The Resilience of Protected Areas of India to Climate Change: Current status and future scenario

SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

in
Forestry (Specialization: Environment Management)

FOREST RESEARCH INSTITUTE UNIVERSITY
by
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Declaration

I hereby declare that the work conducted under the thesis titled "**The Resilience of Protected Areas of India to Climate Change: Current Status and Future Scenario**" is a record of original and independent research work carried out by me and subsequently submitted for fulfilment of the award of the degree of **Doctor of Philosophy** in **Forestry (Environment management)** to the **Forest Research Institute (Deemed to be) University, Dehradun**. The research work has been carried out under the guidance and supervision of Dr. Gautam Talukdar (Scientist-F), Wildlife Institute of India, Dehradun. The work has not formed the basis for the award of any other degree, diploma, associateship, fellowship, or title in this or any other university or institution of higher learning in India or abroad.

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The RAC found the work of the scholar satisfactory and approves the work to be submitted in the form of thesis for evaluation by examiners for the "Award of Ph.D. Degree".

I certify that the research work was appreciated by all who were present, and the comments made by the faculty members and researchers have been appropriately included in the thesis.

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Any comments (Including for example highlights, challenges)

Debanjan performed excellent work while he was on his placement. Not only did he meet the planned outputs in terms of his PhD but also results worthy of 2-3 scientific publications.

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Sarkar, D., Haritha, J., Debnath, A., Talukdar, G., (2024). A systematic review on the potential impact of future climate change on India's biodiversity using species distribution model (SDM) studies: trends, and data gaps. *Biodiversity and conservation*. https://doi.org/10.1007/s10531-024-02785-1

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Conference presentations:

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Sarkar, D., J, Haritha., Debnath, A., Talukdar, G (2023). A systematic review of current knowledge on the impact of climate change on India's biodiversity: trends, and gaps. *Biodiversity and Climate Change Conference, IIT Kharagpur, February 2023. Presenter: Haritha J*

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Summary

Chapter 1. Literature review

In this chapter, a systematic literature review was conducted to assess the future climate change impacts on India's biodiversity across all biogeographic zones. Our findings revealed a significant increase in research on climate change-related distribution modelling studies after 2015. We found, (a) The Himalayan region was the most studied biogeographic zone (n=49), followed by the Western Ghats (n=15). (b) Plants are the most studied taxa (n=77), followed by invertebrates (n=11). (c) Gaps in the literature regarding the climate change impacts on the distribution of amphibians (n=2) and reptiles (n=1), and studies on Islands (n=0) and Coastal (n=2) biogeographic zones. There is a requirement for more studies dedicated to lesser-studied taxa. Limited studies in India have incorporated protected area networks in their analysis.

Chapter 2. Study area.

India has four categories of Protected areas (PA) as per the Indian Wildlife Protection Act, 1972. India has a total of 1022 PAs spread across 10 different biogeographic zones. This chapter describes India's protected area network, its growth over the years, and its state-wise and biogeographic zone-wise distribution. This chapter also details the ten biogeographic zones, their characteristics habitats, and climate conditions over the last two decades. It was found that PAs of three global biodiversity hotspots (i.e., the Himalayas, western ghats and northeast) have comparatively broader climate space than the rest of the biogeographic zones.

Chapter 3. Quantifying the relationship between climate drivers and vegetation changes

This chapter analyses the relationship between climate drivers and vegetation changes in different biogeographic zones of India over the last two decades. MODIS dataset for EVI (Proxy for vegetation changes), temperature, precipitation and evapotranspiration were downloaded and processed through the Google Earth engine. Mann-Kendall (MK) test was performed in R to identify trends in these datasets. A generalized linear modelling test was performed between the climate drivers and EVI trends to assess climate drivers contributing to vegetation changes in different biogeographic zones. In all zones, a similar pattern was observed. A. with increasing temperature trend, EVI has decreased (i.e., led to browning). B. Increased precipitation trends have led to greening and C. With increased greening, evapotranspiration trends have increased.

Chapter 4. Identifying the climatically vulnerable protected areas

This chapter looks into the future climate vulnerability of protected areas of India. A set of environmental variables, and spatial data for PAs was used to quantify vulnerability scores of PA in each biogeographic zone. The climate niche factor analysis method was implemented using the CENFA package in R to analyse the climate sensitivity, exposure and vulnerability of each PA. It was found that a. smaller PAs have higher climate vulnerability and b. PAs located at higher elevations are climatically more exposed.

Chapter 5. Identifying climate-change refugia

This chapter assesses climate change-related impacts on India's terrestrial biodiversity (birds, insects, mammals, amphibians, reptiles, and plants using a species distribution modelling approach. Large reductions in climatic change refugia are projected with 2°C warming (relative to preindustrial levels) with birds and plants seeing the greatest impact. Potential climate refugia for biodiversity are identified within different parts of the country but often overlap with areas already converted to agriculture or set aside for agricultural expansion, and the majority are outside protected areas. Few protected areas contain no projected refugia at higher levels of global warming. Both the Himalayan and trans-Himalayan areas will serve as climate refugia for the modelled taxa even in higher warming scenarios. However, risks to the biodiversity of India are much smaller if the Paris Agreement's goal of limiting global warming to '1.5°C' warming', rather than 2°C. The potential for climate refugia for plants and birds decreases significantly with warming. For example, 52% of the country remains climatically suitable for at least 75% of the plants currently present at 1.5°C warming, compared with 30% at 2°C and 23% at 4°C.

Chapter 6. Synthesis

This chapter presents as final remarks of this thesis the key messages of this research, and then an overall discussion followed by the overall conclusions. The key messages represent the main findings of the thesis relevant for the comparison between narratives that consider an increase in the global annual mean temperature of 1.5ºC and 2ºC above pre-industrial levels. The discussion covers the state of the art of the nexus of climate change, biodiversity conservation and protected areas in India, how this research has contributed and advanced this field, and the main caveats. Finally, the conclusion section of this chapter shows how this thesis is successful in achieving its overarching aim and specific objectives.

Rationale

Climate change and biodiversity studies in India have a notable emphasis on a species-centric approach, with a predominant focus on individual species, limiting our understanding of broader landscape-level consequences. There exists a significant research gap concerning the evaluation of the effects of climate change across different scales, i.e. biogeographic zones and Protected Areas (PA). This study seeks to address the gap by delving into the broader implications of climate change to protected areas of India, specifically homing in on its multifaceted impacts on biodiversity and the identification of potential refugia.

Objectives

- Quantifying the climate drivers contributing to vegetation changes across biogeographic zones (Chapter 3).
- Identify climatically vulnerable protected areas (Chapter 4).
- Suggest management strategies., i.e., identifying climate-change refugia (Chapter 5).

Thesis structure

This thesis examines the impact of climate change on India's biodiversity, biogeographic zones, and protected areas (PA), and aims to identify climatically vulnerable and resilient protected areas of India to climate change. This thesis begins by reviewing existing scientific literature on the nexus of climate change, biodiversity conservation and protected areas of India and highlights the current knowledge gaps in India (Chapter 1). Chapter 2 details the study area (i.e., biogeographic zones and protected areas of India) including, the climatic condition of ten biogeographic zones of India.

Chapter 3 examines the linkage between long-term trends of vegetation and climate drivers in these different biogeographic zones. This chapter examines changes over the last two decades in the vegetation and climate drivers (i.e., factors that influence the behaviour of the climate system), and their correlation with vegetation changes in different biogeographic zones. Chapter 4 identifies the future climatic exposure & vulnerability of PAs in different biogeographic zones of India. Using the Climate and Ecological Niche Factor Analysis (CENFA) method this chapter identifies future climate exposure, sensitivity, and vulnerability of the Indian PAs, by looking at different future warming scenarios.

Chapter 5 identifies climate-change refugia for biodiversity for different taxon and compares and land-use practices to identify areas that will require management intervention, possible areas for restoration. It projects the possible impact of future climate change on biodiversity across different biogeographic zones, by identifying climate-change refugia for biodiversity, which is built on the work of the Wallace initiative (WI) (Warren *et al.,* 2018). Four different levels of future global warming (1.5, 2, 3 and 4ºC above pre-industrial levels) and downscaled projections derived from 21 general circulation models (GCMs) were used to ensure robustness. This chapter also looks at the overlap between refugia and the existing protected area (PA) network. The key messages are presented along with overall discussions and conclusions in Chapter 6.

Chapter 1
Literature review

Chapter 1. Literature review

1.1.Climate change

Climate change is one of the most serious global issues and has a direct effect on biodiversity (Habibullah *et al.,* 2022; Trew & Maclean, 2021; Kannan & James, 2009), influencing species distribution (Gillings *et al.,* 2015), changing phenological cycles (Lima *et al.,* 2021), and developing new physiological traits (Butt *et al.,* 2015; Grimm *et al.,* 2013; Lohmann *et al.,* 2012). Climate change is expected to become the primary driver of biodiversity loss by the end of the century (CBD, 2018). Species incapable of adapting to the rapidly altering, unsuitable climate will face extinction risk (Radchuk *et al.,* 2019). Many species have already experienced and responded to global warming (Thomas, 2010; Sintayehu, 2018) by range-shifting towards higher altitudes and latitudes (Gillings *et al.,* 2015; Couet *et al.,* 2022). Projected future distribution changes in species in response to climate change are primarily studied by employing the Species distribution modelling (SDM) approach, and over the years increasing studies globally and regionally modelled the distribution of species in different warming scenarios to understand species response towards changing climate.

For designing conservation strategies resilient to climate change, it is imperative to delineate regions that are projected to maintain climatic suitability for a substantial proportion of the extant biota (Warren *et al.,* 2013). The second phase of the Conference of Parties (CoP) to the United Nations Convention on Biological Diversity (CBD) in 2022 culminated in the formulation of a novel global biodiversity framework to spearhead worldwide efforts in biodiversity conservation (Hughes & Grumbine, 2023; Stephens, 2023). This framework, known as the 'Kunming-Montreal Global Biodiversity Framework' (GBF) (CBD, 2022), encapsulates four primary goals and 23 targets and has been ratified by representatives from 188 governments. The framework mandates nations to safeguard 30% of terrestrial and aquatic biodiversity by 2030. The realisation of these goals necessitates robust leadership from major countries and the implementation of mechanisms to ensure governmental adherence to their commitments. India has advocated a holistic 'ecosystems-based' approach to address biodiversity issues instead of endorsing area-based targets (Bhattacharya *et al.,* 2023).

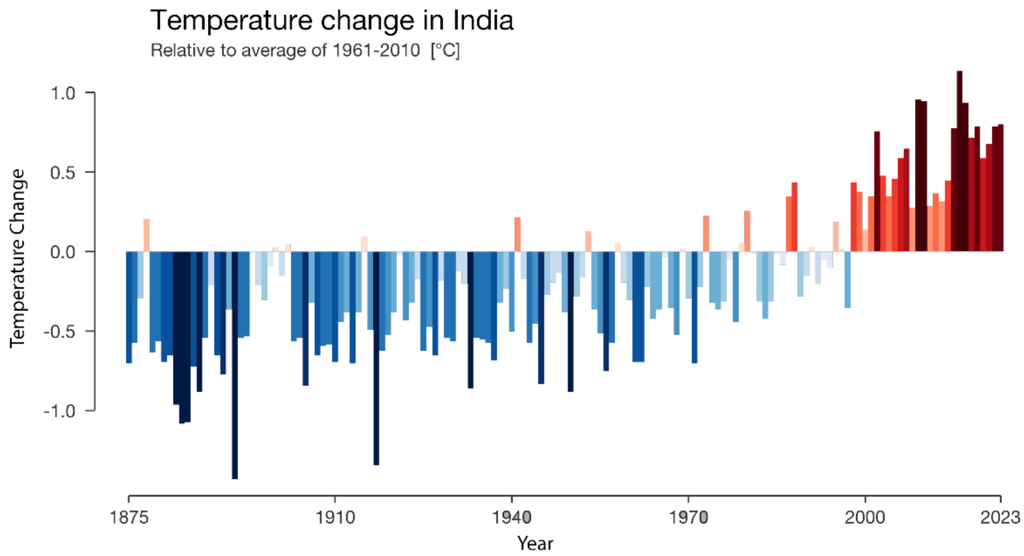

Figure 1. 1 Temperature change in India in the since pre-industrial era (1961-2010) (Source: Warmingstripes).

1.2. India's commitment to combat climate change.

The Intergovernmental Panel on Climate Change (IPCC) report (Lee *et al.,* 2023) suggests that India is on the precipice of enduring irreversible climatic transformations, characterised by increased incidences of heat waves, droughts, and unpredictable rainfall patterns if substantial mitigation strategies are not instituted. The IPCC's projections for the 21st Century indicate an intensification and increased frequency of heat waves and humid heat stress in the South Asian region. The report also anticipates an annual and summer monsoon precipitation increase during this century. It underscores the intensifying role of urbanisation in amplifying climatic impacts, particularly floods. The repercussions of climate change have already manifested in India, inflicting considerable economic and societal losses in recent years. The country has been subjected to severe floods (Chaubey *et al.,* 2023; Jain, 2023), cloudbursts (Samantaray and Gouda, 2023), and landslides in numerous states (Parkash, 2023; Martha *et al*., 2021), resulting in fatalities and widespread devastation.

India's commitment to achieving net-zero emissions by 2070, announced at COP26, represents a significant milestone in global climate action (Dhyani *et al.,* 2023). In its updated Nationally Determined Contributions (NDC) submitted to the UNFCCC in 2022, India pledged to reduce the emissions intensity of its GDP by 45% by 2030, relative to the 2005 level (Vishwanathan *et al.,* 2023; Dhyani *et al.,* 2023). This commitment is a crucial component of India's long-term strategy to achieve net-zero emissions by 2070. It underscores the country's proactive approach to mitigating climate change and its dedication to sustainable development.

1.3.Impact of climate change on Indian biodiversity

India stands as one of the planet's 17 'megadiverse' nations (Mittermeier *et al.,* 1998). Even though it only occupies 2.4% of the Earth's land, it holds 7-8% of the world's biodiversity (MoEFCC, 2018). Out of the global species population, 13.7% of birds, 8.6% of mammals, 7.9% of reptiles, 11.7% of fishes and 11.8% of plants are present in India (FAO, 2013). The climate heterogeneity of India is one of the factors that make the country biodiverse. India is divided into 10 biogeographic zones based on their unique climate, biodiversity, and topography (Rodgers and Panwar, 1988). Four of these biogeographic zones are also global biodiversity hotspots (Myers *et al.*, 2000). Climate change is imposing severe threats to a wide range of India's plants and animals (Telwala *et al.,* 2013; Priti *et al*., 2016). Limited studies have looked at the extent of climate change impacts across taxa and regions in India. There is a pressing need to gather information to identify the gaps in biodiversity and climate change-related studies in India.

For this systematic review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement was followed as a guide (Moher *et al*., 2010). A literature search was performed using 'Publish or Perish' software. Publish or Perish uses different search engines (e.g., Google Scholar, Crossref, Scopus etc) to retrieve a list of relevant studies. The search was limited to papers published between 2011 and 2022. Inclusion criteria involved the presence of the terms "Species Distribution Models", "Climate Change," and "India" in the title, keyword, or abstract sections. Only peer-reviewed articles were considered for inclusion. Following this search strategy, a total of 312 papers were identified. The initial step in paper selection involved screening the abstracts of the identified publications. Articles were excluded if they were i) purely conceptual studies (i.e., comment papers, review, and perspective) and had not included a real case study and ii) only contained SDM for the present condition. Thus, only articles that reported applications of SDM for projecting how the distribution of a particular species will be impacted by the changing future climatic conditions were retained for the analysis. In the end, a total of 105 publications over the years 2011 to 2022 were retained for the quantitative analysis.

1.4. Year-wise trend in publication

The reviewed literature encompassed publications from 2011 to 2022, and we observed an upward trend in the number of publications addressing future climate change impacts on species distribution (Figure 1. 2). These studies have mostly been published in the environment/Ecology journals.

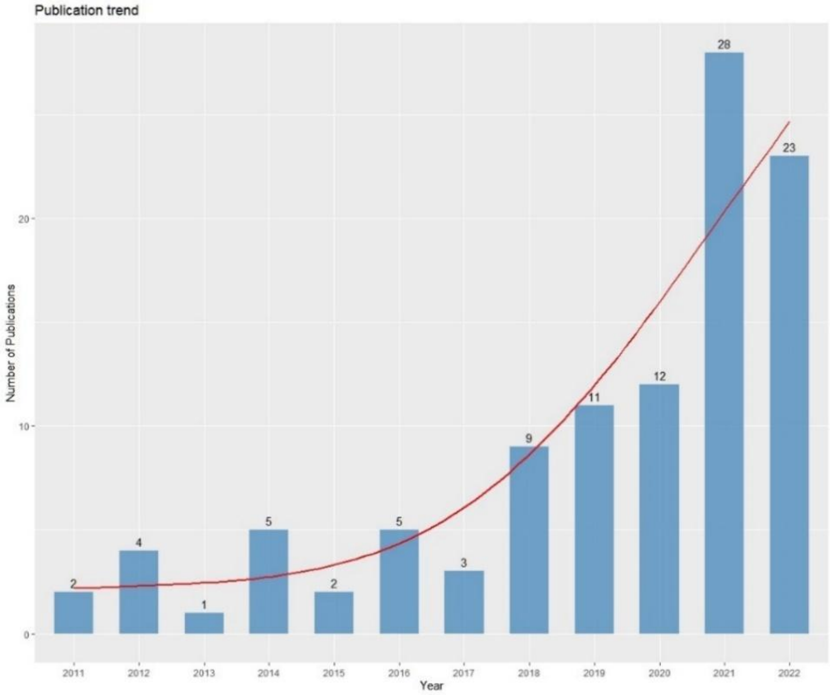

Figure 1. 2 Graph depicting increase of studies on future climate change impact on Indian biodiversity over the years.

1.5.Taxa wise studies

34 studies have taken a multi-species modelling approach, whereas 71 studies have focused on single species. Among the reviewed 105 studies, plants have the highest number of studies (70), followed by invertebrates (11). Both mammals and birds had nine studies conducted on them, while there are only two studies conducted each on Amphibians and Fishes, and one study each on reptiles and fungi. Among the 699 species from different taxa that we analysed, 674 species are native, which includes 542 endemics. 19 invasive species were analysed of which 15 were plant species, three insects and one mollusca (Species: *Achatina fulica*). Studies also included the future distribution of four migratory bird species six species of insect pests and one species of parasitic fungi (*Ophiocordyceps sinensis*). Among the species modelled, *Lantana camara* was the most studied (n=7). Further, of the total 699 species, 11 were listed as Critically Endangered (CR), 22 from Endangered (EN), 38 from Vulnerable (VU), 33 from Near Threatened (NT), 118 from Least Concern (LC) and nine from Data Deficient (DD) categories of IUCN Red List. Both native and migratory species are projected to shift or lose their distribution range in the future while most invasive species and insect pests are projected to gain range in the future.

1.6. Biogeographic zone-wise studies

Out of 105 papers analysed, 23 focused on future SDM at a national level in India. Five papers specifically investigated the Trans-Himalaya region, 49 papers examined the Himalayas, one paper explored the Semi-Arid region, two studies in Desert areas, three in the Gangetic Plains, 5 in the North-East, 14 in Deccan Peninsula, 15 in Western Ghats, and two studies were conducted in the Coastal region. Notably, no studies on future SDM were conducted in the Island biogeographic zones.

1.7. Climate change impacts

The majority of the existing studies report that climate change is projected to have negative impacts on all species across India, except for invasive species. The native species, as well as the migratory species, are projected to experience a drastic reduction of their habitat in future. For the species in the Himalaya and the Western Ghats, an upward shift is reported. Range shift and range contraction posed a threat to multiple endangered native species. Himalayan Oak (Hamid *et al.,* 2020; Rathore *et al.,* 2019) and Himalayan Birch (Dhyani *et al*., 2020; Khan *et al.,* 2022) among other tree species are projected to undergo a steep range contraction with the complete disappearance of its high suitability areas. For different forest types, forest physiological changes such as an increase in biomass, Net Primary Productivity (NPP) and increased Soil Organic Carbon (SOC) are projected in the future (Chaturvedi *et al*. 2011; Gopalakrishnan *et al*. 2011). A few species, such as Indian Peafowl (*Pavo cristatus*) (Nameer 2020), Golden Jackal (*Canis aureus*) (Rather *et al.,* 2020), Crocodile newt (*Tylototriton verrucosus*) (Das *et al*., 2022) is projected to gain suitable habitat in other parts of the country.

Invasive species i.e., Siam weed (*Chromolaena odorata*), *Lantana camara*, Oriental fruit fly (*Bactrocera dorsalis*), Guava fruit fly (*Bactrocera correcta*), Mango fruit borer (*Citripestis eutraphera*), Giant African snail (*Achatina fulica*), are projected to have climate change-induced range expansion. Studies reported some invasive species such as *Prosopis juliflora*, *Ageratum conyzoides, and Parthenium hysterophorus* will reduce their suitable habitat.

There is a considerable disparity in the number of species investigated across various taxa. Plants have been the most studied group, whereas there is a paucity of research on amphibians, reptiles, fishes, and fungi. The Global Biodiversity Information Facility (GBIF) database, commonly utilised in numerous studies to obtain occurrence points, exhibits a taxonomic bias (Troudet *et al.,* 2017). It shows a higher concentration of data for birds, mammals, and plants in contrast to insects, reptiles, and amphibians. This data unavailability in less explored taxa worsens when considered country or region-wise (Rocha-Ortega *et al.,* 2021). This uneven distribution of data may introduce potential limitations when analysing biodiversity and ecological patterns, particularly for the taxa with limited representation in the database. Hence there is a need for promoting research on these under-represented or less charismatic species. Citizen science initiatives have the potential to make valuable contributions to populating large-scale ecological databases (Gouranguine *et al*., 2019; Poisson *et al*., 2020). Most native species reviewed here are majorly losing habitat in the future, while pests and invasives are gaining habitat. This is like the trend observed globally and in other countries where pests and invasive species are expanding their distribution range with the changes in climatic conditions (Jarošík *et al.,* 2015; Rockwell-Postel *et al.,* 2020; Moran & Alexander, 2014). Climate change also leads to the emergence of novel ecosystems with uncertain functioning and contributions to human well-being (Pecl *et al.,* 2017). When combined with other biodiversity threats, such as human land use, interactive effects can further complicate the conservation outlook (Schulze *et al*., 2018).

1.8. Protected Areas & its importance.

Protected areas, which are defined as *recognized geographical spaces managed to achieve long-term nature conservation*, serve as the fundamental pillars of both national and international strategies to mitigate biodiversity loss (Gallardo *et al*., 2017). Globally, these areas constitute approximately 17% of the terrestrial and inland water surface of the Earth and 8% of its oceans. Consequently, these areas are deemed indispensable instruments in the attainment of the Sustainable Development Goals (SDGs) and the Aichi Biodiversity Targets (Mace *et al*., 2018). Most nations have pledged to increase the extent of their protected areas to 30% by 2030, in alignment with the Kunming–Montreal Global Biodiversity Framework of the United Nations Convention on Biological Diversity.

PAs constitute the cornerstone of the existing conservation paradigm (Schulze *et al*., 2018). PAs are instrumental in supporting biodiversity conservation (Lecina-diaz *et al*., 2019). They provide a plethora of indispensable ecosystem services, including carbon sequestration and groundwater recharge (Castro *et al*., 2015), provision of clean water (Segerstedt & Grote, 2015), temperature regulation (Xu *et al*., 2022), soil conservation, and serving as genetic repositories (Dures *et al*., 2019). Furthermore, they bolster local livelihoods (Karimi *et al*., 2020; Nelson & Chomitz, 2011; Stone & Nyaupane, 2016; Coad *et al*., 2008).

PAs function as natural buffers, safeguarding biodiversity against extreme events such as storms and floods. For instance, the vegetation within coastal PAs not only forms effective natural barriers against rising waters but also fortifies embankments, curbs soil erosion, and aids in landslide prevention (Lan & Hsu, 2021). In addition to their ecological benefits, PAs also contribute to socio-economic development by creating employment opportunities and generating substantial tourism revenue (Hasana *et al*., 2022; Balmford *et al*., 2009). It has been observed that local biodiversity is generally higher within PAs than in surrounding areas (Gray *et al.,* 2016). PAs have proven to be more effective in preserving species and populations compared to other conservation strategies (Geldmann *et al.,* 2013).

PAs are particularly effective for global biodiversity conservation when located in biodiversity hotspots (Joppa *et al.,* 2013), and when they are actively managed and adequately funded (Coad *et al*., 2019). PAs have been shown to slow the rate of global biodiversity loss (Geldmann *et al.,* 2019). For instance, vertebrate populations within PAs have been found to decline at a rate five times slower (−0.4% per year) than at comparable sites without protection (−1.8% per year) (Justin *et al.,* 2023).

Therefore, PAs can function as benchmarks for quantifying ecosystem alterations (Watson *et al.,* 2014). The relatively undisturbed and intact ecosystems within PAs offer unrivalled opportunities for research and monitoring of natural systems' responses to climate change (Gauzere *et al.,* 2016). Applied scientific research within these protected areas can enhance our understanding of how ecosystems and species respond to environmental changes. This knowledge can inform planning and management strategies, thereby aiding communities in their adaptation efforts. Thus, PAs not only serve as sanctuaries for biodiversity but also as living laboratories for research.

1.9. Protected areas and climate change

Conservationists regard PAs as an important policy for biodiversity conservation in the context of climate change (Hagerman & Satterfield, 2014), as they play an instrumental role in the global effort to counteract climate change, contributing to both climate change mitigation and biodiversity conservation. Since the 1980s, the scientific community has been cautioning about the inevitable challenges that climate change poses to the effectiveness of PAs (Peters & Darling, 1985). Climate change can exert significant impacts on PAs by altering species distributions, ecological communities, and entire ecosystems, with effects varying across different regions (Langdon & Lawler, 2015). PAs face multiple direct and indirect effects of climate change, including increased temperatures, melting snow and ice, severe droughts and storms, shifting seasons, rising sea levels, and environmental acidification (Gross *et al.,* 2017).

This dynamic environment causes both biodiversity gains and losses within PAs (Berteaux *et al.,* 2018; Velazco *et al.,* 2019). novel and disappearing climates within the PA network indicate that existing species may not have suitable climates in PAs in the future (Parks *et al.,* 2022). To inform conservation management and policymaking regarding climate change impacts on PAs, predicting the future climate within PAs becomes essential (Rannow *et al.,* 2014). While global studies on climate change impact exist, they often do not consider national authorities or the local extent of PAs (Williams *et al.*, 2007; Beaumont *et al.*, 2011). Research on the effects of climate change on PAs frequently exhibits a restricted geographical focus, often concentrating on regions such as North America or Europe (Batllori *et al.*, 2017; Nila *et al.,* 2019). However, to support conservation policies and management at multiple scales and align with global conservation objectives, it is imperative to have a comprehensive national perspective on the local impacts of climate change on individual PAs (Watson *et al.,* 2016). In the face of these challenges, PAs offer significant benefits. They contribute to climate change mitigation by preserving and restoring ecosystems that sequester carbon dioxide (CO_2) from the atmosphere (Melillo *et al.,* 2015). PAs, such as forests and wetlands, serve as carbon sinks, helping regulate the global carbon cycle (Dudley *et al.,* 2010). By protecting these carbon sinks, PAs mitigate greenhouse gas emissions and enhance the planet's capacity to remove CO_2 from the atmosphere. Furthermore, PAs play a crucial role in conserving biodiversity and maintaining ecosystem resilience amidst climate change (Hannah *et al.,* 2020). They protect habitats and ecosystems from human disturbances, preserving ecological processes and interactions that support biodiversity and ecosystem functioning (Dudley *et al.,* 2010). Given the uncertainties associated with climate change projections and impacts, adaptive management of PAs becomes paramount (Heller & Zavaleta, 2009). This approach involves monitoring ecological changes within PAs, evaluating management effectiveness, and adjusting actions based on new information (Williams *et al*., 2009). For instance, monitoring species distributions and habitat conditions can help identify climate-induced changes and inform appropriate management strategies, such as habitat restoration or assisted species migration (Heller & Zavaleta, 2009). Lastly, connectivity between PAs and surrounding landscapes is crucial for species and ecosystem persistence in the face of climate change (Heller & Zavaleta, 2009). It facilitates species movement and range shifts, ensuring viable populations and genetic diversity (Worboys *et al.,* 2016). Moreover, connectivity promotes the exchange of ecological processes and resources, enhancing overall resilience and adaptive capacity (Hannah *et al*., 2020). To achieve this, PAs should be integrated into broader conservation strategies, such as ecological networks and landscape-scale planning (Worboys *et al.,* 2016). In summary, protected areas play a pivotal role in addressing climate change challenges, preserving biodiversity, and enhancing ecosystem resilience, but their effectiveness requires comprehensive planning and adaptive management strategies to navigate the uncertainties of a changing climate.

India will have a considerable climate change impact in the future. With its vast and growing population, India's greenhouse gas emissions are on an upward trajectory. Concurrently, the potential impacts of climate change in India are grave, with encompassing sea-level rise, alterations in monsoon patterns, increased frequency of severe storms, and flooding. India is home to a diverse array of flora and fauna, and the country's network of protected areas plays a crucial role in conserving most of this biodiversity.

1.10. Protected areas of India as per Indian Wild Life Protection Act (IWPA), 1972)

There are four types of protected areas as per IWPA, 1972.

- **National Parks (NPs)** represent a category of protected areas primarily managed for the dual purposes of ecosystem conservation and tourism. These natural territories, encompassing both terrestrial and marine environments, are designated with the following objectives:
  a) To safeguard the ecological integrity of one or more ecosystems for the benefit of current and future generations,
  b) To prohibit exploitation or occupation detrimental to the designated purposes of the area, and
  c) To serve as a platform for spiritually enriching, scientifically enlightening, educationally valuable, recreationally enjoyable, and visitor-friendly opportunities, all of which must be in harmony with environmental and cultural considerations.
- **Wildlife Sanctuary (WLS)** can be defined as a designated protected area that is primarily managed for conservation, necessitating active management interventions. This encompasses terrestrial and/or marine regions that are subjected to proactive management strategies to guarantee the preservation of habitats and/or to cater to the needs of species.
- **Conservation Reserves (ConR)** are PAs that the State Government may declare, following consultations with local communities, as conservation reserves. These areas, particularly those adjacent to National Parks and Sanctuaries or those linking one protected area to another, are typically government-owned. The primary objective of such reserves is the protection of landscapes, seascapes, flora, fauna, and their habitats. To ensure the conservation, management, and maintenance of these reserves, the State Government is mandated to establish a Conservation Reserve Management Committee. This committee is

tasked with providing counsel to the Chief Wildlife Warden, emphasizing the importance of conservation efforts.

- **Community Reserves (ComR)** represent a category of PAs that the State Government may establish on private or community lands, excluding those already designated as National Parks, sanctuaries, or conservation reserves. This declaration is contingent upon the voluntary commitment of a community or an individual to the conservation of wildlife and its habitat. The primary objective of such reserves is the protection of fauna, and flora, and the preservation of traditional or cultural conservation values and practices. To ensure effective conservation, maintenance, and management of these reserves, the State Government is mandated to form a Community Reserve Management Committee, which serves as the authoritative body for these tasks.

Detailed descriptions of these four types of PA, (i.e., numbers, state-wise distribution, climatic conditions, biogeographic zones) are given in Chapter 2.

Within India's protected areas, only several studies have been published to assess the role of PAs in maintaining biodiversity in terms of climate change. This knowledge gap is concerning, as climate change poses a significant threat to Indian biodiversity. It is crucial to understand how Indian PAs can mitigate the impacts of climate change and conserve vulnerable species and ecosystems. Existing studies suggest that protected areas have played a crucial role in preserving habitat for a wide range of species. Further research and studies are needed to fully comprehend the effectiveness of protected areas in maintaining biodiversity under changing climatic conditions within India and develop targeted conservation strategies accordingly.

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Chapter 2

Study area:

Biogeographic zones, protected areas, and its climate conditions

Chapter 2. Study area

2.1. Biogeographic zones of India

Biogeography is the study of the geographical distribution of life on Earth and the reasons for the patterns one observes on different continents, islands, or oceans (Krebs, 2014; Briggs, 1995). *A biogeographic realm* is the broadest biogeographic division of Earth's land surface, based on distributional patterns of terrestrial organisms (Udvardy, 1975) (Figure 2.1). Among the 8 biogeographic realms, most of India falls under the "Indomalayan realm", except for the high Himalayas, which fall in the "Palearctic realm" (Figure 2.1).

Mani, 1974 made significant contributions to the field of biogeography in India. His work emphasized the dynamic nature of India's biogeography and its close correlation with the geomorphological evolution of a region. Later, in 1988, Rogers and Panwar from the Wildlife Institute of India proposed a biogeographical division of India to plan a protected area network for India. They categorized India into ten unique Biogeographic zones and 26 biotic provinces (Figure 2.2). This classification was based on the region's biogeographic traits, which include the spatial distribution of species, organisms, climatic conditions, and ecosystems (Rodgers & Panwar, 1988), enabling conservation planning both at the national and state levels. Four of these ten biogeographic zones are part of the *Global biodiversity hotspots* (Myers, 2000). These are, the Himalaya, Andaman & Nicobar Islands (Part of the Sundalands hotspot), the Northeast (Part of the Indo-Burma hotspot), and the Western Ghats. Two biogeographic zones (i.e., Eastern Himalayas, and Western Ghats) are also part of global priority places (WWF, 2008).

An account of each biogeographic zone, habitat type, and some of the key species is given later in this chapter. Also, each of these biogeographic zones varies climatically, ranging from tundra conditions in Trans-Himalaya to tropical conditions in the Western Ghats. To check the varying climate conditions in different biogeographic zones, 22 years (2000-2022) Land surface temperature (LST) (Source: Landsat) (proxy for temperature) and precipitation data (Source: CHIRPS Pentad) were obtained through Google Earth Engine (GEE) (https://earthengine.google.com/). Data were subsetted for individual biogeographic zones, and monthly Mean LST and total monthly precipitation for 22 (2000-2022) years were computed and plotted. Individual zone-wise analysis is given later in this chapter.

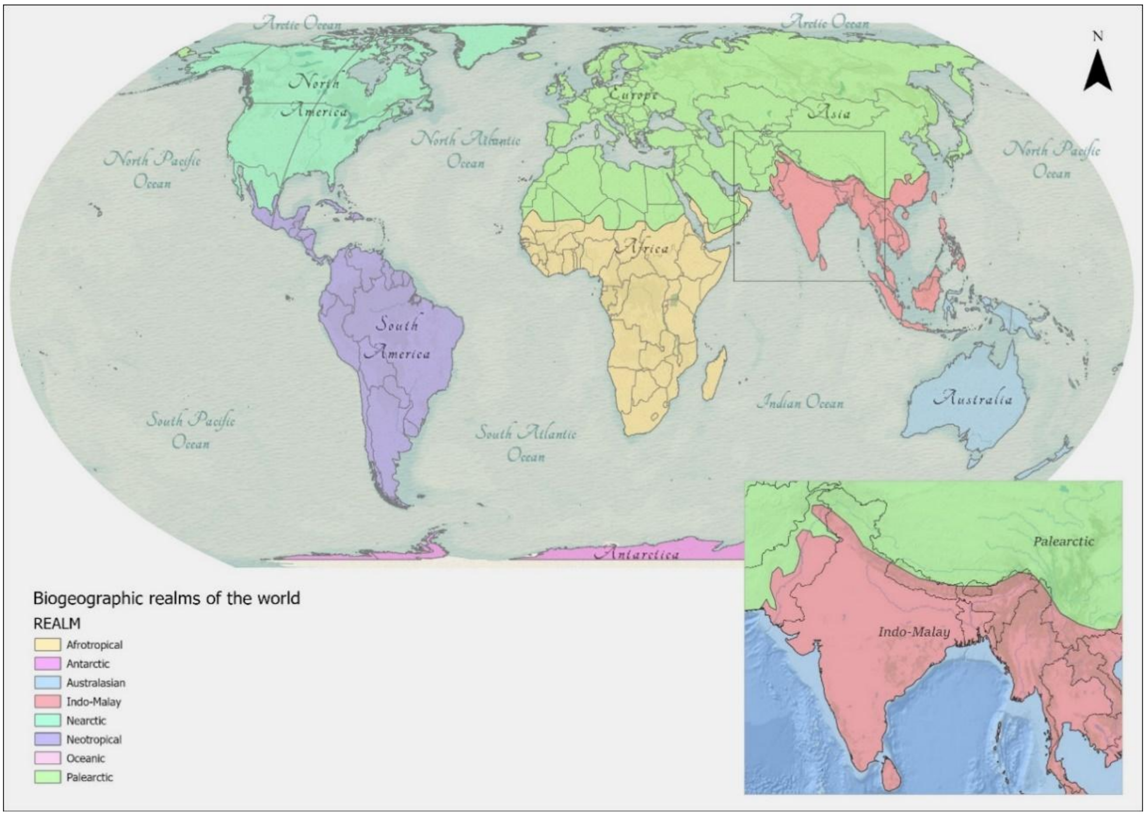

Figure 2. 1. Biogeographic realms of the world. Data source: WWF

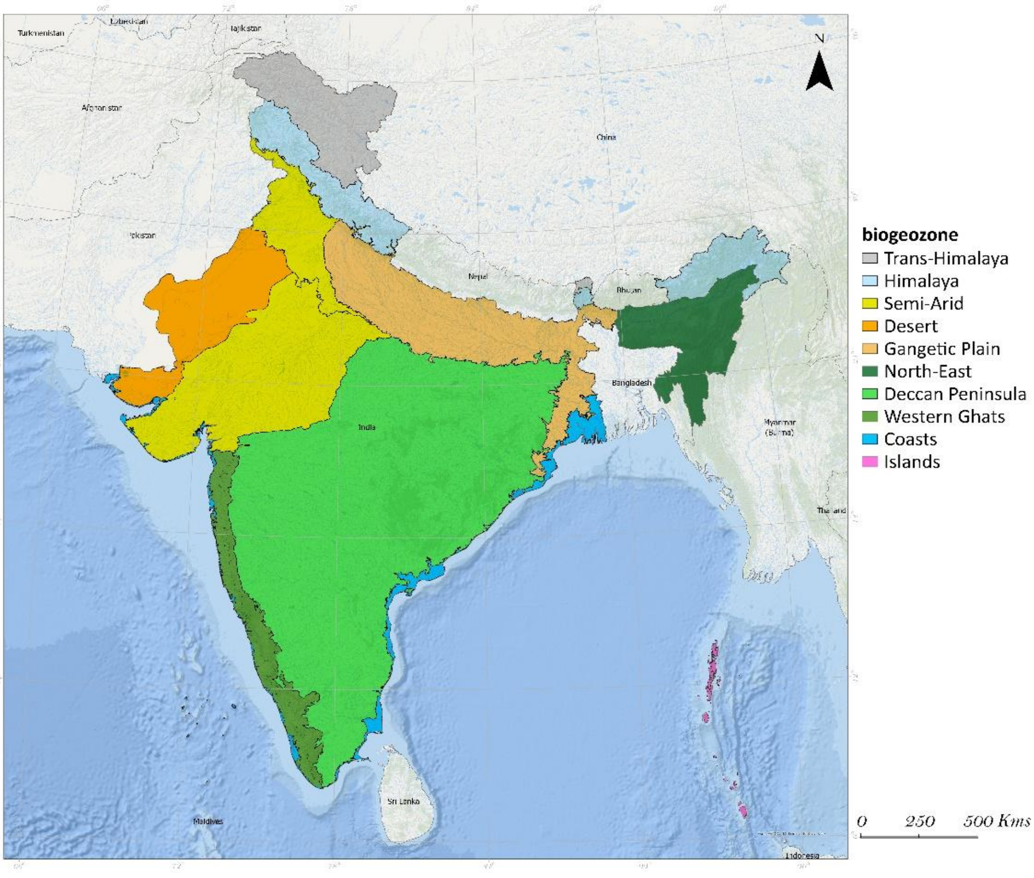

Figure 2. 2 The ten biogeographic zones of India (Data source: WII)

2.2. A brief account of protected areas of India

In 1936, India designated its first National Park, presently named Corbett NP in Uttarakhand designated under the United Provinces National Parks Act, 1935. The oldest declared Wildlife Sanctuary is Ranganathittu Bird Sanctuary, Karnataka, and Mudumalai WLS, Tamil Nadu in 1940. Over the years the number of PAs has increased from 67 to 1022 (Figure 2.3) (source: https://wiienvis.nic.in/). PAs in India now consist of 106 National Parks (NP), 573 Wildlife Sanctuaries (WLS), 123 Conservation Reserves (ConR) and 220 Community Reserves (ComR) (Source: www. wiienvis.nic.in) covering an area of 1,78,640.69 sq. km (Table 2.1). The latest declared NPs are Dihing Patkai NP and Raimona NP, Assam in 2021. The latest declared WLS are Arsikere sloth bear WLS, Pankapura wolf WLS, and Uttaregudda WLS in 2023. These three WLS are located in Karnataka. Community reserves and Conservation Reserves were added to the Wildlife (Protection) Amendment Act, 2003. Total designated area PAs cover 5.43% of the country. However, reserved forest or other governmental land effectively increases the area of available habitat of species (Jhala *et al.,* 2015).

2.2.1. Size of the protected areas

More than 600 Indian PAs (mainly Conservation reserves and Community reserves) are less than 10 sq. km in size (Figure 2.4). 30 PAs are larger than 1000 sq. km while only two are ≥ 5000 km^2. These two PAs are Kachchh Desert WLS (Area: 7506.22 km^2) in Gujarat, and Karakoram WLS (Area: 5000 km^2) in Ladakh. The largest national park in India is Hemis NP (Area: 3350 km^2) in Ladakh, followed by Desert NP (Area: 3162 km^2) in Rajasthan, and Gangotri NP (Area: 2390.02 km^2), in Uttarakhand. Hemis NP and Gangotri are both located in the Indian Himalaya and harbours a diverse species. Desert NP is in the Indian desert and home to xeric-adapted species, e.g., Great Indian Bustard, desert fox, Sandgrouse etc. The smallest NP is Fossil NP in Madhya Pradesh (Area =0.27 sq. km).

Table 2. 1 Types of protected areas of India

Category	No.	Total Area (km^2)	Coverage % of Country
National Parks	106	44,402.94	1.35
Wildlife Sanctuaries	573	127,197.55	3.87
Conservation Reserves	123	5,585.05	0.17
Community Reserves	220	1,455.15	0.04
Protected Areas (PAs)	1022	1,78,640.69	5.43

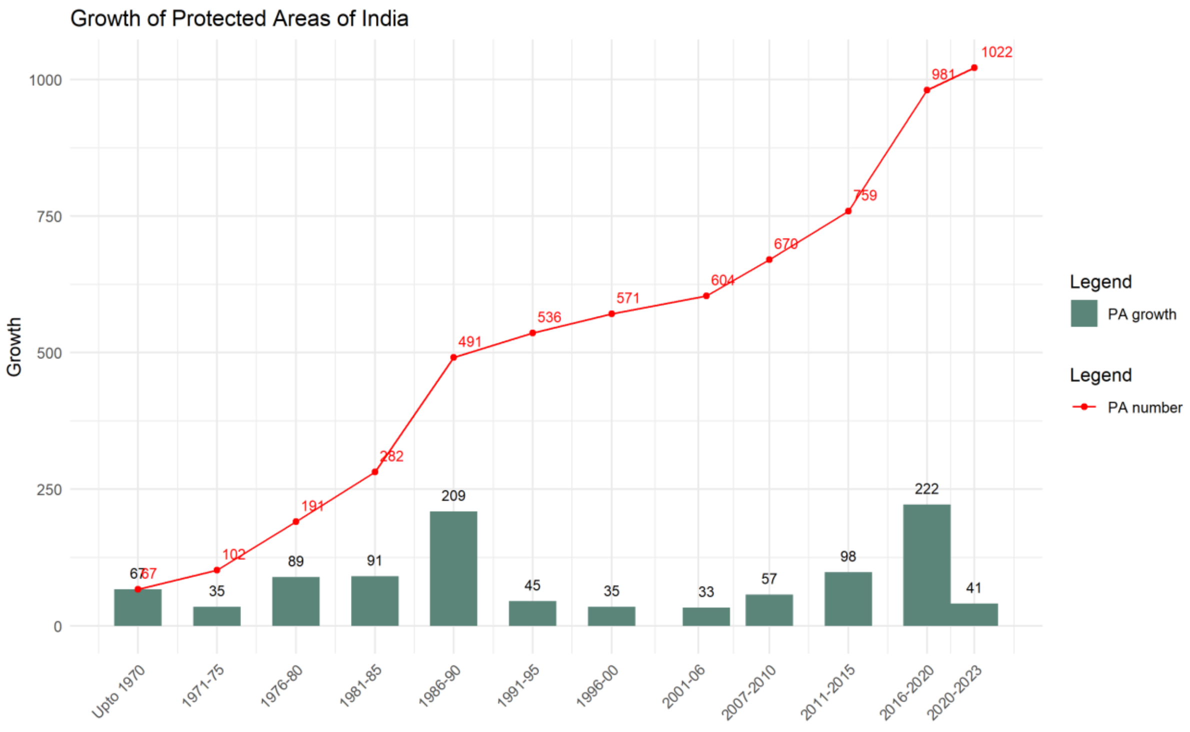

Figure 2. 3 Growth of protected areas of India over the years (Till July 2023) (Source: wiienvis.nic.in)

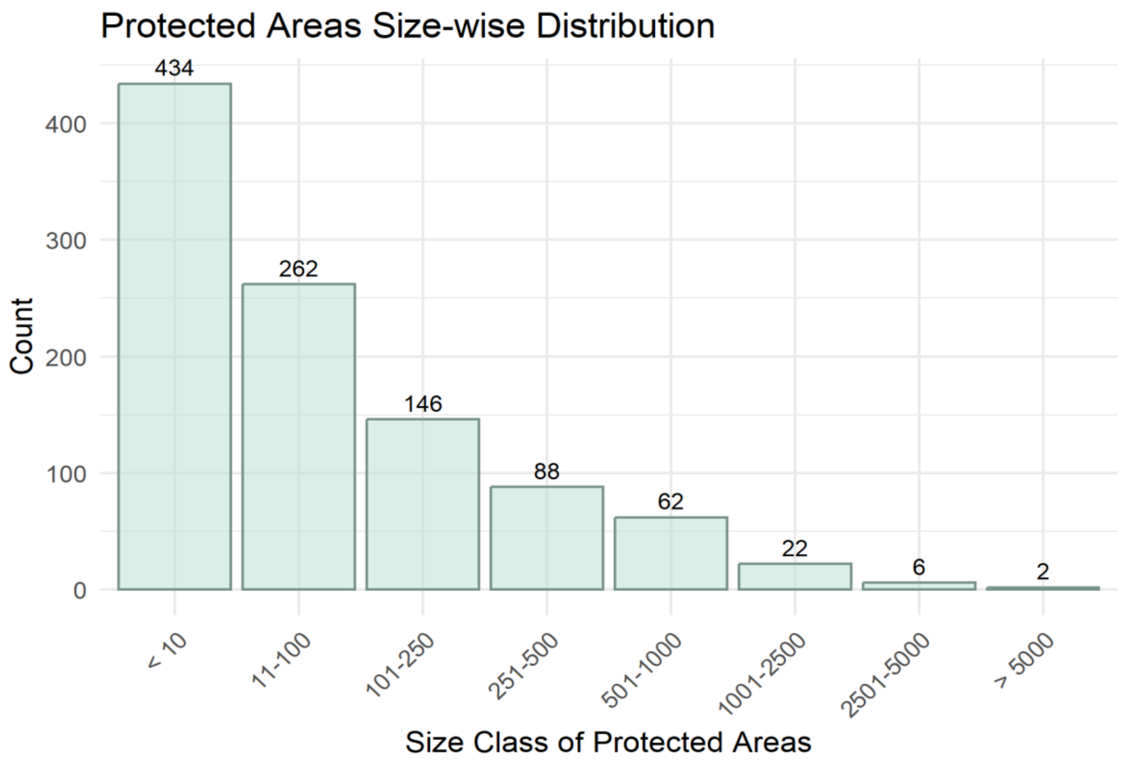

Figure 2. 4 Size wise distribution of protected areas of India (Source: WIIenvis.nic.in)

2.2.2. *State-wise distribution of protected areas*

Nagaland (n=119) has the highest number of designated PAs, followed by Andaman & Nicobar Islands (n=103) and Meghalaya (n=80) (Figure 2.5). Out of 119 PAs in Nagaland, 114 are Community reserves (Figure 2.9). This ensures the conservation of biodiversity, while simultaneously maintaining the rights of Nagaland's native people. Madhya Pradesh has the highest number of National Parks (n=11), followed by Assam (n=7). Andaman & Nicobar Islands (n=97), have the highest no of WLS, followed by Maharashtra (n=49) and Karnataka (n=35). Rajasthan has the highest number of ConR (n=36), followed by Jammu & Kashmir (n=30), and (n=14). Out of all the states, Punjab does not have any national parks. Sikkim has the highest area-wise PA (30.77%) coverage, followed by Goa (20.29%). 15 states have at least one ConR, and 9 states have at least one ComR. It is also to be noted that conservation reserves are more common in the western part (Figure 2.8), where the east has more community reserves (Figure 2.9).

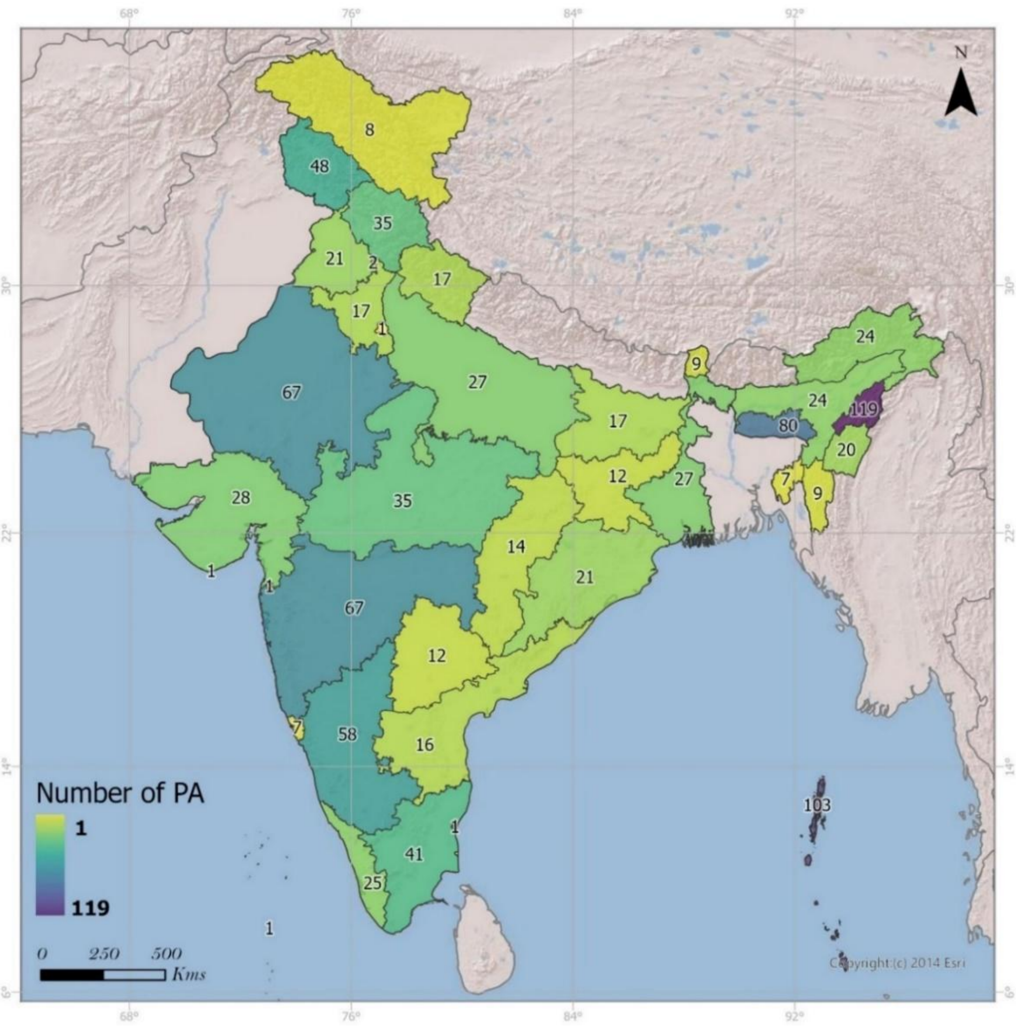

Figure 2. 5 State-wise distribution of protected areas of India (Source: WIIenvis.nic.in)

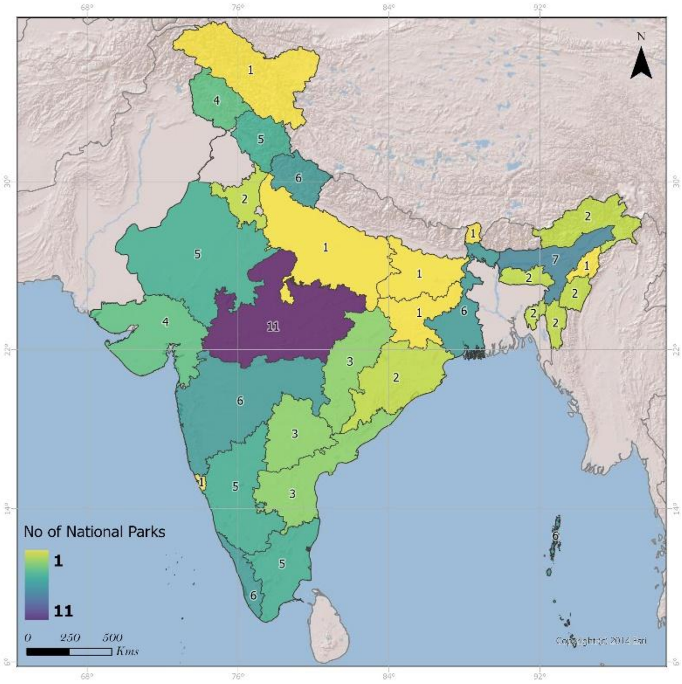

Figure 2. 8 State-wise distribution of National Park.

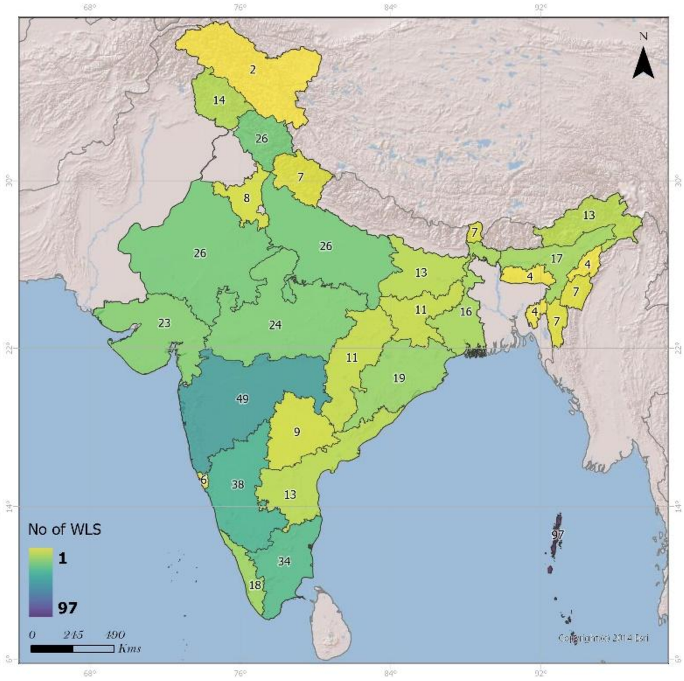

Figure 2. 7 State-wise distribution of Wildlife Sanctuary (WLS).

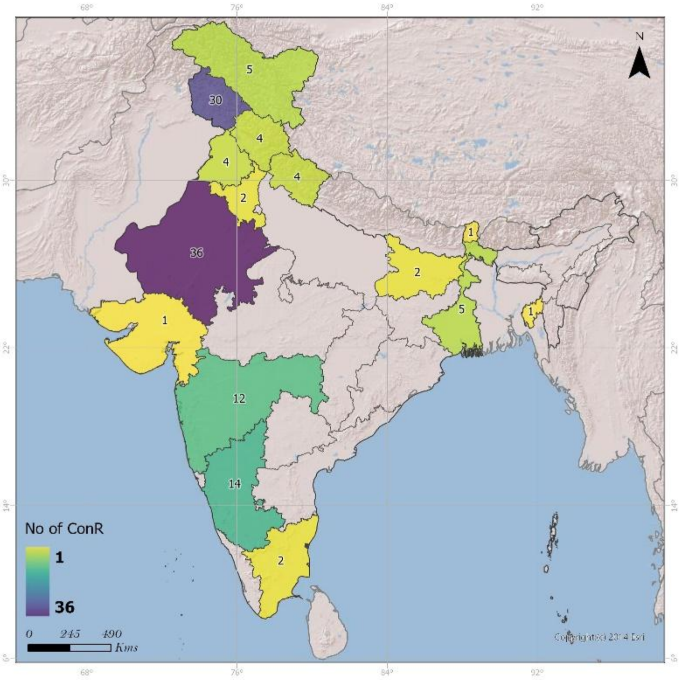

Figure 2. 9 State-wise distribution of Conservation Reserves (ConR).

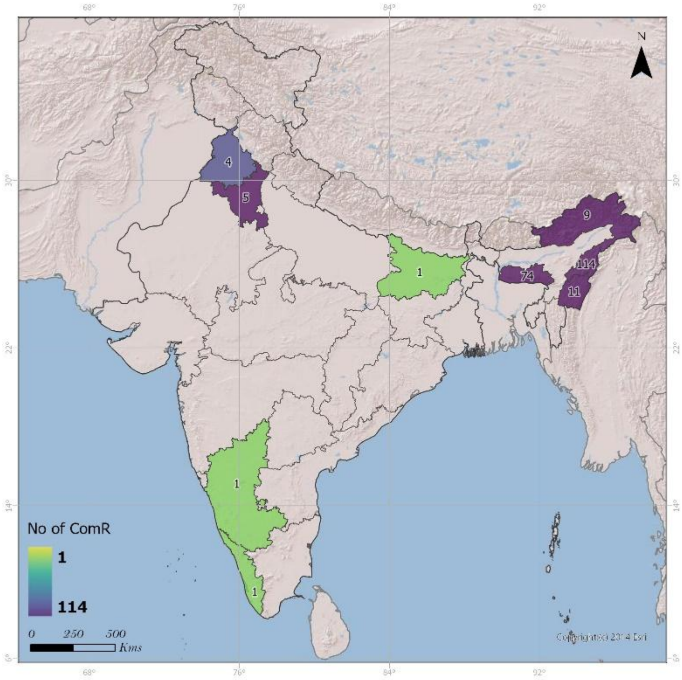

Figure 2. 6 State-wise distribution of Community Reserves (ComR).

