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Assessing Species Vulnerability to Climate Change in Tropical Asia: Implications for Biodiversity Conservation and Forest Management

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Abstract

Global climate change is significantly altering the large scale distributions of plants and animals. The Earth has warmed by 0.7°C during the last century. The consequences are already apparent in forest ecosystems as species are responding to the changing climate with shifts in their phenology and geographic distributions. The potential for large increases in global mean temperatures (e.g., 4.3 ± 0.7°C) by 2100 has significant implications for forest species and ecosystems. Under these varying climatic conditions, some species may go extinct either locally or regionally, with climate change acting synergistically with other extinction drivers. Tropical Asian forests contain several biodiversity hotspots and species-rich ecoregions. Our understanding of species' and forest ecosystems' vulnerability to global climate change in this region is limited. Addressing this problem is a critical task for current tropical Asian ecological research.

The overall aim of this PhD thesis is to investigate the current and potential effects of climate change on the geographic distribution and composition of selected plant and mammal species in tropical Asian forests. The selected plants include Sal (*Shorea robusta*), Garjan (*Dipterocarpus turbinatus*) and Teak (*Tectona grandis*). These all are ecologically and economically important timber trees and are distributed widely across South and Southeast Asia. The selected mammals include Asiatic black bear (*Ursus thibetanus*), Asian elephant (*Elephas maximus*), Western hoolock gibbon (*Hoolock hoolock*) and Bengal tiger (*Panthera tigris tigris*). These threatened large mammals are of high conservation concern and are typically targeted by international conventions.

I present a comprehensive review of the previous literature and new predictive models of species distributions that quantify potential climate change impacts on tropical forests. My results show that projected changes in temperature and rainfall extremes are potential threats to the diverse and species-rich forest ecoregions of tropical Asia.

I used bio-climatic models and two scenarios of climate change (a moderate and an extreme Representative Concentration Pathway (RCP) scenario) to assess climate change impacts on the continental scale distributions of two threatened Dipterocarp trees Sal and Garjan, and the valuable timber species, Teak. Annual precipitation was the key bioclimatic variable for explaining the current and future distributions of Sal and Garjan. Suitable habitat conditions for Sal will decline by 24% and 34% by 2070 under the RCP4.5 and RCP8.5 scenarios, respectively. In contrast, the consequences of climate change appear less severe for Garjan, with a decline of 17% and 27% under RCP4.5 and RCP8.5, respectively. Changes in annual precipitation, precipitation seasonality and annual mean actual evapotranspiration may result in shifts in the distributions of Teak across tropical Asia. These findings can contribute to conservation planning for the species and their management under future climates.

I developed habitat suitability models for the four large threatened mammals (Asiatic black bear, Asian elephant, Western hoolock gibbon and Bengal tiger), across their entire distributions in Asia. The results suggest that changes in annual precipitation, annual mean temperature, precipitation and temperature seasonality, and land use/land cover change could reduce suitable habitat for these large mammals and therefore increase their extinction risks. It can be concluded that increasing climate stress on tropical forests could lead to greater extinction risks of these threatened large mammals.

The findings of this thesis provide a fundamental basis for further studies of climate change impacts on species distribution in tropical Asia, and highlight the conservation importance of the plant and animal species in the region. The modelling outputs can be used to categorize the natural habitats of Sal, Garjan and Teak as low to high risk under changing climates to inform conservation planning and forest management. Given the conservation importance of the threatened large mammals for maintaining a healthy forest ecosystem, the findings of the models can be used to categorize the likely suitable habitats under changing climates and preparing proper guidelines to reduce their extinction risks. To ensure wider applicability to conservation planning for species vulnerable to global climate change, the methods and analyses presented here for tropical Asia could be applied to other tropical regions (i.e., in Africa and the Americas), using different species groups and forest types.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Peer-reviewed papers:

Deb, JC, Phinn, S, Butt, N & McAlpine, CA 2017, 'The impact of climate change on the distribution of two threatened Dipterocarp trees', *Ecology and Evolution* vol. 7, no. 7, pp. 2238-2248 (Incorporated as Chapter 3).

Deb, JC, Phinn, S, Butt, N & McAlpine, CA 2017, 'Climatic-induced shifts in the distribution of Teak (*Tectona grandis*) in tropical Asia: implications for forest management and planning', *Environmental Management* vol. 60, pp. 422-435 (Incorporated as Chapter 4).

Ghose, A, **Deb, JC,** Dakwa, KB, Ray, JP & Reza, AA 2017, 'Amphibian species assemblages in a tropical forest of Bangladesh', *Herpetological Journal* vol. 27, pp. 318-325

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Conference abstracts:

Deb, J.C., Phinn, S., McAlpine, C., & Butt, N. 2016. Predicting climate suitability for three major deciduous trees and forest ecosystems in tropical Asia. In Proceedings of the 101st Ecological Society of America (ESA) Annual Conference 2016.

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Deb, JC, Phinn, S, Butt, N & McAlpine, CA 2017, 'The impact of climate change on the distribution of two threatened Dipterocarp trees', *Ecology and Evolution* vol. 7, no. 7, pp. 2238-2248 (Incorporated as Chapter 3)

Contributor	Statement of contribution
Jiban Chandra Deb	Research design/conceptualisation (90%) Data analysis/interpretation (100%) Write/edit paper (80%)
Stuart Phinn	Research design/conceptualisation (2%) Write/edit paper (5%)
Nathalie Butt	Research design/conceptualisation (4%) Write/edit paper (8%)
Clive A McAlpine	Research design/conceptualisation (4%) Write/edit paper (7%)

Deb, JC, Phinn, S, Butt, N & McAlpine, CA 2017, 'Climatic-induced shifts in the distribution of Teak (*Tectona grandis*) in tropical Asia: implications for forest management and planning', *Environmental Management* vol. 60, pp. 422-435 (Incorporated as Chapter 4)

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Nathalie Butt	Research design/conceptualisation (4%) Write/edit paper (8%)
Clive A McAlpine	Research design/conceptualisation (4%) Write/edit paper (7%)

Contributions by others to the thesis

This thesis contains four jointly authored manuscripts (two published and two submitted in different journals for peer-review). These papers are reproduced in full as chapters of this thesis (2-5). The details of contributions to this thesis are indicated below:

Chapter 1

This chapter was written by the candidate, with editorial input from Professor Stuart Phinn, Dr Nathalie Butt and Professor Clive McAlpine.

Chapter 2

This chapter is taken from a manuscript by the candidate, Stuart Phinn, Nathalie Butt and Clive McAlpine submitted in *Journal of Tropical Forest Science.* The idea for the paper was conceived by the candidate, with guidance and advice from the co-authors. The candidate conducted the literature review, meta-analysis, and wrote the manuscript with editorial input from all authors.

Chapter 3

This chapter is taken from a manuscript by the candidate, Stuart Phinn, Nathalie Butt and Clive McAlpine published in *Ecology and Evolution.* The idea for the paper was conceived by the candidate, with guidance and advice from the co-authors. The candidate carried out the analysis and wrote the manuscript with editorial input from all authors.

Chapter 4

This chapter is taken from a manuscript by the candidate, Stuart Phinn, Nathalie Butt and Clive McAlpine published in *Environmental Management.* The idea for the paper was conceived by the candidate, with guidance and advice from the co-authors. The candidate carried out the analysis and wrote the manuscript with editorial input from all authors.

Chapter 5

This chapter is taken from a manuscript by the candidate, Stuart Phinn, Nathalie Butt and Clive McAlpine submitted in *Environmental Management.* The idea for the paper was conceived by the candidate, with guidance and advice from the co-authors. The candidate carried out the analysis and wrote the manuscript with editorial input from all authors.

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Keywords

Tropical forests, climate change, species distribution modelling, phenology, forest structure, species composition, biodiversity and conservation, forest management, tropical Asia, Maximum entropy algorithm (MaxEnt)

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FoR code: 0502, Environmental Science and Management, 20%

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Acronyms

IPCC	*The Intergovernmental Panel on Climate Change*
ENSO	*El Niño Southern Oscillation*
AICZ	*African Intertropical Convergence Zone*
IUCN	*The International Union for Conservation of Nature and Natural Resources*
LBII	*The Local Biodiversity Intactness Index*
WWF	*World Wildlife Fund*
ITCZ	*Intertropical Convergence Zone*
RCP	*Representative Concentration Pathway*
NAO	*North Atlantic Oscillation*
GBIF	*Global Biodiversity Information Facility*
GHG	*Greenhouse Gas*
GCM	*Global Circulation Models*
MaxEnt	*The Maximum Entropy algorithm*
SDM	*Species distribution model*
BIO1	*Annual Mean Temperature*
BIO2	*Mean Diurnal Range*
BIO3	*Isothermality*
BIO4	*Temperature Seasonality*
BIO9	*Mean temperature of driest quarter*
BIO12	*Annual Precipitation*
BIO14	*Precipitation of driest month*
BIO15	*Precipitation Seasonality*
ACCESS1.0	*Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia*
GFDL-CM3	*NOAA Geophysical Fluid Dynamics Laboratory*
HadGEM2-ES	*Met Office Hadley Centre (contributed by Instituto Nacional de Pesquisas Espaciais)*
CMIP5	*Coupled Model Intercomparison Project Phase 5*
AUC	*Area under the receiver operating characteristic curve*
REDD plus	*Reducing Emissions from Deforestation and Forest Degradation*
ELV	*Elevation*
LULC	*Land Use/Land Cover*

AET	*Actual Evapotranspiration*
MGVF	*Maximum Green Vegetation Fraction*
NDVI	*Normalized Difference Vegetation Index*
ITTO	*The International Tropical Timber Organization*
CBD	*The Convention on Biological Diversity*

CHAPTER 1

INTRODUCTION AND SIGNIFICANCE OF THE RESEARCH

This chapter provides the general context of the research, identifies the knowledge gaps and outlines the overall thesis structure

No paper publication is associated with this chapter

1.1 Changing climates

There is increasing evidence that a wide variety of species are responding to global climate change by altering their phenology and geographical distributions (Araújo et al. 2011; Franklin et al. 2013; Oliver et al. 2009). Changes in climate will have major consequences for the distribution and functioning of forest ecosystems and their constituent biota (Nogués-Bravo & Rahbek 2011; Rosenzweig et al. 2008). Despite over 12% of the terrestrial areas of the earth being designated as protected areas (PAs), global biodiversity continues to decline at an alarming rate (Leverington et al. 2010). With the projected increase of global mean temperature by 4.3 ± 0.7°C by 2100 (IPCC 2013), many floral and faunal species are facing increasing extinction risk from climate change (Thomas et al. 2004). PAs such as national parks, wildlife sanctuaries, game reserves and other conservation sites, require total protection and good management for biodiversity conservation under changing climates (Dudley & Phillips 2006). Climate change impacts in terms of changes in the distribution, timing and intensity of rainfall and temperature may produce considerable alterations to forest site conditions and therefore, successful forest conservation and management requires a clear understanding of both the bioclimatic conditions of a site and the ecological traits of the species that live there (Falk & Mellert 2011).

1.2 Climate change impacts on tropical forests

The tropics have warmed by 0.7-0.8°C over the last century (only slightly less than the global average), and climate models predict a further 1-2°C warming by 2050, and 1-4°C by 2100 (IPCC 2013). Approximately half of the tropical forests disappeared in the past few decades, and peak deforestation during the 1990s was as high as 152,000 km^2 per year (Bonan 2008; Gibbs et al. 2010; Sarker et al. 2011). Tropical forests are at high risk due to deforestation and degradation, and the more insidious threat of accelerating climate change (Deikumah et al. 2014; Laurance 2004; Malhi & Phillips 2005; Sarker et al. 2011). The effect of forest fragmentation in tropical ecosystems can be altered in diverse ways, from local scale (e.g., increased tree mortality, canopy-gap dynamics, plant community composition, biomass dynamics and carbon storage) to regional scale (e.g., consequences for atmospheric circulation, water cycling and precipitation) (Laurance 2004). Therefore, forest-climate interactions in the tropics are complex, heterogeneous, and small changes in climate may drive large scale changes in distributions of species (Bonan 2008). Natural (e.g., El Niño Southern Oscillation, African Intertropical Convergence Zone) and anthropogenic climate factors (e.g., greenhouse gases, ozone depletion, and deforestation) are the key drivers of variability in climate change and extreme events in the tropics (Butt et al. 2015). The Intergovernmental Panel on Climate Change (IPCC) states that several projections indicate that the geographical distribution, species composition, and productivity of tropical forest ecosystems are likely to be significantly impacted by climate change (IPCC 2014). Although tropical forests are the most diverse habitats on earth (Chave 2008), the impacts of climate change on plant and animal species in this region remain poorly studied (Laurance 2004; Malhi & Phillips 2005, Pacifici et al. 2015). For instance, Pacifici et al. (2015) conducted a meta-analysis on species vulnerability to climate change and revealed over 70% of the studies involved only three continents/subcontinents, with almost 33% of the studies in North America, 24% in Europe, and 14% in Australia. In contrast, there is a paucity of studies in the most biodiverse tropical and subtropical regions of the world (Pacifici et al. 2015).Tropical forestry is confronted today with the task of finding strategies and techniques for an integrated approach to forest conservation and management in changing climatic conditions, and there is an urgent need for regional studies in these data deficient area (Montagnini & Jordan 2005).

1.3 Tropical Asian biodiversity in crisis

The climatic regimes in the Asian tropics are highly diverse (e.g., marginal tropics, monsoon tropics and aseasonal tropics) (Figure 1.1) and the effects of climate change and habitat fragmentation may result in increased risks of extinction for many plant and animal species (Corlett & Lafrankie Jr 1998; IPCC 2014). Temperature has been increasing at a rate of 0.14°C to 0.20°C per decade since the 1960s, coupled with a rising number of hot days and warm nights, and a decline in cooler weather across Southeast Asia (IPCC 2014). In East and South Asia, increasing annual mean temperature trends have been observed during the 20th century (IPCC 2014), and heavy precipitation events have been increasing in most Asian regions (IPCC 2014). The ratio of wet season to dry season rainfall increased in Southeast Asia, between 1955 and 2005 (IPCC 2014). Extreme events are increasing in frequency in the northern parts of Southeast Asia, but decreasing trends in such events are reported in Myanmar (IPCC 2014). In Peninsular Malaya, total rainfall and the frequency of wet days decreased, but rainfall intensity increased in much of the region during the southwest monsoon season (IPCC 2014). Projected climate changes also suggest a significant acceleration of warming for tropical Asia for the twenty first century (Figure 1.2). The difference map (2080-2100 compared with 1980-2000) created by averaging the three climate scenarios (RCP4.5, RCP6.0 and RCP8.5) indicates that the mean temperature, mean precipitation, mean evaporation and surface air pressure at sea level will increase in tropical Asia (Figure 1.2).

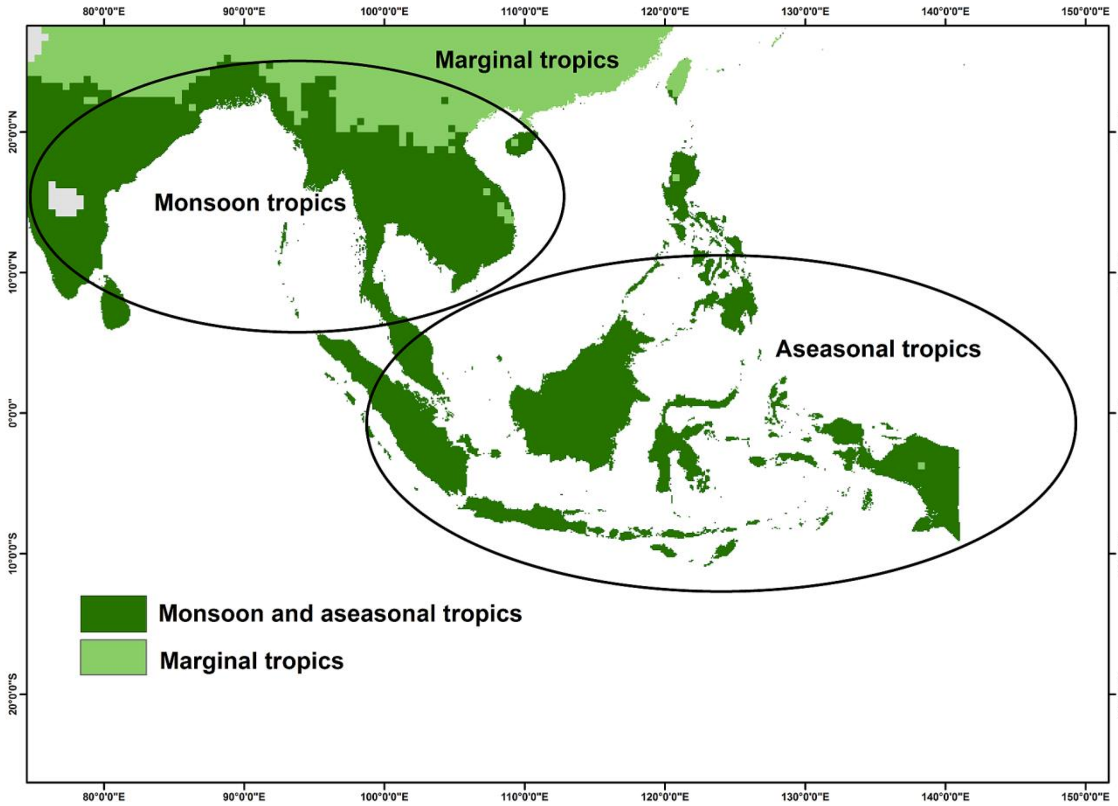

Figure 1.1 The extent of the major climatic zones of tropical Asia: marginal tropics (area indicated as light green colour), monsoon tropics (covers mostly South Asian region; dark green colour and indicated by ellipse curve), and aseasonal tropics (covers mostly the Southeast Asian regions; dark green colour and indicated by ellipse curve) (Source: Corlett & Lafrankie Jr 1998).

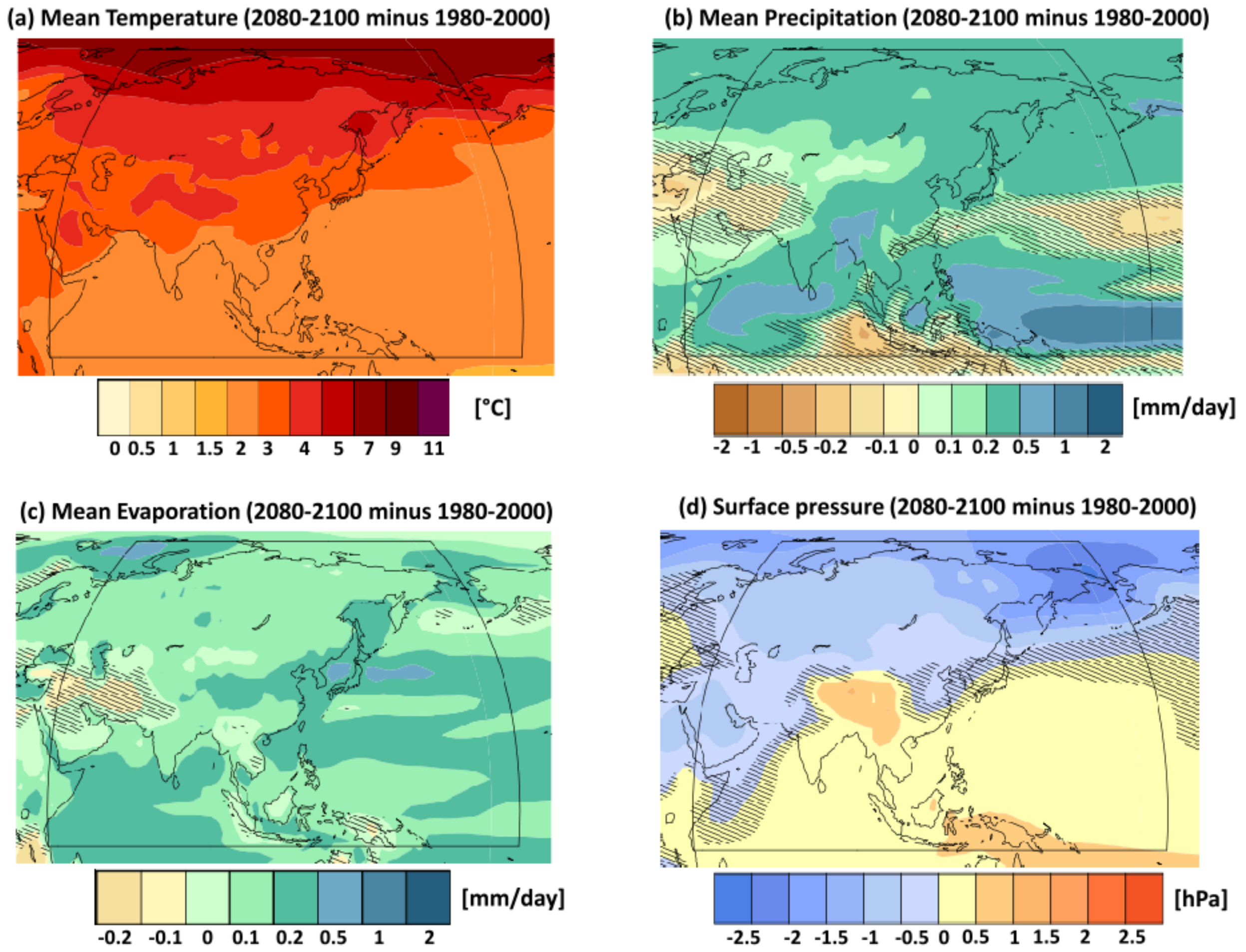

Figure 1.2 Projected increases in four climatic parameters for Asia: (a) mean temperature (Celsius); (b) mean precipitation (mm/day); (c) mean evaporation (mm/day); and (d) mean air surface pressure at sea level (hPa). CMIP5 (IPCC AR5) climate data for mean of RCP4.5, RCP6.0 and RCP8.5 scenarios, 2080-2100 compared with 1980-2000 for Asia. The results suggest an increase in all the climatic indices for tropical Asia. Source: http://climexp.knmi.nl/plot_atlas_form.py

Tropical Asia has lost more forests than other tropical regions (Deikumah et al. 2014), and is likely to exacerbate the effects of climate change on forest ecosystems and their biota. The Local Biodiversity Intactness Index (LBII) forecasts how species richness (the number of species counted at a study site) will change in the future due to the impacts of land-use change, pollution and invasive species (Newbold et al. 2015; WWF 2016). The predicted net loss of local species richness by 2090 is shown in Figure 1.3. The map demonstrates that substantial changes in species richness across the globe will take place if climate change continues to progress at the current pace. Red areas show regions that are expected to experience a loss of over 30% of their initial species richness, while the darker green areas are predicted to experience a gain in species richness. The results suggest that most of the tropical Asian regions are likely to lose more than 20% species richness. Several studies have looked at climate change impacts on humid tropical forests (Zelazowski et al. 2011), while forests in Asia have received little attention. Therefore, understanding the effects of global climate change on tropical Asian ecosystems is essential.

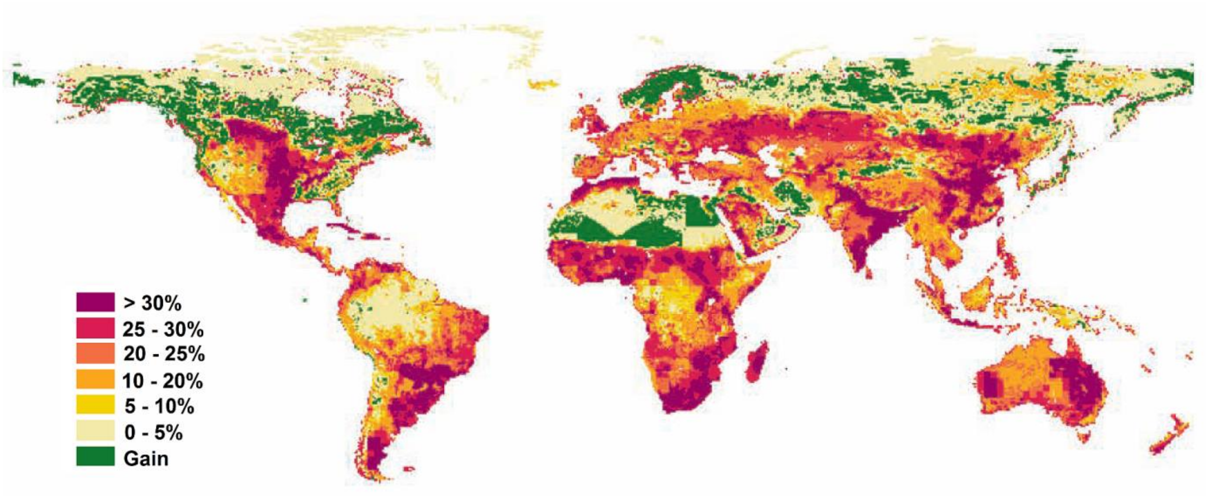

Figure 1.3 Predicted net loss of local species richness by 2090 from climate change (Newbold et al. 2015; WWF 2016). The results suggest that tropical Asian ecoregions are likely to lose more than 20% species richness.

1.4 Importance of a continental scale focus in tropical Asia

We have almost no empirical understanding of the effect of climate change on species distributions at the continental scale in tropical Asia. Forests in the Asian tropics are highly diverse, but lack of studies limit our understanding of species and forest ecosystem vulnerability to global climate change in the region. Very few studies have addressed this issue at the local scale (Chitale & Behera 2012; Gopalakrishnan et al. 2011), and no systematic study has been conducted at the continental scale for tropical Asia. This is due to the lack of data for the entire distribution of species across different ecoregions and biodiversity hotspots of tropical Asia. As the global non-governmental organisations and international agencies are primarily interested in conservation decision-making at a global scale, the global pattern of change is far more important than any local level study (Wilson et al. 2007). Although most of the climate change studies are concentrated in the three continents (North America, Europe, and Australia), the species-rich ecoregions of tropical Asia has received little attention (Pacifici et al. 2015). Successful adaptation of species to global climate change will therefore require an emphasis on continental-scale studies to achieve economic, social, and environment sustainability. The work carried out in this thesis begins to address these issues, and forms the basis for future climate change research in tropical Asia.

1.5 Research aim and thesis overview

The overall aim of this thesis is to provide insights into the effects of climate change on different aspects of tropical Asian forests for biodiversity conservation and forest management. To address the identified research gaps and questions, the thesis is divided into four objectives:

1. To examine the available evidence of climate change impacts on tropical forests and identify the most likely risks to Asian forests from projected climate change.
2. To assess climate change impacts on two ecologically important, and threatened Dipterocarp trees Sal (*Shorea robusta*), and Garjan (*Dipterocarpus turbinatus*) across Asia for their conservation planning.
3. To quantify the climatic-induced shifts in the distribution of Teak (*Tectona grandis*) (both native and non-native) in tropical Asia for timber management and planning under future climates.
4. To assess the extinction risks of four threatened large Asian mammals' namely Asiatic black bear (*Ursus thibetanus*), Asian elephant (*Elephas maximus*), Western hoolock gibbon (*Hoolock hoolock*) and Bengal tiger (*Panthera tigris tigris*) to global climate change and to inform their conservation planning.

This thesis comprises six chapters, including four analytical chapters from the four objectives, followed by a synthesis chapter that ties together the previous chapters (Figure 1.4).

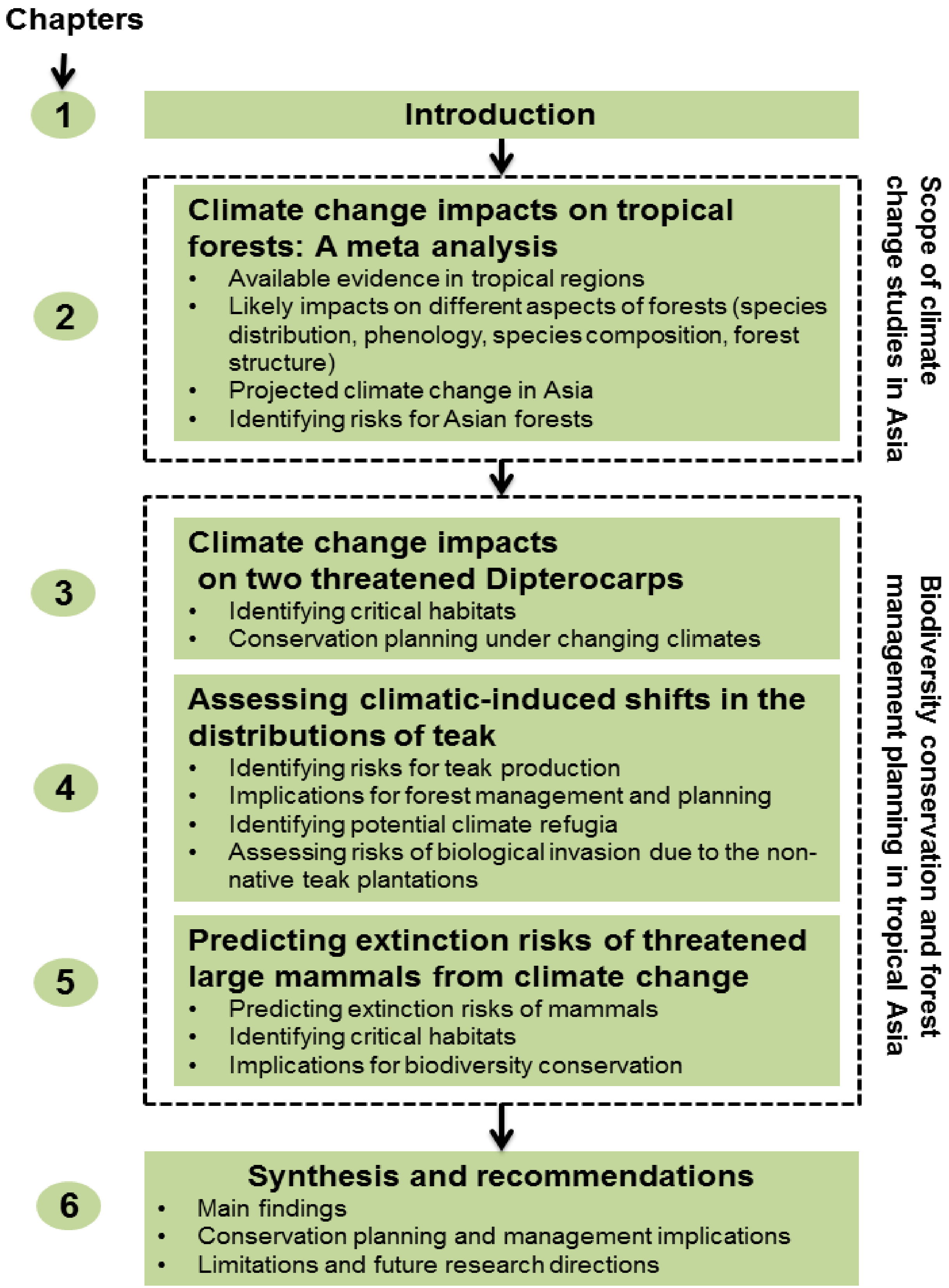

Figure 1.4 Conceptual diagram of the flow of the thesis chapters and the main findings arising from each chapter. Chapters two, three, four and five addressed the objectives one, two, three and four of this thesis respectively.

