Climate Change Impacts on Ecoregions in the Kangchenjunga Landscape of India, Bhutan, and Nepal

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This project was completed as a capstone for the University of Michigan School for Environment and Sustainability (SEAS) in partnership with the International Center for Integrated Mountain Development (ICIMOD). The research presented here functions to help address a knowledge gap documented by the United Nations Framework Convention on Climate Change on the lack of methodologies and tools to quantify impacts of climate change on ecosystem services, biodiversity, and forests within the Hindu-Kush Himalayas. Our study presents a method for linking ecoregion shifts due to climate change to potential cascading impacts for biodiversity and ecosystem services. We hope that this method will serve as a useful foundation for our partner organizations, other research groups, and management personnel within the HKH.

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Best,
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Table of Contents

Abstract

Climate change is causing ecoregions to shift in the Hindu Kush Himalayas, threatening both ecosystem services and biodiversity in the region. As these ecoregions shift, important ecological processes may be disrupted and species ranges may begin to move outside the protected areas that were designed to conserve them. Although transboundary landscape initiatives and adaptive management strategies exist in the HKH to mitigate these negative impacts, researchers and practitioners need methods to project how ecoregions may shift in response to the evolving conditions of climate change. Zomer et al. (2014) present one such method, whereby projected climate data is used to predict ecoregion distributions based on an environmental stratification method. Here, we adapt this approach to help address the priority knowledge gap identified by the Lima Adaptation Knowledge Initiative of the United Nations Framework Convention on Climate Change on the lack of methodologies and tools to quantify the impact of climate change on ecosystem services, biodiversity, and forests in HKH subregion. We accomplish this aim by a) modeling ecoregion shifts in the transboundary Kangchenjunga Landscape of the HKH under two Shared Socioeconomic Pathway projected climate scenarios, b) increasing the transparency, replicability, and accessibility of the modeling process by providing shareable code, and c) examining how these projected ecoregion shifts may impact biodiversity and ecosystem services in HKH protected areas. Our model found that by the year 2100, high-elevation ecoregions (3,000m - 8,586m) will either shrink or shift to higher elevations, mid-elevation ecoregions (500m - 3,000m) will expand, and low-elevation ecoregions (0m - 500m) will shrink substantially. We assess how shifting ecoregions may impact the ability of protected areas to conserve umbrella species (i.e., snow leopard, red panda, Asian elephant, tiger) and ecosystem services as exemplified by the *Rhododendron* genus. Researchers, academics, and practitioners can iterate, expand, and modify this method to inform management plans that protect species, people, and ecosystems from the threat of climate change.

Title Page Photo Credit: Nakul Chettri, International Center for Integrated Mountain Development

1. Climate Change and Ecoregions in the Hindu Kush Himalayas

The Hindu Kush Himalayas (HKH), a region comprised of eight countries within southern Asia, is particularly vulnerable to the impacts of climate change. The region is warming at a higher rate than the rest of the globe, resulting in shorter winters, shrinking glaciers, and an increase in precipitation falling as rain rather than snow (Shrestha et al., 1999; Pepin et al., 2015; Shrestha and Aryal, 2011; Krishnan et al., 2019). One way to assess the on-the-ground impacts of climate change trends is through the use of an ecoregion framework. Created as a system to better compare and prioritize areas for conservation, Olson et al. (2001) define ecoregions as "relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change." Unlike methods derived from biophysical features and patterns (e.g., temperature, rainfall, vegetation), ecoregions account for critical species interactions and features of geologic history when defining ecological units. By incorporating the importance of endemic taxa, existence of distinct assemblages of species, and influences of prehistoric events (e.g., past glaciations, Pleistocene land bridges), ecoregion groupings are more likely to accurately reflect the distribution of communities and species (Olson et al., 2001).

The HKH encompasses 60 ecoregions, which can be broadly characterized as grasslands (39%), rock, ice, snow cover, and water bodies (21%), forest (20%), and shrub land (15%) (Chettri et al., 2008). Due to the heterogeneous topography and vast elevation span (sea level to 8,848 m above mean sea level) of the HKH, specific ecoregions range from semi-deserts and subtropical forests, to conifer and broadleaf forests, to alpine shrubs and meadows (Chettri et al., 2008). Of these ecoregions, those within mountainous areas are experiencing the most extreme impacts due to climate change. Increasing temperatures are causing alpine ecosystems to shrink and sub-alpine species to shift northward (Hamid et al., 2020; Sharma et al., 2009; Tewari et al., 2017; Lamsal et al., 2017). As a result of this lower elevation ecoregion encroachment, the cryosphere is being taken over by treeline advancement (Baker and Moseley, 2007; Gaire et al., 2017). These ecoregion shifts leave species in alpine ecosystems particularly vulnerable; because they do not have the ability to move into higher elevation regions, these flora and fauna will be stranded on mountaintops as the climate continues to warm. Such trends carry large implications for the HKH, as alpine ecosystems account for 60% of the region (Pauchard et al., 2009; Singh et al., 2011; Chettri et al., 2008).

Ecoregion shifts and potential loss of alpine species are of particular concern given the high level of biodiversity contained within the HKH. The region supports 35,000+ species of plants and 200+ species of animals, many of which are endemic to the area. Four of the world's 36 identified biodiversity hotspots are located in the HKH and 29 of the 60 HKH ecoregions are part of the Global 200, a priority portfolio that identifies the top ecoregions for global conservation (Xu et al., 2019; Mittermeier et al., 2004; Wikramanayake et al., 2002).

Preserving this biodiversity is crucial for maintaining the myriad ecosystem services that the HKH region provides to both its population of approximately 240 million people and the 1.6 billion people living in downstream river basin areas (Chettri et al., 2020; Gurung et al., 2019; Xu et al., 2019). For local populations, the HKH provides essential provisioning services including food, timber, fiber, and medicine (Kandel et al.; 2018; Pant et al., 2012; Xu et al., 2019). The region is also a source of 10 major river systems, whereby natural vegetation cover on the mountains help to prevent flooding, stabilize headwaters, and maintain aquifer levels for the river basins (Xu et al., 2009; Molden et al., 2014; Mukherji et al., 2015; Chettri et al., 2020; Xu et al., 2019). Additionally, given its large swaths of forests, the HKH is a key area for carbon sequestration and climate change mitigation. Furthermore, the landscape and biodiversity provide great aesthetic, cultural, and spiritual value. Ecoregion shifts could disrupt the balance of these necessary ecosystem services and have implications for conservation efforts (Sharma et al., 2009; Xu et al., 2019).

Protected areas (PAs) are one tool created for the purpose of protecting essential biodiversity, and by extension, ecosystem services. PAs engender this protection by acting as a legally enforceable mechanism to restrict specified recreation, extraction, and development activities within their designated area (Dudley and Phillips, 2006). Within the HKH, there are 488 PAs, which cover 39% of the land in the region and encompass 25% of the HKH's global biodiversity hotspots (Chettri et al., 2008). However, as climate change impacts cause ecoregions to gradually shift over time, the habitats and species ranges that fall within the boundaries of these PAs are likely to change (Gurung et al., 2019). Thus, climate change may decrease the efficacy of PAs to conserve the habitats they were originally designed to protect (Dobrowski et al., 2021).

To mitigate the negative impacts of these ecoregion and species shifts, recent emphasis has been placed on transboundary landscape initiatives and adaptive management strategies. Transboundary landscape initiatives broaden the scope of management priorities beyond protected area and political boundaries, thus allowing for management at the ecosystem level (Sharma and Chettri, 2005). Adaptive management is a process-driven approach designed to reduce uncertainty about ecosystems through iteratively implementing information learned via monitoring (Lee, 1999). Yet, to effectively utilize both of these frameworks under the evolving conditions of climate change, researchers and practitioners need methods to project how ecoregions may shift in response to biophysical changes.

Zomer et al. (2014) present a method for linking climate data to landscape-level predicted ecoregion distributions based on global environmental stratification methods developed by Metzger et al. (2013). Using projected climate data from Phase 5 of the Coupled Model Intercomparison Project (CMIP), Zomer et al. (2014) identify how ecoregion boundaries may shift under future climate scenarios in the transboundary Kailash Sacred Landscape of the HKH. Given the availability of both global climate modeling datasets and worldwide ecoregion distributions, this modeling approach represents a useful method for linking climate change trends to potential on-the-ground impacts in a variety of contexts. We apply this environmental stratification method to the Kangchenjunga Landscape (KL), another transboundary landscape within the HKH that spans south-western Bhutan, eastern Nepal, and Sikkim and West Bengal of India (Figure 2.1). To increase the replicability and accessibility of this method for the KL and other landscapes, we automated the steps of the model, developed a step-by-step guide that explains the modeling process, and updated projected climate data inputs to incorporate recently released projected climate data from Phase 6 of the CMIP (CMIP 6).

By developing a specific method and guide for linking ecoregion shifts due to climate change to biodiversity and ecosystem service impacts, our approach aims to address a knowledge gap previously identified within the HKH. In 2016 through the Lima Adaptation Knowledge Initiative (LAKI), the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Environmental Programme (UN Environment) identified a priority knowledge gap for researchers and academics on the lack of "methodologies and tools to quantify the impact of climate change on ecosystem services" within the theme of forests and biodiversity in the HKH subregion (LAKI, 2016). In partnering with the UNFCCC and the International Centre for Integrated Mountain Development (ICIMOD) to address this knowledge gap, our goal is to help researchers, practitioners, academics, and other relevant stakeholders plan and implement management strategies across transboundary landscapes that will better support species, people, and ecosystems in light of climate change.

In summary, the aims of our approach are to:

1. Adapt an existing ecoregion shift method to the Kangchenjunga Landscape,
2. Increase the transparency, replicability, and accessibility of this method, and
3. Assess the impacts of projected ecoregion shifts on umbrella species and ecosystem services as exemplified by the *Rhododendron* genus.

2. Methods: Projecting Ecoregion Shifts

We employed an environmental stratification modeling approach adapted from the methods of Zomer et al. (2014) to construct a baseline ecoregion distribution in the Kangchenjunga Landscape and project future ecoregion distributions under two projected climate change scenarios. Through an analysis of these model outputs, we then provide an example of how this method can be used to evaluate the impacts of climate change on biodiversity and ecosystem services. The use of a statistical environmental stratification model based entirely on globally available climatic variables reduces the subjectivity involved in delineating existing ecoregions, as it eliminates the need to rely heavily on expert input (Metzger et al., 2013). This automation increases the accessibility and replicability of the method for application in other regions. Further, our data processing steps have been written in Python coding language and made available to the public to enhance the transparency and reproducibility of the method (Appendix A, Appendix F).

2.1 Study Area: Kangchenjunga Landscape

The Kangchenjunga Landscape (KL) is one of six transboundary landscapes within the HKH (Figure 2.1). It covers approximately 25,080.8 km^2 and is home to over 7 million people (Gurung et al., 2017). The region reaches from the Terai-Duar lowlands of India, Bhutan, and Nepal, through the midhills of north-eastern India, western Bhutan, and eastern Nepal, to the mountainous Himalayan areas of India and Nepal. With an elevational range that spans from 40 m (above sea level) in India to 8,586 m (above sea level) at the top of Mount Kangchenjunga, the KL serves as habitat for a wide variety of species, including 5,198 seed plants, 160 mammals, and 618 birds (Gurung et al., 2017; Gurung et al., 2019; Kandel et al., 2018; Kandel et al., 2019). Nineteen protected areas (PAs) cover 30% of the landscape, nine of which share a border with two separate countries (Figure 2.2; Phuntsho et al., 2017). Management objectives for these protected areas range from strict biodiversity preservation with restrictions on human use and visitation to more general habitat protection that allows for active interventions to maintain species and habitats (Dudley and Phillips, 2006). Nonetheless, many of the region's PAs are vulnerable to climate change, given their small size and lack of both latitudinal and longitudinal connectivity (Gurung et al., 2019).