Table 2. 2 State-wise distribution and percent coverage of PAs of India

State & UT name	National Parks	Wildlife Sanctuaries	Community reserves	Conservation reserves	Percentage
Andaman & Nicobar Islands (UT)	6	97	0	0	19.55
Andhra Pradesh	3	13	0	0	4.99
Arunachal Pradesh	2	13	9	0	11.99
Assam	7	17	0	0	5.60
Bihar	1	13	1	2	4.01
Chandigarh (UT)	0	2	0	0	22.81
Chhattisgarh	3	11	0	0	4.93
Dadra & Nagar Haveli (UT)	0	1	0	0	18.77
Daman & Diu (UT)	0	1	0	0	1.95
Delhi (UT)	0	1	0	0	1.32
Goa	1	6	0	0	20.39
Gujarat	4	23	0	1	8.84
Haryana	2	8	5	2	1.01
Himachal Pradesh	5	26	0	4	14.81
Jammu & Kashmir (UT)	4	14	0	30	8.76
Jharkhand	1	11	0	0	2.74
Karnataka	5	38	1	14	5.83
Kerala	6	18	1	0	6.99
Ladakh	1	2	0	5	7.56
Lakshadweep (UT)	0	1	0	0	0.03
Madhya Pradesh	11	24	0	0	3.70
Maharashtra	6	49	0	12	3.29
Manipur	2	7	11	0	4.30
Meghalaya	2	4	74	0	2.24
Mizoram	2	7	0	0	4.13
Nagaland	1	4	114	0	6.62
Odisha	2	19	0	0	5.19
Puducherry (UT)	0	1	0	0	0.81
Punjab	0	13	4	4	1.02
Rajasthan	5	26	0	36	4.25
Sikkim	1	7	0	1	30.77
Tamil Nadu	5	34	0	2	6.10
Telangana	3	9	0	0	5.08
Tripura	2	4	0	1	6.23
Uttar Pradesh	1	26	0	0	2.63
Uttarakhand	6	7	0	4	14.62
West Bengal	6	16	0	5	5.45

2.3. *A brief account of the biogeographic regions of India*

2.3.1. Trans-Himalaya

The Trans-Himalayan region, as depicted in Figure 2. 10, encompasses an area of over 1,84,000 km², with elevations ranging from 4500 to 6000 meters. This region is divided into two distinct provinces: the Ladakh mountains, which constitute 3.3% of the area, and the Tibetan plateau, which makes up 2.2%. Despite its sparse vegetation and limited species diversity (Kala, 2000), the Trans-Himalaya is home to a variety of unique and endangered plants (Sharma *et al.,* 2018) and animal species (Chandra *et al.,* 2019). Recognized as one of India's most ecologically sensitive biogeographic zones (Rodgers and Panwar, 1988), the Trans-Himalaya faces significant potential instability due to the inherent vulnerability of mountain ecosystems (Skeldon, 1985). Large portions of the region are characterized by bare rock and glaciers (Bajracharya *et al*., 2015). Despite the harsh cold desert conditions, the Trans-Himalayan region supports a low yet highly endemic faunal diversity (Kala and Mathur, 2002). It is the habitat of several species including the snow leopard (*Panthera uncia*), black and brown bears (*Ursus thibetanus & U. arctos*), Himalayan wolf (*C. lupus*), marmots (*Marmota himalayana*), marbled cat (*Pardofelis marmorata*), ibex (*Capra sibirica*), and kiang (*Equus kiang*) (Chandra *et al*., 2018), along with migratory species such as the Black-necked Cranes (*Grus nigricollis*) (Mahar *et al.,* 2022). The Trans-Himalayan region, despite its sparse vegetation, boasts one of the world's richest ungulate communities (Ahmed, 2022).

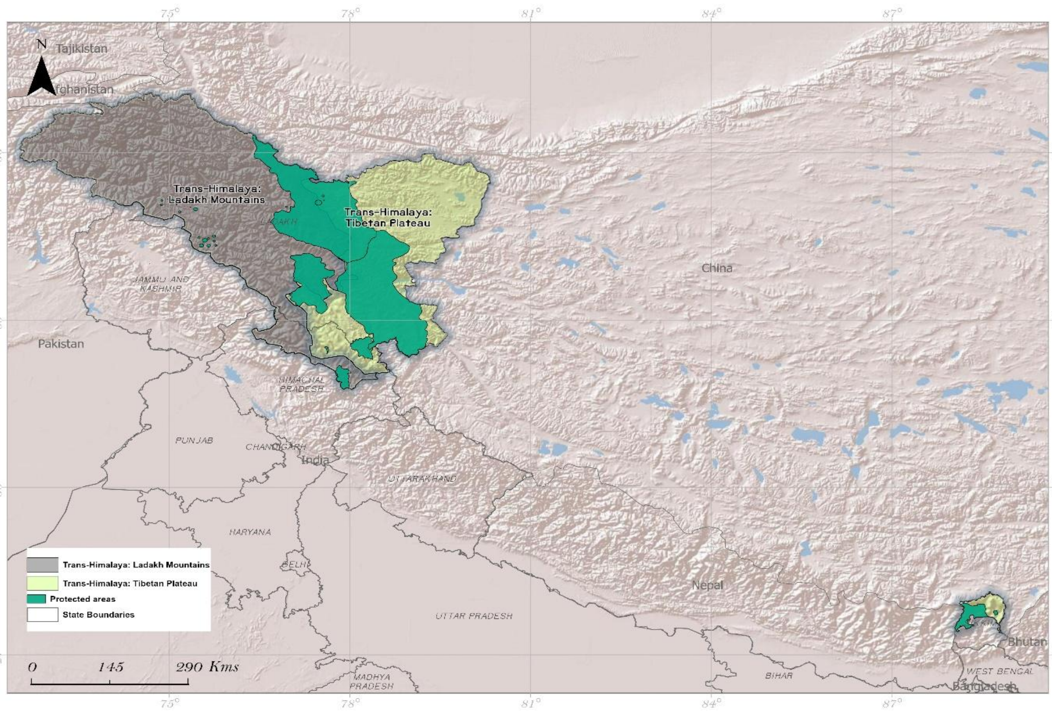

Figure 2. 10 Biogeographic zone, provinces, and PAs of Trans-Himalayas

- ***Climate condition of the Trans-Himalaya region***

Situated at high altitudes, this region experiences extreme variations in temperature and precipitation throughout the year (Phartiyal & Nag, 2023). During the winter months, the mean monthly Land Surface Temperature (LST) plummets to as low as -15°C (Figure 2.11), leading to freezing temperatures and harsh conditions. In contrast, the summer months witness a substantial increase in temperatures, with the mean monthly LST reaching up to 25°C. The Trans-Himalayan region receives a low to moderate amount of rainfall (Rajbhandari *et al.,* 2018). The rainfall can range during the summer months, ranging from 4mm to 76mm (figure 2.12).

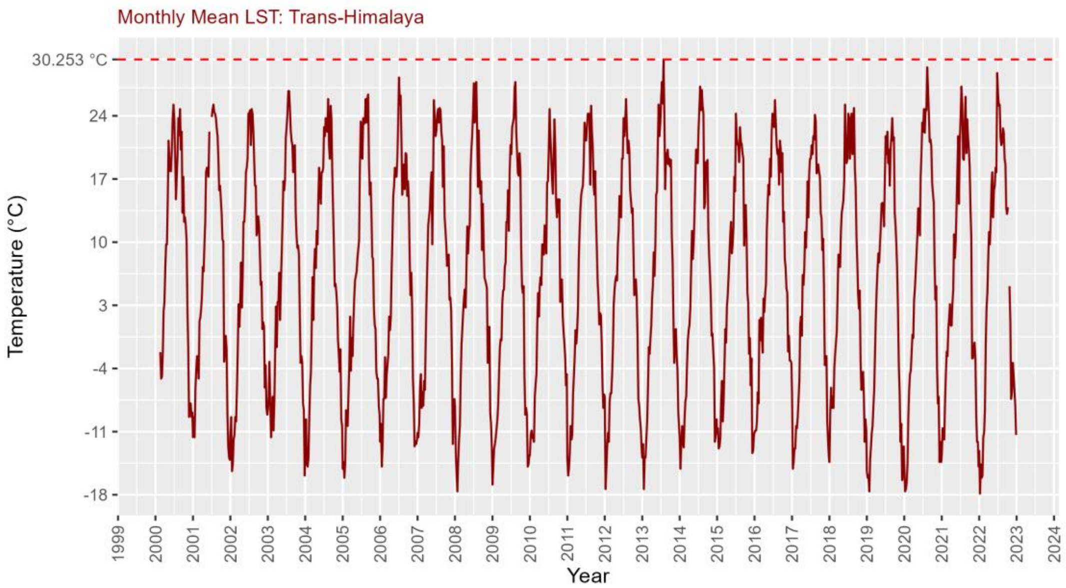

Figure 2. 12 Monthly mean LST of Trans-Himalayas from 2000-2022

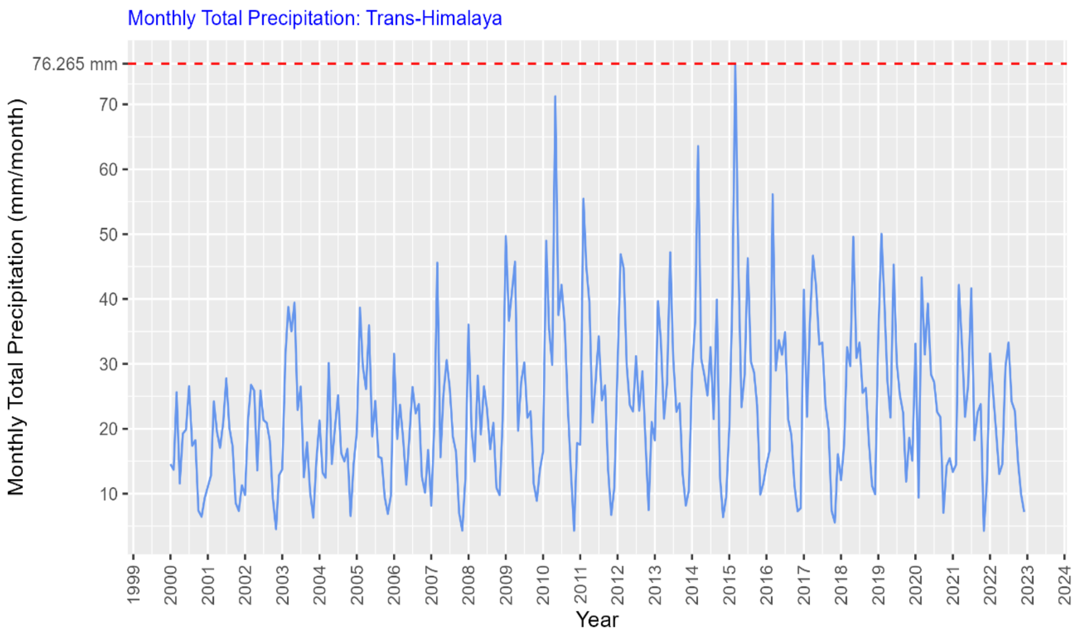

Figure 2. 11 Monthly total precipitation of Trans-Himalaya from 2000-2022

2.3.2. Himalaya

The Himalayan range, the youngest and highest mountain range globally, exhibits a climatic spectrum from tropical to arctic conditions (Mani, 1974). The unique biodiversity of the Himalayas is attributed to its high altitude, steep gradient, and abundant temperate flora. This region is divided into four biogeographical provinces, namely Northwest, West, Central, and East (Rodgers and Panwar, 1988) (Figure 2.13), collectively accounting for approximately 6.4% of the country's total area. The ecology of the Himalayas is predominantly governed by temperature (Mani, 1974), except for the extreme eastern province, which is influenced by Monsoon rainfall. The Himalayas play a pivotal role in modulating and directing the monsoon rainfall across the country (Valdiya, 1999). The fauna of the Himalayan ranges includes significant species such as wild sheep (*Ovis ammon*), mountain goats (*Hemitragus jemlahicus*), ibex (*Capra sibirica hemalayanus*), musk deer (*Moschus leucogaster*), and serow (*Capricornis sumatraensis thar*). Other species like the red panda, black bear, dholes, wolves, martens, weasels, leopards, and snow leopards also inhabit this region (Chandra *et al.,* 2018). However, carnivores are relatively scarce and face threats to their survival (Maheswari and Sathyakumar, 2020; Pal *et al.,* 2021). The Eastern Himalaya is dominated by tropical rainforests, while the Central and Western Himalaya are characterized by dense subtropical and alpine forests. The Himalayan flora is abundant in oak, chestnut, conifer, ash, pine, and deodar (Painuli *et al.,* 2021; Kandel *et al.,* 2019).

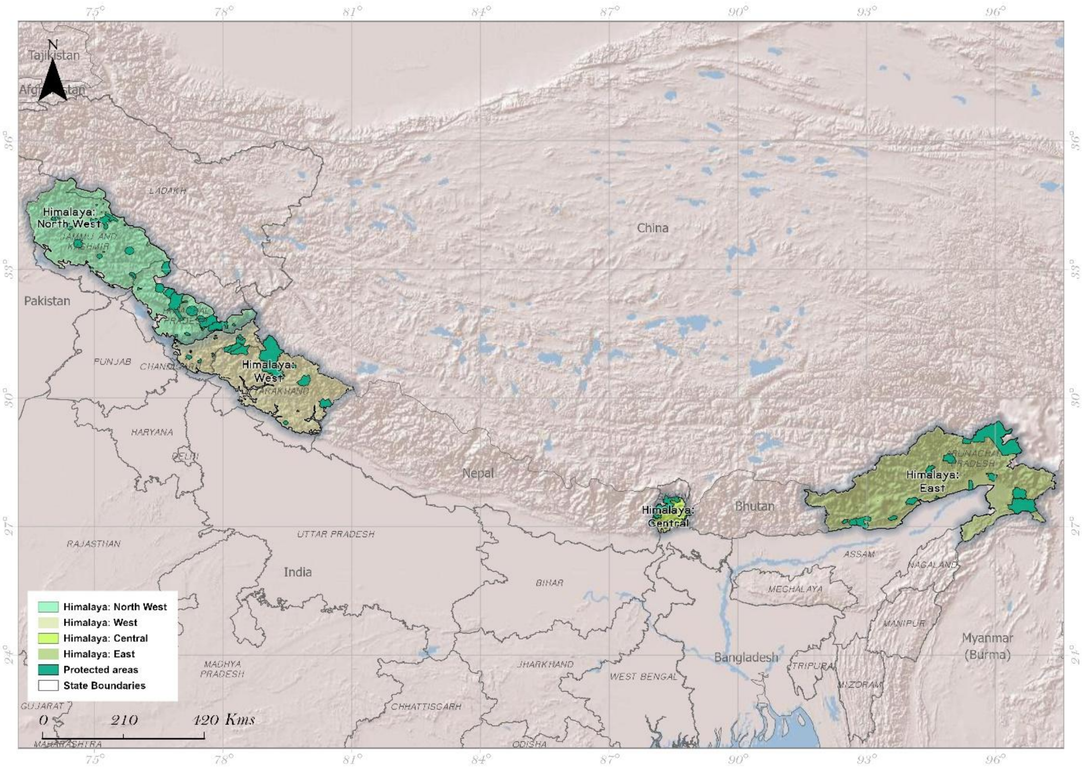

Figure 2. 13 Biogeographic zone, provinces, and PAs of Himalaya

- ***Climate condition of the Himalaya region***

The Himalaya exhibit diverse climatic conditions due to their vast geographical extent and elevation variations (Gautam *et al.,* 2013; Sabin *et al.,* 2020). Total monthly precipitation ranges from 5mm to 350 mm (Figure 2.15) and the mean monthly Land Surface Temperature (LST) (Fig. 2.14) of 15°C to 25°C. Lower regions have milder climates fostering lush greenery, and agriculture (Sati, 2005). As elevation increases, temperatures drop drastically, with mean monthly LST plummeting to 0°C or below in higher reaches (Sabin *et al.,* 2020). These zones feature snow-capped peaks, and glaciers, and have extreme climate conditions. The Himalaya's diverse climates influence monsoon dynamics in the Indian subcontinent, playing a crucial role in the region's climate regulation (Kathayat *et al.,* 2017; Shekhar *et al.,* 2010).

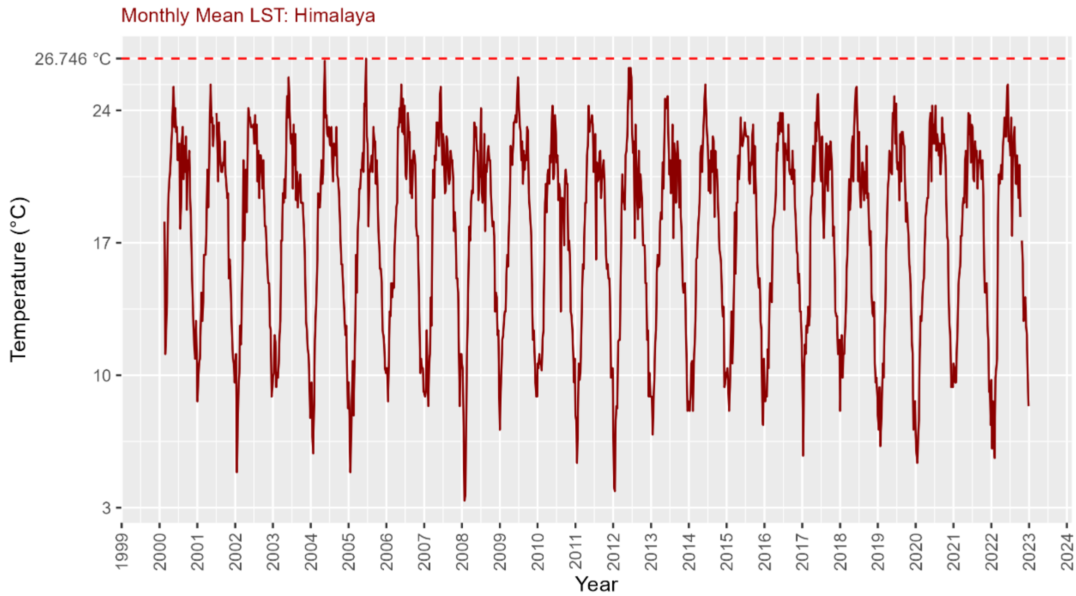

Figure 2. 15 Monthly mean LST of Himalayas from 2000-2022

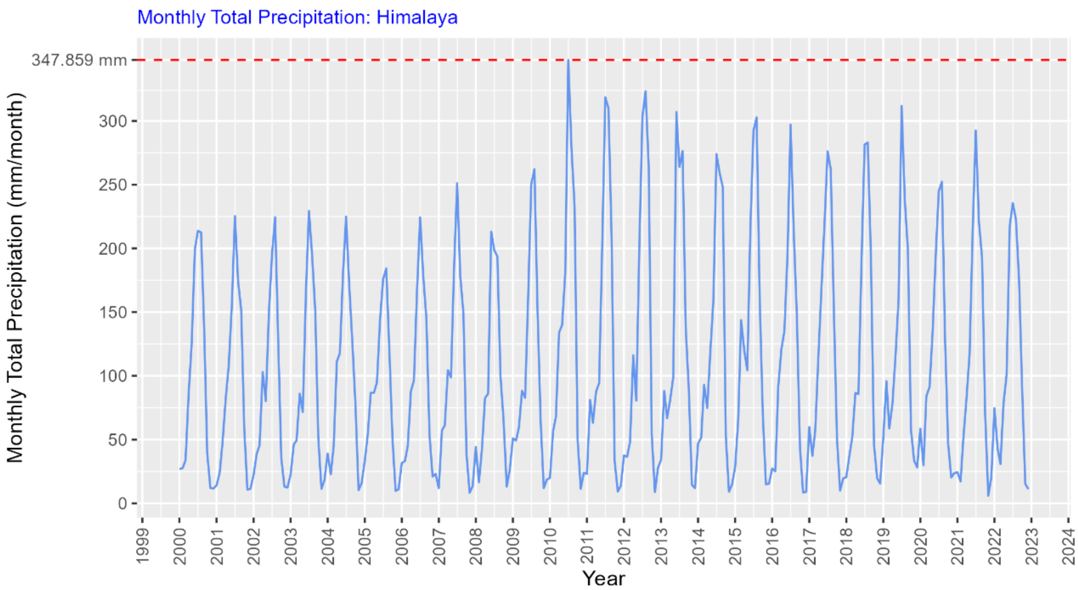

Figure 2. 14 Monthly total precipitation of Himalayas from 2000-2022

2.3.3. Desert

The Indian Desert Zone, which makes up 6.6% of the country's total geographical area, is divided into two biogeographical provinces: the Thar Desert, and the Kachchh Desert (Rodgers and Panwar, 1988). The Thar, or Great Indian Desert, is the larger of the two, bordering Pakistan and encompassing parts of Rajasthan, Punjab, and Haryana (Figure 2.16). It spans 170,000 km^2 within India. The region is marked by extreme climatic conditions, with hot, dry summers and cold winters. It features vast grasslands that are home to several endangered mammalian species, including the wild ass (*Equus hemionus khur*), Wolf (*Canis lupus*), Caracal (*Felis caracal*), and Desert Cat (*Felis libyca*) (Prakash, 1974), as well as birds of conservation concern such as the critically endangered Great Indian Bustard (*Ardeotis nigriceps*) (Dutta *et al.,* 2013). The hot, arid parts of the desert are inhabited by gazelles, foxes, spiny-tailed lizards, and snakes. Kachch desert has a breeding ground for some of the largest flocks of lesser and greater flamingos. The vegetation primarily consists of xerophytic plants, with 206 species documented in the Thar desert (Charan & Sharma, 2016).

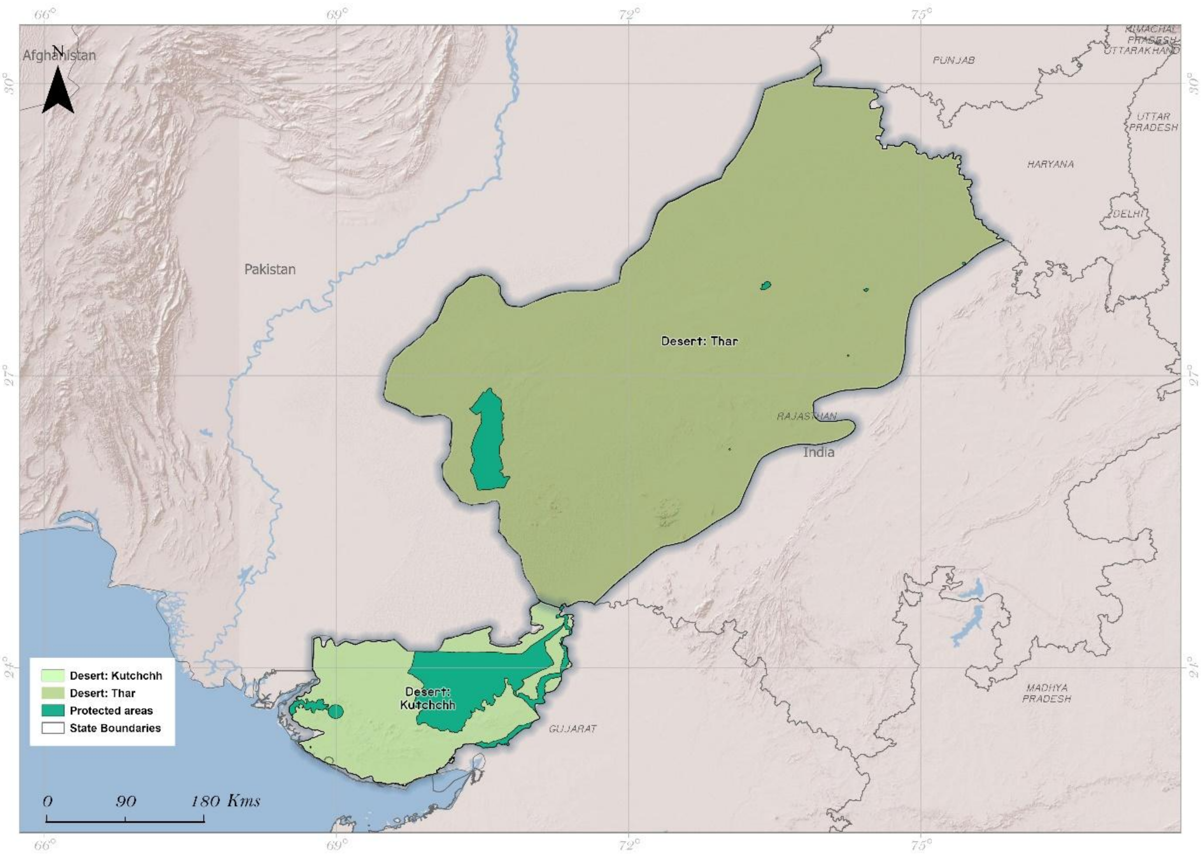

Figure 2. 16 Biogeographic zone, provinces, and PAs of Desert

- ***Climate condition of desert region***

The Indian desert, known for its arid and harsh climatic conditions (Rajesh & Goswami, 2023), exhibits a unique combination of extreme factors that shape its climate. Characterized by total monthly precipitation ranging from 0mm to 276mm (Figure 2.18), the region experiences prolonged periods of dryness and water scarcity. The sparse and sporadic rainfall patterns contribute significantly to the desert's arid landscape and limited vegetation. Moreover, the mean monthly land surface temperature (LST) fluctuates dramatically, ranging from 20°C to 52°C (Figure 2.17). These soaring temperatures are a result of intense solar radiation, prolonged sun exposure, and the scarcity of cloud cover, making the deserts the hottest zone in India

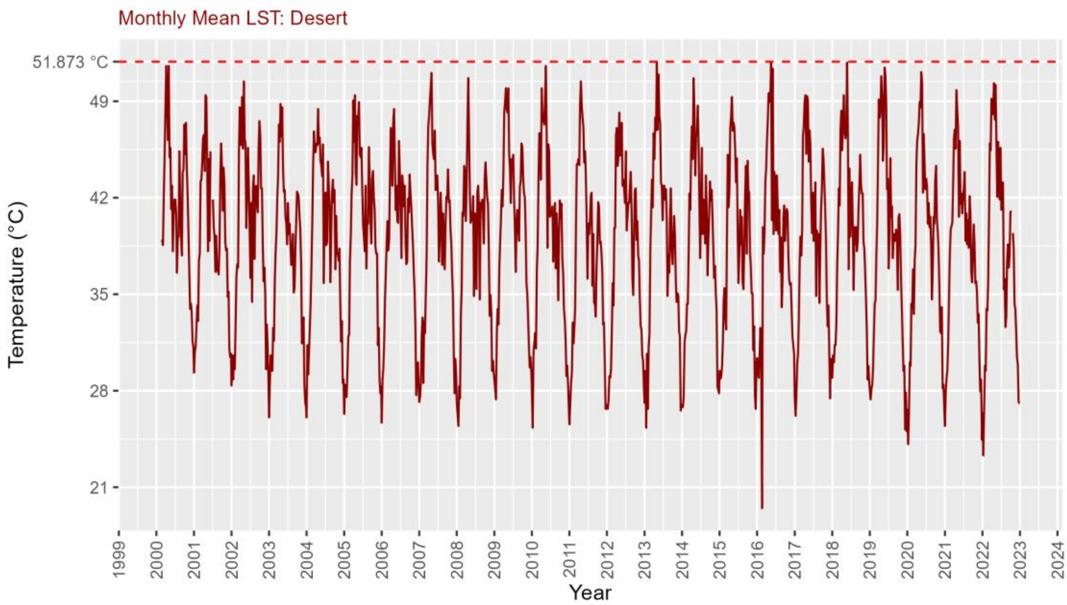

Figure 2. 18 Monthly mean LST of Deserts from 2000-2022

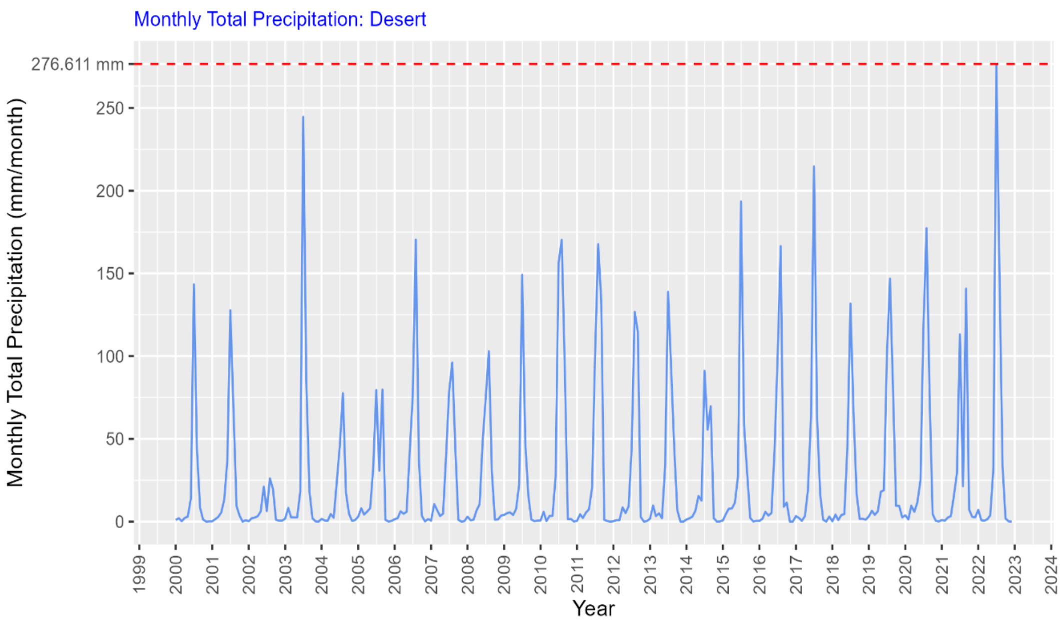

Figure 2. 17 Monthly total precipitation of Desert from 2000-2022

2.3.4. Semi-Arid

The Semi-arid zone, which comprises 16.6% of India's total geographical area, serves as an ecological transition zone between the arid desert and the lush Western Ghats (Fig 2.19). This region is divided into two provinces: the Punjab Plains (3.7%) and Gujarat Rajputana (12.9%) (Figure 2.19) (Rodgers and Panwar, 1988). The region mainly comprises grasslands, xeric or barren lands, agricultural fields (vegetated and fallow), minor water bodies, and urban settlements.

The Semi-arid Region supports a unique array of flora and fauna (Bharucha & Homji, 1965; Dakshini, 1985; Sharma, 2013). It is home to several endangered species that are flagship of this region, including the Asiatic Lion (*Panthera leo persica*), Indian wild ass (*Equus hemionus khur*), Caracal (*Felis caracal*), Golden Jackal (*Canis aureus*), and Indian Wolf (*Canis lupus*) (Jhala *et al.,* 2019; Jhala *et al.,* 2020; Chourasia *et al.,* 2020; Jangid *et al.,* 2022; Jhala *et al.,* 2022). The grasslands of this region provide habitat for cervid species such as the Sambar (*Cervus unicolor*) and Chital (*Axis axis*), as well as the Blackbuck (*Antilope cervicapra*) (Bagchi *et al.,* 2004; Jhala & Isvaran, 2016; Chatterjee *et al.,* 2023).

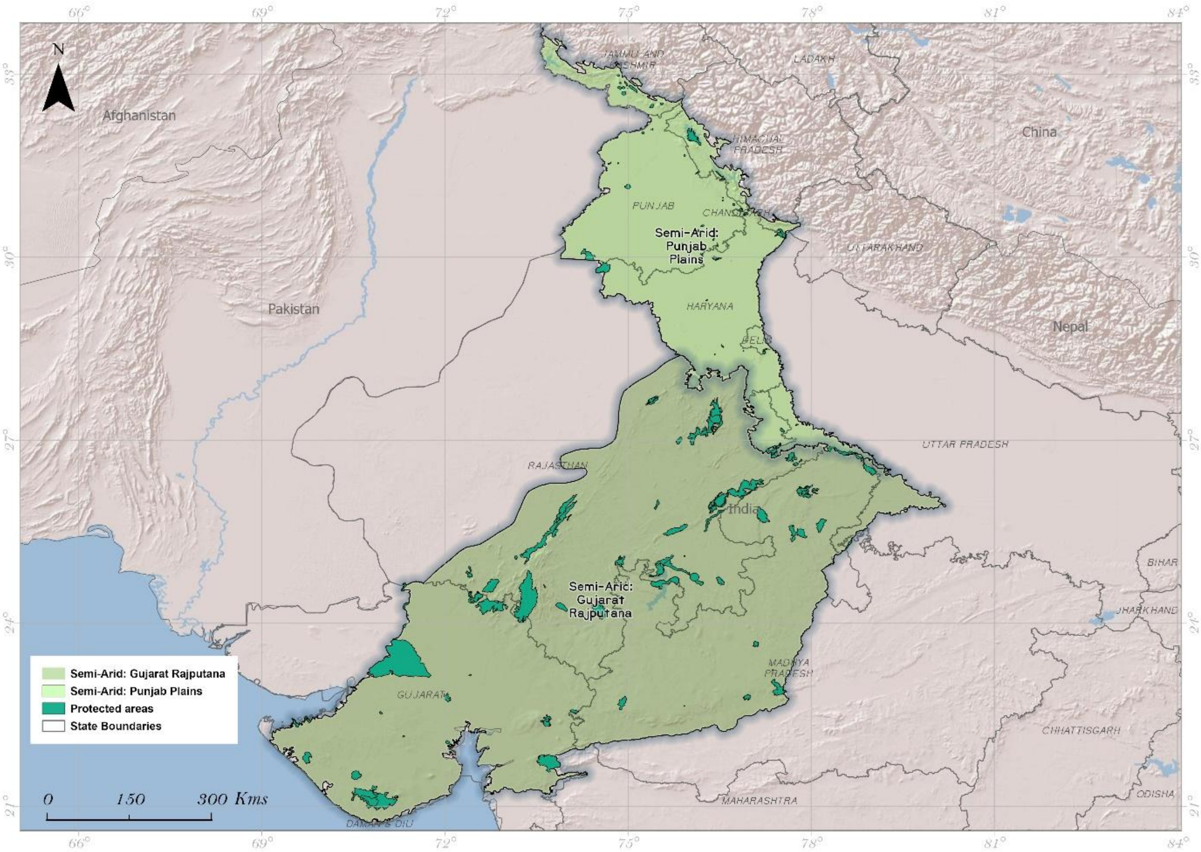

Figure 2. 19 Biogeographic zone, provinces, and PAs of Semi-arid

- ***Climate condition of Semi-arid region***

The semi-arid regions of India exhibit a distinctive climate characterized by a delicate balance between aridity and periodic, moderate rainfall (Singh & Kumar, 2015; Saini *et al.,* 2022). The mean monthly land surface temperature (LST) spans from 20°C to 52°C (Fig 2.19), representing a wide temperature range that influences various ecological processes. During summer, heat stress increases the risk of droughts (Wable *et al.,* 2019). With total monthly precipitation ranging from 0mm to 276mm (Figure 2.21), these regions experience a semi-dry environment, subjecting them to water scarcity and the challenges of sustaining agriculture and ecosystems. However, the semi-arid climate also allows for the establishment of unique flora and fauna that have adapted to survive under these challenging conditions. These regions provide essential contributors to India's biodiversity and play a crucial role in supporting human livelihoods through agro-pastoral activities.

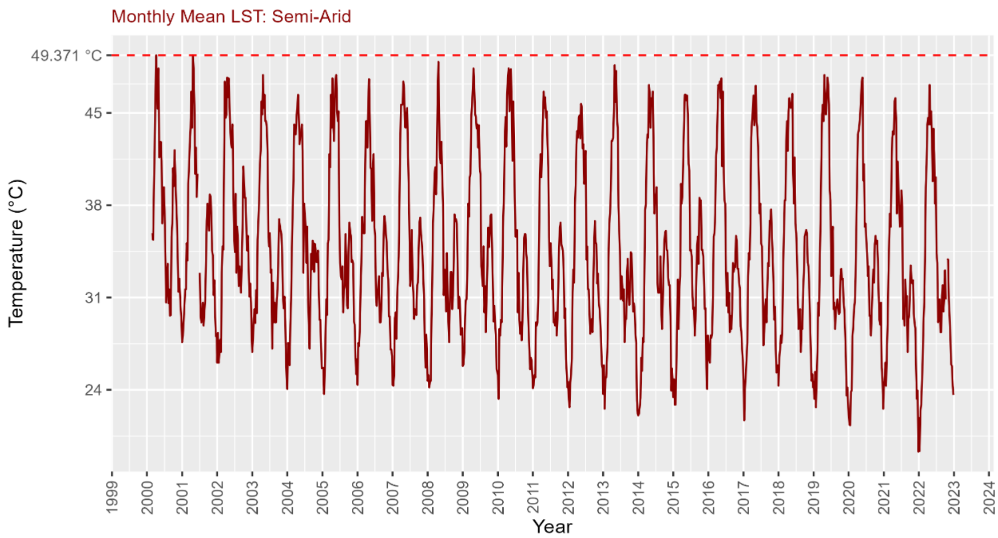

Figure 2. 21 Monthly mean LST of semi-arid from 2000-2022

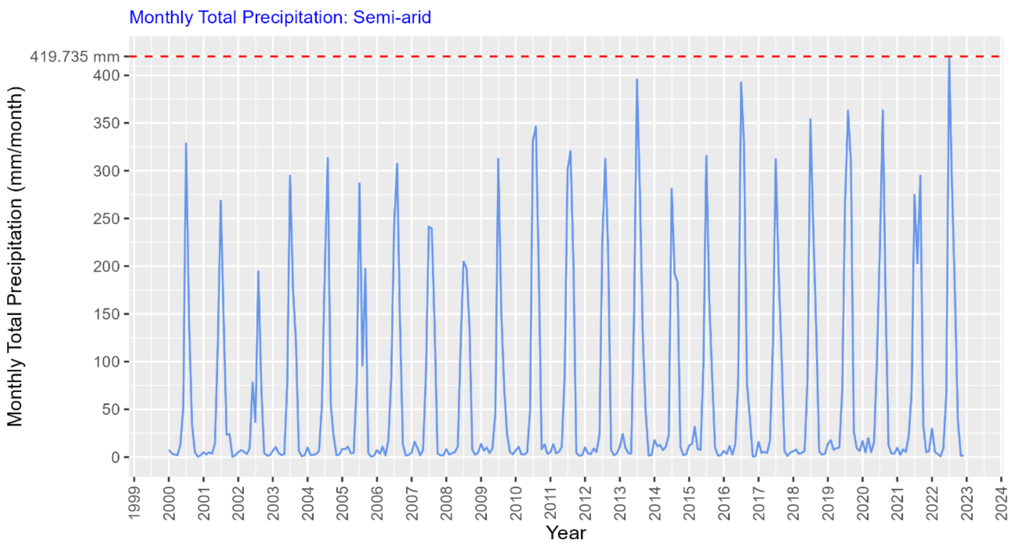

Figure 2. 20 Monthly total precipitation of semi-arid from 2000-2022

2.3.5. Western Ghats

The Western Ghats, covering 4.0% of India's total geographical area, is predominantly a tropical evergreen forest region (Erinjery *et al.,* 2018) and one of the country's four global biodiversity hotspots (Myers, 2000). Stretching 1600km along the west coast of India, this ancient mountain chain, approximately 45-65 million years old, extends from the border of Gujarat and Maharashtra to Kanyakumari at the southernmost tip of the peninsula. The region has two provinces, i. Malabar plains and ii. Mountains (Rodgers and Panwar, 1988) (Figure 2.23). The Western Ghats harbour an abundant and diverse array of flora and fauna, including a high number of endemic species (Subramanyam & Nayar, 1974; Radhakrishna & Rajmohana, 2012). The Western Ghats region is home to a significant number of endemic species, including species like the Nilgiri Langur (*Trachypithecus johnii*), Lion Tailed Macaque (*Macaca silenus*), Grizzled Giant Squirrel (*Ratufa macroura*), Malabar Civet (*Viverricula megaspila*), Nilgiri Tahr (*Hemitragus bylocrius*), Malabar Grey Hornbill (*Ocycerous griseus*) etc (Nameer *et al.,* 2001; Venkatraman *et al.,* 2018). Two endangered turtle taxa, namely the Travancore Tortoise (*Indotestudo travancorica*) and Cochin Forest cane turtle (*Vijayachelys silvatica*), are geographically restricted to a small area within the Western Ghats (Vasudevan *et al.,* 2010).

Figure 2. 22 Biogeographic zone, provinces, and PAs of Western Ghats

- ***Climate condition of Western Ghats***

The Western Ghats region experiences a diverse and unique climate, characterized by a wide range of precipitation and temperature patterns throughout the year. The total monthly precipitation varies from 4mm during drier periods to 892.72 mm during the monsoon season (Figure 2.24). The mean monthly Land Surface Temperature (LST) fluctuates between a pleasant 17°C during the cooler months and a relatively warm 36°C during the hotter periods (Figure 2.23). This climatic diversity contributes to the rich biodiversity and verdant ecosystems found in the Western Ghats. From verdant valleys to mist-clad peaks, the region offers a captivating blend of ecosystems, supporting a vast array of flora and fauna unique to this enchanting part of the world.

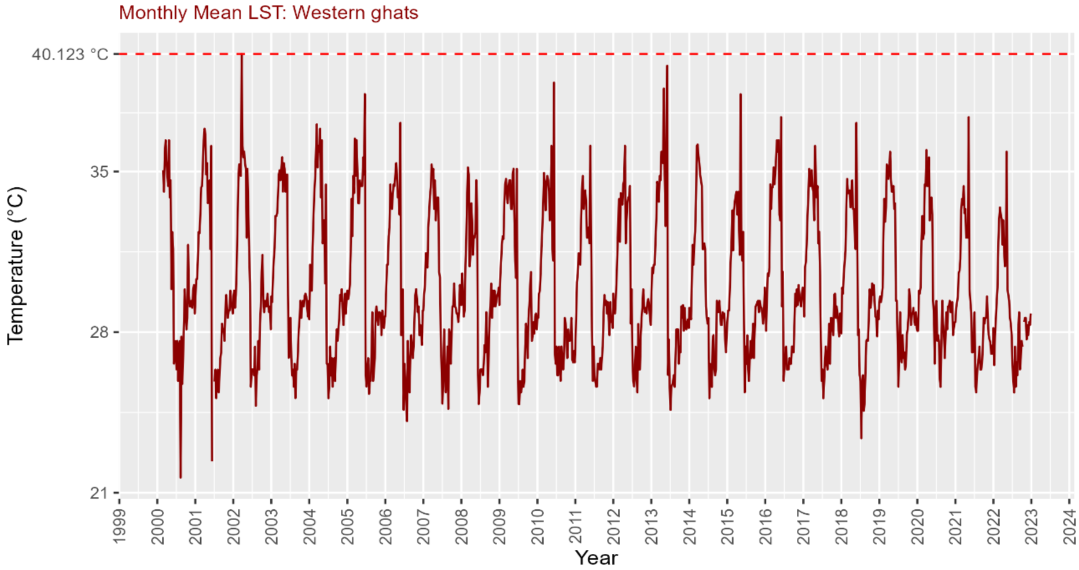

Figure 2. 24 Monthly mean LST of Western ghats from 2000-2022

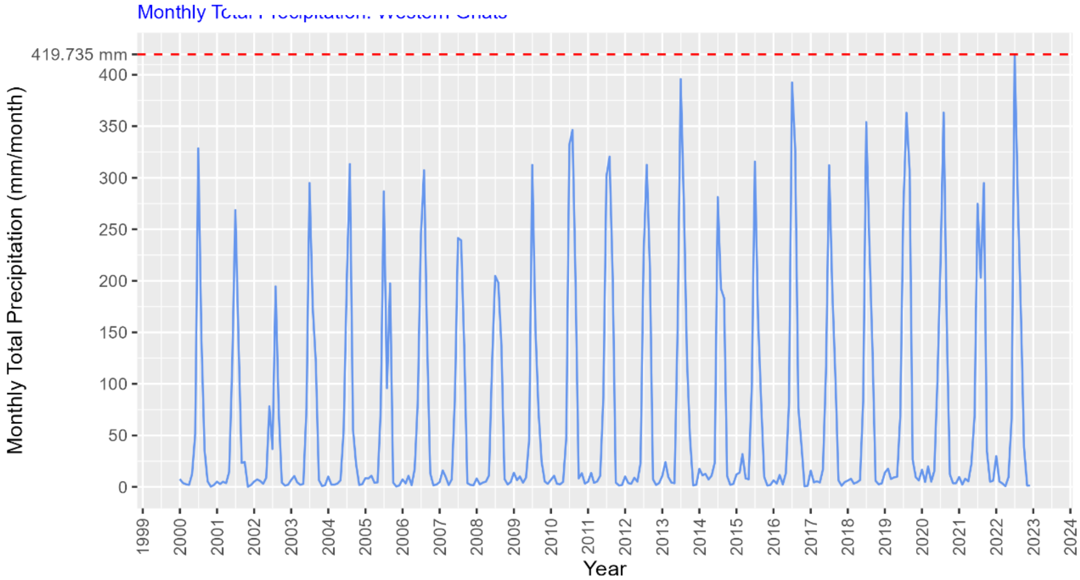

Figure 2. 23 Monthly total precipitation of Western ghats from 2000-2022

2.3.6. Deccan Peninsula

The Deccan Peninsula, constituting 42% of India's total geographical area, is the nation's largest biogeographic region. It is subdivided into five provinces: Central Highlands, Chhota Nagpur, Eastern Highlands, Central Plateau, and Deccan South (Rodgers and Panwar, 1988) (Figure 2.25). Western side of this zone is situated in the rain-shadow region of the Western Ghats (Gaikwad, 1992) and encompasses some of India's most pristine forests, notably in the states of Madhya Pradesh, Maharashtra, and Odisha (Saldanha, 2000). The predominant vegetation type in this zone is deciduous forest, although areas of high biological diversity exist within the hill ranges. The landscape is characterized by a mosaic of deciduous forests, thorn forests, and degraded scrubland (Dar *et al.,* 2019; Agarwala *et al.,* 2016) and supports a diverse array of wildlife species (Harshey and Chandra, 2001; Nagulu *et al.,* 2000; Reddy, 2010). The fauna of this region includes several notable species such as the Chital (*Axis axis*), Sambar (*Cervus unicolor*), Nilgai (*Boselapbus tragocamelus*), Chousingha (*Tetracerus quadricornis*), Barking Deer (*Muntiacus muntjak*), and Gaur (*Antilope cervicapra*). The Elephant (*Elephas maximus*) is found in the Bihar-Odisha and Karnataka-Tamil Nadu belts, while the Wild Buffalo (*Bubalus bubalis*) is confined to a small area at the junction of Odisha, Madhya Pradesh, and Maharashtra. The Hard Ground Swamp Deer (*Cervus duvauceli*) is restricted to Kanha NP in Madhya Pradesh (Porwal *et al.,* 1996; Nagulu *et al.,* 2000).

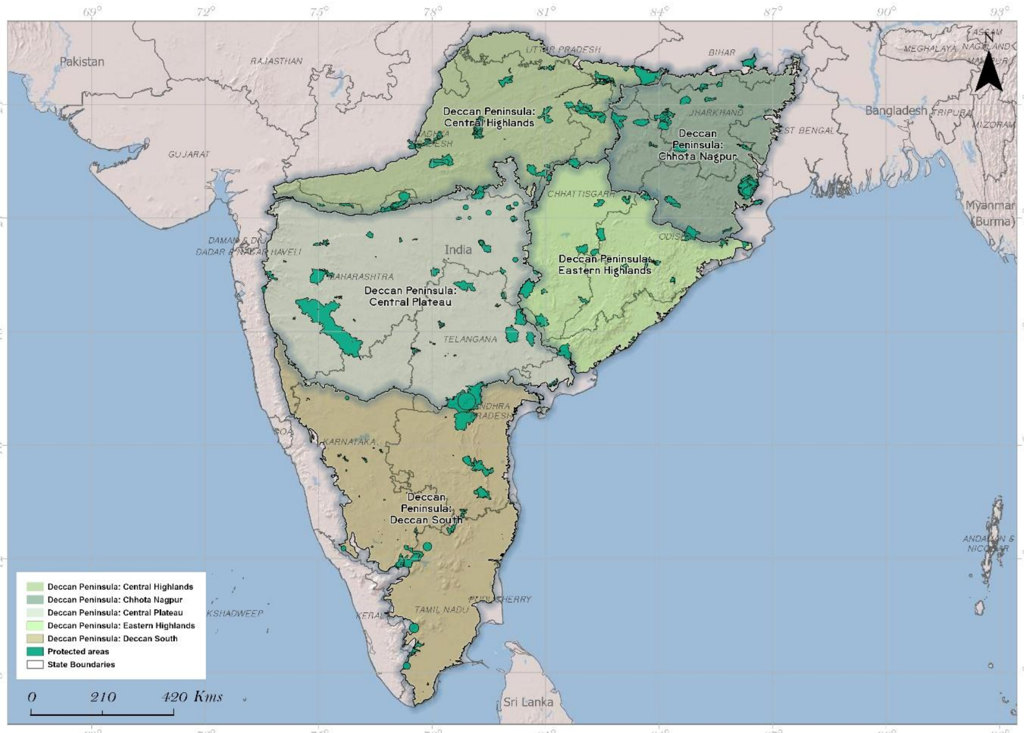

Figure 2. 25 Biogeographic zone, provinces, and PAs of Deccan Peninsula

- ***Climate condition of the Deccan Peninsula***

The Deccan Peninsula, situated in India, experiences a monthly mean Land Surface Temperature (LST) range spanning from 18°C to 46.81°C (Figure 2.26). This range reflects the region's susceptibility to both cold and hot weather extremes. Moreover, the monthly total precipitation exhibits a wide range, fluctuating between 0 mm to 371.63 mm (Figure 2.27). This significant variation in precipitation underscores the Peninsula's susceptibility to seasonal monsoon patterns, with some months witnessing arid conditions while others receive substantial rainfall. Such climatic diversity poses substantial challenges and opportunities for biodiversity conservation and protected areas management within the Deccan Peninsula, as the impact of climate change becomes increasingly evident in altering these patterns.

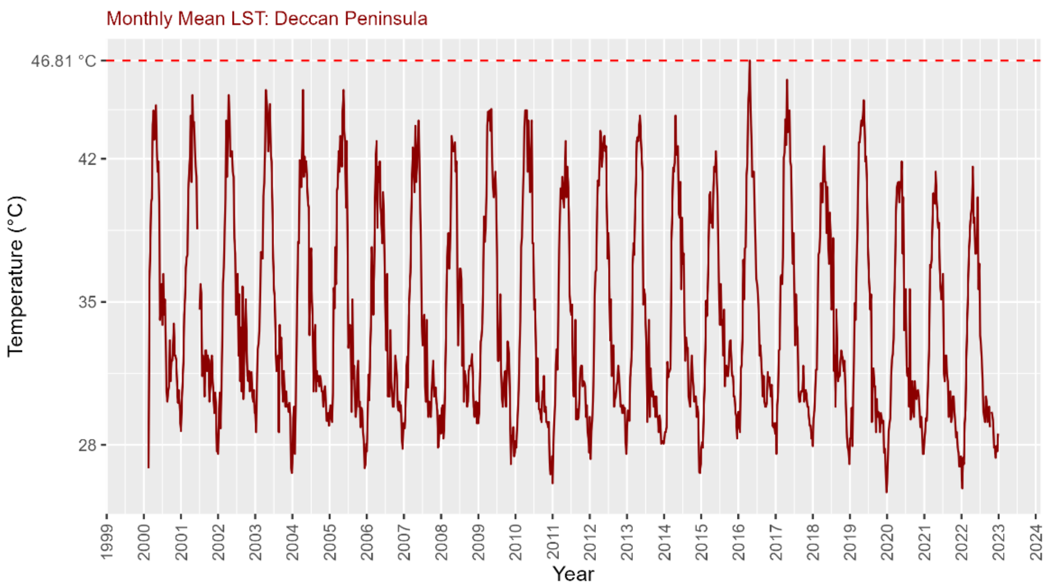

Figure 2. 27 Monthly mean LST of Deccan peninsula from 2000-2022

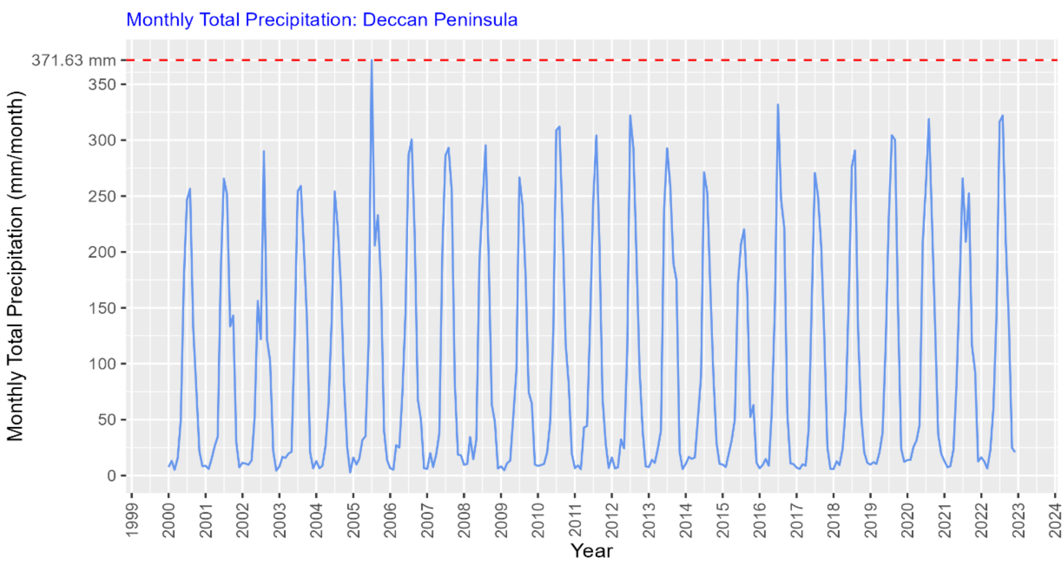

Figure 2. 26 Monthly total precipitation of Deccan peninsula from 2000-2022

2.3.7. Gangetic Plains

The Gangetic Plains, one of the world's largest alluvial plains, span several states in the northern, central, and eastern parts of India. They account for approximately 10.8% of India's total geographical area and are bifurcated into two provinces: the Upper Gangetic Plain and the Lower Gangetic Plain (Rodgers and Panwar, 1988) (Figure 2.28). This region exhibits topographical homogeneity over vast distances, covering a Major portion of Uttar Pradesh, Bihar, and West Bengal. The plain is bounded on the north by the Himalayas, which feed its numerous rivers and are the source of the fertile alluvium deposited across the region by the two river systems.

The characteristic fauna of this region includes Rhino (*Rhinoceros unicornis*), Elephant (*Elephas maximus*), Buffalo (*Bubalus bubalis*), Swamp Deer (*Cervus duvauceli*), Hog-Deer (*Axis porcinus*) and Hispid Hare (*Carprolagus bispidus*) (Jhala *et al.,* 2021). Ganges River also holds a high freshwater biodiversity, starting from the Ganges River dolphin (*Platanista gangetica gangetica*), a diverse array of waterbirds, to different species of freshwater turtles.

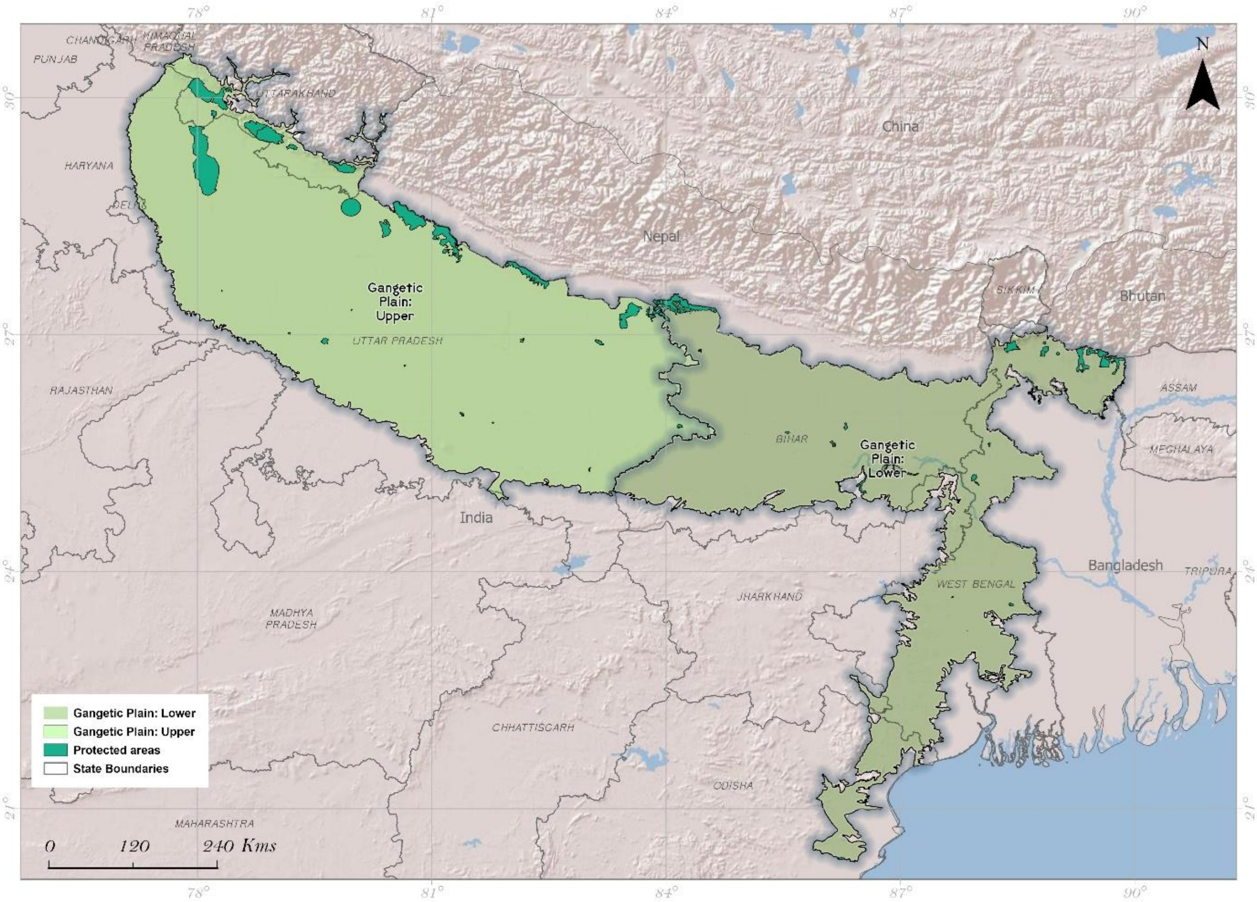

Figure 2. 28 Biogeographic zone, provinces, and PAs of Gangetic Plains

- ***Climate conditions of Gangetic Plains***

The Gangetic Plains of India exhibit a diverse climatic profile, with a monthly mean temperature range spanning from 17°C to 42.91°C (Figure 2.29). This wide temperature range reflects the region's susceptibility to both cooler and warmer weather conditions throughout the year. In terms of precipitation, the monthly total can vary significantly, ranging from 0 mm to 461.214 mm (Figure 2.30). This variability is closely tied to the monsoon system, which dominates the climatic patterns of the Gangetic Plains, resulting in distinct wet and dry seasons. The complex interplay of temperature and precipitation in this region has profound implications for agriculture, water resource management, and overall ecological dynamics, making it a critical area of interest for scholars and conservationists studying the impacts of climate change on this vital agricultural heartland of India.

