Assessing climate change impacts on forest ecosystems for landscape-scale spatial planning in Nepal

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Global climate change is affecting biodiversity and ecological processes. We coupled a general circulation model that uses global datasets with terrain-based analyses to identify potential climate refugia in two conservation landscapes in Nepal for climate change-integrated conservation planning. The results indicate that lower and mid-montane forests are vulnerable to climate change, but the temperate upper montane and subalpine forests are more resilient and represent macrorefugia. However, the terrain-based analysis indicates persistence of climate microrefugia in the lower and mid-mountains. Conservation strategies should prioritize the larger climate-resilient forests as macrorefugia, but also include the microrefugia in landscape conservation plans.

Keywords: Climate change, forest ecosystems, refugia, landscape conservation.

THE Eastern Himalaya is a region of global importance for biodiversity[1,2]. However, the ecosystems throughout the mountain range are extensively converted, fragmented and degraded, primarily from anthropogenic activities, threatening the persistence of this biodiversity[2,3]. Recently, global climate change has been recognized as another emerging driver of ecological change in the Himalaya[4–6]. Assessments show that the Himalaya is more vulnerable to global climate change than most other regions of the world[4,7].

Climate change can cause loss and degradation of biodiversity and of ecological goods and services, with serious consequences on human well-being[5,8–10]. Thus, conservation planning should identify climate vulnerable and resilient areas to develop adaptation strategies[11,12]. Climate-resilient areas[13] can occur along a continuum of spatial scales, representing macro- to microrefugia[14]. Depending on the conservation targets and objectives, macrorefugia will be essential for large and wide-ranging species, ecological communities and ecological processes, whereas the microrefugia become important for smaller-bodied habitat specialist species with smaller spatial requirements, many of which tend to be irreplaceable endemic species that are conservation priorities[15,16]. Microrefugia could also protect point sources of ecosystem services, such as mountain spring sources, and will also contribute to ecological connectivity in landscape-scale conservation planning.

While macrorefugia can be identified through bioclimatic envelope modelling using climate grids interpolated at regional or global scale (e.g. BioClim or WorldClim), microrefugia are influenced by local climates created by terrain complexity, temperature sinks, water balance and insolation, and are therefore decoupled from the regional climatic states and changes[14,17–19]. Thus, microrefugia can be overlooked by coarse-scale models, spatially overestimating the arenas of climate change and how species or communities are affected[14]. In the present analysis, we have used a 'hybrid' approach that combines regional bioclimatic data with terrain-based analyses to identify both macro- and microrefugia for landscape-scale climate change-integrated conservation planning in two important conservation landscapes in Nepal – the Chitwan-Annapurna Landscape (CHAL) and the Terai Arc Landscape (TAL) (Figure 1).

The CHAL provides ecological connectivity between the Terai ecosystems along the base of the Himalaya to the high Himalaya of Annapurna, and the Trans-Himalaya in the Upper Mustang region of Nepal. The elevation of the CHAL ranges from ~200 m to over 8000 m. Within this span the vegetation ranges from the alluvial grasslands and savannas of the Terai to the alpine and nival zones in the north, with subtropical chir pine and broadleaf forests, temperate broadleaf forests, and subalpine conifer forests occurring in between. The CHAL also straddles the deep Gandaki river gorge that is an east-west biogeographic barrier to several species of flora and fauna at higher elevations.

The TAL, spanning Nepal and India, was first designed to protect globally important populations of tiger (*Panthera tigris*) and greater one-horned rhinoceros