CHAPTER 2

CLIMATE CHANGE IMPACTS ON TROPICAL FORESTS: IDENTIFYING RISKS FOR TROPICAL ASIA

Associated publication:

Deb, JC, Phinn, S, Butt, N & McAlpine, CA (in review), 'Climate change impacts on tropical forests: identifying risks for tropical Asia', *Journal of Tropical Forest Science*.

Abstract

Background: There is growing evidence that global climate change is significantly altering forest ecosystems, and will continue to do so in the future. Changes in mean climate and climate extremes such as drought, storms, cyclones and wildfires can fundamentally alter species distribution, composition, phenology, and forest structure.

Aims: Here, we reviewed the available evidence of climate change impacts on tropical forests, identifying the main gaps in current knowledge, and providing directions for further research to understand the potential risks from climate change.

Methods: We selected 85 studies based on two selection criteria and recorded the impacts of climate change on different areas of tropical forests. The projected changes in temperature and rainfall extremes are also reviewed to identify potential future climate threats to the diverse and species-rich ecoregions of tropical Asia. As a case study, we discuss the likely climate change impacts on the fragmented forests of Bangladesh.

Results: Of the four climate domains (tropical, subtropical, temperate and boreal), the climate change impacts on forests have been least studied in the tropical domain.

Conclusions: Based on this review, two research questions are posed to direct future tropical forest research: (1) how does climate change affect extinction risk for tropical trees? and (2) how can climate change risks be integrated into forest policy and management?

Keywords: Climate change; climate extremes; forest disturbance; forest fragmentation; species composition; species distribution; phenology; tropical forests.

2.1 Introduction

Projected changes in climate will produce significant shifts in the distribution and abundance of many forest tree species (e.g., Dale & Rauscher 1994; Koralewski et al. 2015). Climate change affects forest ecosystems through changes in mean temperature and rainfall and through changes in the frequency and severity of weather and climate extremes, such as wildfires, severe storms, cyclones, and drought (Butt et al. 2015; Garcia et al. 2014). These impacts are broadly characterised as changes in: species' distribution (Thuiller et al. 2008); forest composition (relative abundance of species); forest structure (Bai et al. 2011; Grimm et al. 2013); and flowering and fruiting phenology (Butt et al. 2015). Rising temperatures increase the frequency and magnitude of extreme events, and changes in seasonality are altering the structure and function of forest ecosystems (Grimm et al. 2013). Climate change-induced shifts in plant distributions are changing the species composition of some biomes (Gonzalez et al. 2014). For example, a study conducted in Puerto Rico revealed that lowland forests in parts of the Caribbean have changed from drier savannah to more humid forests with resultant changes in the composition of plant communities (Scatena 2001).

The interaction of inter-annual climate variability (*e.g.*, El Niño Southern Oscillation, African Intertropical Convergence Zone) and anthropogenic factors (*e.g.*, greenhouse gases, ozone depletion, and deforestation) is the key driver that increases the frequency of extreme events, which in turn affects tropical forest ecosystems. Extreme climatic events such as severe drought can cause a large-scale ''dieback'' or degradation of forests (Allen et al. 2010), as recently occurred in the Amazonian rainforest (Boulton et al. 2013). Some extreme events can affect forest composition and structure without massive mortality, whereas others can cause large-scale tree mortality (Dale et al. 2001). Changes in the phenology of trees are considered one of the earliest signals of species' response to climate change and could have serious consequences for the functioning of forest ecosystems (Cleland et al. 2007; Corlett & Lafrankie Jr 1998). There is increasing evidence that global climate change is significantly altering the life-cycle events of plants (Bertin 2008).

Tropical forests are some of the most diverse ecosystems on earth (Chave 2008; Gentry 1992; Malhi & Phillips 2004; Sarker et al. 2011). However, they are now under unprecedented threat from deforestation and degradation and accelerating climate change (Malhi & Phillips 2004). The Intergovernmental Panel on Climate Change (IPCC) projected that tropical forest ecosystems are likely to be significantly impacted by climate change (IPCC 2014), and of the four climate domains (tropical, subtropical, temperate and boreal), the tropical domain has experienced the greatest total forest loss in the last decade (from 2000 to 2012), with an annual increment of forest loss by 2101 square kilometres per year (Hansen et al. 2013). Although the extent of forest cover loss is highest in South American tropical forests (approximately 16% of global forest cover loss), tropical Asia is experiencing the highest rates of loss (e.g., Indonesia exhibited the largest increase in forest loss by 1021 km^2/year from 2000 to 2012) (Hansen et al. 2013).

Tropical Asian forests are divided into three broad biomes: (i) the marginal tropics (where seasonal low temperatures may limit the growth of tropical plants; mean temperature of the coldest month < 18^0 C); (ii) the monsoon tropics (where the seasonally of rainfall limits growth; mean rainfall of the driest month < 50 mm); and (iii) the aseasonal tropics (where temperature and rainfall are adequate for growth although droughts may occur at supra-annual intervals) (Corlett & Lafrankie Jr 1998). The forests of Southeast Asia are mostly aseasonal tropics, whereas the forests of the South Asian region are mostly monsoon tropics with tropical South China representing marginal tropics. Large-scale seasonal variations in both temperature and rainfall influence tree phenology and species distributions in the marginal tropical forests, whereas seasonality in rainfall is the influential factor in monsoon tropics (Corlett & Lafrankie Jr 1998; Dudgeon & Corlett 1994). In the aseasonal tropics, drought occurs at supra-annual intervals and may influence the phenology and distributions of species (Corlett & Lafrankie Jr 1998).

Tropical Asia encompasses several biodiversity hotspots and species-rich ecoregions (Myers et al. 2000; Olson & Dinerstein 1998). For instance, teak (*Tectona grandis*) forests are divided into five types in India (very moist, moist, semi-moist, dry and very dry) and occur in four climate zones in Thailand (dry-humid, medium-humid, moist-humid and wet zone), based on different ecological requirements (e.g., rainfall, temperature, soil) (Champion & Seth 1968; Kaosa-ard 1977). The Dipterocarpaceae family comprises 470 species and 13 genera in South and Southeast Asia. Dipterocarps are highly variable in terms of flowering and fruiting phenology, ecological characteristics and geographical ranges, as they occur in evergreen, semi-evergreen and deciduous forests (Appanah & Turnbull 1998). Changes in climate and climate extremes are likely to impact the diverse forests of tropical Asia, and it has been predicted that Asia could lose three quarters of its original forests, and half of its biodiversity, by 2100 (Sodhi et al. 2004). In tropical Asia, most of the forests are degraded and fragmented due to widespread conversion of forests for agriculture (Ashton et al. 2014; Goldewijk 2001; Sarker et al. 2011). As a result, tropical Asian forests are highly vulnerable to climate change (IPCC 2014; Laurance 2004; Sodhi et al. 2010), and understanding its impacts on tropical Asian forests is a priority for their conservation.

In this paper, we review and synthesise the available evidence for climate change impacts on tropical vegetation. We discuss the findings for tropical Asia and other tropical regions. We focus on tropical Asian forests because of their high biodiversity values and their vulnerability to the interacting threats of forest fragmentation and climate change. We review projected climate change and climate extreme events and their likely impacts on tropical Asian forests. As a case study, we discuss the likely climate change impacts on the fragmented forests of Bangladesh. The review provides a synthesis of research findings and identifies two important areas for further research.

2.2 Materials and methods

2.2.1 Literature search and selection criteria

Literature searches were conducted using the online database search engine ISI Web of Science (version 5.21.1) and a combination of the following search strings: Climate change AND (tropical forest*); climate extremes AND (tropical forest*); climate change AND (South Asian forests); forest fragmentation AND (climate change). The search covered the period 1900-2016, including studies published until May 2016 using all databases. We also used Summon UQ (The University of Queensland) Library database and the Google Scholar search engine for all available years. In addition, we reviewed the reference lists of the retrieved papers in order to search for additional papers. The search yielded over 5,000 papers, but most of them were irrelevant to our study purpose. For instance, most of the climate change-related studies were on socio-economic perspectives, forest fauna, or policy governance, and were excluded from our study. We considered the studies based on the following criteria:

1) The peer-reviewed articles written in English that focus on tropical and subtropical forest ecosystems (*i.e.*, South Asia, Southeast Asia, South America, Central America, Africa and Australia)
2) The article must be an original study and not a review or synthesis.
3) The article must have addressed the potential impacts of climate change on forest structure and composition, plant species distribution, or phenology, in tropical or subtropical regions.

We selected 85 studies and recorded forest types, locations, landscape structure, and climate change impacts on different areas of forests (see Table A2.1 for details). The different terminologies that have been used frequently in this study are defined below.

Glossary

Forest fragmentation: the breaking apart of continuous forests into smaller, isolated patches known as forest remnants or forest fragments. (Fahrig 2003).

Species distribution: the spatial arrangement of a biological taxon also referred as species range (Franklin 2010). Many physiological and bioclimatic environmental factors influence a species' distribution. (Franklin 2010).

Forest structure: the distribution of trees and other plants covering a large area or a contiguous group of similar plants. Defined here following the dictionary of forestry by the

Society of American Foresters (http://dictionaryofforestry.org/dict/term/stand).

Forest composition: the relative abundance of the species in the forests or the proportion of each tree species in a stand, generally expressed as a percentage of the total number (http://dictionaryofforestry.org/dict/term/composition).

Phenology: the timing of periodic plant life-history events *e.g.* flowering, fruiting, seeding, leaf shedding etc., as influenced by the seasonal and inter-annual variations in climate. (http://dictionaryofforestry.org/dict/term/phenology).

Climate change: changes in the mean and/or the variability of temperature, precipitation, wind, and all other aspects of climate that persists for an extended period, typically a decade or longer (IPCC 2013). Changes may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2013).

The review first discusses the response of forest plants of tropical regions to climate change based on the findings from 85 studies. We then investigate the climate change impacts on species distribution, forest structure, species composition, and phenology with a specific emphasis on the fragmented forests of tropical Asia. We discuss the observed and projected climate change and climate extremes scenarios of tropical Asia. Because the forests of Bangladesh are highly fragmented, we discuss the likely climate change impacts on the fragmented forests of Bangladesh as a case study and identify the potential areas for further research.

2.3 Results

2.3.1 Climate change impacts on tropical forests

The majority of the studies focussed on South and Central America (*n*=26) followed by South Asia (*n*=24) and Africa (*n*=15) (Table 2.1). We found the same number of studies (*n*=10) from Australia and Southeast Asia (Table 2.1 and Figure 2.1). Most studies reported the response of forest trees to climate change (Table 2.1 and Table A2.1). The impacts of climate change on tropical forests fell mainly into one of three broad categories: (1) changes in the plant species distribution (Gopalakrishnan et al. 2011; Miles et al. 2004; Saatchi et al. 2008); (2) changes in forest stand dynamics, including changes in forest cover, structure and composition (e.g., Anado′n et al. 2014; Laurance et al. 2014); and (3) changes in tree phenology (Gunarathne & Perera 2014; Hopkins & Graham 1987; Numata et al. 2003). The temporal trend of publications indicates that climate change research in all tropical regions has increased over the last decade (Figure 2.2). In the following subsections, we discuss the findings of climate change impacts on tropical Asian forests and other tropical regions.

Table 2.1 Summary of the number of studies that explained climate change impacts on tree species distribution, phenology, forest structure and composition in the tropical regions.

Regions	Landscape Structure		Different types of responses to climate change			Total studies
	Fragmented	Not reported	Species distribution	Forest structure & composition	Phenology	
South Asia	18	6	6	14	4	24
Southeast Asia	7	3	2	7	1	10
South & Central America	23	3	4	22	-	26
Africa	14	1	3	12	-	15
Australia	7	3	2	6	2	10
Total	69	16	17	61	7	85

2.3.2 Changes in species distributions

Our search revealed 17 studies that met our search criteria (Figure 2.1), eight of which focussed on Tropical Asia (six in South Asia and two in Southeast Asia), and the remaining nine focused on other tropical regions (Table 2.1). Two recent studies in India found annual temperature; annual precipitation and precipitation of the wettest month were key drivers of shifts in the distribution of *Myristica dactyloides* and *Myristica fatua* species (Priti et al. 2016; Remya et al. 2015). In another study, soil moisture was found to be the key factor influencing shifts in the distribution of *Shorea robusta* from central India towards northern and eastern India (Chaturvedi et al. 2011). In the dry deciduous teak forests in India, 30% of teak is vulnerable to climate change under both A2 and B2 SRES scenarios of the IPCC Fourth Assessment Report (Gopalakrishnan et al. 2011). One recent study from Bangladesh reported annual precipitation, precipitation seasonality and tree physiological variables as principal factors in the extinction risk of two freshwater swamp forest trees species (*Pongamia pinnata* and *Barringtonia acutangula*) (Deb et al. 2016). In southwest China, 1400 (60%) of 2319 woody plant species are expected to lose more than 30% of their current range under the most extreme climate change scenario by 2080, with increasing temperature variability and declining precipitation predicted during the dry season (Zhang et al. 2014).

A study of tropical Amazon forests found that the potential distribution of 30 (43%) of 69 angiosperm species will change drastically by 2095 (Miles et al. 2004). In another study, remote sensing data were combined with climate data to model the distribution of *Virola surinamensis* in

Amazon forests and revealed variation in temperature mean diurnal range, temperature seasonality, and temperature of the coldest month as the driving factors (Saatchi et al. 2008). Changes in temperature, precipitation and cloudiness, carbon balance, wildfire and anthropogenic disturbances were identified as the key determining factors of tree distributions in the African tropical highlands (Jacob et al. 2015). *Eucalyptus* spp. and *Macadamia integrifolia* trees in tropical and subtropical regions of Australia are also likely to face increasing climate stress (Butt et al. 2013; Powell et al. 2010).

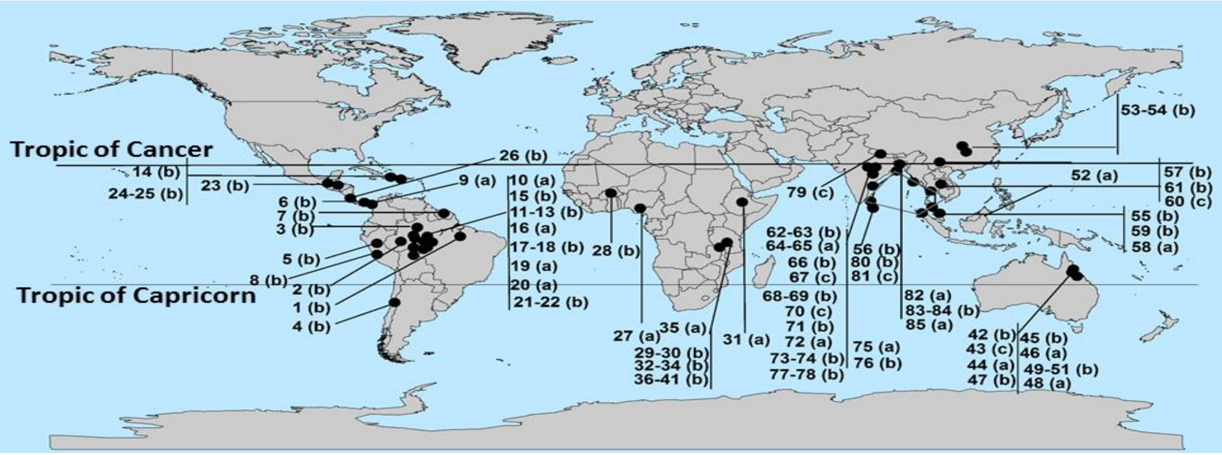

Figure 2.1 The geographic locations of the 85 studies on forest-climate interactions in fragmented tropical landscapes reviewed in this paper (the two straight lines ‘Tropic of Cancer’ and ‘Tropic of Capricorn’ indicate the boundary of tropical regions). Numbers refer to reviewed papers (see ‘Reference’ column on Table A2.1) and also indicate the location of the studies. Letters in parentheses after reference number refer to the climate change impacts on forest plants studied: (a) species distribution; (b) forest structure and composition; and (c) phenology.

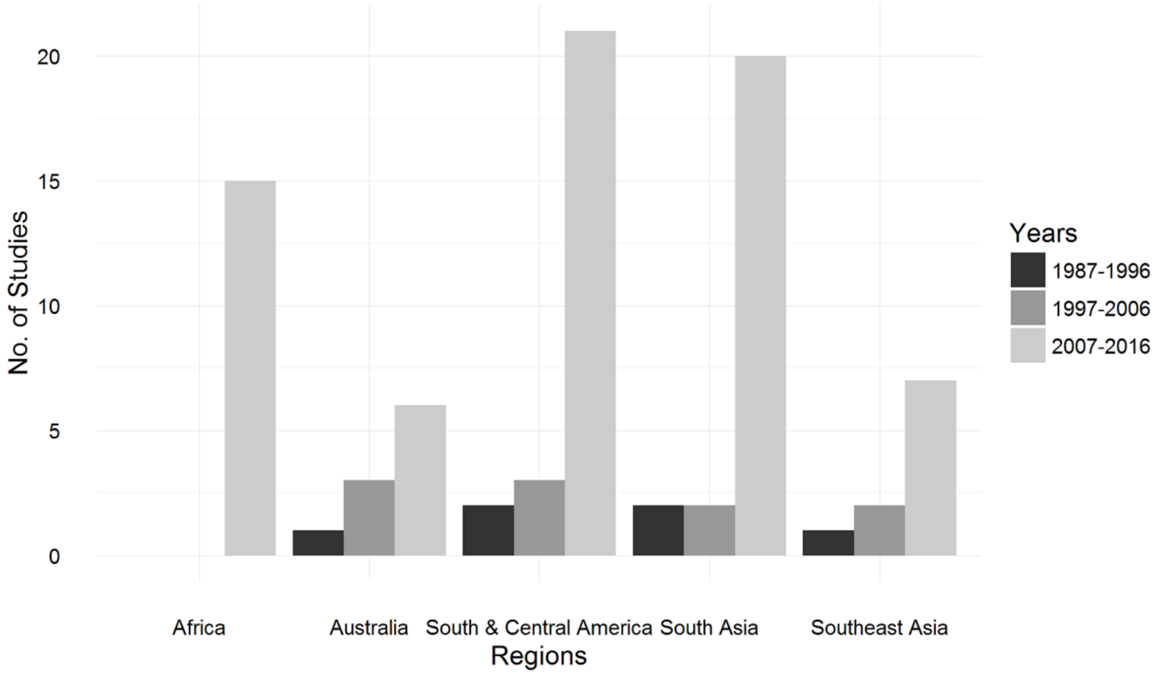

Figure 2.2 The temporal pattern of the studies by regions that were selected for review in our study. The results suggest that most of the climate change studies were conducted in the last decade in all regions.

2.3.3 Changes in forest structure and composition

Most studies (14 in tropical Asia and 40 in other tropical regions) reported climate change impacts on forest vegetation dynamics and species abundance in all tropical regions (see Table A2.1 for details). In Southeast Asia, climate extremes such as drought and fire can increase tree mortality rates (Woods 1989), and high rainfall can drive mortality in dipterocarp trees and influence the dynamics of tropical forests (Margrove et al. 2015). Land use conversion (Sukumar et al. 1995), and population pressure (Srivastava et al. 2015) were recognized along with climate change as the key driving factors for forest vegetation change in India. Sea level rise and alteration of water flows of the Himalayan headwaters are among the major disturbances threatening the world’s largest single block of Sundarbans mangrove forests in Bangladesh (Pethick & Orford 2013; Rahman et al. 2011).

In the Brazilian Amazon, climate change is responsible for shifts in tree species composition (Raghunathan et al. 2015) and changes in liana abundance and biomass (Fearnside 2004; Laurance et al. 2014). Malhi et al. (2009), in a study on climate change induced dieback of Amazon rainforest, found that dry-season water stress caused by high temperature is likely to increase in Amazonia over the 21st century. They found that an increase in rainfall variability may cause a large-scale dieback or degradation of Amazon rainforest. A study of the large-scale drying trend and tree abundance interactions conducted in a tropical moist forest in central Panama found that 10% of tree species are headed for extinction because of a 25 year decline in precipitation (Condit et al. 1996).

2.3.4 Changes in phenology

Very few studies (five in tropical Asia and two in other tropical regions) reported climate change impacts on plant phenology. The periodicity of rainfall and soil water availability regulates flowering phenology in South Asian forests (Sakai 2001; Singh & Kushwaha 2005), because the northeast monsoon in summer, and the southwest monsoon in winter, bring predominantly warm, humid air masses and precipitation to this region (McGregor & Nieuwolt 1998). In northern India, flowering occurs in canopy trees and understory trees during the dry season and rainy season respectively (Shukla & Ramakrishnan 1982). Fruiting phenology of trees is also likely to be influenced by climate change in tropical deciduous forests (Butt et al. 2015; Kushwaha et al. 2011). In tropical regions, fruit production is related most strongly to evapotranspiration (Ting et al. 2008), while seasonal low temperatures drive annual fruiting phenology in the Indo-Malayan subtropics

(Corlett 1998). In the central Himalayan region of India, changes in annual mean maximum temperature was responsible for the shifts in the flowering dates of *Rhododendron arboreum* species (Gaira et al. 2014); while drought conditions resulted in delayed leaf initiation and leaf fall for 26 woody species in north-eastern India (Yadav & Yadav 2008). In semi-deciduous forests in Sri Lanka, rainfall has been recognized as a key mechanism in leafing events of *Manilkara hexandra* (Roxb.), whereas climatic variations such as drought or heavy rain were responsible for the abortion of flowers and young fruits (Gunarathne & Perera 2014). In southern China, seasonal temperature change has been recognized as a driver of flowering phenology of tree species (Corlett & Lafrankie Jr 1998).

In Australia's seasonally dry tropical forests, the flowering of trees generally occurs at the end of the dry, or the beginning of the wet, season, and changes in rainfall seasonality can lead to unusual flowering events and fruit drop (Hopkins & Graham 1987; Numata et al. 2003). The phenology of *Acacia* dominated savannas responded strongly to the variance in annual precipitation across north Australia (Ma et al. 2013). Our review revealed very few studies of climate change impacts on tree phenology in all tropical regions and supports the need for more studies (Table A2.1).

2.3.5 Observed climate change in tropical Asia

Tropical Asia is highly vulnerable to climate change (IPCC 2014). The observed climate trends and variability in tropical Asia are of increasing air temperatures and greater changes in rainfall regimes. Increases in annual mean temperature in East and South Asia have been observed during the 20th century (IPCC 2014). Temperature has been increasing at a rate of 0.14°C to 0.20°C per decade since the 1960s, coupled with a rising number of hot days and warm nights, and a decrease in the number of cold days' across Southeast Asia (IPCC 2014). In terms of inter-seasonal, inter-annual and spatial variability in rainfall trends, an overall decrease in seasonal mean rainfall has been observed over India (IPCC 2014). However, an increase in extreme rainfall events occurred over the central region of India (IPCC 2014). In Southeast Asia, climate variability and trends differ vastly across the region and between seasons. For instance, annual total wet-day rainfall has increased by 22 mm per decade, while rainfall from extreme rain days has increased by 10 mm per decade (IPCC 2014). In the northern parts of Southeast Asia, an increasing frequency of extreme events has been reported, while the trend in Myanmar, in the south, is a decrease (IPCC 2014). In Peninsular Malaya, total rainfall and the frequency of wet days decreased during the southwest monsoon season, but rainfall intensity increased (IPCC 2014). On the other hand, total rainfall, the frequency of extreme rainfall events, and rainfall intensity all increased over the peninsula during the northeast monsoon (IPCC 2014).

2.3.6 Projected climate change in tropical Asia

The climate change projections suggest a significant acceleration of warming for tropical Asia for the twenty-first century (IPCC 2014). For instance, the difference map (2080-2100 compared with 1980-2000) indicates that the mean warming under RCP4.5, RCP6.0 and RCP8.5 will be significant, with an increase of 5-9°C in the Himalayan Highlands, Tibetan Plateau, and arid regions of South Asia (Figure 2.3a). Similarly, mean precipitation is likely to increase in the Tibetan Plateau and Bangladesh (Figure 2.3b). Summer precipitation is likely to increase in South Asia, and droughts associated with summer drying could result in regional vegetation die-offs (Breshears et al. 2005). Mean evaporation is also likely to increase by 0.1-0.2 mm by 2100 (Figure 2.3c). The air pressure at sea level is projected to increase by 0.5-2 hPa by 2100, with a significant increase for Bangladesh (Figure 2.3d).

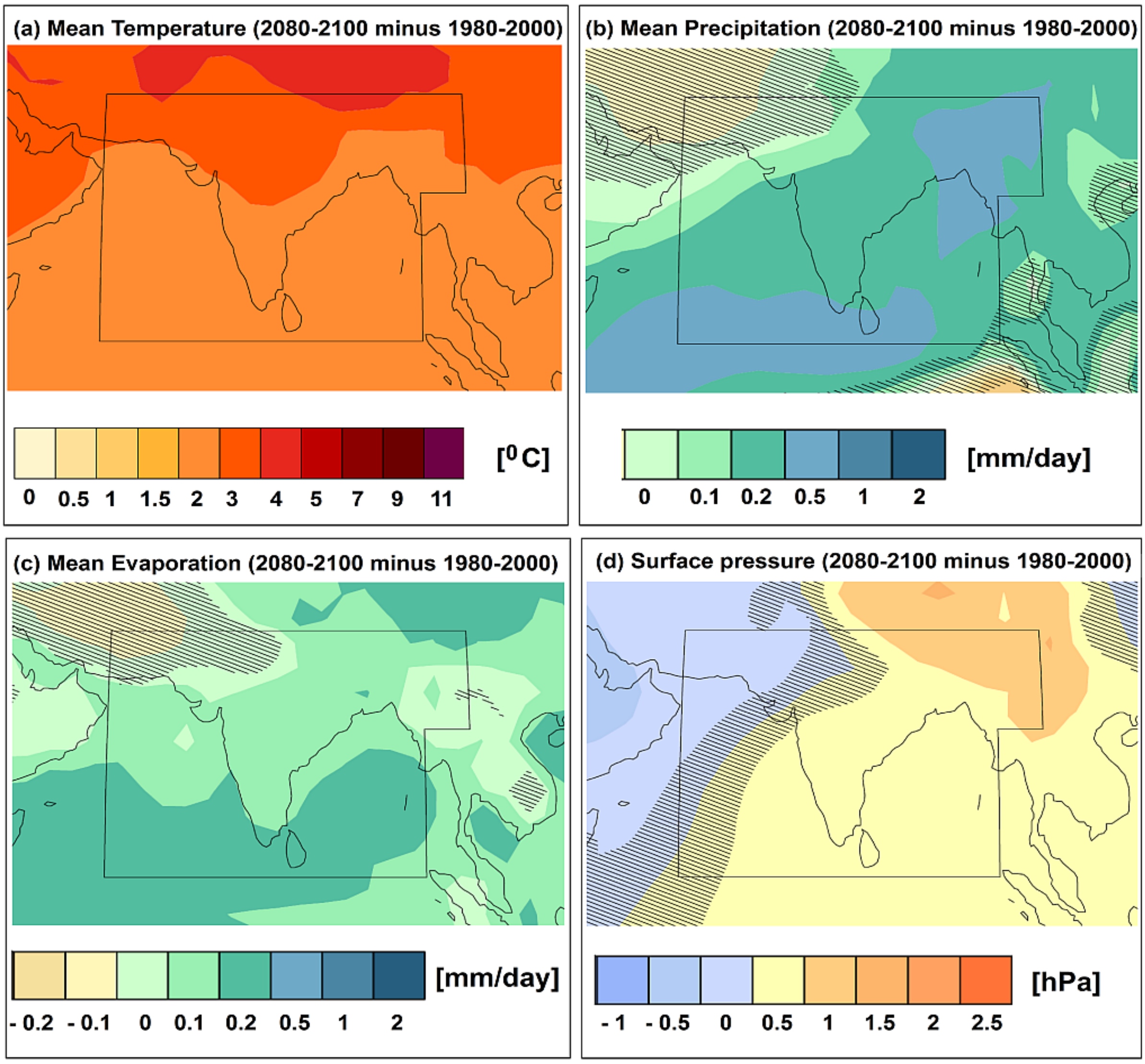

Figure 2.3 Projected increases in four climatic parameters for South Asia: (a) mean temperature (Celsius); (b) mean precipitation (mm/day); (c) mean evaporation; and (d) mean air surface pressure at sea level (hPa). CMIP5 (IPCC AR5) climate data for mean of RCP4.5, RCP6.0 and RCP8.5

scenarios, 2080-2100 compared with 1980-2000 for South Asia. Source: http://climexp.knmi.nl/plot_atlas_form.py

The frequency of extreme events such as, drought, heavy rainfall, and cyclones, may be affected by seasonal- to inter-annual fluctuations of large scale climate variations, such as El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Schwierz et al. 2006). There is a projected increase of 10–20% in the intensity of tropical storms, with an increase in sea-surface temperature of 2–4°C relative to the current temperature in South Asia (Schwierz et al. 2006). A summary of the projected changes in selected climate extreme indices for South Asia is provided in Figure 2.4. The simple precipitation intensity index indicates that the annual mean rainfall for South Asia will increase by 0.5-2 mm per day (Figure 2.4a), and there will be more frequent longer periods of consecutive dry days, with an increase of up to 6 consecutive dry days by 2100 (Figure 2.4b). The annual maximum value of the daily maximum temperatures in most regions will increase by 4-7°C, with an additional 8 days of > 20 mm rainfall by 2100 (Figure 2.4c,d). The projected climate extreme indices for South Asia indicate that Bangladesh will experience a significant increase in all indices by 2100.