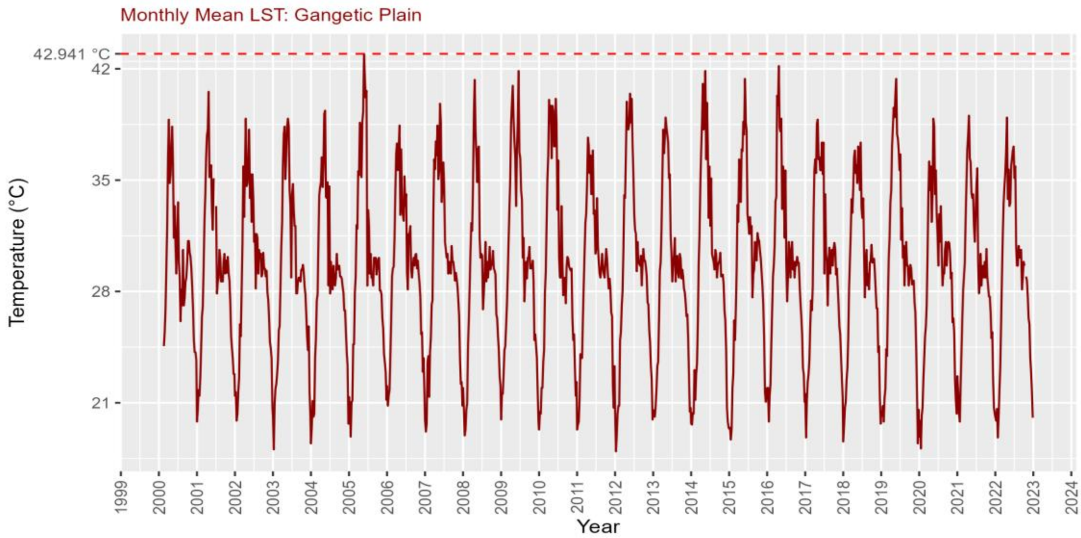

Figure 2. 29 Monthly mean LST of Gangetic plains from 2000-2022

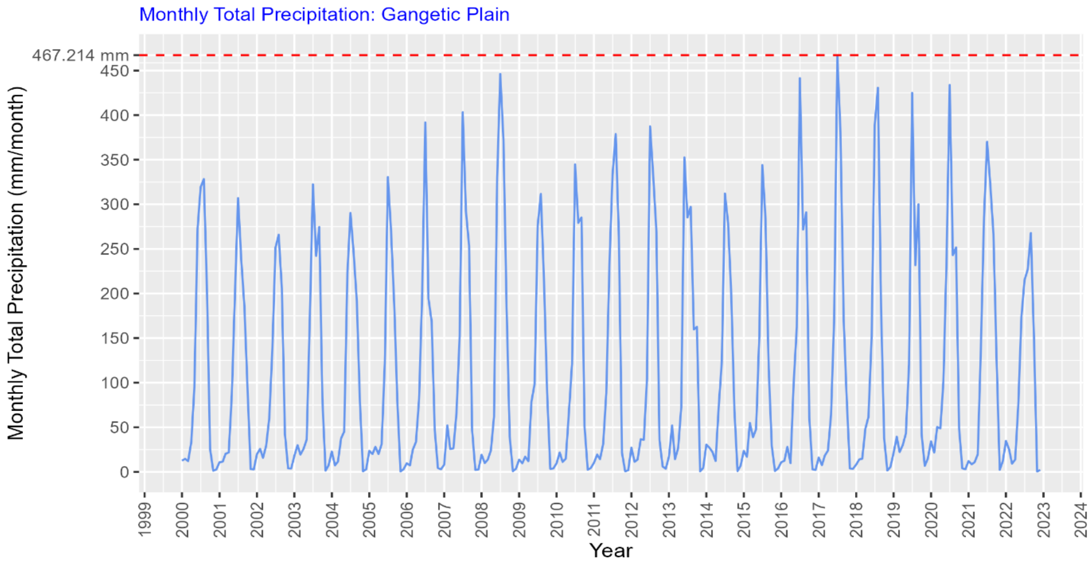

Figure 2. 30 Monthly total precipitation of Gangetic plains from 2000-2022

2.3.8. North-East

North-East biogeographic zone constitutes 5.2 per cent of the total geographical area and has two provinces- the Brahmaputra Valley (2%) and the North-East Hills (3.2%) (Figure 3.31) (Rodgers and Panwar, 1988). This zone comprises 8 states (Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura). Northeast is one of the global biodiversity hotspots (Myers *et al*., 2000). This region represents the transition zone between the Indian, Indo-Malayan, and Indo-Chinese bio-geographical regions, as well as being a meeting point of the Himalayan mountains and peninsular India (Figure 2.31). The North-East is thus the biogeographical 'gateway' for much of India's fauna and flora and a biodiversity hotspot (Eastern Himalaya). Many of the species contributing to this biological diversity are either restricted to the region itself or the smaller localized areas of the Khasi Hills. Out of 9 important vegetation types in India, 6 are found in this region. North-east also harbours approx. 80,000 flowering plants, 267 species of mammals (Talukdar *et al.,* 2021), and approx. 800 bird species (Chandra *et al.,* 2021).

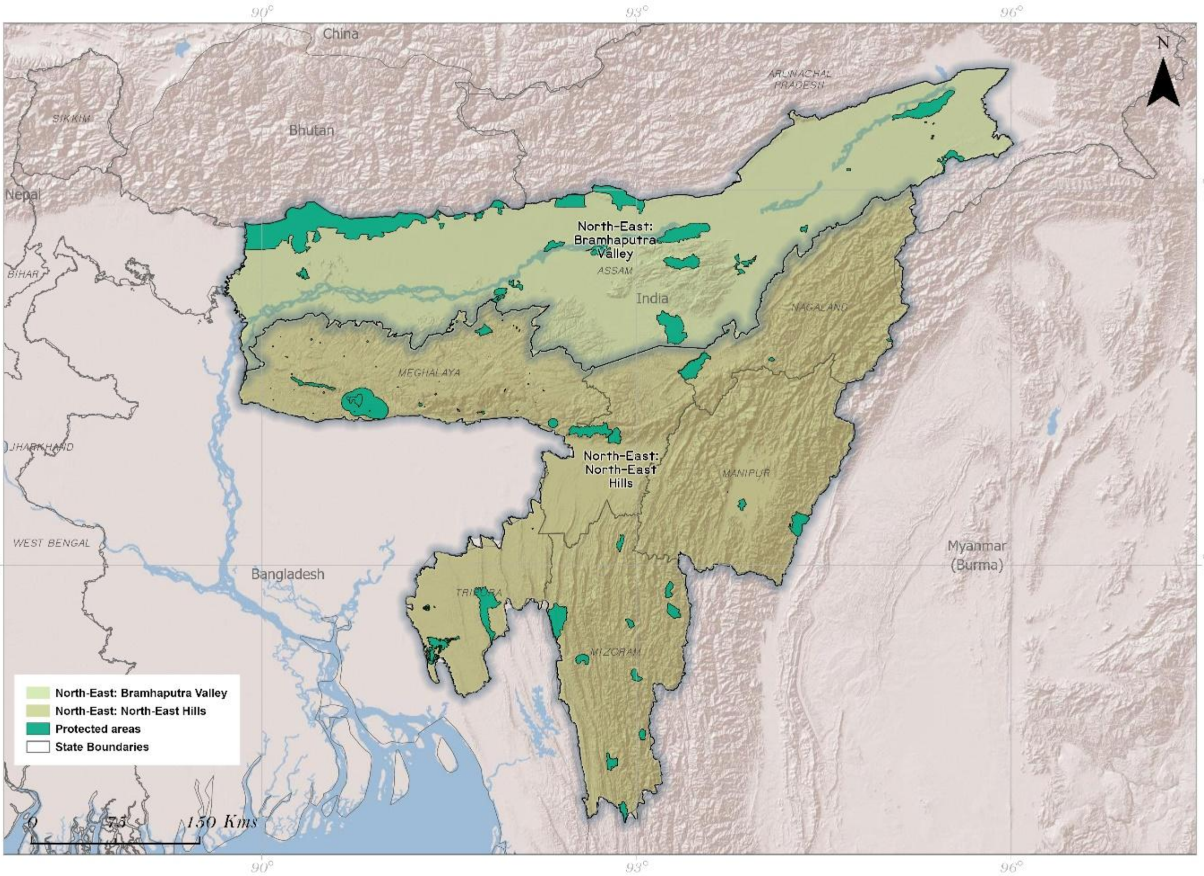

Figure 2. 31 Biogeographic zone, provinces, and PAs of North-East

Climate conditions of North-East

The northeastern region of India presents a highly diverse and dynamic climatic spectrum, with a monthly mean Land Surface Temperature (LST) range fluctuating between 17°C to 32°C (Figure 2.32), indicative of significant temperature variations throughout the year. Moreover, the monthly total precipitation spans from 0 mm to 574.453 mm (Figure 2.33), showcasing the region's susceptibility to both arid and extremely wet conditions. This climatic variability is attributed to the region's geographical complexity, which contributes to distinct seasonal patterns, including heavy monsoonal rainfall during certain months. The unique climatic conditions of Northeast India have profound implications for its rich biodiversity and conservation efforts, making it an area of paramount importance for research and assessment of climate change impacts on this ecologically sensitive region.

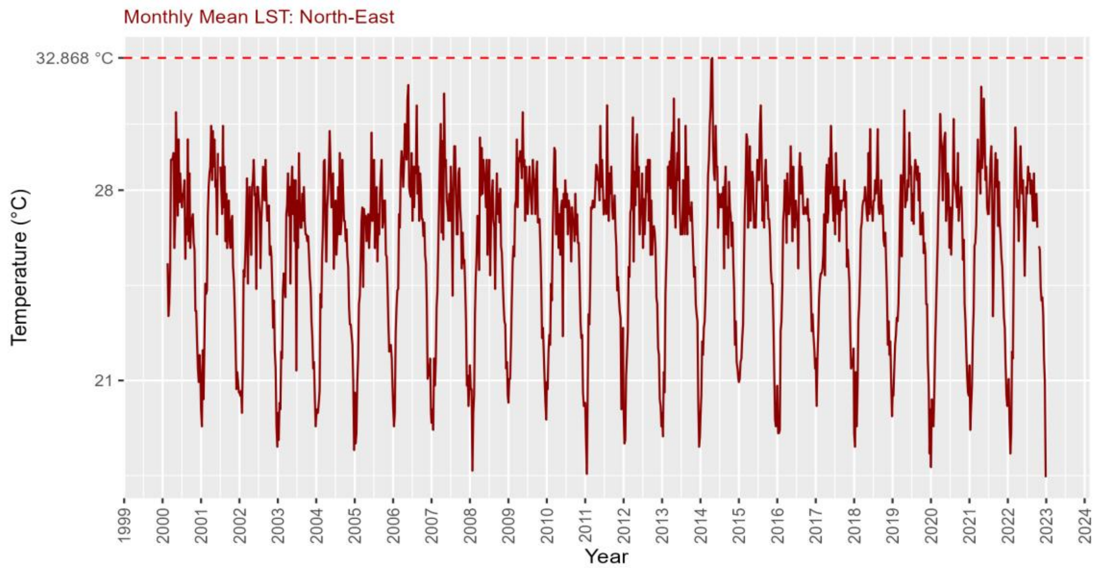

Figure 2. 33 Monthly mean LST of North-east from 2000-2022

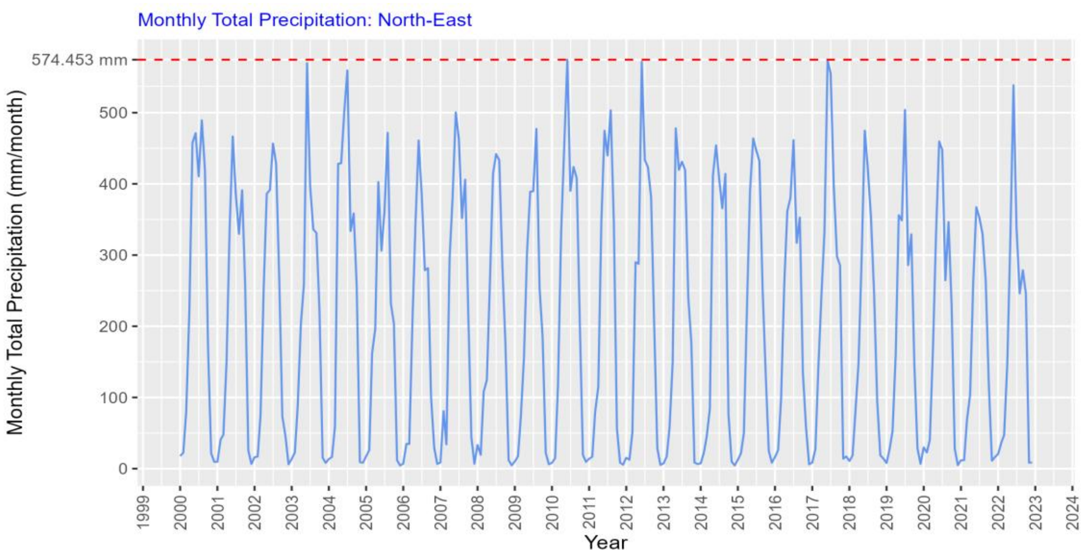

Figure 2. 32 Monthly total precipitation of North-east from 2000-2022

2.3.9. *Coasts*

India's coastal region, accounting for 2.5% of the country's total geographical expanse, is a rich tapestry of diverse ecosystems. This coastal belt is segmented into three distinct provinces (Figure 2.34): the East Coast, the West Coast, and Lakshadweep (Rodgers and Panwar, 1988). The coasts, extending from Gujarat to the Sundarbans, measure approximately 5,423 km. The Lakshadweep, a coral-based system comprising 25 islets, boasts a unique reef lagoon ecosystem teeming with biodiversity. However, the high population density on these islands has led to a significant depletion of natural vegetation.

These zones serve as a cradle for a myriad of marine and terrestrial species. The intertidal zones, mangrove forests, and coral reefs are hotspots for biodiversity, hosting a multitude of organisms ranging from microscopic plankton to large marine mammals. The East Coast, characterized by wide continental shelves and nutrient-rich waters, supports a diverse array of fish species, making it a vital region for the country's fisheries. The West Coast, with its unique upwelling phenomenon, is a breeding ground for several pelagic fish species.

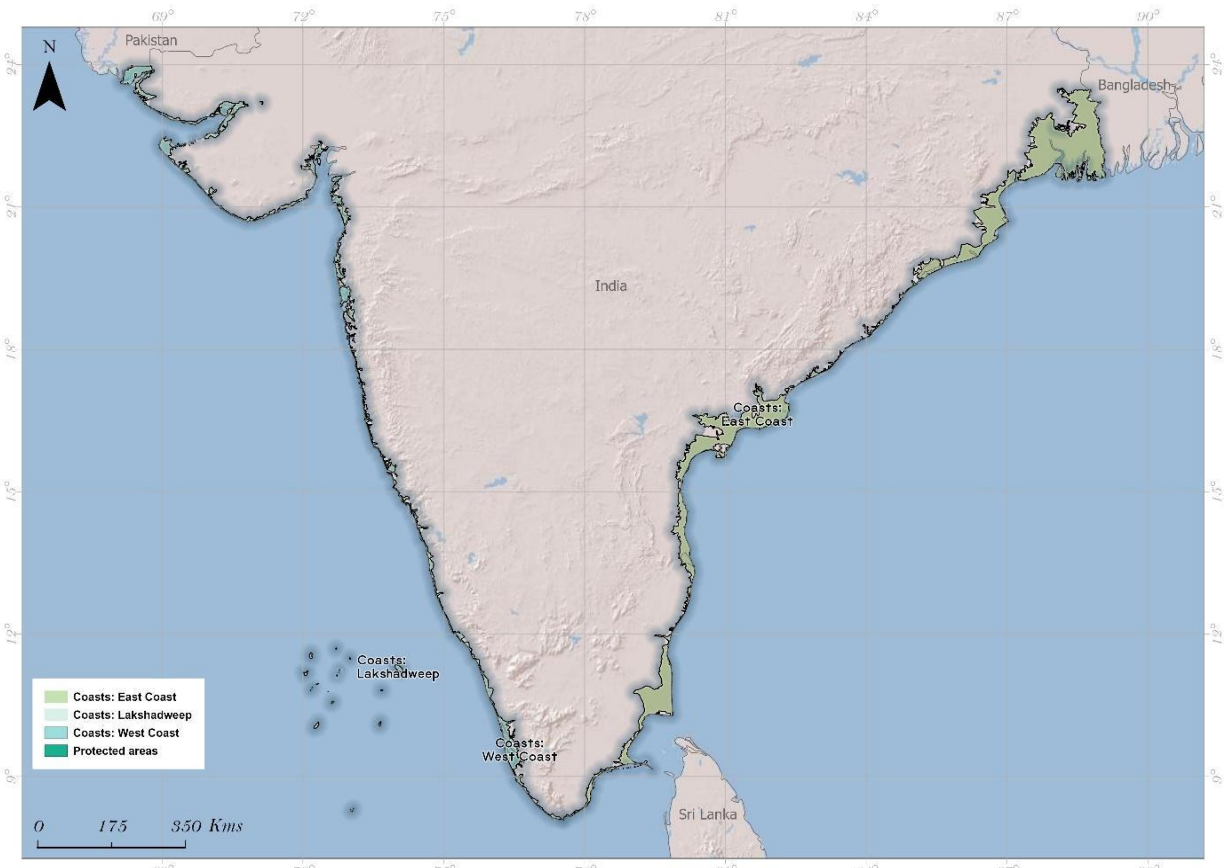

Figure 2. 34 Biogeographic zone, provinces, and PAs of Coasts

- ***Climate condition of Coasts***

The Indian coasts experience a wide range of climatic conditions due to their vast geographic scale and varied topography. The coastal regions of India generally have an equable or maritime climate. This is due to the moderating influence of the Arabian Sea, the Indian Ocean, and the Bay of Bengal. However, the climate can vary, with South India generally being warmer and more humid due to its coastlines. The fluctuations in climatic conditions such as temperature, rainfall trends, and humidity are vital factors that lead to an increase in the intensity and frequency of cyclones and the damage inflicted on the coastal areas of India. Temperatures can vary significantly, ranging from a mild 18°C to an extreme 55°C (Figure 2.35). Monthly total precipitation, can range from as low as 0mm, indicating periods of dryness, up to 433.66mm (Figure 2.36), suggesting heavy rainfall events.

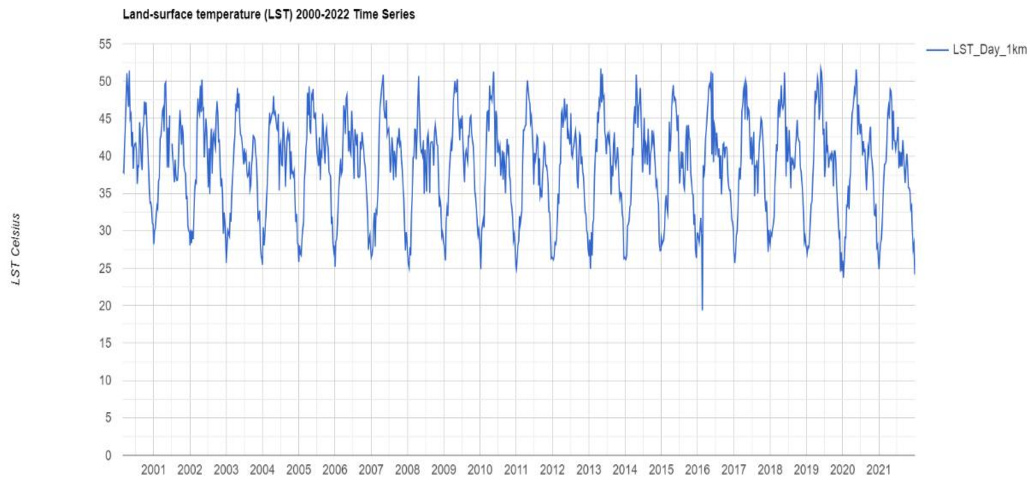

Figure 2. 36 Monthly mean LST of coasts from 2000-2022

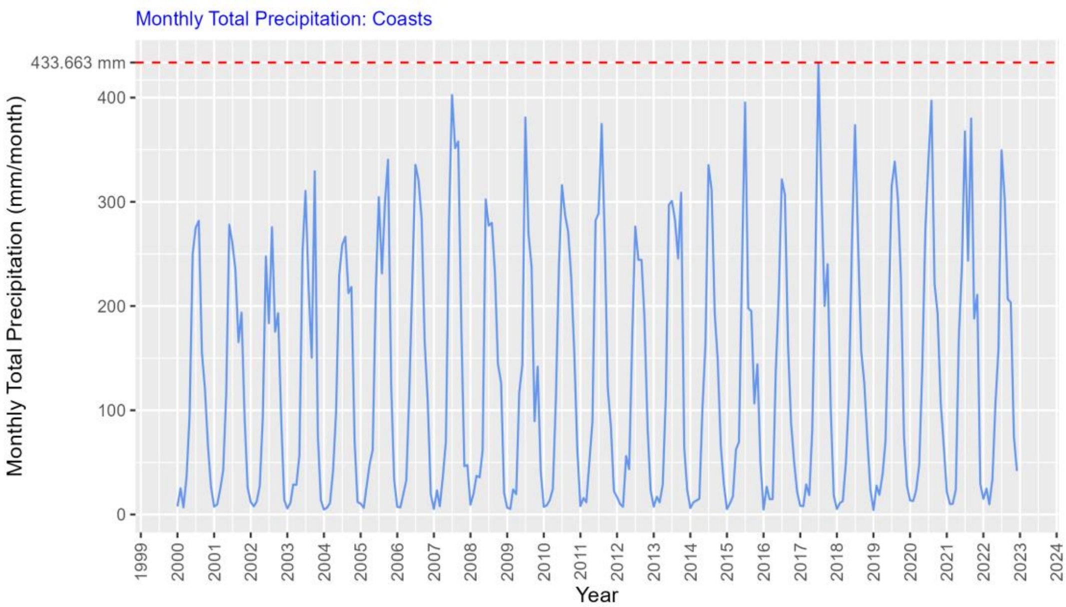

Figure 2. 35 Monthly total precipitation of coasts from 2000-2022

2.3.10. Indian Islands

The Indian islands constitute 0.3 per cent of the total geographical area and mainly moist evergreen forest. There is a total 836 islands/islets/rocky outcrops in the island group. The Islands have two provinces under them- the Andamans and the Nicobar (Figure 2.37) (Rodgers and Panwar, 1988). The Indian islands are part of the *Indo-Burma* and *Sundalands* Global biodiversity hotspots (Myers, 2000). Grasslands occur only in the Nicobar Islands, while evergreen, and deciduous forests are common in Andaman Islands (ISFR, 2021).

Approx 11,009 species, including 56 mammals, 344 birds, and 69 species of reptiles are recorded from Andaman and Nicobar Islands. Some of the endemic fauna of Andaman & Nicobar Islands include the Andaman masked palm civet (*Paguma larvata tytleri*), Nicobar long-tailed macaque (*Macaca fascicularis umbrosa*), Nicobar flying fox (*Pteropus faunulus*), Andaman shrew (*Crocidura hispida andamanensis*), and Narcondam hornbill (*Rhyticeros narcondami*) (Ramakrishna and Sivaperuman, 2010).

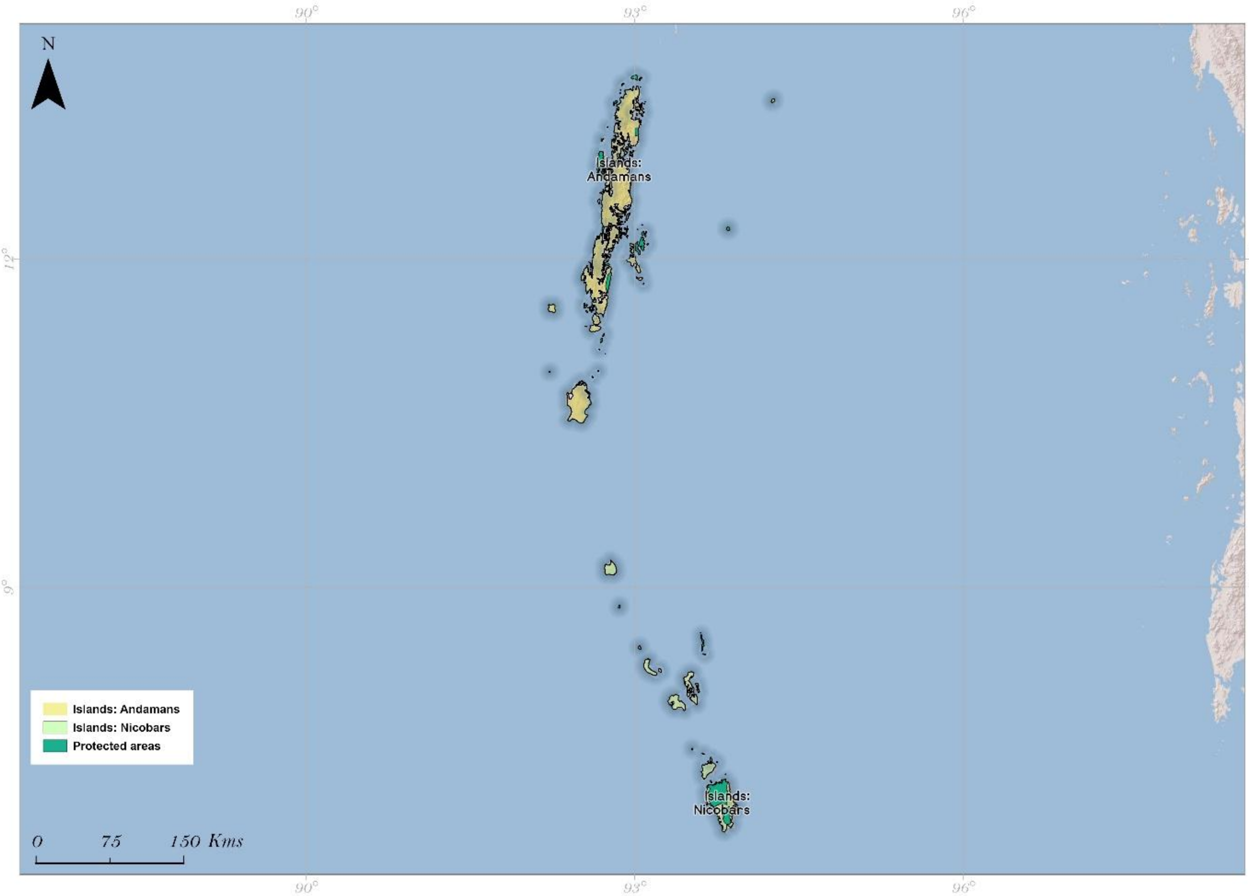

Figure 2. 37 Biogeographic zone, provinces, and PAs of Islands

- ***Climate condition of Indian Islands***

Islands are situated in the equatorial belt and exposed to marine influences and have a tropical climate, warm, moist, and equable. In some years the Islands have experienced rains during all the months of the year, Cyclones occur during the monsoons, accompanied by very strong winds mainly during May and November and in some years during mid-April. The monthly mean LST of Islands can reach up to 32°C (Figure 2.38), and monthly total precipitation can reach 850mm (Figure 2.39).

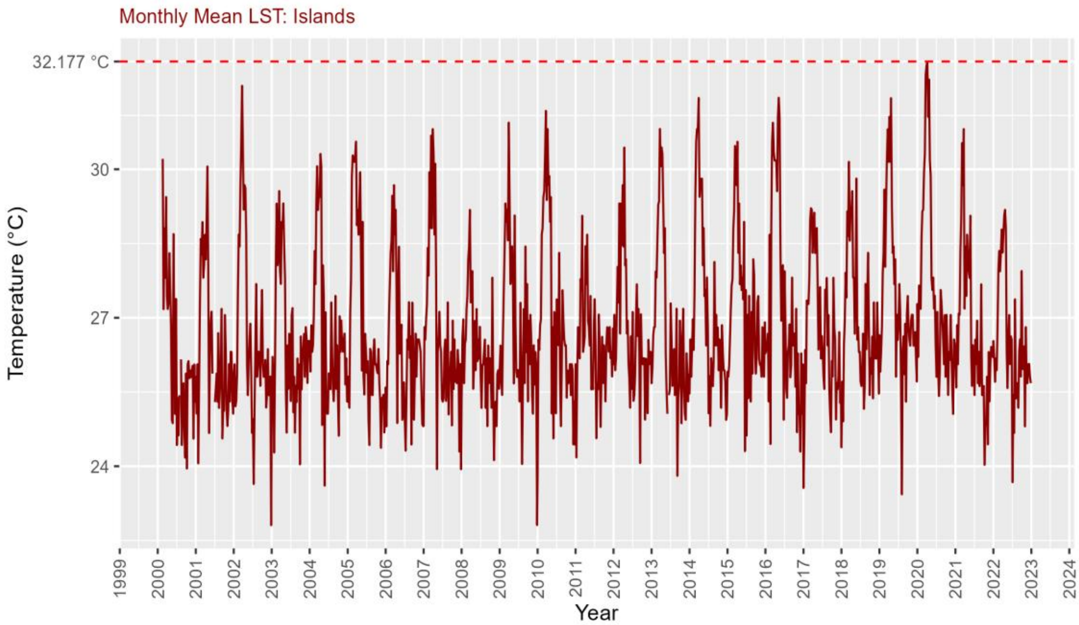

Figure 2. 38 Monthly mean LST of islands from 2000-2022

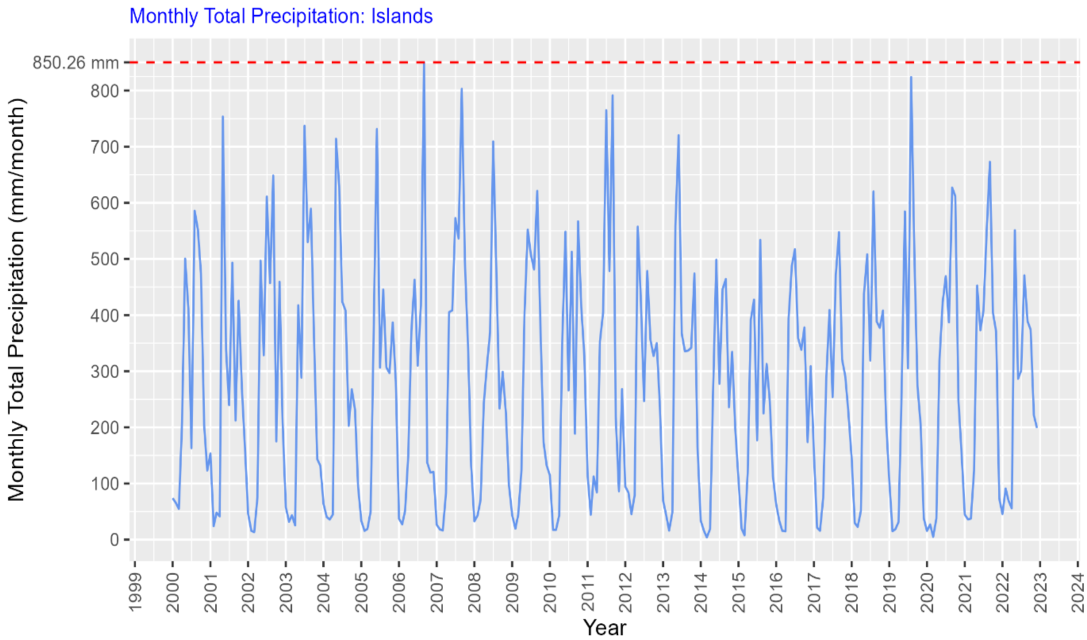

Figure 2. 39 Monthly total precipitation of islands from 2000-2022

2.4. Climate space occupied by protected areas of different biogeographic zones.

To check the climate space occupied by PAs of Individual biogeographic regions, a principal component analysis (PCA) was performed among the PAs within each biogeographic region. 8 bioclimatic variables (Source: Worldclim v2.1) were used for running the model in R (Details of these bioclimatic variables are provided in chapter 3).

It was found that Protected Areas (PAs) situated in three global biodiversity hotspots, i.e., Himalaya, Trans-Himalaya, and Western Ghats, exhibit higher climate heterogeneity, demonstrating a broader climate space compared to other regions (Figure 2.35). A higher climate heterogeneity also explains the high species diversity in these regions (Stevens *et al.,* 2012). Despite being a biodiversity hotspot, Indian Island PAs showed lower climate heterogeneity than mainland PAs. This vulnerability renders island PAs more exposed to the adverse effects of climate change, as they have limited capacity to adapt to shifting climatic conditions. Additionally, the PAs within the Deccan Peninsula, despite being the largest biogeographic region, experience lower climate heterogeneity, characterized by relatively uniform climatic conditions. Similarly, the Trans-Himalaya region faces extremely cold conditions and, consequently, exhibits limited climate heterogeneity.

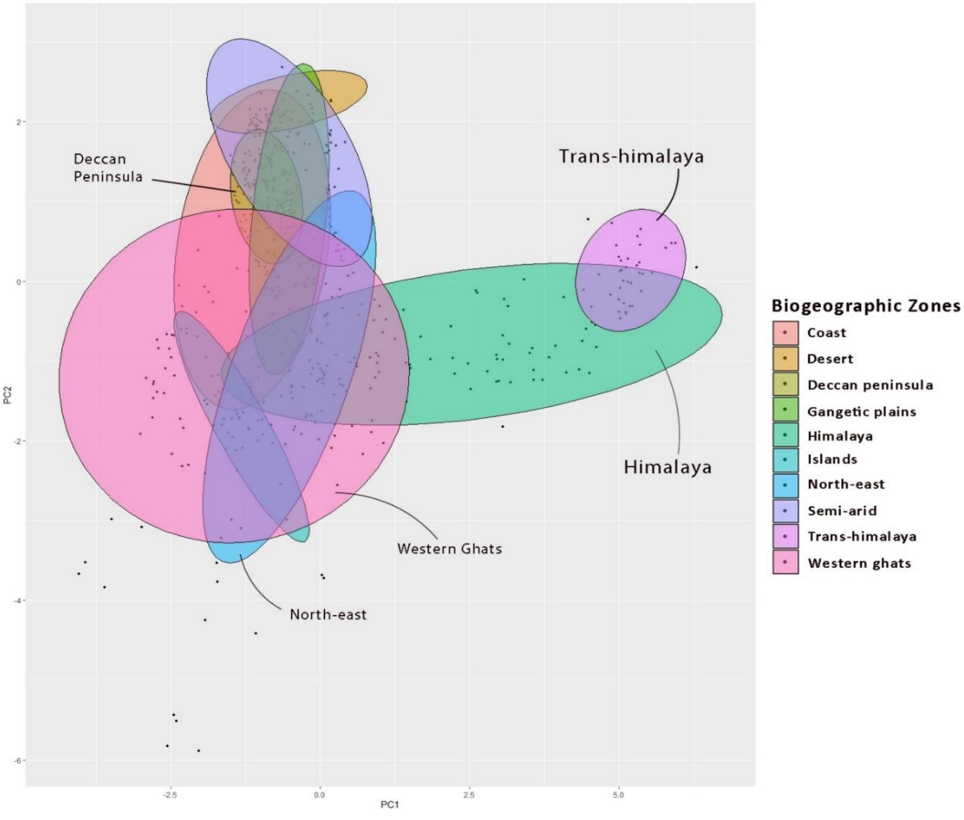

Figure 2. 40 Principal Component Analysis (PCA) of climate space occupied by PAs in different biogeographic zones. Note that Himalayas, North-east and Western ghats has broader climate space than the other biogeographic zones.

PAs of the three biogeographic zones (e.g., Himalaya, Western Ghats, and North-East) have a cumulatively broader climate space compared to the rest. These biogeographic zones are also biodiversity hotspots and have high species richness (Myers *et al.,* 2000). E.g., The Himalaya are one of the biodiversity hotspots and have high climate heterogeneity (Mani, 1974). PAs in this zone can have cold-harsh conditions (e.g., Gangotri NP), to subtropical conditions (e.g., Mussoorie WLS). Islands PAs, despite being one of the biodiversity hotspots, have lower climatic variability. This is due to the smaller area, and unique climate conditions of the islands. This also means changes in climate conditions are more likely to have a serious impact on the endemic islands' species. On the other hand, the Deccan peninsula covers a significant portion of the southern part of the country. A wide variety of ecosystems, such as marshes, woods, grasslands, and coastal regions, are found in this zone. Gangetic plains are one of the highly populated areas of India, and anthropogenic pressures (e.g., urban areas expansion, agriculture land expansion) are likely to augment the adverse effects of climate change in the PAs here. PAs of Semi-arid and desert biogeographic zones have low climatic heterogeneity and are dominated by xeric and desert conditions. In these zones, there are higher chances of extreme weather events (i.e., erratic rainfall), that can significantly impact the functioning of these PAs. Another biodiversity hotspot is Western Ghat, home to one of India's biggest tropical rainforests. The PAs in this area are also recognized as Natural World Heritage Sites. Climate change, along with an increase in agricultural land used for cattle grazing and the production of rubber, oil palm, tea, and coffee, has resulted in a significant loss in the extent of the Western Ghats Forest (Chandran *et al.,* 2010, Chethana and Ganesh, 2013). More precisely, increasing temperatures and changing rainfall patterns can have a big impact on the Western Ghats' general reduction in suitable habitats as well as many species' possible distribution and range shifts (Priti *et al.,* 2016). Furthermore, the entire area covered by forest cover may be decreased due to the Western Ghats' deficit rainfall pattern (Ramachandran *et al.,* 2017).

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Chapter 3

Vegetation changes and climate driver trends in biogeographic zones of India

Chapter 3. Vegetation changes and climate driver trends in biogeographic zones of India

3.1. Introduction

Vegetations are important to terrestrial ecosystems because they connect the earth, water, and air (Piao *et al.,* 2020; Zhu *et al.,* 2016). Vegetation in the natural world is constantly subject to changes that vary greatly in frequency and intensity (Smith *et al.,* 2022). Climate factors are thought to cause long-term changes in vegetation, especially since the 1980s (Zhu *et al.,* 2016).

Indian subcontinent's monsoon-dominant climate plays a critical role in shaping the region's vegetation dynamics. Significant rainfall across most parts of India occurs during the south-west monsoon season from June to September (Mooley & Parthasarathy, 1984; Parthasarathy & Mooley, 1978; Dhar & Nandargi, 2003; Gadgil *et al.*, 2003). About 80% of India's annual precipitation occurs during this period, as indicated by long-term rainfall data, with significant interannual variability in the rainfall patterns (Soman & Kumar, 1990; Gadgil *et al*., 2003). The pre-monsoon period, characterized by stressed vegetation states, is heavily influenced by soil moisture, which is in turn affected by temperature and precipitation. During the monsoon, precipitation aids in vegetation recovery through soil moisture recharge. However, during the monsoon season, photosynthesis can be limited due to a reduction in available radiation caused by the high cloud cover during this period (Matuszko, 2012).

The seasonal trends of monsoon rainfall in India during the last three decades (1980-2010) have shown variability across different regions of the country (Mukherjee *et al.,* 2015; Soman & Kumar, 1990). Shifts in precipitation patterns due to climate change and other factors can have significant impacts on agriculture, forests, and water resources (Sarkar *et al.,* 2021; Wang *et al.,* 2021; Biswas *et al.,* 2019). Previous research indicated that increasing rainfall trends are more pronounced west of 80°E, while generally negative or decreasing trends are prevalent in the eastern region (Pingale *et al.,* 2014; Krishnamurthy *et al.,* 2009; Latif *et al.*, 2017). This asymmetry in patterns of monsoon rainfall between eastern and western portions is mostly connected with changes in large-scale thermodynamic factors, such as wind speed and moisture content (Konwar *et al.,* 2012; Sharma *et al.*, 2016). Research has shown that the variability of the Indian Summer Monsoon significantly affects vegetation growth and recovery, particularly in the context of increasing droughts and heat waves due to global warming (Sarkar & Kafatos, 2004).

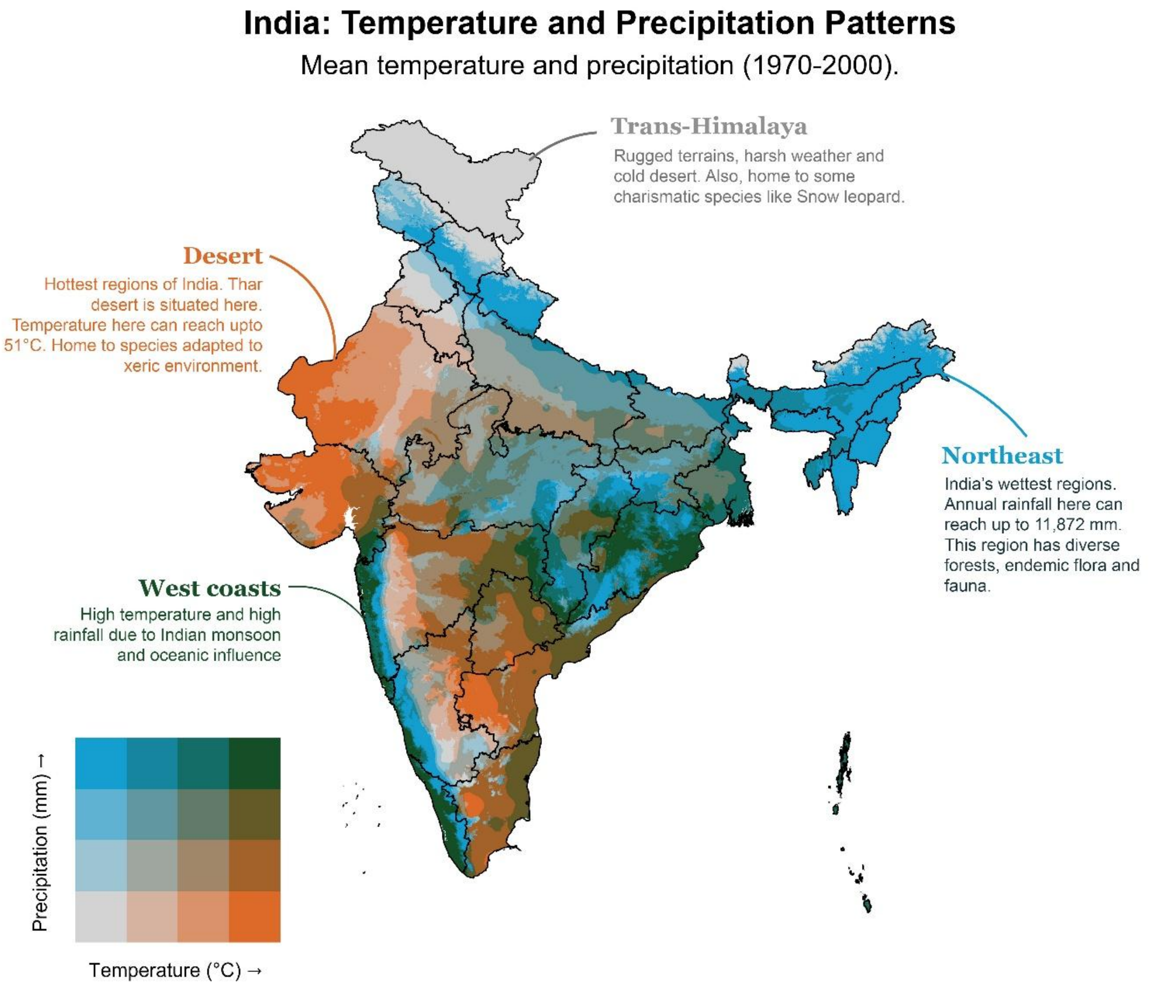


Figure 3. 1 Map showing temperature and precipitation patterns (near present) in India. Areas like northeast experience a significant amount of rainfall, and areas like desert has low precipitation and high temperature. Data source Worldclim.org, and map prepared in R.

Research has shown that evapotranspiration (ET) patterns have changed on both a regional and a global level over the last few decades. These changes have been linked to climate change and anthropogenic activities (Jung *et al.,* 2011; Pascolini-Campbell *et al.,* 2021). Changes in ET have confounding effects on various aspects of human existence, like the supply of food and water and the growth of the economy (Li *et al*., 2018; Zhang *et al.,* 2013). Hence, comprehending the dynamics of ET variations and the underlying factors assumes paramount importance, particularly in the context of climate change, for effective water resources management. Interannual variations of Indian summer monsoon rainfall is influenced by vegetation growth and recovery, with the Leaf Area Index (LAI) playing a major role in influencing precipitation through evapotranspiration.

In recent years, Vegetation trends such as " increasing or greening " and " declining or browning " have become central to discussions on terrestrial vegetation dynamics and their role in climate feedback mechanisms (De Jong *et al*., 2012; Pan *et al.,* 2018). Vegetation greening and browning trends refer to the changes in vegetation cover and productivity across the Earth's surface, often assessed using satellite-derived vegetation indices like the Normalized Difference Vegetation Index (NDVI), and Enhanced Vegetation Index (EVI). These trends are indicative of the health and functioning of ecosystems. Greening and browning are influenced by a combination of climate change, elevation, and human activities.

Greening and browning trends can be either gradual or abrupt, or more rarely, non-existent (De Jong *et al*., 2012). However, these trends are not consistently monotonic and, can exhibit reversals or levelling off, influenced by a complex interplay of climatic changes, such as precipitation patterns and temperature stress, as well as human activities, including land use changes and agricultural practices (Pan *et al.,* 2018; Xu *et al*., 2021; Yang *et al*., 2023). Vegetation greening was found to cause increased annual evapotranspiration and decrease water yield (Liu *et al.,* 2016). Commonly, a browning trend (decreasing EVI) of vegetation is considered to indicate a decrease in the plant growth rate (Feng *et al.,* 2021; Gadgil, *et al.,* 2018) as an indicator of phenological change (Broich *et al.,* 2014), crop status, inter-annual dynamics of vegetation, land cover change, stress and land degradation, temperature-induced drought stress or insect disturbances, fire activity, and ocean circulation anomalies. In contrast to browning trends, a greening trend (increasing EVI) of vegetation greenness is interpreted as increased photosynthesis and plant growth and attributed to increasing temperatures, earlier spring onset, lengthening of the growing season, rainfall or reduced snow cover, the atmospheric CO2 fertilization effect, decreasing cloud cover with associated increases in solar radiation, El Nino-Southern Oscillation (ENSO) and the positive phase of the Arctic Oscillation (AO) signal. Global vegetation has shown an increase in greenness since the 1980s, but recent trends indicate a levelling of this greening, with an increasing area experiencing browning, suggesting soil water limitations as a contributing factor. Browning trends have evolved into greening trends in some regions (Yang *et al.,* 2021), influenced by climatic factors, with nonlinear and nonstationary characteristics of these trends being significant. The global picture is further complicated by the observation that increasing vegetation browning is hidden within the overall greening trend, with a significant increase in browning area since the late 1990s, especially in the northern mid-low latitudes (Pan *et al.,* 2018). This may potentially lead to a shift from long-term greening to browning under future warming scenarios (Krishnaswamy *et al.,* 2014; Pan *et al.,* 2018).

Comprehending the factors influencing vegetation shifts is a fundamental prerequisite for efficacious ecosystem management (Zhu *et al*., 2016; Easdale *et al.,* 2018). Climate is often posited as a principal determinant of alterations in vegetation dynamics (Jiang *et al.,* 2017; Wu *et al.,* 2015). Consequently, it is of paramount importance to evaluate the spatial patterns of vegetation trajectories across diverse biogeographic zones and their responses to climatic variables. The primary aim of this chapter is to identify the correlations between long-term climatic trends (e.g., temperature, precipitation) and changes in vegetation (both greening and browning) across the biogeographic zones of India.

3.2. Methodology

3.2.1. Dataset

In this study, EVI time series, temperature, and environmental variable data are key data. Details of this dataset are given below:

Vegetation data

- **Enhanced vegetation index (EVI):** Vegetation indices from the Moderate Resolution Imaging Spectroradiometer (MODIS), generated at 16-day intervals and across multiple spatial resolutions, facilitate reliable spatial and temporal comparisons of vegetation canopy greenness. This greenness is a composite attribute encompassing leaf area, chlorophyll content, and canopy structure. Two distinct vegetation indices, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), are derived from atmospherically corrected reflectance in the red, near-infrared, and blue wavebands. The EVI, in comparison to the NDVI, mitigates variations between canopy and soil and enhances sensitivity in areas of dense vegetation. These two indices more effectively encapsulate the global diversity of vegetation conditions and processes.

Vegetation indices are derived from daily, atmospherically corrected, bidirectional surface reflectance. These indices employ a MODIS-specific compositing methodology, predicated on product quality assurance metrics, to eliminate pixels of inferior quality. From the residual high-quality vegetation index values, a pixel is selected to represent the compositing period using a constrained view angle approach (the pixel closest to Nadir is chosen from the two highest NDVI values). Given the identical nature of the MODIS sensors on the Terra and Aqua satellites, the vegetation index algorithm generates each 16-day composite with an eight-day phase difference, thereby facilitating a higher temporal resolution product by amalgamating both data records. The MODIS vegetation index product suite has found successful application across all ecosystems, climate studies, and natural resource management research, as evidenced by the steadily growing corpus of peer-reviewed publications.

An augmentation in the Enhanced Vegetation Index (EVI) signifies an intensification of vegetation greenness, while a reduction in EVI denotes a browning effect (Myers-Smith *et al.,* 2020; Wang *et al.,* 2022). Consequently, a time series analysis of EVI can delineate temporal alterations in vegetation, thereby providing a foundation for further investigation into the factors influencing vegetation dynamics. Longitudinal EVI series can be synthesized from readily available remote sensing data, such as that from the Advanced Very High-Resolution Radiometer (AVHRR), Landsat 4/5/7/8/9, and SPOT (Gao *et al.,* 2020). However, the heterogeneity of satellite sensors and data in long time series introduces substantial uncertainty (Peng *et al.,* 2012; Pan *et al.,* 2017). The MODIS EVI dataset, which has utilized consistent sensor data from 2000 to the present, mitigates this issue to some extent. Furthermore, advancements in synthetic data algorithms have enhanced the capacity to monitor changes in MODIS EVI products, thereby circumventing issues related to sensor degradation and data uncertainty (Didan *et al.,* 2015; Chen *et al.,* 2020; Liu *et al.,* 2022).

Time series analysis using Climate drivers

- ***Land Surface Temperature (LST) (MOD11A2 product):***

The MOD11A2 Version 6 product offers an 8-day average Land Surface Temperature and Emissivity (LST&E) on a per-pixel basis, with a spatial resolution of 1 kilometre (km) within a 1,200 by 1,200 km grid. Each pixel value in the MOD11A2 represents a simple mean of all corresponding MOD11A1 LST pixels gathered within the same 8-day interval. This 8-day compositing period was selected due to its alignment with the exact ground track repeat period of the Terra and Aqua platforms, which is twice the compositing period. Accompanying the daytime and nighttime surface temperature bands are associated with quality control evaluations, observation times, view zenith angles, and clear-sky coverages, in addition to bands 31 and 32 emissivities derived from various land cover types.

- ***Precipitation (CHIRPS: PENTAD)***

The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a quasi-global precipitation dataset that spans over 35 years. Covering latitudes from 50°S to 50°N across all longitudes and extending from 1981 to the near-present, CHIRPS integrates proprietary climatology, CHPclim, satellite imagery with a resolution of 0.05°, and ground-based station data. This amalgamation of data sources facilitates the generation of gridded rainfall time series, which are instrumental for conducting trend analyses and monitoring seasonal droughts.

- ***Evapotranspiration (MOD16A2)***

The MOD16A2 Version 6 product, about Evapotranspiration/Latent Heat Flux, is an 8-day composite dataset generated at a pixel resolution of 500 meters (m). The algorithm employed for the collection of MOD16 data is predicated on the principles of the Penman-Monteith equation. This involves the incorporation of inputs from daily meteorological reanalysis data in conjunction with remotely sensed data products from the Moderate Resolution Imaging Spectroradiometer (MODIS), such as dynamics of vegetation properties, albedo, and land cover.

Data pre-processing

LST and evapotranspiration are 8-day composite products, while the precipitation is daily and the EVI is 16-day composite products. These products come in separate tiles. Data from 2000-2022 for all these products were downloaded through the Google Earth engine, and mosaiced. These mosaics were then aggregated to annual means, which resulted in a single raster stack for each product per year.

3.2.2. Trend Analysis (*Mann-Kendall test)*

The purpose of the Mann-Kendall (MK) test (Mann 1945, Kendall 1975, Gilbert 1987) is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time. A monotonic upward trend means that the variable consistently increases through time or vice versa, but the trend may or may not be linear. The MK test can be used in place of a parametric linear regression analysis, which can be used to test if the slope of the estimated linear regression line is different from zero. The regression analysis requires that the residuals from the fitted regression line be normally distributed; an assumption not required by the MK test, that is, it's a non-parametric (distribution-free) test. Hirsch, Slack and Smith (1982) indicate that the MK test is most appropriately used to identify stations where changes are significant or of large magnitude and to quantify these findings. This test is also useful for removing noise from time series (Zhou *et al.,* 2023; Zhang *et al.,* 2022). It is widely used to determine whether processes such as climate, hydrology and vegetation greenness change are undergoing natural fluctuations or have a definite trend of change (Wang *et al.,* 2021; Basarir *et al.,* 2018; Sa'adi *et al.,* 2019).

For this analysis, the MK test was used to identify trends and magnitudes of vegetation greenness change, and trends in different climate drivers. The analysis was performed using the *Kendall* and *raster* package in R to generate the trend rasters for the EVI and climate variables. Subsequently, a generalized additive model in R was used to identify the relation between vegetation trends and different climate drivers for different biogeographic zones. Figure 3. 2 shows the methodology flowchart used in the chapter.

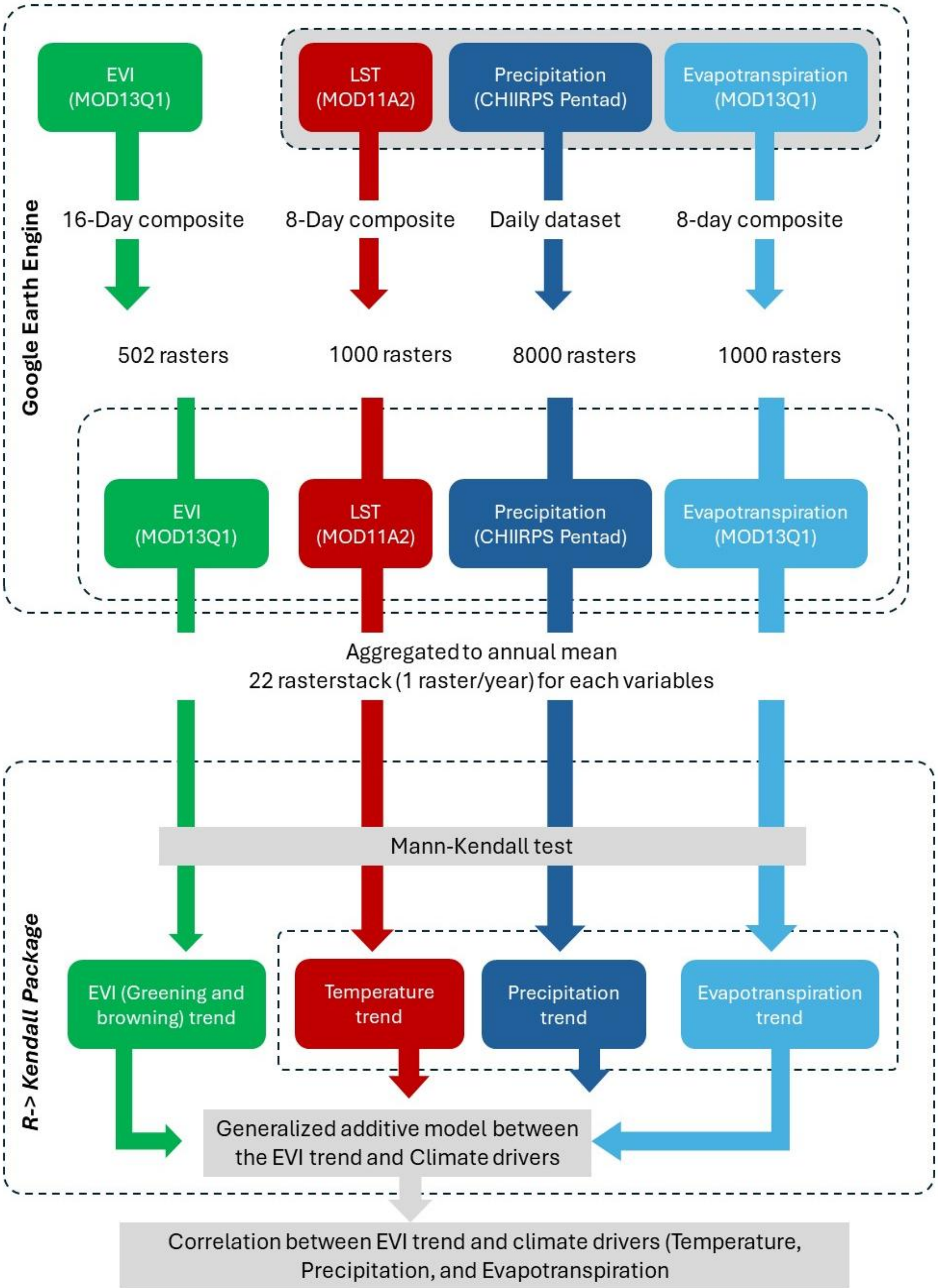


Figure 3. 2 Flowchart of the methodology to estimate the relationship between climate drivers and greening, and browning trends.

3.3. Results

Temperature (Figure 3. 4), precipitation (Figure 3. 5), evapotranspiration (Figure 3. 6), and EVI trend (Figure 3. 7) was computed and mapped for India. In the Himalaya, greening was dominant at lower and middle elevations, while browning occurred more at higher elevations. An increase in temperature had a positive correlation with browning. However, in Trans-Himalayan region model showed an increase in EVI trend with increasing temperature trend (Plate 1.A). It was observed in the trans-Himalayan zone with increasing temperature, Climatic factors like rising CO_2 and nitrogen deposition, along with human activities such as sustainable forestry practices and intensification of agriculture, were likely drivers of greening. Conversely, browning at high altitudes could be attributed to reduced pre-monsoon moisture availability. The Greening trend was observed over semi-arid regions of Northwest India and South India, while some subdivisions in the Indo-Gangetic (IG) plains and Western Ghats (WG) experienced a slight browning trend. The study also noted that croplands (CL) have a significant increasing trend over NWI and SI, which may contribute to the greening trend observed. The browning trend was consistent with increasing altitude, particularly in closed needle leaf forests and alpine shrublands of Trans-Himalaya.

Figure 3. 3 Presents a comprehensive insight into the greening and browning trends across various biogeographic zones. EVI trends show that throughout India there is a greening trend (Figure 3. 7). A significant greening trend is evident in most areas, with the Semi-Arid zone leading at a 96.21% greening percentage, closely followed by the Gangetic Plain and Desert at approximately 95.92% and 94.78%, respectively. The Trans-Himalaya zone exhibits a contrasting trend with a higher browning percentage of 39.51%. The Western Ghats and Deccan Peninsula also showcase substantial greening.