2.2 Environmental Stratification

The environmental stratification model uses climatic variable inputs (e.g., monthly minimum temperature) to statistically generate bioclimatic strata (i.e., areas of similar climatic variable values) which can later be manually aggregated into ecoregions. To construct the baseline ecoregion distributions, we used publicly available gridded climate data from WorldClim 2.1 at a 30 arc-second horizontal resolution (about 1 km at the equator). These data were averaged over the period 1970-2000. The specific climatic variable

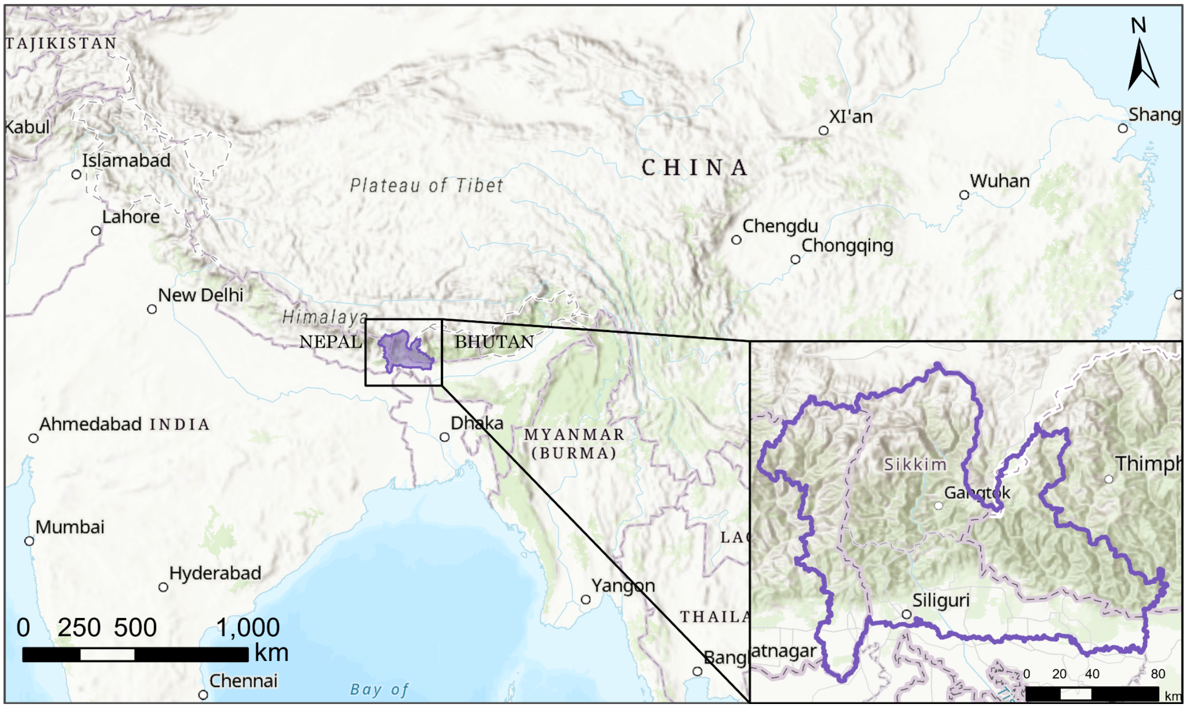

Figure 2.1 Geographic context of the Kangchenjunga Landscape

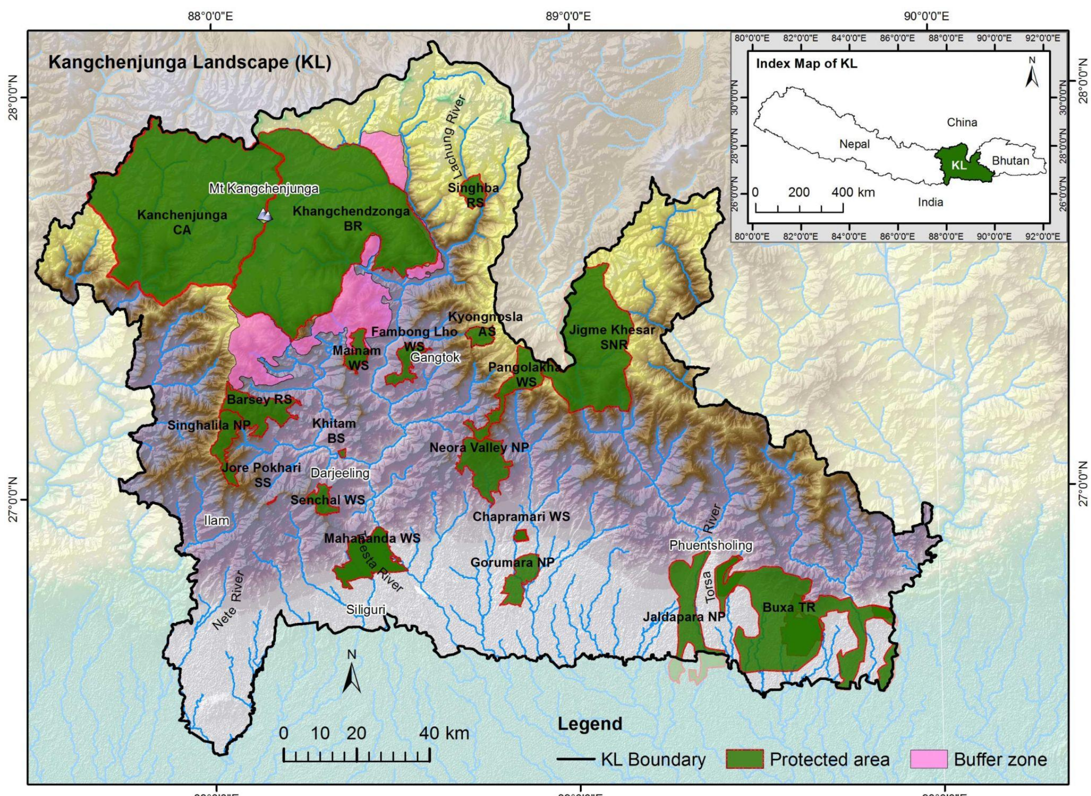

Figure 2.2 Protected areas in the Kangchenjunga Landscape. The Kanchenjunga Conservation Area is within Nepal, the Jigme Khesar Strict Nature Reserve is within Bhutan, and all other protected areas are within India. Map reproduced from Kandel et al. (2016)

inputs for environmental stratification were selected based on Metzger et al. (2013), who ran a principal components analysis on 36 climatic variables and found that the following four variables contributed to 96% of the variability in their global environmental stratification model:

Aridity Index (AI) (Zomer et al., 2008).

Calculated as MAP/MAE, where MAP is Mean Annual Precipitation (Fick & Hijmans, 2017), and MAE is Mean Annual Evapotranspiration, calculated using a version of the Hargreaves evapotranspiration equation (Hargreaves, 1994) adapted by Trabucco et al. (2008).

Monthly Mean Temperature Seasonality (Fick & Hijmans, 2017).

The seasonality of monthly mean temperature, calculated as the standard deviation of monthly mean temperature multiplied by 100.

Potential Evapotranspiration (PET) Seasonality (Trabucco et al., 2008)

The seasonality of PET, calculated as the standard deviation of monthly PET multiplied by 100.

Degree Days (Metzger et al., 2008)

The daily sum of annual degrees of temperature above 0° C. Because our data was at a monthly temporal resolution, we based this calculation on monthly mean temperature. For each month with an average temperature above 0° C, mean temperature was multiplied by the number of days in that month. All monthly values were summed to calculate degree days.

The data inputs, intermediates, and equations used to calculate the climatic variables are depicted as a flowchart in Appendix B. We normalized these variables on a scale of 1 to 100 and fed them into an Iterative Self-Organizing Data Analysis Technique (ISODATA) algorithm that grouped the spatial distribution of climatic variable values into 119 bioclimatic strata. Additionally, a dendrogram displaying the distance comparison and grouping process of the ISODATA algorithm was created as well.

To generate ecologically meaningful groupings from the ISODATA output, we aggregated the 119 bioclimatic strata into 8 ecoregions based on the World Wildlife Fund's (WWF) terrestrial ecoregion definitions (Dinerstein et al., 2017). Aggregation decisions were made using both the dendrogram and secondary GIS layers including slope, elevation, and ecoregion delineations (Udin 2015). The process of aggregation involved evaluating the distances between strata displayed in the dendrogram to group strata together into larger clusters. As multiple sub-clusters were generated, they were assigned ecoregion designations based on secondary data sources. However, this was an iterative process; the ecoregion assignment of smaller sub-clusters were re-evaluated based on linkages with larger nearby aggregated clusters as larger and larger clusters were generated. Each clustering decision was recorded, and this process was repeated until strata were aggregated into a minimal number of clusters while still retaining key splits.

2.3 Accuracy Assessment

We evaluated the efficacy of our environmental stratification model to correctly classify baseline ecoregions by performing an accuracy assessment on 84 randomly selected points within the KL. Each point was manually assigned an ecoregion using external GIS layers and the manual assignment was compared to the environmental stratification model-derived assignment to characterize the accuracy of the model. Manual ecoregion assignments were primarily based on a visual inspection of Landsat7 Google Earth imagery, and were supplemented by secondary GIS data including slope, elevation, and land cover sourced from the ICIMOD Regional Database System (Udin 2015). Landsat7 imagery taken between 1999 and 2001 was selected as a primary validation source due to its temporal proximity to the climate data used to create the WorldClim 2.1 dataset.

2.4 Projecting Ecoregion Distributions

To project future distributions of ecoregions, we employed a Maximum Likelihood Classification algorithm on ensembles of projected climate data under two scenarios. Projected climate data for the period 2081-2100 were sourced from the latest WorldClim projected climate dataset (version 2.1). These data are globally downscaled and bias corrected outputs of Phase 6 of the CMIP (CMIP 6) under multiple Shared Socioeconomic Pathways (SSP) (Future Climate, 30 Seconds Spatial Resolution — WorldClim 1 Documentation, n.d; Riahi et al., 2017; Eyring et al., 2016). The SSP scenarios combine pathways of societal development with radiative forcing levels (O'Neill et al., 2016). We used all model outputs with data available through WorldClim version 2.1 for SSP 3-7.0, which represents a medium-high greenhouse gas emissions scenario, and SSP 5-8.5, which represents a "worst case" or very high greenhouse gas emissions scenario. Given data availability at the time of this study, our multi-model ensembles included 13 model outputs under SSP 3-7.0 and 10 models under SSP 5-8.5 (Appendix D).

We calculated the same four climatic variables (AI, monthly mean temperature seasonality, PET seasonality, and degree days) needed for the environmental stratification process for each model in both of the SSP scenarios. Projected climate data were normalized relative to the minimum and maximum values of the historical climatic variables. For each of the SSP scenarios, we classified the normalized climatic variables from the downscaled CMIP 6 models into the 119 previously identified bioclimatic strata using a Maximum Likelihood Classification method. The aggregation table was then used as a guide to convert the bioclimatic strata into the 8 previously identified ecoregions.

Discrepancies in ecoregion classifications between models in a given SSP scenario were rectified by assigning the most commonly classified ecoregion type for a given cell. If there was no most common ecoregion classification (e.g., 5 models classified a cell as one ecoregion and 5 models classified it as a different ecoregion), then the mean bioclimatic strata value, calculated across all models in the scenario, was used to classify the ecoregion of the cell.

2.5 Sources of Uncertainty

The utility of the methods presented in this paper hinges on the use of defensible downscaled climate data with well-characterized and acceptable levels of uncertainty and associated risk (Hewitson et al., 2014). There are many sources of uncertainty in this process. First, future climate scenarios are built upon assumptions about future societal behaviors and related radiative forcings. We cannot know which pathway, if any, will represent true future scenarios, but to explore a range of plausible futures, we incorporated two of the SSP scenarios into our methods.

A second source of uncertainty stems from assumptions and biases in the underlying CMIP 6 models used for our study. Each CMIP 6 global circulation model (GCM) is produced with a different set of assumptions with associated uncertainties which can lead to biases in outputs. These biases must be thoroughly analyzed and documented in the context of the study area before results from the impact model can justifiably be used for landscape management or planning decisions in the KL. An added challenge in characterizing these biases exists due to the sparse availability of meteorological stations in the KL and many similar high-mountain regions in Asia (Palazzi et al., 2013; Lalande et al., 2021). Any bias analysis or correction for projected climate data in the area is thus based on interpolated data which presents additional opportunity for error. The WorldClim 2.1 data are downscaled and bias adjusted, but additional studies characterizing the specific sources of bias in the KL would be useful to make the data more defensible. Using multi-model ensembles and a majority result for final outputs can mitigate some of these remaining uncertainties (Zomer et al., 2014).

An additional source of uncertainty stems from the limited inputs to the stratification model. While there is utility to limiting inputs to the stratification model to four climatic variables, feedbacks controlling true ecoregion distributions are undoubtedly more complex. Additional factors contributing to ecoregion distribution include disturbance regimes, topography, invasive species distribution, soil and bedrock makeup, rate of soil formation, and biological feedbacks (Forrest et al., 2012; Körner 2007). These may limit ecoregion shifts even if temperature and precipitation regimes are otherwise favorable. As a result, we consider any modeled ecoregions produced through this method to be analogous to fundamental niches with the understanding that realized ecoregion distributions are influenced by a variety of additional factors.

When viewed as a means for exploring plausible future conditions and not predicting a certain future state, this type of impact study is a valuable part of a broader toolkit for decision makers and stakeholders. Additionally, if more reliable climate data become available in the future, the method presented here can be readily reproduced to yield updated results.

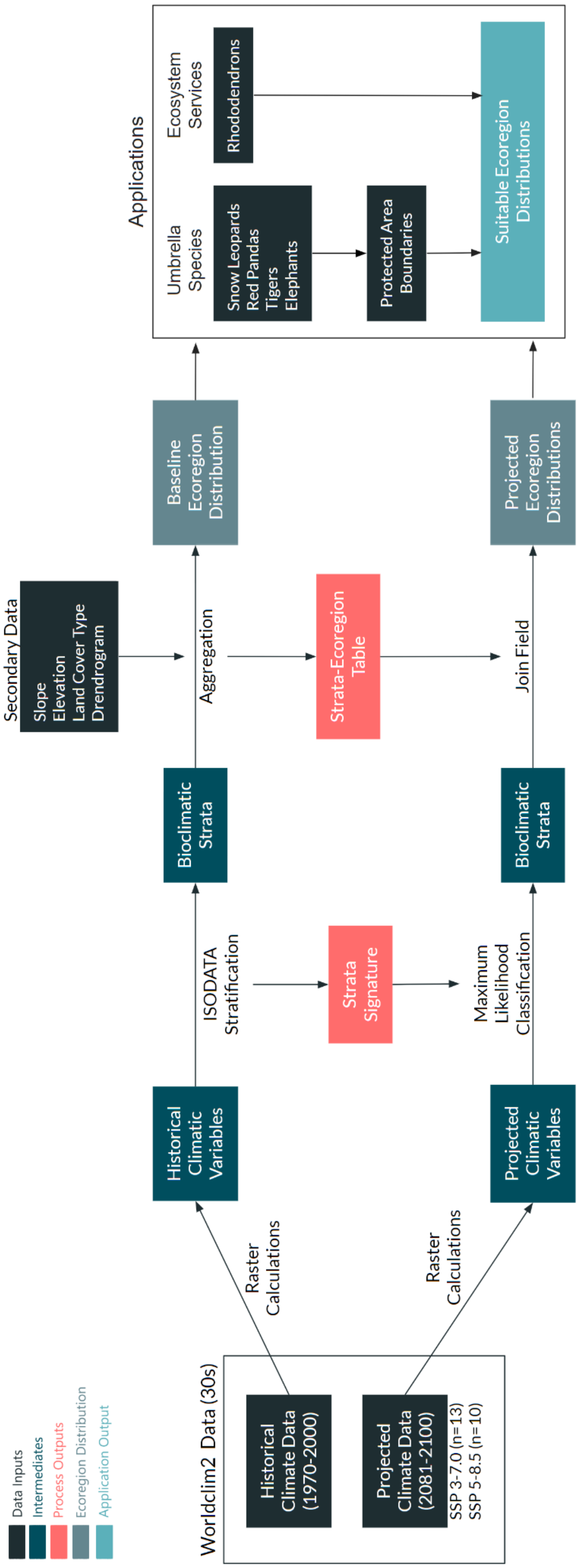

Figure 2.3 Chart outlining steps of study methods, including workflow of the environmental stratification model and application of ecoregion distribution outputs.