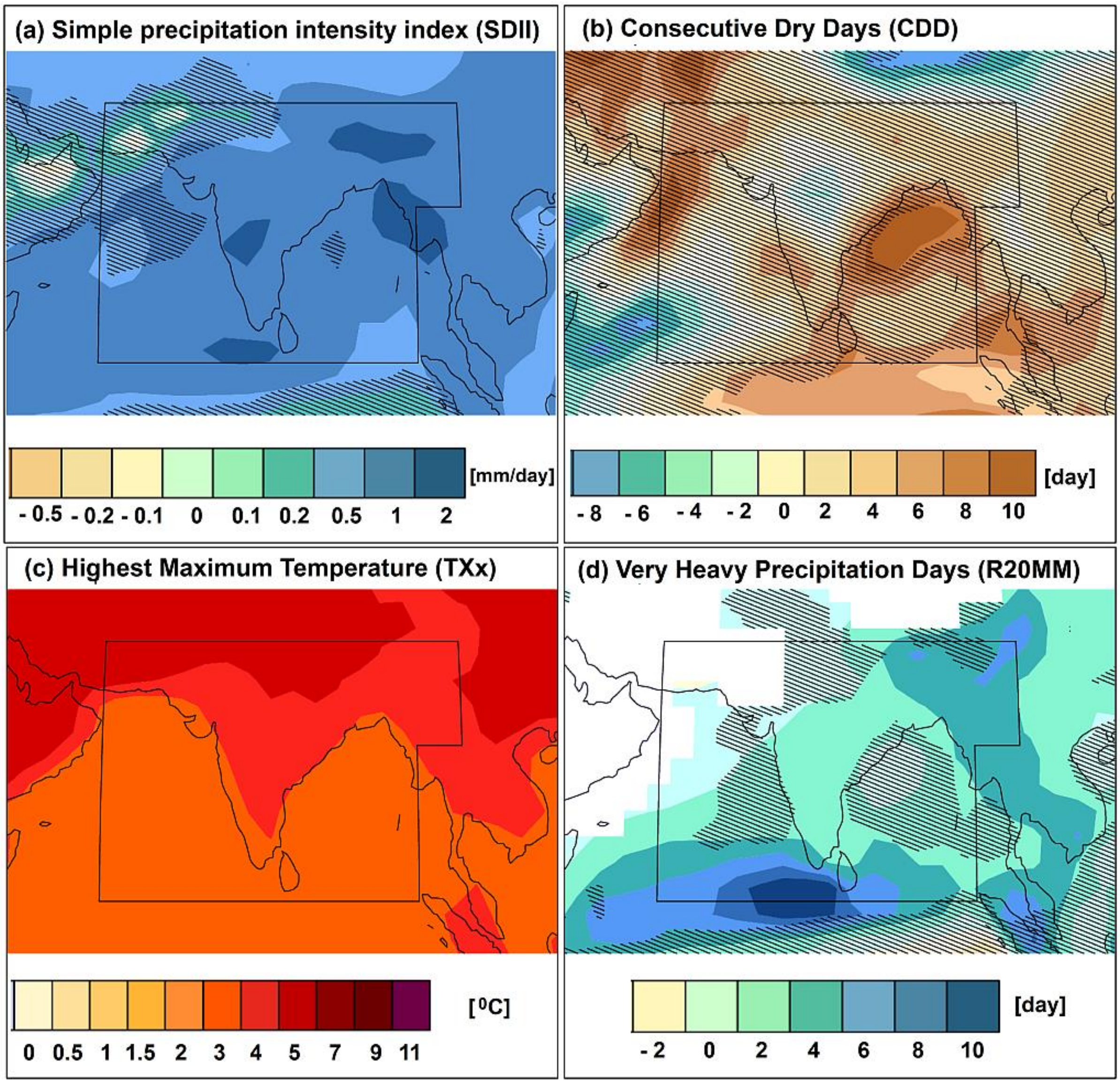

Figure 2.4 Projected increases in selected climate extreme indices under the RCP8.5 climate scenario for South Asia: (a) Simple precipitation intensity index (mm/day); (b) Maximum number of consecutive dry days per year; (c) Value of daily maximum temperature (Celsius); (d) Very heavy precipitation days with daily precipitation > 20 mm, days per year. CMIP5 climate extremes ensemble data, 2080-2100 compared with 1980-2000 for South Asia. Source: http://climexp.knmi.nl/plot_atlas_form.py

2.3.7 Potential risks for tropical Asian forests

In tropical Asia, climate change impacts on many plants and animals' species is likely as a result of the synergistic effects of climate change and habitat fragmentation (IPCC 2014). The rapid nature of projected climate change, coupled with the fragmented state of forests (Laurance 2004), may cause tropical forest ecosystems in Asia to a decrease in resilience, and eventually drive the extinction of rare and endangered tree species (Choudhury & Hossain 2011; Deb et al. 2016; IPCC 2014). The composition and geographic distribution of forest ecosystems will change as the individual species respond to new climate conditions (Pethick & Orford 2013; Rahman et al. 2011). Remnant forests may degrade and fragment in response to climate change and other human pressures, and species that cannot adapt fast enough may become extinct (Deb et al. 2016). Although projected changes in climate are expected to modify the vegetation distribution across the region (Chaturvedi et al. 2011; Gopalakrishnan et al. 2011), the responses will be slowed by limiting factors such as seed dispersal, competition from established plants, rates of soil development, and habitat fragmentation (Corlett & Westcott 2013). For instance, the distributions of major timber trees (*Tectona grandis*, *Shorea robusta*, *Dipterocarpus turbinatus*) across the deciduous, evergreen and semi-evergreen forests of South and Southeast Asia are likely to change due to the increasing rainfall, temperature and climate extreme events (Figure 2.5).

More frequent extreme events such as storms, floods, interannual and decadal climate variations, as well as large-scale circulation changes, such as the El Niño Southern Oscillation (ENSO), may promote plant disease and pest outbreaks in the fragmented forests (Gan 2004). Droughts combined with deforestation will increase fire danger for tropical Asian forests (Laurance 2004), while increased rainfall runoff in open forest areas will drive top soil erosion and leaching, resulting in a net decrease in growth rate, biomass and diversity of forest plant species (Ahmed et al. 1999). In tropical Asia, variation in rainfall intensity, temperatures and evapotranspiration may lead to an increase in the length of periods between mass flowering and fruiting events of tree species (Butt et al. 2015). This may impact the tree phenology particularly irregular flowering and fruiting. In the following box, we focus on Bangladesh as a case study for understanding the likely climate change impacts on different ecosystems of tropical Asia.

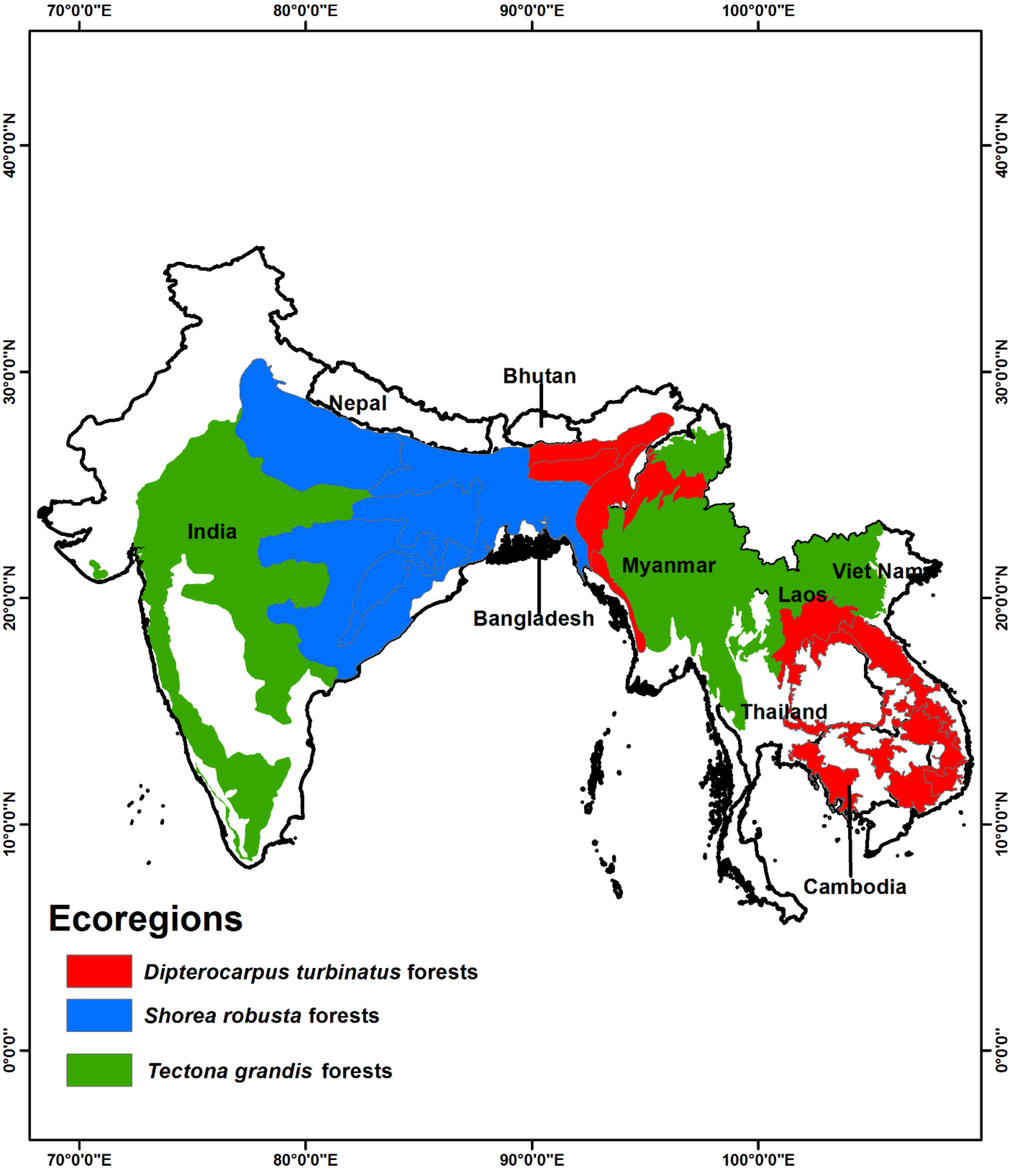

Figure 2.5 The distribution of three major deciduous tree species (*Dipterocarpus turbinatus*, *Shorea robusta*, and *Tectona grandis*) across different ecoregions of tropical Asia (Deb et al. 2017a, 2017b). The tree distributions data were compiled from a variety of sources i.e., fieldwork, Global Biodiversity Information Facility (GBIF) and published literature and then matched with the ecoregions of tropical Asia (Peel et al. 2007). The projected climate change in temperature and precipitation regimes is likely to impact the phenology and distribution of these species (Deb et al. 2017a, 2017b).

Potential climate change impacts on forests in Bangladesh: a case study

The summary of the likely climate change impacts on different forest ecosystems in Bangladesh (Figure 2.6) are described in Table 2.2. In some areas, the projected increases in rainfall may cause increased runoff, resulting in enhanced soil erosion, which would be more pronounced in the hill forest ecosystems (Ahmed et al. 1999). Heavy rainfall resulting in flooding may affect the growth of many timber species and would cause high mortality for *Artocarpus heterophyllus, Artocarpus chaplasha, Azadirachta indica, Cajanus cajan, Leucaena leucocephala* in the hill forests (Ahmed et al. 1999). In contrast, Sal (*Shorea robusta*) forest ecosystems could suffer increased moisture stress due to enhanced evapotranspiration rates in the winter months (Table 2.2). Therefore, deciduous forests may experience much longer periods of consecutive dry periods, which may influence the flowering and fruiting regimes of Sal forest, and its distribution (Chaturvedi et al. 2011). The tea plantations adjacent to the evergreen forests in the north-eastern region may also experience moisture stress (Ahmed et al. 1999).

Sarker et al. (2016) reported that globally endangered *Heritiera fomes* abundance declined as salinity increased, and historical harvesting reduced the stem density of the threatened species in Sundarbans mangroves. Another study reported that annual and monsoon precipitation, as well as salinity intrusion, mainly influence the growth of *H. fomes* (Chowdhury et al. 2016). Model projections of Sundarbans species showed a decrease in species assemblages (*Ceriops decandra, Xylocarpus moluccensis, Avicennia officinalis, H. fomes*) due to the influence of temperature, rainfall and salinity change (Mukhopadhyay et al. 2015). Slow growing mangrove species (*e.g., Heritiera fomes, Ceriops decandra*) are likely to be more adversely affected than fast growing mangroves species (*e.g., Excoecaria agallocha, Sonneratia apetala* etc.) and invasive species (Biswas et al. 2007; Choudhury & Hossain 2011). Hence, fast growing mangrove species are likely to dominate the ecosystem, and species composition and distribution could drastically change with sea-level rise (Rahman et al. 2011). Soil salinity may also increase due to a combination of high evapotranspiration and low stream flow in winter, which would severely affect the growth of freshwater species (Ahmed et al. 1999). Extreme climate events such as drought, cyclones, flood and wildfire may also negatively influence the forest ecosystems (IPCC 2014). The current dense canopy cover may gradually be replaced by non-woody shrubs and bushes, which could produce a significant decline in the rich diversity of flora and overall forest productivity of the Sundarbans mangrove ecosystem (Mukhopadhyay et al. 2015).

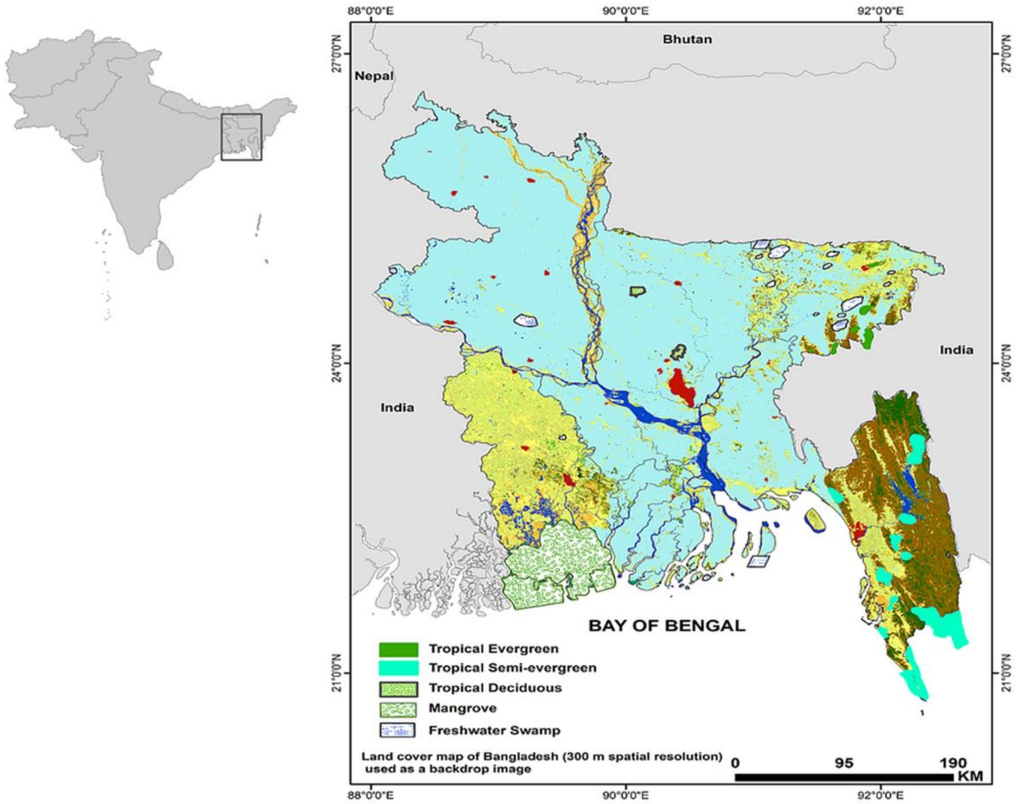

Figure 2.6 The different plant species of the five forest ecosystems in Bangladesh are likely to be impacted due to projected climate change. Some rare and endangered tree species of these forests may become extinct in future climate scenarios. The land cover map of Bangladesh used as a backdrop image in the figure. The other colours except the forest types are different land cover categories in Bangladesh.

Table 2.2 Summary of changes in climatic factors and the likely impacts of these factors on different forest types in Bangladesh.

Forest types	**Changes in climatic factors**	**Impacts**
Tropical evergreen and semi-evergreen	Increased annual rainfall Prolonged floods Increased mean temperature Changes in ENSO cycle	Enhanced soil erosion Mortality of timber trees Restriction of flowering and fruiting phenology Shifts in species distribution Changes in species composition and forest structure
Tropical deciduous	Enhanced evapotranspiration Longer dry periods	Increased moisture stress Affect phenology and species distribution
Mangrove and Freshwater swamp	Sea-level rise Increased salinity High evapotranspiration Low flow in winter	Affect species growth Dense canopy cover replaced by shrubs and bushes Significant decline in forest productivity and floral diversity

2.4 Discussion

The 85 reviewed studies document a wide variety of climate change impacts on tropical forests (Table A2.1). The impacts varied considerably, depending on the forest type, structural and floristic composition, disturbance history, and phenology. Although the spatial and temporal scales of the studies also varied, projected climate change and its interaction with land use change are the greatest overall threat to tropical biodiversity (Corlett 2012; Corlett & Lafrankie Jr 1998; Laurance 2004). Deforestation tends to fragment tropical ecosystems, causing declines in biodiversity. In Southeast Asia, climate change impacts on tree mortality in the tropical deciduous forests are already altering forest structure and species composition (Margrove et al. 2015; Suresh et al. 2010). The projected climate change scenarios in tropical Asia clearly indicate that the forest ecosystems of this region are highly vulnerable to climate change impacts (Figures 2.3 &2.4).

In the Amazon Basin where climate change is already having an impact, rising atmospheric CO_2 and regional climate drivers influence forest fragments dynamics, tree community composition and distribution, tree mortality and aboveground biomass (Laurance et al. 2014; Olivares et al. 2015; Raghunathan et al. 2015). Disturbances, such as hurricanes, cyclones, or typhoons, significantly affect forest structure and species composition in Central America (Anado′n et al. 2014; Shiels & Gonzalez 2014; Shiels et al. 2014). In Africa, biomass and vegetation phenology will be significantly affected due to global climate change (Scheiter & Higgins 2009). In the following section, we pose two key research questions which act as a guide for further research based on the findings of the current review, contemporary ecological theory and forest policy issues.

Research question 1: How does climate change affect extinction risk for tropical trees?

Recent climate change has resulted in shifts in the distribution and abundance of plant species (Thomas et al. 2004). Several lines of research suggest that climate change could become a major cause of species extinctions over the current century, either directly or synergistically with other extinction drivers, such as agricultural expansion, over-exploitation and introduction of invasive alien species (Pacifici et al. 2015). Accurate and widespread estimation of species' extinction risk is difficult at the global scale and it is therefore important to generate as much information as possible on extinction risk at the continental and regional scales (Thomas et al. 2004). This will help inform conservation planning (for example, for forest restoration) under future climates. As tropical forests contain at least half of all earth's species, and they are being depleted faster than any other biome, the current mass extinction is largely concentrated in these forests (Brook et al. 2008). Most of the studies conducted in tropical Asian regions assessed the impacts of climate change on vegetation cover (Table 2.1 and Table A2.1). However, the responses of species' distributions and phenologies to climate change have not been investigated in all tropical regions (Table 2.1). Therefore, assessing the extinction risks of plant species at the local, regional and continental scale has significant scientific value for conservation planning and practice. There are a number of areas where further studies can help quantify the extinction risk of tree species in tropical Asia.

These include:

a) An emphasis on the documentation of phenology, geographical distributions and climatic requirements of all tree species in tropical countries and their conservation status.

b) A greater focus on the quantitative assessment of the impact of climate extreme events *i.e.* drought, cyclones, storms, on species distributions, phenology, and forest structure and composition.

c) A greater focus on the robustness of projected changes in climate and climate extremes regarding the timing, intensity and magnitude of changes.

d) An increase in the number of studies on forest – climate interactions in tropical fragmented landscapes, both at local and regional levels.

Research question 2: How can climate change risks be integrated into forest policy and management?

Forests have significant potential for climate change mitigation as their life cycles range from decades to centuries (Spitlehouse & Stewart 2003). It has been estimated that the world's forests sequester one fourth of annual carbon emission (Braatz et al. 2011). However, the forest sector contributes 17.4% of greenhouse gas (GHG) emissions due to deforestation (Braatz et al. 2011). Tropical deforestation accounts for almost 20% of anthropogenic greenhouse gas emissions, and without effective forest policies, is likely to release an additional 87 to 130 GtC by 2100 (Gullison et al. 2007). Tropical countries therefore need to anticipate the direct and indirect threats posed by climate change to forests, and to formulate appropriate forest policies to reduce vulnerability and increase resilience to climate change (Braatz et al. 2011).

In general, forest vegetation responses to climate change are now well documented across the world. However, vegetation patterns are more diverse and least understood in the tropics. This chapter describes the complex impacts of changing climate and climate extremes on species composition, phenology, distribution and forest structure. The projected changes in climate and climate extremes suggest that all tropical forests are vulnerable to anthropogenic climate change, and this risk is particularly acute in tropical Asia. Recent studies suggest changes in temperature and precipitation regimes along with forest destruction and degradation could lead to the extinction of some species at a local-regional level. Models of forest response to climate change including individual tree-based models, species-specific empirical models, and climate envelope models linked to plant physiological functioning could depict a better scenario of climate change impacts on forest plants in tropical Asia. Tropical countries need to identify the climate change risks for forest vegetation and integrate them into national forest policy and practice for conservation planning. We urge researchers working in tropical regions to link vegetation datasets with projected climate change for better understanding of the relationships between them.

CHAPTER 3

THE IMPACT OF CLIMATE CHANGE ON THE DISTRIBUTION OF TWO THREATENED DIPTEROCARP TREES

Associated publication:

Deb, JC, Phinn, S, Butt, N & McAlpine, CA 2017, 'The impact of climate change on the distribution of two threatened Dipterocarp trees', *Ecology and Evolution* vol. 7, no. 7, pp. 2238-2248.

Abstract

Two ecologically and economically important, and threatened Dipterocarp trees Sal (*Shorea robusta*) and Garjan (*Dipterocarpus turbinatus*) form mono-specific canopies in dry deciduous, moist deciduous, evergreen and semi-evergreen forests across South Asia and continental parts of Southeast Asia. They provide valuable timber and play an important role in the economy of many Asian countries. However, both Dipterocarp trees are threatened by continuing forest clearing, habitat alteration and global climate change. While climatic regimes in the Asian tropics are changing, research on climate change driven shifts in the distribution of tropical Asian trees is limited. We applied a bioclimatic modelling approach to these two Dipterocarp trees Sal and Garjan. We used presence-only records for the tree species, five bioclimatic variables, and selected two climatic scenarios (RCP4.5: an optimistic scenario, and RCP8.5: a pessimistic scenario) and three Global climate Models (GCMs) to encompass the full range of variation in the models. We modelled climate space suitability for both species, projected to 2070, using a climate envelope modelling tool 'MaxEnt' (The Maximum Entropy algorithm). Annual precipitation was the key bioclimatic variable in all GCMs for explaining the current and future distributions of Sal and Garjan (Sal: 49.97±1.33; Garjan: 37.63±1.19). Our models predict that suitable climate space for Sal will decline by 24% and 34% (the mean of the three GCMs) by 2070 under RCP4.5 and RCP8.5, respectively. In contrast, the consequences of imminent climate change appear less severe for Garjan, with a decline of 17% and 27% under RCP4.5 and RCP8.5, respectively. We also combined four static variables i.e., land use/land cover, maximum green vegetation fraction, elevation, and actual evapotranspiration with the dynamic bioclimatic variables in another model which suggest that habitat destruction could be a major driving force in concert with climate change for the distribution of threatened Sal and Garjan forests. The findings of this study can be used to set conservation guidelines for Sal and Garjan by identifying vulnerable habitats in the region. In addition, the natural habitats of Sal and Garjan can be categorized as low to high risk under changing climates where artificial regeneration should be undertaken for forest restoration.

Keywords Climate change; conservation planning; dipterocarp trees; forest fragmentation; species distribution.

3.1 Introduction

Global climate change has produced numerous shifts in the distribution of species over the last three decades, and will act as a major cause of species extinction in the near future, either directly or synergistically with other extinction drivers (Akçakaya et al. 2014; Pacifici et al. 2015; Pearson et al. 2014; Scheffers et al. 2016; Thomas et al. 2004). The potential for large increases in global mean temperatures (e.g., 4.3 ± 0.7°C) by 2100 has significant implications for species and forest ecosystems (Butt et al. 2013; Pacifici et al. 2015). In the context of understanding ecological responses to climate change, regional changes that are highly spatially heterogeneous may be more relevant than approximated global averages (Walther et al. 2002). Among the four global climate domains (tropical, subtropical, temperate and boreal), the tropical biome has the highest rate of forest destruction and degradation (Achard et al. 2002; Hansen et al. 2013; Laurance 2004; Morris 2010). Therefore, forest-climate interactions in highly-modified tropical landscapes are becoming one of the most important subjects of research in conservation ecology (e.g., Laurance 2004; Wiegand et al. 2005; Wilson et al. 2016).

The climate of South and northern continental Southeast Asia is monsoonal with a large-scale seasonal reversal of the wind regime and summer-dominant rainfall (Loo et al. 2015). In this region, climate change is driving increasing air temperatures and changes in rainfall regimes (Loo et al. 2015; Sivakumar & Stefanski 2011). Climate change projections suggest a significant acceleration of warming, increasing annual rainfall, and increases in extreme climate events such as floods, drought and cyclones by 2100 (IPCC 2013; Loo et al. 2015). The predicted increase in temperature by the late 21st century and early 22nd century will cause frequent changes and shifts in monsoon precipitation of up to 70% below normal levels (Schewe & Levermann 2012), and monsoons may be delayed by up to 15 days (Schewe & Levermann 2012). Small scale regional circulations are more vulnerable to monsoonal variations and therefore, temporal and spatial distributions of monsoonal rainfall cannot be represented by general measurements (Loo et al. 2015). The increasing intensity of rainfall during the monsoon season is the major source of extreme climate events such as floods and landslides, which have the potential to affect vegetation (Loo et al. 2015). In some regions, droughts associated with significant changes in tree physiological characteristics (e.g., plant extractable water capacity of soil; annual evapotranspiration rate etc.) could result in regional die-offs in some species (e.g., Breshears et al. 2005). However, the impacts of climate change on tree species widely distributed over many countries, ecoregions (large units of land containing a geographically distinct assemblage of natural communities and environmental conditions) and topographies (Corlett & Lafrankie Jr 1998) in Asia have not been widely investigated (e.g., Pacifici et al. 2015; Thomas et al. 2004).

Among the biotic components of forests, trees are one of the earliest groups to be affected by climate change, through changes in phenology and distribution, and these changes could have cascading effects on the functioning of forest ecosystems (Butt et al. 2015; Cleland et al. 2007; Corlett & Lafrankie Jr 1998). Although trees generally respond slowly to climate change, their long life-spans suggest they will be unlikely to adapt fast enough to avoid negative impacts of climate change, such as heat and moisture stress and resulting high mortality rates (Margrove et al. 2015; Solomon & Kirilenko 1997). The indirect effect of changes in tree flowering and fruiting phenology on pollinators and seed dispersal agents (e.g. mammals, birds, insects) that rely on periodically available plant resources for their survival, may be more serious than the direct effects (Butt et al. 2015; Corlett & Lafrankie Jr 1998).

The Family Dipterocarpaceae comprises approximately 510 species and 16 genera, with 13 genera and 470 species largely restricted to South and Southeast Asia (Appanah & Turnbull 1998). Dipterocarp forests play an important role in the economy of many South and Southeast Asian countries, and dominate the international tropical timber market (Appanah & Turnbull 1998; Poore 1989). Dipterocarps are highly variable in terms of flowering and fruiting phenology, ecological characteristics and geographical ranges, as they occur in evergreen, semi-evergreen and deciduous forests (Appanah & Turnbull 1998). Climatic or geographic variations, along with increasing habitat destruction, are considered key threats for Asian Dipterocarp forests. Among the 13 genera in South and Southeast Asia, the *Shorea* and *Dipterocarpus* are the first and third most diverse genera, respectively, and are important components of Dipterocarp forest ecosystems (Soepadmo et al. 2004). While most of the species of these two genera are currently listed as threatened in different categories (i.e., 109 and 34 critically endangered species for *Shorea* and *Dipterocarpus* respectively), and at least one species from each genus is now regionally extinct (*Shorea cuspidata* in Malaysia and *Dipterocarpus cinereus* in Indonesia), their status is due to be reviewed (IUCN Species Survival Commission 2015). The dominant Dipterocarp trees Sal (*S. robusta*) and Garjan (*D. turbinatus*) of South and northern continental Southeast Asia form mono-specific canopies in dry deciduous, moist deciduous, evergreen and semi-evergreen forests (Appanah & Turnbull 1998; Gautam & Devoe 2006). Further, Sal and Garjan forest ecosystems are the natural habitat of many threatened animal species (e.g., *Elephas maximus*, *Ursus thibetanus*). Projected climate change impacts on Sal and Garjan species have the potential to trigger significant ecosystem-level responses.

Sal is a timber-yielding dominant tree that occurs commonly on the plains and lower foothills of the Himalayas and is distributed both in the tropical moist and dry deciduous forests of India, Bangladesh, Nepal and Bhutan (Gautam & Devoe 2006). Sal forests naturally occur in ecoregions with a mean annual temperature ranging from 22ºC to 27ºC and mean annual rainfall of 1000 to 2000 mm (Das & Alam 2001; Gautam & Devoe 2006). Although Sal is listed as a 'Least Concern' species in the IUCN Red list (IUCN Species Survival Commission 2015), recurrent anthropogenic disturbances such as over-exploitation, deforestation and encroachment combined with climate change, are major threats to Sal forests (Kushwaha & Nandy 2012). Results from previous work suggest that the natural distribution of Sal has contracted very rapidly over the last few decades, and it is thus highly vulnerable to climate change (Chaitale & Behera 2012; Deb et al. 2014; Sarker et al. 2011). Garjan is a 'Critically Endangered' (IUCN Species Survival Commission 2015) commercially important Dipterocarp tree naturally distributed in the tropical evergreen, semi-evergreen and deciduous forests of Bangladesh, India, Myanmar, Thailand, Cambodia and Vietnam (Ashton 1998). Garjan forests are located in wide bioclimatic regions characterised by temperature range of 15.6º to 40.6ºC, and annual rainfall of 1520 to 5080 mm (Das & Alam 2001). Garjan timber is used for lorry bodies, boat building, railway sleepers, transmission poles and other construction purposes (Das & Alam 2001). It is potentially vulnerable to anthropogenic climate change due to the interaction with existing anthropogenic pressures such as over-extraction, deforestation and forest degradation (Ashton 1998).

Several Asian countries, including Thailand, Philippines, China, Sri Lanka, Vietnam, and Bangladesh, have imposed logging bans to halt deforestation and conserve forest resources (Sarker et al. 2011). However, the trend of deforestation and associated biodiversity loss has called into question the effectiveness of these bans, and factors such as lack of effective conservation policies and accounting for climate risks also hinder the success of forest conservation and restoration (Sarker et al. 2011). Species distribution models (SDM) are useful for documenting biodiversity and understanding the effects of climate and human induced changes (Dale et al. 2001; Franklin 2010; Loiselle et al. 2003; Saatchi et al. 2008). Consequently, conservation practitioners have been increasingly using habitat suitability models and evaluating the results critically and cautiously to make management decisions (Loiselle et al. 2003; Saatchi et al. 2008).

