areas marked in circles indicate priority areas requiring readjustment of current corridor boundaries and boxes indicate new priority areas proposed for connectivity.

Annexure 4 – Camera trapping and vegetation survey forms

DATASHEET FOR CAMERA TRAP INSTALLATION AND MONITORING	
Nationwide Camera Trapping, 2014	
Place :	Observer:
GPS Coordinates:	Camera trap Point #:
N:	Camera ID (R):
E:	Camera ID (L):
Datum:	
Set up Date:	Removal Date:
Set up Time:	Removal Time:
Altitude:	Major Habitat Type:
• Topographic feature:	

Date	Time	Observation	Battery Status		Memory Card Status		Remarks
			C (R)	C (L)	C (R)	C (L)	

- Topographic features - River bed, mineral lick, hill top, gullies, plain, etc.

VEGETATION SURVEY	
Place:	Surveyor:
Forest Type:	Camera Trap Point #:
Canopy Cover:	

A. Nearest 10 Tree Species

Species	GBH (cm)	Height (cm)	Distance From Center	Remarks

B. Shrub (Under Growth) Cover

Species	Height	% Cover	Remarks

C. Ground Cover

Species	Height	% Cover	Remarks

- Leaf Litters, Gravels, Sand, Grass, Herbs

Annexure 5 – Draft Protected Area Zonation Guidelines of Bhutan, 2018

Protected Area Zonation Guidelines

Nature Conservation Division

Department of Forests and Park Services

Ministry of Agriculture and Forests

Table of Content

1. Rationale of Zonation

Bhutan has over half the country's land under the protected area system (PAs) including the biological corridors. Unlike other countries, we have local residents living inside the protected areas who are given legal rights to remain inside the PAs and access natural resources for their bona-fide daily consumption. This demands an integrated approach in maintaining the ecological integrity of the PAs and developmental needs of the park residents. Therefore, the fundamental aim of the park zonation is to classify the PAs into different zones to support conservation of key biodiversity features (species, habitat or eco-region) and spatial allocation of natural resources to park residents. Apart from identifying areas important for retaining habitat quality and connectivity for multiple species, habitats or ecosystems, aimed at long-term persistence of biodiversity, park zonation will benefit in providing ecosystem services to park residents, visitors, down-stream residents and hydro-projects. The zonation should target on the balanced and complementarity-based priority ranking based on spatial distributions and local occurrence levels of Very Important Protected Species (VIPS) (classified as threatened, endemic, restricted-ranged, evolutionarily distinct umbrella, flagship, migratory species), important eco-region, cultural sites, key biodiversity areas and critical watershed areas.

Currently there are no standard guidelines for park zonation in the country and methods of zoning were inconsistent among the PAs who have completed the park zonation. This zonation guideline aims to establish uniformity of zonation method and processes among all the protected areas in the country. It is prescribed by using the most recent scientific concepts, methods and tools applied globally for zoning the protected area. While the objectives and expected outcomes of zonation are generally common all over the world, the contextual situation determines the processes. The zonation should also take into consideration the connectivity and minimum population size requirements, habitat loss and degradation, landscape change, climate change, availability of conservation resources and socio-political constraints. Provisions of various Acts on property rights and land use patterns also become important factors in the process of zonation. Therefore, in the context of Bhutan, the framework of zonation in PAs focus on identifying key biodiversity features and processes in which the Dzongkhags, local government, local communities and other relevant stakeholders are consulted before making decisions on various zones, keeping in mind the ultimate conservation goals of protected areas and resource needs of the park residents and visitors.

It was divided into three components – 1) Definition, Principle and Criteria; 2) Process 3) Governance and Legal Aspect

2. Criteria for Zonation

The protected areas in Bhutan will have to classified into 6 zones based on the definition and criteria set below.

2.1 Core zone

Areas set aside to protect particular species or habitats or areas that usually help to protect, or restore flora and fauna species of international, national or local importance; including resident or migratory fauna; and/or habitats ecological integrity of such areas are undisturbed by significant human activity, free of modern infrastructure and where natural forces and processes predominate.

Criteria for designating of core zone

Important Bird and Biodiversity Areas (IBAs): Areas known to support breeding or roosting of endangered species, flagship species or keystone species of that park.