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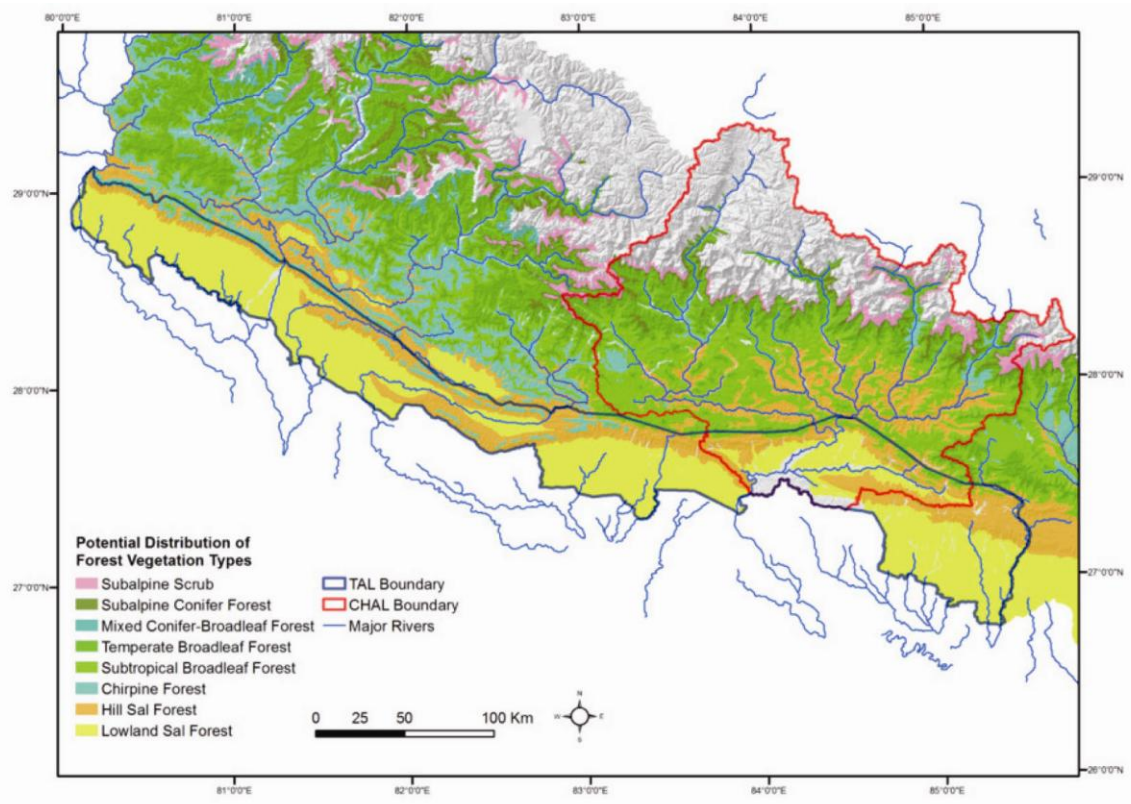

Figure 1. Distribution of the eight forest vegetation types derived from the vegetation zone map of Nepal, prepared by the Department of Forests, Nepal. The map represents the vegetation types based on forest cover prior to anthropogenic forest conversion.

(*Rhinoceros unicornis*)[20], but then evolved as a more holistic conservation landscape to conserve biodiversity and ecosystem services in the Terai–Duar Savanna and grasslands ecoregion[21]. In Nepal, the landscape includes the Terai, Churia mountain range, and the inner Dun valleys (Figure 1). There is widespread forest conversion along the fragile Churia range and in the Terai[21]. Thus, an important goal of the TAL is to conserve – and restore, where necessary – forests and grasslands to create an ecologically connected landscape.

Besides providing habitat for threatened and endemic species, the forests in these two landscapes also play a critical role in sustaining vital ecological services and natural capital that support people, their livelihoods, and national development goals[22]. Forested watersheds regulate river flows, control water run-off, reduce erosion and also sustain other services such as crop pollination by hosting bees and other pollinators[6]. Extensive loss and degradation of the forests from hill slopes can result in the loss of these ecosystem services. Therefore, securing the remaining areas of climate change resilient forests from further loss and degradation is important to conserve biodiversity and sustain ecosystem processes, services and natural capital in Nepal. This analysis helps to identify the climate-resilient forests to aid in landscape-scale climate change-integrated conservation planning.

Caveats

We offer four cautionary caveats for this analysis. First, the analysis is meant to identify climate-resilient forest areas, and not make predictions of range expansions of vegetation types. Different species in a vegetation community could respond differently to climate change parameters depending on their ecophysiological thresholds. Therefore, the forest communities in areas of range expansion could be different from the original forest community.

Second, the forested areas depicted in the projection maps present only the distribution of climate change-resilient forests as indicated by the climate model. They do not indicate anthropogenic forest conversion, which we cannot and do not attempt to project.

Third, we use the term ‘resilience’ in its broader sense, i.e. the ability of ecosystems to resist change or recover to its original structure due to a perturbation[23].