The aim of this paper was to assess the vulnerability of two Dipterocarp trees (Sal and Garjan) of South and Southeast Asia to climate change by modelling their future distributions under two IPCC Representative Concentration Pathway (RCP) scenarios. We projected the potential distributions for both species in 2070 under two climate scenarios (RCP4.5 and RCP8.5). This will allow the identification of future suitable climate space for these Dipterocarp trees, and help inform conservation priorities for these threatened species in the region.

3.2 Methods

3.2.1 Species occurrence data

We combined the presence-only records of Sal and Garjan from a variety of sources including field survey, online database Global Biodiversity Information Facility (GBIF, <http://www.gbif.org/>), and literature records. The GBIF database contains point location of species which are often temporally and spatially biased (Boitani et al. 2011). We assessed the dataset under a set of criteria, including sample size, time relevance, environmental/geographic coverage, representation of areas of permanent and natural presence of the species (Boitani et al. 2011). To reduce potential errors in species locations, records were “cleaned” which included the careful review of literature for each species (Appanah & Turnbull 1998; Champion & Seth 1968; Das & Alam 2001) and the removal of duplicate locations. Finally, we selected 787 and 533 records for Sal and Garjan, respectively, to model their distributions. Sal dominates tropical moist and dry deciduous forests, and Garjan dominates or co-dominates evergreen, semi-evergreen and deciduous forest ecosystems in tropical Asia (Appanah & Turnbull 1998; Champion & Seth 1968; Gautam & Devoe 2006; Huda et al. 2006). We clipped the ecoregions for South and Southeast Asia from the Köppen-Geiger climate classification of the world (Peel et al. 2007) and combined them with the distributions of the two Dipterocarps to show their eco-regions in tropical Asia (Figure 3.1 and Table B3.1).

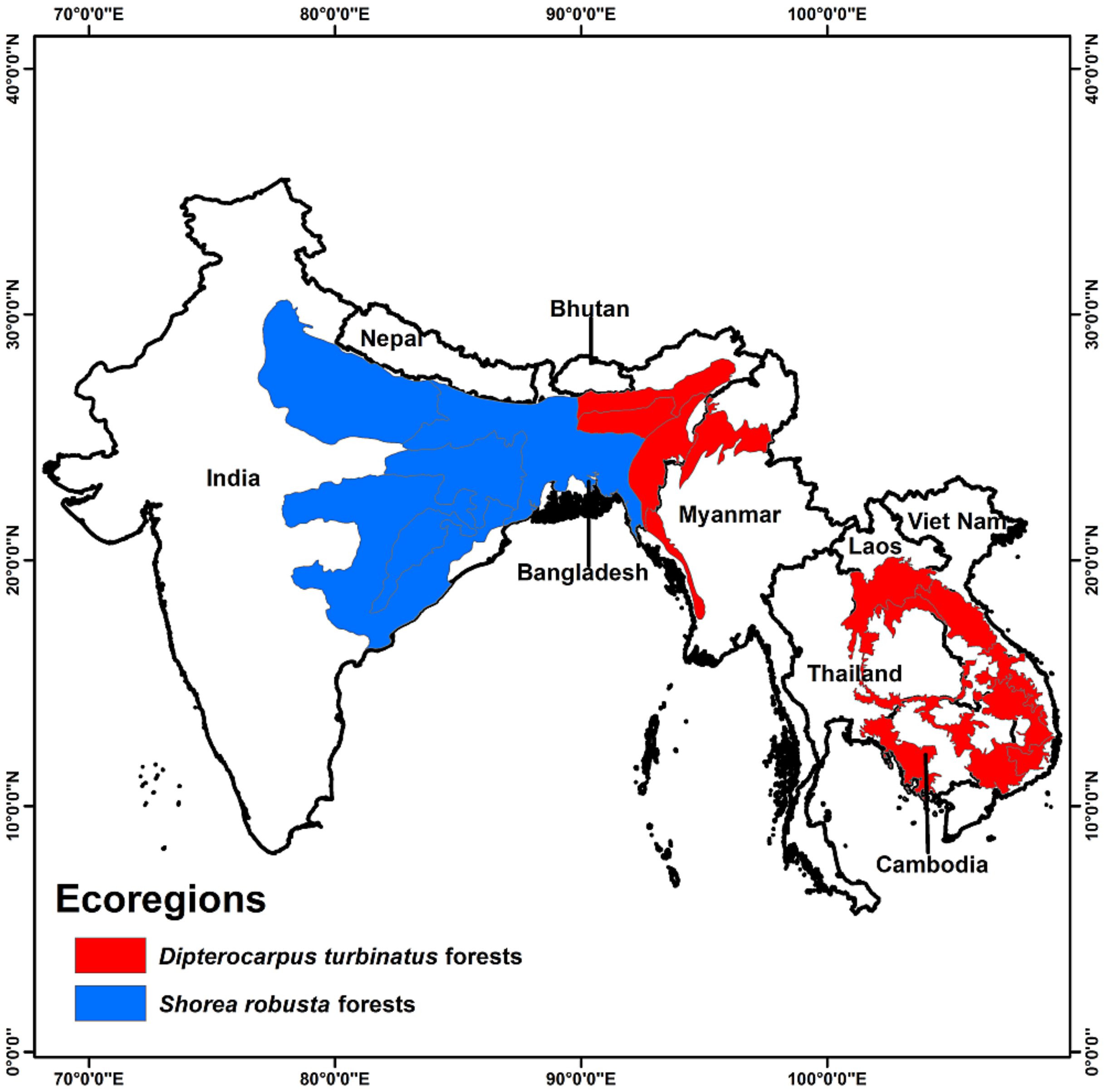

Figure 3.1 The distribution of *Dipterocarpus turbinatus* and *Shorea robusta* forests (Appanah & Turnbull 1998; Champion & Seth 1968; Gautam & Devoe 2006; Huda et al. 2006) were matched with the ecoregions in South and Southeast Asia (Peel et al. 2007; Table B3.1 for details). The red polygon depicts the ecoregions for *D. turbinatus* dominant in the evergreen, semi-evergreen and deciduous forests of Bangladesh, India, Myanmar, Thailand, Cambodia and Vietnam, whereas the blue polygon depicts the ecoregions for *S. robusta* dominant in tropical moist and dry deciduous forests of India, Bangladesh, Nepal and Bhutan.

3.2.2 Environmental variables

The direct effects of human activities such as large scale industrial logging, habitat destruction and fragmentation, illegal logging, and overexploitation are the primary contemporary drivers of tropical forest biodiversity loss along with the indirect effects of anthropogenic climate change (Hansen et al. 2013; Pacifici et al. 2015). Therefore, it is important to include habitat destruction variables along with climate variables in the modelling. Land use (description of land in terms of its socio-economic purpose, e.g., agriculture, forestry, residential etc.) and land cover (physical and biological cover of earth's surface, e.g., forests, agricultural areas, wetlands, water bodies etc.) variables are expected to change over shorter timescales. For instance, Sohl (2014) used land use/land cover (LULC) projections data produced for the conterminous United States, with annual LULC maps from 1992 to 2100 for four Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) for a bird distribution modelling. Although reliable projections of LULC are not available for tropical Asia, future values of climate change are predicted for the next several decades by General Circulation Models (GCM) (Hijmans et al. 2005). Stanton et al. (2012) suggested that combining the important static variables in the model along with the dynamic climate variables showed better result than excluding them (static variables). In this study, we modelled the distribution of Sal and Garjan using climatic variables only, and combining the unchanging or static environmental variables with the projected climate variables.

We initially considered 19 bioclimatic variables (11 temperature and 8 precipitation metrics) from the WorldClim database (Hijmans et al. 2005). All the bioclimatic layers were 1 km resolution. In addition, we also included four other static environmental variables: elevation (ELV) (Hijmans et al. 2005), mean annual actual evapotranspiration (AET) (Trabucco & Zomer 2010); land use/land cover (LULC) (Arino et al. 2012), and annual maximum green vegetation fraction (MGVF) (Broxton et al. 2014) in a different model to compare the model variations. As there is no robust dataset on LULC for tropical Asia, we included LULC variable from the default Global Land Cover Map for 2009 data (300 m resolution; 21 LULC classes) (Arino et al. 2012). The 1 km MODIS-based MGVF data are based on 12 years (2001-2012) of normalized difference vegetation index (NDVI) data (Broxton et al. 2014). Vegetation cover influences the land-atmosphere exchanges of water, energy, momentum, and carbon, and is widely used in global models along with many other applications such as studies of land cover change (Broxton et al. 2014; Dai et al. 2003). MGVF describes the vegetation abundance i.e., green vegetation fraction (vs. non vegetated area) for each land cover class for each year (Broxton et al. 2014). We assume including the LULC and MGVF variables in the model may capture the deforestation scenarios in the Sal and Garjan forests in the study region.

We clipped all the variables for the study area and processed all layers using the same extent, cell size and projection system (WGS84 Longitude-Latitude projection), in ArcGIS 10.1. We applied Spearman's rank correlation to test for collinearity between variables at each level, to allow us to exclude highly auto-correlated variables. For instance, if a pair of variable has a correlation coefficient > 0.7, then they were considered proxies of one another, and one of the variables was removed from the analysis (Table B3.2) (Elith et al. 2010). Test model runs identified five of the 19 bioclimatic variables as most correlated with the current distributions: annual mean temperature (BIO1); mean diurnal range (BIO2); temperature seasonality (BIO4); annual precipitation (BIO12);

and precipitation seasonality (BIO15). The other four static variables i.e. ELV, AET, LULC, and MGVF were considered along with the five bioclimatic variables for the combined model.

3.2.3 Climate scenarios

We selected two IPCC Representative Concentration Pathway (RCP) scenarios for our study: RCP4.5, an optimistic scenario where emissions peak around 2040, and RCP8.5, a pessimistic scenario, which reflects high levels of energy demand and greenhouse gas emissions, resulting in 8.5 W m^{-2} radiative forcing by 2100 (Moss et al. 2010). We constructed models using current climate conditions (average for 1950-2000) and projected to the future (given by WorldClim for the range 2061-2080, hereafter referred to as 2070). We used three Global Circulation Models (hereafter referred to as GCM) for future climatic conditions: ACCESS1.0; GFDL-CM3; and HadGEM2-ES (hereafter referred to as GCM 1, GCM 2, and GCM 3 respectively) (Hijmans et al. 2005; Table B3.3 for details). The reason behind choosing three GCMs was to encompass the full range of variation in the models in the multimodel ensemble CMIP5 that was released 2010-2014 (Taylor et al. 2012).

3.2.4 MaxEnt modelling algorithm

Climate envelope modelling can be evaluated for their ability to predict current species distributions. However, it is unclear whether models that are successful in predicting current distributions are equally successful in predicting distributions under different climates (i.e. different regions or time periods) (Hijmans & Graham 2006). We used a machine learning method ‘Maximum Entropy algorithm’ for modelling changes in species distribution (Phillips et al. 2006; Phillips et al. 2004). Hijmans & Graham (2006) reported that based on point localities extracted from the current suitable area, MaxEnt performed well compared to other models under current climates as well as under past and future climates. However, the ensemble modelling (e.g., Biomod2) cannot be used in the study as the presence/absence data of both studied species for the entire distribution in tropical Asia is not available (Thuiller et al. 2009). MaxEnt derives the probability distribution of species based on geo-referenced occurrence records and environmental variables and the output is continuous. It has advantages over other species distribution models as it requires species presence-only data and both continuous and categorical variables can be used in MaxEnt (Baldwin 2009). Recent studies have demonstrated MaxEnt’s ability to accurately predict species distribution in a wide range of ecological and geographical regions (Araújo & Guisan 2006; Elith et al. 2006; Merow et al. 2013).

Sampling bias is a well-known issue in presence-only distribution models and can have significant impacts on the model results (Elith et al. 2011). We have created a bias file layer to limit the background points to the occurrence areas for the species and accounting for the preferential use of the sites in the study region (Phillips et al. 2009). This provides MaxEnt with a background file with the same bias as the presence locations of the species (Figure B3.1 for details). As the distributions of both species are patchy and occur in different countries (of different areas), we used state boundaries of the countries to limit the background areas for the species (Figure B3.1 for details). In the model, 75% of the species presence data were used as training data and the remaining 25% were used as testing data in order to test the model's predictive strength. We tested different regularization multiplier and selected the default (i.e., 1) option as it performed best, that is, gave the best representation of the current distribution of both Sal and Garjan species without over-fitting the model (see Merow et al. 2013). The maximum number of background points for sampling was kept at 10,000. However, we also checked that increasing the background points (e.g., 100,000) did not change the model. We executed 5 replicates for each species using repeated split samples to measure the amount of variability in the model and then averaged the results. Maximum numbers of iterations were set to 1000 to allow the model to have adequate time for convergence, with $1 * 10^{-6}$ set as the convergence threshold. We used the default 'auto features' which includes all features (i.e., linear, quadratic, product, threshold and hinge features) (Merow et al. 2013). Area under the receiver operating characteristic curve, or AUC values, for training and testing data were calculated for each species. We used the jackknife test to measure variable importance and percent contributions of each variable to estimate the influence of environmental variables on each species. As the data were compiled from a variety of sources and likely to have some errors, we used the 10 percentile training presence logistic threshold to define the minimum probability of suitable habitat for the Dipterocarp trees (Phillips et al. 2006). By using this threshold, we defined suitable habitat to include 90% of the data we used to develop the models (see Phillips et al. 2006).

3.3 Results

3.3.1 Predictor variables

Our models predict that the relative contribution of the bioclimatic variables was more or less consistent for all three GCMs (Table 3.1). The key bioclimatic variable explaining the current and future spatial distributions of Sal and Garjan was annual precipitation (Sal: 49.97±1.33; Garjan: 37.63±1.19). The relative contribution of annual mean temperature to both Sal and Garjan models was almost identical (Sal: 19±1.3; Garjan: 19±1.64). The seasonal climatic variables i.e., temperature seasonality (15.33±0.29) and precipitation seasonality (11.43±0.47) were also important contributors to the Sal models, whereas mean diurnal range (4.2±0.66) was least important. In contrast, temperature seasonality (21.5±0.79) and mean diurnal range (16.53±1.11) were important contributors to the Garjan models, with precipitation seasonality least important

(5.23±1.20). The jackknife test results suggest that annual precipitation (BIO12) variable contributed most individually for both models (Figure B3.2).

Table 3.1 Summary of the bioclimatic variables used in the MaxEnt models and their percent contribution to each model.

Variables	**Description**	**Contribution to MaxEnt models (%)**					
		Shorea robusta			*Dipterocarpus turbinatus*		
		GCM-1	GCM-2	GCM-3	GCM-1	GCM-2	GCM-3
BIO1	Annual Mean Temperature	20.3	17.7	19	18.1	21	18.2
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	3.5	4.3	4.8	15.5	16.4	17.7
BIO4	Temperature Seasonality (standard deviation *100)	15.5	15.5	15	22.1	21.8	20.6
BIO12	Annual Precipitation	49.1	51.5	49.3	39	36.8	37.1
BIO15	Precipitation Seasonality (Coefficient of Variation)	11.6	10.9	11.8	5.3	4	6.4

The AUC values for all three GCM models were better than random (0.5) for both species (mean training AUC of the three GCMs for Sal: 0.897, and for Garjan: 0.825) and showed strong model discrimination ability for predicting changes in species distribution under changing climate scenarios (Table 3.2). The small differences in the AUC value of training and test cases suggested little overfit in the MaxEnt predictions for both species (Table 3.2). The AUC standard deviations indicate the overall performance of the models was high, representing a close approximation of the true probability distribution of the Dipterocarp trees (Table 3.2).

The individual response curves (marginal responses obtained by keeping all other bioclimatic variables at their average sample value) of the two key variables (annual precipitation and annual mean temperature) portray the relationships between each bioclimatic variable and probability of species occurrence (Figure 3.2). In Figure 3.2, (a-c) and (d-f) curves represent the response of annual precipitation and annual mean temperature for three Sal models respectively. Curves (g-i) and (j-l) represent the response of annual precipitation and annual mean temperature for three Garjan models respectively. The results exhibit complex but quadratic relationships between bioclimatic variables and the probability of species occurrence. In general, there was an overall positive nonlinear response observed for annual precipitation for both species (Figure 3.2). The optimum annual mean temperature for the probability of both Sal and Garjan occurrence was approximately 28°C in all models (Figure 3.2). However, the curves showed a high probability of presence of the species at low temperatures (especially for Garjan; Figure 3.2 j, k, l). This might be due to the occurrence of the species in different forest ecosystems with a large range of temperature and elevation.

Table 3.2 Results of threshold independent ROC tests for Dipterocarp tree species. AUC values for training (75%) and test (25%) data of the models. The test AUC describes the fit of the model to the test data and gives strong model discrimination ability for predicting changes in species distribution under future climate scenarios.

Species	Models	Training AUC	Test AUC	AUC Standard Deviation
Shorea robusta	GCM-1	0.894	0.891	0.012
	GCM-2	0.897	0.891	0.012
	GCM-3	0.899	0.886	0.013
Dipterocarpus turbinatus	GCM-1	0.827	0.799	0.025
	GCM-2	0.823	0.790	0.025
	GCM-3	0.824	0.794	0.025

3.3.2 Variability in climate niches for Dipterocarp trees

The predicted climatically suitable habitats of Sal and Garjan are shown for all three GCMs in Figure 3.3 and Figure 3.4 respectively. The 10th percentile training presence logistic threshold values were used to estimate the suitable and unsuitable climatic niches for both Dipterocarp trees across the study region. The proportional changes in suitable climate niches were derived from the difference between the species' modelled current and future climate niches for each scenario. Our models predicted that suitable climate space for both Sal and Garjan will decline by 2070, under both climate scenarios and for all three GCMs (Figure 3.5). On average, suitable habitat conditions for Sal will decline by 24% and 34% (the mean of three GCMs) by 2070 under RCP4.5 and RCP8.5 respectively (Figure 3.5). In contrast, the consequences of climate change appear less severe for Garjan, with a decline of 17% and 27% (the mean of three GCMs) under RCP4.5 and RCP8.5 respectively (Figure 3.5).

The distribution of Sal in Madhya Pradesh, Chhattisgarh, West Bengal, Odisha and Jharkhand in India is likely to lose suitable climate space by 2070 (Figure 3.3). In contrast, the distribution of Sal along the Terai tract in northern India is likely to gain suitable climate space by 2070 (Figure 3.3b-g). The lower belts of the hilly region, inner Terai, and the protected areas of Nepal, such as Chitwan National Park, Bardia National Park and Shukla Phat Wildlife Reserve, which support dense Sal forests, are also likely to lose suitable climate niches (Figure 3.3). The moist deciduous Sal forests in the central and northern region of Bangladesh (e.g., Madhupur National Park, Bhawal National Park) are likely to be affected most by climate change.

The predicted extent of suitable habitat of Garjan is smaller in Bangladesh, Myanmar, Cambodia, Thailand and Vietnam than in India (Assam, Manipur, Tripura, and Meghalaya). In particular, the Garjan-dominated semi-evergreen forests of the Chittagong Hill Tracts region in Bangladesh are likely to face increasing climate stress in the near future which may lead to local extinctions of this species. The extent of suitable habitat for Garjan is likely to be lost on the east side of study region, outside of species geographic range.

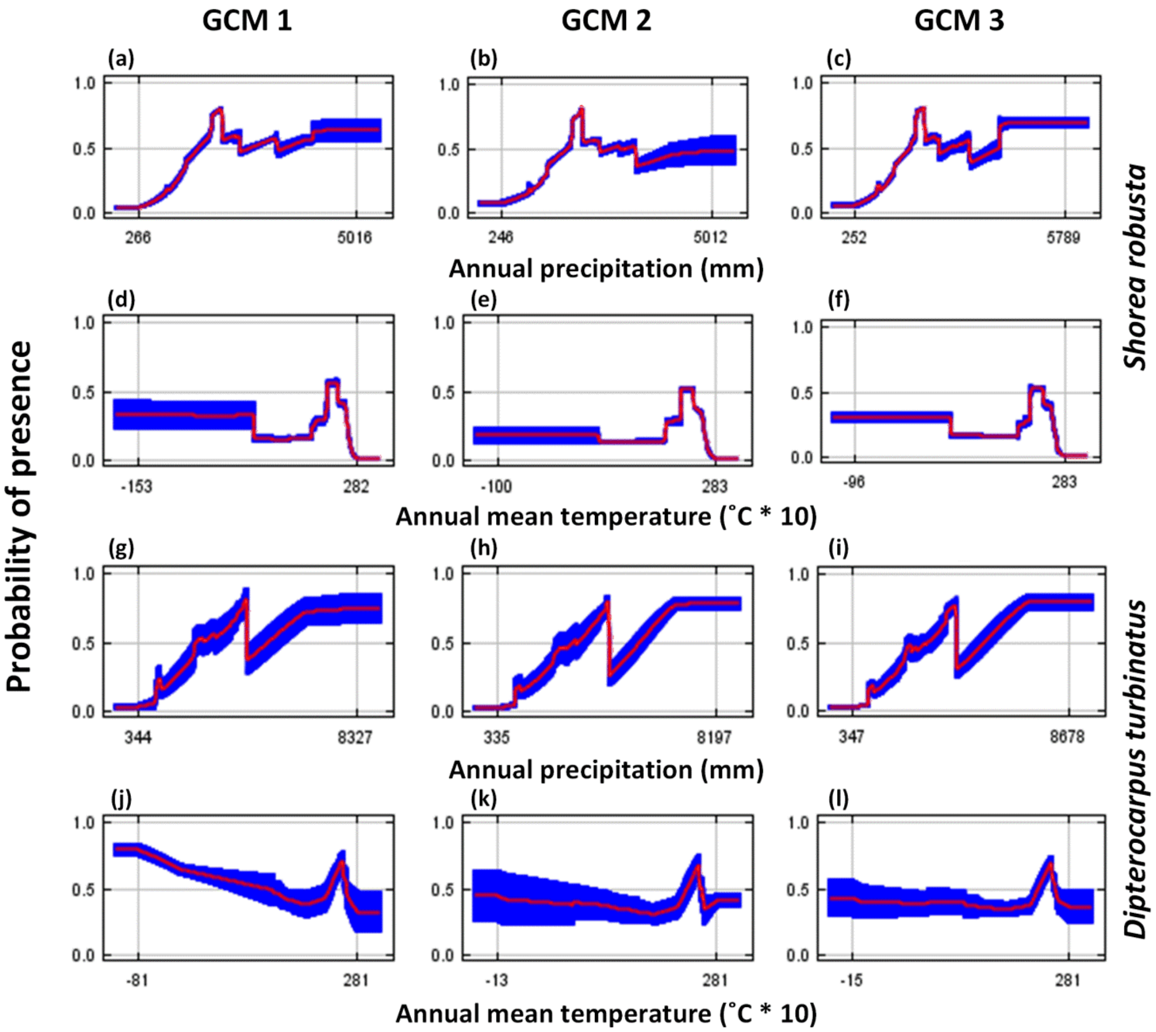

Figure 3.2 Graphs showing the marginal relationship between each bioclimatic variable and the probability of species occurrence: In the figures, the curves (red) and the mean +/- standard deviation (blue) show the response of *S. robusta* and *D. turbinatus* to the two most important variables (i.e., keeping all other bioclimatic variables at their average sample value) annual precipitation, and annual mean temperature. The y-axes indicate logistic output (probability of presence). The results suggest that there was an overall positive nonlinear response observed for annual precipitation for both species. The optimum annual mean temperature for the probability of Sal and Garjan occurrence was approximately 28°C in all models.

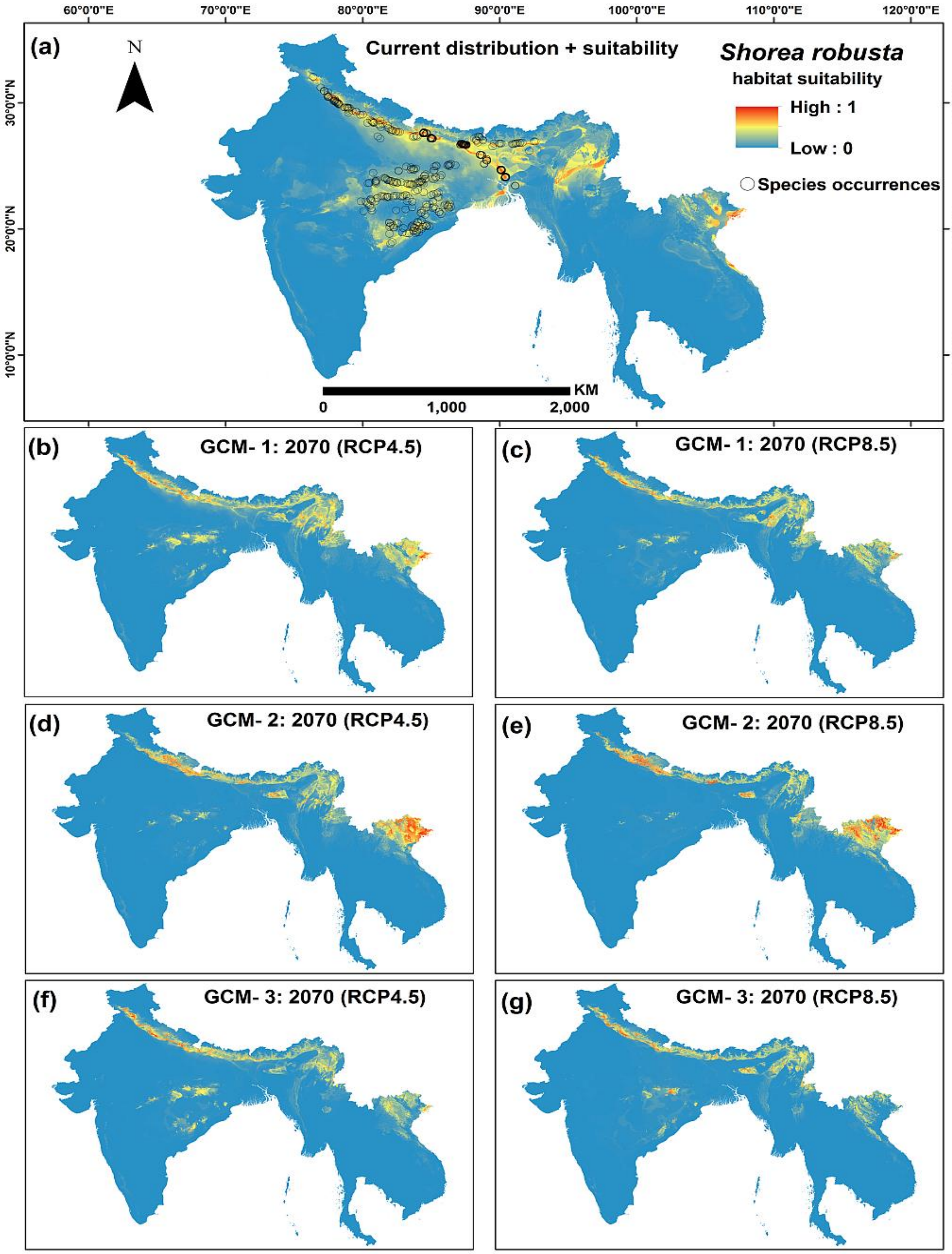

Figure 3.3 Predicted distribution of *S. robusta* species for three GCMs: (a) current distribution and suitability; (b-c) scenarios for CGM 1; (d-e) scenarios for GCM 2; and (f-g) scenarios for GCM 3. Modelling results suggest that climatically suitable habitat conditions for Sal will decline by 2070, with an average of 24% and 34% (the mean of three GCMs) under RCP4.5 and RCP8.5 respectively.

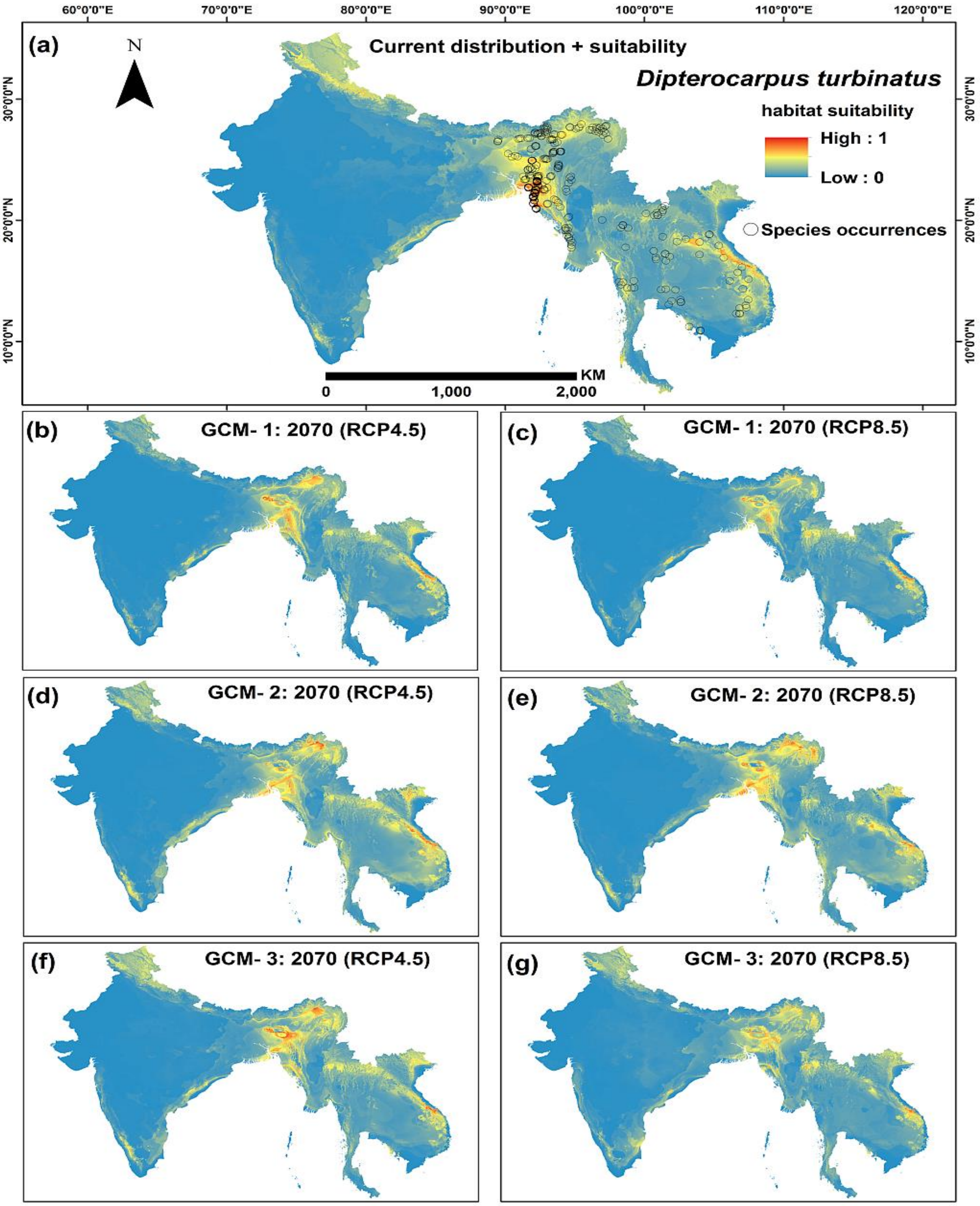

Figure 3.4 Predicted distribution of *D. turbinatus* species for all GCMs: (a) current distribution and suitability; (b-c) scenarios for CGM 1; (d-e) scenarios for GCM 2; and (f-g) scenarios for GCM 3. The consequences of imminent climate change appear less severe for Garjan, with a decline of 17% and 27% (the mean of three GCMs) under RCP4.5 and RCP8.5 respectively.