Important Plant Areas: Areas that supports plants that may be globally or locally threatened.

Areas of high endemism: Areas that supports biodiversity that may be endemic to that particular area or endemic to the country.

Freshwater Habitat of particular concern: A stretch of river that supports spawning of endangered aquatic biodiversity.

Areas serving as wildlife refuge: Areas known to provide refuge for vagrant or migratory population of endangered, flagship or keystone species.

Key wildlife areas such as salt licks and water holes: Areas mapped to have high numbers of saltlicks and waterholes that is frequented by wildlife for its services.

2.2 Wilderness/Transitional/Intermediate zone

This zone consists of important habitat patches or contiguous habitat that serves as an important refuge for wildlife or movement of wildlife from one habitat patches to another e.g. habitat patches between summer and winter roosting area of takin. This zone is important for functionality of core zone. With potential of scientific habitat management interventions and increased protection would sooner or later qualify as a substitute/supporting habitats for core zone.

2.3 Buffer zone

Areas around the core zone and designated mainly to provide cushioning function between core zone and multiple-use zone. The activities are managed or organized in a way that it do not hinder the conservation objectives of the core area but rather help to uphold its essence and protect it from human interference.

Criteria for designating of buffer zone

Buffer zones may involve ways to manage natural vegetation, forests resources, and fisheries or ranch land to enhance overall quality of production while conserving natural processes and biodiversity.

- Buffer zone may be regarded as an area in which human interventions is less intensive than what might be found in the multiple-use zone.
- Buffer zone may serve to be an area for experimental or scientific research.
- Buffer zones may also accommodate environmental education, training, tourism, traditional resource use rights and recreation facilities.
- The area of buffer zones may be decided based on remaining areas of PAs after setting the minimum target for core zone (top priority areas) and multiple use zones.

2.4 Multiple-use Zone or The Zone of Cooperation

This zone is also termed as 'zone of cooperation' underscoring the role of cooperation between the park management and its residents as the main tool to achieve the conservation goals of the protected areas and resource needs of local resident living around the PAs. This is a zone where local communities, conservation agencies, scientists, civil societies, businesses and other stakeholders agree to work together to manage and use the area in a sustainable way that will benefit both people and wildlife who lives there. The areas shall be designated based on the resource mapping exercise and resource need assessment of local communities inside the park. There should be an adequate provision to meet the resource demand of park residence now and in future.

Criteria for designation of Multiple-use Zone

- Areas with existing settlement, private land, agricultural farming and grazing lands;
- Areas for collection of firewood, house building timber, non-wood forest produce, stone, sand and soil to meet the local demand of the park resident;
- Areas set aside for recreational purposes;
- Areas set aside for construction of transmission lines, road, school, hospitals, government offices and other developmental activities;
- Areas set aside for research and trail.

2.5 Traditional zone (TZ)

Traditional zone (TZ) is defined as an area with the traditional user rights. It is traditionally used for grazing, pasture land, herding camps, cultural heritage sites, heritage forests and sacred grooves including Sokshing. This zone is an area of interdependence between the wildlife and humans with user rights, but with limited user rights (seasonal or traditional rights). The protection status of this zone should be at par with the core zone with the regulated exceptions during the operation/use season like Cordyceps collection area.

2.6 Administrative/built-up/Settlement/Human dominated zone

This is the zone of settlement and built-up areas within the PA. This zone is the official designated area of the settlements and administrative offices of various agencies under the RGOB apart from the communities. These zones have to be embedded into the multiple use zones.

3. Process and Methodology

The zonation of the PAs shall be carried out based on the following steps

3.1 Setting objectives/target

The respective PAs have to set an overall objective/target in selecting the priority sites for conservation. The overall aim of zonation should link the species persistence by considering habitat quantity, quality and connectivity for multiple biodiversity features (species, communities, ecoregions, traits, etc.), and meeting resource demand and developmental needs of the park resident (multiple use zones).

3.2 Information Gathering

Prepare a checklist of existing data, both biodiversity and socio-economic data;

The socio-economic data shall be collected to consider useful social and economical interventions during the zonation process.