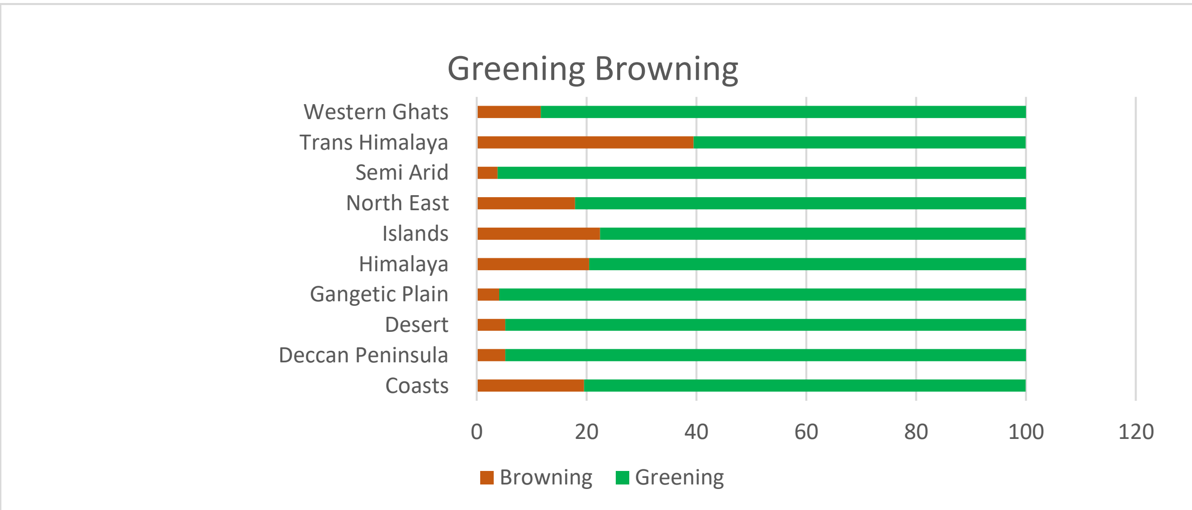


Figure 3. 3 Greening and browning trends in different biogeographic zones of India

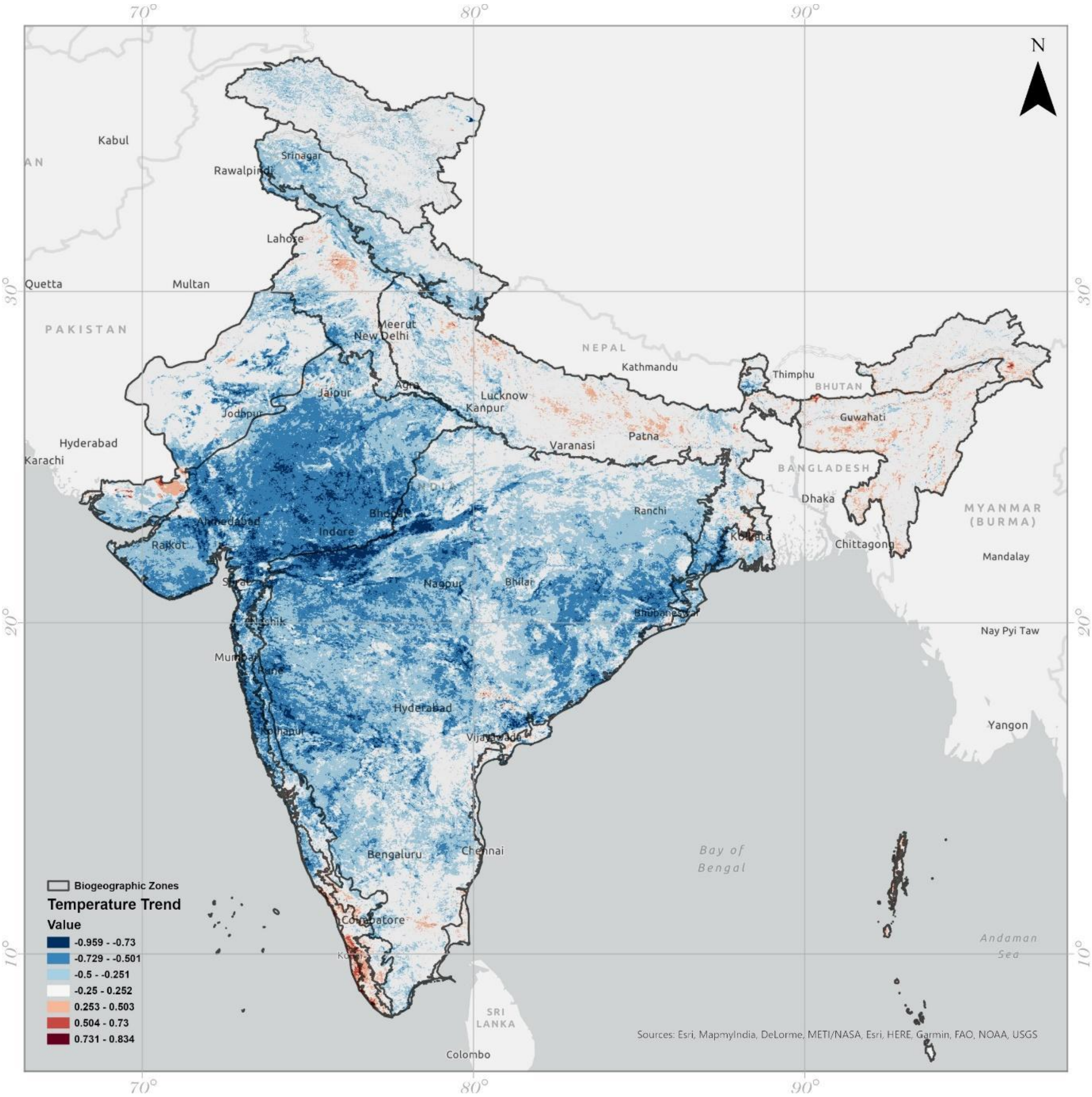


Figure 3. 4 Temperature trends in in India from 2000-2022. Blue depicts decrease in temperature whereas, red depicting increase in temperature.

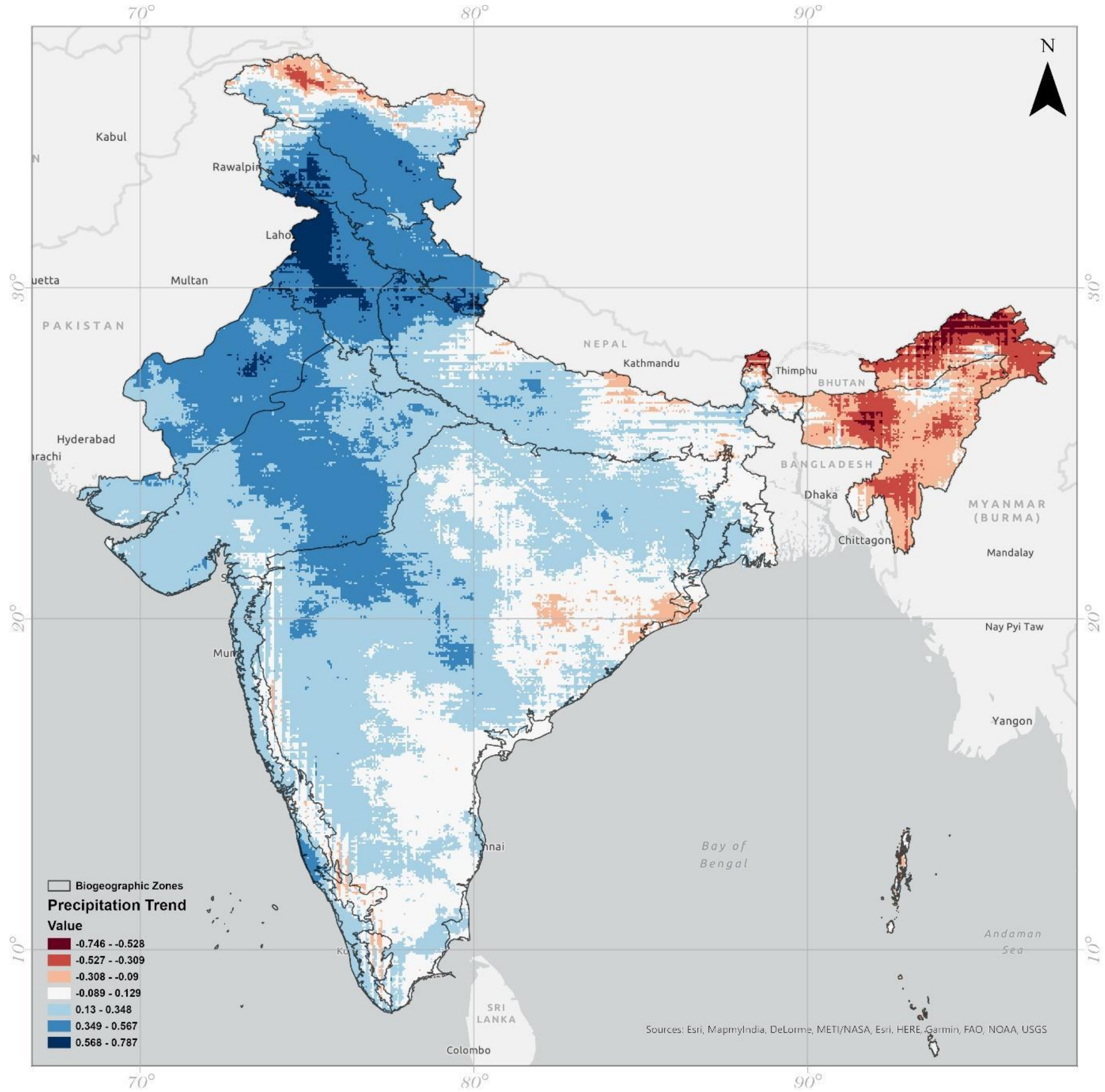


Figure 3. 5 Precipitation trends in in India from 2000-2022. Blue depicts increase in precipitation whereas, red depicting decrease in temperature.

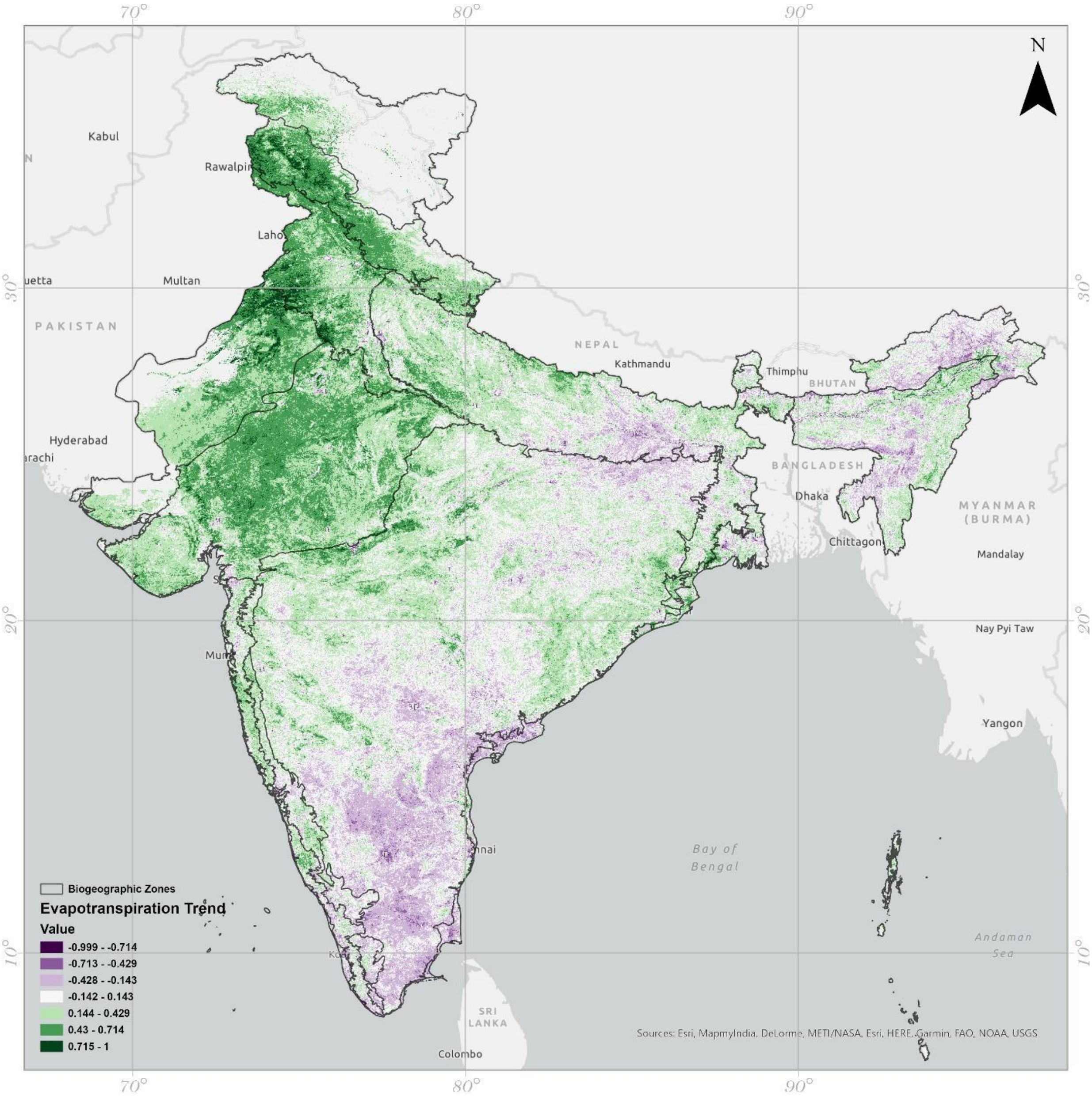


Figure 3. 6 Evapotranspiration trends in in India from 2000-2022. Green depicts increase in precipitation whereas, purple depicting decrease in temperature.

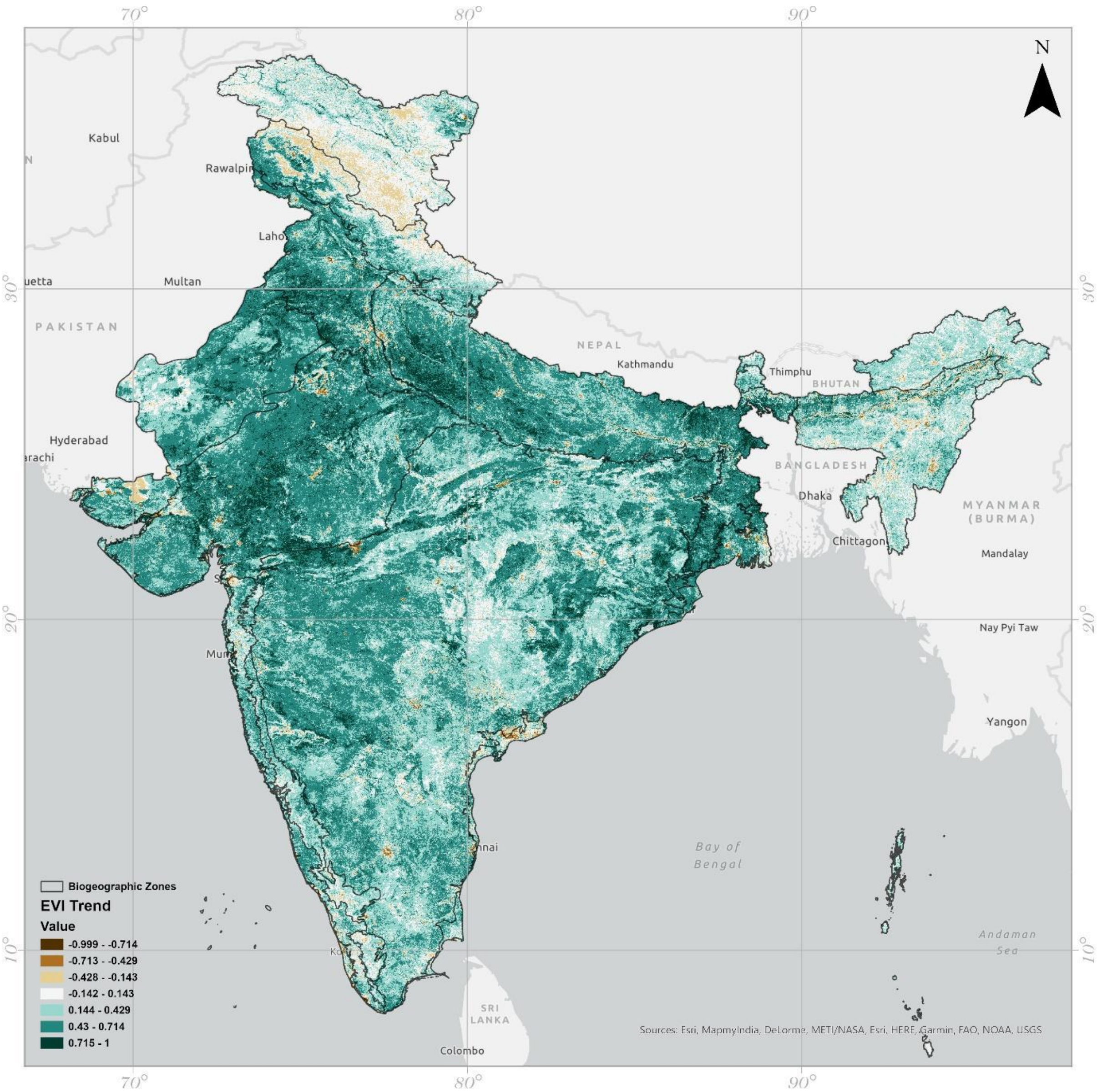


Figure 3. 7 Greening-browning (EVI) trends in India from 2000-2022. Green depicts increase in EVI whereas, brown depicting decrease in EVI.

Zone-wise trends and their correlation

Results depict the trends in different biogeographic zones. The value ranges from -1 to 1, where a negative value depicts a decreasing trend and a positive value depicts an increasing trend. Zone-wise results are given below.

Trans-Himalayas

Northern areas in the Tibetan plateau province show an increasing temperature trend, whereas the western part (i.e., Ladakh Mountains province) shows a comparatively decreasing temperature trend (Plate 1.I). Lower regions of Leh-Ladakh trans-Himalayas show an increase in precipitation, while the upper region shows a decrease. A similar trend in decreasing precipitation is observed in Sikkim trans-Himalayas (Plate 1. II). The northernmost areas The Western part of Ladakh mountains, and Sikkim trans-Himalayas show an increase in evapotranspiration trend (Plate 1.III). Overall, Trans-Himalayas shows a decrease in EVI with increasing temperature (Plate 1.A). Although there was a negative relation in areas with a moderate precipitation change trend (between -0.3 to 0.5), it shows an increase in EVI with an increasing precipitation trend (>0.5) (Plate 1.B).

Himalayas

The North-east province shows an increasing temperature trend (Plate 2.I) and a decrease in temperature trend in the west. In the northeast significant warming around the Brahmaputra plains was observed, with limited areas showing decreasing trends in temperature (Plate 2. I). The northeast province shows a decreasing trend in annual precipitation (Plate 2.II) and evapotranspiration (Plate 2.III), whereas the northwest Himalaya and west Himalayas show an increasing trend. There have been decreasing trends in precipitation and evapotranspiration in the northeast (Plate 2. II, and III). Overall, EVI shows a decreasing trend in the northeast (Plate 2. IV), and EVI increases with increased evapotranspiration and temperature (Plate 2. A and 2.C).

North-east

The North-east biogeographic zone exhibits a notable trend of increasing temperatures across both of its provinces (Plate 3.I). This warming trend is consistent and highlights the overarching impact of climate change on the region. In terms of annual precipitation patterns, a significant decrease has been observed in the upper regions of Meghalaya, as well as in Mizoram and Manipur. Conversely, certain areas within Assam and Tripura demonstrate an increase in annual precipitation (Plate 3.II). A decreasing trend in evapotranspiration has been observed particularly in the southern parts of Meghalaya and in certain areas of Manipur (Plate 2.III). This decline may have significant implications for water balance and vegetation dynamics in these areas. Across the entire North-east biogeographic zone, a decline in the Enhanced Vegetation Index (EVI) has been documented (Plate 3.IV). The decline in EVI suggests a reduction in vegetation health and productivity, which could be attributed to the changing climatic conditions. The Generalized Additive Model (GAM) results provide additional insights into the relationship between climate variables and vegetation health. The model indicates that EVI tends to increase with rising temperatures and precipitation levels (Plate 3.A and 3.B). This relationship suggests that, while certain areas are experiencing adverse effects due to reduced precipitation and increased temperatures, there are also regions where vegetation could potentially benefit from the changes, assuming other conditions remain favourable.

Western ghats

The northern region of the Western Ghats shows a decreasing temperature trend, whereas the southern parts, including the Nilgiris and southern coastal areas, exhibit an increase in temperature (Plate 4.I). The Konkan and Malabar coastal regions in the central parts experience increase in precipitation, while the Nilgiris, Anaimalai, and Agasthyamalai regions, being rain-shadow areas, show a decreasing rainfall trend (Plate 4.II). The central and northern parts of the Western Ghats have seen a higher evapotranspiration rate over the years, whereas the southern parts, including the Nilgiris, Anaimalai, and Agasthyamalai, have shown a decrease in evapotranspiration rate (Plate 4.III). Although precipitation and evapotranspiration in the Western Ghats positively related with EVI (i.e., EVI increases with precipitation and evapotranspiration) (Plates 4.B and 4.C, respectively), temperature exhibits a negative relation with the EVI trend (Plate 4.A).

Semi-arid

The northern parts of the semi-arid zone, particularly the central regions of the Punjab plains, show an increasing temperature trend, whereas the southern parts of the zone in Gujarat Rajputana exhibit a decreasing temperature trend (Plate 5.I). Precipitation, on the other hand, shows an increasing trend in the central parts of the Punjab plains and the central regions of Gujarat Rajputana. The northeastern and southwestern regions of Gujarat Rajputana show a significant decrease in precipitation trends (Plate 5.II). The regions experiencing increased precipitation trends also show an increased evapotranspiration trend, and vice versa (Plate 5.III). Although the temperature trend has a negative relationship with EVI (Plate 5.A), the overall semi-arid zone shows a strong positive relationship between EVI and evapotranspiration and a moderate positive relationship with the precipitation trend (Plates 5.B and 5.C, respectively).

Desert

The southwestern, western, northwestern, and northeastern parts of the Thar Desert, along with the northern parts of the Kachchh Desert, exhibit an increasing temperature trend. In contrast, the southern, southeastern, and central parts of the Thar Desert, as well as the southern parts of the Kachchh Desert, show a decreasing temperature trend (Plate 6.I). Precipitation has increased in the northern and central parts of the Thar Desert, while the entire Kachchh Desert, along with the southern and southwestern regions of the Thar Desert, shows a significant decrease in precipitation (Plate 6.II). The northern region of the Thar Desert and parts of the central region exhibit an increasing evapotranspiration trend, whereas most of the Kachchh Desert and the southern parts of the Thar Desert show a decrease in evapotranspiration (Plate 6.III). The EVI trend is decreasing across the entire Kachchh Desert and most parts of the Thar Desert, except for some scattered areas in the northern Thar Desert. Overall, evapotranspiration shows a strong positive relationship with EVI, and there is a moderate positive relationship between EVI and precipitation (i.e., EVI increases with higher evapotranspiration and precipitation) (Plates 6.B and 6.C, respectively). However, there is a strong negative relationship between temperature and EVI (Plate 6.A).

Deccan peninsula

In deccan peninsula, deccan south show an increasing temperature trend (Plate 7.I), followed by northern areas of central highlands and Chhota Nagpur province. Central plateau shows a decreasing trend in temperature (Plate 7. I). On the other hand, Eastern highlands show a decrease in annual precipitation trend, followed by deccan south (Plate 7. II). Increase in precipitation trend was observed in central plateau, and some regions of Chhota Nagpur province (Plate 7. II). In terms of evapotranspiration, decreasing trend was observed primarily in Deccan south province and in some parts of central plateau (Plate 7. III). Increasing evapotranspiration trend was mainly observed mainly in northern, and eastern areas of deccan peninsula (Plate 7. III). EVI trend was mostly declining in different parts of the deccan peninsula. Increasing trend was observed in few areas of central plateau. GAM results showed similar trends like other zones, where with increased precipitation, vegetation greening (EVI) was increasing (Plate 7.B) and reverse when temperature is increased (Plate 7.A). Increase in EVI is positively correlated with increase in evapotranspiration (Plate 7.C).

Gangetic plains

Increasing temperature trend was observed in mid-section (i.e., Uttara Pradesh and Bihar) of Gangetic plains (Plate 8. I). Decreasing trend was observed in southern areas of Gangetic plains (mainly in Odisha). Upper Gangetic plain shows increasing precipitation trend (Figure 8.II) whereas middle and lower Gangetic plain shows decrease in precipitation trends over the year (Plate 8. II). Declining evapotranspiration trend was observed in Bihar (Plate 8. III), and western section shows an increasing trend. Interestingly, despite having negative precipitation, and increasing temperature, almost majority of the Gangetic plains shows a greening trend (Plate 8. IV), except a small part of upper Gangetic plains. An increasing temperature trend was observed in the mid-section of the Gangetic plains, particularly in the states of Uttar Pradesh and Bihar (Plate 8.I). This trend highlights the rising temperatures in these areas, which can have significant implications for agriculture, water resources, and overall climate resilience. Conversely, a decreasing temperature trend was noted in the southern areas of the Gangetic plains, primarily in Odisha. In terms of precipitation, the upper Gangetic plain demonstrates an increasing trend (Figure 8.II). However, the middle and lower Gangetic plains show a decrease in precipitation trends over the years (Plate 8.II). This declining trend in precipitation in these areas could exacerbate water scarcity and stress on agricultural systems, potentially impacting food security. Bihar exhibits a declining trend in evapotranspiration (Plate 8.III), which could indicate reduced water loss from the soil and vegetation, possibly due to decreased precipitation or changes in land use. On the other hand, the western section of the Gangetic plains shows an increasing trend in evapotranspiration. This increase may be driven by higher temperatures and altered vegetation patterns, influencing water availability and agricultural productivity.

Interestingly, despite the negative precipitation trends and increasing temperatures, most of the Gangetic plains show a greening trend (Plate 8.IV). This greening trend, indicative of increasing vegetation cover or health, could be attributed to various factors such as improved agricultural practices, irrigation, and adaptation strategies by local communities. The exception to this trend is a small part of the upper Gangetic plains, which does not follow the overall greening pattern.

Coasts

The southern parts of the coastal zone, including the Malabar Coast in the west, and the Coromandel Coast, southern parts of the Andhra Coast, and the northeastern parts of the Utkal Coast in the east, show an increasing temperature trend. Conversely, other regions in the coastal zone exhibit a decreasing temperature trend (Plate 9.I). Precipitation trends show a decrease along the eastern coast, particularly in some parts of the Coromandel Coast, Utkal Coast, and the northern parts of the Utkal Coast, whereas the western regions show an increase (Plate 9.II). Evapotranspiration trends indicate a decrease along the Coromandel Coast and in the northern parts of the Utkal Coast, while an increased trend is observed in some scattered regions along the eastern coastline (Plate 9.III). Overall, the EVI trend is increasing along both coastlines (Plate 9.IV). The EVI shows a strong positive relationship with evapotranspiration (Plate 9.C), but it exhibits a negative relationship with temperature (Plate 9.A) and a weak positive relationship with precipitation (Plate 9.B).

Islands

The temperature shows an overall increasing trend in most parts of the Andaman and Nicobar Islands (Plate 10.I). Conversely, precipitation exhibits a decreasing trend across the Andaman and Nicobar Islands, except in Lower and Little Andaman, where it has increased (Plate 10.B). Evapotranspiration shows an increasing trend in North and Middle Andaman, while other regions experience a comparatively decreasing trend (Plate 9.III). The EVI has increased more significantly in Great Nicobar Island compared to the Andaman Islands (Plate 10.IV). Additionally, EVI shows a moderately strong positive correlation with both precipitation and evapotranspiration (Plates 10.B and 10.C, respectively), but a negative correlation with temperature (Plate 10.A).

Greening browning and temperature trends in different biogeographic zones

Trans-Himalayas

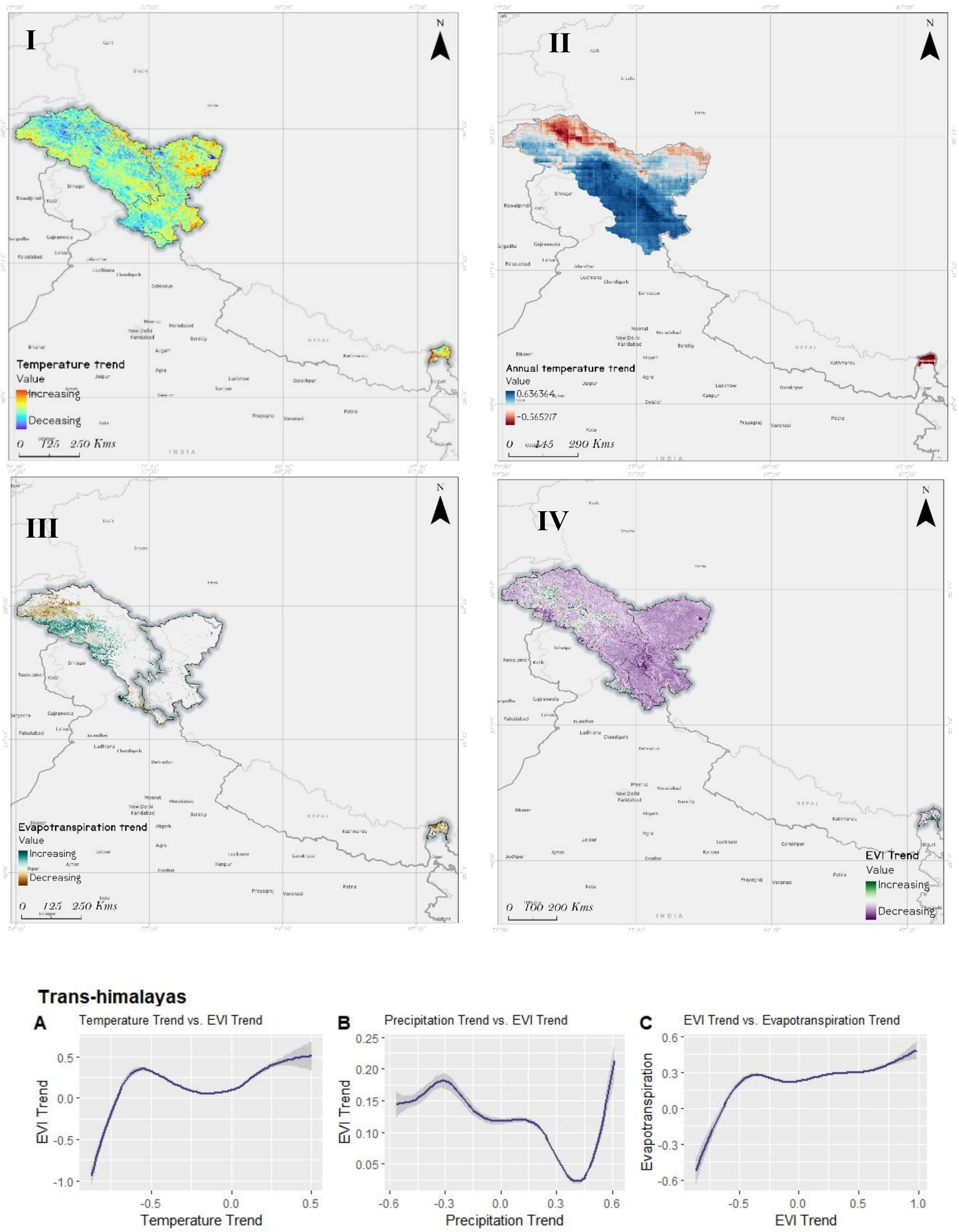


Plate 1 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in Trans-Himalayas, and their correlation.

Himalayas

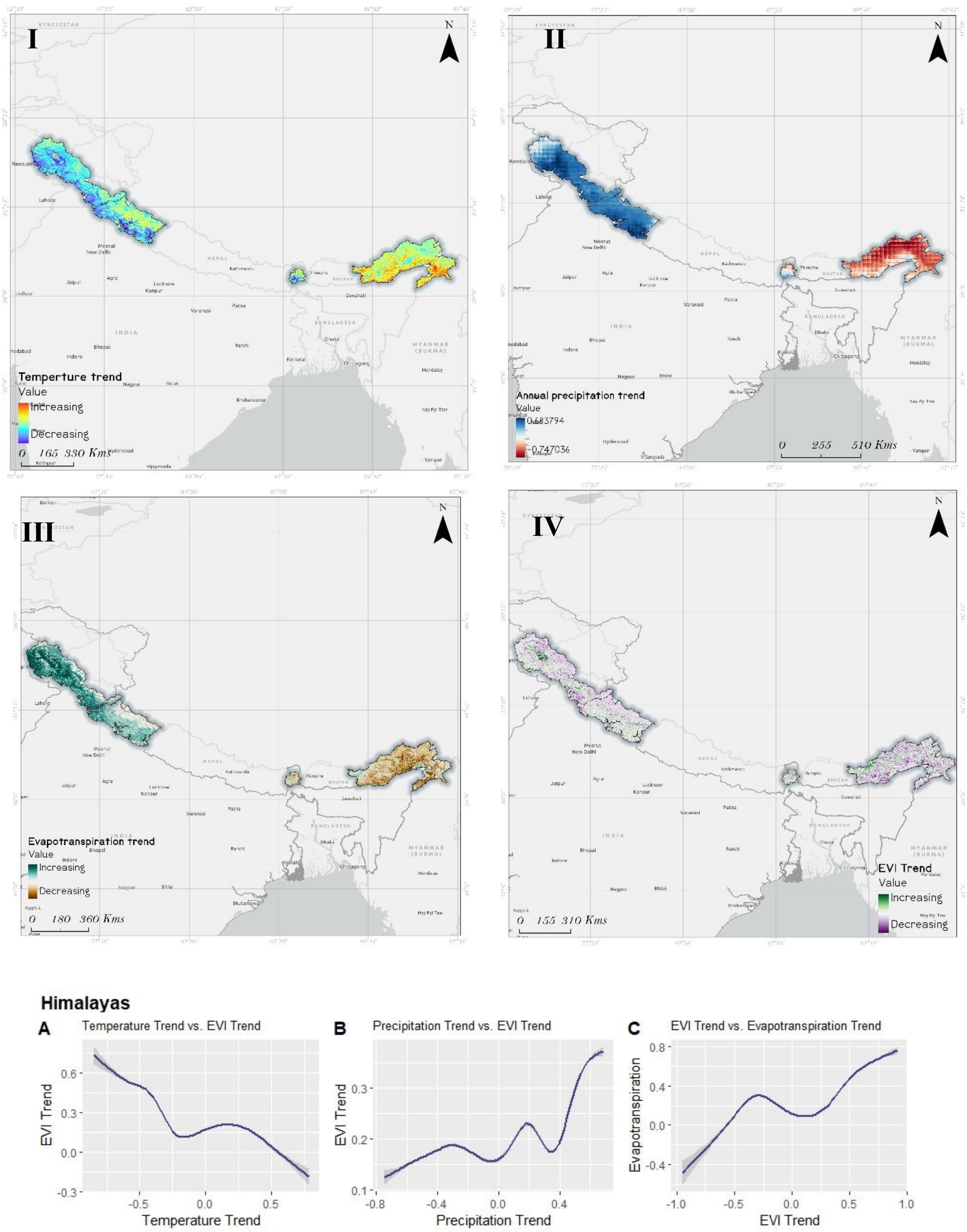


Plate 2 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in Himalayas, and their correlation.

North-East

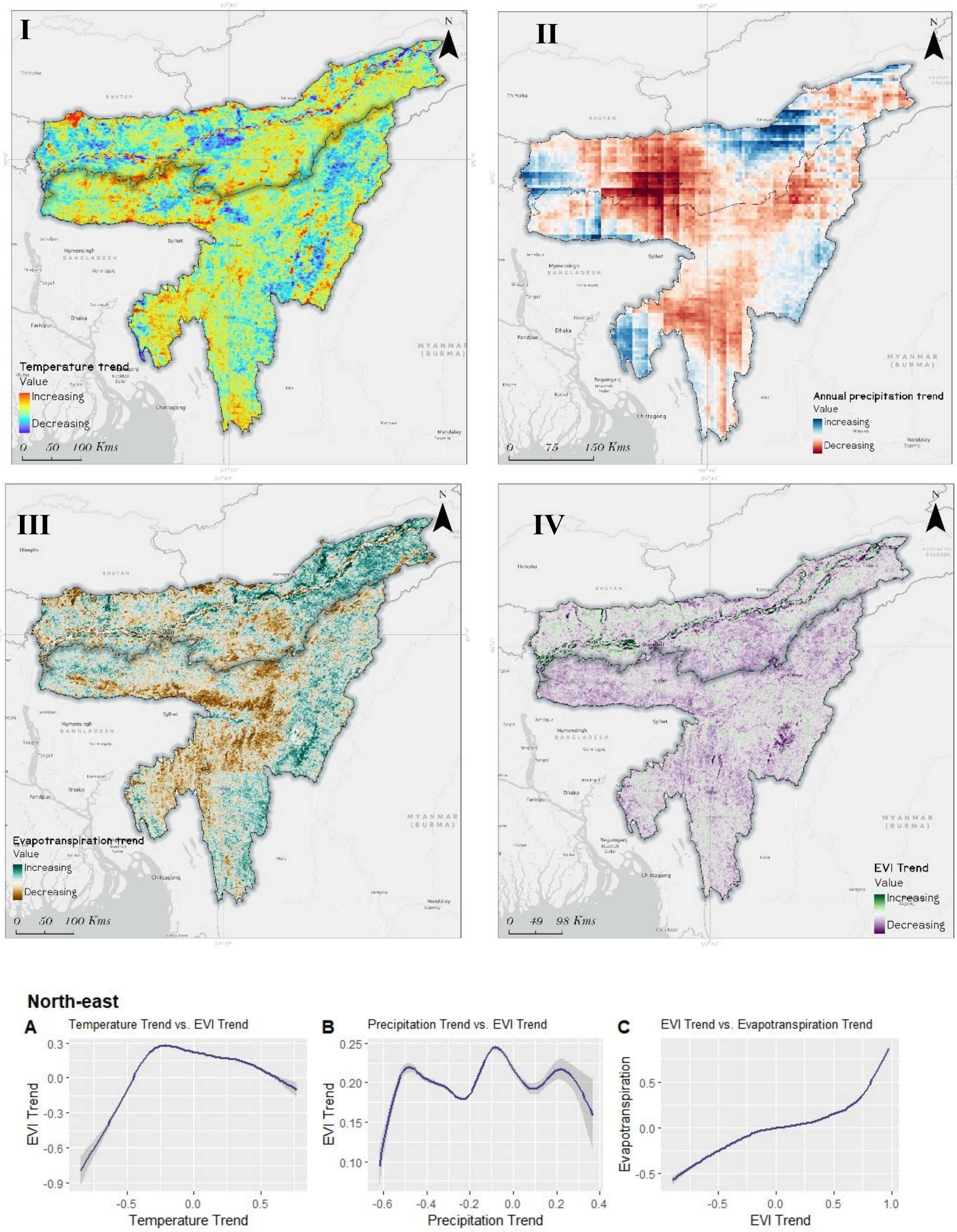


Plate 3 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in North-east, and their correlation.

Western Ghats

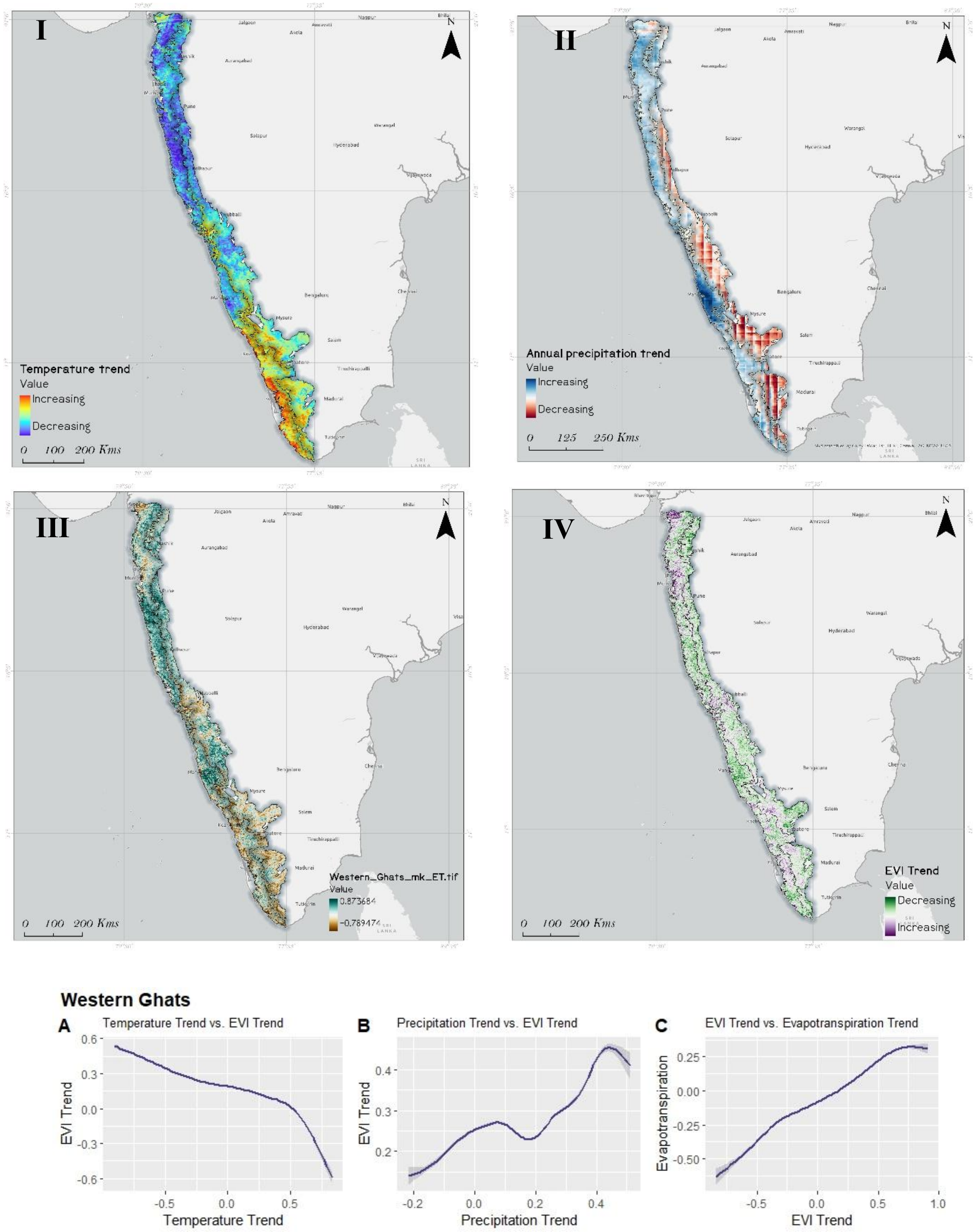
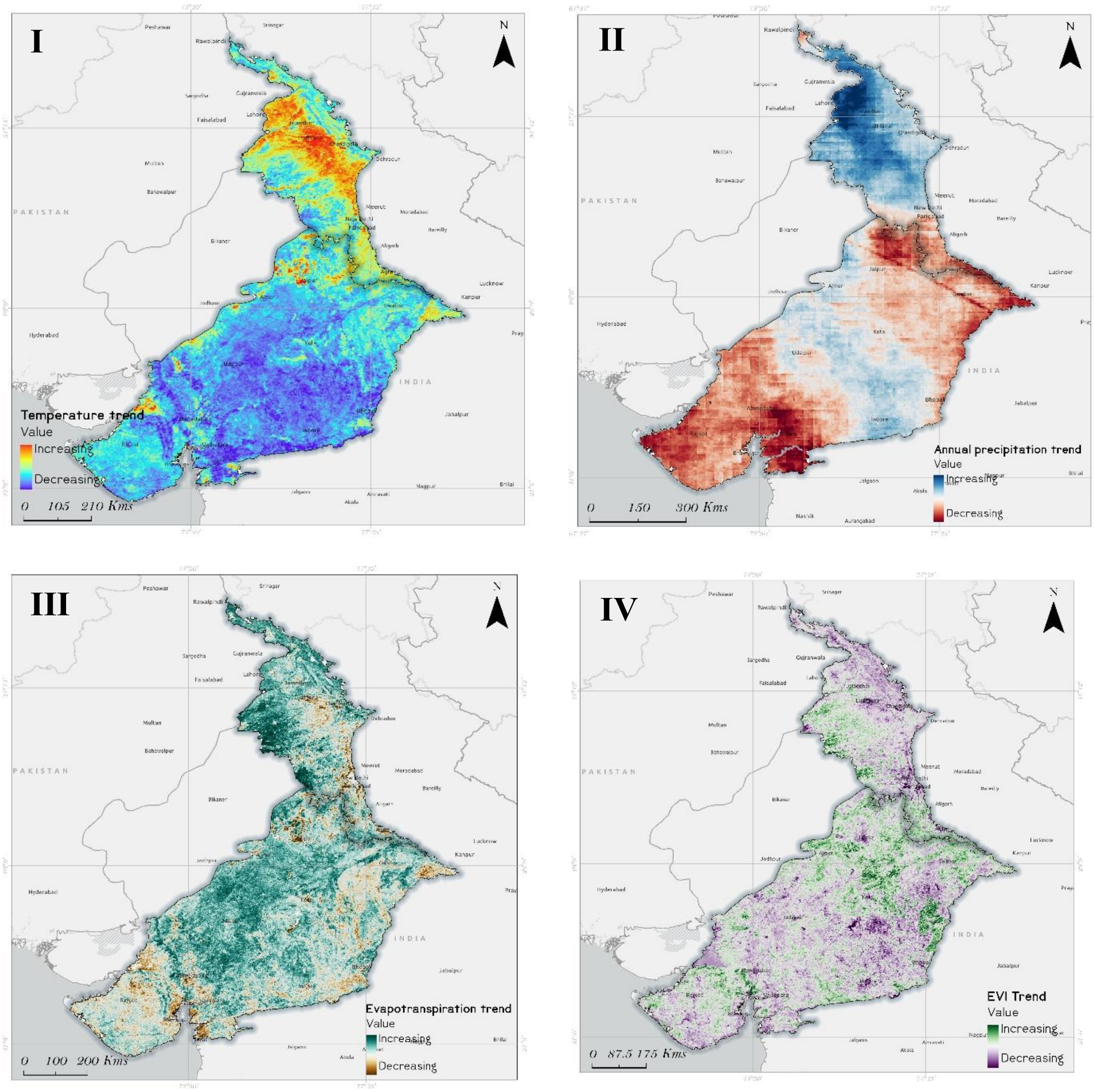


Plate 4 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in western ghats, and their correlation.

Semi-Arid



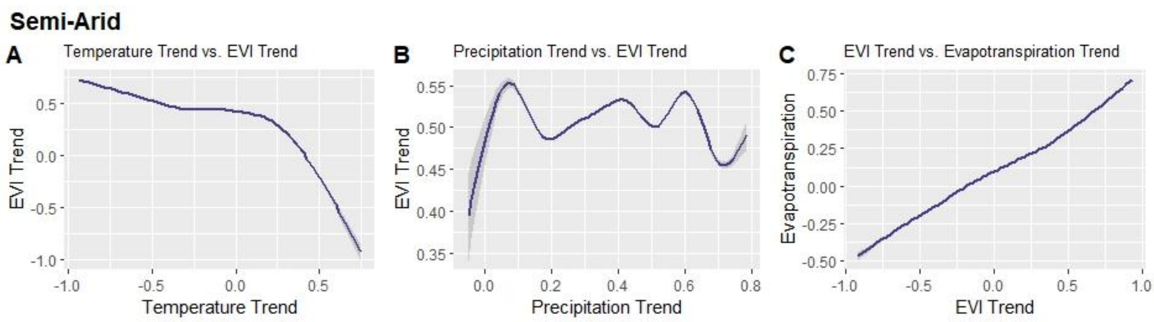


Plate 5 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in semi-arid, and their correlation.

Desert

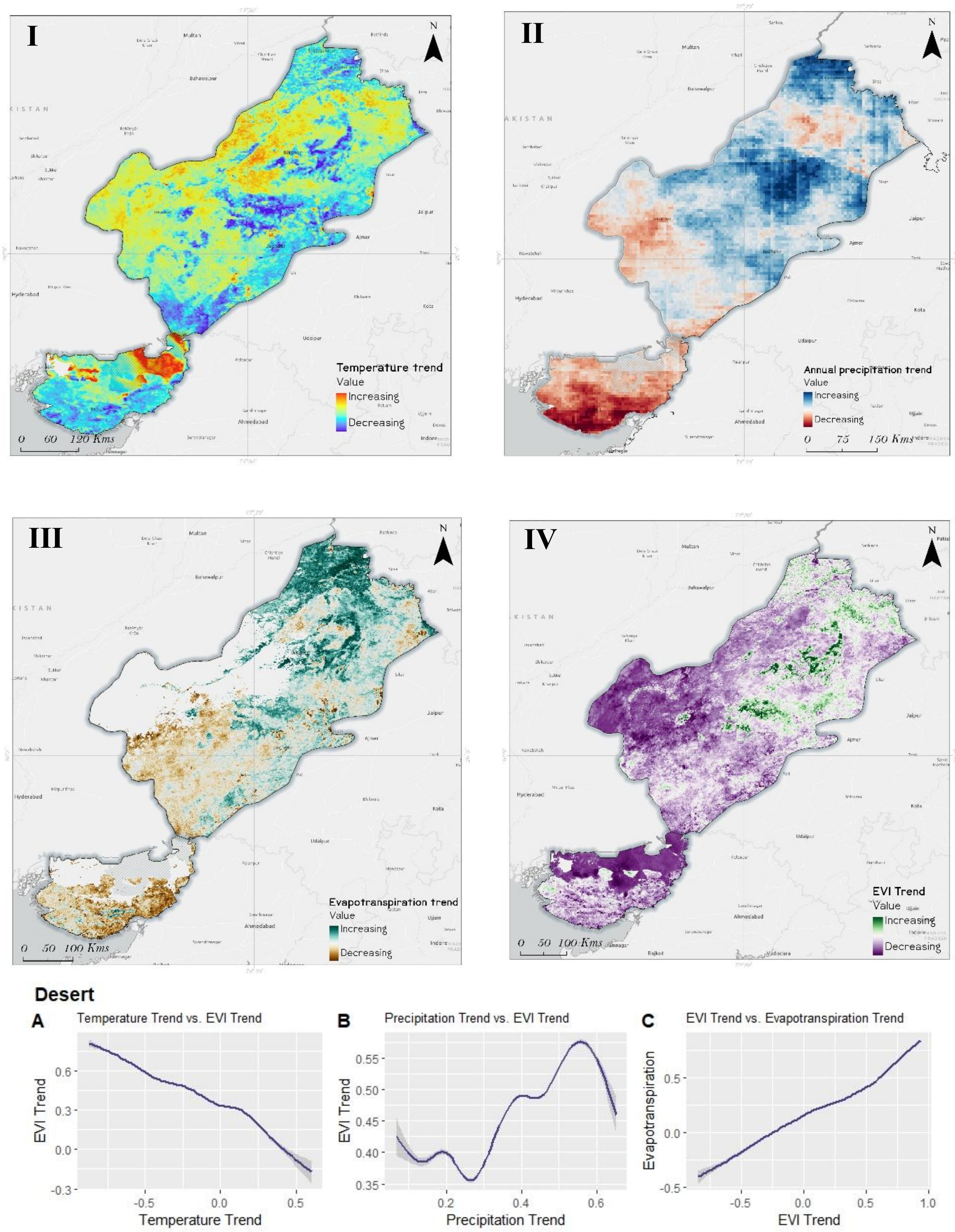


Plate 6 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in desert, and their correlation.

Deccan Peninsula

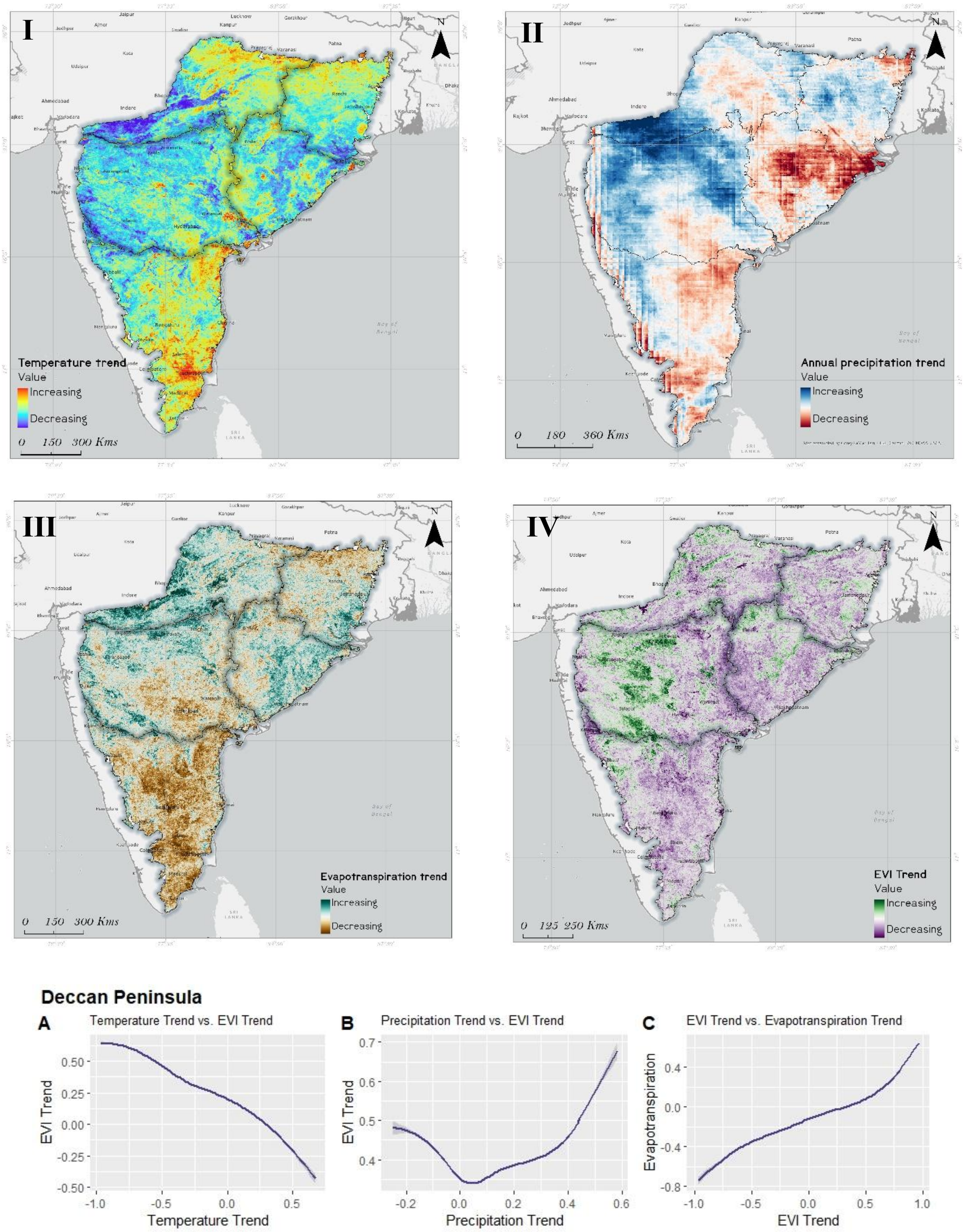


Plate 7 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in deccan peninsula, and their correlation.

Gangetic Plains

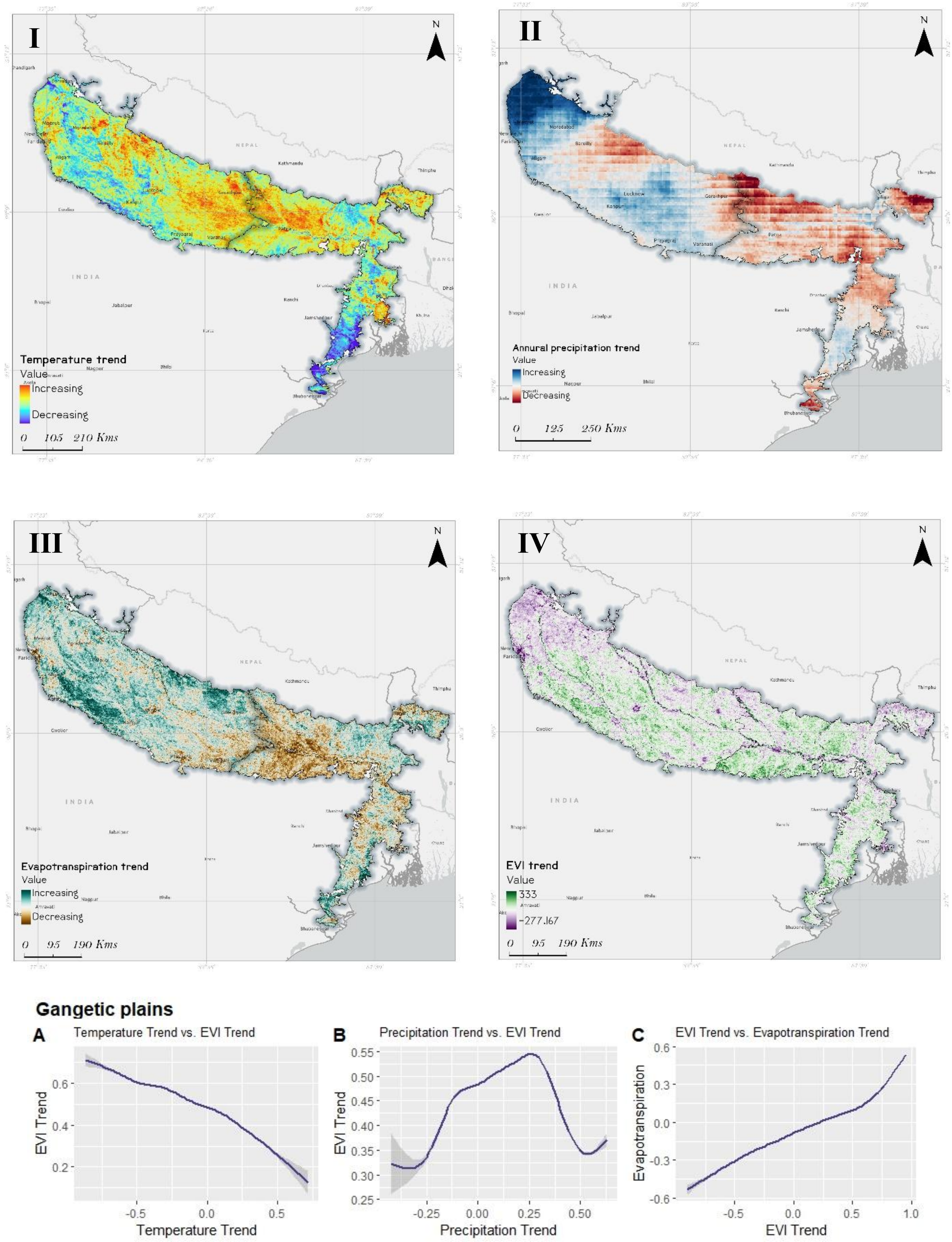


Plate 8 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in Gangetic plains, and their correlation.