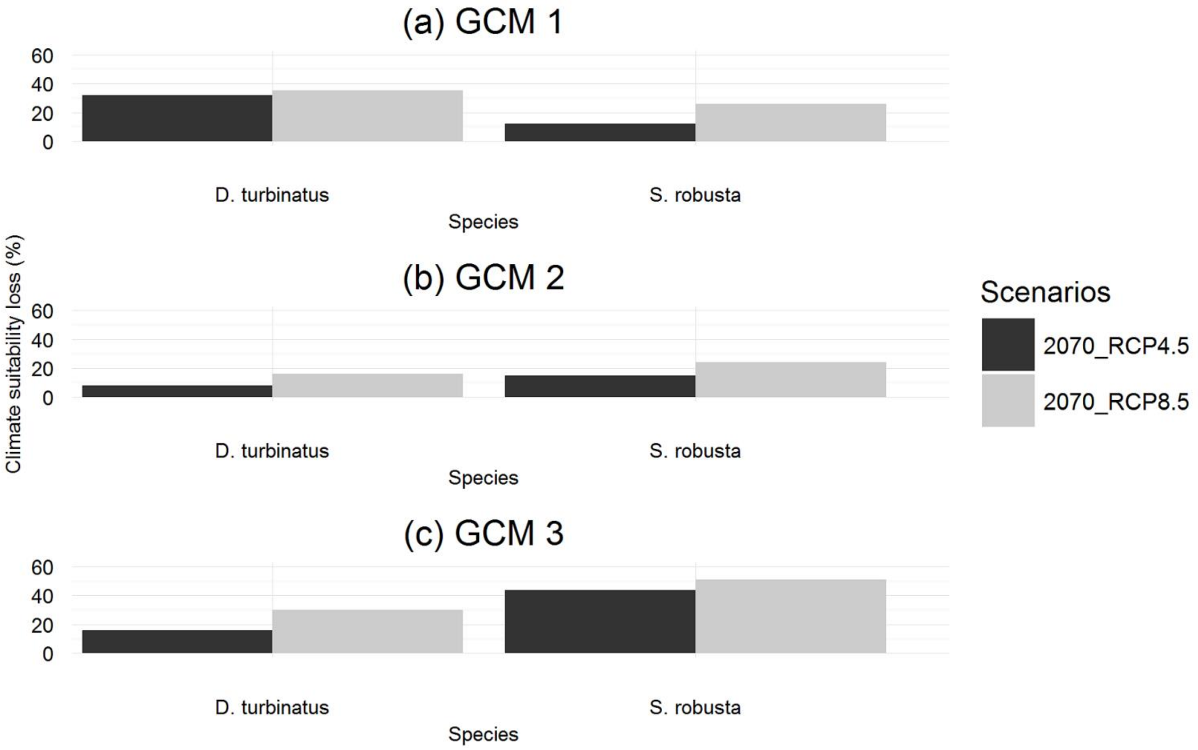

Figure 3.5 Proportional changes (%) in climate niches for both Dipterocarp species by 2070 under both climate scenarios. Predicted losses of pixel were calculated as a proportion of the pixels occupied in current scenario for the study area. The results of all GCMs suggest that both species are likely to lose climate suitability by 2070 under both climate scenarios.

The other models which included all bioclimatic and environmental variables also suggest that both Sal and Garjan species are likely to lose suitable climate space by 2070 (Figures B3.3, 3.4 & 3.5). The relative contribution of static LULC, MGVF, ELV and AET variables for species distribution are also apparent in the Sal and Grajan forests (on an average 24% for Sal and 42% for Garjan; Table B3.4 for details). It indicates that the Garjan dominated semi-evergreen forests in the Southeast Asia are more vulnerable due to the anthropogenic land use change than moist deciduous Sal forests.

3.4 Discussion

Although the projected distribution scenarios for the three GCMs were not identical in terms of climatically suitable habitat conditions for Sal and Garjan, the relative contribution of all bioclimatic variables used in the models and their AUC values were similar (Tables 3.1 &3.2), and the trends of the response curves of the variables for all GCMs were identical (Figure 3.2). Our results suggest that climate niches for both Dipterocarp trees are likely to come under increasing stress and potentially result in range contraction and distribution shifts across the region during the 21st century.

The study reveals that projected increases in annual precipitation and annual mean temperature may limit the distribution of Sal, as identified by our models (the optimum annual mean temperature was 28 ºC and annual precipitation ranges from 1000 to 2000 mm; Figure 3.2 for details) (Das & Alam 2001; Gautam & Devoe 2006). The variation of temperature seasonality may also regulate the distribution of Sal as it grows in areas where the dry period does not exceed four months (Gautam & Devoe 2006). The predicted shift in the distribution of Sal towards north-east in India is consistent with the findings of a similar study on Sal in India (Chitale & Behera 2012). Chitale & Behera (2012) predicted the distribution of Sal for the year 2020 under HadClim emission scenario SRES-A1B and included all 19 bioclimatic variables without considering their relative contributions. They also found that moisture (annual precipitation) was a key driver of Sal distribution: our consideration of the relative contribution of the bioclimatic variables revealed that annual mean temperature was also important. Increased rainfall variability and extreme drought conditions in the central and northern parts of Bangladesh may result in unsuitable climate conditions for Sal forests (Shahid 2010). The projected increase in annual rainfall and variation in temperature seasonality may restrict the distribution of Garjan in the region, with increasing local level extinction risk in the Chittagong hill tract regions of Bangladesh (Das & Alam 2001; Sarker et al. 2011).

Dipterocarp trees are confined to wet climates, with a dry season of four months and more abundant in aseasonal than seasonal climates (Ashton 1988). However, the ecoregions for Sal and Garjan are restricted to monsoon tropics where water availability is seasonally limiting (mean rainfall of driest month < 50 mm) (Corlett & Lafrankie Jr 1998): significant climatic anomalies such as increasing temperature seasonality and drought conditions may affect the growth of these Dipterocarp trees.

3.4.1 Impacts on Sal and Garjan forest ecosystems

The consequences of climate change may result in the absence of Sal and Garjan either locally or regionally, the disappearance of entire ecosystems, or their replacement by other ecosystem types (Thomas et al. 2004). Changes in precipitation and temperature regimes, including the duration of the dry season, may result in phenological shifts of both Dipterocarp trees, with indirect effects on floral and faunal species dependent on them. Many terrestrial birds, mammals and insects that rely directly and indirectly on the flowers, fruits and seeds of Dipterocarps are likely to be adversely affected by climate change (Butt et al. 2015). The continuing deforestation and threats associated with climate change could lead to the extinction of mammal species such as the leopard cat (*Felis bengalensis*), fishing cat (*Felis viverrina*), jungle cat (*Felis chaus*) and small Indian civet (*Viverricula indica*) inhabiting Dipterocarp forests (Alam et al. 2008; Thomas et al. 2004).

3.4.2 Partitioning the contribution of static and dynamic variables in the models

The biotic factors (e.g., competition, dispersal abilities) are largely independent of the abiotic factors (environmental variables) in their explanatory capacity for the full range of fundamental (potential) niche of tree species (Pearson 2010). Although including the biotic factors will improve the ability of the models to predict small-scale distribution patterns, a clear improvement in the continental-scale distribution of species is difficult to predict. Furthermore, there is no dataset available for the biotic factors in tropical Asia. We did not incorporate the changes in habitat loss variables (for the future climate scenarios) in the model, and therefore, could not control for confounding correlation between climate change and habitat loss variables. However, adding the static limiting factors (constraints) in the model provides the realized (occupied) niche of the species (Pearson 2010). The static environmental variables contributed less than the dynamic bioclimatic variables in the MaxEnt models for all three GCMs (Table B3.4). Annual precipitation was the key bioclimatic variable for the distribution of Sal and Garjan forests. However, the relative contribution of LULC, MGVF, ELV, and AET variables indicate the importance of including them in the model, as these drivers and climate change are known to interact in their effects on biodiversity. It may be argued that leaving the static variables out of the analysis might be better as these variables do not fully account for their effect on the future habitat suitability of species. Our results suggest that as these variables affect species distribution, including them in the model is better or no worse than excluding them (Figures B3.3 & B3.4), even making unrealistic assumptions that their values will not change in future (Stanton et al. 2012). The MaxEnt models suggest that land use patterns across the Dipterocarp forests in tropical Asia will affect regional climates by altering the balance of carbon in terrestrial and atmospheric pools (Oliver & Morecroft 2014). Conversely, climate change can also influence LULC with a direct influence on the climax vegetation type, and through changes to socioeconomic systems (Oliver & Morecroft 2014). All these impacts of climate on land use and land use on climate, may strong effects on the biodiversity of Sal and Garjan forests in tropical Asia. We acknowledge the limitations and assumptions on our modelling due to the lack of robust dataset in tropical Asia. However, future studies should incorporate more dynamic biotic and abiotic variables (associated with species ecology) and explore more methodologies (e.g., statistical, machine learning, and bioclimatic modelling) to describe the combined effects of habitat loss, climate change and other variables on the distribution of Dipterocarp species in tropical Asia.

3.4.3 Implications for conservation planning

The findings of our models can be tailored to suit conservation guidelines for Sal and Garjan in South and Southeast Asia by identifying critically vulnerable habitats and potential climatically suitable habitats where artificial regeneration should be undertaken for forest restoration. Our models detected a shift in the distribution of suitable climate space for Sal outside of its natural distribution towards the deciduous and semi-evergreen forests of north-eastern India, Myanmar, Laos and Vietnam (Figure 3.3d,e). As a conservation strategy, assisted migration of Sal into these potentially climatically suitable areas may be possible under a wide range of possible future climates (e.g., Hällfors et al. 2016). In addition, the modelling outputs of our study can be used to categorize the natural habitats of Sal and Garjan trees as low to high risk under changing climates in the study region to inform conservation planning. For instance, Sal and Garjan plantations should be preferentially introduced to the climatically suitable sites, and more conservation care for the natural regeneration of these trees should be taken in the sties calculated as high risk under future climates. The rotation period of Sal and Garjan timber may be shortened in those sites and replaced with other species assessed as more suitable under changing climatic conditions.

Forests play an important role in the global carbon cycle as they hold more carbon than the atmosphere (Pan et al. 2011). Sal and Garjan are the long rotation species in South and Southeast Asia and are important for ecosystem functioning and carbon storage. Therefore, small changes in their distributions can have large implications in terms of carbon storage and stocks as they are distributed over a large area in Asia (e.g., Sal forests cover over 11 million ha in India, Bangladesh, and Nepal). Bioclimatic and ecological traits of Dipterocarp species in a particular forest ecosystem are very important for successful forest management, as climate change can drive significant alterations in forest site conditions (Falk & Mellert 2011). This type of study, of changes in suitable climate space, and therefore the distribution of tree species, could inform forest carbon management.

3.4.4 Future research directions

Although MaxEnt cannot be viewed as an entirely objective modelling method due to the effects of choosing different settings (Merow et al. 2014), we consider the final models not to be unnecessarily complex based on the knowledge of vegetation types, the environmental space and the specific data set used in this study. In our study, the results may be influenced by several factors. Firstly, we compiled the presence-only data from different sources and it is highly likely that not all native occurrence records of the species have been included in this study. Secondly, the distributions of Dipterocarp trees are relatively well known across India, Bangladesh, Nepal, and Myanmar (e.g., Alam et al. 2008; Appanah & Turnbull 1998; Champion & Seth 1968; Chitale & Behera 2012). This may be partly responsible for the higher number of species occurrence records in these areas compared to other native ranges. The ensemble distribution modelling (Biomod2) of species using presence/absence data for the entire distribution should be focused in future research

(Thuiller et al. 2009). In addition, sampling bias should be corrected using target-group bias correction or true effort bias correction to understand the model variations in future research (Ranc et al. 2016). As the main objective of our study was to assess species vulnerability to climate change, we used only bioclimatic variables in the model. The realized climatic niche for the Dipterocarp trees that we describe here represents a close approximation to reality (Alam et al. 2008; Champion & Seth 1968; Chitale & Behera 2012). In addition, we also included elevation, mean annual actual evapotranspiration, land use/land cover, and annual maximum green vegetation fraction variables in a different model to capture the impact of deforestation scenarios along with climate change in the study region (Figures B3.3, 3.4 & 3.5). The results suggest that environmental variables are also important to predict the distribution of species. Future research needs to focus on mechanistic modelling of the Dipterocarp trees using detailed understanding of the physiological response of species to environmental factors such as competition, predation, soils, phenology, dispersal mechanisms, reproductive success, and biotic interactions (Pearson 2010). Also, anthropogenic variable such as logging pressures should be considered into the combined effects of land use change and climate change in future modelling (Asner et al. 2010; Mantyka-Pringle et al. 2014).

CHAPTER 4

CLIMATIC-INDUCED SHIFTS IN THE DISTRIBUTION OF TEAK (*Tectona grandis*) IN TROPICAL ASIA: IMPLICATIONS FOR FOREST MANAGEMENT AND PLANNING

Associated publication:

Deb, JC, Phinn, S, Butt, N & McAlpine, CA 2017, 'Climatic-induced shifts in the distribution of Teak (*Tectona grandis*) in tropical Asia: implications for forest management and planning', *Environmental Management* vol. 60, pp. 422-435

Abstract

Modelling the future suitable climate space for tree species has become a widely used tool for forest management planning under global climate change. Teak (*Tectona grandis*) is one of the most valuable tropical hardwood species in the international timber market, and natural teak forests are distributed from India through Myanmar, Laos and Thailand. The extents of teak forests are shrinking due to deforestation and the local impacts of global climate change. However, the direct impacts of climate changes on the continental-scale distributions of native and non-native teak have not been examined. In this study, we developed a species distribution model for teak across its entire native distribution in tropical Asia, and its non-native distribution in Bangladesh. We used presence-only records of trees and twelve environmental variables that were most representative for current teak distributions in South and Southeast Asia. MaxEnt (maximum entropy) models were used to model the distributions of teak under current and future climate scenarios. We found that land use/land cover (LULC) and elevation were the two most important variables explaining the current and future distributions of native and non-native teak in tropical Asia. Changes in annual precipitation, precipitation seasonality and annual mean actual evapotranspiration may result in shifts in the distributions of teak across tropical Asia. We discuss the implications for the conservation of critical teak habitats, forest management planning, and risks of biological invasion that may occur due to its cultivation in non-native ranges.

Keywords Climate change, forest management, exotic species, species' distribution models, biological invasions

4.1 Introduction

Climatic niche models have been used widely for predicting shifts in species distributions in response to climate change. They also have been used for testing of ecological theory (Austin et al. 2006), understanding biological processes (Leathwick & Austin 2001) and climate change impacts on biodiversity (Guisan et al. 2006; Loiselle et al. 2003; Pearson et al. 2007). Modelling the potential (future) distribution of a species rather than its realized (current) distribution is a valuable tool for environmental management and planning under climate change (e.g., Falk & Mellert 2011; Hanewinkel et al. 2010; Mezquida et al. 2010). As the inherent natural adaptive capacity of forest ecosystems to changing climatic conditions is limited by the long life span of trees, mitigation strategies such as the introduction of tree species well adapted to changing environmental conditions may reduce the impacts of predicted future climate change on forests (Köhl et al. 2010). Knowledge of the potential distributions of climatically suitable habitat allows forest managers to assess the vulnerability of species and ecosystems to climate change (Wang et al. 2016). Global climate change is forecast to become a prominent cause of species extinction during the 21st century by directly increasing climatic stress on species and through synergies with other drivers such as land use change, overexploitation and introduction of alien invasive species (Pacifici et al. 2015).

The forests of tropical Asia are particularly vulnerable to climate change due to their fragmented state (Corlett & Lafrankie Jr 1998; Hansen et al. 2013). Climatic niche modelling of Asian forests could provide a valuable, first-order assessment of the potential impacts of climate change and provide a scientific basis for developing adaptive and mitigation strategies in forest management planning (Wang et al. 2016). Teak (*T. grandis*), belonging to the family Verbenaceae, is arguably the best-known and most valuable Asian tropical hardwood species (Bermejo et al. 2004; Nunifu & Murchison 1999). The discontinuous natural distribution of teak ranges from peninsular India through Myanmar, Laos, and Thailand (Midgley et al. 2015; Nidavani & Mahalakshmi 2014). The global area of natural teak forest is estimated to cover over 29 million ha, and the area of planted teak forests in 38 countries is estimated to be 4.4 million ha, of which 83% is in Asia, 11% in Africa, and 6% in tropical America (Kollert & Cherubini 2012). The physical and aesthetic properties of teak make it a very valuable timber species and it is widely used to produce indoor and outdoor furniture, housing materials, crafts, ships and many other products (Bermejo et al. 2004; Midgley et al. 2015).

In the late 1800s, commercial teak plantations were introduced to South and Southeast Asian countries as the demand exceeded the sustainable supply from natural forests (Roshetko et al. 2013). However, during the late 1960s and early 1970s, deforestation in the natural teak belt of South and Southeast Asia triggered a crisis in teak timber production and consequently teak plantations expanded worldwide (Midgley et al. 2015). India, Laos, Thailand and Myanmar imposed logging bans in natural teak forests due to deforestation pressures, and allowed only a limited sustainable harvest from natural forests (Roshetko et al. 2013). Globally, Asia remains the largest exporter of teak, mainly due to Myanmar's teak supplies from natural and plantation forests (Raiyani 2013) (Figure 4.1). Africa is a consistently large supplier, and there has been a greater than 20% increase in teak supplies from Latin American countries during the period 2005-2010 (Figure 4.1).

Bioclimatic variables such as rainfall, soil moisture, temperature, light, geological formations and soil conditions influence the distribution and growth of teak (Troup 1921). Teak is a light-demanding species and grows fastest in moist conditions with a varying range of temperatures (Kaosa-ard 1981). Soil organic matter, soil nitrogen and a relatively large amount of soil calcium are important for its growth and development (Kaosa-ard 1981). Projected climate changes are likely to affect the distribution of the species. Climate change can alter forest site conditions (e.g., changes in rainfall pattern in the tropical rainforests or changes in climatic conditions of droughty forest sites), which may result in shifts in species distribution (Thuiller et al. 2005). Therefore, it is important to understand the bioclimatic conditions and ecological traits of teak forests to inform their sustainable management under changing climates (Falk & Mellert 2011).

Teak was introduced to the hill forests of Bangladesh as an exotic plantation species in 1871 from Myanmar (Das & Alam 2001). Despite its importance in the international timber market, very few studies have investigated the impacts of climate change on the distribution of teak forests in Asia. Gopalkrishnan et al. (2011) investigated the long-term effect of climate change on teak and its productivity in India and revealed that 30% of teak in India is vulnerable to climate change under both A2 and B2 SRES scenarios of the IPCC Fourth Assessment Report (IPCC 2007). However, no systematic study has been conducted across the entire natural distribution ranges of teak, or for teak plantations.

In this study, we address the following questions: 1) How is the Asian distribution of teak (both natural and plantation) likely to shift under a future climate? 2) What are the most important bioclimatic variables for the spatial distribution of teak forests? We address these questions by applying a climate envelope modelling approach using Maxent (Maximum Entropy) algorithm. We used presence-only species occurrence records, twelve environmental variables, and two climate change scenarios (RCP6.0 and RCP8.5), and compared the distributions at current, 2050 and 2070 time steps. Finally, we discuss the implication for teak management and the risk of invasion in teak forest ecosystems.

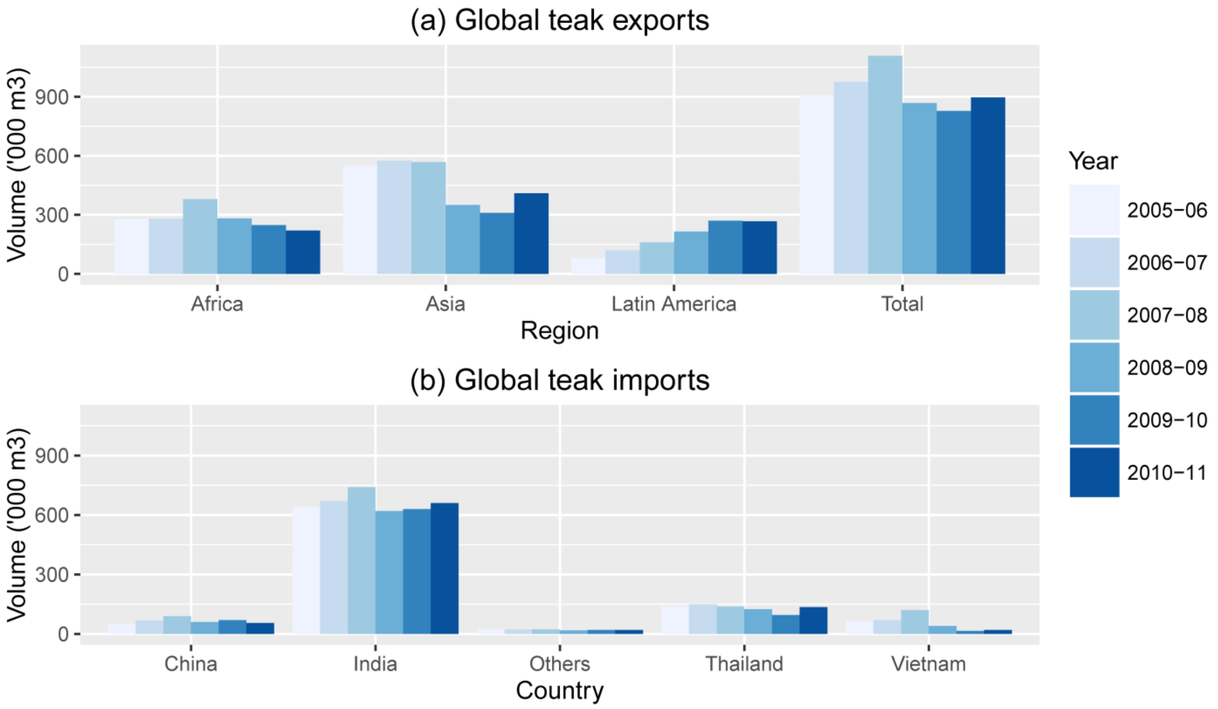

Figure 4.1 The global teak trade scenario for the period 2005 to 2011: (a) global teak exports by tropical regions; (b) global teak imports by countries. Asian countries are the largest teak exporters in the world followed by Africa and Latin America. India is the largest teak importer country (imports from a range of countries dominated by Myanmar) followed by Thailand and China (adapted from Raiyani 2013)

4.2 Methods

4.2.1 Study Species and Region

Teak prefers fertile, well-drained deep alluvium soils in hilly and undulating terrain up to 1,000 m altitude, with annual rainfall of 1,250–3,750 mm, minimum temperature of 13–17°C, and maximum temperature of 30–43°C (Pandey & Brown 2000). Champion & Seth (1968) classified the teak forests in India into five types by correlating the amount of rainfall, stand composition and stand density (Table 4.1). Similarly, Kaosa-ard (1977) ascribed the teak zones in Thailand to four different zones (Table 4.1) by using a P: T ratio moisture index method (P = annual rainfall (mm); T = annual mean temperature (°C)). We created species distribution models of naturally distributed teak found in deciduous forests in India, Myanmar, Laos and Thailand (Figure 4.2a), and non-native teak distributed in evergreen and semi-evergreen forests in Bangladesh (Figure 4.2b). The climatic requirements, soil conditions, stand composition and natural regeneration vary across the different teak forests in the study areas (e.g., different types of teak forests in India and Thailand; Table 4.1 for details).

Table 4.1 The different types of teak forests in India and Thailand based on ecological, silvicultural and climatic conditions (Champion & Seth 1968; Kaosa-ard 1977)

Country	Teak forest types		Characteristics
India	i.	Very moist	Rainfall > 2500 mm/annum; deep alluvial soils; low stand density (< 10%); very dense undergrowth; little natural regeneration; no fires.
	ii.	Moist	Rainfall 1600-2500 mm/annum; deep loamy soils; fair to medium stand density (10-25%); dense undergrowth; fair but patchy natural regeneration; no fires.
	iii.	Semi-moist	Rainfall 1300-1600mm/annum; moderately deep and loamy soils; medium to high stand density (20-60%); moderate undergrowth; fairly adequate natural regeneration; occasional fires.
	iv.	Dry	Rainfall 900-1300 mm/annum; shallow or sandy or stiff clayey soils; high (50%) to almost purse stand; light and patchy undergrowth; group or patchy natural regeneration; frequent fires.
	v.	Very dry	Rainfall < 900 mm/annum; poor, shallow and rapid run-off or drainage soils; medium stand density; scanty ground cover; particularly absent natural regeneration; annual fires.
Thailand	Zone 1		Dry-humid zone with P/T ratio < 40 (P = annual rainfall in mm; T = annual mean temperature in °C)
	Zone 2		Medium-humid zone with P/T ratio of 40-50
	Zone 3		Moist-humid zone with P/T ratio of 50-60
	Zone 4		Wet zone with P/T ratio > 60

4.2.2 Species distribution and environmental data

We compiled georeferenced presence-only species occurrence records of native and non-native teak stands from a variety of sources including field survey, the Global Biodiversity Information Facility Data Portal (GBIF: http://www.gbif.org/) and published literature. To clean the records, we undertook a number of steps including: removal of duplicate records; correction of coordinate records where possible, and removal of spurious locations outside the species known geographic range (Champion & Seth 1968). The final teak dataset comprised 581 records in native ranges and 171 records in non-native ranges, with the latter concentrated in Bangladesh. For this reason, we selected 'Bangladesh' as a case study to assess the likely climate change impacts on non-native distributions of teak. The area of commercial teak plantations in Bangladesh was estimated to be approximately 73,000 ha in 2010 (Kollert & Cherubini 2012), and the growth of teak plantations in the hill forests of Bangladesh was financially viable (Das & Alam 2001).

We used both dynamic climatic variables (future values are predicted by general circulation models) and static environmental variables (reliable projections are not available) in the models (Stanton et al. 2012). Bioclimatic variables were obtained from WorldClim v 1.4 (Hijmans et al. 2005). In addition, four other static environmental variables: elevation (ELV) (Hijmans et al. 2005), mean annual actual evapotranspiration (AET) (Trabucco & Zomer 2010); land use/land cover (LULC) (Arino et al. 2012), and annual maximum green vegetation fraction (MGVF) (Broxton et al. 2014) were included in the models. The LULC change for future climate scenarios are not available for tropical Asia and therefore, we included LULC variable from the default Global Land Cover Map for 2009 data (300 m resolution; 21 LULC classes) (Arino et al. 2012). The 1 km MODIS-based MGVF data are based on 12 years (2001-2012) of normalized difference vegetation index (NDVI) data (Broxton et al. 2014). The LULC and MGVF variables have the potential to capture deforestation patterns resulting from human land use in the study region. All these variables provide a mix of means, extremes and seasonality of climate, topographical variation of different forest types and land use change, and tree physiological factors, and play a vital role in teak establishment and growth. We used ArcGIS 10.1 to extract the predictor variables for the study area, and to standardise the cell size, extent and coordinate system. Data were aggregated to the landscape scale (1 km grid resolution). We initially tested 23 bioclimatic and environmental variables (Table C4.1 for details).

We selected two Representative Concentration Pathway (RCP) scenarios (i.e. one mid-range: RCP6.0 and one extreme: RCP8.5) for our study (Hijmans et al. 2005). These reflect the most likely climate outcomes for teak forests given the current level of mitigation activity. We compared the bioclimatic scenarios for current conditions (average for 1950-2000) with those for projected time periods of 2050 (average for 2041-2060) and 2070 (average for 2061-2080) from the HadGEM2-ES Global Circulation Model (GCM) (Hijmans et al. 2005).

4.2.3 Exploratory data analysis

Spearman’s rank correlation was applied to test for collinearity between variables at each level. Elith et al. (2010) suggest that if a pair of variables has a correlation coefficient > 0.7, then they should be considered proxies of one another, and one of the variables should be removed. We followed this general rule and selected a sub-set of twelve environmental variables (nine for native distributions and eleven for non-native distributions): annual mean temperature (BIO1); mean diurnal range (BIO2); isothermality (BIO3); temperature seasonality (BIO4); mean temperature of driest quarter (BIO9); annual precipitation (BIO12); precipitation of driest month (BIO14), precipitation seasonality (BIO15); elevation (ELV); land use/land cover (LULC); actual evapotranspiration (AET); and maximum green vegetation fraction (MGVF).

4.2.4 Species distribution models

We used MaxEnt version 3.3.3 k (Phillips et al. 2006) to model the distribution of teak under present and future climates. Species distribution models of teak were created at 1 km spatial scale both for native and non-native ranges. MaxEnt algorithms are often used as they produce robust results with limited and spatially biased presence data (Elith et al. 2006; Loiselle et al. 2008; Phillips et al. 2006; Pearson et al. 2007). MaxEnt can assess variable importance by providing the percent contribution of each variable (continuous or categorical or both) to the predicted models (Elith et al. 2011). The probability output of the model is continuous (values between 0 and 1) and is calculated by minimizing the relative entropy between the two probability densities of the landscape covariates, with and without species presence (Elith et al. 2011). We set the random test percentage to 25% and five replicates using repeated split samples to measure the amount of variability in the model, and then averaged the results (Phillips et al. 2006). We created a bias file layer using the state boundaries of the countries and defined MaxEnt Background selection by limiting the sampling locations from where they were selected (Phillips et al. 2009). The bias layer limits the background point to areas that we assume were surveyed for the teak and provides MaxEnt with a background file with the same bias as the presence locations, to improve the robustness of the model extrapolation. We validated the models using the threshold-independent metric, Area under the Receiver Operating Curve (AUC). The AUC metric (value ranges between 0 and 1.0) provides an assessment of how accurately the model predicts the probability of occurrence for a species within a given area (Phillips et al. 2006; Phillips & Dudík 2008). Models with AUC values are greater than 0.75 have good discrimination ability in accurately identifying the potential distribution of a species (Elith et al. 2011).