3. Results: Baseline Ecoregions and Ecoregion Shift Projections

3.1 Accuracy of Baseline Ecoregions

Through the environmental stratification and aggregation processes using historical data (1970-2000), we identified 8 ecoregions for our baseline scenario in the KL (Figure 3.1). The modeled baseline ecoregion distributions match existing WWF-defined ecoregions, with overall ~60% accuracy (Appendix C). The accuracy assessment itself is limited in that it was based entirely on satellite imagery and secondary GIS data without ground-truthing.

Overall, modeled ecoregion distributions based on historical data generally follow elevation trends closely, as would be expected due to the interaction between temperature and precipitation trends and topography. However, the strata generated by the ISODATA stratification in the lowlands are noticeably larger than the strata at higher elevations. This trend continues in the maximum likelihood classification, with large amounts of cells being classified to the same strata in the southern parts of the map.

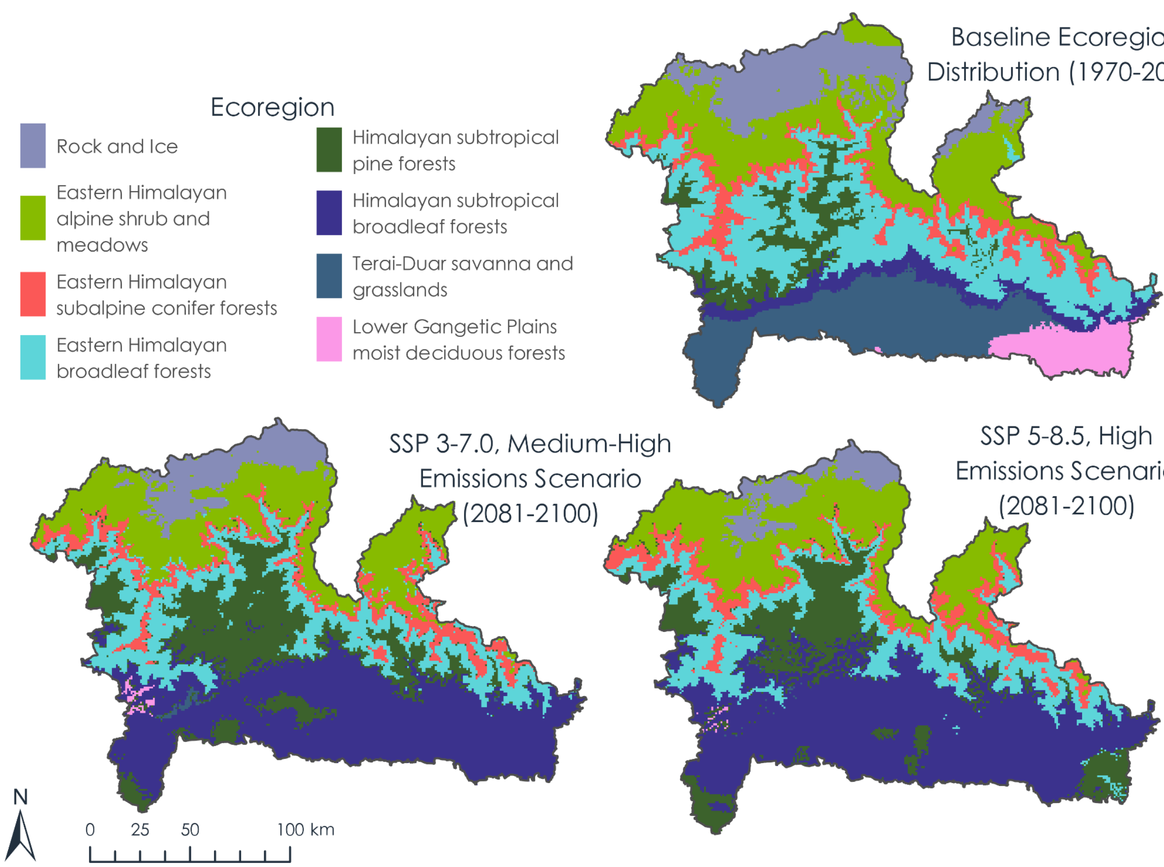

Figure 3.1 Historical (1970-2000) and projected (2081-2100) ecoregion distributions defined by environmental stratification and aggregation process using multi-model ensembles under two SSP scenarios, SSP3-7.0 and SSP5-8.5.

This trend indicates that the environmental stratification model may have more difficulty detecting differences in climate in the lowlands, and that ecoregion distributions in that area may be more dependent on non-climatic factors such as hydrology. As such, we acknowledge that projections of ecoregion distribution in the southern parts of the study area may be less reliable than those in higher elevation zones with finer stratification.

The identified ecoregions can be categorized into high elevation, mid-elevation, and lowland zones based on their baseline distributions. A brief description of each ecoregion type is included below (with paragraph colors corresponding to map legends of Figures 3.1 and 3.8)

3.2 Ecoregion Descriptions

High elevation ecoregions (3,000m - 8,586m)

Rock and Ice. While not an official ecoregion defined by the WWF, ice cover is related to glacial coverage, which is vital for the region's hydrology that provides water to lower elevation communities and ecosystems during warmer, dry seasons. Regions dominated by Rock and Ice do not contain nearly as much biodiversity as other regions, but glacial melt originating from these regions is an important water source for drinking, irrigation, and hydropower and supports ecosystems and biodiversity downstream (Phuntsho et al., 2017). This ecoregion type is generally found at the highest elevations in the landscape.

Eastern Himalayan alpine shrub and meadows. This ecoregion is generally found between the treeline and the snowline in high-mountain portions of the eastern Himalayas. Variability in precipitation due to topography, aspect, and rainshadow effect leads to a wide variety of localized micro-climates and biodiversity within the ecoregion. It harbors an estimated 7,000+ plant species including a wide variety of *Rhododendron* and many herbs, some of which are used for medicinal purposes (Singh and Chatterjee, 2021). Habitats in this ecoregion also harbor around 100 mammalian species and 115 bird species, some of which are endangered or threatened (Wikramanayake et al., 2002).

Figure 3.2 Eastern Himalayan alpine shrub and meadows example (Reproduced from OneEarth, n.d., Creative Commons)

Eastern Himalayan subalpine conifer forests. Typically found as a transitional region between alpine shrub and meadows and forested ecoregions, Eastern Himalayan subalpine conifer forests are dominated by mature, temperate pine forests, usually on steep, north-facing slopes. These forests support many important faunal species including four endemic mammalian species as well as red pandas, snow leopards, and musk deer. The region also contains over 200 bird species, six of which are endemic (Wikramanayake et al., 2002).

Mid elevation ecoregions (500m - 3,000m)

Eastern Himalayan broadleaf forest. This ecoregion exists as a linkage between subtropical forests and alpine ecoregions. Containing both evergreen and deciduous temperate, broadleaf forests, it provides habitat for over 100 mammalian species, 500 bird species, many *Rhododendron* species, and other important flora. Additionally, these forests provide altitudinal connectivity between ecoregions which is vital for the seasonal migrations of many bird and mammalian species (Wikramanayake et al., 2002).

Figure 3.3 Eastern Himalayan broadleaf forest example (From A. J. T. Johnsingh, 2014 Creative Commons 4.0)

Himalayan subtropical pine forests. These forests are dominated by the drought-resistant chir pine with little undergrowth due to frequent fires. This ecoregion has less species richness and endemism than other ecoregions in the HKH, though it still provides habitat for hundreds of flora and fauna including 11 endemic bird species (Wikramanayake et al., 2002). Forests in this ecoregion are often used as fuelwood sources and for livestock grazing (CEPF 2005).

Figure 3.4 Himalayan subtropical pine forest example (From Sanjoy Ghosh, 2006, Creative Commons 2.0)

Himalayan subtropical broadleaf forests. Specific forest types within this ecoregion generally depend on localized topography, soils, and precipitation trends, but they range from scrublands, to dry forests, to tropical wet evergreen forests. This ecoregion is considered rich in biodiversity and important for connectivity between its adjacent ecoregions. It supports 97 mammalian species including the endemic golden langur as well as tigers and Asian elephants (Wikramanayake et al., 2002).

Lowland ecoregions (0m - 500m)

Terai-Duar savanna and grasslands. This ecoregion is found at the base of the mountains. It contains a wide variety of habitats including the world's tallest grasslands, which are critical for tiger populations and endemic pygmy hogs. Also present are broadleaf forests, thorn forests, and steppe habitats. The region generally experiences mesic to wet conditions and has rich soils which make it attractive for agriculture (Wikramanayake et al., 2002).

Figure 3.5 Terai-Duar savanna and grasslands example (Reproduced from OneEarth, Meg Rahul, n.d.)

Lower Gangetic Plains moist deciduous forest. These lowland forests are generally tropical and moist with semi-deciduous vegetation. This ecoregion provides habitat for over 120 mammalian and 380 bird species, several of which are considered threatened. Though it has relatively low levels of endemism, it is seen as providing important habitat for wide-ranging mammals in the area including the Asian elephant (Wikramanayake et al., 2002)

3.3 Projected Ecoregion Shifts

Projected ecoregion distributions under both SSP scenarios for the years 2081-2100 show substantial shifts compared to baseline distributions, though shifts appear more pronounced in the higher emissions scenario (Figure 3.1; Figure 3.6; Figure 3.7; Appendix E). Under both SSP scenarios, high elevation ecoregions are projected to shift to higher elevations or shrink in area. Specifically, Eastern Himalayan alpine shrub and meadows shrink by around 8% under SSP 3-7.0 (medium-high emissions scenario) and 4% under SSP 5-8.5 (high emissions scenario) and shift north and up in elevation in both scenarios, covering areas that were previously Rock and Ice. In turn, Rock and Ice coverage is projected to shrink by 43% under SSP 3-7.0 and 62% under SSP 5-8.5 relative to the baseline. This shift has implications for glacial coverage which would impact hydrology and water supply in the region, especially during the dry season. Coverage of Eastern Himalayan subalpine conifer forests is also not projected to change much; under both SSP scenario ensembles, the ecoregion shift model projects about a 7% decrease. Still, under both scenarios, this ecoregion is projected to shift north and higher in elevation. In some portions of the KL, these projected shifts create isolated patches of subalpine conifer forests surrounded by broadleaf forests where there used to be contiguous conifer forest.

In the mid-elevation ecoregions, the results are more variable. Eastern Himalayan broadleaf forests are projected to shrink substantially – 31% under SSP 3-7.0 and 34% under SSP 5-8.5. Along with these reductions, the Eastern Himalayan broadleaf forests are projected to retreat to higher elevations. In contrast, both Himalayan subtropical forest ecoregions are projected to expand. Himalayan subtropical pine forests are projected to substantially increase in area under both SSP scenarios, but slightly more under SSP 3-7.0 (150%) compared to SSP 5-8.5 (117%). Himalayan subtropical broadleaf forests are projected to expand even more – 432% under SSP 3-7.0 and 518% under SSP 5-8.5. This large scale expansion may be plausible given projected temperature increases but could also be an artifact of the stratification model's difficulty in differentiating between lower elevation strata.

Meanwhile, ecoregions in the lowlands are projected to nearly disappear in the KL under both emissions scenarios. Terai-Duar savanna and grasslands are projected to see a 98% decrease under SSP 3-7.0 and a 99% decrease under SSP 5-8.5. Similarly, the Lower Gangetic Plains moist deciduous forest is projected to experience a 93% decrease under SSP 3-7.0 and a 98% decrease under SSP 5-8.5. It is notable that the lowland ecoregions are projected to shrink so considerably instead of shifting upwards in elevation and maintaining similar area. However, these lower ecoregions are also influenced by factors that are not captured by our model (e.g., watersheds and hydrology), which could mean reductions may not be as extreme as our model projects. Alternatively, while our model inputs are confined to the KL, it is possible that the climatic conditions conducive for these lowland ecoregions could shift southward outside of the KL.