Finally, the alluvial grasslands and savannas in the Terai were not included as a major vegetation type because, unlike forests, these ecosystems are primarily maintained by annual floods and fires, rather than long-term drivers related to climate change. However, changes in annual flood and fire regimes because of climatic change could potentially have some impact.

Methods

Macrorefugia

We used the IPCC A2A GHG scenario[24] to project the future distributions of eight major forest vegetation zones in order to identify areas resilient to change, representing climate change macrorefugia. We chose the highest IPCC GHG emission scenario, A2A, because recent assessments indicate that the resulting trajectories exceed the highest predictions by the IPCC[25,26], especially affecting the Himalaya[4].

To produce maps of the eight vegetation types under current and future climate conditions, we selected random occurrence points to train the model using a national-scale map of the distribution of vegetation zones extrapolated to a state of pre-anthropogenic conversion, and thus eliminate bias[27] because of anthropogenic forest conversion. This map[28] was made by the Nepal Department of Forests (DoF) with input from scientists and experts in Nepal, and is the best available option to train our model. The DoF map presents 13 vegetation types. We reclassified them into eight major forest vegetation types that also represent major wildlife habitat types: (1) lowland Sal forest, (2) hill Sal forest, (3) chir pine forest, (4) subtropical broadleaf forest, (5) temperate broadleaf forest, (6) mixed conifer–broadleaf forest, (7) subalpine conifer forest and (8) subalpine scrub (Figure 1).

We generated more than 1000 random occurrence points for each vegetation type and used them in Maxent[29] along with 19 WorldClim bioclimatic variables[30] (Table 1) to project the current and future distributions of the eight vegetation types. The area under the Maxent model ROC curves (AUC) for all vegetation types was above 0.89 (see Supplementary Material Figure 1 online), indicating the suitability of the model.

Table 1. The 19 bioclimatic variables from WorldClim used in the analysis (http://www.worldclim.org/bioclim)

BIO1 = Annual mean temperature
BIO2 = Mean diurnal range (mean of monthly (maximum temperature – minimum temp)
BIO3 = Isothermality (BIO2/BIO7) (* 100)
BIO4 = Temperature Seasonality (standard deviation *100)
BIO5 = Maximum temperature of warmest month
BIO6 = Minimum temperature of coldest month
BIO7 = Temperature annual range (BIO5 – BIO6)
BIO8 = Mean temperature of wettest quarter
BIO9 = Mean temperature of driest quarter
BIO10 = Mean temperature of warmest quarter
BIO11 = Mean temperature of coldest quarter
BIO12 = Annual precipitation
BIO13 = Precipitation of wettest month
BIO14 = Precipitation of driest month
BIO15 = Precipitation seasonality (coefficient of variation)
BIO16 = Precipitation of wettest quarter
BIO17 = Precipitation of driest quarter
BIO18 = Precipitation of warmest quarter
BIO19 = Precipitation of coldest quarter

The future distributions represent equilibrium climates for the years 2050 and 2080 under the A2A GHG emission scenario as projected by a downscaled HADCM3 General Circulation Model, selected because it is a moderate model that replicates the historical climate in Nepal fairly well[31]. Since the 2050 projection of resilient forests is based on a ‘wall-to-wall’ vegetation map, we used the 2010 forest cover map of Nepal[32] as an overlay to mask out forests that have been already converted to other land uses, and select only the remaining forest cover from the 2050 resilient forest vegetation map (Figure 2). The 2050 resilient vegetation map was then, in turn, used as a template to clip and select the resilient patches in the 2080 vegetation map (Figure 3). Thus, the 2050 and 2080 resilient forest vegetation is based on the current forest cover. It does not include future projections of direct anthropogenic forest conversions. Figure 4 shows the steps involved in the process.

Microrefugia

We identified climate microrefugia by selecting major terrain features that are decoupled from the influences of regional climate change, namely areas of cold air drainage, such as valley bottoms, local depressions and sinks that promote cold-air pooling and maintain temperature inversions, and slope and aspect that have a greater influence on water balance than temperature[17].

We used a ruggedness index applied to the SRTM 90m Digital Elevation Model (DEM) in ArcGIS 10 to determine terrain complexity and identify steep, deep areas that are potential climate microrefugia. The ruggedness index is an expression of the difference in elevation between the centroid of each DEM grid cell and the eight surrounding cells. The squares of the values were calculated to obtain positive values and the eight values averaged. The topographic ruggedness index was then derived by taking the square root of this average value, which corresponds to the average elevation change between any point on a grid and its surrounding area and reflects the combination of steepness, elevation and rate of change in elevation.