Coasts

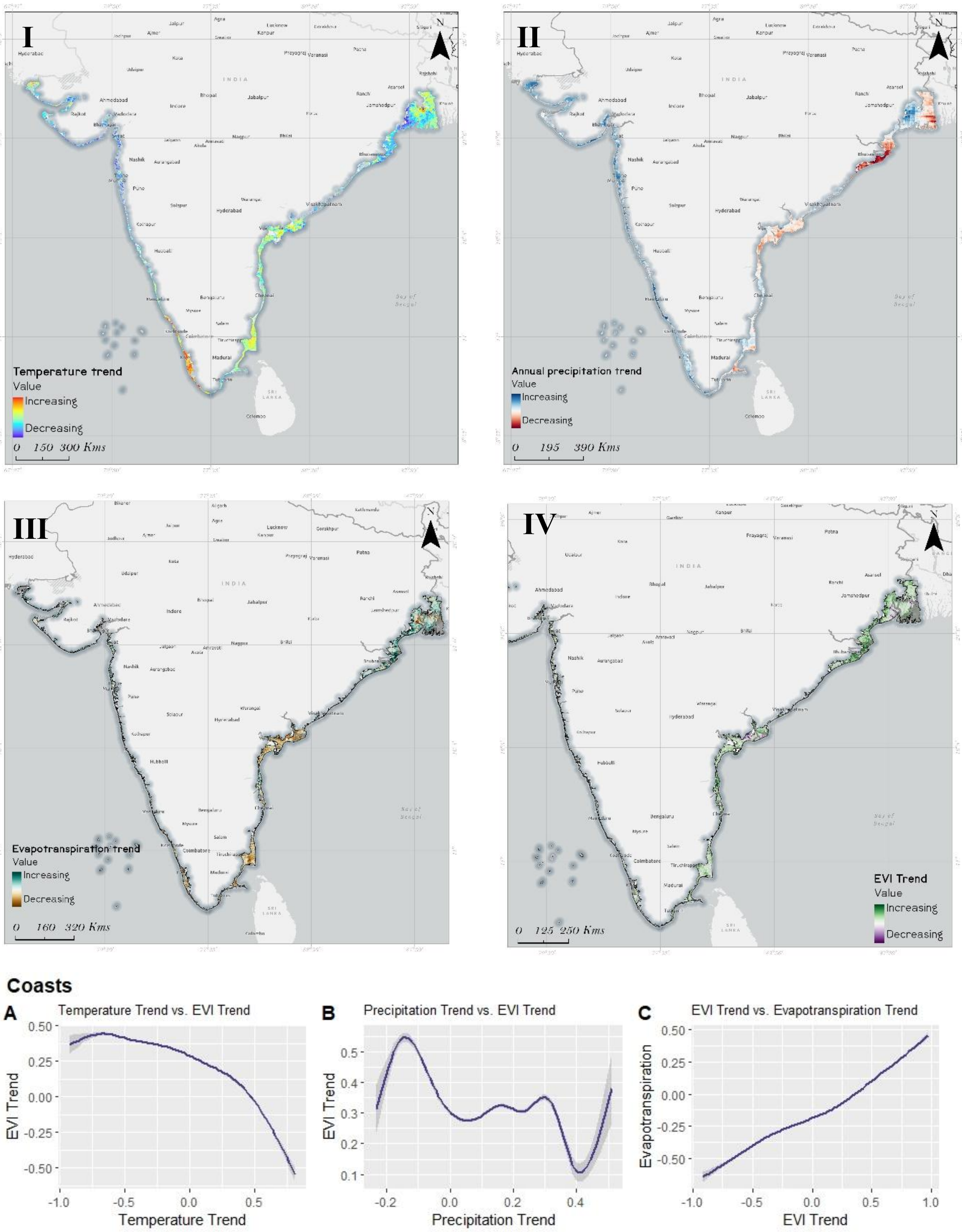


Plate 9 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in coasts, and their correlation.

Islands

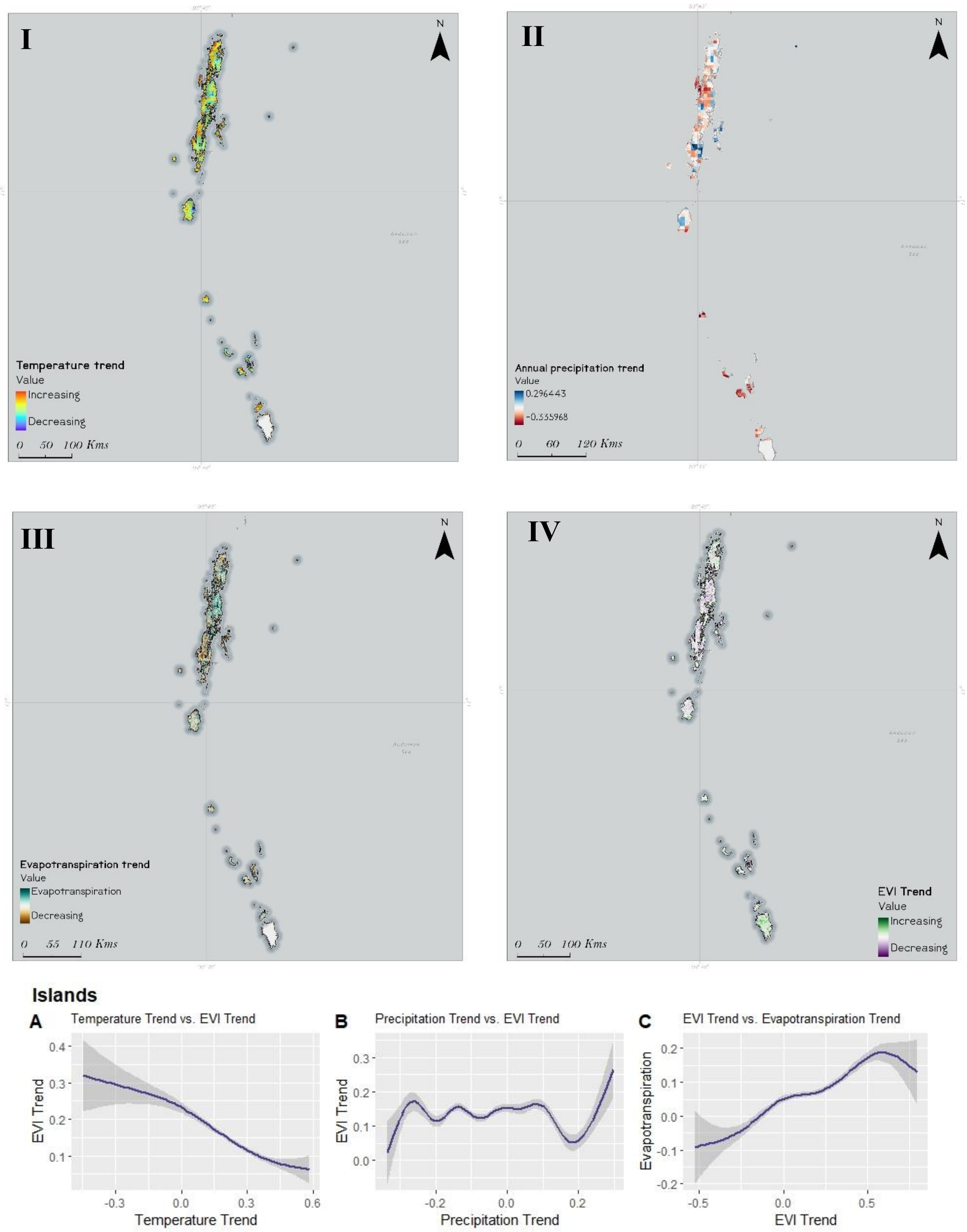


Plate 10 Greening-browning (EVI), and climate drivers (Temperature, precipitation, and evapotranspiration) trends in Indian islands, and their correlation.

3.4. Discussion

This work utilized satellite-derived EVI time-series (2000-2022) data to trends in vegetation over India and understand the role of climatic drivers behind the observed changes. MK test was performed for every pixel to acquire the spatial patterns of EVI and climatic variables, and the correlation was computed among EVI and climatic variables using a Generalized additive model.

Most of the earlier studies related to greening and browning trends have analysed NDVI data over the Northern parts of India and South Asia by using either the 1982–2005 period or in some cases 2001–2017 using either NDVI3g data or MODIS-based NDVI and LAI data (Sarmah *et al.,* 2018; Chen *et al.,* 2019; Pandey & Ghimire, 2012; Chakraborty *et al.,* 2018; Mishra & Chaudhuri, 2015; Mishra & Mainali, 2017).

In the present study, EVI and climatic trend statistics were presented for different biogeographic zones of India. The key findings revealed that the majority of India shows a greening trend. However, this greening might not be from forests. Chen *et al.,* (2021) analysed the whole of India using MODIS-based LAI records throughout 2001–2017 and concluded that the greening is mainly from croplands (82%) with minor contributions from forests (4.4%) in India. In contrast, Chakraborty *et al.,* (2018) indicated 12% browning trends and 67% greening trends in natural vegetation (mostly forests and woody trees) in India by using MODIS NDVI data throughout 2001–2014. Our results depicted that vegetation over Northeast India and the Himalayas had a browning trend over the period 2000–2022 because of a declined precipitation trend and with increased warming trend, a phenomenon known as temperature-induced moisture stress or temperature-induced drought stress. These findings are also consistent with negative trends suggested by other studies (Wang *et al.,* 2017; Mishra and Mainali, 2017) which were attributed to deforestation, shifting cultivation and human-induced land use conversion for urban expansion. In the Uttarakhand Himalayas, browning of vegetation was also reported by Mishra and Chaudhari (2015) associated with temperature-induced moisture stress which arose due to increased temperature with declines or no changes in precipitation. This phenomenon has an adverse impact on vegetation productivity (D'Arrigo *et al*., 2004; Krishnaswamy *et al.,* 2014) along with rising forest fires in Himalayan states (Bar *et al.,* 2020). The key findings also depicted a greening of Northwestern Plain and Central India, and that can be attributed to increased vegetation productivity related to shrublands due to favourable environmental variables such as increased rainfall with decreased temperatures. In contrast, the browning of the Deccan peninsula (Maharashtra) and western ghats mostly associated is due to temperature-induced moisture stress (Wang *et al*., 2017, and Sarmah *et al.,* 2018). For all zones except the Trans-Himalayas, browning had a positive correlation with temperature increase. This could be because warming might be beneficial for vegetation growth in trans-Himalayas (Dolezal *et al.,* 2021). Results also show an increase in precipitation trends in the semi-arid zone. Earlier studies have suggested globally there will be an increase in precipitation in the semi-arid zone (Guan *et al.,* 2021). Over the years, there has been a decrease in precipitation trend in the North-east zone. This trend is seen in other works (Kulkarni *et al.*, 2020; Choudhury *et al.,* 2019). The weakening of the south-westerly heat-trough circulation and reduced moisture transport is likely the reason for reduced rainfall over northeast India as well as in Gangetic plains (Maharana *et al*., 2021). Lower Gangetic plains show substantial greening, even if there is increased warming, reduced evapotranspiration and precipitation. This greening in this province is likely to be in croplands, as also found by Chen *et al.,* 2021.

While substantial greening patterns exist throughout India, likely attributed to cropland expansion, browning trends in ecologically sensitive regions like Northeast India and the Himalayas emphasize the vulnerability of these ecosystems to temperature-induced moisture stress. Changes in the pattern of vegetation and climate conditions can cause drastic changes in species diversity, abundance, and distribution (Burrows *et al.,* 2014). As species in different biogeographic zones are adapted to certain climatic conditions, long-term changes in these conditions can have adverse impacts on them. An increase in precipitation over the years in the semi-arid zone can have an adverse impact on the species adapted to the xeric conditions. Similarly, a decreasing trend in precipitation in the north-east can have a negative impact on the species adapted to wet conditions.

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Chapter 4

Climate vulnerability of protected areas

Chapter 4. Climate vulnerability of protected areas

4.1. Introduction

Climate change impacts can threaten the long-term functioning of PAs and the species they are intended to protect (Singh, 2020; Lemieux *et al*., 2011). It can also have negative impacts on the communities and economies that depend on these resources. Identifying and quantifying climate-vulnerable areas is critical for guiding effective conservation activities (Stanton *et al.,* 2015). Changing climate could influence fire regimes (Batllori *et al.,* 2013; Pausas & Fernández-Muñoz, 2012), species richness and distribution pattern (Monzón *et al.,* 2011), invasive species spread (Hellmann *et al.,* 2008), hydrological cycle change (Al-Mukhtar *et al.,* 2014) and biome shifts (Salazar and Nobre, 2010) within protected areas. Thus, many of the present protected areas may not be climatically suitable for, or able to safeguard, the species and ecosystems in the future (La Sorte and Jetz, 2010). Thus, it is important to assess the climatic change vulnerability to identify the PAs which are most prone to climate change impact for developing efficient conservation policies (Hoffmann and Beierkuhnlein., 2020). Predicting future climate conditions inside PAs is necessary to inform conservation management and policymakers about potential climate change implications (Rannow *et al.,* 2014). Conservation policy and management are mostly established at the national or local levels. Global studies on climate change impact do not consider national authorities or the local extent of PAs (Williams *et al.,* 2007; Beaumont *et al.*, 2011; García-López & Allué, 2013; Bellard *et al.,* 2014; Garcia *et al.,* 2014; Ordonez *et al.,* 2016; Li, Wu *et al.,* 2018; Li, Kou *et al.,* 2018). Additionally, climate change studies focusing on PAs are primarily in North America (Batllori *et al.,* 2017) or Europe (Nila *et al.,* 2019). A national perspective based on the impact of local climate change on individual PA is lacking, but it is important for supporting local to national conservation policy and management to meet global commitments beyond 2020 (Watson *et al.,* 2016).

Three key components of climate change vulnerability are outlined in a common framework: a. *sensitivity,* which measures how much a species' ability to persist depends on the climate in its habitat; b. *exposure*, which measures how much of a climate change the species will experience throughout its range; and c. *adaptive capacity*, which measures a species' capacity to adapt to changes in climate, usually through phenotypic plasticity, dispersal, and evolutionary responses (Williams *et al*., 2008). There are numerous methodologies for evaluating these three factors, and most of them rely on species traits or climate modelling techniques to generate coarse indices or vulnerability categories (Thomas *et al.,* 2011; Foden *et al.,* 2013).

India is one of the 17 mega-biodiverse countries in the world (Mittermeier *et al.,* 1997). Its proportion of the world's species variety is 8.1% despite making up only 2.4% of the planet's geographical area (Vattakaven *et al.,* 2016). The diverse climate and terrain of India have given rise to a wide array of ecosystems such as forests, grasslands, wetlands, coastal and marine networks, and deserts (Chaturvedi, 2017). To manage natural resources for the preservation of biodiversity and the welfare of populations that depend on such resources, India has established a network of protected areas. This represents around 5.43% of the nation's total land area (WII ENVIS 2023). Like elsewhere in the world the protected areas and their biodiversity in India are also facing grave challenges from climate change. Climate studies conducted across India over the last century show that there have been notable changes in precipitation patterns as well as a tendency toward rising surface temperatures (Sinha *et al.,* 1999; Sharma *et al.* 2004; Dash and Hunt 2007; Niyogi *et al.,* 2010). The instances of climate change would, however, be distributed differently across India's geographical area. Some areas of India are thought to be more vulnerable to both the existing climate variability and the anticipated effects of climate change (Panda., 2009). Thus, climate change vulnerability assessment of different PAs across India would shed light on how they are affected by the changing climate and how effective they are for biodiversity protection in the future. Till now, there are no studies which have modelled the vulnerability of PAs of India to climate change. Objectives of this chapter are, a) Identifying the climate sensitivity, exposure, and vulnerability of protected areas of India to climate change. and b) identifying the most vulnerable and resilient protected areas in different biogeographic zones of India. The outcomes of this chapter can aid in informing adaptive management to compensate for the negative impacts of climate change on PA effectiveness.

4.2. Materials and methods

4.2.1. Data used

- *Biogeographic zones of India*

India is divided into ten biogeographic zones based on distinctions in topography, land use, geography, and climate (Rodgers and Panwar, 1988). These zones include the Trans-Himalayan (TH), Himalayas (Hm), North-East (NE), Semi-Arid (SA), Gangetic Plains (GP), Desert (Ds), Western Ghats (WG), Deccan Peninsula (DP), Coasts (Cs), and the Islands (Is). Each of these zones possesses its characteristic flora and fauna. Rodgers and Panwar (1988) used these biogeographic zones to develop a plan for PA networks of India that guided both National and State Institutions. Out of the 34 major global biodiversity hotspots, four major hotspots (Myers *et al.,* 2000): the Himalayas, Western Ghats, Indo-Burma, and the Sundalands, lie within these biogeographic zones & these hotspots account for nearly 7–8% of all the recorded species residing in various ecosystems (Myers *et al.,* 2000). Details of each biogeographic zone of India along with unique characteristics, and climatic condition is given in Chapter 2.

- *Protected areas of India*

India has a large and diverse network of PAs, which are managed by various government agencies at the national, state, and local levels. The primary legislation governing protected areas in India is the Wildlife Protection Act of 1972, which provides for the protection of wildlife and the management of protected areas. India has four different types of Protected areas as per the Wild Life (protection) Act, of 1972. National Park, Wildlife Sanctuary, Community reserve, and Conservation reserve. For our analysis, protected areas of India information (Source: WII PA database) was used. PAs less than 1km^2 areas were excluded from the analysis. In total 505 PA were used in the analysis (Figure 4. 1). More details of individual PAs are given in chapter 2.

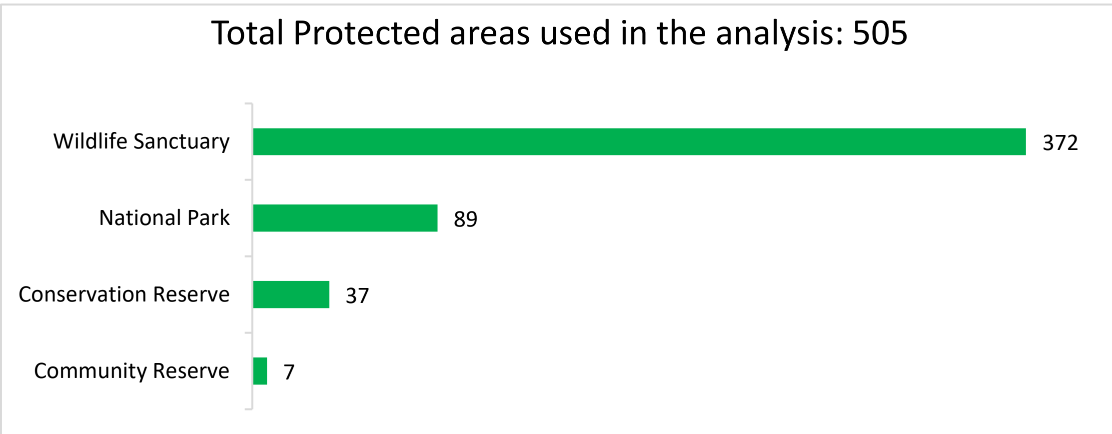

Figure 4. 1 Protected areas used in the Climate and Ecological Niche Factor (CENFA) analysis.

- *Bioclimatic variables*

Bioclimatic variables are derived from the monthly temperature and rainfall values to generate more biologically meaningful variables. These are often used in species distribution modelling and related ecological modelling techniques (Hijman *et al.,* 2005). The bioclimatic variables were downloaded from the WorldClim 2.1 website (Fick & Hijmans, 2017) at a resolution of 30 arc-seconds (≈1 km^2). The downloaded dataset covers the temporal span of 1970 to 2020 (near present), providing average climatic conditions for this period. WorldClim's current climate data were generated by interpolating climate station data.

For future climatic scenarios, WorldClim's future climate data downscaled from the GCMs of the MIROC-E2SL Global Circulation model (GCM) based dataset were downloaded for 2081-2100 (end of the century). These projections were based on four distinct Coupled Model Intercomparison Project Phase 6 (CMIP6) derived Shared Socioeconomic Pathways (SSPs): SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5. These SSPs represent various plausible future emission scenarios, considering diverse socioeconomic assumptions and potential trajectories. For this analysis, two pathways were considered, SSP245 (Middle of the road) and SSP585 (Worst-case scenario). Among the total 19 variables downloaded, recommended (Warren *et al.,* 2013) bioclim variables (Table 4.1) were selected that represent annual trends (BIO1 = Annual Mean Temperature, BIO12 = Annual Precipitation), extreme environmental factors (BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter) and seasonality (BIO4 = Temperature Seasonality, BIO15 = Precipitation Seasonality). Before conducting the analyses, all bioclimatic variables were spatially clipped using ArcGIS 10.8 to align with the specific boundaries of different biogeographic regions. Clipped bioclimatic variables were used as the reference area.

Table 4. 1 List of bioclimatic variables used in the analysis.

S. no.	Bioclimatic variables	Abbreviation	Remarks
1	Annual Mean Temperature	Bio1	Source: www.worldclim.org Resolution: 1km^2
2	Temperature Seasonality	Bio4	
3	Max Temperature of Warmest Month	Bio5	
4	Min Temperature of Coldest Month	Bio6	
5	Annual Precipitation	Bio12	
6	Precipitation Seasonality	Bio15	
7	Precipitation of Wettest Quarter	Bio16	
8	Precipitation of Driest Quarter	Bio17	

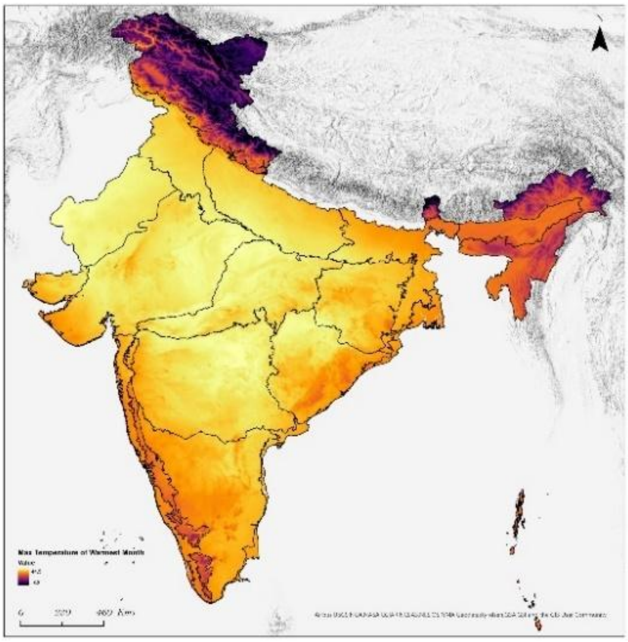

Figure 4. 4 Map of maximum temperature of warmest month of India.

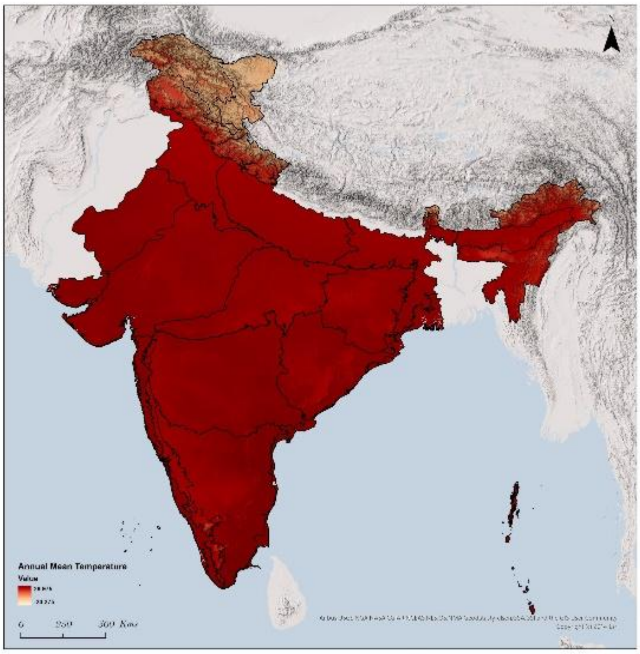

Figure 4. 2 Map of Annual Mean Temperature of India.

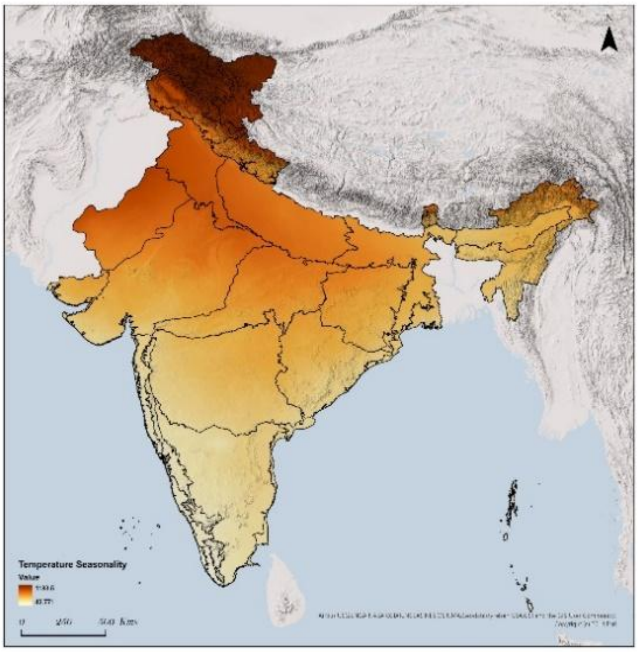

Figure 4. 3 Map of temperature seasonality of India.

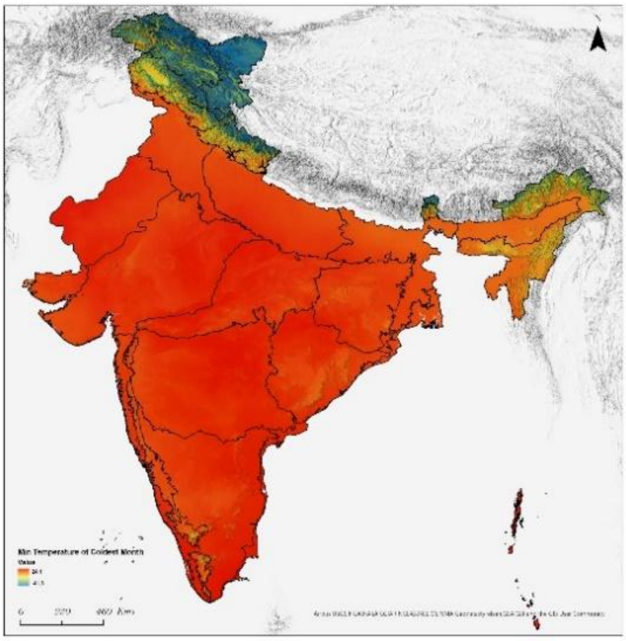

Figure 4. 5 Map of minimum temperature of coldest month of India.

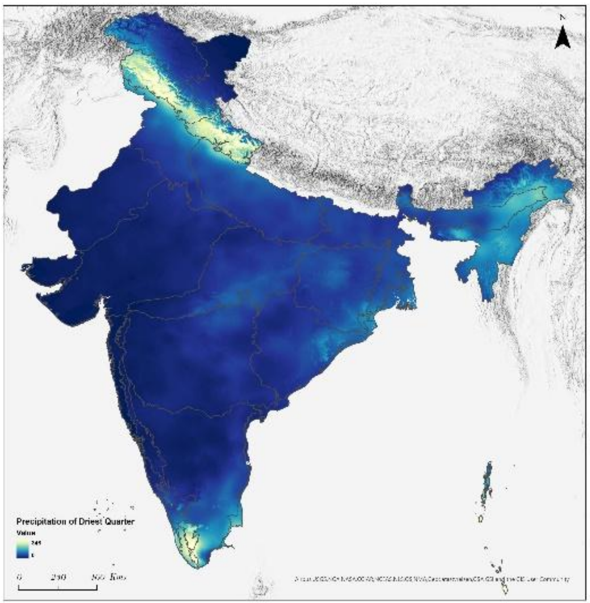

Figure 4. 8 Map of precipitation of driest quarter of India.

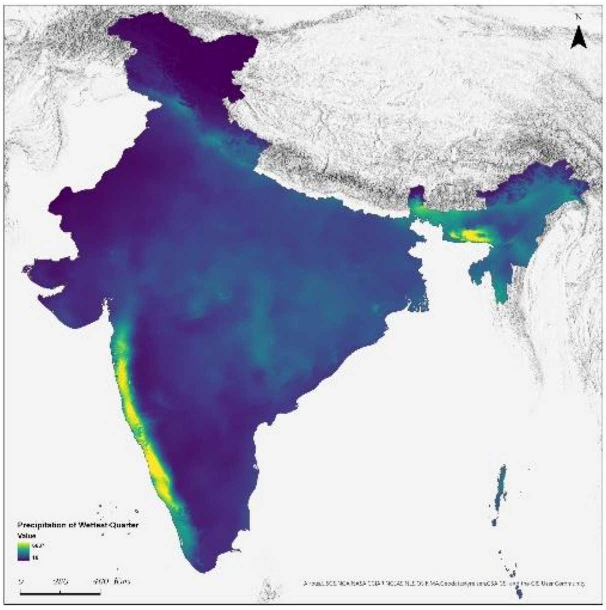

Figure 4. 9 Map of precipitation of wettest quarter of India.

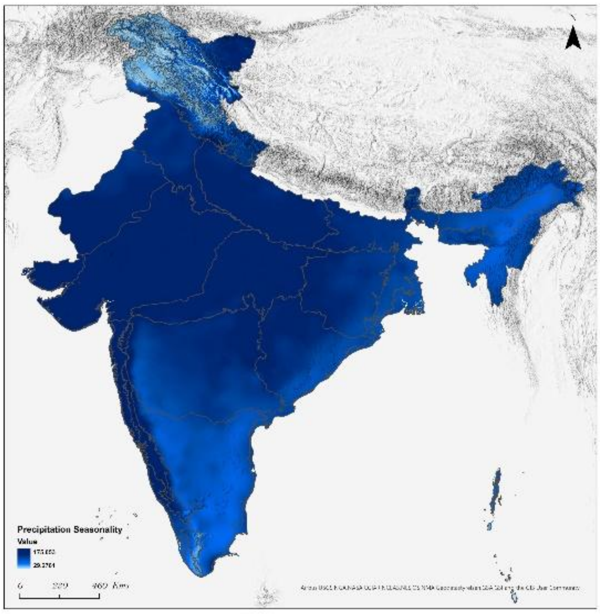

Figure 4. 6 Map of precipitation seasonality of India.

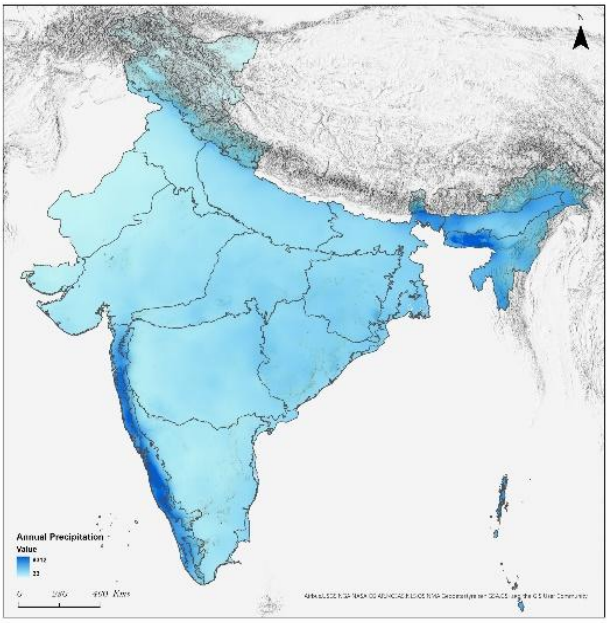

Figure 4. 7 Map of Annual precipitation of India.

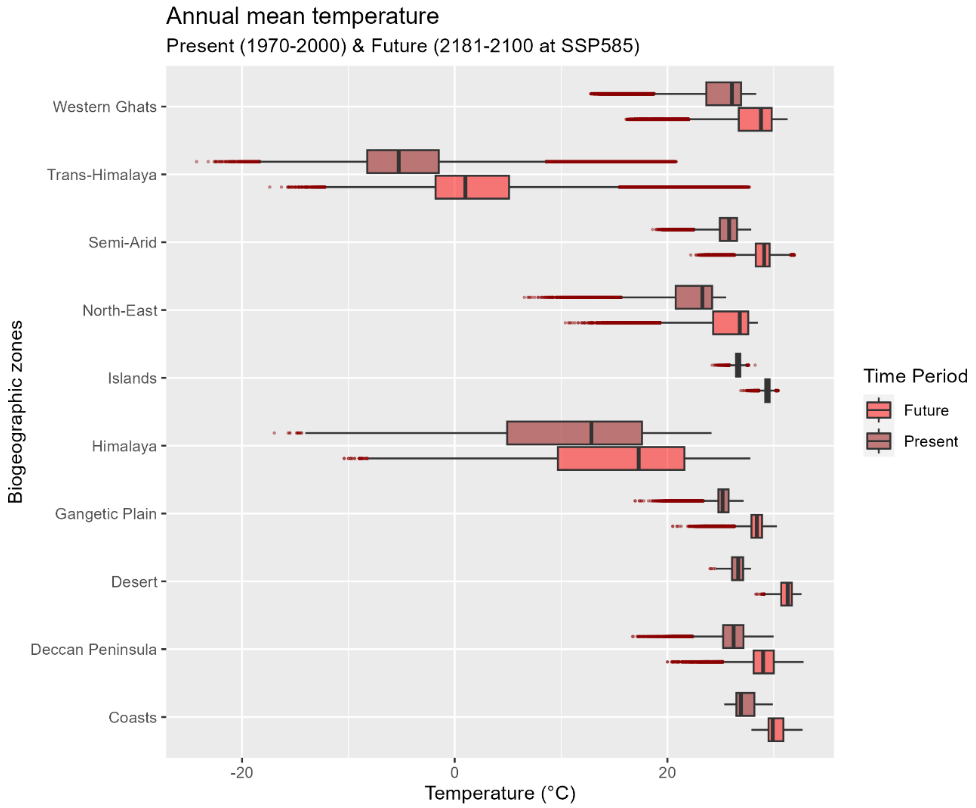

Figure 4. 11 Annual mean temperature of different biogeographic zones in present and future (2081-2100)

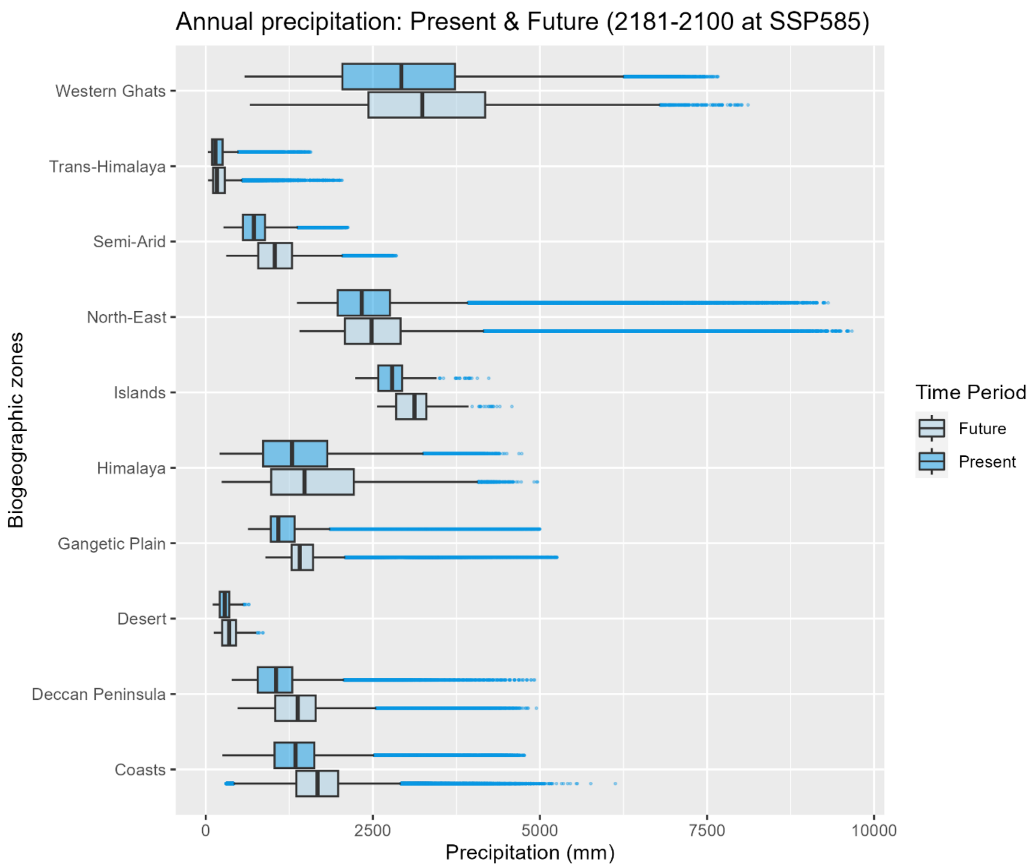

Figure 4. 10 Annual precipitation of different biogeographic zones in present and future (2081-2100)

4.2.2. Assessing the vulnerability of protected areas to climate change

Climate change vulnerability assessments are techniques for determining how vulnerable a species, ecosystem, or ecosystem function is to climate change. They can aid in the development of effective adaptive management strategies (Füssel, & Klein, 2006). For this study, protected areas' vulnerability to climatic variables was calculated by following the CENFA approach, which was implemented by Rinnan and Lawler (2019). This approach derives (i) Sensitivity and (ii) Exposure to climate change, i.e., departure, (iii) a combination of departure and sensitivity is considered as vulnerability (Figure 4. 12).

- ***Quantifying sensitivity to climate change***

Sensitivity is calculated as the array of environmental conditions an area tolerates concerning a given environmental variable. The rationale behind this metric is that the smaller the range of environmental conditions within an area, the smaller its width and, consequently, the more sensitive the area will be to strong deviations from climate change (Rinnan & Lawler, 2019).

The higher the overall climate sensitivity of an area, the smaller the climatic space that area has. If a PA only encompasses a narrow range of climatic conditions, it is reasonably expected the area to be more sensitive to the effects of climate change. Thus, environmental variables are all climate variables, the sensitivity factor(s) of a PA is a direct reflection of its sensitivity in each climate dimension. The overall sensitivity reflects the average specialization in each variable and provides a useful measure for comparison between species, provided the same reference study area is used.

- ***Quantifying exposure to climate change***

Exposure is calculated as a dissimilarity measure between present and future environmental conditions within an area: the higher such dissimilarity, the larger the amount of climatic change the area might experience.

- ***Quantifying vulnerability to climate change***

Vulnerability to climate change reflects the interaction between sensitivity and exposure to climate change.

More details and equations used in the analysis are given in Rinnan and Lawler, (2019). Following the CENFA framework, Sensitivity, exposure, and vulnerability were measured for each PA (Rinnan & Lawler, 2019) within each biogeographic zone for SSP245 and SSP585 scenarios. All analyses were carried out using the “CENFA” R package using the cnfa function

(Rinnan & Lawler, 2019). For ease of understanding, different resulting scores of the PA of each biogeographic zone were rescaled from 1-10. It is to be noted that the scores of the PA cannot be compared between different biogeographic zones.

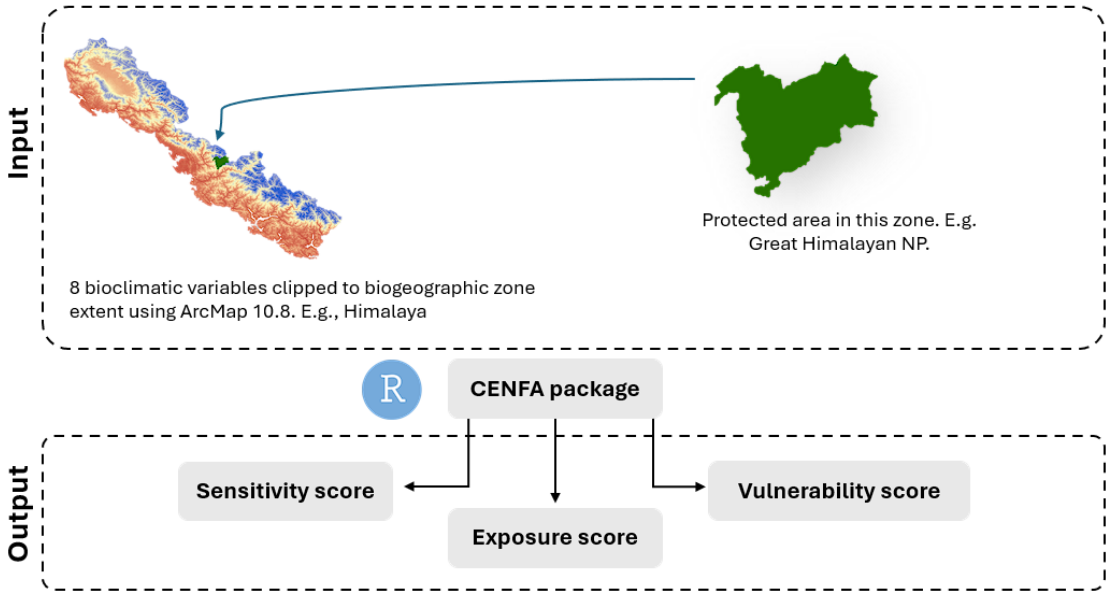

Figure 4. 12 Protected areas used in the Climate and Ecological Niche Factor (CENFA) analysis.

4.2.3. Climate vulnerability and area of the PA

Large, protected areas are likely to have higher climate heterogeneity, as they occupy larger climate space. Also, PAs located at higher elevations are more likely to have higher climate exposure.

To test these, a linear regression test was performed,

a. between the area of the PAs and the resulting vulnerability scores to test if smaller PAs are more vulnerable to climate change.
b. Between the elevation of the PAs and the resulting exposure scores test if PAs located at higher elevations are more climatically exposed.

4.3. Results

Vulnerability analysis was performed for each PA using the CENFA approach. Sensitivity, departure, and vulnerability scores of the individual PA are given in Tables 2-11 for each biogeographic zone. The resulting vulnerability scores do not have any scale (Rinnan and Lawler, 2019). Thus, the scores were rescaled from 1-10, where 10 denotes a higher scale of vulnerability, and value one denotes the lowest in the scale. For the majority of the PAs, the SSP585 scenario had greater vulnerability scores than the SSP245 scenario, reflecting the increase in climate change-related threats in those PAs. E.g. Figure 4. 14 Depicts the sensitivity, exposure, and vulnerability maps of Great Himalayan National Park produced through the analysis. Through the linear regression test, it was found that PAs at higher elevations have higher climate exposure (Figure 4. 14). Also, smaller PAs have higher climate vulnerability (Figure 4. 15).

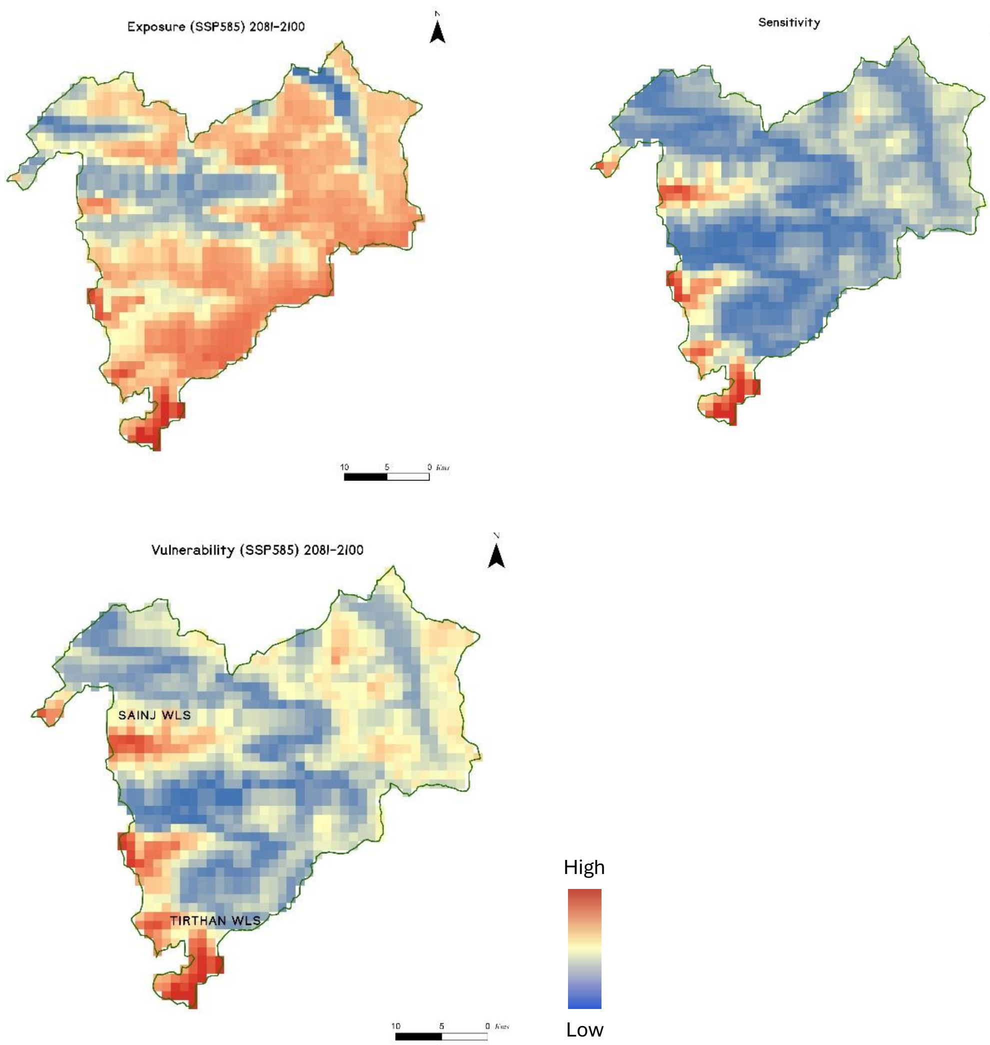

Figure 4. 13 Sensitivity, exposure, and vulnerability maps of the Great Himalayan national park

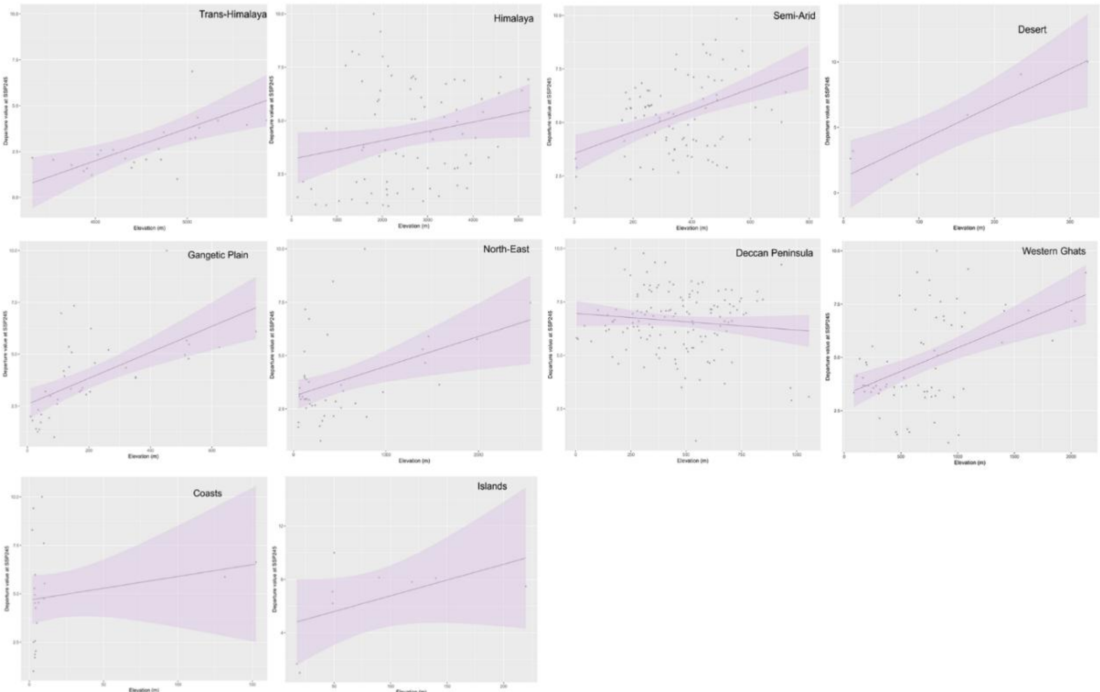

Figure 4. 14 Correlation between Elevation and climate exposure of different biogeographic zones. X axis denotes Elevation and Y axis denotes climate exposure. Climate exposure of PAs generally increasing with increasing temperature

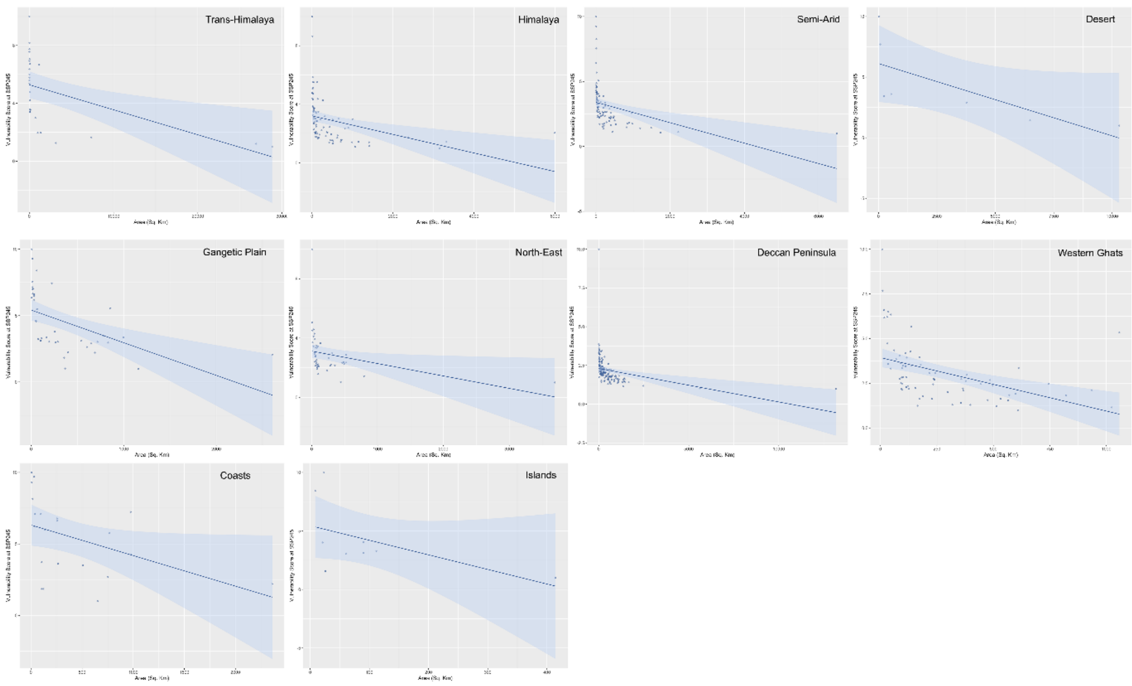

Figure 4. 15 Correlation between PA area and climate exposure of different biogeographic zones. X axis denotes Elevation and Y axis denotes vulnerability. Climate vulnerability of PAs is decreasing with increasing PA area.

Biogeographic zone-wise vulnerability results

- ***Trans-Himalayas***

Total 26 PAs from Trans-Himalayas were included in the analysis (Figure 4. 16; Table 4. 2). Highest sensitivity was found to be in Panyar CR (sensitivity=10), followed by Sabu CR (sensitivity=7.057), and Shallabugh Wetland CR (sensitivity=6.658). Highest climatic exposure (at ~4°C) is in Great Himalayan NP (Departure=10), followed by Pin valley NP (Departure=6.853), and Sabu CR (Departure=4.973). Lowest climatic exposure was found to be in Khangchendzonga NP (Departure factor=1), followed by Singba NP (Departure=1.356). These two protected areas are situated in the Eastern Trans-Himalayan landscape and exhibited lower climatic exposure.

The Vulnerability factor is highest in Panyar CR (Vulnerability factor=10), followed by Sabu CR (Vulnerability=8.178), and Shallabugh (WL) WLS (Vulnerability=7.674). Panyar CR, and Sabu CR is an important habitat for endemic Kashmir Stag (*Cervus hanglu hanglu*). Shallabugh WLS is a Ramsar site and important habitat for migratory birds. Karakoram WLS has the lowest vulnerability score (vulnerability= 1), followed by Changthang WLS (Vulnerability score= 1.215) and Khangchendzonga NP (Vulnerability Score= 1.245), owing to their large area.

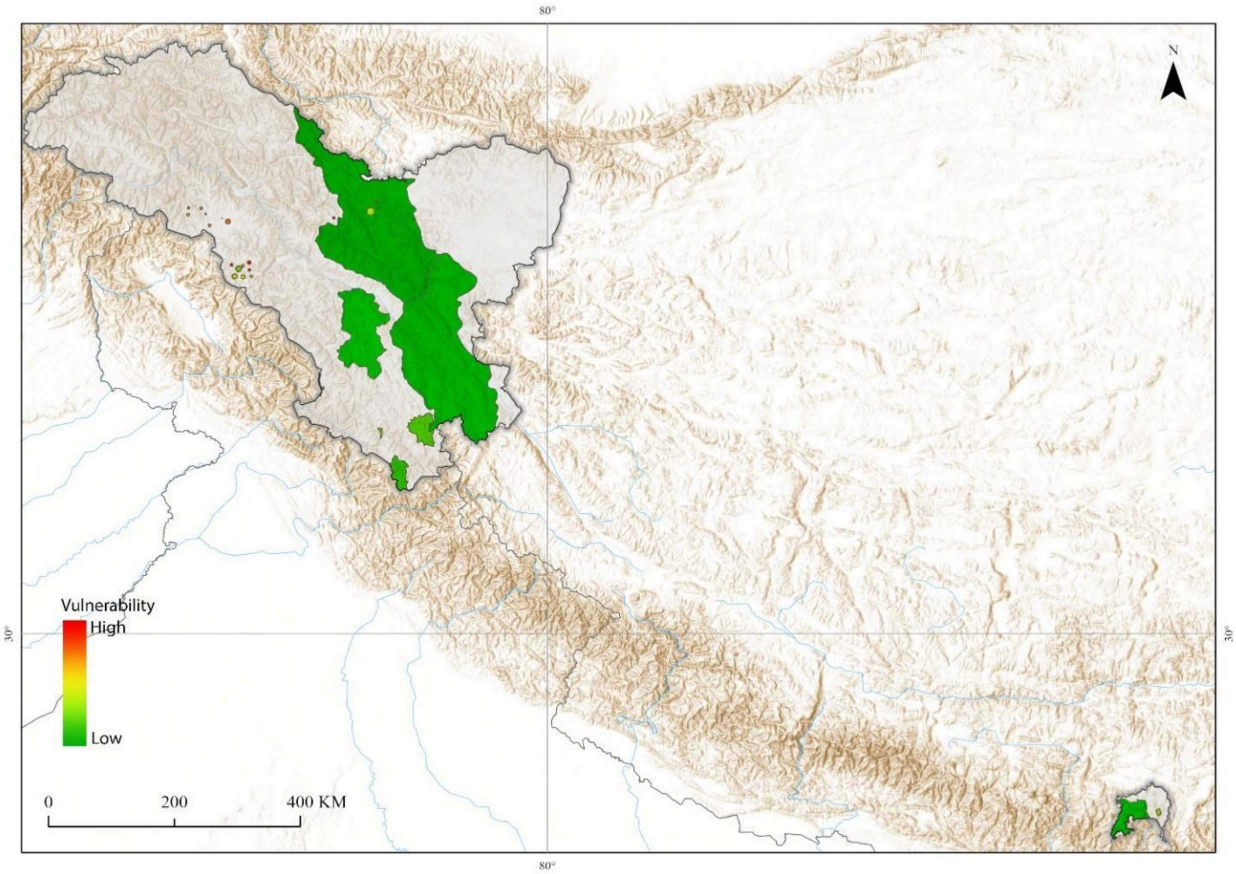

Figure 4. 16 Vulnerability factors of Trans-Himalaya (Red denotes a higher vulnerability)

Table 4. 2 Sensitivity, Departure, and vulnerability scores of the PAs in Trans-Himalayas (1 is lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Karakoram WLS	1	3.802	4.477	1	1
2	Changthang WLS	1.05	3.269	3.958	1.202	1.215
3	Khangchendzonga NP	1.07	1	1	1.257	1.245
4	Hemis WLS	1.192	2.647	3.162	1.652	1.661
5	Pin valley NP	1.276	6.873	6.853	1.957	1.984
6	Kibber WLS	1.289	4.197	4.497	1.985	2.004
7	Sechu tuan nala WLS	1.801	3.204	3.272	2.996	3.014
8	Khonmoh CR	2.135	1.586	1.58	3.431	3.424
9	Chandratal CR	2.047	3.55	3.689	3.407	3.431
10	Tsomoiri WLS	2.14	3.948	4.645	3.547	3.54
11	Shingba CR	2.195	1.22	1.356	3.561	3.569
12	Khrew CR	2.688	1.439	1.458	4.218	4.212
13	Khimber-dara-sharazbal CR	3.29	1.614	1.577	4.778	4.777
14	Sikargarh CR	3.622	2.057	2.061	5.367	5.322
15	Wangat-chatergul CR	3.786	2.074	2.063	5.58	5.541
16	Brain-nishat CR	4.225	1.915	1.881	5.776	5.785
17	Khanagund CR	4.269	2.558	2.559	5.991	5.933
18	Khiram CR	4.735	2.122	2.133	6.36	6.3
19	Ajas CR	5.095	2.334	2.31	6.735	6.694
20	Great Himalayan NP	4.489	10	10	6.685	6.773
21	Hokera CR	5.338	2.159	2.255	6.927	6.892
22	Zaloora-harwan CR	5.786	2.061	1.988	7.059	7.021
23	Boodh karbu CR	6.35	4.359	4.935	7.559	7.545
24	Shallabugh CR	6.658	1.765	1.779	7.743	7.674
25	Sabu CR	7.047	4.197	4.973	8.177	8.178
26	Panyar CR	10	2.586	2.573	10	10

- ***Himalaya***

Total 79 PAs from Himalayas were included in the analysis (Figure 4.17; Table 4.3). Highest sensitivity at SSP585 was found to be in Binsar WLS (Sensitivity=10), followed by Hokarsar lake WLS (Sensitivity= 8.409), City Forest WLS (Sensitivity= 3.976). Lowest sensitivity was found in Khangchendzonga NP (Sensitivity= 1), Govind Pashu Vihar WLS (Sensitivity= 1.014), Kedarnath WLS (Sensitivity= 1.022). Highest climatic exposure (SSP585) is in City Forest WLS (Departure=10), Hokarsar Lake WLS (Departure=8.557), Binsar WLS (Departure =5.817). Lowest climate exposure was found to be in Namdapha NP (Departure=1), Pakhui WLS (Departure =1.11), Kamlang WLS (Departure=1.13). The Vulnerability factor is found to highest in City Forest (Salim Ali) NP (Vulnerability= 10), Hokarsar Lake WLS (Vulnerability= 8.557), Binsar WLS (Vulnerability= 5.817). City forest NP (Area: 9.07 sq. km), located in Srinagar is an important habitat for species like Himalayan Musk Dear, Himalayan Black bear etc. Lowest vulnerability was found in Khangchendzonga NP (Vulnerability= 1), Govind Pashu Vihar WLS (Vulnerability= 1.119), Kedarnath WLS (Vulnerability= 1.164).