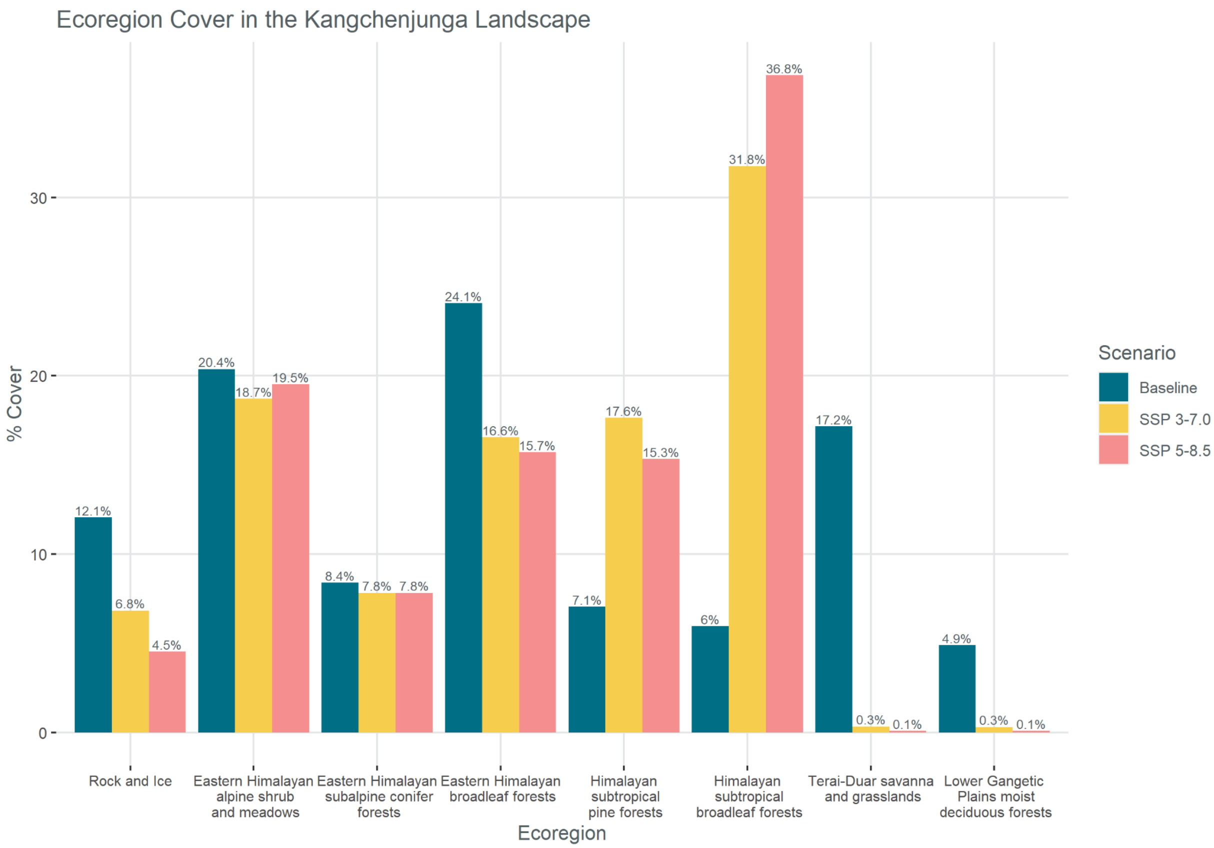

Figure 3.6 Percent cover of each ecoregion in the baseline and under the medium-high emissions scenario (SSP 3-7.0), and high emissions scenario (SSP 5-8.5)

Ecoregion Cover in the Kangchenjunga Landscape

	% Cover			% Change		
Ecoregion	Baseline	SSP 3-7.0	SSP 5-8.5	Baseline to SSP 3-7.0	Baseline to SSP 5-8.5	SSP 3-7.0 to SSP 5-8.5
Rock and Ice	12.1	6.8	4.5	-43.2	-62.3	-33.6
Eastern Himalayan alpine shrub and meadows	20.4	18.7	19.5	-8.2	-4.2	4.3
Eastern Himalayan subalpine conifer forests	8.4	7.8	7.8	-6.7	-6.7	0.0
Eastern Himalayan broadleaf forests	24.1	16.6	15.7	-31.2	-34.7	-5.1
Himalayan subtropical pine forests	7.1	17.6	15.3	149.8	117.3	-13.0
Himalayan subtropical broadleaf forests	6.0	31.8	36.8	432.4	517.8	16.0
Terai-Duar savanna and grasslands	17.2	0.3	0.1	-98.0	-99.4	-69.9
Lower Gangetic Plains moist deciduous forests	4.9	0.3	0.1	-93.5	-98.0	-68.6

Figure 3.7 Percent ecoregion cover and percent change in ecoregion cover in the Kangchenjunga Landscape in the baseline, and under the medium-high emissions scenario (SSP 3-7.0) and high emissions scenario (SSP 5-8.5)

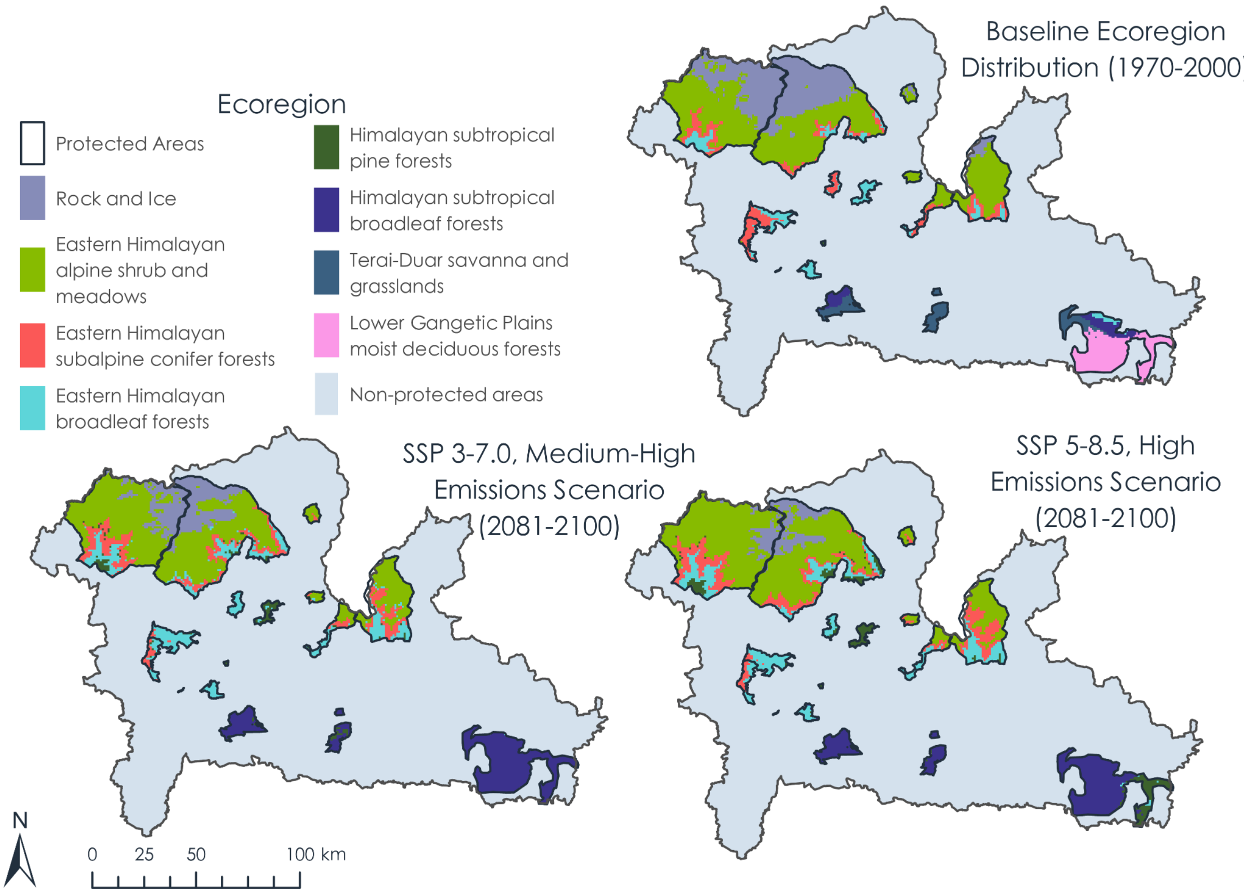

Figure 3.8 Historical (1970-2000) and projected (2081-2100) ecoregion distributions within protected area boundaries

3.4 Trends in Protected Areas

The model projects sizable changes in ecoregion coverage in most PAs (Figure 3.8; Figure 3.9; Figure 3.10; Figure 3.11; Appendix E). About half of PAs lose one or more ecoregions entirely under both scenarios. High elevation PAs are projected to substantially decrease in Rock and Ice cover and increase in historically mid-elevation ecoregion cover. These PAs include the Khangchendzonga Biosphere Reserve and the Kangchenjunga Conservation Area, the two largest PAs within the KL, as well as the Singhba Rhododendron Sanctuary. The Jigme Khesar Strict Nature Reserve experiences a decrease in Rock and Ice cover as well, but to a lesser extent. While the general upward shift trends observed in the KL at large can also be seen within the PAs, there are some differences between landscape and PA-level trends. Notably, while projected Eastern Himalayan alpine shrub and meadows cover decreases slightly in the KL as emissions increase, its relative area within PAs increases 4% under SSP3-7.0 (medium-high emissions scenario) and 11% under SSP5-8.5 (high emissions scenario). Similarly, under both SSP3-7.0 and SSP 5-8.5, there is a projected increase in Eastern Himalayan subalpine conifer forest cover in PAs (34% and 46% increase, respectively) despite shrinking in the KL as a whole. Still, the projected upward shifts of these two alpine ecoregions result in variation between specific

PA trends with some PAs losing alpine ecoregion cover partially or entirely (e.g., the Barsey Rhododendron Sanctuary, Mainam Wildlife Sanctuary, Singhalila National Park).

All three mid-elevation ecoregions are projected to see increased coverage within PAs as emissions increase. Eastern Himalayan broadleaf forest coverage within PAs is projected to expand about 75% under both SSP scenarios. As its coverage also shifts northward and up in elevation, it takes over some PAs that were dominated by subalpine conifer forests in the baseline period, such as in the Barsey Rhododendron Sanctuary, Mainam Wildlife Sanctuary, and Singhalila National Park. On the other hand, a couple of the mid to low elevation PAs lose Eastern Himalayan broadleaf forest coverage (e.g., the Fambong Lo Wildlife Sanctuary, Senchal Wildlife Sanctuary), while others remain relatively unchanged (e.g., the Jore Pokhari Salamander Sanctuary, Buxa Tiger Reserve). The two Himalayan subtropical forest ecoregions are projected to see substantial coverage increases in PAs under both SSP scenarios, as their distributions are projected to expand both north and south within the KL. Specifically, the subtropical pine forests increase in PAs by 4,222% and 8,871% under the SSP 3-7.0 and SSP5-8.5 scenario ensembles, though the total percent coverage of this ecoregion within PAs in the baseline was only 0.1%. Meanwhile, the subtropical broadleaf forests see 472% and 403% coverage increases within PAs under SSP3-7.0 and SSP5-8.5. With these projections, the subtropical pine forests expand into PAs in the central portion of the KL where they were previously absent, such as in the Fambong Lo Wildlife Sanctuary, while subtropical broadleaf forests take over most of the southern PAs that previously included more lowland ecoregion coverage (e.g., Gorumara National Park, Chapramari Wildlife Sanctuary, Mahananda Wildlife Sanctuary, and the Buxa Tiger Reserve).

Because of the projected expansion of the mid-elevation ecoregions and the sharp decrease in overall coverage of lowland ecoregions, the Terai-Duar savanna and grasslands and the Lower Gangetic Plains moist deciduous forest ecoregions lose all coverage in PAs under the two SSP scenarios. Though we hypothesize that the ecoregion model may generate less accurate ecoregion distributions in the lowland areas of the KL, these projected trends would carry substantial implications for species within lowland protected areas, if realized. Thus, additional research and monitoring are needed.

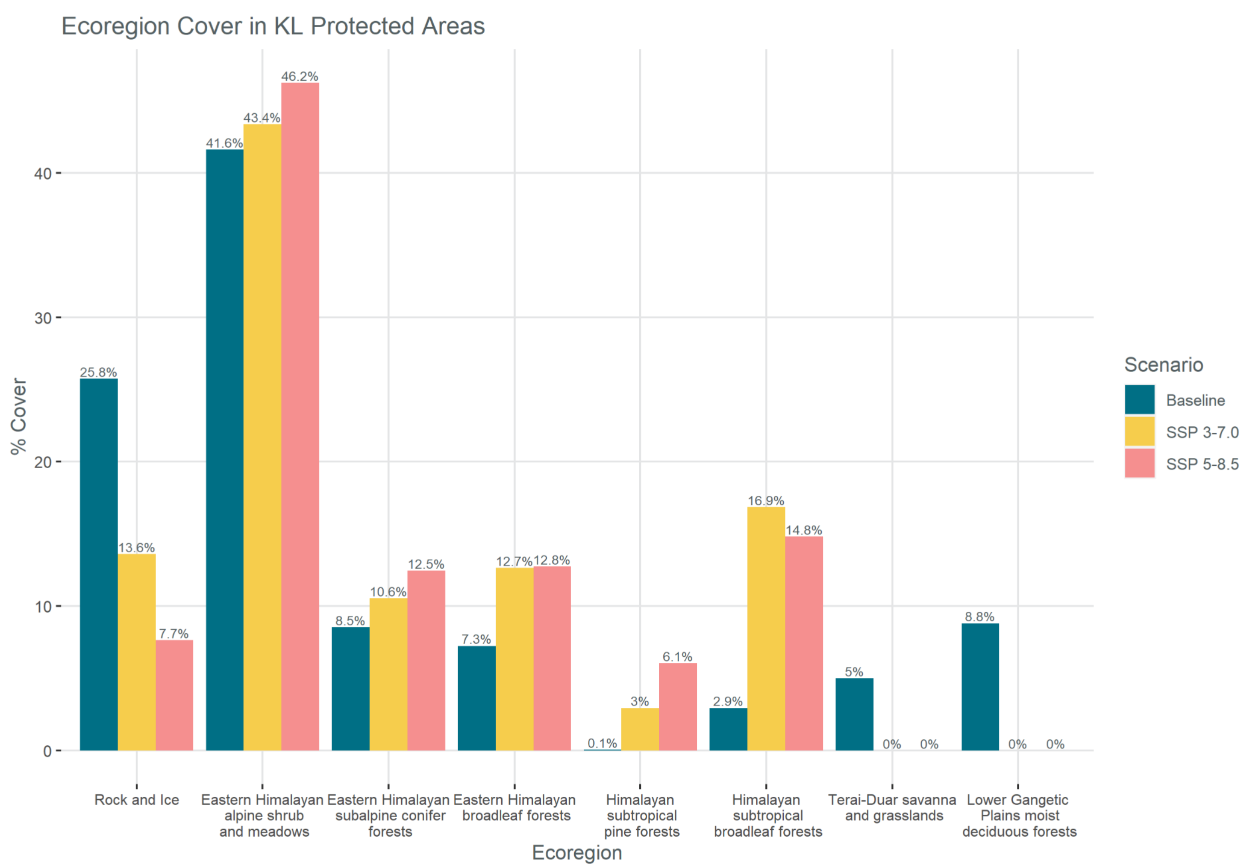

Figure 3.9 Percent cover of each ecoregion in protected areas in the baseline, medium-high emissions scenario (SSP 3-7.0), and high emissions scenario (SSP 5-8.5)