We also applied the solar radiation extension in ArcGIS 10 to the DEM to identify slopes that receive low levels of insolation and are potential climate-refuge land facets. We used the SRTM DEM as an input raster with a floating point type for the output raster with Watt hours per square metre as units. Default values for the northern hemisphere were used for latitude, sky size, azimuth, and zenith. Next we identified old-growth forests by selecting the forest types classified as closed broadleaf forests, closed needle-leaf forests, and closed mixed forests from the 2010 land use-land cover map of Nepal[32], and clipped it by the two outputs for the analyses to identify terrain-based microrefugia with old-growth forests.

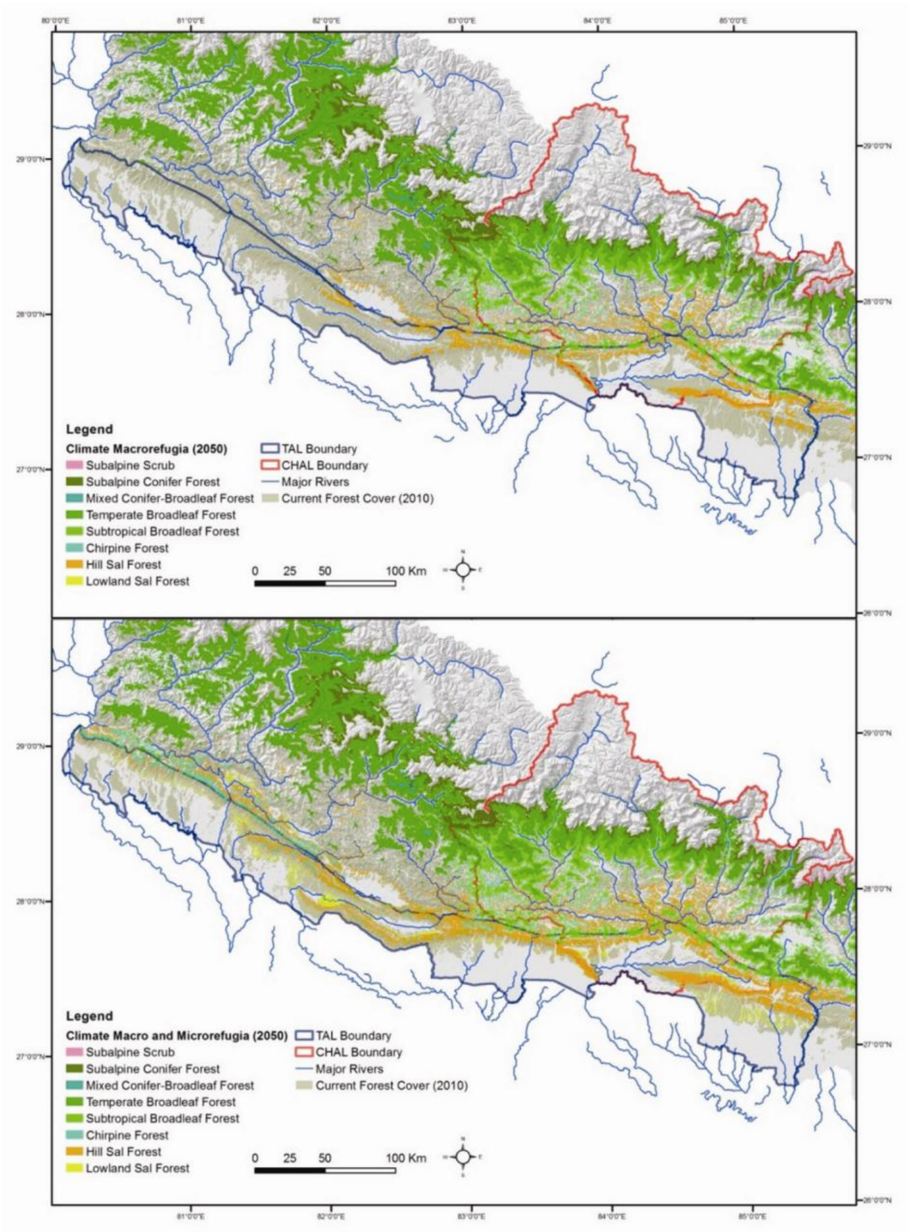

Figure 2. Distribution of climate change-resilient forest vegetation based on the 2050 projection. (Top) Climate change macrorefugia. (Bottom) Both macro- and microrefugia. The analyses for determining the macro- and microrefugia are detailed in the text. Current forest cover is indicated in the background. The areas without climate refugia do not indicate forest loss, but that the current forest vegetation composition and community could change due to climate change impacts. The maps do not show non-forest vegetation such as alpine and lowland grasslands.

Results

The analysis of climate macrorefugia indicates that most of the lower and mid-montane forests – lowland Sal, hill Sal, subtropical broadleaf forests, and chir pine forests – are not resilient to climate change under the A2A GHG scenario. By 2050 and 2080, these forest vegetation types will become fragmented into smaller patches in a matrix of changed vegetation communities (Table 2). But the temperate broadleaf forests in the upper montane areas are resilient to climate change, with larger patches surviving as climate macrorefugia (Table 2). Most of the subalpine scrub will, however, become converted as the forests intrude northwards.

The microrefugia outputs show that considerable areas of lowland and hill Sal forests, chir pine forests, and subtropical broadleaf forests are in climatically stable microrefugia, albeit as smaller patches (Figures 2 and 3). In the TAL, considerable forests in climate microrefugia lie along the northern boundary, along the north-facing