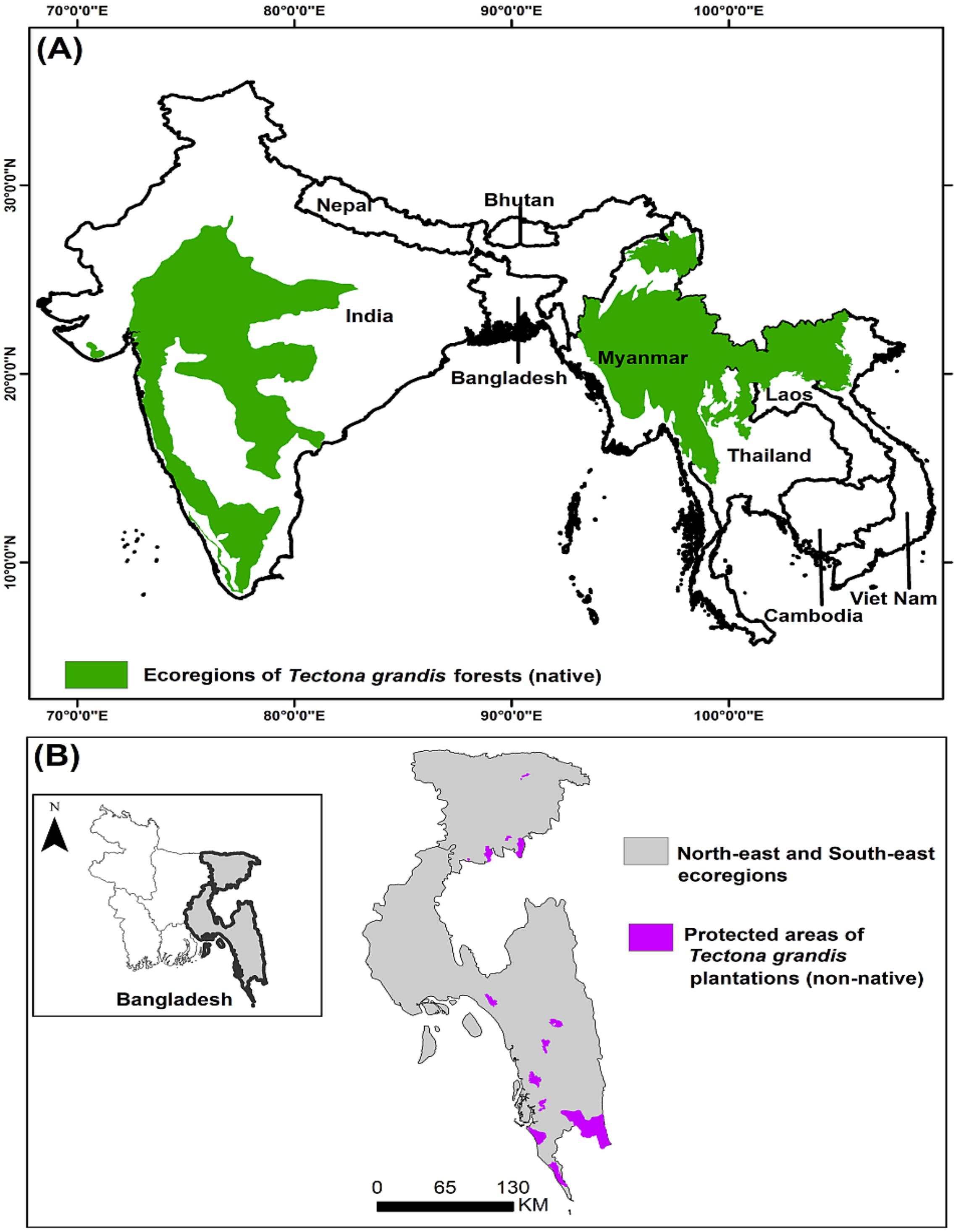

Figure 4.2 The distribution of *Tectona grandis* in tropical Asia: (A) the green polygon represents the distribution of natural teak across the ecoregions that range from the deciduous forests of peninsular India through Myanmar, Laos and Thailand (Peel et al. 2007; Table C4.2 for details of eco-regions); (B) teak plantations were introduced in Bangladesh in 1871 from Myanmar and teak is now acclimatized across the tropical evergreen and semi-evergreen forests of the north-east and south-east climatic regions (grey colour). The pink polygon represents the different protected areas of Bangladesh where the teak plantations are currently distributed (Das & Alam 2001)

4.3 Results

4.3.1 Predictor variables, response curves and model performance

The final set of predictor variables and their percentage contribution in the final MaxEnt models are shown in Table 4.2. The predictor variables for the distribution of both native and non-native forests were similar. For native distributions of teak, LULC (25.4%) and elevation (19.0%) were the key predictor variables along with significant contributions from the variables precipitation seasonality (13.7%), actual evapotranspiration (13.7%), annual precipitation (9.1%) and MGVF (9.0%). Land use change and deforestation at different elevations of deciduous teak forests were the key drivers of the distributions of natural teak in India, Myanmar, Laos and Thailand. The key predictor variables for exotic teak plantations in Bangladesh were LULC (37.7%), elevation (19.4%), annual precipitation (11.3%) and isothermality (7.9%). The results highlight that climate seasonality rather than the mean annual climate is more important for the distribution of natural teak (Table 4.2), whereas seasonal and extreme temperatures and precipitation are the key factors for the distributions of teak plantations in Bangladesh (Table 4.2).

The response curves of the two most important variables along with annual mean temperature (BIO1) and annual precipitation (BIO12) are presented in Figure C4.1 (a-d for natural distributions; e-h for non-native distributions). The response of naturally growing teak to temperature and rainfall indicates that there is a distribution limit at a minimum annual mean temperature of 30°C and maximum annual rainfall of 3500 mm (Figure C4.1, a-b). The teak plantations located in the evergreen and semi-evergreen forests of Bangladesh have a distribution limit at a minimum annual mean temperature of 26°C and maximum annual rainfall of approximately 4500 mm (Figure C4.1, e-f).

The training and test AUC scores and the AUC standard deviation (training AUC: 0.844 ± 0.051 for native distributions; and 0.974 ± 0.007 for non-native distributions) for all replicated models indicate that both sets of models showed good to strong discrimination ability in predicting the potential current and future distributions of teak under different climate scenarios (Table C4.3 for details).

Table 4.2 Sub-set of twelve key environmental predictors (nine for native and eleven for non-native ranges) identified following a multicollinearity test for the MaxEnt models of *Tectona grandis* and their percent contribution to each model

Variables	**Description**	**Contribution to MaxEnt models of *Tectona grandis* (%)**	
		Native ranges	Non-native ranges
BIO1	Annual Mean Temperature	0.9	0.1
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	3.0	-
BIO3	Isothermality (BIO2/BIO7) (*100)	-	7.9
BIO4	Temperature Seasonality (standard deviation *100)	6.1	5.6
BIO9	Mean Temperature of Driest Quarter	-	6.4
BIO12	Annual Precipitation	9.1	11.3
BIO14	Precipitation of Driest Month	-	1.9
BIO15	Precipitation Seasonality (Coefficient of Variation)	13.7	5.8
ELV	Elevation (SRTM)	19.0	19.4
MGVF	Maximum Green Vegetation Fraction	9.0	2.6
LULC	Land use/land cover	25.4	37.7
AET	Actual Evapotranspiration	13.7	1.4

4.3.2 Scenarios of current and future distribution

The final MaxEnt model under both scenarios (RCP6.0 and RCP8.5), predicts that the suitability of climate for teak forests will change across its native ranges by 2050 and 2070 (Figure 4.3). Some forest patches in central India are likely to become climatically suitable for teak in the future (i.e. 2050 and 2070) under RCP6.0 and RCP8.5, whereas some patches are likely to lose climatic suitability (Figure 4.4). The deciduous teak forests of Myanmar, Laos and Thailand are also likely to lose suitable climate under both climatic scenarios (Figure 4.4). In contrast, the climatic conditions of moist deciduous forests in the northern parts of India may become suitable for teak in future under extreme climate scenarios. The deciduous and semi-evergreen forests of Laos and Thailand where teak is not naturally distributed, are also likely to become climatically suitable in the future (Figure 4.3; Table C4.4 for details).

Non-native teak plantations in the evergreen and semi-evergreen forests of north-eastern Bangladesh are likely to lose suitable climate space by 2050 and 2070 under both climatic scenarios (Figures 4.5 & 4.6). However, some patches of the semi-evergreen forests in south-eastern Bangladesh are likely to gain suitable climate space for teak plantations (Figures 4.5 & 4.6; Table C4.5 for details).

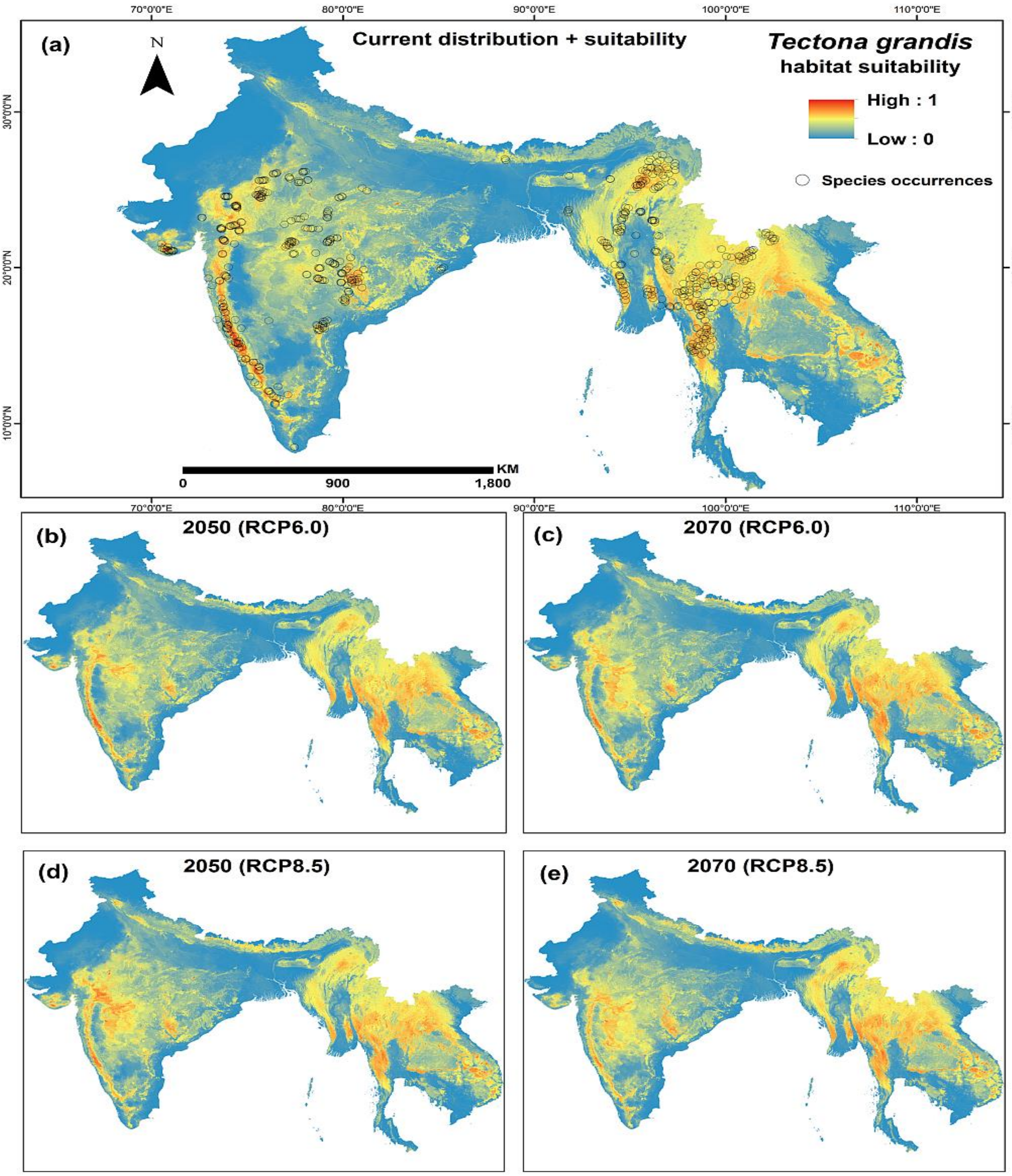

Figure 4.3 The potential climate suitabilities for teak (*Tectona grandis*) in its native ranges (tropical Asia): (a) species occurrences across India, Myanmar, Laos and Thailand and mapped current climate suitability for teak; and (b-e) the four projected climate suitability for teak in different scenarios. The blue colour indicate low suitability while the red colour indicates high suitability. The models indicate that the likely climate suitability for some teak forests may contract under extreme climate scenarios (RCP8.5) by 2050 and 2070. However, the climate suitability may expand to the deciduous forests of tropical Asia in future under both scenarios (RCP6.0 and RCP8.5) where teak forests are not naturally distributed.

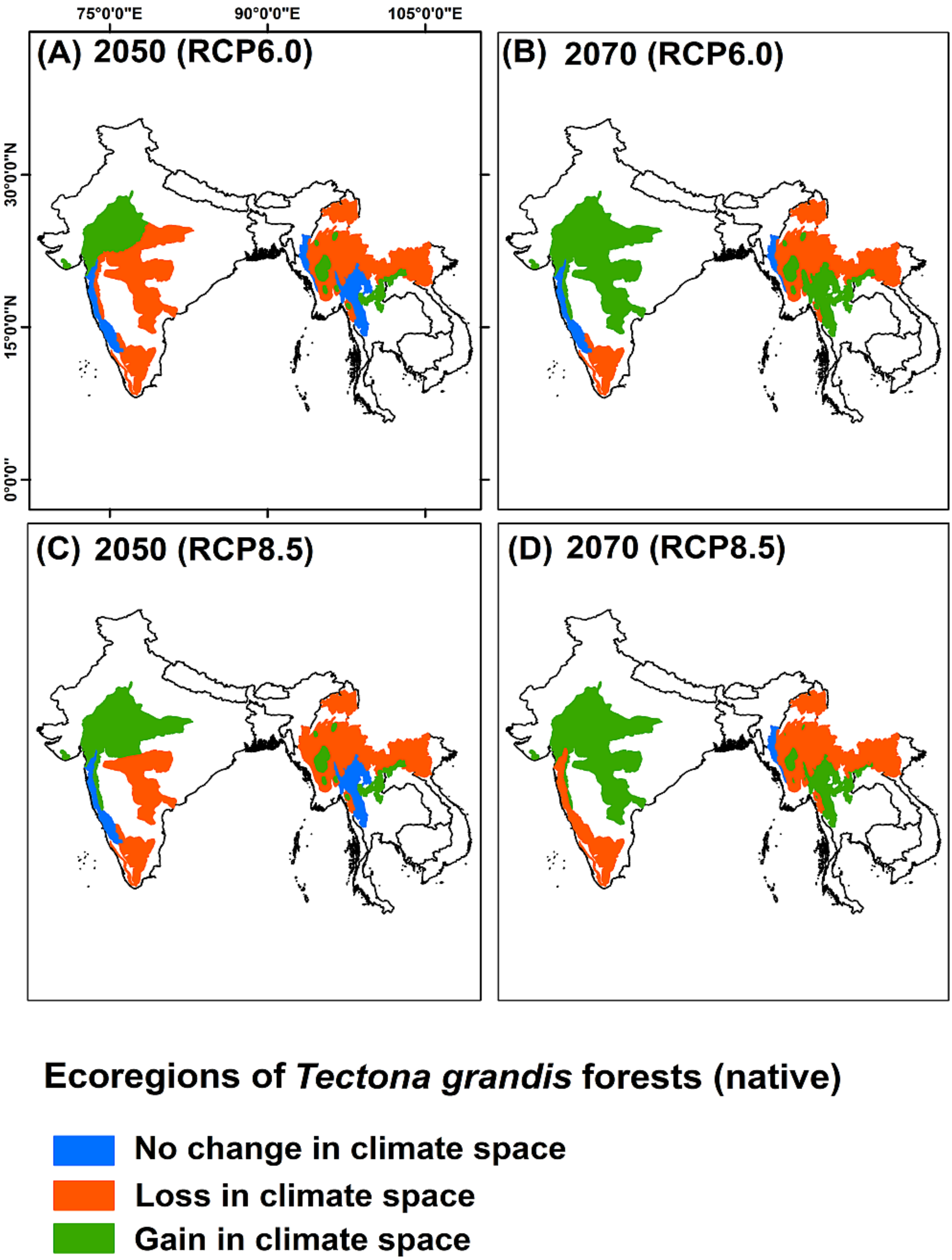

Figure 4.4 The different ecoregions of natural teak (*Tectona grandis*) across tropical Asia those are likely to lose or gain in climate space by 2050 and 2070 under RCP6.0 and RCP8.5: the blue areas indicate no change in occupied climate space, the red shading indicates loss of climate space and the green shading indicates climate gain.

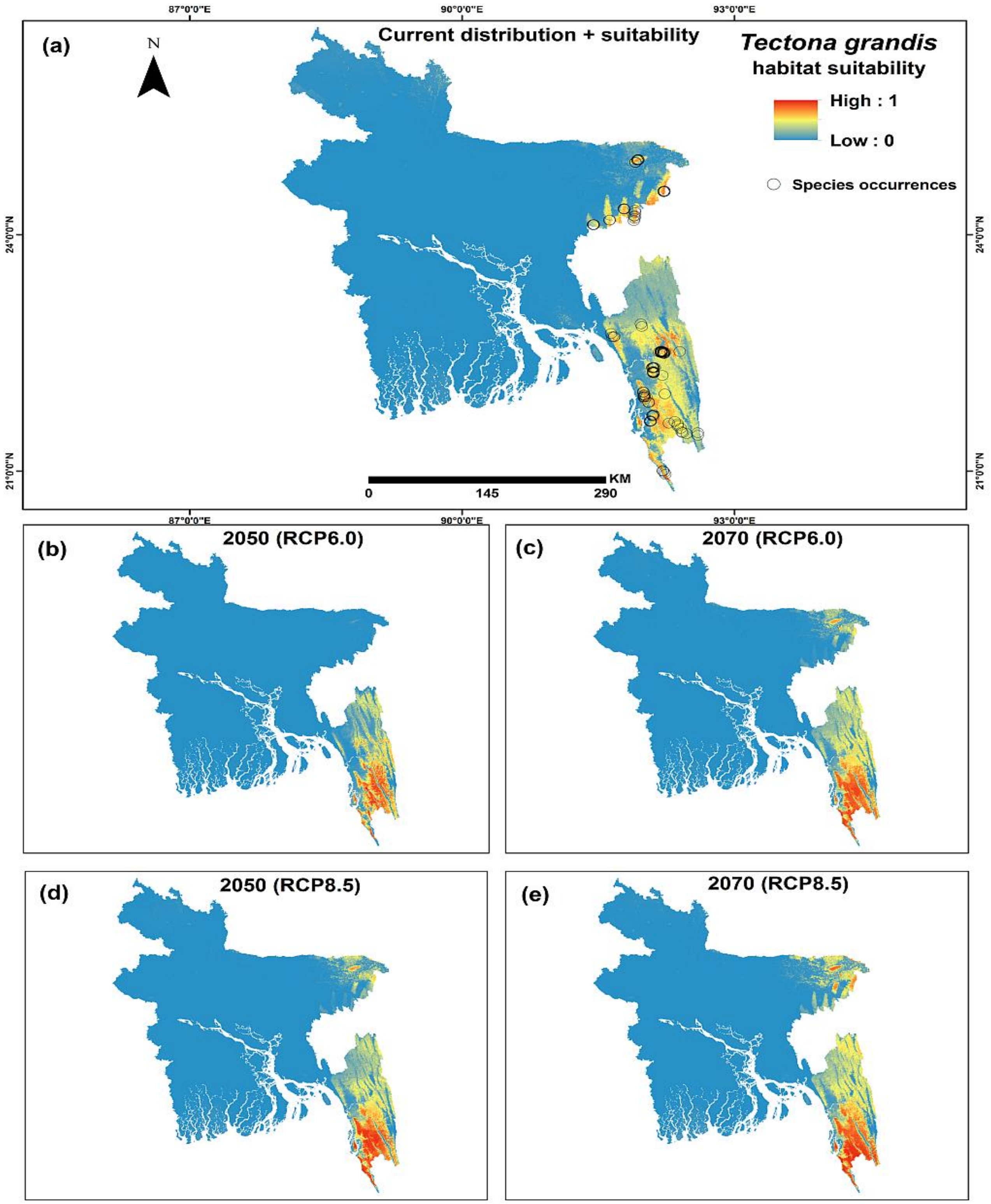

Figure 4.5 Changes in climate suitable conditions for teak (*Tectona grandis*) across its non-native distributions in Bangladesh: (a) species occurrences across the evergreen and semi-evergreen forests in the north-east and south-east regions and mapped climate suitability for teak; and (b-e) the four projected likely climatic conditions scenarios. The MaxEnt models indicate that the teak plantations in the evergreen forests of north-east region will face increasing climate stress (b-d) whereas the semi-evergreen forests in near south-east region are likely to gain suitable climate in future (b-e).

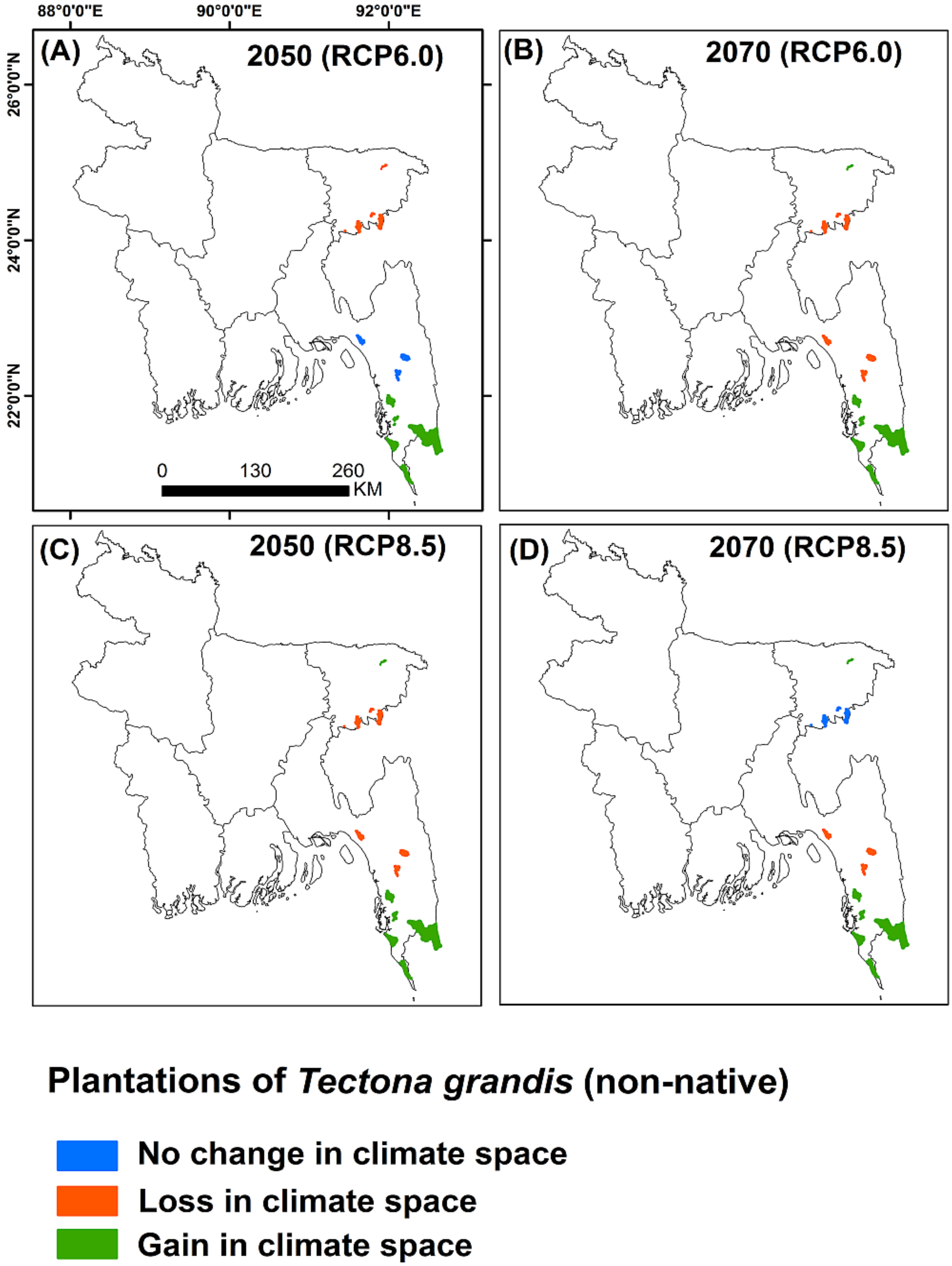

Figure 4.6 The non-native teak (*Tectona grandis*) plantations in Bangladesh are likely to lose or gain in climate space by 2050 and 2070 under RCP6.0 and RCP8.5: the blue areas indicate no change in occupied climate space, the red shading indicates loss of climate space and the green shading indicates climate gain.

4.4 Discussion

The overall prognosis for teak forests is of increasing climatic stress and potentially large distribution shifts across tropical Asia. The most important predictor variables were LULC and elevation. Annual rainfall, seasonal rainfall and temperature were secondary drivers of the distribution of natural teak. Hansen et al. (2013) reported that tropical Asia experienced high rates of forest loss in the last decade (2000 – 2012). Continuing fragmentation in the natural teak forests make it vulnerable to climate change due to interaction with land use pressures. The predicted distributions of suitable climate space for native teak included the areas where the species currently occurs naturally (forest patches of India, Myanmar, Laos and Thailand), and also in the non-native areas where climatic conditions may become suitable for the species in future (Figure 4.3). Some large patches of teak forests in central India (Madhya Pradesh, Maharashtra) recognised as the best teak growing areas in the world are likely to lose suitable climate space by 2050 (Figure 4.4). In a local study of climate change impact on Indian teak, Gopalkrishnan et al. (2011) identified 30% of teak forests in India as vulnerable to climate change under both the A2 and B2 SRES scenarios, as the future climate may not be optimal for teak growth. This is also the case for some teak growing sites of Myanmar, Thailand and Laos (Figure 4.3).

Teak was introduced to the evergreen and semi-evergreen hill forests of Bangladesh for timber production, and it has acclimatized well and become a major timber species. Our study identified that two environmental variables i.e. LULC and elevation features rather than climatic variables were the key predictor variables for the distribution of teak in those forests. Changing mean and extreme temperature and rainfall were also driving factors for teak growth in Bangladesh. The different anthropogenic drivers of deforestation, illegal felling, and encroachments, indicate that the hill forests are likely to face increasing climate stress in future (Salam et al. 1999; Sarker et al. 2011). It has been estimated that Bangladesh has approximately 73,000 ha of planted teak forests, which contribute significantly to national timber production (Kollert & Cherubini 2012). Therefore, climate suitability for teak plantations in the different forest sites can be taken into consideration for timber management planning under climate change in Bangladesh.

4.4.1 Ecological processes influencing changes in teak distributions

Teak occurs extensively in the tropical dry deciduous forests in monsoon climates. The production of high-quality timber requires a marked dry season of at least four months with less than 60 mm precipitation (Bunyavejchewin 1983; Kaosa-ard 1981; Kondas 1995). Therefore, changes in the precipitation seasonality will affect the distribution of teak as indicated in our results. Although teak can grow in a variety of soils, the quality of its growth depends on the depth, structure, porosity, drainage and moisture-holding capacity of the soil (Kaosa-ard 1981). Teak develops best on deep, well-drained and fertile soils with a soil pH of between 6.5 and 7.5 (Kaosa-ard 1981). The growth of teak varieties differs between forest types, depending on their ecological requirements (Table 4.1). For instance, four teak forest types in India (very moist, semi-moist, dry and very dry) have different requirements of rainfall, soil, stand density, and undergrowth vegetation for their growth whereas the four teak zones of Thailand (dry-humid, medium-humid, moist-humid and wet zone) have different requirements of the relationship between annual rainfall and annual mean temperature (Table 4.1). Our results suggest that changes in temperature seasonality and annual mean actual evapotranspiration in the study region will affect the distribution of teak by influencing the photosynthesis, respiration, transpiration, absorption of water, germination, growth and reproduction of teak. Changes in annual precipitation will be a secondary factor, affecting the amount of available soil water required for tree growth.

4.4.2 Habitat destruction influencing teak distributions

The LULC variable has been used along with other climatic variables in several bioclimatic envelope studies (e.g., Mantyka-Pringle et al. 2014; Sohl 2014). However, relevant studies in tropical Asia are lagging behind due to the limited access to high quality robust data and to a large number of projections for future climates (Wang et al. 2016). We included the static LULC and MGVF variables along with other dynamic bioclimatic variables in our study to address this knowledge gap. The important contribution of LULC variable to the MaxEnt models suggest that habitat destruction rather than climate, is one of the most significant variables that influences the teak distributions in tropical Asia. As teak is one of the most valuable timber of the tropics, commercial logging of teak and deforestation in the natural teak belt of South and Southeast Asia triggered a crisis in teak timber production (Midgley et al. 2015). India, Laos, Thailand and Myanmar imposed logging bans in natural teak forests due to deforestation pressures (Roshetko et al. 2013). However, the scenario remain unchanged and commercial teak plantations were introduced to South and Southeast Asian countries as the demand exceeded the sustainable supply from natural forests (Roshetko et al. 2013). Our models suggest that different ecoregions of both natural and plantation teak are likely to lose suitable habitat in future due to the combined effect of habitat destruction and climate change (Table 4.2, Table C4.4 & 4.5). Deforestation as a consequence of timber exploitation, agricultural expansion, human settlements, and development projects, is acute in tropical Asian region (Sodhi et al. 2004). Although Asia remains the largest exporter of teak timber, the continuous habitat destruction and land use change could result a serious threat to the natural and plantation teak distributions in future (Figures 4.4 & 4.6). As a consequence of our findings, we expect the addition of biotic predictors (e.g., competition, predation, dispersal mechanism etc.), projected LULC change (under future climate scenarios) along with climate variables to improve the ability of species distribution models to produce a clear improvement in the prediction of species large-scale ranges.

4.4.3 Implications for future teak production

SDM is a useful, widely applicable method that can inform guidelines for forest management under global climate change (Falk & Mellert 2011; Guisan & Thuiller 2005; Hampe 2004). In this study, we focused on current species/environment relationships that will form the basis for teak forest management practices. The climatic niche modelling of our study revealed the projected suitability of climates for both natural and planted teak in relation to their bioclimatic parameters that can be used for forest risk assessment and management. This type of information is necessary for forest management planning under climate change as long-rotation teak varieties are not capable of tracking rapidly changing climate and decisions have to be made in the short-term for a rotation period of about 40-70 years (Falk & Mellert 2011; Pandey & Brown 2000). The modelling outputs of our study can be used to calculate the suitability and risks of different teak forest sites under changing climates in the study region (Table 4.1). For example, teak plantations should not be introduced to the sites calculated as high risk under future climates, and should be replaced with other species assessed as more suitable under those climatic conditions (e.g., Falk & Mellert 2011). The rotation period of teak can also be shortened in different sites according to the level of risk posed by climate change. The gain and no change in climate space indicated in different teak ecoregions can be considered as potential climate change refugia (Figures 4.4 & 4.6; Tables C4.4 & C4.5 for details). The *in situ* and *ex situ* climate refugia in the study region can be an important option for teak forest conservation as they are characterized by the occurrence of relatively stable local climatic conditions that persist over time, despite change at regional and global scales (Gavin et al. 2014; Morelli et al. 2016). Teak forests grow in a wide range of climates and they may also be able to adapt to new climatic conditions (i.e. novel climates) in their natural habitat (Champion & Seth 1968). Therefore, transplantation of high risk teak to climatically more suitable areas can be an important step to conserve their genetic resources *in situ* (e.g., van Zonneveld et al. 2009). In addition, exploiting phenotypic plasticity and choice of genotypes with adaptive potential to future conditions can also improve teak persistence (Gratani 2014).