Ecoregion Cover in KL Protected Areas

	% Cover			% Change		
Ecoregion	Baseline	SSP 3-7.0	SSP 5-8.5	Baseline to SSP 3-7.0	Baseline to SSP 5-8.5	SSP 3-7.0 to SSP 5-8.5
Rock and Ice	25.8	13.6	7.7	-47.2	-70.3	-43.7
Eastern Himalayan alpine shrub and meadows	41.6	43.4	46.2	4.2	11.1	6.6
Eastern Himalayan subalpine conifer forests	8.5	10.6	12.5	23.5	45.7	18.0
Eastern Himalayan broadleaf forests	7.3	12.7	12.8	74.6	75.9	0.7
Himalayan subtropical pine forests	0.1	3.0	6.1	4222.1	8781.1	105.5
Himalayan subtropical broadleaf forests	2.9	16.9	14.8	472.3	403.2	-12.1
Terai-Duar savanna and grasslands	5.0	0.0	0.0	-100.0	-100.0	0.0
Lower Gangetic Plains moist deciduous forests	8.8	0.0	0.0	-100.0	-100.0	0.0

Figure 3.10 Percent cover and percent change in cover in protected areas in the baseline, medium-high emissions scenario (SSP 3-7.0), and high emissions scenario (SSP 5-8.5)

Kanchenjunga Landscape Protected Areas

Name	Area Extent (sq km)	Country of Jurisdiction	Transboundary Countries	Notable Species	Baseline Ecoregions (>= 30% cover)	SSP 3-7.0 Ecoregions (>= 30% cover)	SSP 5-8.5 Ecoregions (>= 30% cover)
Khangchendzonga Biosphere Reserve	2,620	India	Nepal	Orchids, Rhododendrons, Junipers, Brahminy shelduck, Black-necked crane, Flying squirrel, Red panda, Snow leopard, Tibetan wolf	Rock and Ice, Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows
Kangchenjunga Conservation Area	2,035	Nepal	India	Himalayan larch, Orchids, Legumes, Rhododendrons, Yellow-throated marten, Porcupines, Red panda, Assamese macaque, Himalayan black bear, Snow leopard	Rock and Ice, Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows
Buxa Tiger Reserve	760	India	Bhutan	Herbs, Orchids, Sedges, Bamboo, Guar, Wild pig, Common pangolin, Asian elephant, Crested serpent eagle, Hornbill	Lower Gangetic Plains moist deciduous forests	Himalayan subtropical broadleaf forests	Himalayan subtropical broadleaf forests
Jigme Khesar Strict Nature Reserve	651	Bhutan	India	White poppy, Takin, Serow, Red panda, Himalayan musk deer, Himalayan thar, Tiger, Clouded leopard, Snow leopard	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows
Pangolakha Wildlife Sanctuary	128	India	Bhutan	Bamboo, Greater spotted eagle, Rufous-necked hornbill, Ward's trogon, Hoary-throated barwing, Yell-throated martin, Goral, Musk deer, Takin, Tiger	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows, Eastern Himalayan broadleaf forests	Eastern Himalayan alpine shrub and meadows, Eastern Himalayan broadleaf forests
Mahananda WIldlife Sanctuary	127	India	--	Khair, Udal, Bamboos, Orchids, Serow, Wild boar, Black capped langur, Asian elephant, Himalayan black bear, Tiger	Himalayan subtropical broadleaf forests, Terai-Duar savanna and grasslands	Himalayan subtropical broadleaf forests	Himalayan subtropical broadleaf forests
Barsey Rhododendron Sanctuary	104	India	Nepal	Rhododendrons, Magnolia, Oaks, Bamboo, Crimson horned pheasant, Yellow-throated marten, Palm civet, Chinese pangolin, Red panda, Serow, Assamese macaque, Himalayan black bear	Eastern Himalayan subalpine conifer forests, Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests
Gorumara National Park	80	India	--	Sal, Bamboo, Khair, Indian hornbill, Scarlet minivet, Indian rhinocerous, Gaur, Pygmy hog, Asian elephant, Indian wolf, Tiger	Terai-Duar savanna and grasslands	Himalayan subtropical broadleaf forests	Himalayan subtropical broadleaf forests
Singhalila National Park	79	India	Nepal	Rhododendrons, Orchids, Blood pheasant, Satyr tragopan, Barking deer, Serow, Yellow-throated marten, Red panda, Black panther, Himalayan black bear	Eastern Himalayan subalpine conifer forests	Eastern Himalayan subalpine conifer forests, Eastern Himalayan broadleaf forests	Eastern Himalayan subalpine conifer forests, Eastern Himalayan broadleaf forests
Fambong Lo Wildlife Sanctuary	52	India	--	Oak, Katus tree, Orchids, Rhododendron arboreum, Rusty-bellied shortwing, Hoary-throated barwing, Hodgson's flying squirrel, Chinese pangolin, Red panda, Leopard cat, Asiatic black bear	Eastern Himalayan broadleaf forests	Himalayan subtropical pine forests	Himalayan subtropical pine forests
Shingba Rhododendron Sanctuary	43	India	--	Rhododendrons, Junipers, Alpine herbs, Himalayan griffon, Blood pheasant, Musk deer, Himalayan langur, Red panda, Long-eared bat, Snow leopard	Eastern Himalayan alpine shrub and meadows, Eastern Himalayan subalpine conifer forests	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows
Senchal Wildlife Sanctuary	39	India	--	Rhododendrons, Orchids, Birch, Oaks, Golden back woodpecker, Emerald cuckoos, Hornbills, Barking deer, Himalayan flying squirrel, Wild pig, Assam macaque, Himalayan black bear	Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests
Maenam Wildlife Sanctuary	35	India	--	Medicinal plants, Grey peacock pheasant, Pale-headed woodpecker, Sultan tit, Himalayan crestless porcupine, Ornage-bellied Himalayan squirrel, Barking deer, Goral, Yellow-throated marten, Red panda, Leopard cat, Asiatic black bear	Eastern Himalayan subalpine conifer forests, Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests
Kyongnosla Alpine Sanctuary	31	India	--	Rhododenron, Juniper, Poppies, Magnolias, Blood pheasant, Black eagle, Musk deer, Takin, Yellow-throated marten, Red panda, Hill fox, Himalayan black bear, Snow leopard	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan alpine shrub and meadows, Eastern Himalayan subalpine conifer forests
Chapramari Wildlife Sanctuary	10	India	--	Orchids, Sal trees, Teak, White breasted kingfisher, Hornbills, Green magpie, Braking deer, Pangolin, Indian bisons, Asian elephants	Terai-Duar savanna and grasslands	Himalayan subtropical broadleaf forests	Himalayan subtropical broadleaf forests
Kitam Bird Sanctuary	6	India	--	Sal-chir pines, Various butterfly species, Rufous-necked hornbill, Yellow-vented warbler, Grey-crowned prinia, Ward's Trogon, Black-breasted parrotbill	Himalayan subtropical pine forests	Himalayan subtropical pine forests	Himalayan subtropical pine forests
Jore Pokhari Salamander Sanctuary	0.04	India	--	Himalayan Salamander, [forest is artificially decorated]	Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests	Eastern Himalayan broadleaf forests

Figure 3.11 Informational table on protected areas in the KL including area, jurisdiction, notable species, and primary ecoregions (≥ 30% cover) under the baseline, medium-high emissions scenario (SSP 3-7.0) and high emissions scenario (SSP 5-8.5).

4. Implications of Ecoregion Shifts for Biodiversity and Ecosystem Services

Projecting ecoregion shifts under SSP climate scenarios provides a convenient starting point for decision makers and stakeholders to understand the potential on-the-ground impacts of climate change and plan for these plausible futures. To provide example applications of our model, we highlight four umbrella species to explore how projected ecoregion shifts may impact biodiversity (Figure 4.1; Figure 4.2) and one floral genus to exemplify potential impacts on ecosystem services (Figure 4.2; Figure 4.3). Roberge and Angelstam (2004) define an umbrella species as "a species whose conservation confers protection to a large number of naturally co-occurring species". An umbrella species approach is useful when there is a large number of species but data and resource limitations make it difficult to consider all species independently within analyses. Thus, an umbrella species can be used as "a representative of the state of a community or ecosystem" (Shi et al., 2019). Conserving habitat for a particular umbrella species therefore benefits the many other species that rely on those same habitats, as well as some of the ecosystem services those habitats provide (Forrest et al., 2012).

4.1 Snow Leopard (*Panthera uncia*)

The snow leopard is considered an umbrella species for alpine ecoregions due to the species' wide distribution and low density (Wikramanayake et al., 2001; McCarthy and Chapron 2003). Specifically, it is found in the Eastern Himalayan alpine shrub and meadows (EHASM; Wikramanayake et al., 2002). They tend to favor areas with "steep, rugged terrain and rocky outcrops" (Jackson et al., 2010). In addition to being an umbrella species, the snow leopard is listed as a vulnerable species, with numbers of mature individuals (currently estimated between 2,710-3,386) declining globally (McCarthy et al, 2017). Main threats to snow leopards have historically included poaching for pelts, human-wildlife conflict, and habitat fragmentation and degradation, the latter of which also affects their prey species (Körner 2007). Climate change is expected to exacerbate many current threats and introduce new ones, such as heightened competition with forest predator species as their suitable ranges also shift upwards. (Forrest et al., 2012; Körner 2007).

In the entire KL, the ecoregion shift model projected an upward shift in elevation and slight shrinking of the EHASM ecoregion, which is driven by an upward shift of Eastern Himalayan subalpine conifer forests (EHSCF; Figure 3.1; Figure 3.6; Figure 3.7).

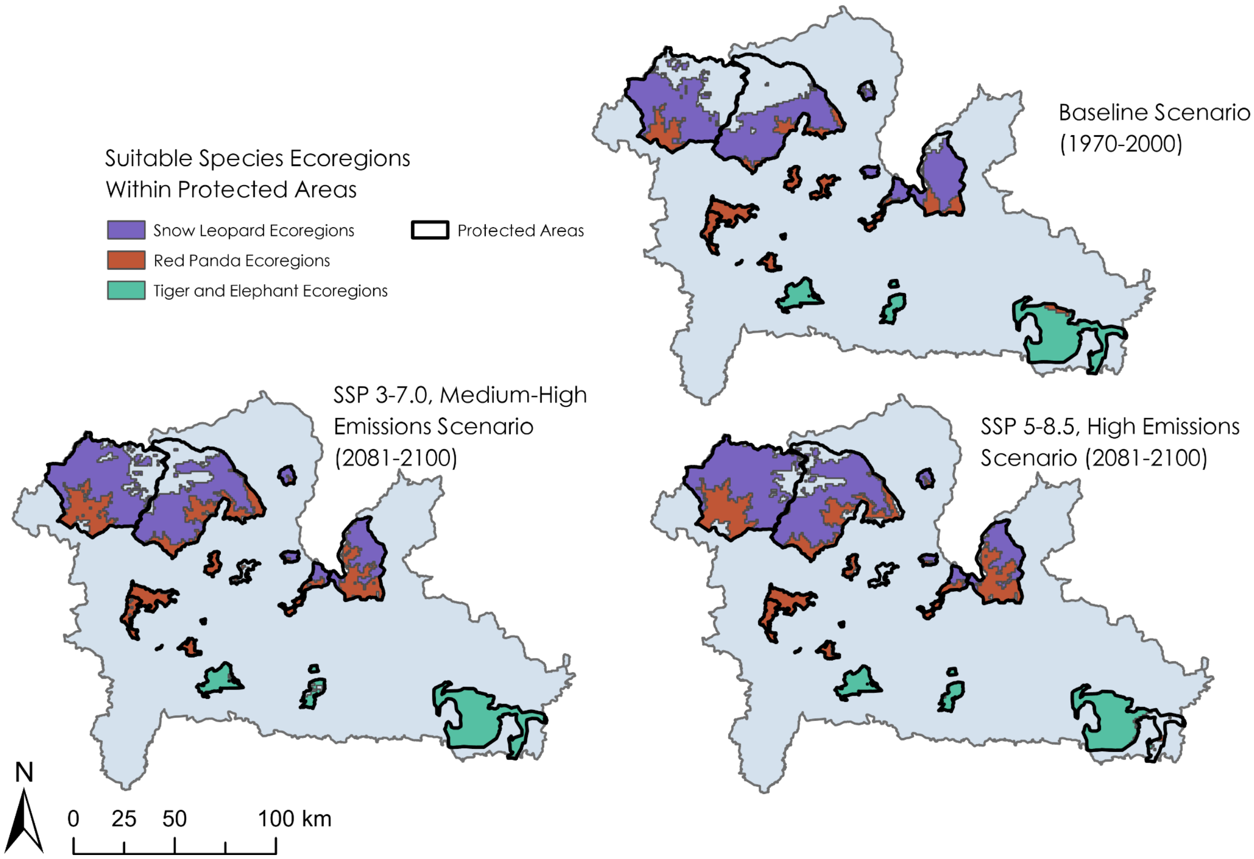

Figure 4.1 Distribution of suitable ecoregions for each evaluated umbrella species within the boundaries of protected areas. Snow Leopard: Eastern Himalayan alpine shrub and meadows. Red Panda: Eastern Himalayan Subalpine Conifer Forest and Eastern Himalayan broadleaf forest. Tiger and Asian Elephant: Himalayan subtropical broadleaf forests, Lower Gangetic Plains moist deciduous forest, and Terai-Duar savanna and grasslands