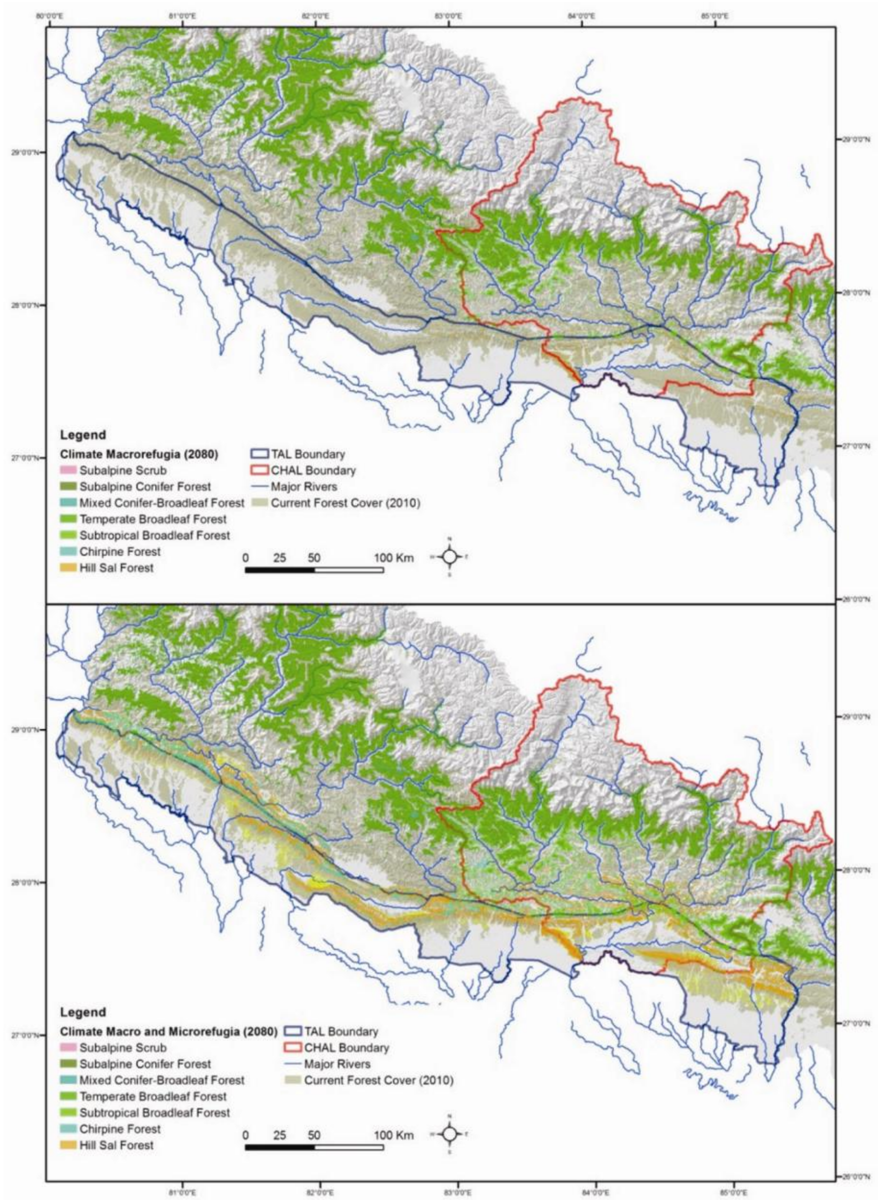

Figure 3. Distribution of climate change-resilient forest vegetation based on the 2080 projection. (Top) Climate change macrorefugia. (Bottom) Both macro- and microrefugia. The analyses for determining the macro- and microrefugia are detailed in the text. Current forest cover is indicated in the background. The areas without climate refugia do not indicate forest loss, but that the current forest vegetation composition and community could change due to climate change impacts. The maps do not show non-forest vegetation such as alpine and lowland grasslands.

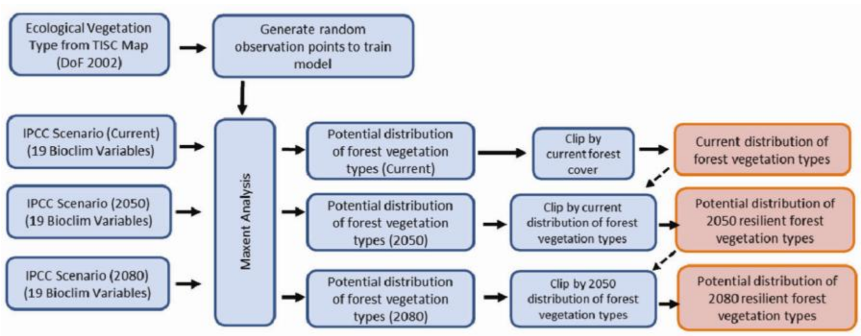

Figure 4. Flow chart showing the steps of the spatial analysis.

slopes of the Churia and valley to the north, whereas in the CHAL, the hill Sal forests and the subtropical broadleaf forests in microrefugia are along the steep-sided deep gorge of the lower and mid reaches of the rivers in the Gandaki basin (Figures 2 and 3).

Discussion

The CHAL and the TAL support some of the most threatened and endangered biodiversity in Nepal[1]. Many of these species are habitat specialists or require large expanses of connected habitat. For instance, Nepal has 99 endangered bird species[33], and 79 are forest-dependent, with preferences for particular forest types (e.g. subtropical or temperate broadleaf forests, conifer forests, etc.). The herpetofauna of Nepal is poorly studied, but the few studies indicate that some species of lizards and frogs are restricted to specific forest zones, e.g. the lizard *Japalura tricarinata* and the frogs *Scutiger sikimmensis* and *Rana sikkimensis* are restricted to temperate broadleaf forest zone[34]. Several rare and uncommon butterflies are also known to be restricted to specific forest zones, with the highest number of rare butterflies (11 species) recorded in the mixed conifer–broadleaf forest zone[35,36]. There is little overlap in the distribution of these rare butterflies among forest vegetation types, indicating host plant specificity. Field studies have also shown that the temperate forests between 3800 and 4200 m have the highest floral endemism[37].

Large species such as the tiger, greater one-horned rhinoceros, clouded leopard (*Neofelis nebulosa*), common leopard (*Panthera pardus*), golden cat (*Pardofelis temminckii*) and wild dog (*Cuon alpinus*) require large expanses of connected habitat. Habitat fragmentation and loss of prey populations – that are tied to vegetation and food plants – can compromise their ecology and long-term survival.