Biodiversity

- Presence, abundance or probability of plant, mammal, bird, reptile, amphibian and lepidoptera;
- Key wildlife features like important wildlife habitats, migratory routes; waterholes, salt licks, roosting areas or direct sighting of keystone species;
- Optimize use of prevailing socio-ecological survey data;
- Social
- Agriculture and grazing land;
- Resource collection areas of residents;
- Recreational areas – eco-trail, camping site, look-out, hotspring, etc.;
- Infrastructure development areas – road, transmission, health, school, park offices, dzongkhag offices and local government offices;
- Religious and cultural sites and pristine undisturbed forests or areas including sacred forests (Nyeshing);
- Cultural heritage sites - dzongs and monasteries, traditionally protected forest (Nyeshing).

3.3 Resource Mapping

Conduct rapid/participatory rural appraisal to map resource collection areas and different land-use facets of the park residents (primary stakeholders):

- settlement, herders camp, road, mule-track, trails, etc.
- firewood, timber, fencing and rooding materials;
- agricultural land;
- non-wood forest product;
- traditional grazing areas;
- ophiocordyceps and medicinal plants collection areas.

Infrastructural development plan - integrate zonation with national master plans of road, hydro-electric plants and transmission lines, tourism, urban, school, dzongkhags and local governments development plans;

Integrate zonation with the national cadastral land survey maps to determine exact boundary of private and communal land holdings of the park residents;

The draft zonation plans shall be presented to all stakeholders before delineating actual boundary of the zones.

3.4 Target Setting (Species)

The respective PAs shall identify single/multiple species of high conservation significance as a target species. Such species may be threatened, endemic, restricted-ranged, evolutionarily distinct, umbrella/flagship and migratory species.

Threatened Species: Such species are Critically Endangered (CR), Endangered (EN), and Vulnerable (VU) based on the IUCN's Red List of threatened species.

Endemic Species/Restricted-ranged species: Species unique to a particular geographic location, such as country (Bhutan), PA, habitat type, region (the Eastern Himalayan region) and zones e.g. *Meconopsis sheriffii* is endemic to Wangchuck Centennial National Park in Bumthang; Critically endangered Pygmy hog is restricted to grass-land of Royal Manas National Park and Jomotshangkha Wildlife Sanctuary in southern Bhutan.

Evolutionarily Distinct: The species that have few close relatives on the tree of life and are often extremely unusual in the way they look, live and behave, as well as in their genetic make-up. They represent a unique and irreplaceable part of the world's natural heritage, yet alarming proportions are on the verge of extinction (http://www.edgeofexistence.org).

Migratory species route and their habitat: Some faunal species migrate to specific areas using various habitat conditions as a passage/migratory routes. It is important to conserve both their habitat and migratory routes by designating appropriate zones e.g. takin and black-necked crane.

Totally protected species: The zonation should ensure maximum protection of "Totally Protected Species" listed under the Forest and Nature Conservation Act 1995 and Forest and Nature Conservation Rule 2017.

Umbrella Species: Umbrella species require large habitat for their survival whose conservation results in many other species being conserved at the ecosystem or landscape level e.g. tiger, snow leopard and Asiatic elephants. Restoring connectivity across large landscapes for multiple animals and plants can be challenging because species that differ in habitat, body size, dispersal ability, or lifespan (among other traits) may require connectivity at different scales or in different design.

3.5 Target Setting (Priority Areas)

The respective PAs should set a target to identify landscapes that are important for retaining habitat quality and connectivity simultaneously for single/multiple biodiversity features (e.g. species, land cover types, ecosystem services, etc.), thus providing a quantitative method for enhancing the persistence of biodiversity in the long-term. In addition, the resource allocation, developmental activities and ecotourism program shall be considered to alleviate conflict of interests among stakeholders. The priority areas should also account for changing distributions due to climate change, where necessary.

3.5.1 Single Species Conservation Priority Area

The zoning should identify priority areas, otherwise species poor locations where a single target species or a few biodiversity features have an important occurrence. The dispersal capability of the target species should be also taken into account to optimize the retention of well-connected high-quality patches for the species (e.g., to protect foraging and breeding areas) while avoiding harmful features such as human habitation or developmental infrastructure.