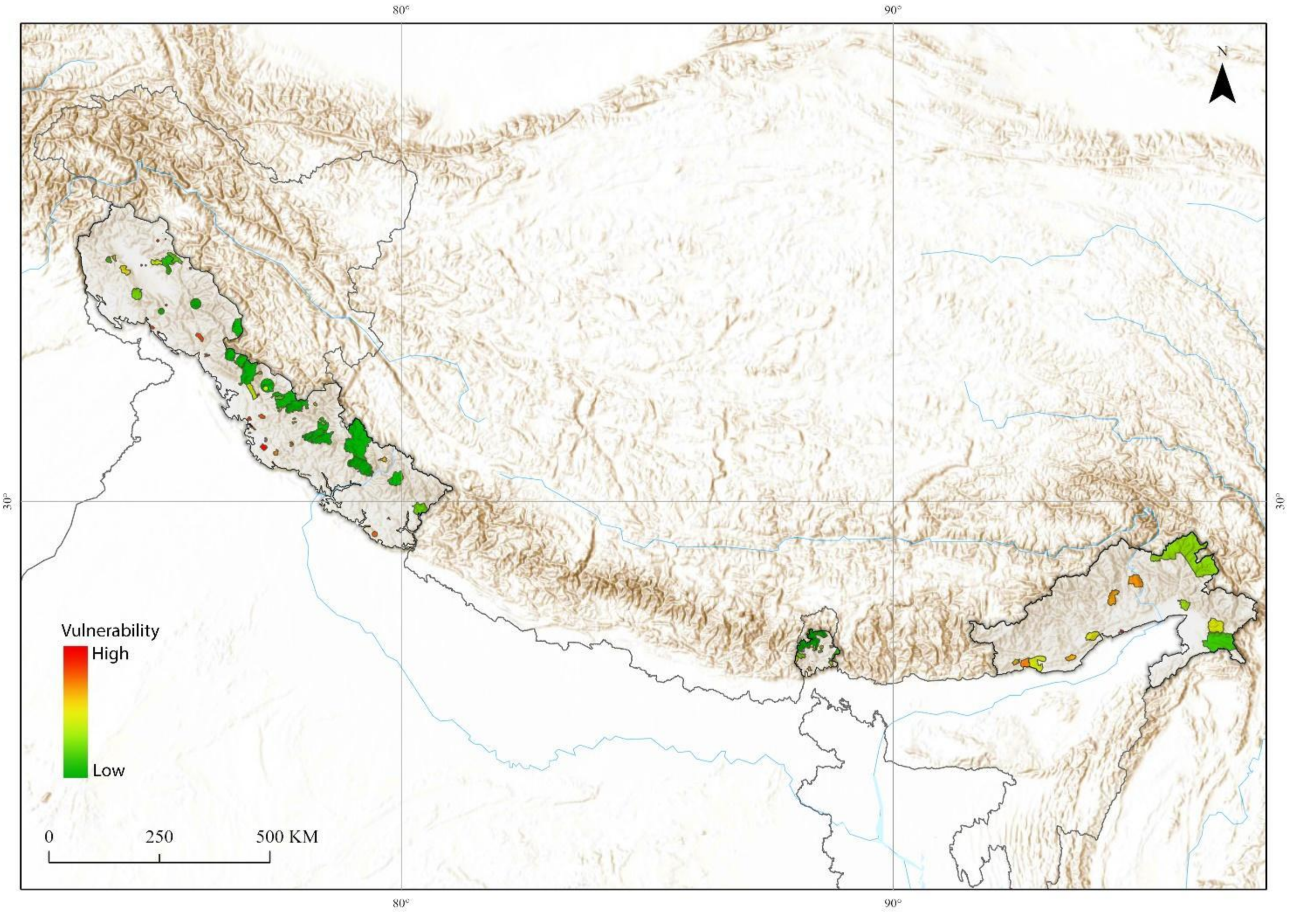

Figure 4. 17 Vulnerability factors of Himalaya (Red denotes a higher vulnerability)

Table 4. 3 Sensitivity, Departure, and Vulnerability scores of the PAs in Himalaya (1 is lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Khangchendzonga NP	1	1.814	2.143	1	1
2	Govind Pashu Vihar WLS	1.014	6.877	7.33	1.109	1.119
3	Kedarnath WLS	1.022	6.725	8.465	1.151	1.164
4	Govind WLS	1.055	6.928	7.379	1.333	1.342
5	Kishtwar NP	1.073	3.461	4.424	1.391	1.386
6	Dhauladhar WLS	1.077	4.376	4.689	1.408	1.412
7	Rupi Bhaba WLS	1.085	5.511	5.68	1.409	1.415
8	Khirganga NP	1.081	5.068	5.484	1.441	1.444
9	Gangotri WLS	1.086	6.419	6.449	1.441	1.446
10	Great Himalayan WLS	1.091	5.41	5.29	1.452	1.455
11	Tundah WLS	1.1	5.182	5.644	1.516	1.518
12	Kugti WLS	1.103	4.198	4.599	1.532	1.53
13	Sangla Valley (Raksham Chitkul) WLS	1.102	7.045	6.903	1.537	1.544
14	Sechu Tuan Nala WLS	1.112	3.778	4.305	1.545	1.537
15	Nanda Devi NP	1.121	5.608	5.876	1.573	1.576
16	Sudhmahadev CR	1.146	3.341	3.883	1.67	1.667
17	Overa-Aru WLS	1.156	2.757	3.749	1.708	1.696
18	Pangolakha WLS	1.167	1.463	1.521	1.735	1.718
19	Namdapha NP	1.168	1.151	1	1.749	1.721
20	Lacchipora WLS	1.162	3.34	4.536	1.762	1.761
21	Kanawar WLS	1.166	5.074	5.463	1.784	1.786
22	Baltas-Thajwas WLS	1.207	3.002	3.775	1.835	1.817
23	Askot Musk Deer WLS	1.207	5.905	7.246	1.869	1.877
24	Barsey Rhododendron WLS	1.218	1.603	1.637	1.925	1.905
25	Hirpora WLS	1.227	2.788	3.627	1.952	1.942
26	Sainj WLS	1.235	4.964	5.169	1.986	1.993
27	Tirthan WLS	1.234	5.858	5.941	1.999	2
28	Dibang WLS	1.337	1.962	2.622	2.046	2.021

29	Fambong Lho WLS	1.271	2.256	2.221	2.052	2.037
30	Mehao WLS	1.287	1.308	1.429	2.078	2.042
31	Limber WLS	1.271	3.254	4.473	2.091	2.091
32	Nargu WLS	1.277	7.549	7.878	2.098	2.108
33	Neora Valley NP	1.299	1.786	1.824	2.116	2.103
34	Dachigam WLS	1.322	2.779	4.087	2.226	2.218
35	Manali WLS	1.34	4.137	4.75	2.275	2.267
36	Pakhui WLS	1.377	1.047	1.11	2.355	2.318
37	Kamlang WLS	1.419	1	1.13	2.392	2.34
38	Gulmarg WLS	1.395	2.995	4.068	2.429	2.418
39	Tale Valley WLS	1.411	1.6	1.396	2.45	2.409
40	Inderkilla NP	1.416	6.4	6.775	2.485	2.491
41	Singalila NP	1.475	1.234	1.448	2.602	2.576
42	Lippa Asrang WLS	1.526	6.02	6.263	2.704	2.702
43	Daranghati WLS	1.503	6.479	7.129	2.706	2.711
44	Maenam WLS	1.572	1.801	1.995	2.786	2.751
45	Valley Of Flowers NP	1.627	6.285	6.983	2.832	2.83
46	Eagle Nest WLS	1.618	1.053	1.198	2.86	2.818
47	Yorde-Rabe-Supse WLS	1.662	2.137	2.158	2.948	2.916
48	Itanagar WLS	1.648	1.237	1.141	2.953	2.909
49	Pin Valley NP	1.627	6.934	6.413	2.982	2.974
50	Senchal WLS	1.696	1.53	1.589	3.007	2.955
51	Mouling NP	1.702	2.129	2.278	3.007	2.966
52	Churdhar WLS	1.719	6.953	7.651	3.037	3.029
53	Talra WLS	1.721	7.079	8.101	3.128	3.129
54	Sessa Orchid WLS	1.77	1.072	1.143	3.176	3.119
55	Kais WLS	1.787	5.644	6.129	3.264	3.257
56	Naina devi Himalayan bird CR	1.935	5.296	6.408	3.4	3.397
57	Shikari Devi WLS	1.896	7.002	6.872	3.478	3.465
58	Gamgul Siahbehi WLS	1.896	6.087	6.465	3.49	3.476
59	Kyongnosla Alpine WLS	2.015	1.834	2.013	3.5	3.446
60	Trikuta WLS	2.006	3.623	4.03	3.51	3.497
61	Bandli WLS	1.963	8.239	8.359	3.59	3.584
62	Kalatop-Khajjair WLS	2.031	9.174	9.911	3.704	3.727

63	Majathal WLS	2.021	7.586	7.721	3.738	3.733
64	Rajparian (daksum) WLS	2.167	3.28	4.061	3.805	3.752
65	Jawhar tunnel CR	2.286	3.629	4.69	3.871	3.828
66	D Ering Memorial (Lali) WLS	2.516	1.419	1.3	4.28	4.184
67	Shimla Catchment WLS	2.516	7.116	7.352	4.326	4.302
68	Chail WLS	2.457	6.844	7.113	4.365	4.349
69	Darlaghat CR	2.449	8.104	8.252	4.405	4.4
70	Naganari CR	2.943	3.396	4.364	4.723	4.659
71	Hygam (WL) CR	2.864	4.472	5.933	4.776	4.767
72	Mussoorie WLS	3.064	10	10	5.061	5.033
73	Khokhan WLS	3.104	8.006	8.271	5.14	5.147
74	Kane WLS	4.041	1.8	1.516	5.495	5.311
75	Kukarian (WL) CR	3.555	4.635	5.239	5.504	5.485
76	Dihing Patkai WLS	3.496	2.146	1.931	5.512	5.406
77	Binsar WLS	3.976	5.986	6.998	5.855	5.817
78	Hokarsar lake WLS	8.409	3.754	5.289	8.648	8.557
79	City forest (Salim Ali) NP	10	3.875	5.757	10	10

- ***Semi-Arid***

Total 90 PAs from the Semi-Arid region were included in the analysis (Figure 4.18; Table 4.4). Highest sensitivity was in Jhajjar Bacholi WLS (sensitivity=10), followed by Bir Gurdialpura WLS (sensitivity=9.328), and Sangral-Asa chak Wetland CR (sensitivity=9.03). Lowest sensitivity was found in Wild Ass WLS (sensitivity=1), Gir NP (sensitivity=1.011), Phulwari Ki Nal WLS (sensitivity=1.037).

Highest climatic exposure (SPS585 scenario) is for Thein Wetland CR of J&K (Departure factor=10) followed by Majathal WLS (Departure factor=9.885), and Sangral-Asa Chak (WL) CR (Departure factor= 9.579) while the lowest is for Marine (Gulf of Kuchchh) NP (Departure factor=1), Blackbuck NP (Departure factor = 2.809), and Narsingarh WLS (departure= 3.082).

Vulnerability factor was highest for Jhajjar Bacholi WLS (Vulnerability factor=10) followed by Sangral-Asa chak Wetland CR (Vulnerability= 9.218) and Bir Gurdialpura WLS (Vulnerability factor = 8.036). Lowest vulnerability was found for part of the Wild ass WLS which falls in the semi-arid zone (Vulnerability=1), followed by Gir NP (Vulnerability= 1.061), and Phulwari Ki Nal WLS (Vulnerability= 1.14). Gir NP is home to the last remaining population of Asiatic Lions (*Panthera leo. leo*). The endemic Asiatic wild ass (*E. h. khur*) population lives in Wild ass WLS. Although it has a lower climate vulnerability, anthropogenic risks may pose a threat to these species.

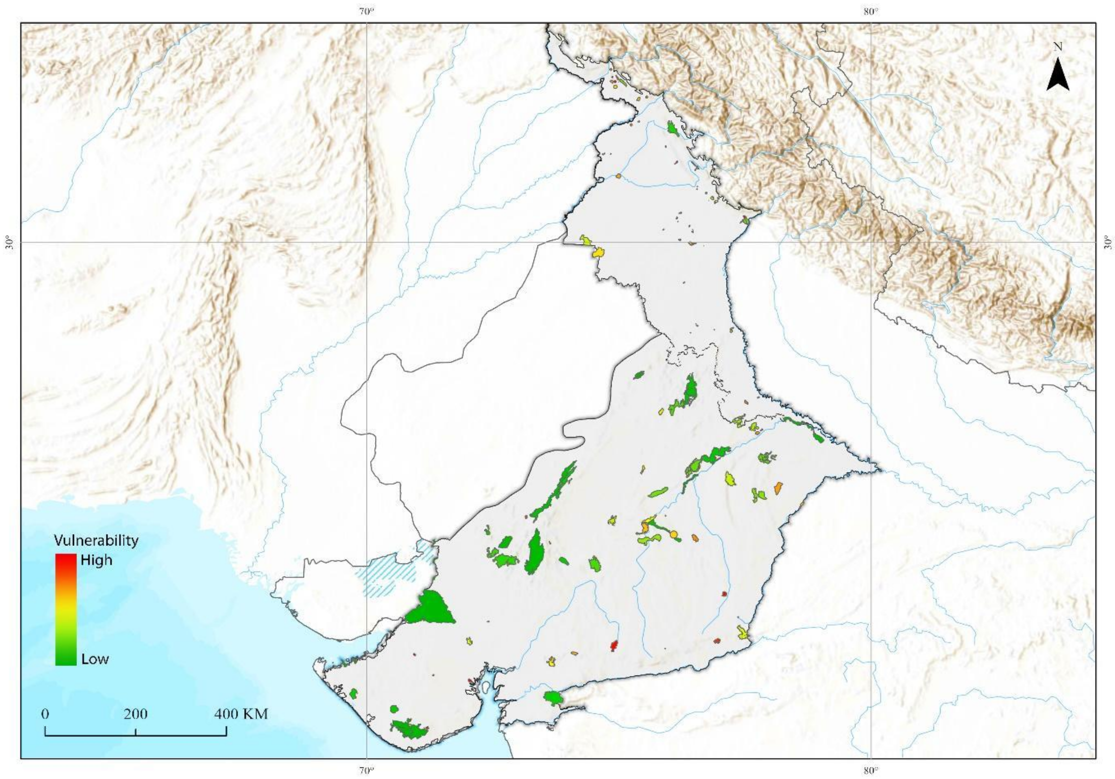

Figure 4. 18 Vulnerability factors of Semi-arid (Red denotes a higher vulnerability).

Table 4. 4 Sensitivity, Departure, and vulnerability scores of the PAs in Semi-arid zone (1 is the lowest, 10 is highest).

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Wild Ass WLS	1	3.318	4.143	1	1
2	Gir NP	1.011	2.897	4.983	1.051	1.061
3	Phulwari Ki Nal WLS	1.037	4.212	5.366	1.115	1.14
4	Mount Abu WLS	1.05	5.015	7.205	1.143	1.193
5	National Chambal WLS	1.132	5.103	5.234	1.36	1.335
6	Kumbhalgarh WLS	1.156	4.214	5.201	1.399	1.397
7	Marine (Gulf of Kachchh) NP	1.206	1	1	1.435	1.425
8	Sariska NP	1.167	6.288	6.64	1.477	1.444
9	Shakambhari CR	1.166	5.706	6.733	1.497	1.47
10	Darrah WLS	1.267	3.932	4.162	1.635	1.603
11	Kela Devi WLS	1.343	5.459	5.165	1.747	1.674
12	Todgarh Raoli WLS	1.389	4.231	5.304	1.702	1.7
13	Girnar WLS	1.277	3.549	6.671	1.601	1.722
14	Jaisamand WLS	1.448	3.237	3.791	1.729	1.743
15	Sundha Mata CR	1.318	4.331	5.633	1.719	1.755
16	Shoolpaneswar WLS	1.292	4.712	8.062	1.746	1.789
17	Barda WLS	1.323	2.347	3.891	1.779	1.83
18	Pong Dam Lake WLS	1.361	8.25	7.712	1.944	1.892
19	Balaram Ambaji ComR	1.475	4.285	5.672	1.843	1.9
20	Jessore WLS	1.427	4.175	5.382	1.862	1.901
21	Sitamata WLS	1.505	3.392	4.325	1.996	2.014
22	Jamwa Ramgarh WLS	1.487	6.105	6.492	2.165	2.106
23	Ghatigaon WLS	1.565	6.247	5.708	2.187	2.109
24	Ranthambhore NP	1.654	5.397	5.294	2.208	2.127
25	Ramgarh Vishdhari WLS	1.548	4.304	4.589	2.217	2.169
26	Kalesar NP	1.518	8.654	7.68	2.257	2.187
27	Surinsar Mansar WLS	1.509	7.486	7.793	2.214	2.198
28	Madhav NP	1.659	5.145	4.354	2.283	2.203

29	Sawaimadhopur WLS	1.729	5.365	5.283	2.337	2.25
30	Gandhi Sagar WLS	1.616	3.907	4.347	2.309	2.267
31	Bandh Baratha WLS	1.692	5.761	5.695	2.356	2.284
32	Shri Nainadevi CR	1.565	6.413	6.408	2.373	2.316
33	Paniya WLS	1.635	3.439	5.998	2.263	2.382
34	Ramsagar WLS	1.668	5.681	5.628	2.438	2.392
35	Bassi WLS	1.748	3.916	4.821	2.38	2.395
36	Kuno-Palpur NP	1.861	5.068	4.539	2.573	2.47
37	Sawai Man Singh WLS	1.978	5.216	5.21	2.637	2.541
38	Asola Bhati (Indira Priyadarshini) ComR	1.792	4.528	5.036	2.639	2.578
39	Abohar WLS	2.029	6.098	7.331	2.667	2.579
40	Ratapani WLS	1.87	3.154	3.643	2.561	2.584
41	Nal Sarovar WLS	1.836	2.895	3.644	2.526	2.593
42	Nahargarh WLS	1.898	6.05	6.542	2.68	2.598
43	Morni Hills WLS	1.791	6.966	6.645	2.713	2.629
44	Jawahar Sagar WLS	1.824	4.2	4.614	2.672	2.635
45	Sukhna Lake WLS	1.888	6.629	6.4	2.798	2.711
46	Jambughoda WLS	1.805	4.137	7.237	2.605	2.721
47	Bisalpur CR	2.244	4.887	5.47	2.839	2.78
48	Abubshehar ComR	2.305	5.663	7.23	2.902	2.784
49	Orcha WLS	2.273	5.323	4.531	3.017	2.909
50	Mukundra Hills (DARRAH) NP	1.982	3.735	3.886	2.985	2.935
51	Pargwal (WL) CR	2.068	6.967	7.295	2.98	2.94
52	Jasrota WLS	2.022	8.166	8.259	3.048	3.004
53	Bhensrodgarh WLS	2.187	4.142	4.647	3.082	3.068
54	Ratanmahal WLS	2.199	3.252	5.043	3.071	3.164
55	Harike Lake WLS	2.354	5.216	5.679	3.295	3.176
56	Van Vihar NP	2.207	5.784	5.633	3.286	3.215
57	Ramnagar Rakha WLS	2.289	7.131	7.477	3.267	3.229
58	Karera WLS	2.494	5.727	4.954	3.346	3.23
59	Saraswati CR	2.669	4.406	4.859	3.498	3.358
60	Shergarh WLS	2.631	3.753	3.598	3.419	3.376
61	SISWAN ComR	2.324	7.228	7.106	3.497	3.399
62	Keoladeo Ghana NP	2.666	5.639	6.007	3.569	3.499

63	RANJEET SAGAR CR	2.343	6.493	7.268	3.604	3.551
64	Nandni WLS	2.491	7.624	8.017	3.644	3.589
65	THEIN CR	2.31	10	10	3.647	3.608
66	Nanga (WL) CR	2.536	7.941	8.42	3.651	3.608
67	Jawai Bandh Leopard CR	2.637	4.82	5.849	3.663	3.712
68	Kesarbagh WLS	2.741	6.619	6.707	3.795	3.725
69	Bir Bhadson WLS	2.72	5.819	6.357	3.976	3.863
70	Kheoni WLS	2.987	2.668	3.172	3.859	3.908
71	Sardarpur WLS	2.947	2.895	4.024	3.866	3.942
72	Narsingarh WLS	3.018	2.997	3.082	4.03	4.013
73	Lalwan ComR	3.383	5.681	5.95	4.185	4.019
74	Bir Motibagh WLS	2.798	6.485	7.144	4.149	4.04
75	Simbalbara NP	2.896	9.842	8.754	4.187	4.059
76	BAHU ComR	2.898	7.482	7.878	4.105	4.068
77	Blackbuck NP	3.026	2.467	2.809	4.044	4.094
78	Bir Bara Ban CR	2.929	6.835	8.199	4.307	4.274
79	Bir Bunerheri WLS	3.757	5.807	6.402	4.51	4.332
80	Rakh Sarai Amanat Khan CR	3.312	6.204	7.111	4.606	4.524
81	Mitiyala WLS	3.573	2.812	4.104	4.56	4.718
82	Bir Shikargarh WLS	3.547	8.343	7.997	4.871	4.724
83	Sajjangarh WLS	4.052	5.594	7.019	4.713	4.82
84	Majathal WLS	3.383	9.811	9.885	5.063	5.016
85	Rampara Vidi WLS	4.658	3.407	4.17	5.686	5.808
86	Takhni-Rehampur WLS	5.061	7.121	7.185	6.423	6.333
87	Sur Sarovar WLS	7.525	6.4	7.088	7.541	7.435
88	Bir Gurdialpura WLS	9.328	5.717	6.481	8.258	8.036
89	Sangral-as chak (WL) CR	9.03	8.865	9.579	9.245	9.218
90	Jhajjar Bacholi WLS	10	8.178	8.621	10	10

- ***Gangetic Plains***

Gangetic plains are one of the densely populated regions of India. For the analysis, a total of 40 PAs from Gangetic Plains were included (Figure 4.19, Table 4.5). Highest sensitivity was in Saman WLS of Uttar Pradesh (Sensitivity=10), followed by Raiganj (Kulik) WLS (sensitivity=8.906), and Rajgir WLS (sensitivity=8.339). Lowest sensitivity was in Buxa NP (Sensitivity=1), Rajaji NP (Sensitivity=1.016), Nandhaur WLS (Sensitivity=1.33). Highest climatic exposure (SPS585 scenario) is for Asan Wetland CR (Departure factor = 10) followed by Saman WLS (Departure factor = 7.627) and Samaspur Bird WLS (Departure factor = 6.098). Asan CR is wintering ground for diverse migratory species, and a higher climate exposure is likely to affect their habitat.

The vulnerability factor (SSP585) was highest in Saman WLS (Vulnerability = 10), followed by Raiganj WLS (Vulnerability= 9.171) and Rajgir WLS (Vulnerability = 8.247). Saman WLS is Ramsar site, and home to birds like Sarus crane (*Antigone antigone*), Eurasian Spoonbill (*Platalea leucorodia*) etc. Raiganj WLS has breeding colonies of Asian openbill stork (*Anastomus oscitans*). Lowest vulnerability factor was for Rajaji NP (Vulnerability= 1), followed by Buxa NP (Vulnerability= 1.048), and Nandhaur WLS (Vulnerability= 1.846).

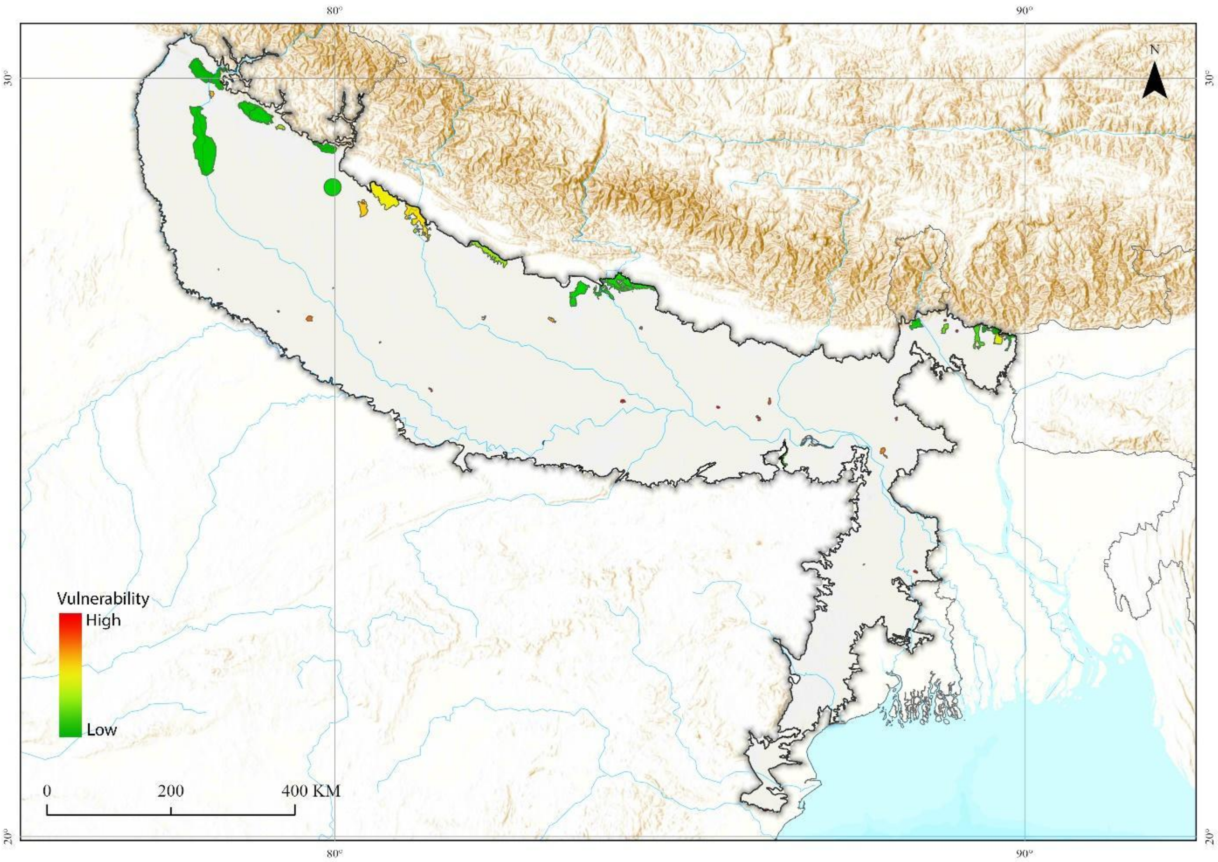

Figure 4. 19 Vulnerability factors of Gangetic plains (Red denotes a higher vulnerability)

Table 4. 5 Sensitivity, Departure, and vulnerability scores of the PAs in Gangetic plains (1 is the lowest, 10 is highest)

S. no.	**Protected area**	**Sensitivity factor (Near present)**	**Departure factor SSP245**	**Departure factor SSP585**	**Vulnerability factor SSP245**	**Vulnerability factor SSP585**
1	Rajaji NP	1.016	5.475	5.011	1	1
2	Buxa NP	1	3.899	3.682	1.016	1.048
3	Nandhaur WLS	1.33	5.332	4.844	1.828	1.846
4	Hastinapur WLS	1.375	4.58	4.722	2.067	2.065
5	Corbett NP	1.491	4.967	4.659	2.207	2.204
6	Sonanadi WLS	1.52	4.785	4.451	2.251	2.242
7	Pilibhit WLS	1.764	3.055	2.239	2.639	2.638
8	Sohagibarwa WLS	2.06	2.809	1.647	2.899	2.864
9	Bhimbandh WLS	2.197	1	1	2.963	2.899
10	Mahananda WLS	2.126	4.342	4.108	3.045	2.959
11	Valmiki NP	1.901	3.187	2.36	3.023	2.983
12	Kuldiha WLS	1.914	1.924	2.715	3	2.984
13	Jaldapara NP	1.993	3.937	3.829	3.032	3.002
14	Gorumara NP	2.001	4.38	4.241	3.113	3.068
15	Neora Valley NP	2.054	6.094	5.884	3.135	3.075
16	Sohelwa WLS	2.238	3.362	2.442	3.12	3.126
17	Pawalgarh CR	2.011	5.667	5.422	3.243	3.237
18	Vikramshila WLS	2.299	1.255	1.198	3.316	3.251
19	Buxa NP	2.218	3.85	3.937	3.357	3.325
20	Dudhwa NP	2.309	3.186	2.497	3.369	3.349
21	Katarniyaghat WLS	2.336	3.327	2.861	3.495	3.473
22	Kishanpur WLS	2.768	3.256	2.568	3.811	3.802
23	Jhilmi Jheel CR	3.049	5.208	4.884	4.569	4.415
24	Bakhira WLS	3.3	2.981	1.875	4.621	4.573
25	Kaimur WLS	4.515	4.19	4.331	5.563	5.416
26	Udhwa Lake WLS	4.145	1.394	1.682	5.504	5.434
27	Lakh Bahosi WLS	4.146	5.09	4.928	5.476	5.472
28	Kusheshwar Asthan WLS	5.762	1.71	1.398	6.194	6.054

29	Asan Wetland CR	4.85	10	10	6.346	6.332
30	Kanwarjheel WLS	5.261	1.369	1.482	6.484	6.357
31	Surha Tal WLS	5.044	3.204	2.897	6.609	6.473
32	Samaspur WLS	5.423	6.978	6.098	6.645	6.526
33	Bethuadahari WLS	5.298	1.801	2.449	7.018	6.831
34	Barela Jheel Salim Ali Bird WLS	6.076	2.094	1.946	6.977	6.878
35	Pakhi bitan bird WLS	5.771	5.358	5.4	7.14	7.017
36	Chapramari WLS	6.282	6.238	6.067	7.565	7.449
37	Hadgarh WLS	5.802	1.996	2.512	7.441	7.501
38	Rajgir WLS	8.339	2.598	3.063	8.39	8.247
39	Raiganj WLS	8.906	2.323	2.761	9.303	9.171
40	Saman WLS	10	7.333	7.627	10	10

- ***Western Ghats***

Total 72 PAs from these zones were included in the analysis (Figure 4.20; Table 4.6). Western ghat is one of the four biodiversity hotspots of India. PAs in this zone's climate is mainly tropical, however, it also has PAs with temperate conditions. Highest sensitivity was in Bondla WLS (sensitivity=10), followed by Thattekadu WLS (sensitivity=5.77), and Pambadum Shola WLS (sensitivity=5.54). Lowest sensitivity was in Bondla WLS (sensitivity=10), followed by Thattekadu WLS (sensitivity=5.77), and Pambadum Shola WLS (sensitivity=5.54). Kottiyoor WLS found highest climatic exposure (Departure=10), followed by Nugu WLS (Departure=9.09), Aralam WLS (Departure=9.062). Lowest climatic exposure in western ghats is found to be in Kalakkad WLS (Departure factor=1) and Mundunthurai WLS (Departure factor=1.317). These PAs are located in the far south of the Western ghat and one of the important habitats of the Bengal tiger. Vulnerability (SSP585) was lowest Kodaikanal WLS, Indira Gandhi WLS Mukurthi NP. Vulnerability was highest in Bondla WLS (Vulnerability factor=10), followed by Pambadum shola NP (vulnerability=7.687) and Mathikettan shola NP (vulnerability=6.531). "Shola" forests are the tropical montane forests of western ghat. These forests are home to several endemic species. High climate vulnerability will likely increase the existing threats of invasive species in these forests and impact the distribution of the endemic species.

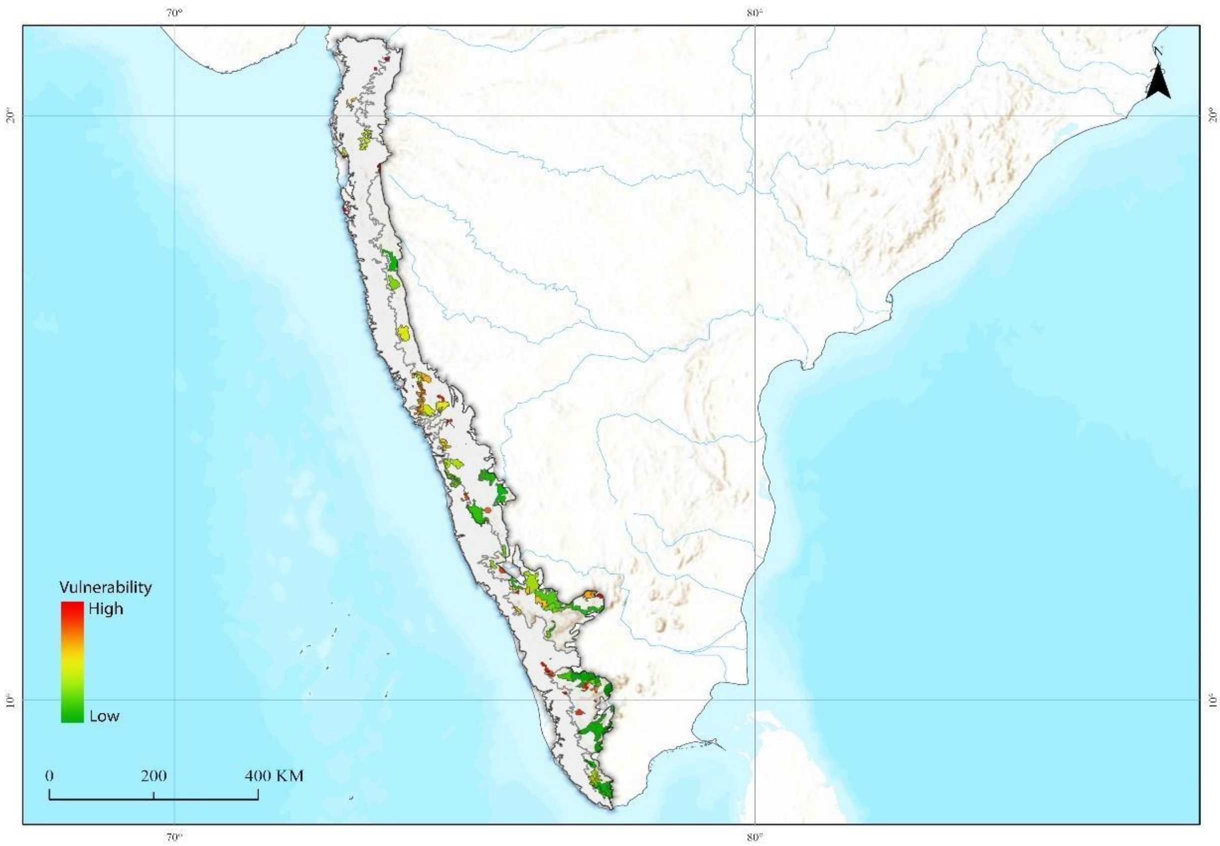

Figure 4. 20 Vulnerability factors of western ghats (Red denotes a higher vulnerability)

Table 4. 6 Sensitivity, Departure, and vulnerability scores of the PAs in Western ghats zone (1 is the lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Kodaikanal WLS	1	7.19	4.974	1	1
2	Indira Gandhi WLS	1.073	7.096	4.962	1.151	1.125
3	Mukurthi NP	1.106	5.794	5.371	1.241	1.218
4	Srivilliputhur WLS	1.074	3.394	2.656	1.214	1.237
5	Periyar NP	1.146	3.529	2.837	1.29	1.286
6	Megamalai WLS	1.1	5.101	3.726	1.296	1.315
7	Nellai WLS	1.143	1.942	1.933	1.403	1.436
8	Kanyakumari WLS	1.196	1.499	1.551	1.547	1.574
9	Koyna WLS	1.19	3.206	4.089	1.56	1.601
10	Shendurney WLS	1.236	1.64	1.611	1.621	1.63
11	Bhadra WLS	1.296	3.162	4.316	1.639	1.632
12	Kalakad WLS	1.243	1	1	1.643	1.688
13	Brahmagiri WLS	1.24	7.617	8.755	1.765	1.802
14	Shettihalli WLS	1.312	3.124	3.899	1.838	1.851
15	Satyamangalam WLS	1.459	8.997	5.898	1.922	1.872
16	Kudremukh NP	1.292	3.593	5.679	1.829	1.884
17	Parambikulam WLS	1.499	5.693	4.701	2.001	1.934
18	Bandipur NP	1.471	6.74	6.913	2.117	2.104
19	Indira Gandhi (Annamalai) NP	1.424	7.473	5.304	2.127	2.111
20	Silent Valley NP	1.534	5.699	5.415	2.198	2.165
21	Mookambika WLS	1.439	3.569	5.285	2.091	2.165
22	Mudumalai WLS	1.608	6.516	6.388	2.244	2.185
23	Pushpagiri WLS	1.441	5.32	6.652	2.189	2.234
24	Chandoli NP	1.529	3.457	4.149	2.21	2.265
25	Talakaveri WLS	1.502	5.636	7.565	2.286	2.351
26	Neyyar WLS	1.525	1.502	1.671	2.351	2.375

27	Mundanthurai WLS	1.63	1.358	1.317	2.445	2.448
28	Rajiv Gandhi NP	1.631	6.874	7.759	2.46	2.449
29	Sharavathi Valley WLS	1.621	3.682	4.939	2.387	2.471
30	Chinnar WLS	1.623	7.76	5.42	2.508	2.488
31	Tansa WLS	1.63	4.659	7.953	2.465	2.548
32	Tungareshwar WLS	1.573	3.683	6.257	2.487	2.599
33	Anshi NP	1.697	3.635	3.824	2.627	2.673
34	Madei WLS	1.804	3.496	3.13	2.7	2.683
35	Radhanagari WLS	1.742	3.406	3.284	2.68	2.691
36	Dandeli WLS	1.856	3.609	3.619	2.736	2.745
37	Peppara WLS	1.706	1.386	1.711	2.745	2.79
38	Aganashini LTM CR	1.78	3.628	4.452	2.746	2.819
39	Aralam WLS	1.802	7.908	9.062	2.821	2.836
40	Malabar WLS	1.771	7.242	8.662	2.849	2.894
41	Dadra & Nagar Haveli WLS	1.789	4.132	6.12	2.852	2.933
42	Wayanad WLS	1.869	6.929	7.514	2.975	2.965
43	Bhimgad WLS	2.15	3.701	3.374	3.065	3.032
44	Netravali WLS	1.962	3.314	3.436	3.073	3.11
45	Biligiri Rangaswami Temple WLS	2.694	9.146	6.005	3.354	3.255
46	Kurinjimala WLS	2.018	7.593	5.563	3.325	3.301
47	Cotigao WLS	2.278	3.377	3.48	3.351	3.375
48	Bhagwan Mahavir WLS	2.363	3.399	3.222	3.486	3.463
49	Mollem NP	2.179	3.677	3.353	3.464	3.468
50	Anamudi Shola NP	2.355	7.191	5.482	3.588	3.524
51	Jogimatti WLS	2.279	3.14	5.016	3.481	3.526
52	Someshwara WLS	2.104	3.685	5.308	3.436	3.552
53	Chimmony WLS	2.463	4.81	4.408	3.641	3.554
54	Kappathagudda WLS	2.417	6.449	7.951	3.541	3.591
55	Idukki WLS	2.785	4.479	3.954	3.935	3.842

56	Bedthi CR	2.669	3.746	3.883	3.848	3.874
57	Hornbill CR	2.725	4.037	3.859	4.062	4.057
58	Eravikulam NP	2.734	6.703	4.736	4.189	4.134
59	Bhimashankar WLS	2.754	3.241	5.842	3.966	4.151
60	Peechi-Vazhani WLS	3.118	4.771	4.417	4.269	4.168
61	Phansad WLS	2.921	3.697	6	4.346	4.542
62	Kottiyoor WLS	3.105	8.622	10	4.724	4.727
63	Malai Mahadeshwara WLS	4.082	10	6.157	5.341	5.23
64	Sanjay Gandhi NP	4.163	3.353	5.481	5.668	5.891
65	Nugu WLS	4.474	7.918	9.09	6.169	6.105
66	Thattekadu WLS	5.77	4.937	4.591	6.518	6.345
67	Bansda NP	4.679	4.047	5.208	6.21	6.428
68	Purna WLS	5.386	2.149	1.71	6.343	6.521
69	Mathikettan Shola NP	4.858	7.205	5.731	6.59	6.531
70	Pambadum Shola NP	5.54	8.976	7.648	7.681	7.687
71	Bondla WLS	10	5.526	5.89	10	10

- ***North-East***

Total 44 PAs were analysed from the North-east zone (Figure 4.21; Table 4.7). Highest overall sensitivity was in Lumkohkriah CoR (sensitivity=10), followed by Fakim WLS (sensitivity=4.401), and Hoollongapar Gibbon WLS (sensitivity=3.351). Lowest sensitivity was in Manas NP (sensitivity=1), Barail WLS (sensitivity=1.004), Balphakram NP (sensitivity=1.12). Highest climate exposure (at SSP585) was found to be in Fakim WLS (departure=10), Keibul-Lamjao NP (departure =9.613), Yangoupokpi-Lokchao WLS (departure=8.438). Lowest climate exposure was for Dihing Patkai WLS (departure =1), Marat Longri WLS (departure =1.93), Barnadi WLS (departure =2.22).

Overall vulnerability (SSP585) was highest in Lumkohkriah ComR (vulnerability=4.97), followed by Fakim WLS (vulnerability=3.901), and Yangoupokpi-Lokchao WLS (vulnerability=1.817). Overall vulnerability (SSP585) was lowest in Manas NP (vulnerability=1), Barail WLS (vulnerability=1.024), Balphakram NP (vulnerability=1.428). North-east zone is home to many endemic species and climate change will have adverse impact on them. E.g., Keibul lamjao NP, has high climate exposure and this PA is home to the Manipur brow-antlered deer (*Rucervus eldii eldii*).

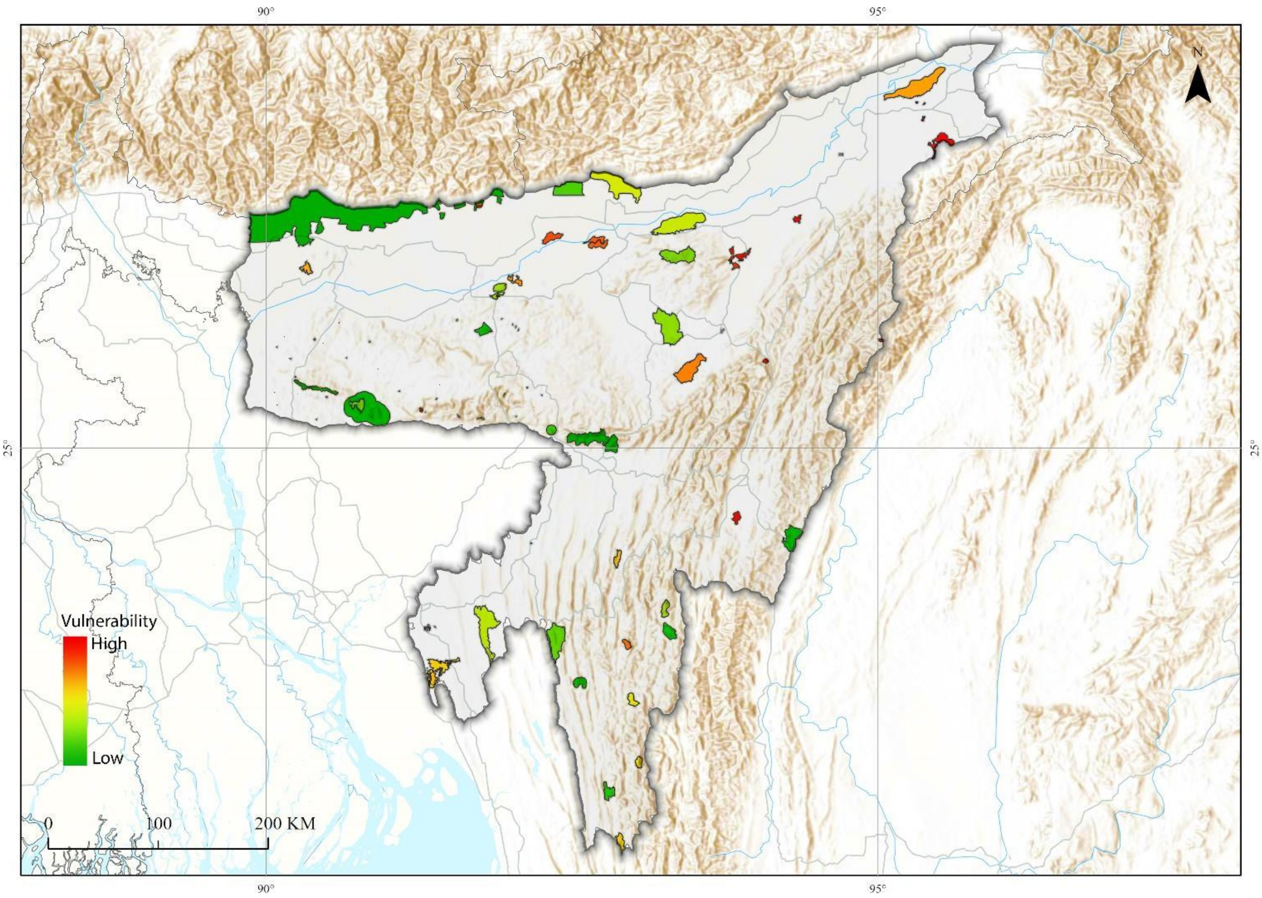

Figure 4. 21 Vulnerability factors of North-east (Red denotes a higher vulnerability)

Table 4. 7 Sensitivity, Departure, and vulnerability scores of the PAs in Semi-arid zone (1 is the lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Manas NP	1	2.956	2.672	1	1
2	Barail WLS	1.004	3.618	2.43	1.03	1.024
3	Balphakram NP	1.12	1.942	2.344	1.432	1.428
4	Nokrek NP	1.157	2.128	2.954	1.569	1.578
5	Yangoupokpi-Lokchao WLS	1.284	8.475	8.438	1.826	1.817
6	Nongkhyllem WLS	1.333	2.549	2.53	1.911	1.917
7	Thorangtlang WLS	1.368	2.763	3.305	2.044	2.037
8	Murlen NP	1.418	5.298	5.712	2.09	2.072
9	Ngengpui WLS	1.42	1.7	3.428	2.114	2.106
10	Narpuh WLS	1.442	2.847	2.946	2.136	2.107
11	Sonai-Rupai WLS	1.49	3.761	3.28	2.152	2.131
12	Dampa WLS	1.49	2.177	2.222	2.163	2.134
13	Siju WLS	1.466	2.169	2.782	2.181	2.167
14	East Karbi Anglong WLS	1.519	3.338	2.773	2.221	2.201
15	Marat Longri WLS	1.639	2.656	1.93	2.265	2.217
16	Amchang WLS	1.46	2.678	2.624	2.225	2.223
17	Lengteng WLS	1.527	5.892	6.031	2.291	2.275
18	Gumti WLS	1.582	2.539	2.972	2.333	2.286
19	Kaziranga NP	1.565	2.956	2.516	2.345	2.317
20	Nameri NP	1.499	3.956	3.154	2.363	2.362
21	Khawnglung WLS	1.609	3.287	4.173	2.403	2.382
22	Phawngpui (Blue Mountain) WLS	1.557	3.639	5.048	2.4	2.397
23	Tokalo WLS	1.668	1	3.043	2.518	2.515
24	Trishna WLS	1.764	1.645	2.426	2.664	2.598
25	Pualreng WLS	1.87	6.721	5.263	2.762	2.71
26	Chakrasila WLS	1.73	2.97	3.502	2.804	2.846
27	Dibru-Saikhowa NP	1.814	5.194	4.382	2.861	2.876
28	Pabitora WLS	1.937	3.07	2.534	2.922	2.898
29	Intanki NP	2.159	2.904	2.914	2.988	2.922

30	Tawi WLS	1.95	4.662	4.849	3.02	2.999
31	Burachapori WLS	2.164	3.481	2.559	3.351	3.32
32	Lawkhowa WLS	2.157	3.191	2.372	3.346	3.322
33	Orang NP	2.584	3.091	2.456	3.445	3.375
34	Nambor WLS	2.327	3.885	3.84	3.451	3.406
35	Nambor-Doigurung WLS	2.188	2.959	3.226	3.499	3.487
36	Dihing Patkai WLS	2.653	2.736	1	3.658	3.597
37	Puliebadze WLS	2.499	5.771	7.004	3.703	3.684
38	Keibul-Lamjao NP	2.728	10	9.613	3.931	3.901
39	Barnadi WLS	2.718	2.921	2.22	4.121	4.131
40	Bison (Rajbari) NP	3.177	1.869	3.048	4.297	4.17
41	Bherjan-Borajan-Padumoni WLS	3.044	7.169	6.528	4.52	4.485
42	Hollongapar Gibbon WLS	3.351	4.051	4.434	4.58	4.52
43	Fakim WLS	4.401	7.48	10	5.05	4.97
44	Lumkohkriah ComR	10	5.978	6.599	10	10

- ***Desert***

Total 11 PAs were included in the analysis (Figure 4.22; Table 4.8). Highest overall sensitivity was in Bir Jhunjhunu CR (sensitivity=10), followed by Jor Beed Gadwala Bikaner CR (sensitivity=6.898), and Narayan Sarovar Chinkara WLS (sensitivity=2.609). Lowest sensitivity score was in Kachchh Desert WLS (sensitivity=1), Wild Ass WLS (sensitivity=1.176), Desert NP (sensitivity= 2.455). Climate exposure score was found highest in Bir Jhunjhunu CR (Departure=10), Jor Beed Gadwala Bikaner CR (Departure=9.413), Desert NP (Departure=5.905). Lowest climate exposure was for Narayan Sarovar WLS (Departure=1), Chharidhandh CR (Departure=1.811), Kachchh Desert WLS (Departure=2.338)

Overall vulnerability was highest in Bir Jhunjhunu CR (vulnerability=10), followed by Jor Beed Gadwala Bikaner CR (Vulnerability=7.58) and Narayan Sarovar Chinkara WLS (Vulnerability=3.666). These PAs have population of Indian gazelle (*Gazella bennettii*), desert fox (*Vulpes vulpes pusilla*). These species are adapted to xeric conditions of desert. Changing in climate condition will have adverse impact on them. Vulnerability was found to be lowest in Kachchh Desert WLS (vulnerability=1), Wild Ass WLS (Vulnerability=1.49), Desert NP (Vulnerability=2.849). This is owing to the large size of these PA.

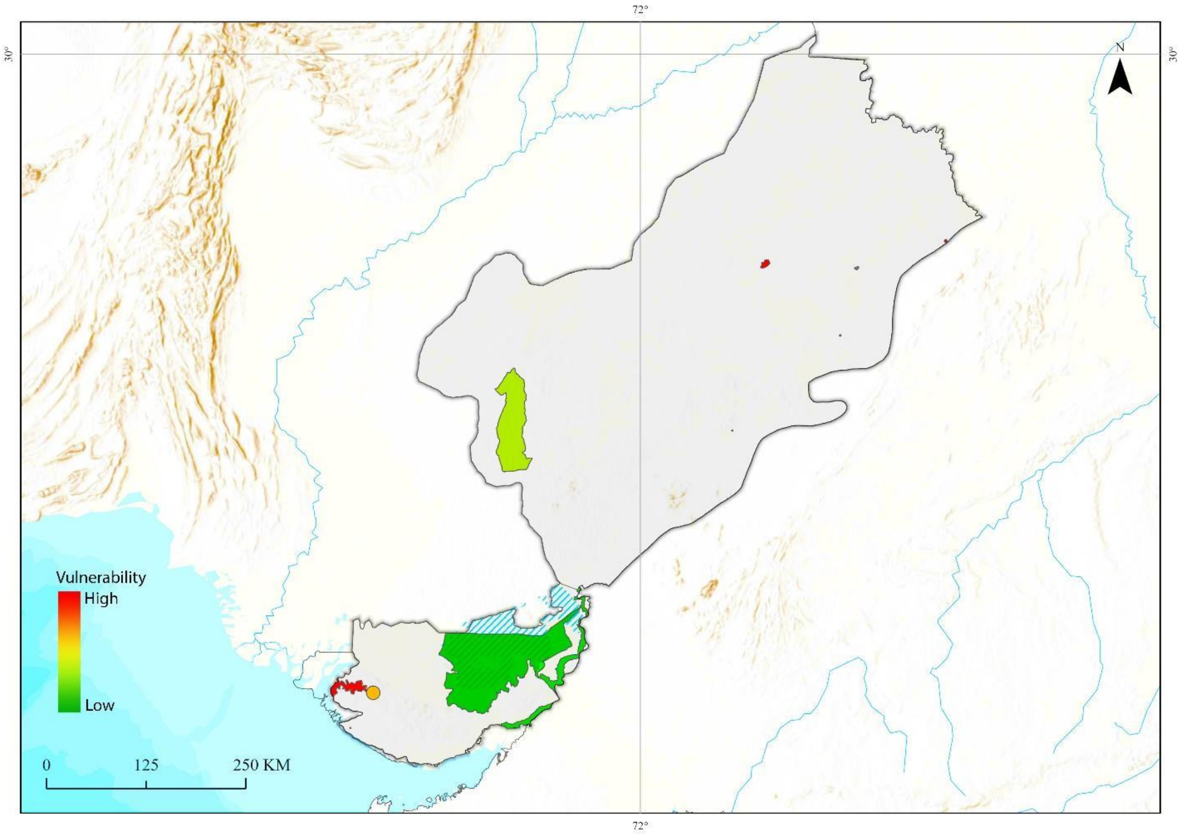

Figure 4. 22 Vulnerability factors of Desert (Red denotes a higher vulnerability).

Table 4. 8 Sensitivity, departure, and vulnerability scores of the PAs in desert zone (1 is the lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Kachchh Desert WLS	1	2.621	2.338	1	1
2	Wild Ass WLS	1.176	3.194	3.708	1.437	1.49
3	Desert NP	2.455	5.943	5.905	2.901	2.849
4	Chharidhandh CR	2.491	1.421	1.811	3.433	3.549
5	Narayan Sarovar WLS	2.609	1	1	3.6	3.666
6	Jor Beed Gadwala Bikaner CR	6.898	9.059	9.143	7.701	7.58
7	Bir Jhunjhunu CR	10	10	10	10	10

- ***Deccan Peninsula***

Total 137 PAs were analysed in the Deccan peninsula (Figure 4.23; Table 4.9). Highest overall sensitivity was in Nakti Dam WLS (sensitivity=10), followed by Rollapadu WLS (sensitivity=2.381), and Vellanadu Blackbuck WLS (sensitivity=2.173). Lowest sensitivity was found in Great Indian Bustard WLS (sensitivity=1), Nagarjunasagar Srisailam WLS (sensitivity=1.001), Sri Peninsula Narasimha WLS (sensitivity=1.019). Climate exposure (at SSP585) was highest for Kalsubai WLS (Departure=10), Bhimashankar WLS (Departure=8.814), Ken Gharial WLS (Departure=7.978). Climate exposure was lowest for Nellai WLS (Departure=1), Biligiri Rangaswami Temple WLS (Departure=2.306), Kodaikanl WLS (Departure=2.323).

Overall vulnerability (at SSP585 scenario) was highest in in Nakti Dam WLS (Vulnerability=10), followed by Rollapadu WLS (Vulnerability= 3.83) and Vellanadu Blackbuck WLS (Vulnerability= 3.802). Climate vulnerability was lowest for Great Indian Bustard WLS (Vulnerability= 1), Nagarjunasagar Srisailam WLS (Vulnerability= 1.009), Sri Penusila Narasimha WLS (Vulnerability= 1.135). Despite having diverse habitats, deccan peninsula has comparatively lower climate heterogeneity. PAs with higher climate exposure and vulnerability are likely to lose current climate condition, and species residing in these PA will be adversely affected.