Natural teak forests cover a large area of tropical Asia (e.g., 6.3 Mha in India; Figure 4.2a) and are significant for carbon stock management and to reduce emissions from deforestation and degradation (Gibson et al. 2011; Wheeler et al. 2016). Teak plantations are an important management mechanism for establishing secondary growth forests and can play a major role in the reforestation of tropical Asia (Ashton et al. 2014). Potential changes in climate suitability for teak plantations should therefore be taken into account to promote carbon storage through sustainable forest management practices and restoration. The findings of our study could be employed to identify the critical natural teak habitats for conservation prioritization under future climates (Figure 4.3). ITTO (2009) estimates that approximately 31 Mm^3 teak wood is grown annually around the world, and Asia reported the highest removal of planted teak at 523,000 m^3. Our study provides further evidence of different levels of risk associated with the cultivation of teak in the study region under changing climate scenarios. The different natural habitats and plantations of teak are likely to lose suitable climate space in near future which may impact the teak production in tropical Asia. Therefore, forest management planning focusing on teak plantations will have to consider the impact of climate change on that species and whether or not the plantations will persist.

4.4.4 Assessing the risk of biological invasion

Climatic niche modelling of non-native species has been increasingly used as a tool for monitoring and predicting changes in species geographic location from local to global scale for ecological management of biological invasion (Beaumont et al. 2014; Uden et al. 2015). Introducing teak plantations to non-native ranges without taking into account the bioclimatic conditions of the sites may harm native ecosystems both ecologically and economically as exotic species may out-compete the natives. For instance, a total number of 348 plant species were recorded at Satchari reserve forest in Bangladesh, of which 31 were reported as exotic species (including teak) having low to high risk of biological invasion (Uddin et al. 2013). The government of Bangladesh imposed logging bans on all natural forests in 1970s and 1980s and converted them to protected areas in order to halt deforestation and conserve biodiversity (Sarker et al. 2011). However, ineffective implementation of logging bans lacking proper guidelines and policies has failed to conserve the biodiversity of protected areas (Sarker et al. 2011). For instance, a total number of 106 vascular plant species have been identified as threatened by the Bangladesh National Herbarium (Khan et al. 2001). Introducing alien invasive species, including teak, in the protected areas will increase the extinction risk of the threatened native species. The information from climatic niche modelling of invasive species can be used to direct management aimed at preventing, eliminating or minimizing biological invasion and their effects (Sakai et al. 2001).

4.4.5 Future applications

The major aim of using climatic niche modelling in ecology is to predict a species' distribution in either space or time (Guisan & Thuiller 2005; Peterson 2006). With the focus on the consequences of climate change on forestry, the future distributions of a species is important so that adaptations (e.g., introduction of species that are capable of adapting changing environments) to the predicted changes can be made (Falk & Mellert 2011). However, using different GCMs to project probable future distribution of species entails some uncertainties as they rely on different parameters and may project different consequences for the same level of greenhouse gas emissions (Wiens et al. 2009). To reduce the level of uncertainty, we used HadGEM2-ES GCM as terrestrial dynamic vegetation scheme is included in this model and it portrays the changes in vegetation distribution (Collins et al. 2011). Different GCMs need to be incorporated in future studies to encompass the full range of model variations in the study region (Deb et al. 2017). The bioclimatic variables of the study region incorporated in the MaxEnt models can inform the species distributions under future climate scenarios (Mellert et al. 2011). Although MaxEnt models are useful to indicate the climate suitability of species in a wide geographic range, there are limitations (Elith et al. 2006). For instance, we compiled the species occurrence dataset of teak from a variety of sources, which may have some sampling bias. We therefore included a sampling bias file in the models to reduce the sampling error (Phillips et al. 2009). The predictor variables such as LULC and MGVF have the potential to capture human impacts in the study region. The predictor variables employed in the MaxEnt models represent a mixture of mean, extreme and seasonal climate, topography, soil and tree physiological characteristics and the AUC values indicate that the projected climatic niche models in this study can be adapted as a tool for planning teak forest management in its patchy distribution in native and non-native ranges that have undergone extensive disturbance. However, the direct effect of CO_2, non-climate drivers such as competition, predation, soils, dispersal mechanisms, and biotic interactions need to be incorporated in mechanistic approach for future tree distribution modelling.

4.5 Conclusion

Our findings have significant implications for teak forest management. The patchy distributions of teak in tropical Asia face increasing climate stress, which may affect teak productivity in the region. The potential climate suitability for both native and non-native teak forests in tropical Asia presented in this study provides useful information for forest management planning under global climate change. The maps produced provide a quantitative view of the regional climate risks associated with teak cultivation. The identification of the bioclimatic variables that influence the future distributions of teak was an important step towards better understanding of the ecological niche of the species in tropical Asia. Teak forest management planning in the study region that does not consider patterns and directions of range shifts would incur a high risk of failure. Future efforts should develop mechanistic modelling of species distribution that explicitly incorporate tree physiological processes and limit distributions so that they can be used more confidently to predict climate change impacts.

CHAPTER 5

INCREASING CLIMATE STRESS ON TROPICAL FORESTS REVEALS GREATER EXTINCTION RISK FOR THREATENED LARGE MAMMALS

Associated publication:

Deb, JC, Phinn, S, Butt, N & McAlpine, CA (in review), 'Increasing climate stress on tropical forests reveals greater extinction risk for threatened large mammals', *Environmental Management.*

Abstract

Mammals can serve as an indicator of global climate change impacts on species' distributions due to the wide range of ecological niches they utilise. Tropical Asia encompasses several biodiversity hotspots, is the largest reservoir of mammalian diversity on earth, and has already experienced the extinction of several mammal species either regionally or locally. Global climate change could become a significant driver of species extinction, either directly or synergistically with other factors, such as habitat loss, agricultural expansion, overexploitation, and land use change. Despite the variability of climatic regimes across tropical Asia, the potential impacts of climate change on continental-scale distributions of mammals have not been examined. To address this issue, we developed habitat suitability models for four threatened large mammals (Asiatic black bear, Asian elephant, Western hoolock gibbon and Bengal tiger), across their entire distributions in Asia. We used presence-only distribution records and nine bioclimatic and environmental variables and built species-specific habitat suitability models using a maximum entropy algorithm (MaxEnt). We used a moderate and an extreme climate scenario (RCP6.0 and RCP8.5) and three time steps: current, 2050 and 2070. Our results suggest that changes in annual precipitation, annual mean temperature, precipitation and temperature seasonality, could reduce suitable habitat for these mammals and therefore increase their extinction risks. We conclude that increasing climate stress on tropical forests could lead to greater extinction risks of these threatened large mammals.

*Keywords***:** Mammal distribution ranges; threatened species; habitat suitability models; mammal extinction; conservation planning; protected areas

5.1 Introduction

There is growing observational evidence that global climate change is having a significant impact on species distributions, phenology, and vegetation dynamics, and could become a major cause for species extinction in concert with other global change drivers, such as agricultural expansion, overexploitation, habitat destruction and fragmentation, land use change and invasive species (Brook et al. 2008; Franklin et al. 2016; Pacifici et al. 2015; Thomas et al. 2004). Terrestrial plant communities (such as forests, woodlands, shrublands and grasslands) provide natural habitat for many animal species, and climate change-driven shifts in vegetation distribution could have cascading effects on the distribution of wildlife (Butt et al. 2015; Franklin et al. 2016). Mammals can serve as an indicator of climate change impacts on wildlife populations due to the wide range of ecological niches they exploit (Ceballos & Ehrlich 2002). Results of previous studies showed that extinction risk is greater in large mammals than small mammals (Cardillo et al. 2005). This is driven by a combination of extrinsic (environmental) factors and intrinsic species traits, such as small geographic range, low population density, slow life history, low reproductive rates and large body size (Davidson et al. 2009; Fisher & Owens 2004). Therefore, future loss of large mammals due to climate change acting synergistically with other extinction drivers, such as habitat loss, land use change, poaching, and hunting could be far more rapid than expected (Figure 5.1) (Cardillo et al. 2005).

Of the four forest biomes (tropical, subtropical, temperate and boreal), tropical forests are the richest biologically and contain the highest number of threatened species (Brook et al. 2008; Butler & Laurance 2008; Corlett & Lafrankie Jr 1998). For instance, it has been estimated that mammal species are approximately seven times more numerous (http://www.iucnredlist.org/) within tropical biodiversity hotspots, compared with non-tropical hotspots (Myers et al. 2000). Southeast Asia encompasses four biodiversity hotspots and several of the most species-rich ecoregions (Myers et al. 2000; Olson & Dinerstein 1998). It has the highest relative rate of deforestation of any tropical region (Hansen et al. 2013), and could lose three quarters of its original forests and half of its biodiversity by 2100 (Sodhi et al. 2004). In Southeast Asia, 13 mammal species have already experienced 83% habitat loss (Ceballos & Ehrlich, 2002), of great concern as this region holds the highest reservoirs of biodiversity on earth and is home to one of the highest concentrations of endemic species (Sodhi et al. 2004). South Asia represents approximately 10% of the world’s mammalian diversity, and includes 502 species belonging to 215 genera and 14 orders (Srinivasulu & Srinivasulu, 2012). Approximately 32 mammal species have become extinct regionally or locally in South Asia due to habitat loss and fragmentation, and other extinction drivers such as land use change and climate change (Figure 5.1) (Srinivasulu & Srinivasulu, 2012). With an annual forest loss increment of 2101 square kilometres in tropical Asia (from 2000 to 2012) (Hansen et al. 2013), the region's mammal populations are losing their natural habitats (Srinivasulu & Srinivasulu, 2012). The extent of habitat loss in concert with global climate change is increasing the extinction risks of the large mammals (Sala et al. 2000; Thomas et al. 2004).

Habitat suitability models or species distribution models have been widely used in ecology to detect the climatically suitable habitat of mammals and inform conservation planning (Elith & Leathwick 2009; Franklin 2010; Guisan & Zimmermann 2000; Rondinini et al. 2011). Despite mammals being among the most intensively studied taxa, lack of detailed large scale information on their potential distribution under future climate scenarios may hinder conservation efforts (Rondinini et al. 2011). In Asia, most studies of climate change impacts on mammal distributions focus on the local scale and do not consider the entire distribution ranges of the species (e.g., Alamgir et al. 2015; Loucks et al. 2010; Pokharel et al. 2016; Trisurat et al. 2012). Thus, continental-scale studies in Asia are limited, despite the conservation significance of mammal diversity in the region (Catullo et al. 2008). In this study, we have addressed this research gap by modelling the habitat suitability of four large threatened mammals under different climate scenarios across their entire distribution range.

The unique and globally endangered Bengal tiger (*Panthera tigris tigris*), Asian elephant (Elephas maximus), Western Hoolock Gibbon (*Hoolock hoolock*) and vulnerable Asiatic black bear (*Ursus thibetanus*), are naturally distributed in different Asian forest ecosystems (Table 1 and Table A1for details), and their main threats are the combined effects of habitat loss, forest fragmentation, human interference, hunting and global climate change (Alamgir et al. 2015; IUCN 2016; Loucks et al. 2010; Srinivasulu & Srinivasulu 2012). These species are already extinct locally in several countries, and the remaining disjunct populations are declining (IUCN 2016; Sala et al. 2000; Thomas et al. 2004). They play key roles in their forest ecosystems (e.g., grazing, predation, and seed dispersal), and are important for ecosystem function, such as in relation to food chains and food webs (Franklin et al. 2016). We focused on these threatened large mammals of Asian continent as these species are of highest conservation concern and typically targeted by international conventions (Secretariat of the CBD 2010).

The aim of the paper was to assess the four species' vulnerability to global climate change and examined the importance of mean and seasonal climate; topography; land use/land cover and maximum green vegetation fraction of landscape variables for habitat suitability for the mammals under different climate scenarios and for different time periods. This allowed us to identify the potential extinction risks for each species, with implications for conservation planning.

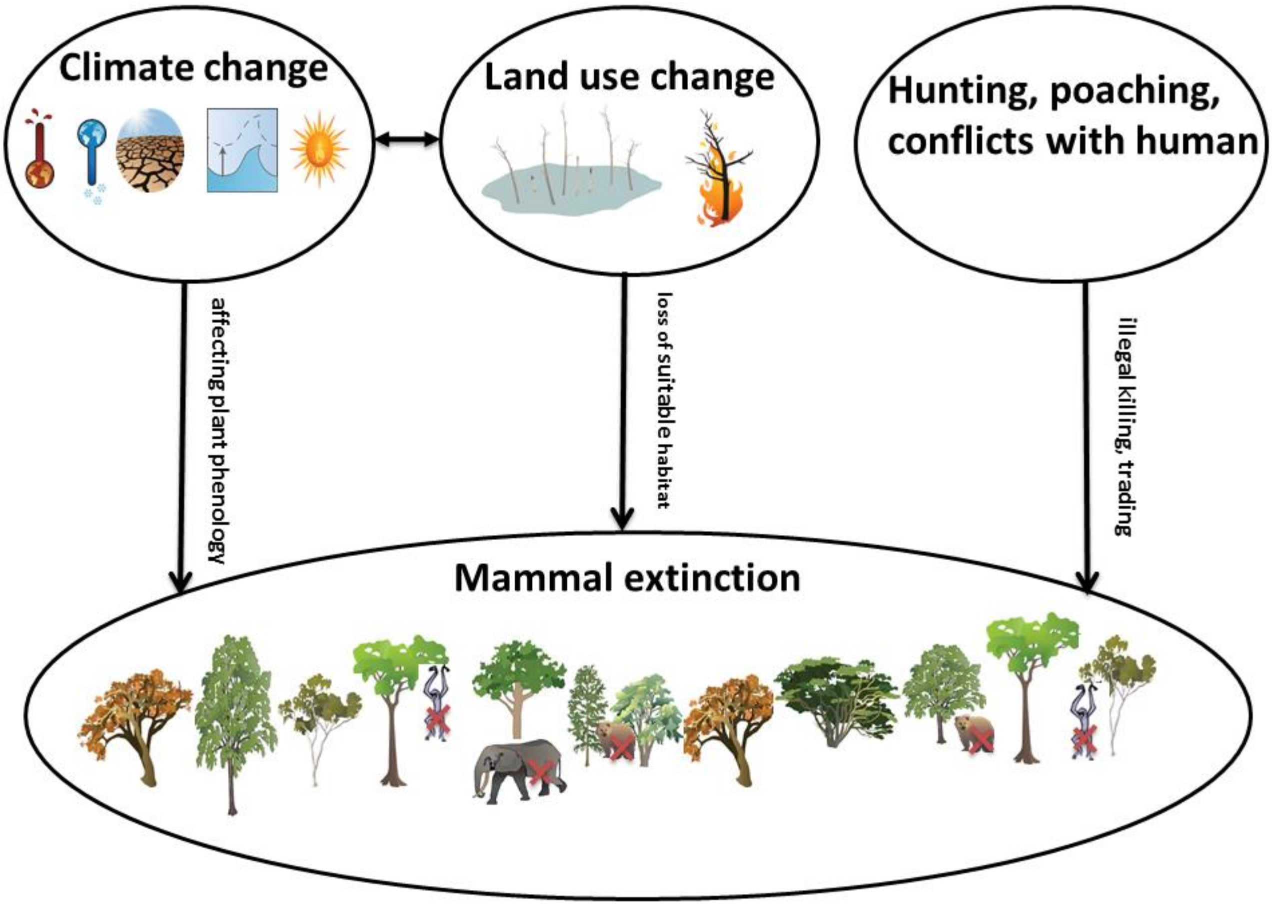

Figure 5.1 A schematic representation of different extinction drivers (climate change, habitat loss, deforestation, land use change, hunting and poaching) for threatened large mammals in tropical Asia (for details see Table D5.1).

5.2 Materials and methods

5.2.1 Ecology of study species

The four mammals occupy a variety of forested habitats, grasslands, cultivated and secondary forests across Asia (Figure 5.2 and Table D5.1 for details). They play important ecological roles, and help maintain ecosystem health and diversity (Franklin et al. 2016). For instance, the Asian elephant and Bengal tiger are considered keystone species, and their presence in the forests is an indicator of ecosystem well-being. The Asiatic black bear, Asian elephant and Western hoolock gibbon rely on tree flowering and fruiting, and also on the shoots, forbs and leaves of many plants (Corlett & Lafrankie Jr 1998; IUCN 2016). Bengal tiger is at the apex of the food chain and maintains the balance between prey herbivores and the vegetation upon which they feed (IUCN 2016). Although no rigorous population estimates exist for these mammals, recent studies suggest that the current populations of these species are declining (Table 5.1), which may lead to local or regional extinction in the near future (IUCN 2016). Temperature and rainfall variations (e.g., drought, heavy rainfall) have the potential to affect the phenology of tropical and subtropical Asian forests through significant perturbations to the timing of fruit, seed and flower availability, with cascading effects on the distribution and population dynamics of large mammals (Parmesan 2006).

Table 5.1 The studied threatened mammals of tropical Asia and their conservation status (IUCN 2016).

Species	Local name	Family	Conservation status	Current population trend
Ursus thibetanus	Asiatic black bear	Ursidae	Vulnerable	Decreasing
Elephas maximus	Asian elephant	Elephantidae	Endangered	Decreasing
Hoolock hoolock	Western hoolock gibbon	Hylobatidae	Endangered	Decreasing
Panthera tigris tigris	Bengal tiger	Felidae	Endangered	Decreasing

5.2.2 Species distribution and environmental data

We obtained occurrence records for the four mammals from the terrestrial mammals' data of the IUCN Red List (IUCN 2014), and the Global Biodiversity Information Facility (GBIF, <http://www.gbif.org/>). We compiled the datasets and cleaned the occurrence records by removing overlapping locations or spurious points after reviewing the literature for each species (Khan 2008). Finally, we used 398, 160, 52 and 75 records for Asiatic black bear, Asian elephant, Western hoolock gibbon and Bengal tiger, respectively, to model the distributions (Figure 5.2).

In addition to bioclimatic variables from WorldClim (www.worldclim.org) (Hijmans et al. 2005), we obtained four other potentially important static variables: elevation (ELV) (Hijmans et al. 2005), mean annual actual evapotranspiration (AET) (Trabucco & Zomer 2010); land use/land cover (LULC) (Arino et al. 2012), and annual maximum green vegetation fraction (MGVF) (Broxton et al. 2014). We included the LULC and MFVG variables in the modelling as the combined effects of habitat destruction and climate change likely pose greatest threat to biodiversity of tropical forests (Brook et al. 2008). It is important to include the projection of LULC for different climatic scenarios in the modelling (e.g., Sohl 2014). However, we used the static LULC data of 300 m resolution (Arino et al. 2012) in our modelling (projections of LULC are not available for tropical Asia) to estimate the contribution of the variable in the MaxEnt model for species distribution (e.g., Alamgir et al. 2015). The annual MGVF dataset is based on the annual maximum NDVI (normalized difference vegetation index) and linear mixing models that describe green vegetation fraction (vs. non vegetated area) for each land cover in the study region (Broxton et al. 2014). The relative contribution of these environmental variables is important to estimate the distribution and ecological needs of a species occurring in the forests that have undergone extensive disturbance (Wilson et al. 2013). We used ArcGIS 10.1 to extract all of the required variables for the extent of the study area, and to standardise the cell size, extent and coordinate system (Table D5.2). Data were aggregated to the landscape scale (1 km grid resolution).

We selected two of the four Representative Concentration Pathway (RCP) scenarios: RCP6.0, a stabilization-without-overshoot pathway to 6 W m^{-2} by 2100, corresponds to a peak in greenhouse gases by 2060 and RCP8.5, a rising radiative forcing pathway resulting in 8.5 W m^{-2} by 2100, which reflects high levels of energy demand and greenhouse gas emissions without climate change policies (Moss et al. 2010). We used data for current conditions (the average for 1950-2000) and projected climate data for the time periods of 2050 (the average for 2041-2060) and 2070 (the average for 2061-2080) from the HadGEM2-ES Global Climate Model (Hijmans et al. 2005).

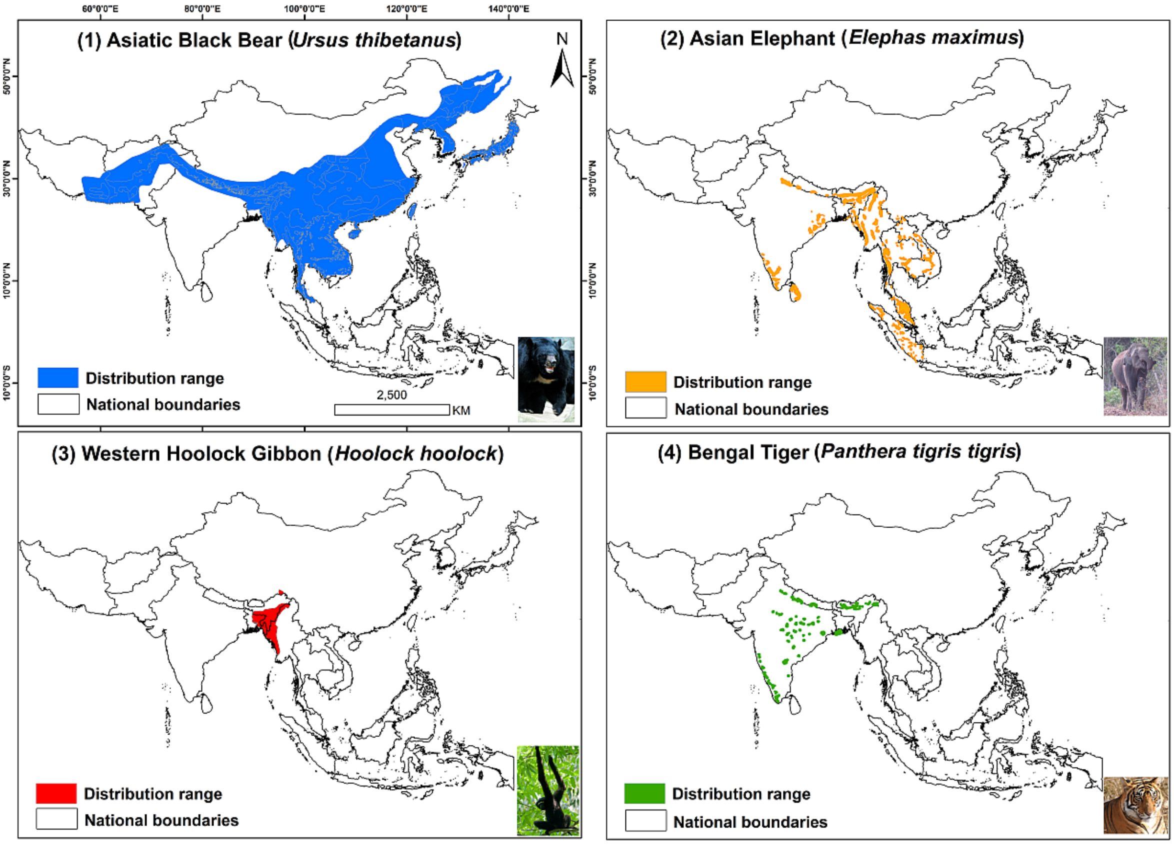

Figure 5.2 The current distribution ranges of the threatened large mammals in different landscapes across Asian continent: (1) Asiatic black bear (*Ursus thibetanus*); (2) Asian elephant (*Elephas maximus*); (3) Western hoolock gibbon (*Hoolock hoolock*); and (4) Bengal tiger (*Panthera tigris tigris*) (for details see Table D5.1) (Source: IUCN 2014).

5.2.3 Exploratory data analysis

As this study aimed to understand which variables were driving distributions, we applied Spearman's rank correlation to test for collinearity between variables at each level. Dormann et al. (2013) suggest that a threshold of 0.7 is the most common in ecology (i.e., if a pair of variables has a correlation coefficient > 0.7, then they should be considered proxies of one another). We applied this general rule and removed 14 of the variables (Table D5.2). We used nine predictor variables for habitat suitability modelling: annual mean temperature; mean diurnal range; isothermality; temperature seasonality; annual precipitation; precipitation seasonality; elevation; LULC; and MGVF. The elevation variable is important because the mammals occupy different topographic features of the landscapes. We used the LULC and MGVF (the average data of 2001-2012) variables to predict current distributions of the species. However, there are no models for the future estimates of these two variables for each climate scenarios; we projected the distributions to 2050 and 2070, with and without these 'fixed' variables.

5.2.4 Habitat suitability models

We built the models of the relationship between each species' occurrences and the climatic conditions using the niche modelling software MaxEnt version 3.3.3 k (Phillips et al. 2006; Phillips & Dudik 2008). The MaxEnt (maximum entropy) algorithm has been shown to perform well, even with low sample sizes, and has the advantages over other species distribution models in that it is designed to operate without data on true absences (Elith et al. 2006; Phillips et al. 2004; Phillips & Dudik 2008). To improve the robustness of the model extrapolation, we created a bias file layer and defined MaxEnt Background selection by limiting the sampling locations from where they were selected (Phillips et al. 2009). This limits the background point to areas that we assume were surveyed for the mammals, and provides MaxEnt with a background file with the same bias as the presence locations (Phillips et al. 2009). We generated the MaxEnt models from a cross-validation on the data and setting the default background points to 10,000, regularization multiplier to 1 and maximum iterations to 500. We also used the jackknife test to measure the variable importance to the models. We validated the models using the threshold-independent Area under the Receiver Operating Curve (AUC) metric (value ranges between 0 and 1.0) that describes the fit of the model to the test data and gives strong model discrimination ability for predicting changes in species distribution under future climate scenarios (Phillips et al. 2006; Phillips & Dudík, 2008). An AUC value greater than 0.75 indicates that the model has good discrimination ability in accurately identifying the potential distribution of a species (Elith et al. 2011). We used the 10 percentile training presence logistic threshold to define the minimum probability of suitable habitat (Phillips et al. 2006) and account for sampling error: we defined suitable habitat to include 90% of the data used to develop the model.

We generated the MaxEnt models for the threatened mammals in two different settings: (a) incorporating the bioclimatic variables only as predictor variables, and (b) including the three other environmental variables (i.e., elevation; LULC; and MGVF) along with bioclimatic variables. As the mammals have wide distributions across different ecosystems in Asia, variations in topographic heterogeneity, deforestation scenarios and land use change, are likely to have a significant influence on the distributions, even for a given set of climatic conditions (Hansen et al. 2013; Wilson et al. 2013).

5.3 Results

Overall, the MaxEnt models performed well in predicting habitat suitability for the threatened mammals across Asia. Mean AUC values across all models (for models that includes climatic variables only: 0.80 ± 0.05; and models including all variables: 0.82 ± 0.04) fell within the range of good performance (Table D5.3).

There were some similarities found in the relative contributions of the predictor variables that influence the spatial distribution of the large mammals in the study region (Figure 5.3). The key bioclimatic predictor variable for the Asiatic black bear, Asian elephant and Bengal tiger was annual precipitation (BIO12) for both models, i.e. models with climatic variables only and with all variables. In contrast, the key variable for the Western hoolock gibbon was mean diurnal range (BIO2) (Figure 5.3). Precipitation and temperature seasonality coupled with annual mean temperature and elevation features may also influence the distribution of Asiatic black bear as they were important variables in the model. The important contribution of temperature seasonality along with annual mean temperature, MGVF and elevation or topographical variables in the model indicates that variation in these variables may influence the distribution of Asian elephant in the region (Figure 5.3). The relative contribution of annual precipitation, precipitation seasonality, elevation and isothermality were important in both models for the Western hoolock gibbon (Figure 5.3). Annual mean temperature, LULC and precipitation seasonality variables were also important for the distribution of Bengal tiger.

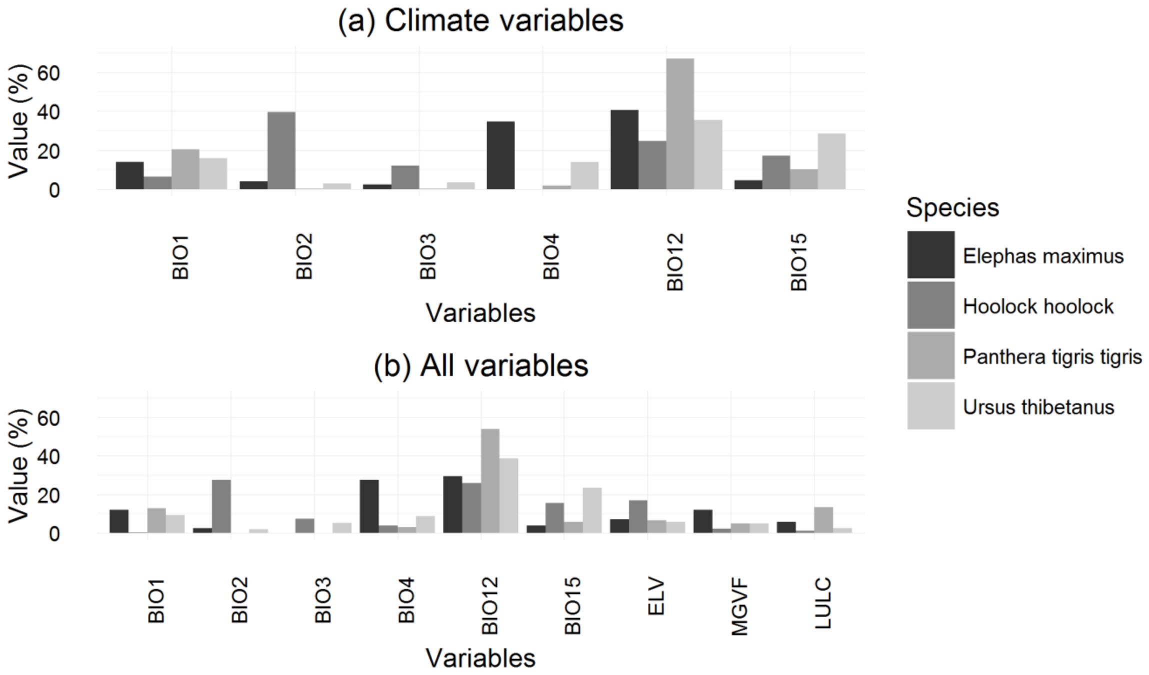

Figure 5.3 Summary of the bioclimatic and environmental variables used in the habitat suitability models and their percent contribution to each model: (a) models with only bioclimatic variables as predictors; and (b) models with all variables. Annual precipitation (BIO12) was the most regulatory variable found in both models that influence the habitat suitability of all the mammals.