3.5.2 Multiple Species Priority Areas

The multiple species priority area zoning is to maximize complementarity representation of habitat or community types and identify biodiversity hotspot or core area for conservation. The species are weighted by their rarity, endemism, evolutionarily distinctiveness, migratory pattern and their distribution range type. The dispersal ability of the species should be taken into accounts in order to retain a well-connected core habitat within and outside the PAs. The respective park management should set a target in defining percentage of areas to be conserved under such priority areas based on the socio-ecological condition of the park.

3.5.3 Other Key Biodiversity Areas

Key Habitat Areas (breeding sites, waterholes, salt licks, mudflats, grass-land: Breeding sites, waterholes, salt licks, mudflats are critical for sustenance of any wildlife and adequate protection must be provided by assigning appropriate zones to such sites.

Critical Watersheds: The zonation should provide adequate protection of critical watershed areas inside PA for sustenance of livelihood and economy of the country.

3.5.4 Balancing alternative land uses considering multiple costs of conservation off-sets

The zonation should balance between biodiversity conservation and resource demand of the park resident including ecotourism activities. The aim is to separate conservation priorities from competing land uses. Areas with ongoing or intended use for other purposes should be identified and delineated in the multi-purpose zones. This will help to identify multiple land use priorities and alleviate conflicts of interests. Assessment of existing resource use and future resources allocation trend will provide useful information for delineating various zones. The zonation should take into accounts the existing and future developmental plans of local government, dzongkhag and central government.

3.5.5 Setups for climate change

Identifying priorities areas to account changing distribution of target species due to climate change. Connectivity of suitable habitats at different time steps needs special attention in this type of analysis.

3.6 Stakeholders Consultation

Stakeholder analysis shall be conducted to determine the primary and secondary stakeholders of respective Pas. The stakeholders shall be consulted twice during the zonation process – first during the planning and resource mapping process and then during the presentation of the zonation draft plan.

4. Governance

4.1 Legal Status of Zones

The following activities shall be prohibited within a core zone, except for research and habitat management purpose with a written permission from DoFPS, when deemed necessary to accomplish the objectives of nature conservation and the conservation of the protected areas.

- any kind of construction, including motor roads, buildings, fences, or any physical structures;
- settlement or cultivation;

- any logging, commercial or non-commercial;
- grazing by livestock except in special cases relating to traditional or other necessary local use, only after determination by the Department that such an exception shall not be a violation of the Conservation Management Plan of the protected area;
- collection of firewood and non-wood forest produce;
- undertaking any forestry activities;

(b) The following activity shall be prohibited in any buffer and wilderness zone within a protected area, except with a written permission from DoFPS routed through the park management, and only following determination that the activity is necessary to accomplish the objectives of nature conservation and the zone designation of the protected area.

- settlement or cultivation except in a multiple-use zone for local residents;
- commercial logging;
- collection of firewood, timber, NWFP, sand, stone and soil except with permission from DoFPS when the resource need of the local park resident could not be met from the multi-purpose zones.
- undertaking any forestry activity without a permit

Annexure of zonation guideline

1. Steps in zoning protected area

Setting objectives

- Identifying target species.
- Setting target of priority area (core and multiple use zones).

Data Collection

- Ecological, social, resource mapping, expert opinion and land use data.

Weigting of features

- Weighting of target species based on rarity, endemism, evolutionary distinctiveness, migratory and range-type.
- Weighting of landuse features.

Setting Boundary Quality Penalty

- Species dispersal ability - add simple connectivity considerations for species, habitats, climate change projection (Boundary Quality Penalty)

Add Cost Layer

- Adding cost layers (negatively weighted features) viz. road, transmission lines, settlements, recreational areas

Add Habitat Condition and Retention Layer

- Add habitat condition layers (traditional grazing land, water source, salt lick, cultural sites, etc.).
- Add complicated considerations such as administrative units analysis and conduct retention analysis, if necessary.

Zonation Analysis

- Conduct zonation analysis using complementarity and target based planning analysis on ZONATION software.

GIS analysis

- GIS analysis to make inferences of zonation analysis output and other landuse facets based on the target settings.

Field Verification

- Conduct field verification and ground truthing.