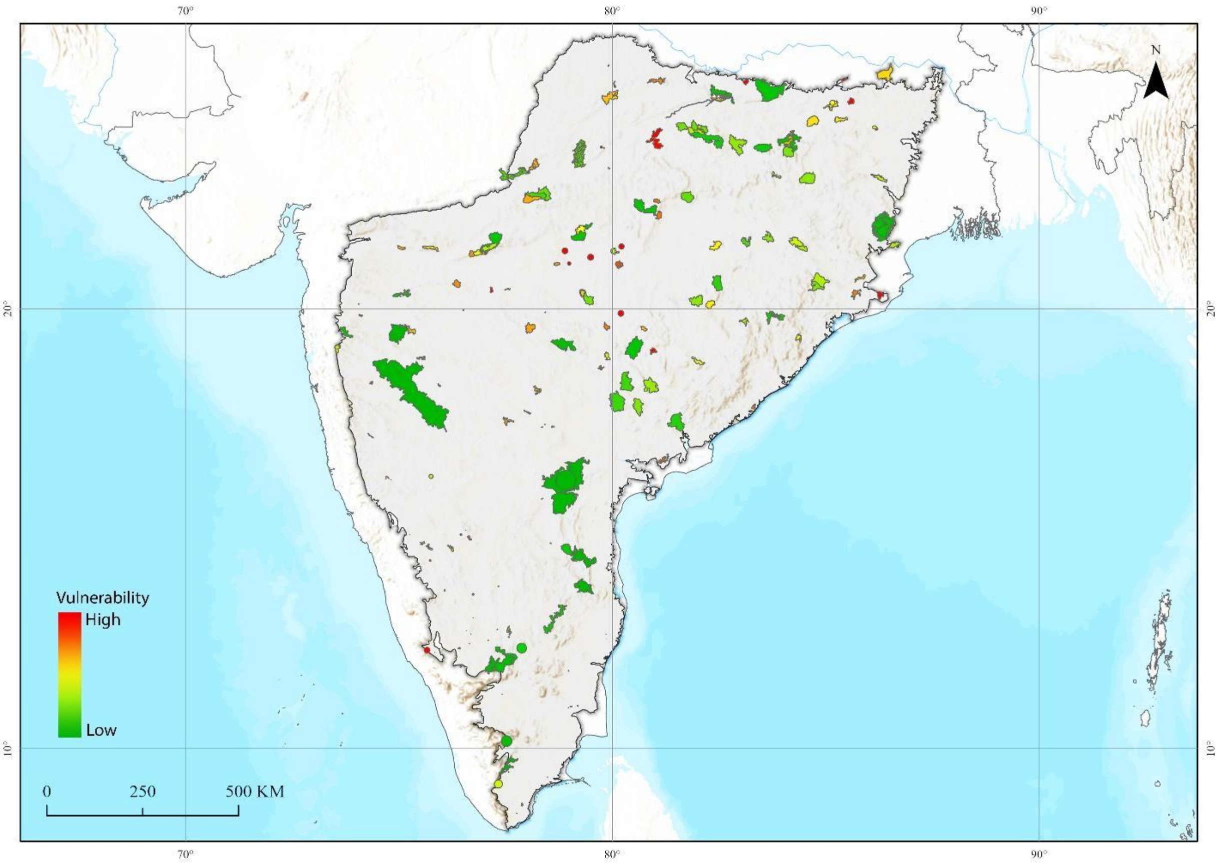

Figure 4. 23 Vulnerability factors of Deccan peninsula (Red denotes a higher vulnerability

Table 4. 9 Sensitivity, departure, and vulnerability scores of the PAs in deccan peninsula zone (1 is the lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Great Indian Bustard WLS	1	5.358	5.325	1	1
2	Nagarjunasagar Srisailam WLS	1.001	4.81	4.248	1.021	1.009
3	Sri Penusila Narasimha WLS	1.019	5.262	4.596	1.141	1.135
4	Gundla Brahmeswaram WLS	1.031	4.606	4.003	1.179	1.163
5	Srivilliputhur WLS	1.053	3.844	3.424	1.296	1.285
6	Sri Venkateswara NP	1.049	5.317	4.822	1.29	1.286
7	Biligiri Rangaswami Temple WLS	1.08	3.059	2.306	1.372	1.336
8	Malai Mahadeshwara WLS	1.057	7.291	5.666	1.361	1.342
9	Kodaikanal WLS	1.083	2.891	2.323	1.415	1.39
10	Kawal WLS	1.086	5.749	5.632	1.408	1.417
11	Simlipal NP	1.082	7.58	7.141	1.416	1.419
12	Cauvery WLS	1.082	7.855	6.113	1.447	1.421
13	Palamau WLS	1.081	6.929	6.369	1.429	1.425
14	Son Gharial WLS	1.066	9.012	7.389	1.428	1.426
15	Indravati NP	1.076	6.945	7.013	1.438	1.466
16	Kaimur WLS	1.098	8.062	6.825	1.479	1.468
17	Melghat WLS	1.081	7.27	7.121	1.482	1.5
18	Kanha WLS	1.107	6.993	6.434	1.51	1.517
19	Pench NP	1.096	6.087	5.718	1.519	1.52
20	Gautala WLS	1.108	3.682	4.011	1.524	1.525
21	Kalsubai WLS	1.084	9.245	10	1.483	1.536
22	Semarsot WLS	1.122	7.388	6.594	1.56	1.549
23	Sri Lankamalleswaram WLS	1.111	5.037	4.174	1.575	1.562
24	Kaundinya WLS	1.127	6.023	4.882	1.59	1.573
25	Kothagarh WLS	1.127	8.055	7.156	1.56	1.576

26	Guru Ghasi Das NP	1.113	8.014	6.784	1.584	1.579
27	Cauvery North Sanctuary WLS	1.128	7.548	5.778	1.608	1.581
28	Papikonda NP	1.13	6.444	6.414	1.6	1.612
29	Sunabeda WLS	1.141	8.419	7.554	1.6	1.617
30	Pakhal WLS	1.133	5.826	5.512	1.619	1.619
31	Eturnagaram WLS	1.138	6.147	5.725	1.623	1.628
32	Satpura NP	1.125	8.087	7.528	1.633	1.65
33	Ratapani WLS	1.146	3.5	3.257	1.663	1.657
34	Noradehi WLS	1.125	6.826	5.836	1.661	1.659
35	Gomardha WLS	1.133	8.297	7.34	1.705	1.709
36	Thimlapura CR	1.193	6.603	6.249	1.752	1.721
37	Achanakmar WLS	1.168	7.031	6.379	1.736	1.735
38	Pachmarhi WLS	1.158	7.474	6.873	1.73	1.748
39	Sanjay Dubri WLS	1.147	8.434	6.953	1.765	1.773
40	Andhari WLS	1.159	6.512	6.643	1.751	1.775
41	Mahauaduar WLS	1.173	6.979	6.466	1.791	1.788
42	Baisipalli WLS	1.206	7.853	6.989	1.776	1.792
43	Kinnerasani WLS	1.192	6.083	5.851	1.785	1.794
44	Palkot WLS	1.185	7.157	6.632	1.803	1.8
45	Sitanadi WLS	1.196	8.017	7.461	1.781	1.802
46	Debrigarh WLS	1.187	8.272	7.338	1.802	1.806
47	Tamorpingla WLS	1.204	7.725	6.75	1.823	1.81
48	Pamed WLS	1.215	6.665	6.542	1.825	1.843
49	Karlapat WLS	1.226	8.467	7.483	1.832	1.854
50	Khalasuni WLS	1.205	8.172	7.301	1.863	1.87
51	Bannerghatta NP	1.215	7.612	6.021	1.903	1.871
52	Kuldiha WLS	1.2	6.268	6.041	1.875	1.877
53	Satkosia Gorge WLS	1.26	7.757	6.98	1.864	1.881
54	Gugamal NP	1.188	7.123	7.08	1.859	1.888
55	Sanjay NP	1.203	8.349	6.909	1.914	1.908
56	Yadahalli Chinkara WLS	1.204	6.474	5.962	1.938	1.93
57	Nagzira WLS	1.21	6.834	6.777	1.916	1.944
58	Badarma WLS	1.225	8.284	7.336	1.947	1.955
59	Nellai WLS	1.282	1	1	2.008	1.958
60	Parasnath WLS	1.216	6.982	6.036	1.966	1.962
61	Dalma WLS	1.297	7.018	6.415	1.998	1.965
62	Badalkhol WLS	1.266	7.324	6.732	1.984	1.978

63	Bhimashankar WLS	1.203	7.525	8.814	1.923	1.979
64	Kangaer Valley NP	1.241	7.944	7.318	1.945	1.979
65	Wan WLS	1.25	5.882	5.865	1.979	2.006
66	Lakhari Valley WLS	1.256	7.084	6.756	1.981	2.012
67	Pranahita WLS	1.264	6.386	6.161	2.013	2.03
68	Gautam Budha WLS	1.245	6.338	5.713	2.052	2.042
69	Indira Priyadarshini Pench NP	1.283	6.084	5.701	2.037	2.043
70	Ranebennur WLS	1.251	5.884	5.911	2.062	2.047
71	Barnawapara WLS	1.276	7.985	7.245	2.036	2.049
72	Hazaribagh WLS	1.255	6.599	5.863	2.069	2.06
73	Udanti WLS	1.285	8.309	7.51	2.041	2.063
74	Sagareshwar WLS	1.295	6.546	6.147	2.086	2.08
75	Lawalong WLS	1.26	6.799	6.087	2.087	2.083
76	Rangayyanadurga WLS	1.307	6.128	5.987	2.126	2.101
77	Yawal WLS	1.291	4.765	4.844	2.072	2.102
78	Bhimbandh WLS	1.399	4.608	4.16	2.164	2.132
79	Kapilash WLS	1.331	7.146	6.921	2.111	2.14
80	Tadoba NP	1.279	6.599	6.736	2.103	2.142
81	Pocharam WLS	1.335	5.349	5.408	2.192	2.181
82	Jaikwadi WLS	1.342	4.36	4.604	2.168	2.185
83	Bagdara WLS	1.322	8.9	7.391	2.21	2.192
84	Panna NP	1.334	9.345	7.493	2.214	2.204
85	Panna (Gangau) WLS	1.334	9.345	7.493	2.214	2.204
86	Bhamragarh WLS	1.291	7.304	7.35	2.188	2.207
87	Aner Dam WLS	1.382	4.44	4.503	2.205	2.242
88	Betla NP	1.379	6.947	6.389	2.262	2.244
89	Bori WLS	1.371	7.133	6.553	2.228	2.257
90	Chincholi WLS	1.33	4.699	5.115	2.261	2.266
91	Singhori WLS	1.35	7.088	6.386	2.243	2.267
92	Painganga WLS	1.32	5.346	5.605	2.258	2.268
93	Bor WLS	1.344	5.956	5.772	2.271	2.286
94	Amba Barwa WLS	1.358	5.639	5.624	2.276	2.307
95	Dhyanganga WLS	1.412	3.926	4.194	2.313	2.323
96	Ranipur WLS	1.363	9.774	7.816	2.342	2.33
97	Kambalkonda WLS	1.349	6.586	6.248	2.311	2.335
98	Chandaka WLS	1.427	7.116	6.9	2.296	2.336
99	Chaprala WLS	1.347	6.573	6.636	2.308	2.339

100	Phen WLS	1.449	6.909	6.324	2.384	2.394
101	Bhoramdev WLS	1.486	6.805	6.354	2.427	2.44
102	Kolleru WLS	1.396	5.818	5.722	2.435	2.445
103	Naigaon Peacock WLS	1.491	4.672	5.053	2.441	2.455
104	Narnala Bird WLS	1.398	6.196	6.099	2.433	2.459
105	Nawegaon WLS	1.395	7.063	7.176	2.42	2.462
106	Arabithittu WLS	1.408	7.988	7.229	2.516	2.479
107	Mayureswar Supe WLS	1.419	5.953	5.799	2.471	2.482
108	Lanja Madugu Sivaram WLS	1.497	6.212	5.851	2.507	2.527
109	Gudekote Sloth Bear WLS	1.462	6.375	5.909	2.576	2.551
110	Bandhavgarh NP	1.589	7.574	6.36	2.589	2.566
111	Bhairamgarh WLS	1.532	7.224	7.196	2.626	2.647
112	Koderma WLS	1.541	6.303	5.554	2.721	2.697
113	Topchanchi WLS	1.577	6.896	6.112	2.756	2.735
114	Katepurna WLS	1.615	4.864	5.018	2.728	2.754
115	Yedsi Ramlin Ghat WLS	1.598	5.263	5.45	2.728	2.756
116	Kolamarka CR	1.584	7.078	7.312	2.745	2.798
117	New Nazira WLS	1.588	7.06	7.014	2.761	2.81
118	Daroji Bear WLS	1.635	6.6	6.338	2.896	2.864
119	Hadgarh WLS	1.694	5.768	5.832	2.854	2.891
120	New Bor WLS	1.649	6.167	6.053	2.873	2.898
121	Nandur Madhameshwar WLS	1.773	4.642	4.581	2.939	2.967
122	Mansingdeo WLS	1.683	5.918	5.675	2.964	2.975
123	Ken Gharial WLS	1.705	10	7.978	3.036	3.019
124	Panpatha WLS	1.83	7.98	6.61	3.053	3.025
125	Rajgir WLS	1.862	4.921	4.435	3.204	3.173
126	Karanja Sohal WLS	1.902	5.34	5.438	3.217	3.242
127	Manjira WLS	1.897	5.177	5.329	3.255	3.246
128	Basur Amruth Mahal Kaval CR	1.761	7.668	7.338	3.289	3.277
129	Ghataprabha WLS	1.92	7.148	6.441	3.32	3.298
130	Chandraprabha WLS	2.067	8.744	7.336	3.382	3.34
131	Mahaveer Harina Vanastha NP	2.043	5.52	5.191	3.414	3.371

132	Kappathagudda WLS	2.007	3.469	3.381	3.435	3.411
133	Veerangna Durgavati WLS	2.123	7.713	6.483	3.507	3.517
134	Karaivetti WLS	2.022	6.378	5.793	3.607	3.591
135	Vellanadu Blackbuck WLS	2.173	5.656	5.543	3.794	3.802
136	Rollapadu WLS	2.381	6.35	5.136	3.877	3.83
137	Nakti Dam WLS	10	6.886	6.242	10	10

- ***Coasts***

Total 21 PAs were analysed in the coasts (Figure 4.24; Table 4.10). Highest overall sensitivity was in Khijadia WLS (sensitivity=10), followed by Chilika (Nalabana) WLS (sensitivity=9.91), Point Calimere WLS (sensitivity=9.816). Lowest sensitivity was found in Marine NP (sensitivity=1), Sanjay Gandhi NP (sensitivity=1.053), Wild ass WLS (sensitivity=1.294). Climate exposure (at SSP585) was highest for Khijadia WLS (Departure=10), Wild Ass WLS (Departure=9.521), Thane Creek Flamingo WLS (Departure=8.624). Climate exposure was lowest for Pulicat Lake WLS (Departure=1), Sajnakhali WLS (Departure=2.537), Chintamani Kar Bird Sanctuary (Departure=2.663).

Overall vulnerability (at SSP585 scenario) was highest in Khijadia WLS (Vulnerability=10), followed by Point Calimere WLS (Vulnerability= 9.462) and Chilka (Nalaban) WLS (Vulnerability= 9.308). These sites harbour migratory species like Greater flamingos (*Phoenicopterus roseus*), Spoonbills, different species of storks, herons etc. Khijadia WLS and Chilika WLS are a Ramsar sites as well. Climate vulnerability was lowest for Marine (Gulf of Kachchh) NP (Vulnerability= 1), Wild Ass WLS (Vulnerability= 1.926), Sanjay Gandhi NP (Vulnerability= 2.077).

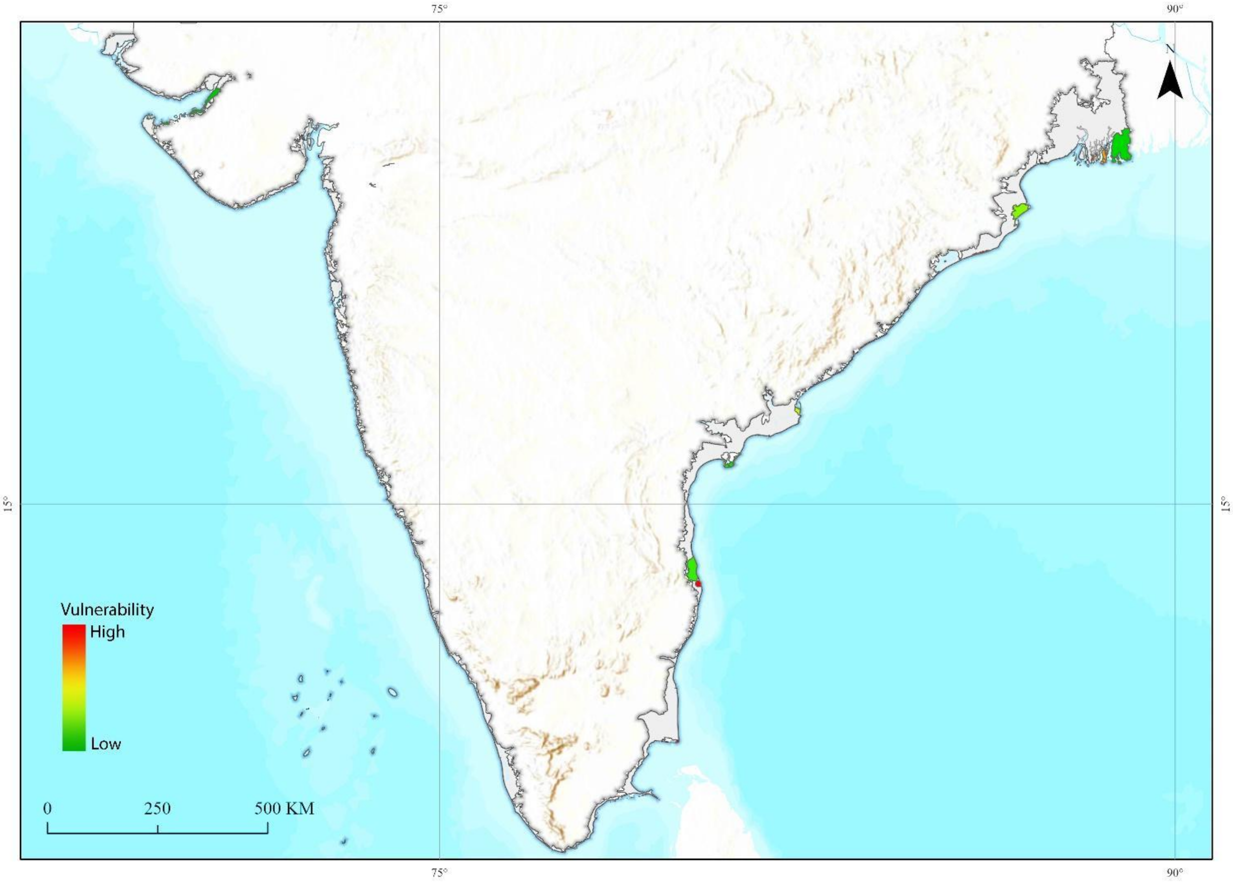

Figure 4. 24 Vulnerability factors of Coasts (Red denotes a higher vulnerability)

Table 4. 10 Sensitivity, departure, and vulnerability scores of the PAs in Coasts zone (1 is the lowest, 10 is highest)

S. no.	Protected area	Sensitivity factor (Near present)	Departure factor SSP245	Departure factor SSP585	Vulnerability factor SSP245	Vulnerability factor SSP585
1	Marine (Gulf of Kachchh) NP	1	5.977	5.945	1	1
2	Sanjay Gandhi NP	1.053	5.869	7.614	1.853	2.077
3	Wild Ass WLS	1.294	9.411	9.521	1.854	1.926
4	Sundarbans NP	1.305	2.038	2.79	2.202	2.151
5	Chintamani Kar Bird Sanctuary WLS	1.598	1.868	2.663	2.703	2.656
6	Sajnakhali WLS	2.335	1.7	2.537	3.494	3.339
7	Krishna WLS	2.584	4.523	4.599	3.611	3.52
8	Narayan Sarovar WLS	2.71	7.607	8.319	3.722	3.612
9	Pulicat Lake WLS	4.091	1	1	4.277	3.996
10	Bhitarkanika WLS	5.448	4.953	5.763	5.748	5.581
11	Coringa WLS	4.625	4.54	4.773	5.979	5.784
12	Fudam WLS	5.177	5.524	4.851	6.207	6.149
13	Gahirmatha WLS	6.492	3.488	4.131	6.623	6.39
14	West Sundarban NP	5.817	2.561	3.476	6.779	6.486
15	Lothian Island WLS	6.432	4.263	5.343	7.103	6.871
16	Balukhand Konark WLS	6.89	4.756	5.063	7.108	6.966
17	Pulicat lake WLS	7.237	2.5	2.704	7.237	6.89
18	Thane creek flamingo WLS	6.377	6.632	8.624	8.159	8.572
19	Chilka (Nalaban) WLS	9.91	8.295	8.389	9.31	9.308
20	Point Calimere WLS	9.816	5.282	6.539	9.719	9.462
21	Khijadia WLS	10	10	10	10	10

- ***Islands***

Total 09 PAs were analysed in the Islands (Figure 4.25; Table 4.11). Highest overall sensitivity was in Mahatma Gandhi Marine NP (sensitivity=10), followed by Barren Island WLS (sensitivity=6.958), Rani Jhansi NP (sensitivity=3.308). Lowest sensitivity was found in Campbell NP (sensitivity=1), Saddle Peak NP (sensitivity=1.048), Mount Harriett NP (sensitivity=1.985). Climate exposure (at SSP585) was highest for Barren Island WLS (Departure=10), Mount Harriett NP (Departure=8.078), Galathea NP (Departure=8.05). Climate exposure was lowest for Mahatma Gandhi Marine NP (Departure=1), Landfall Island WLS (Departure=1.687), Rani Jhansi NP (Departure=6.145).

Overall vulnerability (at SSP585 scenario) was highest in in Mahatma Gandhi Marine NP (Vulnerability=10), followed by Barren Island WLS (Vulnerability= 8.665) and Rani Jhansi NP (Vulnerability= 4.189). Climate vulnerability was comparatively for Campbell NP (Vulnerability= 1), Saddle Peak NP (Vulnerability= 1.778), Mount Harriett (Vulnerability= 3.171). It is to be noted that, some PAs within Andaman and Nicobar Islands excluded from the analysis, due to their small size, and unavailability of environmental pixels. However, these sites are likely to be more vulnerable.

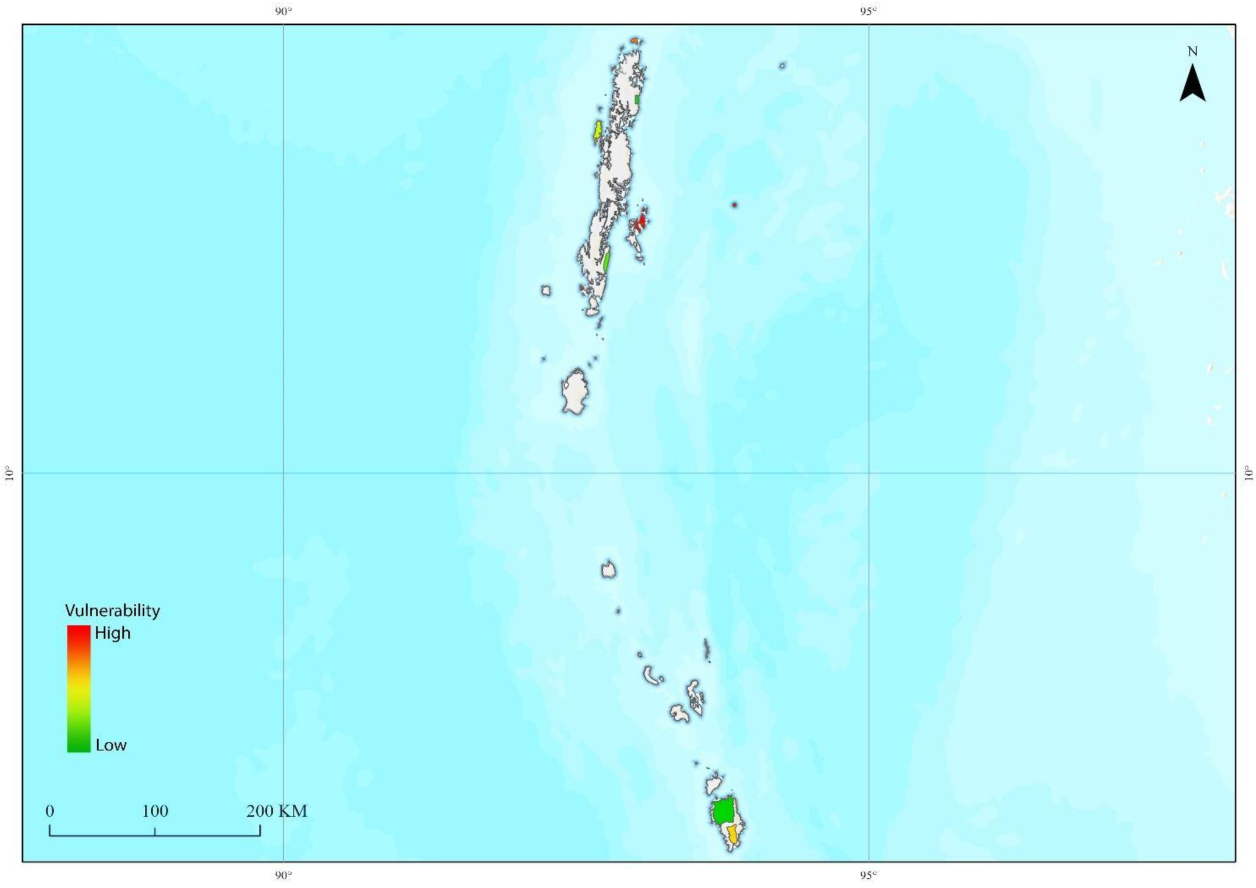

Figure 4. 25 Vulnerability factors of Islands (Red denotes a higher vulnerability)

Table 4. 11 Sensitivity, departure, and vulnerability scores of the PAs in Islands (1 is the lowest, 10 is highest)

S. no .	**Protected area**	**Sensitivity factor (Near present)**	**Departure factor SSP245**	**Departure factor SSP585**	**Vulnerability factor SSP245**	**Vulnerability factor SSP585**
1	Campbell NP	1	7.813	7.842	1	1
2	Saddle Peak NP	1.048	7.488	7.425	1.571	1.778
3	Mount Harriett NP	2.369	8.088	8.078	3.064	3.171
4	Interview Island WLS	2.118	7.08	7.031	3.125	3.261
5	Galathea NP	1.985	8.128	8.05	3.29	3.396
6	Landfall Island WLS	3.308	1.67	1.687	4.013	3.985
7	Rani Jhansi NP	3.225	6.202	6.145	4.049	4.189
8	Barren Island WLS	6.958	10	10	8.431	8.665
9	Mahatma Gandhi Marine NP	10	1	1	10	10

4.4. Discussion

In this chapter, the sensitivity, departure, and vulnerability scores of each protected area (PA) were quantified. Findings indicate that smaller PAs exhibit higher climate vulnerability. E.g. within Himalaya biogeographic zone, City Forest NP (area: 9.07 km^2) has highest vulnerability and Khangchendzonga NP (area: 1784 km^2) has lowest vulnerability (Table 4.3). Largest PA in India, Kachchh WLS has the lowest climate vulnerability in desert zone compared to smaller PAs like Bir Jhunjhunu CR (Table 4.8). This can be attributed to habitat heterogeneity & more climate space in larger PAs. Earlier studies have shown that PAs having large areas and habitat heterogeneity can escape from the risks posed by the changing environment due to the presence of larger climate space (Krobsy *et al.,* 2010). Higher habitat heterogeneity possesses a resilience mechanism, enabling them to mitigate the challenges posed by the changing climatic conditions (Krobsy *et al.,* 2010). This result aligns with prior research by Hoffmann and Beierkuhnlein (2020), wherein larger PAs demonstrated a comparatively lower degree of climate vulnerability. Species within Small PAs are more likely to get extinct, because of smaller climate space and lack of connectivity with other PAs (Hodgson *et al.,* 2009). Additional negative effects of small PAs include reduced genetic diversity, more parasitic infestation etc (Ram *et al.,* 2016; Natesh *et al.,* 2017; Chakraborty *et al.,* 2015). Results also suggests that PAs located in higher elevation has higher exposure to climate change. For example, two of the national parks with Shola habitats, Pambadum shola NP, and Mathikettan shola NP located in higher elevation in western ghats has higher climate departure or exposure (Table 4.7). Langdon and Lawler (2015) found similar results for in North America, where PAs in higher elevation had more climate vulnerability. It is to be noted that only 7 PAs in Andaman-Nicobar Islands were used in the analysis as rest of the PAs are the smaller size ($<1km^2$). However, these island PAs are likely to be more climatically vulnerable due to their smallness, remoteness, and exposure to natural hazards (Véron *et al.,* 2019).

PAs are defined by their fixed boundary, and with increasing temperature there will be changes in the PA's climate conditions. The species living in disappearing climate space will need to find other places where their requirements are fulfilled. This will lead to losses and additions of species into the native communities in the PAs since climate change will cause the shift of species distribution (Wiens *et al.,* 2011). Those species that will not move beyond the current climate space of PAs will come across novel challenges from species invading from elsewhere (Rowland *et al.,* 2016). This will lead to increase in competition, and potentially local extinction. Furthermore, climate vulnerability of PAs is likely to be augmented with other factors, such as reduced connectivity among PAs due to developmental activities/urbanization outside PAs, and other threats to the biodiversity (e.g., habitat degradation within PA). For examples, in North-east, Manas NP, has comparatively lower climate vulnerability than the smaller PAs. However, northeast has faced drastic changes in LULC over the few decades, and these factors will increase the vulnerability of PAs.

It was found that large PAs in India has comparatively lower sensitivity, i.e., spanning a variety of climatic gradients, making them likely to serve as refugia in the face of climate change or to assist species movement. Large PAs can accommodate species latitudinal range shifts caused by climate change (Hannah *et al.* 2002, 2007). The survival of species in large PAs is heavily dependent on the maintenance of their contiguity amidst climate change. It's crucial that human activities, especially those causing habitat fragmentation, are kept outside PA boundaries (Fuller *et al.,* 2008).

- ***Importance of small PAs***

Large PA areas, high terrain ruggedness, are advantageous for conservation in the face of climate change. However, small PAs dominate in India, but their cumulative contributions to biodiversity conservation are less documented. Small regions can help to conserve biodiversity globally by improving matrix habitats, increasing connectivity, and preserving localized ecosystems. Small PA areas can face several issues. It includes constraints on resources and capacity, as well as pressure from development and other land uses. However, Small PAs can also contribute significantly to the conservation of natural and cultural resources while also providing several advantages to local people. To effectively conserve natural and cultural resources, small PAs must be well-managed and supported by both local and national governments. This can include giving technical and financial assistance, as well as collaborating with local communities to create long-term management strategies. Nonetheless, small-scale opportunities for local distribution of species and habitat changes may still exist in small PAs. A well-connected network of small sized PAs can act as *steppingstone corridor* for the species for dispersing to larger areas.

Novel species assemblages and interactions are likely to evolve in areas with significant climate vulnerability (Rinnan & Lawler, 2019). Species that live near their climatic tolerance limits and have little adaptation capacity are the most vulnerable to higher climate exposures (Garcia *et* *al.,* 2014), potentially leading to population decline (Foden *et al.,* 2007) and local extinctions (Sinervo *et al.,* 2010).

Effectiveness of PAs can not only be measured by the presence of species richness, and size of the PAs, but the habitat quality, spatial configuration (Mortelliti *et al.,* 2010), and management practices (Fahrig, 2003) need to be considered. Management responses must be developed in the context of individual PAs because the climate predictions, their uncertainties (Belote *et al.,* 2018), ecosystem intactness (Watson *et al.,* 2013), conservation targets (Belote *et al.,* 2017), the conservation capacity of land (Gillson *et al.,* 2013), the management resources available (Wintle *et al.,* 2011) and the risks of management actions (Ando *et al.,* 2018) differ between PAs. When management resources are limited, national authorities should prioritize and pro-actively improve the characteristics of their national PA estates that are strongly associated with high climate change exposure and indicate climate change vulnerability. Generally, large PA area, high terrain ruggedness and high irreplaceability are beneficial for conservation under climate change exposure. However, some characteristics of established PAs cannot simply be improved by conservation management to decrease climate change vulnerability. While reducing human footprints, restoring habitat of endangered species, and expanding PA area might be feasible, terrain ruggedness can hardly be modified at larger scales. Moreover, not each particular conservation objective of individual PAs might be supported by large area, high terrain ruggedness, high irreplaceability and small human footprints. Small, protected areas dominate some databases and are common features of landscapes, yet their accumulated contributions to biodiversity conservation are not well known. Small areas may contribute to global biodiversity conservation through matrix habitat improvement, connectivity, and preservation of localized ecosystems. Overall, small PAs can make a significant contribution to the conservation of natural and cultural resources and can also provide a range of benefits to local communities. Small PAs can face a number of challenges, however, including limited resources and capacity, and pressure from development and other land uses. To effectively conserve natural and cultural resources, it is important for small PAs to be well-managed and supported by both local and national authorities. This can involve providing technical and financial assistance, as well as working with local communities to develop sustainable management strategies.

PAs with high climate vulnerability factors are more likely to have increased climate exposure/anomaly and reduced climate heterogeneity. In general, large PA's low climate vulnerability means that current biodiversity and ecosystem functioning are expected to remain despite ongoing climate change.

However, conservation management cannot simply improve some aspects of established PAs to reduce their vulnerability to climate change. While it may be possible to reduce human footprints, restore endangered species habitat, and expand PA space, terrain ruggedness cannot be changed on a wide scale (Lawrence, Hoffman, and Beierkuhnlein, 2021). Furthermore, not every conservation goal of PAs may be supported by wide areas, harsh terrain, high irreplaceability, and minimal human footprints.

However, some characteristics of established PAs cannot simply be improved by conservation management to decrease climate change vulnerability. While reducing human footprints, restoring habitat of endangered species and expanding PA area might be feasible, terrain ruggedness can hardly be modified at larger scales. Moreover, Climate-smart management guidelines generally aim at the persistence and resistance of present biodiversity despite climate change, or at the adaption of biodiversity to climate change (Gross *et al.,* 2017).

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Chapter 5

Identifying climate-change refugia for biodiversity

Chapter 5. Identifying climate-change refugia for biodiversity

5.1. Introduction

This chapter presents analysis that takes into consideration the locations projected as potential future refugia for biodiversity. Here climate-change refugia for biodiversity approach was used, a species dependent approach to identify the regions where areas will be supporting species climatic niche in future.

Recent climate change has been affecting different levels of biodiversity, from organisms to biomes (Bellard *et al.,* 2012), already causing observed impacts (Parmesan and Hanley 2015; Settele *et al.,* 2014). Previous analyses of climate change impacts on biodiversity have shown that the trends of species range shifts are matching climate change predictions, with ranges shifting towards higher latitudes (Parmesan and Yohe 2003; Franco *et al.,* 2006), or towards higher altitudes (Franco *et al.*, 2006; Chen *et al.,* 2011) and sometimes both (Parmesan, 1996; Parmesan *et al.,* 1999), following a suitable climate. Furthermore, studies that analysed possible future impacts of different climate change scenarios on biodiversity (Jetz, Wilcove, and Dobson 2007; Pimm, 2008; Bellard *et al.,* 2012; Warren *et al.,* 2013) have reached the conclusion that even in the best-case scenario (that usually means that greenhouse gas –GHG– emissions would immediately stop or would be negative) biodiversity will still be affected.

In previous periods of climate instability (e.g., cyclical warming and cooling in the Quaternary), species have "retreated to, persisted in and expanded from" areas called refugia (Keppel *et al*. 2012). Although projected changes in future climate do not suggest a return to pre-industrial levels in this century under any explored scenario (IPCC 2023), the concept of refugia as areas where species could survive despite future climate change is still considered valuable for biodiversity conservation (Keppel *et al.,* 2012; Morelli *et al.,* 2020). Therefore, a growing body of research has aimed at identifying future refugia (Keppel *et al.,* 2012; Baumgartner *et al.,* 2018) and planning their conservation and protection (Keppel *et al.,* 2015; Morelli *et al.,* 2016; Graham *et al.,* 2019). However, most proposals are usually targeted at one or few species of the same taxonomic group (e.g., Monsarrat, Jarvie, and Svenning (2019), Ribeiro, Sales, and Loyola (2018), Borges and Loyola, (2020)) and are mainly not at scales most pertinent to biodiversity conservation (Selwood and Zimmer, 2020). Identifying future refugia for a species is important and should be included in the conservation planning of critically endangered species. Despite that, as resources for conservation are often scarce, conservation planning aimed at the ecosystem level would greatly benefit from the identification of locations that are projected as potential future refugia simultaneously for more than one taxon, i.e., cross-taxon refugia. This thesis adopts the simplistic assumption that cross-taxon refugia are more likely to retain their current ecosystem structure and function due to their higher number of species and taxa in comparison with non-refugia locations. Hence, identifying cross-taxon refugia is useful for long-term conservation measures that aim to protect currently healthy ecosystems (creation of new PAs) or to recover the functionality of degraded ecosystems (restoration actions).

Climate plays a crucial role in shaping species' distributions and generating overall spatio-temporal patterns of biodiversity (Bellard *et al.,* 2012; Warren *et al.,* 2013). Species will be at risk if their tolerated habitat and climatic conditions to which they have adapted disappear in the future. (Garcia *et al.,* 2014; Mantyka-pringle *et al.,* 2012; Newbold *et al.,* 2018). Biodiversity faces a global threat due to climate change and has been identified as the main driver of species extinctions in the next decades (Dawson *et al.,* 2011; Parmesan & Yohe, 2003; Thomas *et al.,* 2004). Also, geographic range shifts (i.e. range area, latitude, and elevation shifts) induced by climate change is now well acknowledged and it is anticipated to modify community composition of different taxa in future (Bagaria *et al.,* 2020; Jenkins *et al.,* 2021; Price *et al.,* 2018; Thuiller, 2004; Zhu *et al.,* 2012). With the increase of global temperature, it has been predicted that these distributional changes will intensify, depending on the scenario of greenhouse gases emissions till the end of this century (IPCC, 2023).

Throughout history, biodiversity has responded and adapted to climate change, but many species may be ill-prepared to deal with the recent, faster rate of warming (Root *et al.,* 2003). There will be species that prefer warmer climates and will proliferate (Johnston *et al.,* 2013). However, for many, higher temperatures will increase the risk of extinction or necessitate the ability to relocate to colder regions. Species range shifts have already been observed in studies and attributed to climate change (Parmesan *et al.,* 2022). Mobile species, such as birds and butterflies (Breed *et al.,* 2013; Hill *et al.,* 2021), may be better able to track climate changes than less mobile species, such as many plants which will lag (Alexander *et al.,* 2018) suggesting multiple groups of plants and animals are susceptible in different ways. As a result, even if global rate of warming is limited, and the Paris Agreement goals of constraining warming to well below 2°C are met, significant threats to global biodiversity are likely to remain (Foden *et al.,* 2013; Warren *et al.,* 2018)

Faced with numerous impacts and risks, including climate change, a crucial approach for protecting biodiversity is to identify areas remaining climatically suitable for species in future, i.e., climate-change refugia. Warren *et al*, 2018 defines climate-change refugia as areas that are projected to remain climatically suitable for at least 75% of the total number of species modelled to currently be there. In the context of global change, identifying and safeguarding climate-change refugia in landscapes is a crucial and effective conservation strategy. (Groves *et al.,* 2012; Jenkins *et al.,* 2021; Morelli *et al.,* 2016; Ribeiro *et al.,* 2021; Stralberg *et al.,* 2020; Struebig *et al.,* 2015).

Land degradation increases the vulnerability of biodiversity (Newbold *et al.,* 2015; Gibson *et al.,* 2011). The United Nations has designated the years 2021-2030 as the UN Decade on Ecosystem Restoration (UNEP & FAO, 2020), which aims to restore degraded land to help combat climate change and protect natural resources. Almost 50% of India's total land has already been converted to agriculture (Roy *et al.,* 2016). As a result, protecting existing natural lands will not be enough. Identifying refugia overlapping with the land-use that might require restoration is necessary to protect species in a warming environment,

By 2100, it is predicted that 68% of terrestrial assemblages will have more than 20 percent of their constituent species exposed to unprecedented temperatures (Trisos *et al.,* 2020). India is tropical mega-diverse country, home to nearly 7-8 percent of all recorded species and four globally identified biodiversity hotspots (Himalaya, Indo-Burma, Western Ghats, and Sundaland) (Myers *et al.,* 2000). India's diverse set of ecosystem and landscapes broadly divided into 10 biogeographic zones and 27 biogeographic provinces, all with unique species, geographic and climate characteristics. Among the 10 biogeographic regions, the Deccan peninsula biogeographic zone covers over 40% of India's total geographical area.

India has been identified as one of the most vulnerable countries to the effects of climate change (IPCC, 2023), and efforts are being made to determine the impact of climate change on Indian biodiversity (Sarkar & Talukdar, 2023; Bagaria *et al.,* 2020; Chhetri *et al.,* 2018; Jose V & Nameer, 2020; Mungi *et al.,* 2018; Pati *et al.,* 2021; Rathore *et al.,* 2022) in different warming scenarios. However, most of these studies focus on a species level with a few focusing on regions (Banerjee *et al.,* 2023). This chapter is the first country-level study performed to identify of climate-change refugia for terrestrial biodiversity for different taxonomic groups in different biogeographic zones and provinces and how current land-use practices overlaps with these refugia.

To achieve that, the research presented in this chapter uses output taken from the existing Wallace Initiative database to determine the location of future climate change refugia for terrestrial species of six taxa (Amphibia, Aves, Insects, Mammalia, Plantae, and Reptilia) in six different future climatic scenarios (1.5°C, 2°C, 3°C and 4°C above pre-industrial levels) mapping them to individual grid cells at a scale of 20x20km.

The results of species distribution models developed by Wallace Initiative (Warren *et al.,* 2018; Warren *et al.,* 2013) are used in this study to assess the effects of projected climate change on biodiversity (mammals, birds, reptiles, insects, and plants) in India. These data help determine the areas where climate-change refugia are projected to exist. The findings of this study will be useful to the policymakers to make strategic, science-based decisions for protecting India's biodiversity in the face of climate change in a national and regional scale.

5.2. Materials and methods

5.2.1. Study Area

We used India (Source: https://surveyofindia.gov.in/) (20.5937° N, 78.9629° E) as our study area. The total geographical area of the country is 32,87,263 km², divided into 28 States and 8 Union Territories. India's climate is primarily of a tropical monsoon type; however, it encompasses a varied range of climate conditions across a vast geographic scale and diverse topography. India experiences an annual mean temperature of 21°C and average rainfall of 1045mm. The total forest cover of the country is 713789 km² (21.71% of total geographic area) (FSI, 2021).

5.2.2. Data used.

- **Species distribution model data**

Wallace initiative (WI) is a global database with the goal of quantifying the projected climate change impacts on species at various warming levels in order to identify potential areas of greatest resilience to climate change (Warren *et al*., 2013, 2018). In Brief, The WI uses GBIF data (Lane & Edwards, 2020) and ClimGen (Osborn, 2010) data using Maxent (Phillips *et al.,* 2023). to estimate potential distributions of more than 135,000 species. The ClimGen data consists of different projected variables of temperature and precipitation data. The outputs were then projected to 21 CMIP5 general circulation models of four warming scenarios (i.e., 1.5°C, 2°C, 3°C and 4°C). These four warming scenarios are proxy to different Representative Concentration Pathways (RCP): RCP 8.5, 2080s (i.e., average of 2071–2100), as a proxy for 4°C (no-mitigation business as usual); RCP 6.0, 2080s, as a proxy for 3°C; RCP 2.6, 2080s, as a proxy for 2°C; and RCP 8.5, 2030s (i.e., average of 2021 –2050), to approximate 1.5°C (Warren *et al*. 2018)

The resulting outputs were aggregated into maps of refugia, i.e., areas remaining climatically suitable for ≥ 75% of species currently found within each 20km grid cell. While modelling the refugia, current land use and potential land use change are excluded.

The base WI models and aggregations have a spatial resolution of approximately 20 km owing to a combination of computational limitations and, especially, constraints imposed by the underlying observed climate and climate change (i.e., GCM output) data (Suggitt *et al*., 2017). The summary WI biodiversity data, but not the individual species models, were elevationally downscaled to 1km for the analysis. For caveats and limitations of the data, check Warren *et al*, 2014.

- **Landcover data**

Current anthropogenic impacts on climate-change refugia were assessed using remote sensing data (Source: daac.ornl.gov). The land cover data used from decadal LULC project (Roy *et al.,* 2016) and has a spatial resolution of 100 m. The LULC map is ground-truthed (12,606 stratified random samples) and overall accuracy of the LULC map is 94.46% (Roy *et al.,* 2016). all WI biodiversity data (i.e., refugia and richness remaining) were resampled to 100m using the nearest neighbour technique in ArcMap 10.8's resample tool to match the current LULC data. The results presented here are at a 100m resolution.

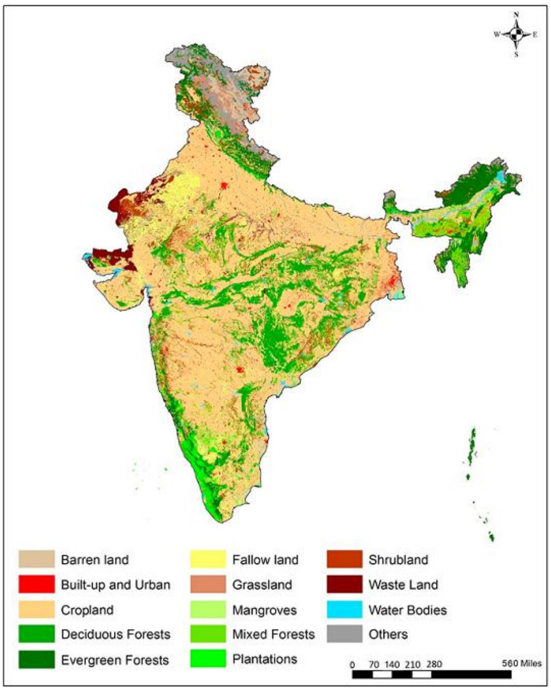


Figure 5. 1 Land-use land-cover map of India (Source: Roy et al, 2005)

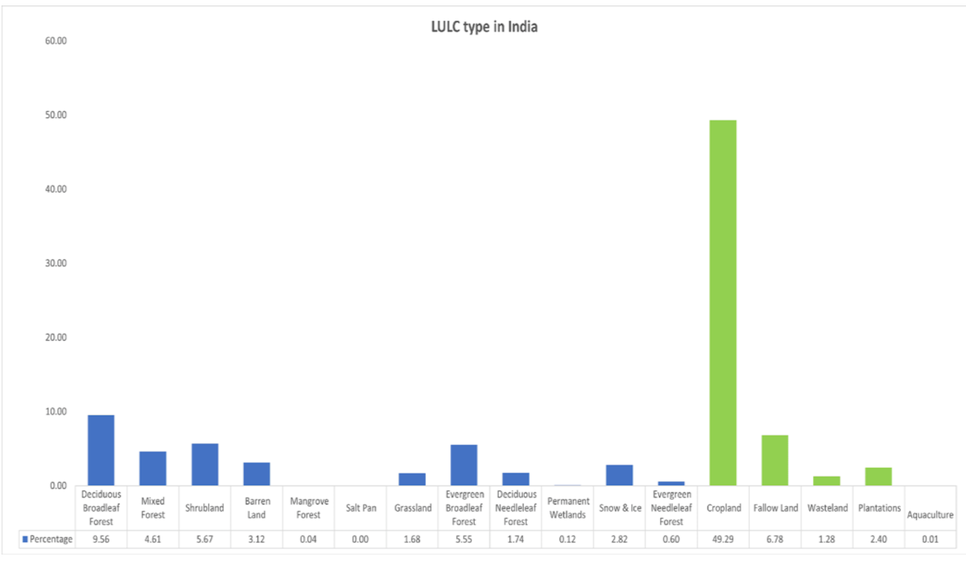


Figure 5. 2 Percentage of different Land-use Landcover of India

5.2.3. Analysis

Further analysis involves two steps. First, the extent to which the climate-change refugia in different biogeographic zones and provinces is affected with different warming conditions was determined. The Wallace Initiative defines "refugia" as cells in which at least 75 percent of the current species richness can survive in a changing climate in at least 11 of the 21 GCMs used. The data ranges from 0-21, representing the number of GCM agreeing that a given cell would be refugia. The refugia data were reclassified into binary maps, i.e., presence (1) and absence (0) of refugia based on a threshold of 11 (i.e., each cell received 1 from at least half of all GCMs). Zonal statistics tool in ArcGIS 10.8 was used to identify the extent of climate-change refugia in each biogeographic region and provinces under different warming scenarios.

Second, the extent to which current land-use practices potentially impact future refugia was assessed. The land-cover data was reclassified (Reclassify tool: ARCGIS 10.8) into areas that need conservation (i.e., natural areas) and areas that require restoration (i.e., Converted lands) (Figure 2). The climate-change refugia layers were overlaid to reclassified LULC data to identify, i. refugia located in natural areas, ii. Refugia located in semi-natural areas and will require restoration measures.

Additionally, a similar set of analyses was performed with species richness data to identify the areas with 50% species richness remaining under different warming scenarios. Richness data ranges from 0 to 1 and reclassified with a threshold of 0.5.

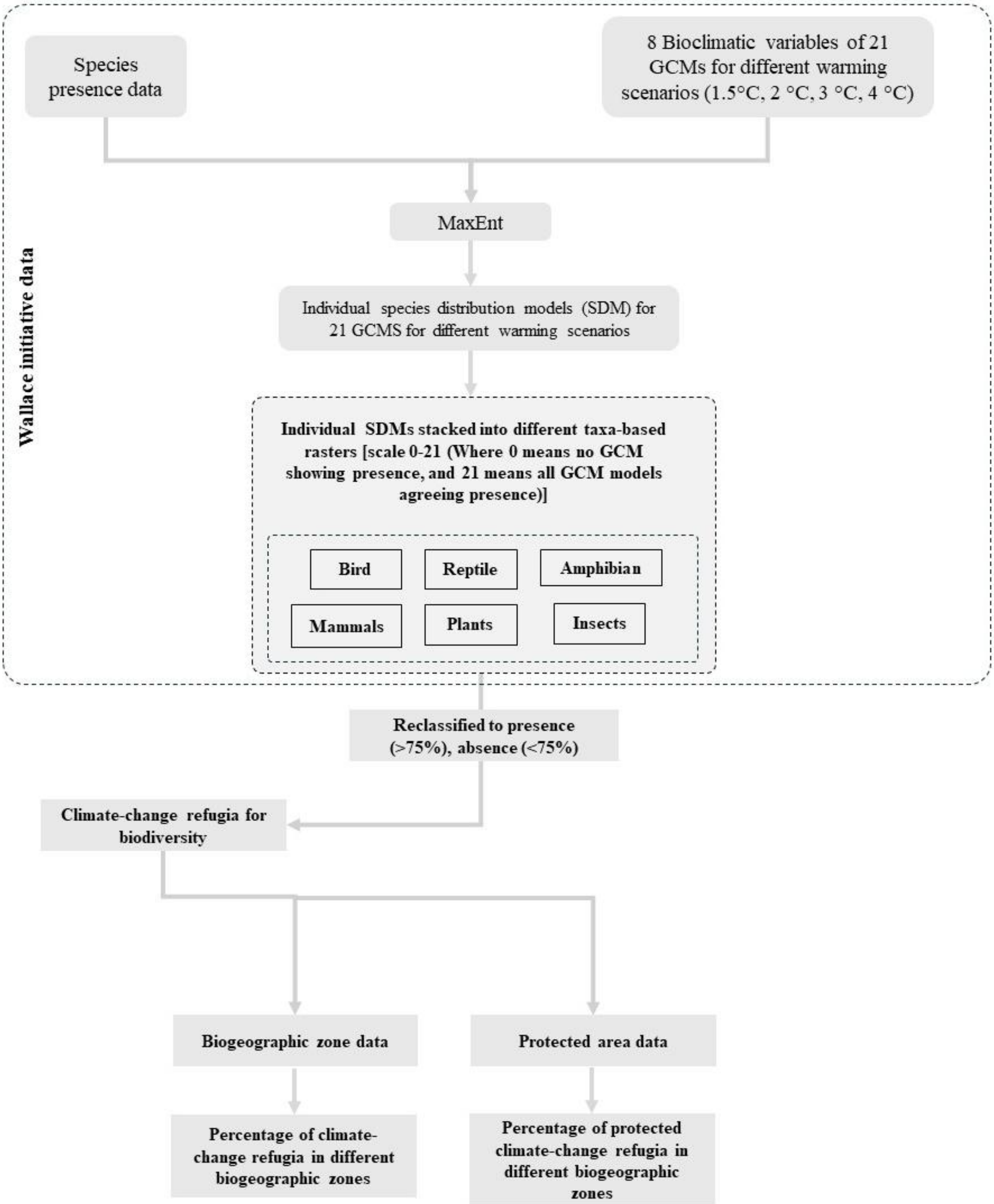


Figure 5. 3 Flowchart of methodology for modelling the climate-change refugia for biodiversity

5.3. Results

5.3.1. Climate-change refugia

Climate-change refugia were identified for targeted six taxa within India (Figure 5.7). Results project that climate change poses a substantial threat to the biodiversity of India and limiting temperature rise will play crucial role in conserving these refugia. When warming is limited to 1.5°C, most of the country is expected to serve as a refugia for all modelled taxa, ranging from 47% of India for insects to 27% for birds. (Table 5.1). Limiting global temperature rise has been shown to be especially beneficial for plants, which means that animals may benefit indirectly because they rely on plants for survival (as they provide habitat and food sources). The proportion of taxa at risk gradually increases with increasing warming levels for all six taxa studied. At least 45% of the projected refugia for all taxon in 1.5°C is in semi-natural areas (mainly agriculture). Although there are species thriving in these semi-natural areas, some level of management will be required to safeguard these refugia. For birds, with increasing warming, refugia projected majorly within natural areas (Figure 5.4). Around 50% of the projected refugia for all plants and mammals at 1.5°C warming falls within semi-natural areas. The actual extent of climate-change refugia is smaller if only natural land is considered, and even less if only natural habitat within protected areas is considered (Figure 5.4). Himalaya, Trans-Himalaya, and North-east will be refugia for at least 5 taxa in all scenarios. In business-as-usual scenario (i.e., 4°C), around 6% of India will remain refugia for birds. Considerable areas of Himalaya, North-East, Western Ghats biogeographic regions projected to contain climate-change refugia for all the model taxa (Table 5.1). However, beyond 2°C, refugia considerably decreases for Islands, followed by Western ghats, and North-east (Table 5.1). Trans-Himalaya and Himalaya remains refugia for most of the modelled taxa at 4°C. Due to extreme cold conditions, small percentage of area is projected as refugia for amphibians.

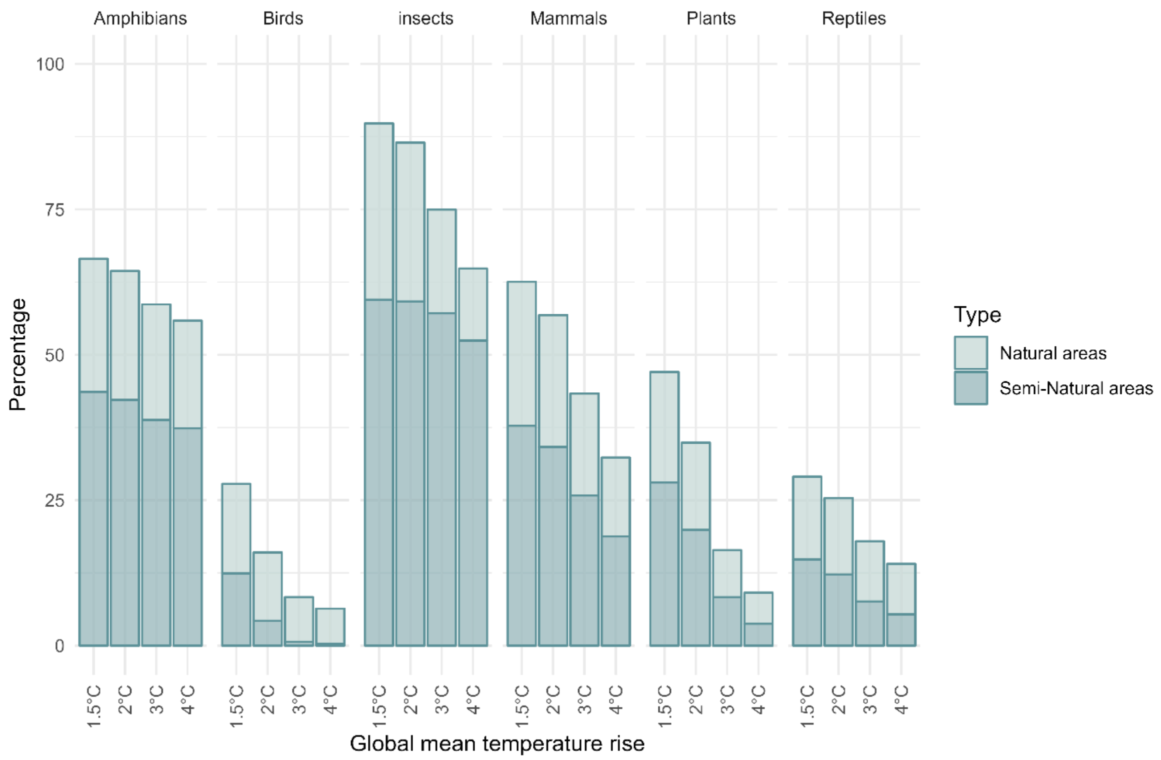


Figure 5. 5 Percentage of India's Climate-change refugia in India in different warming scenarios.

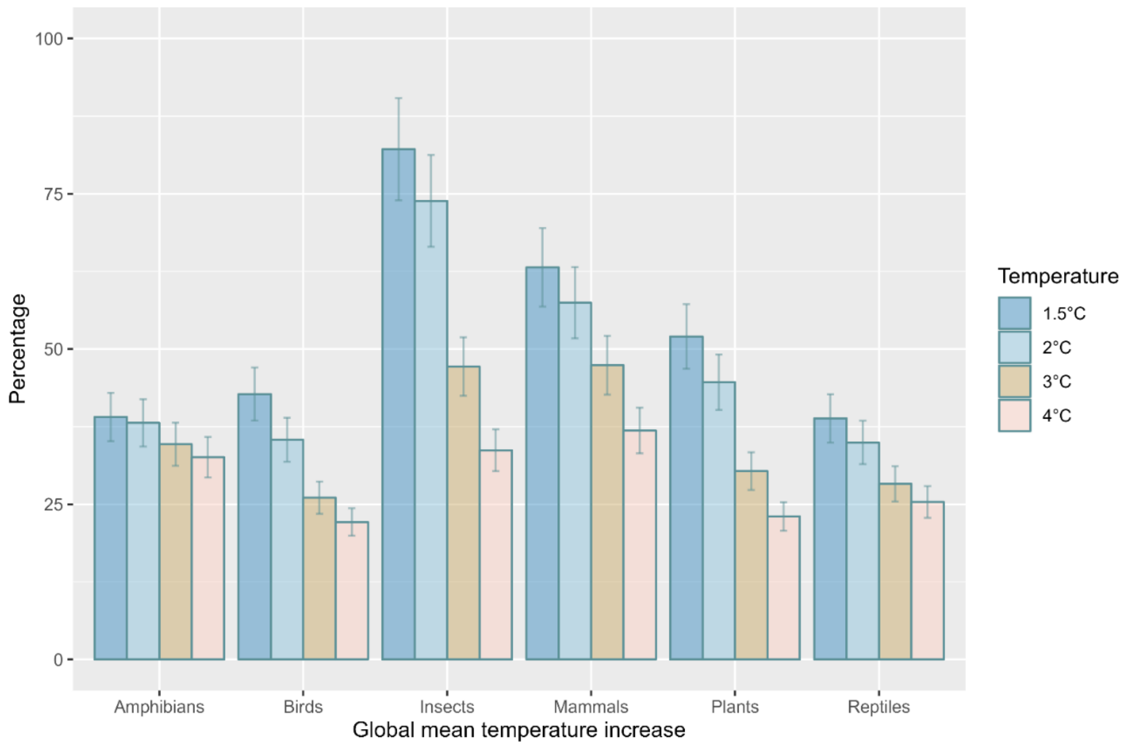


Figure 5. 4 Climate-change refugia in protected areas in different warming scenarios.

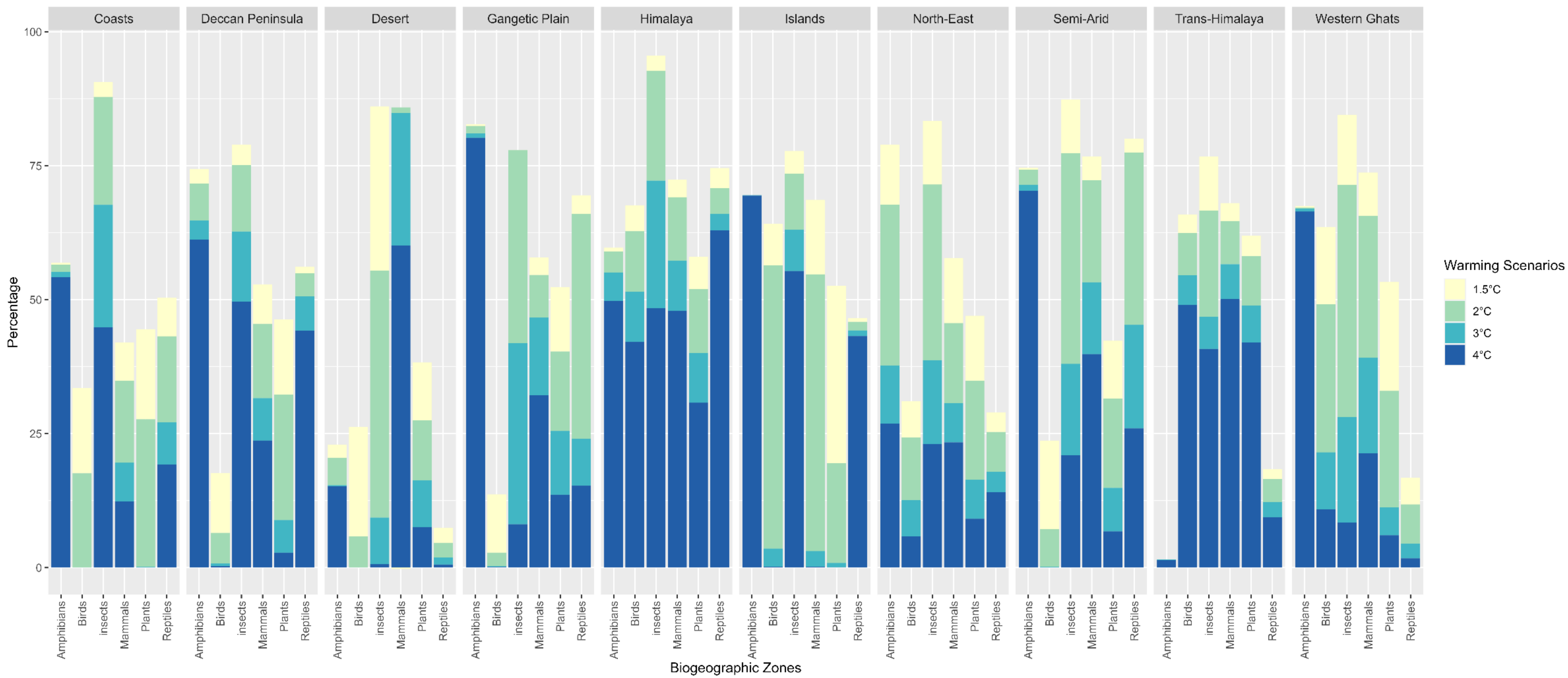


Figure 5. 6 Percentage of India's Climate-change refugia in different biogeographic zones of India in different warming scenarios.