These projected upward shifts of alpine ecoregions are consistent with findings from other studies conducted in similar areas (Forrest et al., 2012; Zomer et al., 2014). If realized, these shifts would result in increased total suitable snow leopard ecoregion cover within KL PAs (Figure 4.1; Figure 4.2). Specifically, EHASM cover within the Kangchenjunga Conservation Area, Khangchendzonga Biosphere Reserve, and Singhba Rhododendron Sanctuary is projected to increase (Figure 4.1; Appendix E). However, it is likely that not all the area within this ecoregion expansion would be realistically used by snow leopards due to their sparse dispersal and the insular nature of suitable habitat within alpine ecoregions (Wikramanayake et al., 2001). Instead, snow leopard habitat will likely become patchier and more fragmented as the EHASM ecoregion shifts upward (Forrest et al., 2012). Additionally, EHASM ecoregion cover is projected to decrease or disappear in other PAs (e.g., the Jigme Khesar Strict Nature Reserve, Barsey Rhododendron Sanctuary, Kyongnosla Alpine Sanctuary, etc.). Given these nuances, the projected ecoregion shift trends should be used in combination with snow leopard occurrence data, land use/land cover data, local community input, and other relevant data sources to inform management plans that will remain effective in the future.

Preferred Ecoregion Cover

	% Cover			% Change		
	Baseline	SSP 3-7.0	SSP 5-8.5	Baseline to SSP 3-7.0	Baseline to SSP 5-8.5	SSP 3-7.0 to SSP 5-8.5
Protected Areas						
Snow Leopard	41.6	43.4	46.2	4.3	11.1	6.5
Red Panda	15.8	23.3	25.3	47.5	60.1	8.6
Tiger and Elephant	16.7	16.9	14.8	1.2	-11.4	-12.4
Kangchenjunga Landscape						
Rhododendron	52.9	43.1	43.0	-18.5	-18.7	-0.2

Figure 4.2 Percent cover and change of our focus species' preferred ecoregion cover in the baseline, medium-high emissions scenario (SSP 3-7.0), and high emissions scenario (SSP 5-8.5). For umbrella species, only cover within protected areas is evaluated. For rhododendrons, the entire area of the Kangchenjunga Landscape is evaluated.

4.2 Red Panda (*Ailurus fulgens*)

The red panda is an umbrella species for subalpine forests in the Himalaya, with a range that overlaps with the Eastern Himalayan Subalpine Conifer Forest (EHSCF) and Eastern Himalayan broadleaf forest ecoregions (EHBF; Wikramanayake et al., 2001). It is a habitat specialist and largely arboreal, residing in mature fir and juniper forests with a bamboo understory in areas of high precipitation (Wikramanayake et al., 2001). Red pandas' primary diet consists of young bamboo shoots and leaves (Bista et al., 2022). As a result, these herbivores prefer fir-ringal forests but will use other habitat types within their range (Wikramanayake et al., 2001). They are listed as endangered by the International Union for Conservation of Nature (IUCN; Glatston et al., 2015), with habitat loss and fragmentation, habitat degradation, and poaching representing their main threats (Glatston et al., 2015). Climate change is expected to compound these threats. Additionally, natural disasters could leave red pandas more vulnerable as certain populations become more isolated by habitat fragmentation such that recolonization is unlikely (Glaston et al., 2015). With shifting climate trends in the KL, areas prone to natural disasters may experience even faster ecoregion shifts, which give species within them even less time to adapt or migrate. Because ecosystems that experienced natural disasters would likely be recovering under vastly different climatic conditions than when they were formed, species from different ecoregions may be able to colonize the area faster.

Under both scenarios, the model projects less overall suitable ecoregion area in the KL for red pandas due to shrinkage of both EHSCF and EHBF (Figure 3.1; Figure 3.6; Figure 3.7), which threatens their already fragmented patches of suitable habitat.. However, protected areas are projected to see a substantial increase in the percent cover of the EHSCF ecoregion (Figure 4.1; Figure 4.2; Appendix E). These projections align with results from Lyon et al. (2022) who found through maximum entropy modeling for the period 2061-2080 that suitable climate and flora distributions for red pandas will largely remain represented in PAs, though their locations will shift upwards in elevation. This presents an opportunity for existing PAs to promote red panda conservation, but connectivity between PAs via conservation corridors or other methods may be required to ensure red pandas can migrate with the shifting of suitable ecoregions (Lyon et al., 2022). For example, under the two climate change scenarios, suitable red panda ecoregions are projected to move into the Kyongnosla Alpine Sanctuary and the Singhba Rhododendron Sanctuary which do not contain these ecoregion types under the baseline conditions. In order for the new ecoregion cover within these PAs to be useful to Red Panda conservation, they have to be able to migrate there.

4.3 Asian Elephant (*Elephas maximus*)

The Asian elephant's migration patterns, wide range, and large space requirement make it an umbrella species representing the Lower Gangetic Plains moist deciduous forest (LGPMDF), Terai-Duar savanna and grasslands ecoregions (TDSG), and Himalayan subtropical broadleaf forests ecoregions (Wikramanayake et al., 2001). Asian elephants are herbivorous generalists and can eat a variety of plants depending on their specific habitat. However, because they require fresh water availability for drinking and bathing, they are highly susceptible to drought (Williams et al., 2020). Asian elephants are on the IUCN list of endangered species due to threats from human-wildlife conflict, poaching and illegal trade, and habitat loss and fragmentation related to development activities (Williams et al., 2020). These threats, coupled with likely changes in monsoonal patterns, prolonged dry seasons, and projected warming trends in Asian elephant ranges, are expected to hinder their ability to adapt (Kanagaraj et al., 2019).

Under both future scenarios (SSP 3-7.0 - medium-high emissions, and SSP 5-8.5 - high emissions), our model projected substantial reductions of ecoregions suitable for Asian elephants within the KL as a whole. The LGPMDF ecoregion effectively disappeared (decreased by ≥ 98% under both scenarios) and the TDSG shrunk by about half (Figure 3.1, Figure 3.6, Figure 3.7). Additionally, subtropical broadleaf forest expanded into the areas previously occupied by LGPMDF and TDSG ecoregions. While Asian elephants can use broadleaf forests as habitat, loss of grasslands may have important implications for them. In PAs, suitable ecoregion coverage for the Asian elephant is projected to increase slightly under SSP3-7.0 but decrease under SSP5-8.5 (Figure 4.1, Figure 4.2). These projected trends would be best used in combination with fine-scale land use/land cover data, local input, and Asian elephant occurrence data to identify comprehensive conservation strategies that will enable any necessary elephant migrations under climate change.

4.4 Tiger (*Panthera tigris*)

The tiger is considered an umbrella species for the eastern portion of the KL because of its extensive space requirements; adult tigers are generally solitary and maintain exclusive territories (Wikramanayake et al., 2001; Goodrich et al., 2015). Additionally, tigers are designated as an endangered species by the IUCN with an estimated 2,154-2159 mature individuals globally (Goodrich et al., 2015). Major threats include poaching, human-wildlife conflict, diminishing availability of preferred prey, and habitat loss and fragmentation. Like the Asian elephant, tigers reside in the Lower Gangetic Plains moist deciduous forest (LGPMDF), Terai-Duar savanna and grasslands ecoregions (TDSG), and Himalayan subtropical broadleaf forests. However, their distribution is more limited within those ecoregions as they are less willing to cross open areas (Wikramanayake et al., 2002). Furthermore, the tiger's extensive space requirements mean that most current protected areas alone are already too small to support them.

Projected ecoregion shifts would slightly increase suitable tiger ecoregion coverage within PAs under SSP3-7.0, but decrease suitable tiger ecoregion coverage within PAs under SSP5-8.5 (Figure 4.1; Figure 4.2). In both scenarios, projected changes in the makeup of suitable tiger ecoregions within PAs (i.e., near disappearance of the LGPMDF, reduction of the TDSG by about half, and expansion of subtropical broadleaf forest; Figure 3.8; Figure 3.9; Figure 3.10) could have important consequences for tigers. For example, these projected ecoregion changes imply less habitat heterogeneity in the tiger's range (e.g., the LGPMDF ecoregion is replaced largely with subtropical broadleaf forest in the Buxa Tiger reserve) which could lead to reduced prey abundance (Bhattarai et al., 2012). Conservation planners can use these projected ecoregion shifts along with knowledge about tiger life history and data on land use patterns in the lowlands of the KL to strategically adapt landscape management plans. Among other solutions, such plan adaptations would likely involve the establishment of protected corridors between known tiger habitats, as well as the implementation of active management strategies to maintain habitat heterogeneity within current tiger ranges.

4.5 Rhododendron *(Rhododendron sp.)*

Rhododendrons are a genus of flowering shrubs and trees found in temperate climates with high rainfall and high humidity (Bhattacharyya, 2011; Gibbs et al., 2011). They play a vital role in slope stabilization, watershed protection, and structural contribution to plant communities, and thus, represent an assemblage of keystone species within the HKH (Gibbs et al., 2011; Singh and Chatterjee, 2021). In addition to their ecological value and stabilizing ecosystem services, this genera provides important provisioning ecosystem services for local communities. The flowers of *Rhododendron arboreum*, for example, are used for decoration, food, and medicinal purposes. They are worn as an ornament by individuals during cultural ceremonies, are prepared within appetizers, jams, and jellies, and are used to treat diarrhea, blood dysentery, and headaches (Tiwari and Chauhan, 2006; Singh and Chatterjee, 2021).

Additionally, the bark and wood of other species of rhododendrons are used as fuel wood due to their ability to burn even under wet conditions (Singh and Chatterjee, 2021; Sekar and Srivastava, 2010). Rhododendrons are also of high value to horticulturalists globally. Many rhododendrons growing in gardens across America and Europe have been derived from species occurring in the Himalayas (Bhattacharyya, 2011).

Over 40 species of rhododendrons occur within the Kangchenjunga Landscape (KL), spanning an altitudinal range of 1500-500m (Gurung et al., 2017; Singh and Chatterjee, 2021). They grow closer to the treeline within the Eastern Himalayan alpine shrub and meadows ecoregion, and several rhododendrons grow in the understory of Eastern Himalayan subalpine conifer forests (Wikramanayake et al., 2002). They are found most prominently, however, in Eastern Himalayan broadleaf forests. Within the HKH broadly, there are more than 60 species in Sikkim, India and over 50 species in Bhutan within this ecoregion (Wikramanayake et al., 2002). Additionally, the majority of protected areas within the KL contain species of rhododendrons. In fact, two protected areas within the KL are designated for the purpose of conserving rhododendrons (i.e., Barsey Rhododendron Sanctuary and Singbha Rhododendron Sanctuary; Tiwari and Chauhan, 2006).

Under our two projected climate scenarios, rhododendrons would experience a decrease in conditions that are climatically suitable to their growth. Specifically, our results show substantial shrinking of the Himalayan Broadleaf Forest ecoregion, which is crucial for supporting rhododendron biodiversity. However, this overall shrinkage is also coupled with an increase of climatically suitable areas for rhododendrons within protected areas. Such an increase is due to the northward shift of both the Eastern Himalayan alpine shrub and meadows and the Eastern Himalayan subalpine conifer forests ecoregions. While the broad altitudinal range of rhododendrons may allow them to more easily adapt to these northward ecoregion shifts, their viability may be limited by the availability of suitable soil. Rhododendrons prefer acidic and humus-rich soil, which may not be available under projected climate scenarios, depending on geologic factors and competition for nutrients with other plant species (Tiwari and Chauhan, 2006). Additionally, given that deforestation, land development, and unsustainable harvesting are some of the greatest threats facing rhododendron species, conservation efforts will need to consider human impacts in addition to climatic and ecoregion conditions (Sekar and Srivastava, 2010).

As a result, researchers and practitioners will likely need to reimagine the structure of protected areas so that PAs can function to both conserve rhododendron populations and maintain the vital provisioning services they provide. Such changes could include implementing additional PAs with restrictions on harvesting within key rhododendron hotspots that may expand under climate change, establishing connectivity corridors to support rhododendron migration, and implementing more community-based conservation efforts.