Stakeholder Consulation

- Consulation with primary stakeholders (park resident and local government).
- Consultation with secondary stakeholders (NLC, BPC, Dzongkhag, DoR, DoT, etc.).

Boundary Demarcation

- Demarcation of boundary in collaboration with local communities, local government, NLC and Dzongkhag administration

Protected Areas Zonation Reporting Format

Abstract

Introduction

Background

3.1 Brief history of PA

3.2 Conservation significance of PA

3.3 Bio-physical

3.4 Floral Characteristics

Conservation Goals

4.1 Vision Statement

4.2 Mission Statement

4.3 Conservation Objectives

Methodology

5.1 Preliminary data gathering

5.2 Mapping GPS data with the help of Google earth and topo-sheet

5.3 Park boundary correction

5.4 Park Range boundary correction

PA Zonation

6.1 Principles of zoning

6. 2 Criteria for delineation of Zones in JDNP

6.3 Criteria for delineation of core zones

6.4 Criteria for delineation of multiple-use zones

6.5 Criteria for delineation of buffer zones

6.6 Zoning Decision

6.7 Definition of Zones

6.8 Types of Zones and their protection status

6.9 Stakeholders' consultation

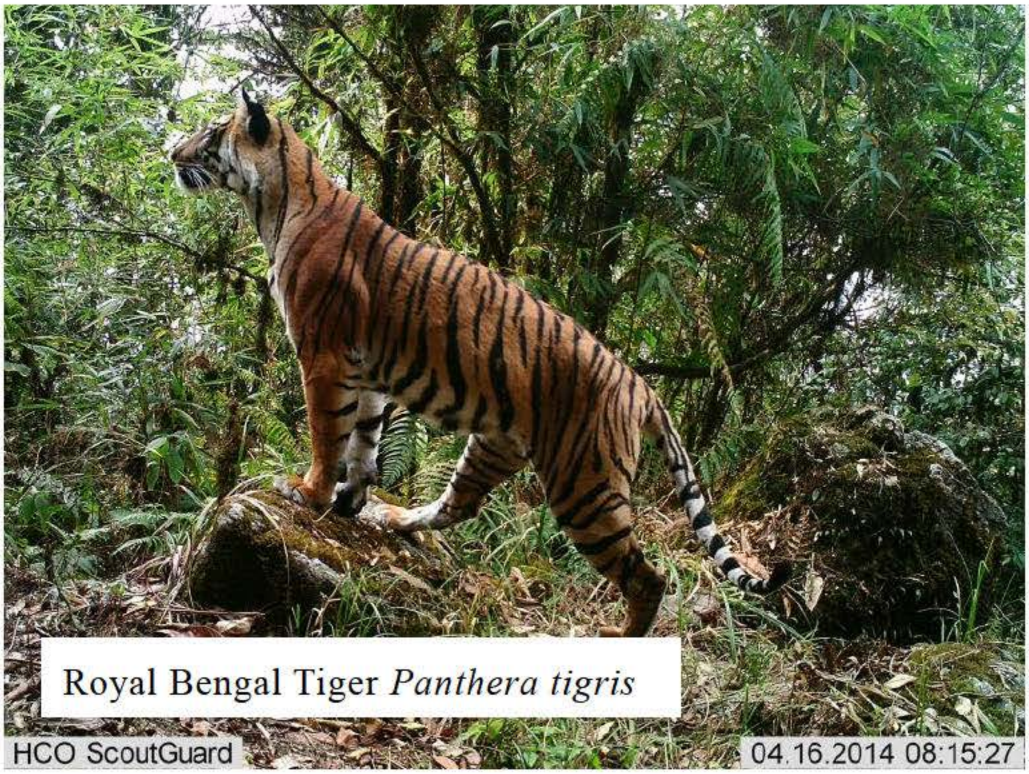
7. Implementation

7.1 Description of park boundary

7.2 Designation and description of zones

7.2.1 Core Zone

Additional camera trap and field work photos from the field


Royal Bengal Tiger *Panthera tigris*
HCO ScoutGuard
04.16.2014 08:15:27


Sambar Deer (*Cervus unicolor*)
IUCN Status: Vulnerable
HCO ScoutGuard
05.06.2014 13:21:14