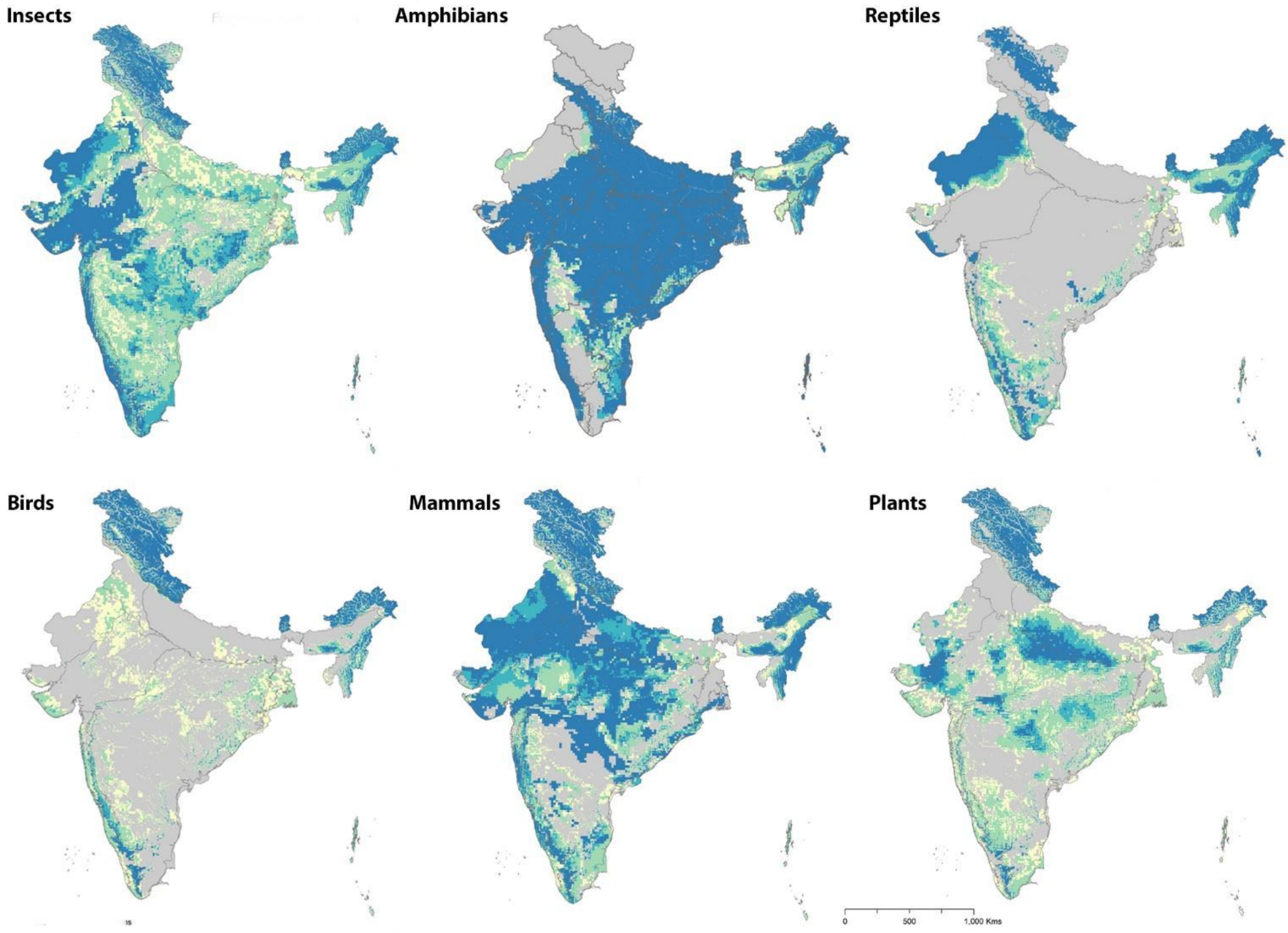
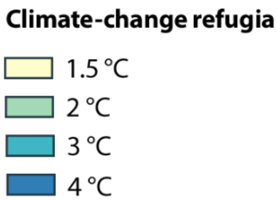


Figure 5. 7 Climate-change refugia for different taxa in different warming scenarios.



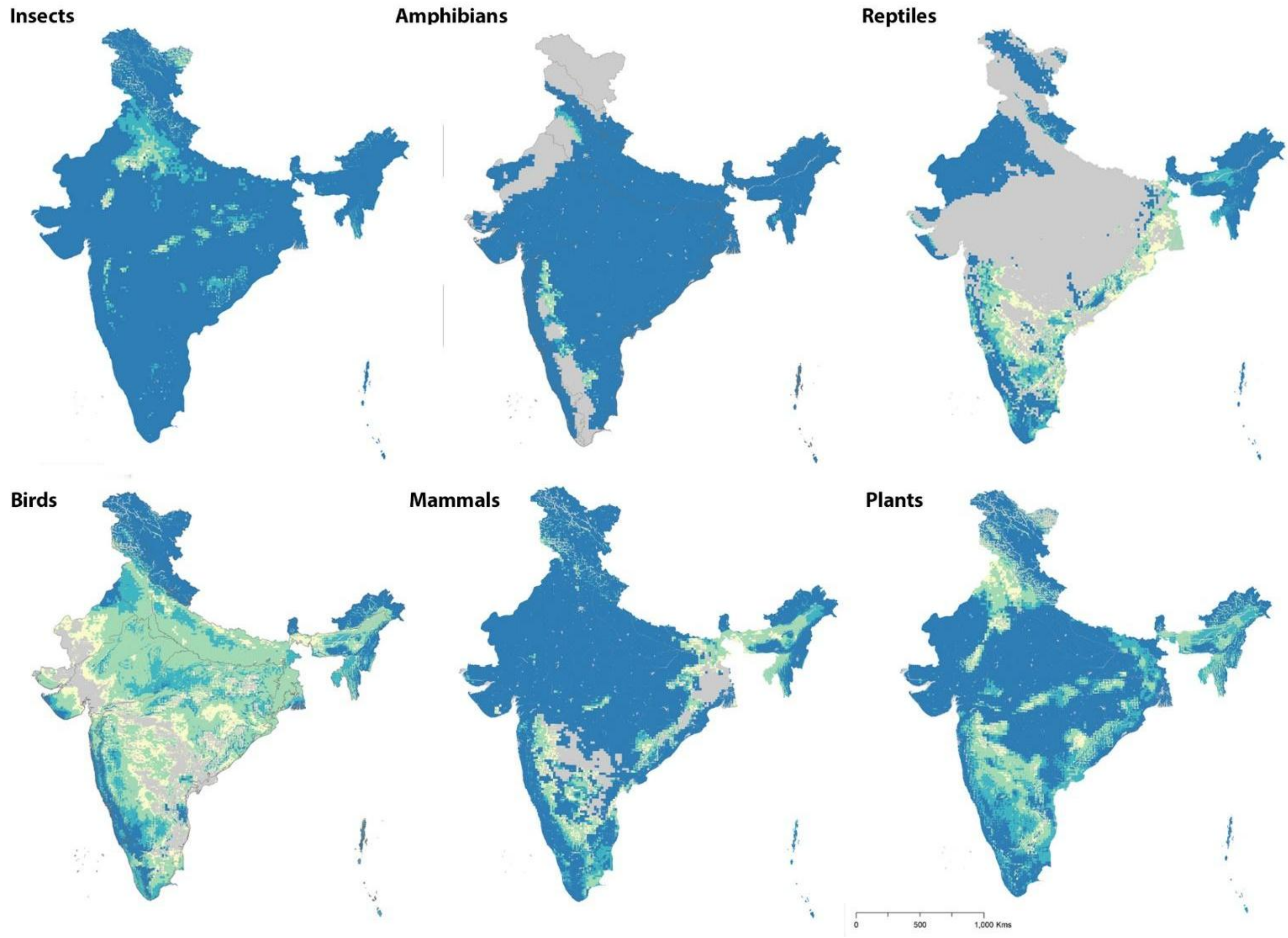


Figure 5. 8 50% species richness remaining in different warming scenarios

50% Species richness remaining

- 1.5 °C
- 2 °C
- 3 °C
- 4 °C

5.3.2. Biogeographic zone wise results

The land extent that is projected to have the potential to act as future climatic-change refugia in the Himalayas decreases with higher levels of global warming, exhibiting a similar decreasing trend to the one shown on the country-scale analysis.

Himalayas are expected to have the most areas as climate-change refugia. Under all warming scenarios, at least 30% of the Himalayas will remain refugia for all modelled taxa (Figure 5.6). Among the three biogeographic provinces of Himalayas, North-eastern Himalayan province will have greater reduction in refugia above 2°C. Compared to the North-west province, more areas of Western Himalaya projected as refugia at 4°C.

With increasing temperatures, less areas of PA will remain refugia different taxa. For birds at 1.5°C, 38 PAs in Himalayas projected to contain more than 90% of its total area as refugia, compared to 17 PAs in 4°C. At 1.5°C, 9 PAs projected to have less than 50% of its area as refugia compared to 30 PAs in 4°C. For insects, at 1.5°C, 46 PAs will have more than 90% areas as refugia, and 19 PAs as in 4°C. For mammals, at 1.5°C, 49 PAs will have more than 90% areas as refugia, and 24 PAs as in 4°C. PAs like Singalila NP, Nanda Devi NP, Neora Valley NP, Khangchendzonga NP, etc., is projected to contain above 90% areas as refugia in all warming scenarios. In a 1.5ºC warmer world, only a quarter of the Himalayas land area is identified as cross-taxon refugia for any three taxa, and just above 14% of its extent is projected to act as future cross taxon refugia for plants and any two animal taxa. In a 2.0ºC warmer world, the proportion of India's land area identified as cross-taxon refugia declines to 9% for any three taxa, and 4% for plants and any two animal taxa. In levels of warming above the ones set as "safe" limits by the Paris Agreement, a very small proportion of the biome's land area is identified as future cross-taxon refugia for at least two taxa, regardless of if its conditional on being refugia to plants (~0.02% in a 2.7ºC warmer world) or not (3.4-1.2% in a 2.7-3.2ºC warmer world, respectively). With increasing temperatures, less areas of PA will remain refugia different taxa. For birds at 1.5°C, 38 PAs in Himalayas projected to contain more than 90% of its total area as refugia, compared to 17 PAs in 4°C. At 1.5°C, 9 PAs projected to have less than 50% of its area as refugia compared to 30 PAs in 4°C. For insects, at 1.5°C, 46 PAs will have more than 90% areas as refugia, and 19 PAs as in 4°C. For mammals, at 1.5°C, 49 PAs will have more than 90% areas as refugia, and 24 PAs as in 4°C. PAs like Singalila NP, Nanda Devi NP, Neora Valley NP, Khangchendzonga NP, etc., is projected to contain above 90% areas as refugia in all warming scenarios.

The Western Ghats are home to several endemic species, and increased warming has a significant impact on biodiversity in this region. It will have at least 50% of the area as a refugia for all modelled taxa at 1.5°C, with a rapid decline beyond that. For an example, Plants' refugia projected highest decline in 4°C in Malabar plains province. At 4°C, bird refugia declined to 0.09% in Malabar plains. 21.8% area of western ghat mountains projected refugia for birds at 4°C. Comparatively, Western ghats mountains will have more areas as refugia compared to Malabar plains. The north-east zone India is a biodiversity hotspot (Myers, 2000), with at least 30% (at 1.5° C) of its land area projected as a refugia for all modelled taxa. Beyond 1.5° C, there is a significant decline for all modelled taxa, particularly for plants and birds in 4°C. In all warming scenarios, North-east hills will contain more areas as refugia compared to the Brahmaputra valley province. Islands will have at least 40% areas as refugia for all taxa in the 1.5°C scenario. However, limiting warming will be critical for islands, because beyond 2°C, there is <40% decline in refugia for all taxa. At 4°C warming, less than 1% of the land area will remain as a refuge for birds and plants. Below 5% area is projected as refugia for coasts under all warming scenarios.

The Gangetic plains are one of India's most densely populated areas. In 1.5°C, at least 50% of the plant and mammal refugia are already in converted land and required to be restored or managed properly. In 1.5°C, Lower gangetic plains have more projected areas (21%) as refugia for birds compared to the upper gangetic plains. In 1.5°C, for mammals and plants, the upper gangetic plain's 75% and 62% of areas projected as refugia. Only 0.11% area remains refugia for birds in 4°C warming. DP is the largest biogeographic zone in India comprising 5 biogeographic provinces. Approx. 50% of its total area projected as refugia for plants and mammals in 1.5°C. For birds, refugia are mainly in the natural areas in DP. Within this zone, in 2°C warming, Chhota Nagpur plateau is projected to have 33.5% area as bird refugia and minimum (7%) in central plateau. within 2°C, Central and eastern Highlands are projected to have at least 50% area as refugia for mammals. Beyond 2°C, refugia declined for all taxa, 2.8% in 4°C for plants. In desert and semi-arid regions, major decline is present above 2°C warming for birds and less than 1% area will remain as refugia. At least 60% of area will be refugia in the mammals under all warming scenarios.

Table 5. 1 Percentage of area projected as future climate-change refugia under four different levels of global warming (in relation to the baseline).

taxa	Biogeographic Zone	Percentage of area projected as refugia			
		1.5°C	2°C	3°C	4°C
Birds	Coasts	33.57	17.60	0.06	0.00
	Western Ghats	63.60	49.19	21.52	10.90
	Deccan Peninsula	17.69	6.50	0.77	0.29
	Himalaya	67.60	62.78	51.52	42.11
	Desert	26.25	5.81	0.01	0.00
	Gangetic Plain	13.66	2.80	0.29	0.11
	Islands	64.19	56.40	3.55	0.20
	Trans-Himalaya	65.94	62.43	54.59	49.05
	Semi-Arid	23.73	7.23	0.20	0.04
	North-East	31.05	24.33	12.63	5.87
Total		27.79	15.99	8.33	6.36
Amphibians	Coasts	56.95	56.57	55.17	54.21
	Western Ghats	67.46	67.20	67.00	66.47
	Deccan Peninsula	74.43	71.68	64.81	61.20
	Himalaya	59.71	58.98	55.12	49.82
	Desert	22.98	20.52	15.38	15.15
	Gangetic Plain	82.78	82.46	81.04	80.24
	Islands	69.54	69.54	69.54	69.43
	Trans-Himalaya	1.51	1.51	1.48	1.41
	Semi-Arid	74.65	74.27	71.45	70.30
	North-East	79.00	67.74	37.75	26.90
Total		66.46	64.37	58.62	55.84
Mammals	Coasts	42.06	34.91	19.57	12.37
	Western Ghats	73.74	65.63	39.16	21.32
	Deccan Peninsula	52.83	45.52	31.63	23.73
	Himalaya	72.41	69.16	57.30	47.91
	Desert	85.65	85.91	84.88	60.15
	Gangetic Plain	57.91	54.63	46.67	32.15
	Islands	68.67	54.76	3.07	0.14
	Trans-Himalaya	68.06	64.69	56.62	50.12
	Semi-Arid	76.77	72.31	53.27	39.86
	North-East	57.78	45.65	30.73	23.38
Total		62.50	56.78	43.31	32.31
Plants	Coasts	44.50	27.69	0.13	0.02
	Western Ghats	53.31	32.99	11.24	6.03

	Deccan Peninsula	46.33	32.30	8.86	2.80
	Himalaya	58.02	52.00	40.06	30.77
	Desert	38.28	27.52	16.30	7.60
	Gangetic Plain	52.40	40.36	25.49	13.62
	Islands	52.63	19.47	0.85	0.09
	Trans-Himalaya	61.93	58.12	48.95	42.03
	Semi-Arid	42.35	31.55	14.88	6.76
	North-East	47.01	34.86	16.41	9.10
Total		19.03	12.24	4.44	1.96
Reptiles 	Coasts	50.36	43.19	27.14	19.28
	Western Ghats	16.80	11.80	4.45	1.72
	Deccan Peninsula	56.14	54.95	50.62	44.25
	Himalaya	74.59	70.83	66.03	62.94
	Desert	7.43	4.64	1.93	0.58
	Gangetic Plain	69.53	66.02	24.08	15.28
	Islands	46.59	45.89	44.29	43.21
	Trans-Himalaya	18.43	16.52	12.27	9.42
	Semi-Arid	80.03	77.51	45.31	25.97
	North-East	29.01	25.33	17.91	14.04
Total		68.09	64.90	38.37	12.14
Insects 	Coasts	90.64	87.88	67.71	44.85
	Western Ghats	84.54	71.43	28.08	8.41
	Deccan Peninsula	78.96	75.15	62.76	49.64
	Himalaya	95.58	92.70	72.24	48.41
	Desert	86.06	55.44	9.34	0.64
	Gangetic Plain	77.96	77.92	41.89	8.10
	Islands	77.79	73.55	63.05	55.37
	Trans-Himalaya	76.71	66.67	46.85	40.84
	Semi-Arid	87.39	77.36	38.03	20.98
	North-East	83.38	71.52	38.69	23.10
Total		47.01	34.86	16.41	9.10

Table 5. 2 Percentage of climate-change refugia protected by PAs.

taxa	Biogeographic Zone	1.5°C	2°C	3°C	4°C
Birds	Coasts	32.96	23.08	0.14	0.00
	Western Ghats	66.94	61.11	38.81	22.12
	Deccan Peninsula	22.25	10.39	1.89	0.76
	Himalaya	75.89	73.56	66.59	59.52
	Desert	2.00	0.36	0.00	0.01
	Gangetic Plain	14.62	9.27	2.71	1.19
	Islands	56.17	33.49	5.16	0.50
	Trans-Himalaya	79.44	76.62	69.06	63.29
	Semi-Arid	27.79	15.18	2.34	0.53
	North-East	14.81	9.42	4.48	2.66
Total		42.74	35.41	26.06	22.14
Amphibians	Coasts	38.40	38.39	38.32	38.09
	Western Ghats	41.47	41.47	41.47	41.47
	Deccan Peninsula	65.21	60.25	54.66	50.50
	Himalaya	60.82	59.96	57.32	54.00
	Desert	48.27	46.61	45.61	45.61
	Gangetic Plain	80.18	79.99	77.47	73.64
	Islands	59.77	59.77	59.77	59.76
	Trans-Himalaya	16.10	16.01	15.88	15.71
	Semi-Arid	55.01	54.10	50.16	49.60
	North-East	64.63	57.60	20.73	12.95
Total		39.05	38.11	34.67	32.58
Mammals	Coasts	14.22	13.03	5.24	2.85
	Western Ghats	67.03	62.96	45.47	30.51
	Deccan Peninsula	48.16	38.20	26.23	18.32
	Himalaya	74.42	72.02	64.14	57.08
	Desert	83.82	83.82	83.82	60.35
	Gangetic Plain	50.00	46.56	45.43	36.04
	Islands	58.72	34.77	3.63	0.41
	Trans-Himalaya	81.67	79.11	71.71	64.63

	Semi-Arid	73.65	70.78	55.98	31.22
	North-East	43.49	24.25	10.09	5.56
Total		63.15	57.46	47.39	36.88
Plants	Coasts	33.67	27.65	0.40	0.16
	Western Ghats	59.08	49.58	24.87	13.38
	Deccan Peninsula	34.61	24.36	6.83	1.72
	Himalaya	71.28	67.75	59.68	51.50
	Desert	66.11	63.54	55.23	32.45
	Gangetic Plain	20.36	7.87	2.40	1.61
	Islands	24.89	14.34	1.68	0.20
	Trans-Himalaya	77.49	74.07	63.61	55.33
	Semi-Arid	52.76	43.06	24.55	18.46
	North-East	19.53	11.02	4.65	2.44
Total		52.01	44.66	30.34	23.04
Reptiles	Coasts	15.17	2.42	0.57	0.51
	Western Ghats	55.02	51.31	41.89	32.68
	Deccan Peninsula	19.41	12.82	4.12	2.70
	Himalaya	63.55	62.94	60.68	58.23
	Desert	45.23	35.20	20.80	20.64
	Gangetic Plain	11.19	9.81	7.57	4.74
	Islands	59.77	59.10	46.14	43.94
	Trans-Himalaya	63.99	63.44	61.94	60.61
	Semi-Arid	7.50	6.62	4.56	3.80
	North-East	76.99	73.88	42.66	17.46
Total		38.83	34.95	28.29	25.37
Insects	Coasts	68.05	67.41	37.17	3.99
	Western Ghats	87.77	83.90	59.61	35.25
	Deccan Peninsula	77.02	65.60	24.57	5.81
	Himalaya	83.99	81.76	74.54	66.58
	Desert	97.99	97.43	69.34	60.84
	Gangetic Plain	82.65	44.82	12.97	3.01
	Islands	78.05	78.05	28.12	8.08

	Trans-Himalaya	84.77	82.20	72.89	64.75
	Semi-Arid	78.31	68.15	41.36	37.45
	North-East	91.16	69.43	21.54	7.37
Total		82.17	73.85	47.18	33.70

- **Validation of the Wallace initiative modelling data:**

Wallace initiative data is a global database, to validate whether a country-scale analysis will produce the same result, an additional validation step was taken. Presence records of 1033 bird species in India from GBIF, updated version of climatic projections (i.e., Worldclim 2.1 data based on Shared Socioeconomic Pathways (SSP) and applied the dataset to MaxEnt to predict distribution range maps of each species at present and projected it to mid-century (2041-2060) and end of the century scenarios (2081-2100). These analyses were performed to check whether a country-scale analysis produced similar results, validating the robustness of Wallace initiative data.

Materials and methods:

Location data

1,67,48,412 occurrence (presence-only) data were downloaded for Indian birds from the start of 2000- End of 2020 global biodiversity information facility (GBIF) (http://www.gbif.org). GBIF is the largest international network and data infrastructure funded by the world's governments providing open access data about all types of life on Earth. Records were cross-checked after downloading to ensure species identification information.

Data downloaded from GBIF are often biased and clustered leading to model overfitting as citizen science data does not always meet the requirements of systematic sampling. "Spatially rarefy tool" in SDMtoolbox in ArcGIS 10.8 was used and a single record per 2.5 arc min grid were retained to remove duplicate points and minimize potential spatial clusters in the presence locations. This data cleaning process has been proven to effectively match the results of the MaxEnt model and improve model performance. After rarefication species records were selected with at least 15 presence locations. Finally, 8,27,212 rarefied presence locations were used to models potential distributions for 1033 bird species. Total distribution range were modelled rather than considering only the breeding sites, because if only breeding sites are considered, many wintering habitats for required these birds may be omitted from the conservation planning and these crucial habitats may face serious threats.

Bioclimatic variables

To predict the response of species distribution to future climate change, it is necessary to select appropriate variables to construct species climate niches by considering the complex interactions among bioclimatic variables. All bioclimatic variables of Current and future climatic raster data were downloaded in Geotiff format from Worldclim V2.1.

(www.worldclim.org). Current climatic data are average for the years 1970-2020 and downloaded at a spatial resolution of 2.5 arc-mins to match the finest available data for future climatic scenarios. Future climatic data of MIROC-E2SL Global Circulation model (GCM) were downloaded for mid-century, i.e., 2041-60 and end of the century, i.e., 2081-2100 of three different Coupled Model Intercomparison Project Phase 6 (CMIP6) based Shared socioeconomic pathways (SSPs) (i.e., SSP1-2.6, SSP2-4.5, and SSP5-8.5). SSPs are a new set of emissions scenarios driven by different socioeconomic assumptions. We selected bioclim variables (warren *et al*., 2017) that represents annual trends (BIO1 = Annual Mean Temperature, BIO12 = Annual Precipitation) seasonality (BIO4 = Temperature Seasonality, BIO15 = Precipitation Seasonality) and extreme environmental factors (BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter)

Distribution modelling

MaxEnt 3.4.1 was used to model potential climatic niche of species using the filtered presence-only data and selected environmental variables. Maxent provides robust results by implementing a machine learning approach for presence-only data. The model established based on cross-validation by 10 replicates (each replicate used 70% of the data for training and 30% of the data for test) for each bird with Cloglog output. AUC values were used as the measure of our model performance. Where an AUC value >0.7 is considered an indicator of good performance in Maxent and models that met these criteria was used in the final analysis. Cloglog transformation is an updated algorithm in MaxEnt 3.4.1 for estimating the probability of presence by yielding a Bernoulli generalized linear model based on the Poisson distribution. Compared with the traditional Logistic transform used in previous MaxEnt versions, Cloglog transformation can improve model performance to reduce the effects of sample selection bias while maintaining the same area under the receiver operating characteristic curve (AUC) value. The background in MaxEnt was set as the entire land area of India for all species. After modelling the distribution range in the current scenario, we projected the model with different GCMs for four SSPs (i.e., SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5). The average Cloglog output for each bird and scenario was used to prepare the potential distribution of the species. The maximum test sensitivity plus specificity (MTSS) values for each species were used as thresholds to convert Cloglog raster outputs to “presence (1)/ absence (0)” binary maps, named predicted distribution range maps (DRMs). Next, using the individual binary maps, we calculated species richness of birds of under present and each future scenarios were calculated in SDMtoolbox in ArcGIS. To measure the effect of climate change on the shift direction of the distribution, species range-shift of each species was estimated using Centroid change estimation tool in SDMToolbox.

Results:

By overlaying the DRMs of the current scenario, species richness map of birds in India was prepared for current and future scenarios (Figure 5. 9- Figure 5. 12). The bird richness maps produced results similar to the Wallace initiative data, with areas acting as refugia in the western ghats, Himalayas, and the North-east. The endemicity is found higher in North-east, Andaman-Nicobar and Himalayan region. Although Andaman-Nicobar Islands had lower species richness compared to the mainland, highest CWE (Cost Weighted Endemism) (5.17), i.e., areas with range restricted species were found in these islands.

After incorporating climate scenarios into the model, it was found that the richness pattern of bird species in India changed significantly (Figure 5. 10 - Figure 5. 12). Overall, bird species richness will increase in Himalayan, North-east and western ghats region, and decrease in desert region, semi-arid region, Indo-Gangetic plains, and part of the deccan peninsula, under all future scenarios, i.e., SSP 126, 245, and 585 (original richness maps considering climate change are shown in Figure 5. 10- Figure 5. 12).

For the SSP126 scenario (Figure 5. 10), increase in species richness is mainly in are in 1) East and West Himalayan regions, 2) Northeast, 3) Western ghats. Areas where species richness predicted decrease, include 1) Semi-arid, 2) desert, and 3) few parts of the Deccan peninsula. With the increase in SSP scenarios, the richness in the above-mentioned areas is decreasing gradually. In end of the century (2081-00) under SSP585 scenario (Figure 5. 12), there is a drastic decline in species richness in desert, semi-arid, Gangetic plains and deccan peninsula. The decline in species richness is comparatively less in Himalaya (east and west), North-east and western ghats biogeographic zone.

In present, species endemism (WE) is highest in North-east region and Andaman & Nicobar Islands, followed by Indian Himalayan region, and CWE map shows species with restricted range is highest in Andaman Nicobar Islands. In SSP585 (2081-2100), apart from a high CWE value was observed in Trans-Himalayan regions as well.

Among the 1033 modelled species, displacement vectors of each bird species range are mapped over the geographical scope of India to understand the detailed spatial patterns of range shifts under in four different scenarios and two temporal scale. This result shows that the northward shift of the distribution range may be a holistic trend (Figure 5. 13). Himalayan species shows an overall Northwest direction. Species from Northeast India shows Northeast shift towards hills. Species from Western ghats shows an overall southern shift towards hills.

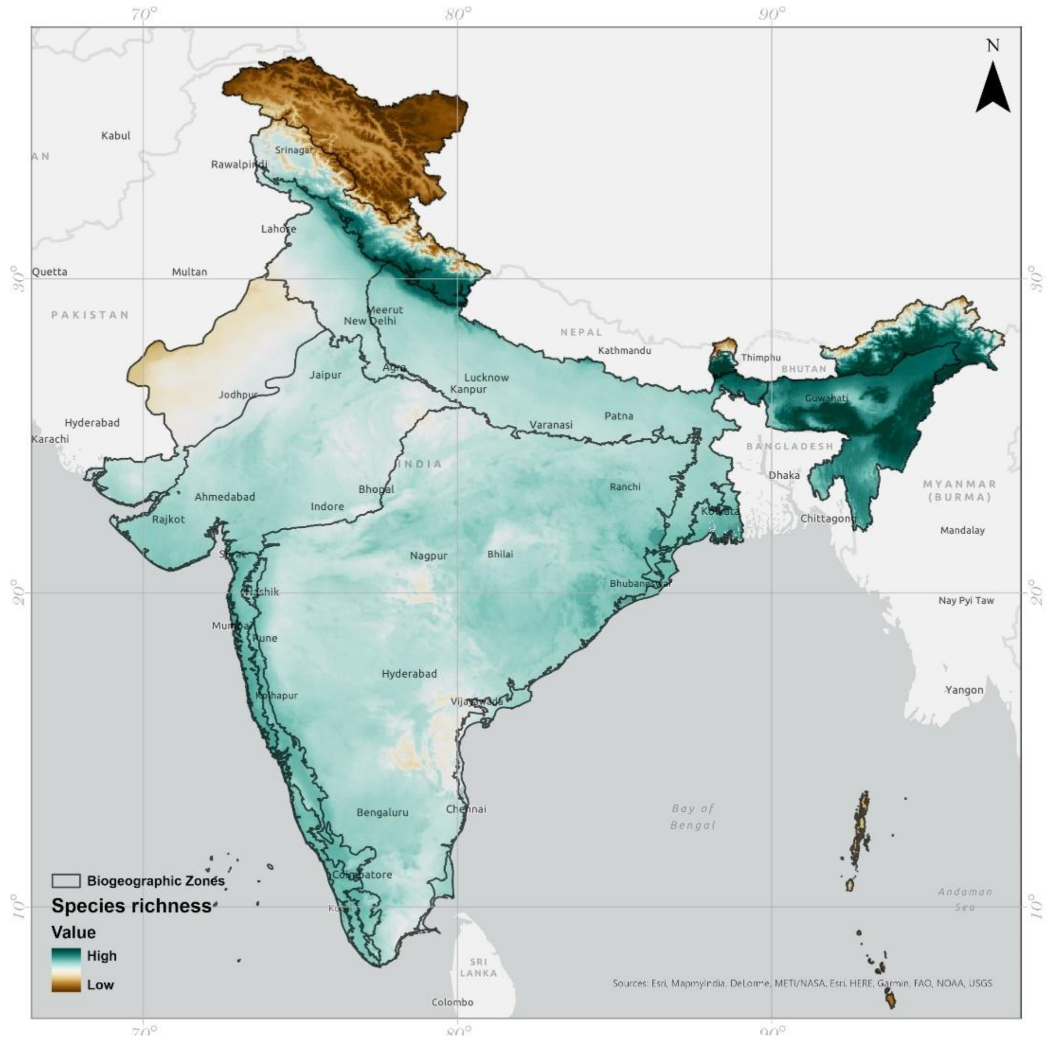


Figure 5. 9 Current richness patterns of birds of India.

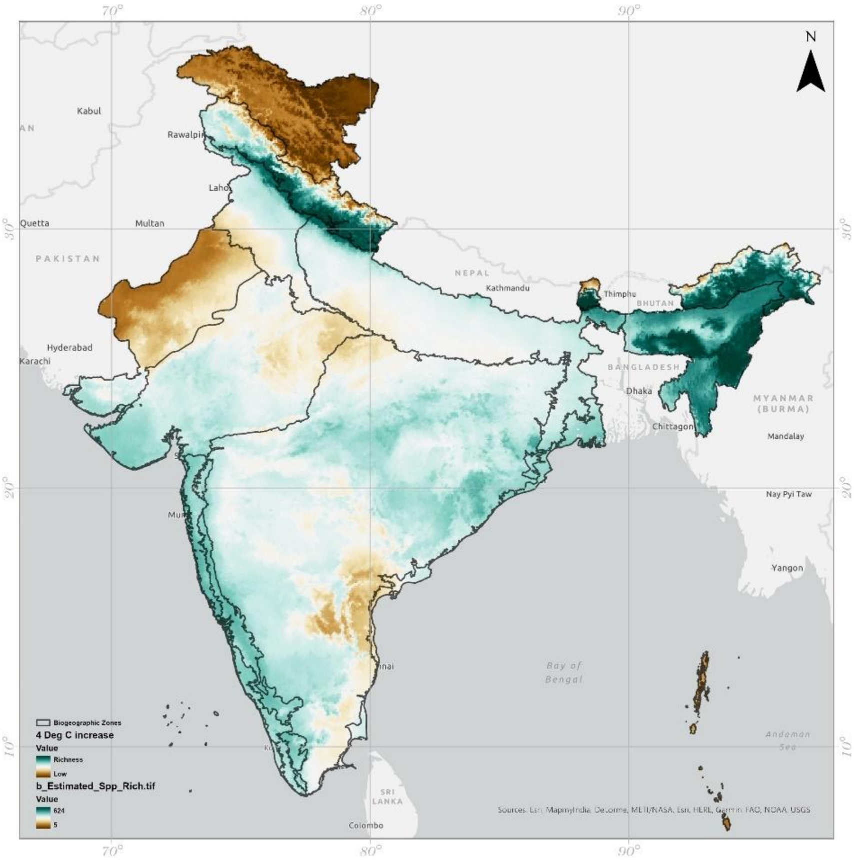


Figure 5. 10 Bird richness pattern at SSP126 2081-2100.

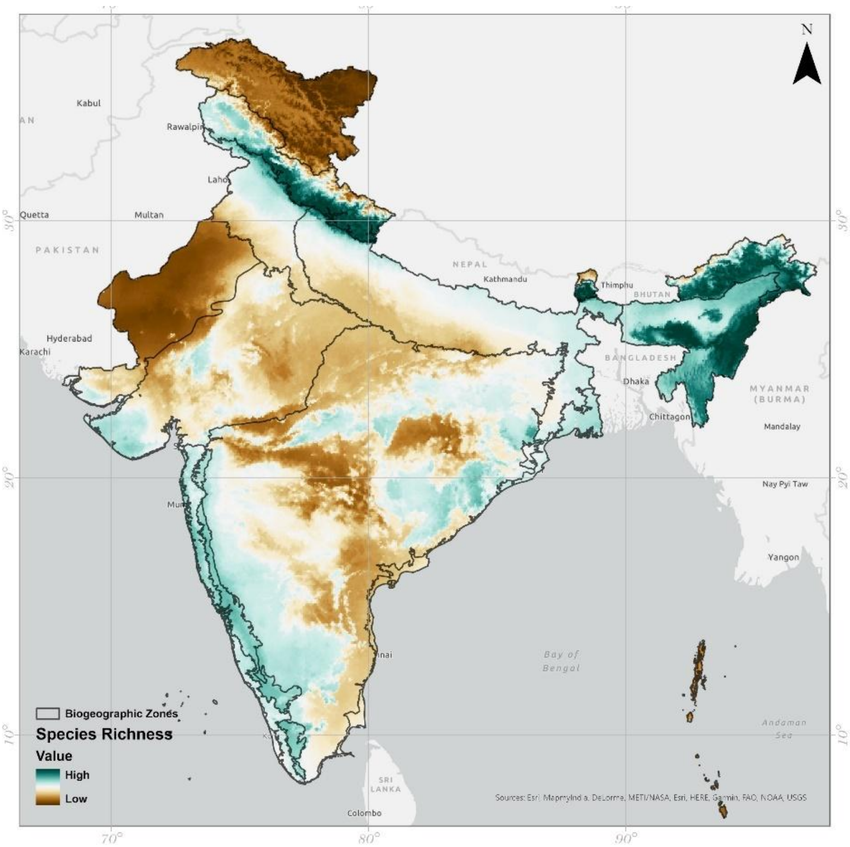


Figure 5. 11 Bird richness pattern at SS245 2081-2100.

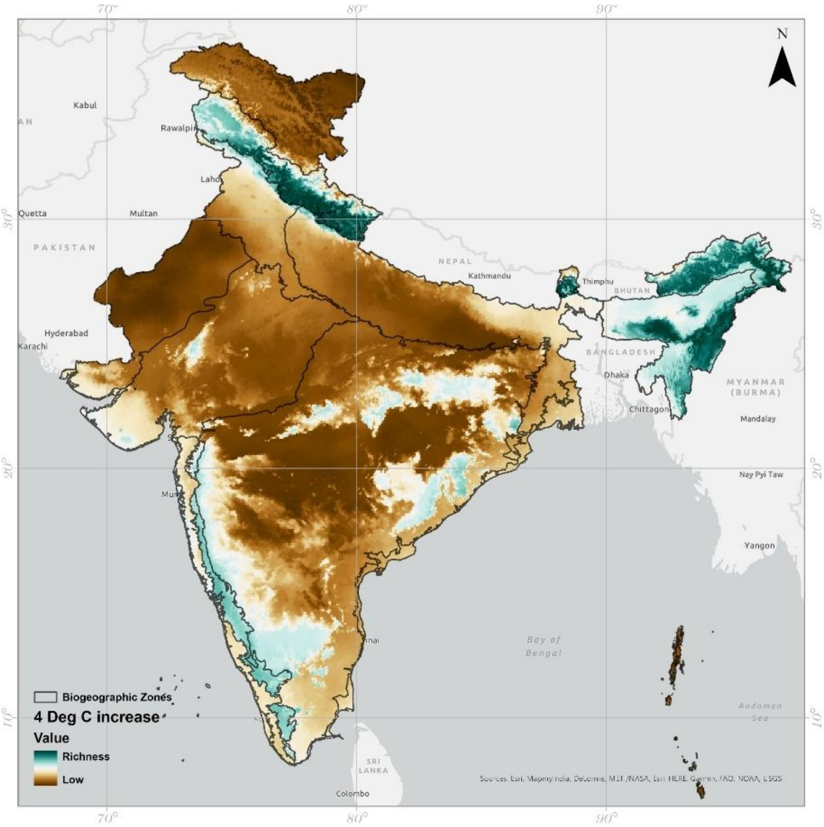


Figure 5. 12 Bird richness pattern at SSP585 2081-2100.

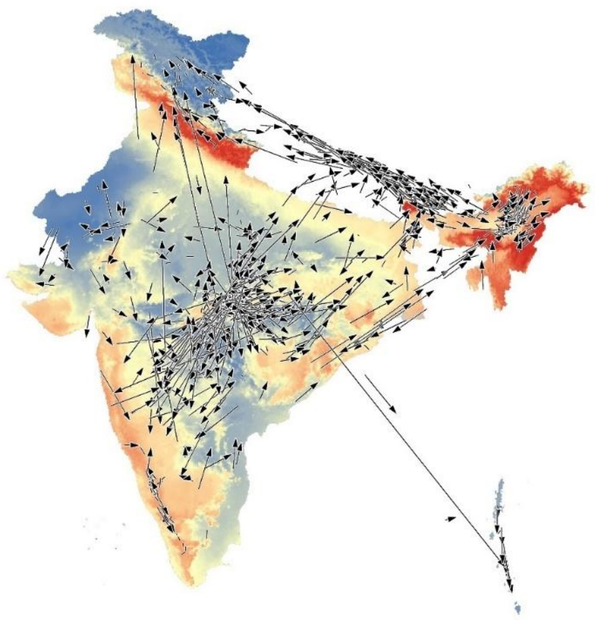


Figure 5. 13 Centroid shift of the distribution of birds.

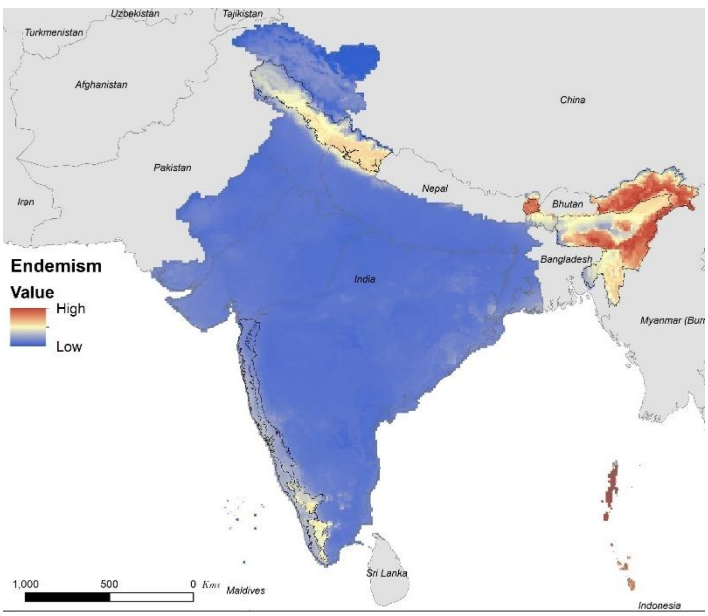


Figure 5. 14 Cost-weighted endemism of Indian birds. Red represents higher endemicity.

5.4. Discussion

The results underscore the critical importance of limiting global warming to 1.5°C to preserve significant portions of biodiversity refugia across India. The Himalayas, Western Ghats, North-east, islands, Gangetic plains, DP, and desert regions all show varying degrees of vulnerability, with notable declines in refugia areas as temperatures rise. The findings highlight the urgent need for robust climate action and effective conservation strategies to protect these vital ecosystems and the myriad species they support. Conservation efforts should prioritize areas projected to remain as refugia across various warming scenarios to enhance the resilience of biodiversity in the face of climate change.

Himalaya has highest refugia area for birds, followed by Trans-Himalaya, Islands and Western Ghats. Even with 4°C warming, climate-change refugia for birds and mammals in Himalaya and Trans-Himalaya is identified. If these areas remain climatically suitable as temperatures increases to 4°C, management interventions will aid in the conserving species existing in these zones. On the other hand, climate-change refugia in Western ghats, North-East and Islands projected to decrease beyond 2°C, indicating the implications of limiting the warming in these zones. These zones are inhabited by a variety of endemic species, and the disappearance of refugia suggests an increased threat to these species in the future. As an example, there is more than 50% decline in the bird refugia in Western ghats and islands if warming is not limited to 2°C.

Limiting 2°C warming has been projected beneficial for insects in Gangetic plains. more than 50% of desert zones will remain suitable for reptiles under all warming conditions. For mammals, major decline (<20%) is projected in coasts and islands zones in a 3°C warming scenario. If the temperature rise is limited to 1.5°C, all biogeographic zones will have at least 40% areas as refugia for plants. Whereas, with business-as-usual scenario (4°C), only the Himalaya and Trans-Himalaya will have more than 30% land as plant refugia. Plants may be especially vulnerable to climate change. Changes in plants refugia are likely to have a multiplier effect on the animals that rely on them for food and shelter.

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Chapter 6
Synthesis

Chapter 6. Synthesis

This chapter presents as final remarks of this thesis the key messages of this research, and then an overall discussion followed by the overall conclusions. The key messages represent the main findings of the thesis relevant for the comparison between narratives that consider an increase in the global annual mean temperature of 1.5ºC and 2.7ºC above pre-industrial levels. These two levels of future warming were chosen to represent the ultimate temperature goal of the Paris Agreement (‘to pursue efforts to limit warming to 1.5ºC’) and 2.7ºC corresponding to the more optimistic interpretation of the current NDCs pledges, and to simplify the discussion presented here. The discussion covers the state of the art of the nexus of climate change, biodiversity conservation and land use in India, how this research has contributed to and advanced this field, questions that are left unanswered, and the main caveats. Finally, the conclusion section of this chapter shows how this thesis is successful in achieving its overarching aim and specific objectives.

Key messages

- **significant research gap in smaller taxa such as amphibians, reptiles, fishes, and fungi, urging more studies on these underrepresented groups. It emphasizes the need for increased research on the impacts of climate change on biodiversity, especially within protected areas, to inform effective conservation strategies.**

A significant disparity in the study of various taxa, emphasizing that taxa such as amphibians, reptiles, fishes, and fungi are less studied compared to plants, birds, and mammals (Figure 1. 2.). This taxonomic bias, is reflected in databases like the Global Biodiversity Information Facility (GBIF), restricts our understanding of biodiversity and ecological patterns, particularly for less represented species. To address this gap, there is a pressing need to promote research on these underrepresented taxa, possibly through citizen science initiatives, which can significantly contribute to ecological databases. he critical importance of focusing more studies on the impacts of climate change. Current research indicates that climate change is projected to have overwhelmingly negative effects on native and migratory species in India, with notable shifts and contractions in habitat ranges, particularly in the Himalaya and Western Ghats. Conversely, invasive species are expected to expand their ranges, potentially leading to the emergence of novel ecosystems with unpredictable consequences for human well-being and biodiversity. Protected areas (PAs) play a vital role in mitigating the impacts of climate change on biodiversity. These areas not only serve as refuges for species but also provide essential ecosystem services such as carbon sequestration and temperature regulation. However, the document stresses the need for more focused research on the impacts of climate change on species within these protected areas, considering both global and local scales. This research is crucial for informing conservation management and policymaking, ensuring that PAs can effectively preserve biodiversity and maintain ecosystem resilience in the face of climate change.

- **Dry biogeographic zones in India are getting wetter, and wet biogeographic zones are getting drier. Climate drivers such as precipitation and temperature are correlated to changes in vegetation. And with an increase of EVI, evapotranspiration is also increasing in different biogeographic regions and within protected areas.**

The observed climatic shifts in India's biogeographic zones reveal a trend where traditionally dry regions are experiencing increased precipitation, while typically wet areas are facing a decline in rainfall (Figure 3. 5). In semi-arid regions such as Northwest India and parts of South India, significant greening trends have emerged (Figure 3. 7), driven by rising precipitation levels and enhanced agricultural practices. This greening is indicative of a shift towards wetter conditions in these areas. Conversely, regions historically characterized by high rainfall, such as the Northeast and the Western Ghats, are witnessing a decrease in precipitation (Figure 3. 5) and evapotranspiration (Figure 3. 6), leading to browning trends and a reduction in vegetation cover. This drying trend in wet biogeographic zones suggests a complex interplay of climatic factors, possibly exacerbated by anthropogenic influences and global climate change. The resulting shifts in water availability and vegetation dynamics underscore the need for adaptive management strategies to mitigate the impacts on ecosystems and local communities. These contrasting trends highlight the intricate and region-specific responses of vegetation to changing climatic conditions, necessitating a nuanced approach to conservation and resource management in India's diverse ecological landscape.

- **Smaller protected areas (PAs) in India are more vulnerable to climate change. Also, Indian PAs located in higher elevation are more climatically exposed.**

Smaller PAs in India exhibited heightened climate vulnerability due to their limited climate space, reduced habitat heterogeneity, and higher sensitivity to climatic changes, which increase the risk of species extinction and reduce resilience. For instance, smaller PAs in the Himalaya zone, like City Forest National Park, are more vulnerable compared to larger counterparts such as the Khangchendzonga National Park (Table 4. 3). Similarly, in desert zones, larger PAs like Kachchh Wildlife Sanctuary are less vulnerable than smaller ones like Bir Jhunjhunu Conservation Reserve Table 4. 8. Additionally, protected areas located at higher elevations face greater climatic exposure due to significant changes in climatic conditions, leading to higher exposure scores (Figure 4. 14). These high-elevation PAs, such as those with Shola habitats in the Western Ghats, including Pambadum Shola and Mathikettan Shola National Parks, are particularly susceptible. This increased climatic exposure correlates with the elevation, indicating that higher elevation PAs experience more pronounced climate changes. These findings highlight the need for targeted conservation strategies to address the unique challenges of smaller and higher elevation PAs, emphasizing habitat connectivity and mitigation of external threats to enhance resilience.

- **The amount of area available for climate-change refugia for biodiversity decreases as global mean temperature rises.**

The Himalayas, Western Ghats, and North-East India are projected to become crucial climate-change refugia for biodiversity with rising temperatures (Figure 5. 5). In the Himalayas, significant areas will remain refugia for various taxa even under moderate warming scenarios, with key Protected Areas retaining over 90% of their areas as refugia at all warming levels (Figure 5. 6). The Western Ghats will have substantial refugia at 1.5°C warming (Figure 5. 6), though this declines rapidly beyond that point, particularly affecting endemic species. North-East India will maintain at least 30% of its land as refugia at 1.5°C, but this also decreases significantly at higher temperatures (Table 5. 1). Limiting the global temperature increase to below 2°C is essential for preserving these refugia, maintaining ecosystem stability, and ensuring the survival of numerous species. Beyond 2°C, the areas acting as refugia for multiple taxa decline drastically, emphasizing the need for effective conservation and management strategies to protect these vital ecosystems and the biodiversity they support.

Contribution to the field

This research utilizes satellite-derived Enhanced Vegetation Index (EVI) time-series data spanning from 2000 to 2022. This analysis, focusing on various biogeographic zones of India, identifies greening and browning trends and correlates these with climatic variables such as temperature, precipitation, and evapotranspiration. The study's findings reveal that most of India exhibits a greening trend, primarily driven by croplands, while regions like Northeast India and the Himalayas show browning trends due to decreased precipitation and increased temperature, leading to moisture stress. By employing statistical methods, including the Mann-

Kendall test and Generalized Additive Models, the research provides robust insights into the spatial and temporal patterns of vegetation changes in India and their relationship with climatic drivers.

The research also provides first comprehensive assessment of the climate change vulnerability of protected areas (PAs) in India in all biogeographic zones. This research fills a critical gap in terms of impact of climate change on Indian PAs, by delivering a national perspective specific to India's diverse biogeographic zones and its vast network of PAs. The study employs the Climate and Ecological Niche Factor Analysis (CENFA) approach to quantify the sensitivity, exposure, and vulnerability of 505 PAs across various climate scenarios. By identifying the most vulnerable and resilient PAs, the research offers valuable insights for adaptive management strategies tailored to mitigate climate change impacts. This localized assessment is essential for developing effective conservation policies that align with both national priorities and global commitments. The findings highlight the varying degrees of climate change threats across different regions and the necessity for targeted interventions to preserve biodiversity and ensure the long-term effectiveness of India's PA network.

Furthermore, this study is one of the first comprehensive, country-level analysis aimed at identifying climate-change refugia for terrestrial biodiversity across various taxonomic groups in different biogeographic zones of India. Utilizing data from the Wallace Initiative database, the research delineates potential future refugia for six taxa (amphibians, birds, insects, mammals, plants, and reptiles) under multiple climate scenarios (1.5°C, 2°C, 3°C, and 4°C above pre-industrial levels). By mapping these refugia to 20x20 km grid cells, the study provides detailed insights into the areas, most likely to sustain biodiversity in the face of climate change. The findings are intended to guide policymakers in making informed, science-based decisions for biodiversity conservation on both national and regional scales, addressing the urgent need for strategic planning in the face of ongoing and future climate impacts. This work underscores the importance of integrating climate change projections with land-use practices to develop effective conservation strategies that can protect India's rich and diverse ecosystems.

Limitations

There are several relevant factors that have not been included in this analysis due to the spatial scale used in the Wallace Initiative database. These factors include the potential spread of disease pathogens and pests, interactions between species (food availability, predator-prey relationships and competitive interactions). the effects of extreme climatic events, and the direct biotic effects of increases in CO2 concentrations on plants. In addition, many species, especially narrow-ranged endemic species, are not included in the Wallace Initiative database. Narrow-ranged species are generally sensitive to climate change, so many of the endemic species not included in this analysis will also be vulnerable to the effects of global temperature rise. Species with fewer than 10 data points (occupied grid cells) were excluded from the Wallace Initiative database in order to maintain a robust analysis. Despite these limitations, the Wallace Initiative fulfils many of the criteria recently set out as contributing to best practice in species distribution modelling. GBIF data combines many datasets worldwide and the data was further cleaned (checked for locational consistency and outliers) before use. Commission errors were accounted for by clipping species to their biogeographic zones and omission errors were taken into account by generous buffers around species distributions. Furthermore, uncertainty is taken into account by considering a range of GCMs and dispersal rates.

There are some general limitations with species distribution models which should also be considered. In some cases, there is not sufficient data available to fully inform the model as to the true distribution of a species. Datasets used to drive the SDM are often biased because of an unequal sampling effort across the study area. SDMs can be overfitted, which can lead to flawed outputs by limiting the model's capacity to generalise. During the development of the Wallace Initiative, a reduced set of variables was used to minimize potential autocorrelation. SDMs cannot include and account for all biotic and abiotic factors. Even though various uncertainties exist, SDMs are extremely useful for examining the future impacts of climate change on species. This knowledge is fundamental for policymakers and conservation planners.

Final remarks:

There are evident benefits of limiting warming to 1.5°C for conserving India's biodiversity. Earlier studies have discussed the risks of higher warming to biodiversity in terms of climatic range loss which correlates with this study (Foden *et al.*, 2013; Price *et al.,* 2018). Limiting global temperature rise to 2°C could avoid around 60% of global climatic range loss compared to higher (3.6–4°C) warming (Warren *et al.,* 2013). A trait-based analysis of birds, amphibians, and corals discovered that a large proportion of them were extremely vulnerable to 2°C warming (Foden *et al.,* 2013).

The rate of climate change will also have an impact on biodiversity. Few species will have time to disperse and adapt if temperature thresholds are crossed too soon. Birds and mammals experience the greatest population declines in areas that have experienced the most rapid warming, with birds having a stronger relationship (Spooner *et al.,* 2018). Furthermore, decision-makers will have less time to facilitate movement, such as by expanding PAs or creating corridors (Price *et al.,* 2018). A slower rate of warming allows for more time for conservation action, as well as natural processes of dispersal and, in some cases, evolutionary change (Lavergne *et al.,* 2010). This emphasises the importance of mitigation for biodiversity preservation, as mitigation 'buys time' for adaptation. Stringent climate change mitigation goals, together with strategic incorporation of refugia into land management, will enable achievement of forward-looking conservation targets in India.

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and presented a talk titled:

"Climate change and Indian avifauna "

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REVIEW PAPER

A systematic review on the potential impact of future climate change on India's biodiversity using species distribution model (SDM) studies: trends, and data gaps

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Abstract
Species Distribution Modelling (SDM) is used to identify a species' potential current and future distribution. While numerous global studies have reported species distribution changes in various future climate change scenarios, regional relevance has often been overlooked. In this study, we conducted a systematic literature review to assess the future climate change impacts on India's biodiversity across all biogeographic zones. Our findings revealed a significant increase in research on climate change related SDM after 2015. These studies were published mainly in ecological, and biodiversity conservation journals. We found that (a) The Himalayan region is the most studied biogeographic zone (n = 49), followed by the Western Ghats (n = 15). (b) Plants are the most studied taxa (n = 77), followed by invertebrates (n = 11). (c) Gaps in the literature regarding the climate change impacts on the distribution of amphibians (n = 2) and reptiles (n = 1), and studies specific to Islands (n = 0) and Coastal (n = 2) biogeographic zones. (d) 60% of studies did not mention or calculate uncertainties arising from data gaps and model parameters. We highlight the need for more studies dedicated to lesser-studied taxa. We recommend that in the future the quality of SDM-related studies be critically reviewed to ensure that they are reproducible.

Keywords SDM · Biogeographic zone · Data gaps · ENM · Climate envelope modelling · Climate change

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Predicting the impact of future climate changes and range-shifts of Indian hornbills (family: Bucerotidae)

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ABSTRACT

Climate change influences species distribution and is regarded as a major threat to biodiversity. Hornbills (Family: Bucerotidae) are large tropical birds in Asia and Africa. They are seed dispersers known as forest farmers because they help maintain the ecological community structure by allowing forest regeneration. They are keystone species, and their presence in a forest implies a healthy ecosystem. Range shifts due to climate change is a serious threat because their long-term survival is already imperilled by anthropogenic disturbances. This study models the current and future potential climatic niches of eight of the nine hornbill species present in India. We used GBIF-mediated species presence records along with eight WorldClim V2.1 bioclimatic variables to model the current climatically suitable areas and projected it into the future (mid-century, i.e., 2041–60 and end of the century, i.e., 2081–2100) for different CMIP6 based Shared Socioeconomic Pathway (SSPs) (i.e., SSP126, SSP245, 370 and 585). Range shifts, centroid changes, and the impact of current land use practices for each of the eight species under various climatic conditions were also examined. The Area Under Curve (AUC) values for final models ranged between 0.736 and 0.994. Result indicates that majority of species' climatic niche shift is towards the west, followed by northwest and northern shifts. The species are expected to lose >40% of their suitable present climatic niche under the SSP 585 scenario in 2081–2100. Natural areas were found to be climatically suitable for hornbills throughout the study area, implying the merit of conserving their existing habitats. Our research provides detailed information on how the distribution of Indian Hornbills may change because of future climatic conditions. Detailed spatial and temporal distribution and range shift patterns will aid in a targeted approach for conserving hornbills and their habitat in a changing climate.

1. Introduction

There are numerous anthropogenic pressures on the world's biodiversity that are leading to the extinction of species (Alkemade et al., 2009; Ripple et al., 2017). Because of human-induced climate change, ecosystem services and ecosystem functioning may change (Intergovernmental Panel on Climate Change, 2021; Mooney et al., 2009). According to the Intergovernmental Panel on Climate Change (IPCC) climate projections, there will be at least a 1-degree temperature rise between 2030 and 2050 from the preindustrial level (IPCC, 2021). Climate change can cause a variety of effects on biodiversity, including fluctuations in populations (Graae et al., 2018), species phenological changes (Visser and Both, 2005), range shifts (Lenoir and Svenning, 2015), rapid alterations in species assemblage and richness (Steinbauer et al., 2018), and local extinctions (Bosso et al., 2022; Panetta et al., 2018). Endangered species may become trapped in landscape patches because they are less likely to be able to latitudinally or altitudinally change their habitat (Freeman et al., 2018). Understanding the effects of climate change on species diversity is critical for developing long-term conservation strategies (Ali et al., 2021; Jenkins et al., 2021; Jones et al., 2013; Range et al., 2019). Ecological niche modelling (ENM) aid us in determining the connection between species occurrence and environmental variables. (Jose and Nameer, 2020). It also aids in predicting a species' previously unknown habitats (Elith et al., 2011; Paul et al., 2020).

Hornbills are regarded as one of the most significant bird species in Africa and Asia's tropical and subtropical forests (Sun et al., 2019). Hornbills are large-bodied birds in the Bucerotidae family, with 31 of the 59 surviving species found in the Asian continent (Franco and Minggu, 2019). Apart from being a flagship species owing to their striking appearance and interesting nesting behaviour, which involves the female imprisoning herself within a large tree cavity (Poonswad, 1993),

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