The climate projections from this study indicate that large blocks (>500 sq. km) of temperate broadleaf and subalpine conifer forests may persist in the upper hills of the CHAL, even in 2050 and 2080, and retain the current vegetation composition (Figures 2 and 3 and Table 2). These forest types represent Global 200 ecoregions with biodiversity of global importance[38]. Therefore, conservation of these resilient forests should be a priority. Loss of forest habitats or even changes to the forest composition due to climate change can compromise the survival of the species that depend on specific habitat structure, microclimates and food plants[3]. Threatened and endangered Himalayan species such as red panda (*Ailurus fulgens*), and musk deer (*Moschus leucogaster*) require old growth, upper-montane broadleaf and conifer forests. The red panda also requires *Arundineria* bamboo in the understory[39]; a more specialized habitat type than the musk deer. Even if the mature forests of the CHAL that harbour red panda shift northwards as predicted by climate models[40], the new forests with younger, smaller trees may not represent suitable habitat for red panda, or for other old-growth forest specialist fauna, because the forest composition and structure may not provide suitable microhabitat and food plants. Thus, the existing old-growth-resilient forests should be protected, especially against more proximate drivers of anthropogenic conversion and degradation that can threaten the ecological integrity of these forests and compromise their climate resilience[41].

Most of the subtropical broadleaf and lowland Sal forests in the TAL have already been converted into human uses. Although restoration through community forestry has increased forest cover in parts of the Terai, they do not reflect the vegetation composition of the original forests[42]. Thus, the large remaining resilient old-growth forest patches should be conserved, where possible.

The smaller patches of resilient forests along the north-facing slopes of the Churia and the inner valleys could also become important 'stepping stone' climate corridors for species that would have to seek refuge at higher elevations if environmental conditions become unfavourable in the future. Forest connectivity should also extend to the mid and upper mountains to facilitate migrations; several bird species use the deep valleys in the Gandaki basin as migratory corridors to and from the Trans-Himalayan region, and other mammals, birds and insects (e.g. butterflies) also undertake altitudinal migrations. Species such as leopards, wild dogs and hornbills require large areas of connected mature forest habitat. Large-scale loss of forests, especially along the valleys and surrounding hill slopes, will disrupt the movements and compromise the natural history of these species, affecting reproductive success and eventually their survival, but the smaller patches can contribute to connectivity and support endemic species with small habitat requirements.

Conservation of the climate-resilient forests in mountain systems is also important for critical services that the intact natural ecosystems provide. Ad hoc conversion or clearing of forests can make the steep montane watersheds susceptible to drying, with subsequent erosion, landslides and flashfloods[6]. Most climate projections suggest that extreme weather events will become more severe, with the likelihood of more frequent natural disasters of greater magnitudes[43]. Thus, maintaining forested watersheds in the upper catchments will help reduce vulnerabilities of natural and human communities. Therefore, the continuous or contiguous climate-resilient forest patches should be identified and secured from anthropogenic conversion and degradation to conserve important and irreplaceable biodiversity, and ecosystem processes and services of the Himalaya.

Because of the complex, interacting variables that determine climate change trajectories, accurate predictions of ecological impacts and resulting changes are difficult, especially when relying on global datasets applied

Table 2. Distribution of forest vegetation patches in the Chitwan Annapurna Landscape and Terai Arc Landscape in Nepal

Forest vegetation type	Current forest patch size distribution (sq. km)				Forest patch size distribution for 2050 projection (sq. km)				Forest patch size distribution for 2080 projection (sq. km)			
	<100	100–500	501–10,000	>10,000	<100	100–500	501–10,000	>10,000	<100	100–500	501–10,000	>10,000
Subalpine scrub	354	3	2	0	330	3	0	0	237	1	0	0
Subalpine conifer forest	548	14	1	0	559	13	1	0	456	0	0	0
Mixed conifer–broadleaf forest	148	0	0	0	82	0	0	0	55	0	0	0
Temperate broadleaf forest	435	1	2	1	383	4	3	1	377	7	6	0
Chirpine forest	448	0	0	0	94	0	0	0	73	0	0	0
Subtropical broadleaf forest	902	3	4	0	862	4	5	0	992	8	1	0
Hill sal forest	638	5	4	0	909	19	2	0	1060	0	0	0
Lowland sal forest	287	1	0	0	787	1	0	0	919	0	0	0

to complex topographies[17,44]. Our ‘hybrid’ approach that combines bioclimatic envelopes with terrain-based analyses of microrefugia provides a simple methodology to better assess and predict the impact of climate change on natural ecosystems. Integrating these climate refugia into corridors, buffer zones and sustainable use areas for spatial planning will be a ‘win-win’ strategy for conservation of biodiversity of the region, even if the projected climate impacts do not occur along the expected trajectory.

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