2015-04-09 9:13:38 AM M 1/3
7°C
Himalayan Serow (*Capricornis thar*)
IUCN Status: Near Threatened
TSNR03


Himalayan Serow carcass


Yellow-throated marten (*Martes flavigula*)
IUCN Status: Least Concern
HCO ScoutGuard
03.18.2015 11:16:31


Yellow-bellied weasel (*Mustela kathiah*)
IUCN Status: Least Concern


Spotted linsang (*Prionodon pardicolor*)
IUCN Status: Least Concern
HCO ScoutGuard
06.06.2014 02:36:28


Asiatic elephant *Elephas maximus*
IUCN Status: Endangered
3/14/2014 2:33 PM


Crab-eating mongoose *(Herpestes urva)*
IUCN Status: Least Concern


2014-03-16 9:58:32 AM M 1/3 35°C
Malayan giant squirrel *Ratufa bicolor*
IUCN Status: Near threatened
G-02 HAZARBIGHA


2014-12-31 1:27:49 PM M 1/3 14°C
Marbled Cat *Pardofelis marmorata*
IUCN Status: Near threatened
HC500 HYPERFIRE


Royal Bengal tiger *Panthera tigris*
HCO ScoutGuard
05.13.2015 11:11:13


Large Indian civet *Viverra zibetha*
IUCN Status: Least concern
HCO ScoutGuard
04.07.2014 22:10:49


Indian crested porcupine *Hystrix indica*
IUCN Status: Least concern
HCO ScoutGuard
03.25.2014 20:31:08