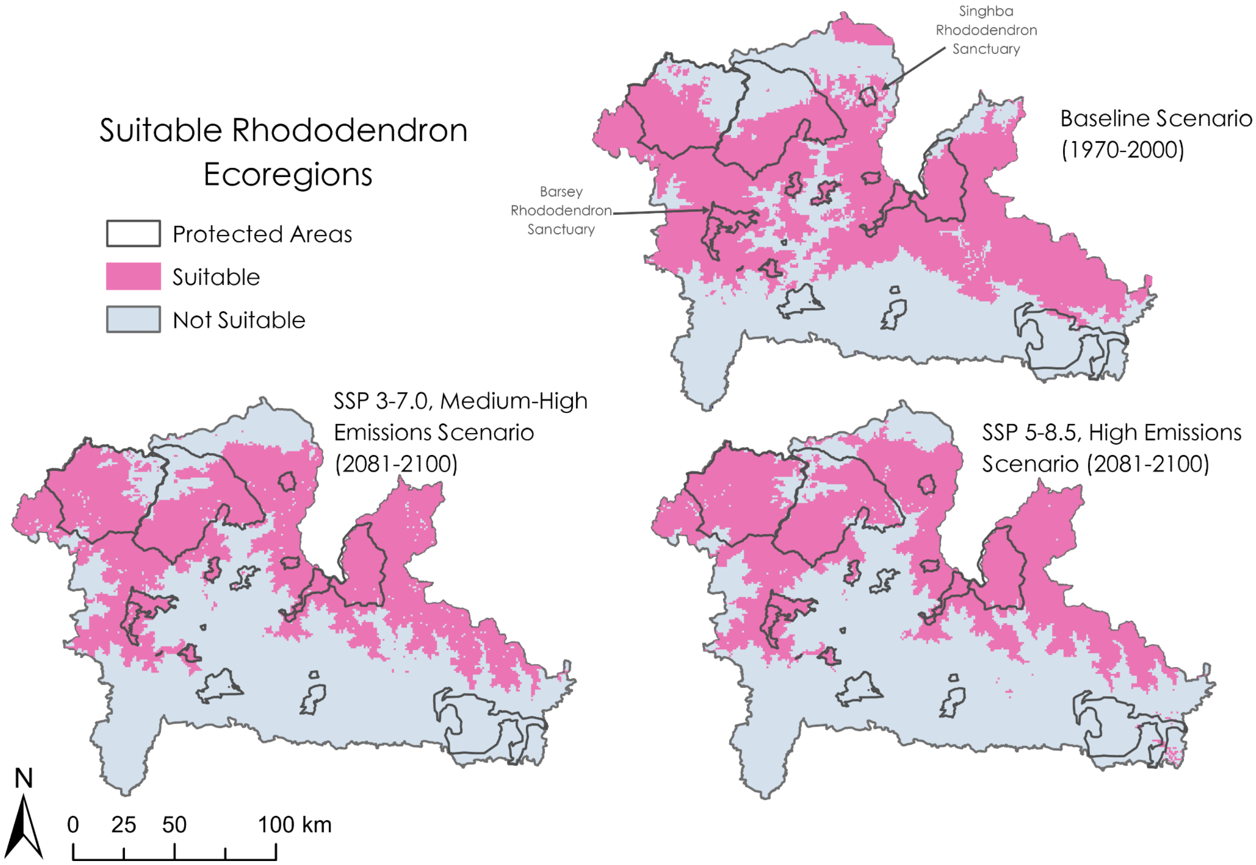

Figure 4.3 Distribution of suitable ecoregions for *Rhododendron* species within the Kangchenjunga Landscape. Suitable ecoregions include Eastern Himalayan alpine shrub and meadows, Eastern Himalayan subalpine conifer forests, and Eastern Himalayan broadleaf forests.

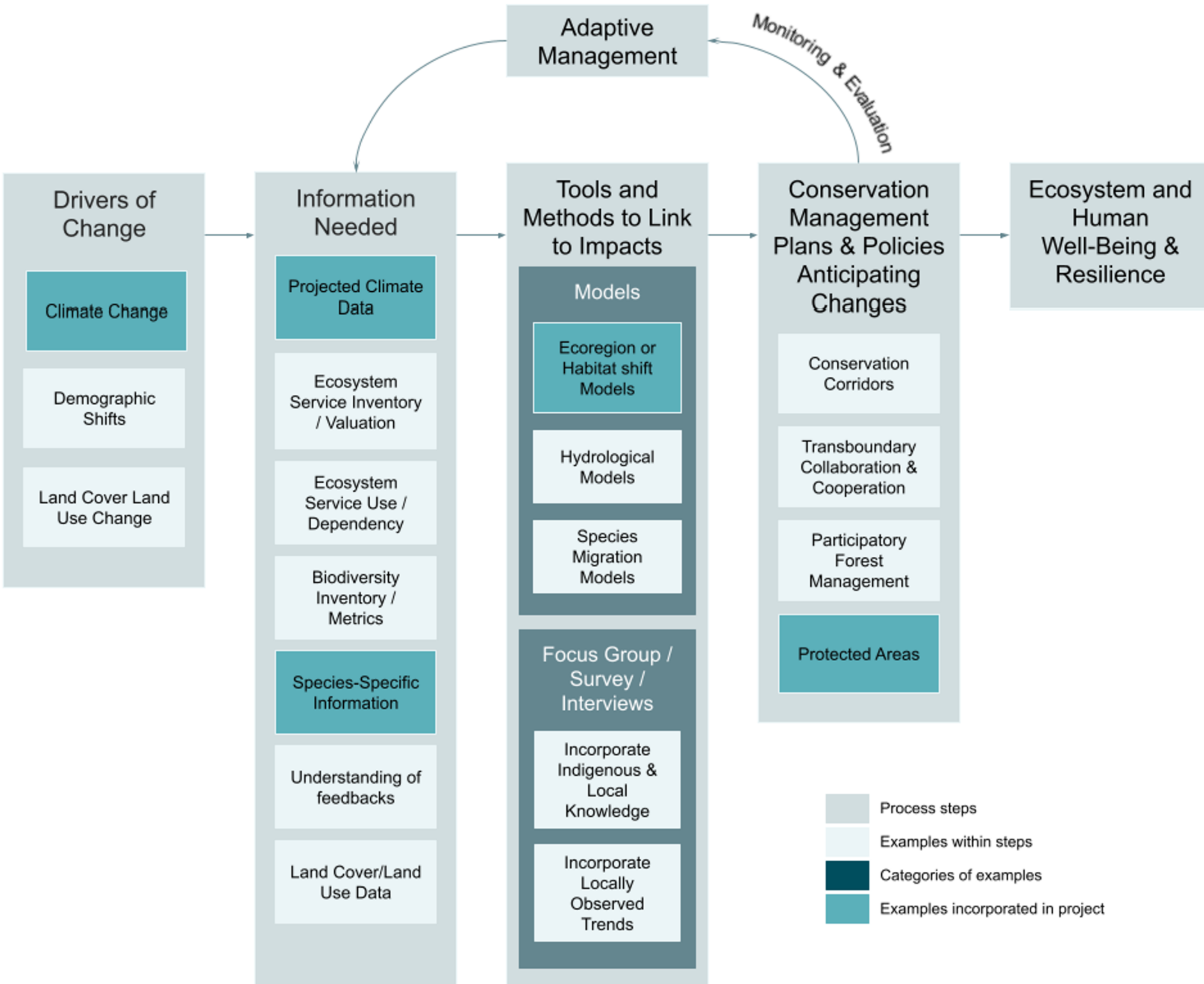

Figure 4.4 A conceptual framework for incorporating drivers of change into plans and policies that promote ecosystem and human well-being and resilience. Once drivers of change are identified (e.g., climate change, demographic shifts, land cover and land use change, etc.), practitioners can determine data and information needed and develop and employ tools and methods for studying cascading impacts of anticipated changes. With the knowledge gained, practitioners and policy makers can develop informed management plans that account for anticipated changes and impacts. Implemented plans can be monitored, evaluated, and adapted iteratively to improve ecosystem and human well-being and resilience.

In this figure, we highlight examples in each step that are related to our project. To explore climate change impacts on biodiversity and ecosystem services, and how this knowledge can be used to inform management plans, we use projected climate data as inputs to an ecoregion shift model. With the model outputs, we consider species-specific information to qualitatively assess the likely utility of protected areas in the future. As visualized in this flowchart, our project encompasses only a few pieces of the broader picture. Additional drivers of change, information sources, and tools and methods will ultimately need to be integrated to develop holistic conservation management plans and reach the goal of improving ecosystem and human well-being and resilience.

4.6 Conclusions

In this study, we applied a geospatial clustering model to project ecoregion shifts in the KL, captured the process in reproducible code, and demonstrated potential avenues for applying the method to examine cascading impacts on biodiversity and ecosystem services. The outputs of this work serve to address the identified LAKI knowledge gap on the lack of methodologies and tools to quantify the impact of climate change on biodiversity and ecosystem services in the HKH subregion. Although we specifically focus on four umbrella species and provisioning ecosystem services provided by rhododendrons in this study, this geospatial model can be used in combination with other data to investigate additional ecosystem service impacts.

The knowledge gained through applying this method could enable policy makers and conservation organizations to more effectively protect portions of suitable ecoregions that are less vulnerable to climate change and ensure connectivity between existing species ranges and projected distribution of suitable ecoregion cover within transboundary landscapes. At a basic level, this could mean assigning static protected area boundaries to encompass areas that contain key ecoregions for conservation goals and are less vulnerable to climate change impacts. However, such a strategy will only be effective if connectivity corridors are added between existing PAs and future PAs. Although ICIMOD has proposed seven conservation corridors in the KL to connect existing PAs to one another (Gurung et al., 2017), these corridors have yet to be employed and would likely need to be modified if PA boundaries are changed, additional PAs are added to the landscape, or additional development takes place in these areas before conservation corridors are implemented. Moreover, given the extent of some of the possible ecoregion shifts under climate change, more active management interventions may be necessary to conserve species within particularly vulnerable ecoregions. This ecoregion shift modeling approach could be coupled with more detailed data and information on species-specific behaviors, physiologies, and life histories to better inform such specific interventions within an adaptive management process.

PAs and conservation corridors are embedded within complex socio-ecological systems, and thus their efficacy hinges on the consideration of both social and political factors in addition to ecological trends and data availability. Therefore, to ensure that conservation initiatives also support the people residing in the HKH, the approach presented here should be applied as part of a larger framework that considers additional drivers of change, data inputs, and impact assessment techniques to develop comprehensive management plans that can be evaluated and improved over time (Figure 4.4). In such a framework, geospatially modeled projected ecoregion shifts could be a valuable starting point to identifying priority locations for adaptive conservation and management plans.

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Appendix A: Code Availability/Supplemental Materials

To facilitate replicability of our methods, code for the GIS processing steps in the methods has been made available for download in a github repository.

Github Repository

https://github.com/lspero0/masters_project_code

File Formats

`.ipynb` - notebook format, can be opened in ArcGIS Pro

`.py` - Python source code

`.html` - non-editable format for viewing and embedding

File Descriptions

`strat_model` - Contains code for calculating the four climatic variables, normalizing the climatic variables, and ISODATA stratification.

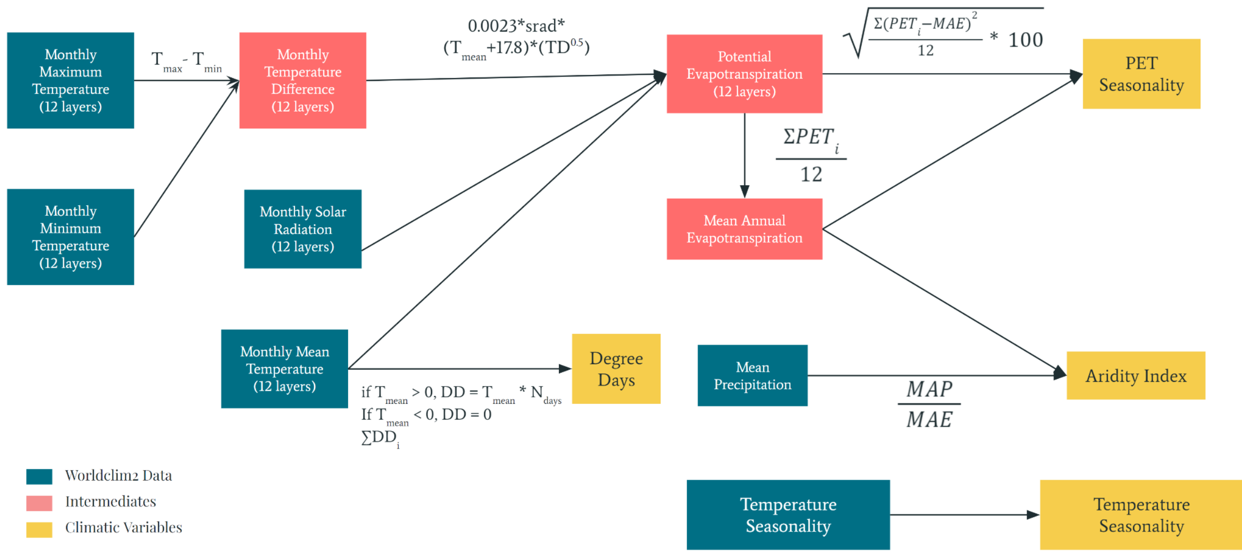
`maxlikelihoodclass` - Contains code for running the maximum likelihood classification, classifying maxclass outputs into ecoregions, finding the mode of ecoregion classifications, finding the mean of projected climatic variables, repeating maximum likelihood classification steps on mean climatic variables, and combining the mode and mean outputs to generate final projected ecoregion distribution outputs.

`output_stats` - Contains code for calculating the percent cover and percent change in ecoregion cover within the entire study area and in protected areas. The outputs of this are four .csv tables that were used to generate tables and graphs.

`eco-relate.csv` - Table containing the final strata-ecoregion associated used to classify the maximum likelihood classification outputs into ecoregions.

`dendrogram2.txt` - A text file containing a table depicting the distances between strata and an accompanying dendrogram.

Appendix B: Climatic Variable Calculation Flowchart



The calculation workflow of climatic variables. The teal boxes represent data layers downloaded from Worldclim 2.1. Pink boxes represent intermediates calculated during the climatic variable generation process. Yellow boxes represent the four final climatic variables used. Temperature seasonality was downloaded directly from Worldclim 2.1 and used as a climatic variable without any modification.