Common leopard *Panthera pardus*
IUCN Status: Vulnerable
HCO ScoutGuard
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2015-02-16 8:59:10 AM M 3/3
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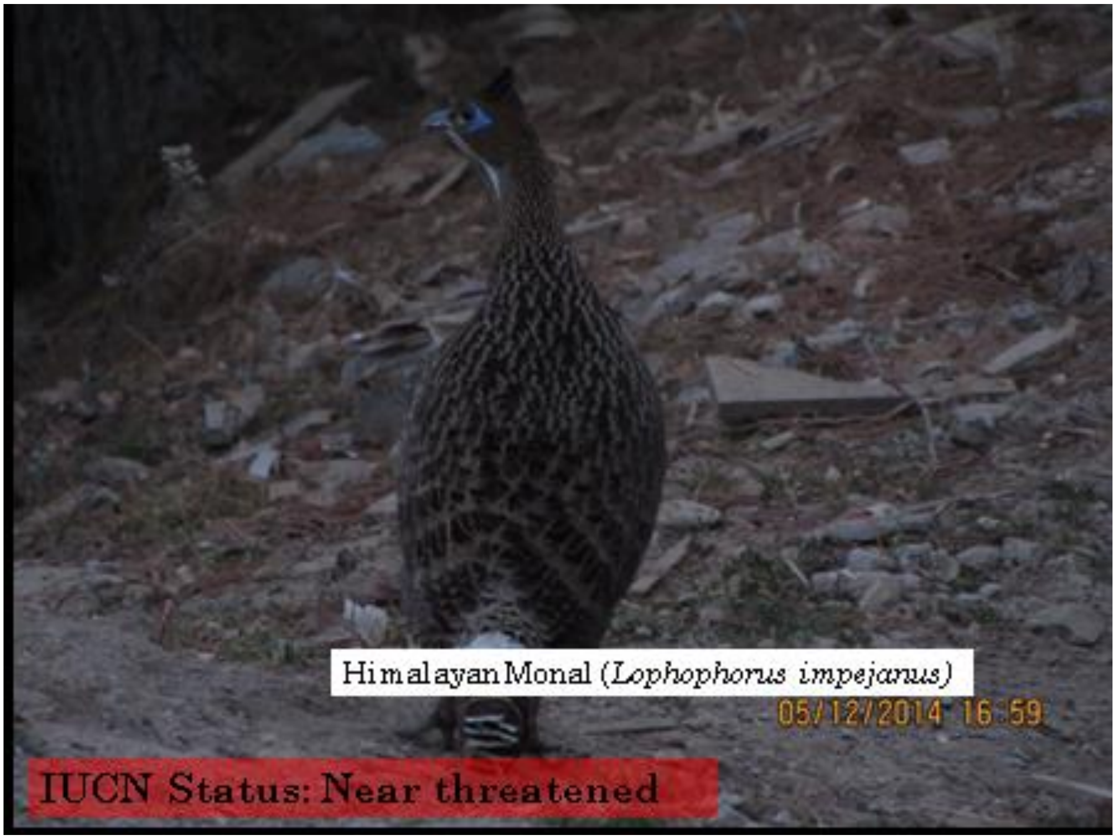
Red panda *Ailurus fulgens*
IUCN Status: Endangered
HC500 HYPERFIRE
RECONYX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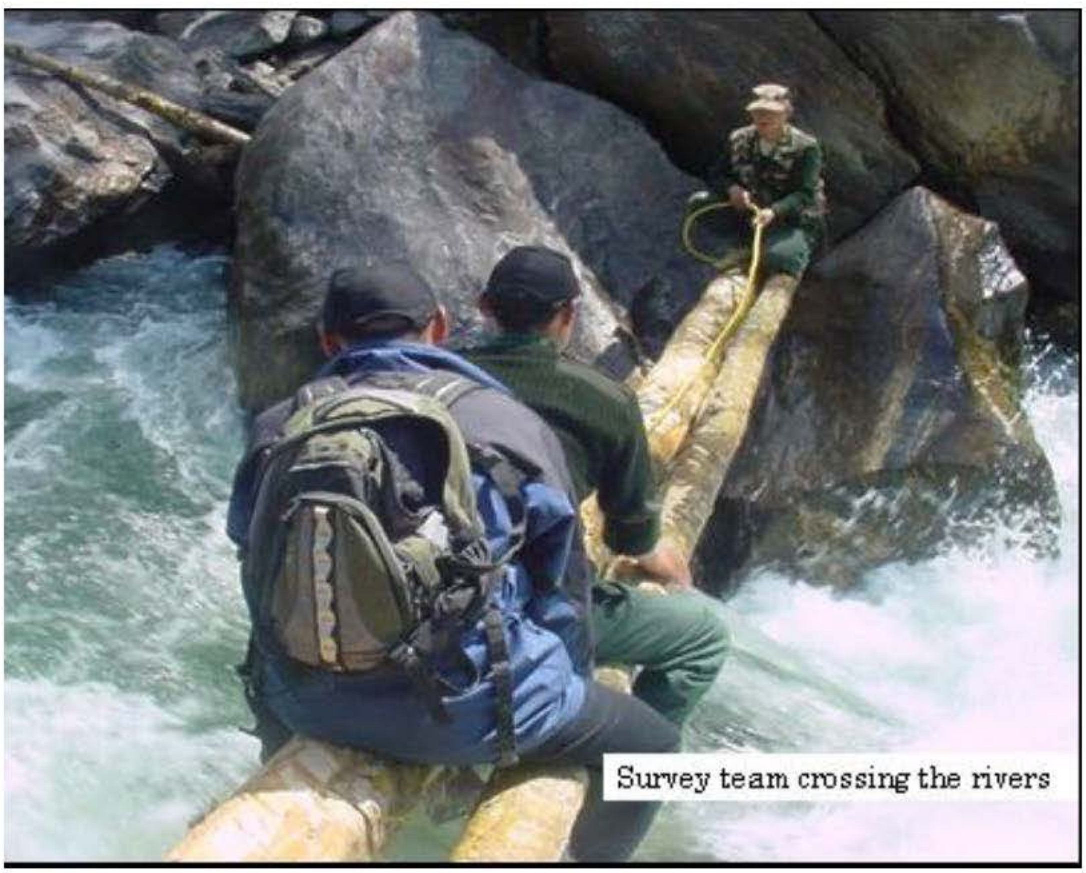
05/12/2014 16:59
IUCN Status: Near threatened


Red jungle fowl (***Gallus gallus***)
IUCN Status: Least concern
Cuddeback

Himalayan Monal (*Lophophorus impejanus*)


Survey team crossing the rivers

Different means of sleeping in the forests

Wildlife snares

Cooking in the rain

Survey team crossing the rivers