Appendix C: Accuracy Assessment Matrix

Error Matrix

Error Matrix

	Accuracy Assessment Values								
Model Values	**Rock and Ice**	**Eastern Himalayan alpine shrub and meadows**	**Eastern Himalayan subalpine conifer forests**	**Eastern Himalayan broadleaf forests**	**Himalayan subtropical pine forests**	**Himalayan subtropical broadleaf forests**	**Terai-Duar savanna and grasslands**	**Lower Gangetic Plains moist deciduous forests**	
Rock and Ice	7	4	0	0	0	0	0	0	11
Eastern Himalayan alpine shrub and meadows	5	4	3	0	0	0	0	0	12
Eastern Himalayan subalpine conifer forests	0	0	5	4	0	0	0	0	9
Eastern Himalayan broadleaf forests	0	0	0	10	2	3	0	0	15
Himalayan subtropical pine forests	0	0	0	1	4	5	0	0	10
Himalayan subtropical broadleaf forests	0	0	0	0	0	5	1	0	6
Terai-Duar savanna and grasslands	0	0	0	0	0	1	9	5	15
Lower Gangetic Plains moist deciduous forests	0	0	0	0	0	0	0	6	6
	12	8	8	15	6	14	10	11	84

An error matrix showing the model classification (rows) and the human accuracy assessment classification (columns) of each point.

Omission and Commission Error

Ecoregion	Omission Error	Comission Error
Rock and Ice	41.67%	36.36%
Eastern Himalayan alpine shrub and meadows	50.00%	66.67%
Eastern Himalayan subalpine conifer forests	37.50%	44.44%
Eastern Himalayan broadleaf forests	33.33%	33.33%
Himalayan subtropical pine forests	33.33%	60.00%
Himalayan subtropical broadleaf forests	64.29%	16.67%
Terai-Duar savanna and grasslands	10.00%	40.00%
Lower Gangetic Plains moist deciduous forests	45.45%	0.00%

Omission and commission error for each ecoregion type in the accuracy assessment.

Overall Accuracy

Overall Accuracy	K_{hat}
59.52%	53.72%

Overall accuracy, defined as the percent of agreement of points, and K_{hat}, defined as a measure of the actual agreement of point values minus the chance of agreement by chance.

Appendix D: CMIP 6 Models Used for Each Scenario Ensemble

Downscaled outputs from the following CMIP 6 models were used for projected ecoregion distribution scenarios. A total of 13 model outputs were used for the SSP3-7.0 scenario ensemble and 10 were used for the SSP5-8.5 scenario ensemble.

CMIP 6 Model	Key Reference	SSP3-7.0 Ensemble	SSP5-8.5 Ensemble
ACCESS-CM2	Bi et al. (2012)	x	
ACCESS-ESM1-5	Law et al. (2017)	x	x
BCC-CSM2-MR	Wu et al. (2019)	x	x
CanESM5	Swart et al. (2019)	x	
CNRM-CM6-1	Voldoire et al. (2019)	x	x
CNRM-CM6-1-HR	Voldoire et al. (2019)	x	x
CNRM-ESM2-1	Séférian et al. (2019)	x	x
FIO-ESM-2-0	Bao et al. (2020)		x
GFDL-ESM4	Held et al. (2019)	x	
GISS-E2-1-G	Kelley et al. (2020)	x	x
GISS-E2-1-H	Kelley et al. (2020)	x	x
INM-CM4-8	Volodin et al. (2018)	x	
INM-CM5-0	Volodin et al. (2018)	x	
IPSL-CM6A-LR	Boucher et al. (2020)	x	
MIROC-ES2L	Hajima et al. (2020)		x
MPI-ESM1-2-HR	Müller et al. (2018)		x

Appendix E: Detailed Ecoregion Distribution and Change

Ecoregion Cover (%)

	Rock and Ice	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan subalpine conifer forests	Eastern Himalayan broadleaf forests	Himalayan subtropical pine forests	Himalayan subtropical broadleaf forests	Terai-Duar savanna and grasslands	Lower Gangetic Plains moist deciduous forests
Kangchenjunga Landscape								
Baseline	12.1	20.4	8.4	24.1	7.1	6.0	17.2	4.9
SSP 3-7.0	6.8	18.7	7.8	16.6	17.6	31.8	0.3	0.3
SSP 5-8.5	4.5	19.5	7.8	15.7	15.3	36.8	0.1	0.1
All Protected Areas								
Baseline	25.8	41.6	8.5	7.3	0.1	2.9	5.0	8.8
SSP 3-7.0	13.6	43.4	10.6	12.7	3.0	16.9	0.0	0.0
SSP 5-8.5	7.7	46.2	12.5	12.8	6.1	14.8	0.0	0.0
Barsey RS								
Baseline	0.0	0.8	43.2	56.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	6.2	85.2	8.5	0.0	0.0	0.0
SSP 5-8.5	0.0	0.0	9.1	85.8	1.7	3.4	0.0	0.0
Buxa TR								
Baseline	0.0	0.0	0.0	4.1	0.0	14.2	13.7	68.0
SSP 3-7.0	0.0	0.0	0.0	0.1	0.0	99.9	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	1.8	18.5	79.7	0.0	0.0
Chapramari WS								
Baseline	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
SSP 3-7.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
Fambong Lho WS								
Baseline	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	0.0	9.9	90.1	0.0	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Gorumara NP								
Baseline	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
SSP 3-7.0	0.0	0.0	0.0	0.0	23.6	76.4	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	0.0	2.8	97.2	0.0	0.0
Jigme Khesar SNR								
Baseline	8.5	72.0	13.2	6.2	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	55.7	22.2	20.8	1.2	0.0	0.0	0.0
SSP 5-8.5	0.0	47.5	28.7	22.5	1.4	0.0	0.0	0.0
Jore Pokhari SS								
Baseline	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0

Kanchenjunga CA								
Baseline	38.8	50.7	6.5	4.0	0.0	0.0	0.0	0.0
SSP 3-7.0	19.8	59.4	11.4	7.1	2.2	0.0	0.0	0.0
SSP 5-8.5	9.1	66.1	14.0	8.1	2.7	0.0	0.0	0.0
Khangchendzonga BR								
Baseline	40.9	49.9	5.7	3.4	0.0	0.0	0.0	0.0
SSP 3-7.0	24.7	53.7	10.3	10.1	1.2	0.0	0.0	0.0
SSP 5-8.5	16.3	59.6	11.0	8.9	4.2	0.0	0.0	0.0
Khitam BS								
Baseline	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Kyongnosla AS								
Baseline	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	75.0	17.5	7.5	0.0	0.0	0.0	0.0
SSP 5-8.5	0.0	65.0	35.0	0.0	0.0	0.0	0.0	0.0
Mahananda WS								
Baseline	0.0	0.0	0.0	0.0	0.0	40.3	59.7	0.0
SSP 3-7.0	0.0	0.0	0.0	0.0	2.5	97.5	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
Mainam WS								
Baseline	0.0	0.0	60.8	39.2	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	70.2	29.8	0.0	0.0	0.0
Pangolakha WS								
Baseline	0.0	60.1	28.9	11.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	43.6	18.8	33.9	3.6	0.0	0.0	0.0
SSP 5-8.5	0.0	40.6	18.2	40.0	0.0	1.2	0.0	0.0
Senchal WS								
Baseline	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	0.0	94.0	4.0	2.0	0.0	0.0
SSP 5-8.5	0.0	0.0	0.0	78.0	4.0	18.0	0.0	0.0
Singhalila NP								
Baseline	0.0	2.1	85.8	12.1	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	0.0	43.7	49.5	6.8	0.0	0.0	0.0
SSP 5-8.5	0.0	0.0	44.7	55.3	0.0	0.0	0.0	0.0
Singhba RS								
Baseline	15.5	32.7	51.8	0.0	0.0	0.0	0.0	0.0
SSP 3-7.0	0.0	88.1	11.9	0.0	0.0	0.0	0.0	0.0
SSP 5-8.5	0.0	83.1	15.3	0.0	1.7	0.0	0.0	0.0

Percent ecoregion cover for the entire KL, all protected areas, and each individual protected area in the baseline, SSP 3-7.0 (medium-high emissions), and SSP 5-8.5 (high emissions) scenarios.

Ecoregion Change (%)

	Rock and Ice	Eastern Himalayan alpine shrub and meadows	Eastern Himalayan subalpine conifer forests	Eastern Himalayan broadleaf forests	Himalayan subtropical pine forests	Himalayan subtropical broadleaf forests	Terai-Duar savanna and grasslands	Lower Gangetic Plains moist deciduous forests
Kangchenjunga Landscape								
Baseline to SSP 3-7.0	-43.2	-8.2	-6.7	-31.2	149.8	432.4	-98.0	-93.5
Baseline to SSP 5-8.5	-62.3	-4.2	-6.7	-34.7	117.3	517.8	-99.4	-98.0
SSP 3-7.0 to SSP 5-8.5	-33.6	4.3	0.0	-5.1	-13.0	16.0	-69.9	-68.6
All Protected Areas								
Baseline to SSP 3-7.0	-47.2	4.2	23.5	74.6	4222.1	472.3	-100.0	-100.0
Baseline to SSP 5-8.5	-70.3	11.1	45.7	75.9	8781.1	403.2	-100.0	-100.0
SSP 3-7.0 to SSP 5-8.5	-43.7	6.6	18.0	0.7	105.5	-12.1	0.0	0.0
Barsey RS								
Baseline to SSP 3-7.0	0.0	-100.0	-85.5	52.3	100.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	-100.0	-79.0	53.3	100.0	100.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	45.5	0.7	-80.0	100.0	0.0	0.0
Buxa TR								
Baseline to SSP 3-7.0	0.0	0.0	0.0	-97.5	0.0	605.6	-100.0	-100.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	-57.3	100.0	463.2	-100.0	-100.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	1600.0	100.0	-20.2	0.0	0.0
Chapramari WS								
Baseline to SSP 3-7.0	0.0	0.0	0.0	0.0	0.0	100.0	-100.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	100.0	-100.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fambong Lho WS								
Baseline to SSP 3-7.0	0.0	0.0	0.0	-90.1	100.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	-100.0	100.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	-100.0	10.9	0.0	0.0	0.0
Gorumara NP								
Baseline to SSP 3-7.0	0.0	0.0	0.0	0.0	100.0	100.0	-100.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	0.0	100.0	100.0	-100.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	0.0	-88.0	27.2	0.0	0.0
Jigme Khesar SNR								
Baseline to SSP 3-7.0	-100.0	-22.7	68.0	235.9	100.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	-100.0	-34.0	116.8	261.9	100.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	-14.7	29.1	7.7	10.0	0.0	0.0	0.0
Jore Pokhari SS								
Baseline to SSP 3-7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Kanchenjunga CA								
Baseline to SSP 3-7.0	-48.9	17.2	77.0	75.9	100.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	-76.4	30.4	115.9	101.8	100.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	-53.9	11.2	22.0	14.7	21.6	0.0	0.0	0.0
Khangchendzonga BR								
Baseline to SSP 3-7.0	-39.7	7.5	80.2	194.8	3901.9	0.0	0.0	0.0
Baseline to SSP 5-8.5	-60.3	19.5	93.0	159.7	13285.5	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	-34.1	11.1	7.1	-11.9	234.5	0.0	0.0	0.0
Khitam BS								
Baseline to SSP 3-7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kyongnosla AS								
Baseline to SSP 3-7.0	0.0	-25.0	100.0	100.0	0.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	-35.0	100.0	0.0	0.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	-13.3	100.0	-100.0	0.0	0.0	0.0	0.0
Mahananda WS								
Baseline to SSP 3-7.0	0.0	0.0	0.0	0.0	100.0	142.0	-100.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	0.0	0.0	148.2	-100.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	0.0	-100.0	2.6	0.0	0.0
Mainam WS								
Baseline to SSP 3-7.0	0.0	0.0	-100.0	154.8	0.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	-100.0	78.8	100.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	-29.8	100.0	0.0	0.0	0.0
Pangolakha WS								
Baseline to SSP 3-7.0	0.0	-27.4	-35.1	209.5	100.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	-32.4	-37.2	264.8	0.0	100.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	-6.9	-3.2	17.9	-100.0	100.0	0.0	0.0
Senchal WS								
Baseline to SSP 3-7.0	0.0	0.0	0.0	-6.0	100.0	100.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	0.0	0.0	-22.0	100.0	100.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	0.0	-17.0	0.0	800.0	0.0	0.0
Singhalila NP								
Baseline to SSP 3-7.0	0.0	-100.0	-49.1	310.7	100.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	0.0	-100.0	-48.0	359.0	0.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	0.0	2.2	11.8	-100.0	0.0	0.0	0.0
Singhba RS								
Baseline to SSP 3-7.0	-100.0	169.2	-77.1	0.0	0.0	0.0	0.0	0.0
Baseline to SSP 5-8.5	-100.0	153.7	-70.5	0.0	100.0	0.0	0.0	0.0
SSP 3-7.0 to SSP 5-8.5	0.0	-5.8	28.6	0.0	100.0	0.0	0.0	0.0

The percent change in ecoregion cover for the entire KL, all protected areas, and each individual protected area between the baseline, SSP 3-7.0 (medium-high emissions), and SSP 5-8.5 (high emissions) scenarios.

Appendix F: Storymap

To visually walk through the steps of our methods and code, as well as to add some interactivity to our output maps, we have generated a storymap as an additional resource. It can be found here: https://storymaps.arcgis.com/stories/2bce8dd7f5f6421ca7a7a9a57689a3ac