Both MaxEnt models (for ‘climate variables’ and ‘all variables’) revealed a consistent pattern of predicted habitat suitability for all four mammals, i.e. range contraction of their natural habitat (Figures 5.4-7 and Figures D5.1-4). Our models predicted that climatically suitable habitat conditions for the threatened large mammals will decline across Asia. However, Western hoolock gibbon is likely to gain climatically suitable habitat outside of its current natural habitats. The projected impacts of climate change on the habitats of Asiatic black bear are severe under both RCP scenarios, with a 38% decline by 2070 under RCP8.5 for the model with climate variables only, and 40% for the model with all variables (Figure 5.8). The model with climate variables only indicates a decline of up to 59% of suitable climate space for the Asian elephant by 2070 under RCP8.5. However, the model with all variables indicates a relatively low percentage (5%) of decline in habitat suitability for Asian elephant. This may be due to the wide variety of ecosystems (grasslands, tropical evergreen, semi-evergreen, dry and moist deciduous, dry thorn forests) the Asian elephant occupies, with an elevation ranging from sea level to 3,000 m across tropical Asia (Table D5.1). The habitat suitability of Bengal tigers will decline up to 14% across Asia by 2070 under RCP8.5 indicated by the model with climatic variables. However, the model with all variables indicates that Bengal tigers may gain some climate space (1%) by 2070 under RCP8.5, with relatively low declines in habitat suitability by 2050 and 2070 under RCP6.0. In contrast to the other three mammals, Wester hoolock gibbon will gain suitable climatic conditions in all climatic scenarios for both models: up to 12% by 2070 under RCP8.5 for the model with climatic variables and up to 20% for the other model (Figure 5.8). All models revealed the likely range contraction of climatically suitable natural habitats of the threatened large mammals. However, climatically suitable range expansion outside of their natural habitats may provide potential for species migration.

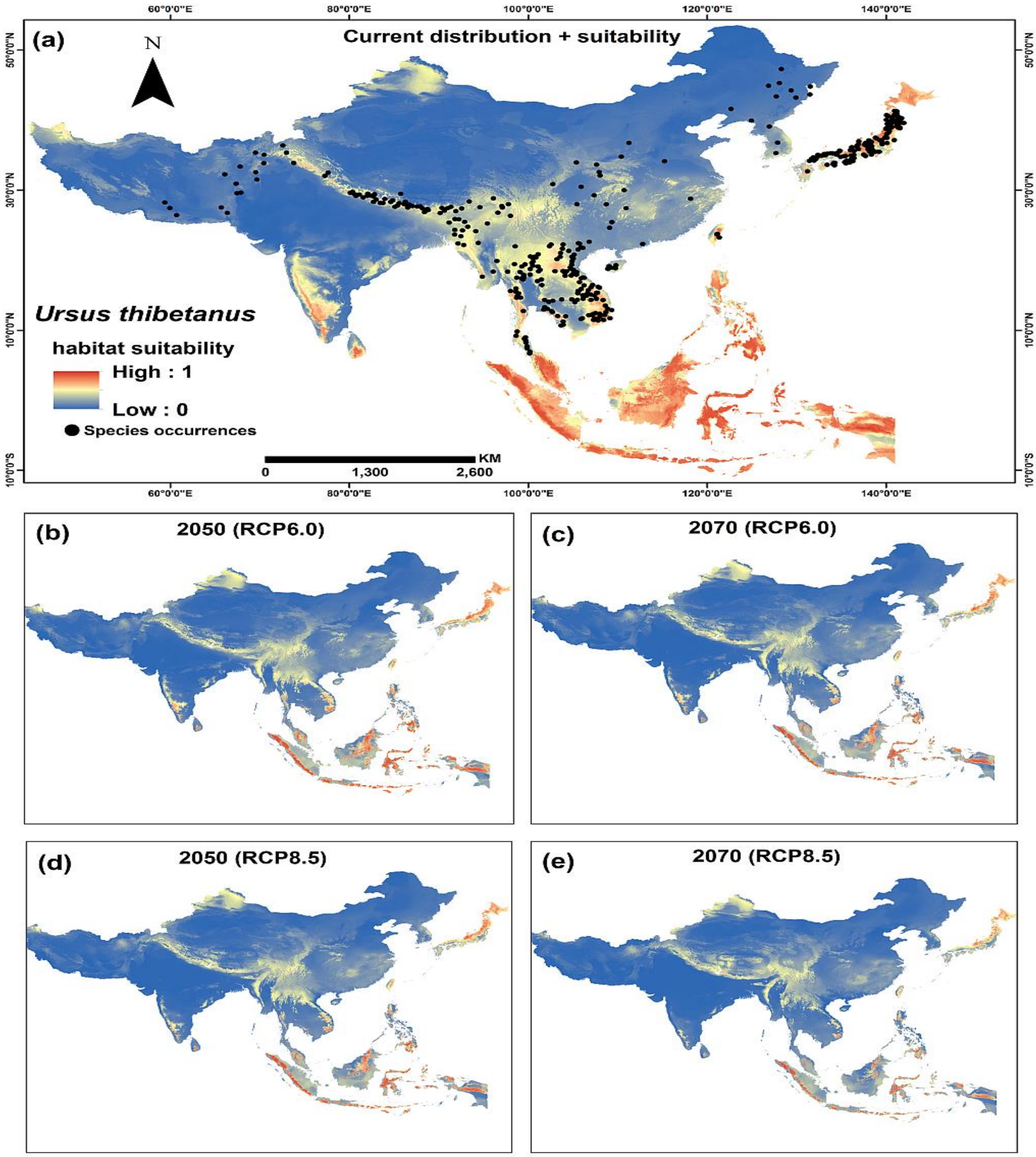

Figure 5.4 The potential habitat suitability for Asiatic black bear (*Ursus thibetanus*) across its entire distributions in Asia: (a) species occurrences across Asia and mapped current habitat suitability for bear; and (b-e) the four projected habitat suitability for bear in different scenarios. The models indicate that the likely habitat suitability for bear will decline under both climate scenarios (RCP6.0 and RCP8.5) by 2050 and 2070. Changes in annual precipitation, precipitation and temperature seasonality, annual mean temperature may influence the distribution of Asiatic black bear.

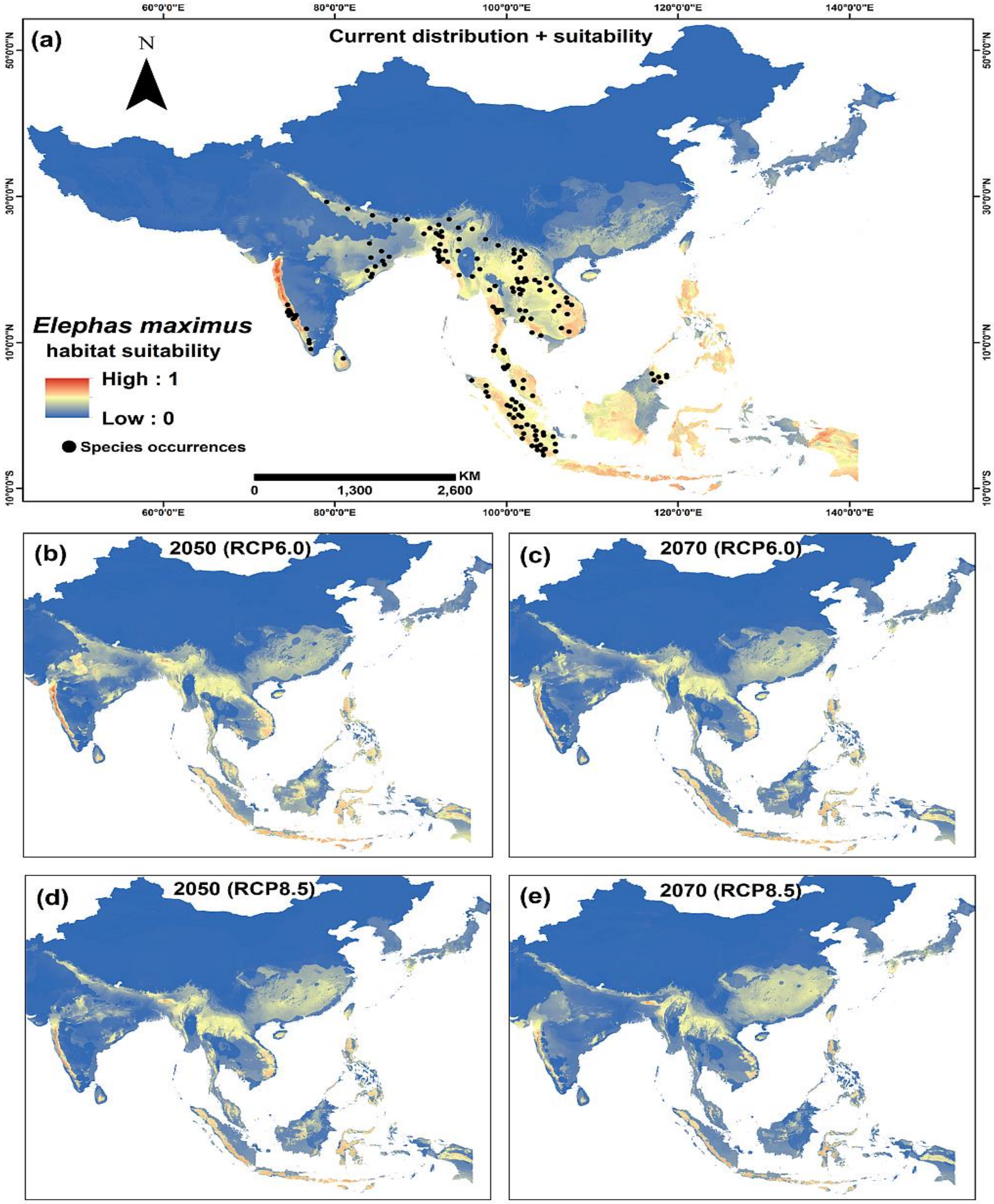

Figure 5.5 The predicted habitat suitability for Asian elephant (*Elephas maximus*) across its entire distributions in Asia: (a) species occurrences across Asia and mapped current habitat suitability for elephant; and (b-e) the four projected habitat suitability for elephant in different scenarios. The models indicate that the Asian elephant are likely to face extinction risk under both climate scenarios (RCP6.0 and RCP8.5) by 2050 and 2070. The key bioclimatic variables that influence the distribution of Asian elephant are annual precipitation, temperature seasonality and annual mean temperature.

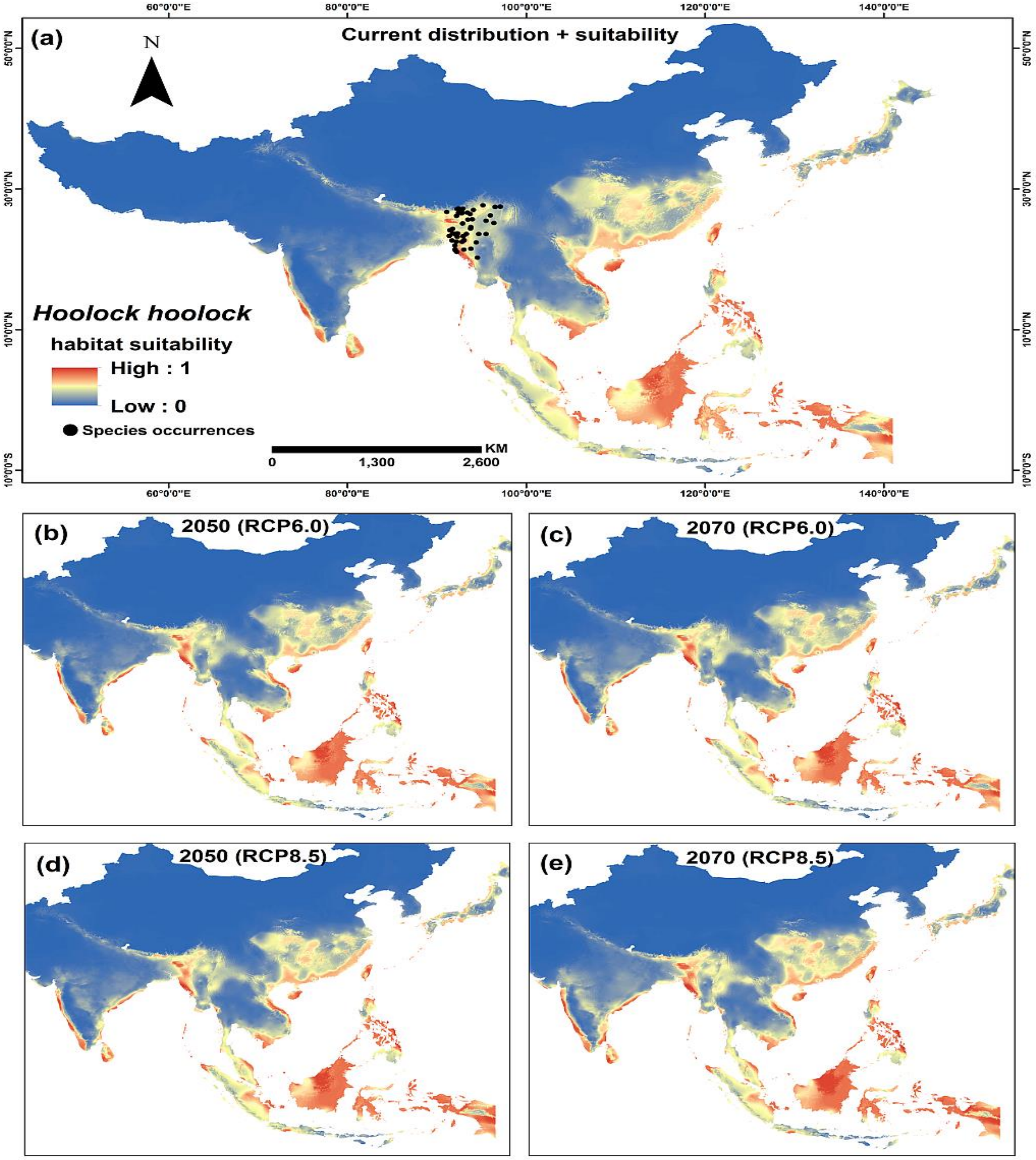

Figure 5.6 The projected habitat suitability for Western hoolock gibbon (*Hoolock hoolock*) across Asia: (a) species occurrences across Asia and mapped current habitat suitability for gibbon; and (b-e) the four projected habitat suitability for gibbon in different scenarios. The models indicate that the habitat suitability of gibbon is likely to contract under both climate scenarios (RCP6.0 and RCP8.5) by 2050 and 2070. However, there is a shift in the distribution for gibbon outside of its native ranges where assisted migration of the species can reduce the species extinction risks. The key bioclimatic variables that influence the distribution of gibbon are mean diurnal range, annual precipitation, isothermality and precipitation seasonality.

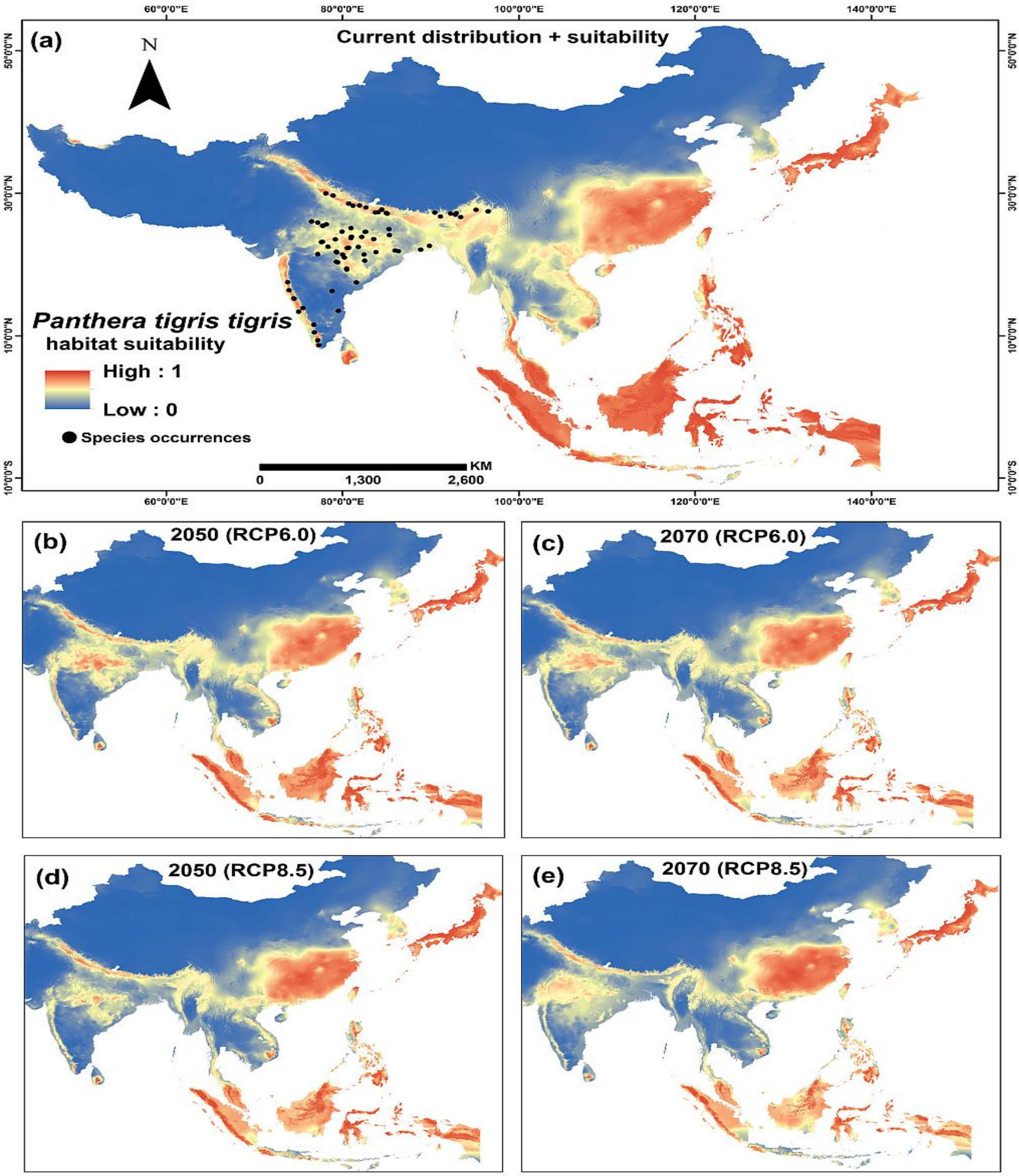

Figure 5.7 The potential habitat suitability for Bengal tiger (*Panthera tigris tigris*) across Asia: (a) species occurrences across Asia and mapped current habitat suitability for tiger; and (b-e) the four projected habitat suitability for tiger in different scenarios. The models indicate that the habitat suitability of tiger is likely to contract under both climate scenarios (RCP6.0 and RCP8.5) by 2050 and 2070. However, there is a shift in the distribution for tiger outside of its native ranges. The key bioclimatic variables that influence the distribution of tiger are annual precipitation, annual mean temperature and precipitation seasonality.

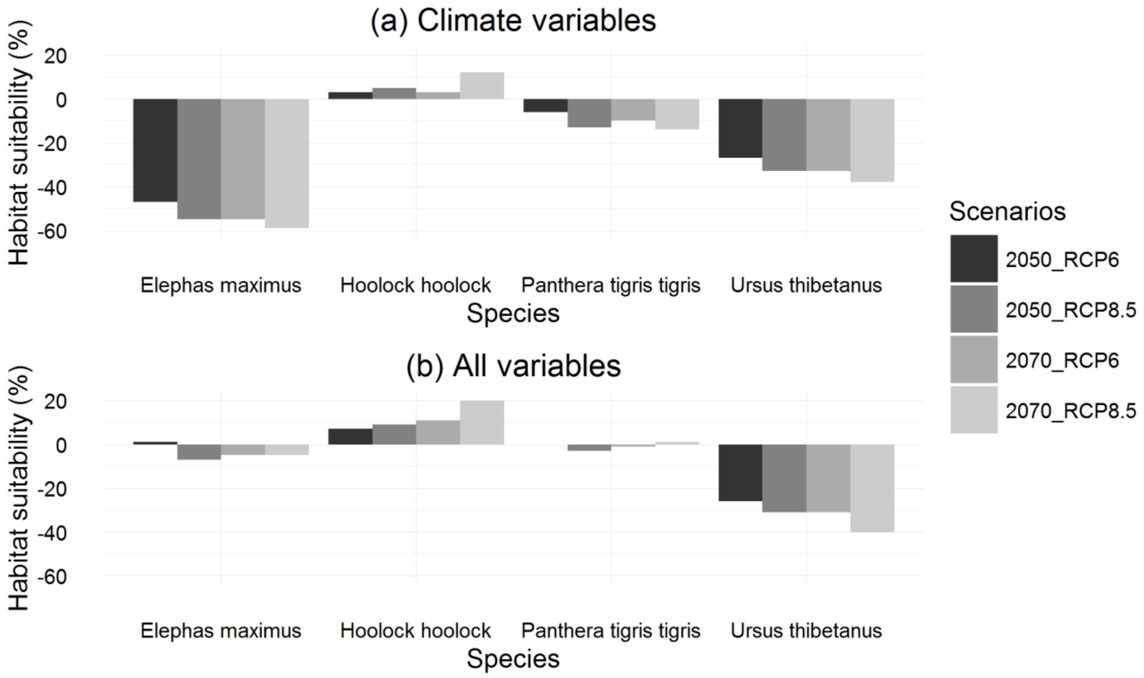

Figure 5.8 The climatically suitable habitat conditions for the threatened mammals by 2050 and 2070 under RCP6.0 and RCP8.5: (a) models with bioclimatic variables only, and (b) models with all variables. Results of both models suggest that the habitat suitability of Asiatic black bear (*Ursus thibetanus*), Asian elephant (*Elephas maximus*), and Bengal tiger (*Panthera tigris tigris*) will decline across Asia except Western hoolock gibbon (*Hoolock hoolock*) which will likely to gain climatically suitable habitat outside of its natural habitats.

5.4 Discussion

Our results suggest that global climate change could severely impact the distributions of threatened large mammals across Asia, with contraction and shifts in climatically suitable habitat conditions. The projected changes in annual precipitation and annual mean temperature and changes in seasonal climate (precipitation and temperature regimes) could be the key regulatory factors for the mammals' distributions in tropical Asia. In addition to increasing climate stress, land use change and other anthropogenic factors may drive the distribution of mammals and lead them to become extinct, either locally or regionally in Asia (Franklin et al. 2016; Hansen et al. 2013; Thomas et al. 2004). Visconti et al. (2016) found that the extinction risks of terrestrial carnivore species increases for 8-23% depending on assumptions about species responses to climate change, which is consistent with our findings.

5.4.1 The influences of climatic variability on mammals' distribution

Climatic regimes in the Asian tropics are highly diverse and can be divided into three zones: the marginal tropics (mean temperature of the coldest month < 18°C; low seasonal temperatures may limit the growth of plants); the monsoon tropics (mean rainfall of the driest month < 50 mm; water availability limits plant growth); and the aseasonal tropics (temperature and water supply are adequate for growth year round) (Corlett & Lafrankie Jr 1998). Climate change is already impacting vegetation in this region through an influence on phenology (Corlett & Lafrankie Jr 1998). The Asiatic black bear, Asian elephant, and Western hoolock gibbon occupy a large variety of ecosystems across Asia and rely on periodically available plant resources for their survival (Corlett & Lafrankie Jr 1998; IUCN 2016).

The habitat of the Asiatic black bear includes both broad-leaved and coniferous forests and they mostly occur in the marginal and monsoon tropics (Corlett & Lafrankie Jr 1998). The bear moves to different habitats and elevations seasonally for tracking changes in food abundance and relies on fruit at different times of the year (Izumiyama & Shiraishi 2004). Seasonal low temperatures drive annual fruiting phenology in the Indo-Malayan subtropics and variations in temperature and precipitation seasonality, coupled with annual precipitation, annual mean temperature, and elevation features, are important for Asiatic black bear distribution (Corlett 1998). Asian elephant browse a wide variety of ecosystems and in South India, 70% of their diet comes from dry season browsing, while in the wet season grasses make up about 55% of their diet (Sukumar 1992). Although the annual diet of Asian elephant is dominated by grass (84%), dry deciduous forest species also contribute a considerable amount (Baskaran 1998). Variation in seasonal temperature, annual mean temperature and annual precipitation such as drought or heavy rains can lead the plants to flower and fruit drop, with therefore potentially significant effects on elephant populations (Gunarathne & Perera 2014). As the elephant mostly rely on crops and grass rather than wild fruits, other factors such as roads, poaching, and conflicts with humans may also be important for their distribution.

The Western hoolock gibbon is a frugivorous species found in the tropical evergreen, semi-evergreen, mixed deciduous and subtropical broad leaf forests of India, Bangladesh and Myanmar (IUCN 2016). Ting et al. (2008) revealed that fruit production in tropical regions was related most strongly to evapotranspiration. Therefore, seasonal changes in climate (e.g., mean diurnal range, annual precipitation, precipitation seasonality, isothermality) leading to variations in evapotranspiration could affect fruiting phenology, with potential effects for the gibbon species (Butt et al. 2015).

The loss of highly suitable habitat for Bengal tiger is associated with flooding resulting from heavy rainfall in Nepal’s Chitwan district (Carter et al. 2013), and is consistent with our modelling results. Increasing annual mean temperatures and variation in precipitation seasonality, such as drought or heavy rain, are likely to affect the phenology of tropical evergreen, dry deciduous, moist deciduous, mangrove, subtropical, temperate uplands and alluvial grasslands across India, Bangladesh, Nepal and Bhutan. This may affect the population of prey herbivores and thereby the Bengal tiger, with disruption to ecosystem food webs.

5.4.2 The relative contribution of LULC and climate change to the mammals' distribution

Our modelled responses to global changes may be overoptimistic for the studied mammals in tropical Asia because we did not account for all threats to mammals, especially hunting, poaching, and human-wildlife conflicts which are major threats to the species considered here. In addition, we used the static LULC and MGVF variables as reliable projections are not available for tropical Asia. However, assessing the biodiversity consequences of climate change is complicated due to the uncertainty of the degree, rate and nature of projected climate change (IPCC 2007), and the interaction of climate change effects with biotic factors (competition, trophic relationships, dispersal abilities etc.) and stressors (land use, habitat fragmentation etc.) (Wiegand et al. 2005). In contrast, predicting spatially explicit maps for LULC change is difficult as deforestation may spread unexpectedly to areas that are currently pristine, and forests may be allowed to regrow in previously cleared areas (Asner et al. 2010). We acknowledge that our correlative approach of modelling based on dynamic bioclimatic and static LULC variables for the studied species are not a representative subset of all mammals in tropical Asia. However, it can form a basis for the mammal studies in tropical Asian region. Although human land use remains the main driver of present day species extinction and habitat loss (Hoffmann et al. 2010), our models suggest that climate change is projected to become equally or more important in the coming decades for mammals distribution in tropical Asia (Figure 5.8). It is difficult to rely on a single scientific approach for the conservation policy and management of the threatened mammals in tropical Asia given the underlying assumptions of that approach are under debate. Additional research is needed to assess the optimum combination of covariates (e.g., LULC change, climate change, biotic factors and other variables such as hunting, poaching, and human-wildlife conflicts) using different methods (rather than relying on one single method) and how covariate choice impacts results.

5.4.3 Extinction risks of the mammals

The current population trend of these threatened large mammals is negative, and there are multiple pathways (e.g., habitat loss, fragmentation, human interference, poaching, hunting and global climate change) to extinctions for these species (Davidson et al. 2009; IUCN 2016). Although no rigorous population estimates exist for Asiatic black bear for the whole continent, a study in Bangladesh suggests that the distributions of this species is highly fragmented/patchy and it is 'Critically Endangered' according to IUCN (2000) guidelines (Garshelis & Steinmetz 2008; Islam et al. 2010). Sport hunting and trading of Asiatic black bears in Japan, South Korea, China, Vietnam and several other countries is increasing the extinction risk for this species (IUCN 2016). One estimate for the global population size of Asian elephant was 41-52,000, of which more than 50% occurred in India (Choudhury et al. 2008). However, a more recent study reported a significant decrease in the population of Asian elephant in India (Puyravaud et al. 2016), and Alamgir et al. (2015) reported that there is likely to be a 38% loss in suitable habitat in Bangladesh for the remaining Asian elephant populations (300-350) in the near future.

The scenarios for Western hoolock gibbon populations (approximately 300) are extreme in Bangladesh, with 100% habitat loss and therefore possible extinction by 2070 under RCP8.5 (Alamgir et al. 2015). Sanderson et al. (2010) reported a 41% decline in population and occupied area for Bengal tiger in India. It has been estimated that tiger habitat and tiger populations in the Sundarbans are likely to reach a critical threshold at sea level rise between 24 and 28 cm above the year 2000 baseline; beyond 28 cm the remaining tiger habitat in Bangladesh’s Sundarbans would decline by 96%, and the number of breeding individuals would be reduced to fewer than 20 (Loucks et al. 2010). Horev et al. (2012) reported that the entire population of Bengal tigers in India is likely to go extinct in 21.5 years as six tigers are being poached annually. The number of extinct mammal species in South Asian countries is greatest for Bangladesh (11 species), followed by Afghanistan (7), Pakistan (5), Bhutan (3), Nepal (3), India (2), and Sri Lanka (1) (Srinivasulu & Srinivasulu, 2012). Extinction rates are usually high in large mammals due to the interaction between small geographic ranges and slow reproductive rates (Cardillo et al. 2005; Davidson et al. 2009), and our results also suggest that there will be declines in the suitable habitat for the threatened large mammals of Asia, which may lead to local or regional extinction with the current rates of population decrease.

5.4.4 Implications for conservation planning

The habitat of the threatened large mammals occurs in a variety of land management regimes (e.g., protected areas, reserved forests, multiple land-use areas) across tropical Asia (Carter et al. 2013; IUCN 2016). The habitat preferences differ among mammal species. For instance, Bengal tigers prefer habitats with more grasslands and higher landscape connectivity in Chitwan district of Nepal (Carter et al. 2013), whereas Asian elephants prefer areas close to a permanent source of fresh water as they need 80–200 litres of water a day for drinking and bathing (Shoshani & Eisenberg 1982). Results from previous studies suggest that the area of highly suitable habitat for Bengal tigers has decreased inside the park over 20 years in the Chitwan district of Nepal, while outside the park habitat suitability increased, especially from 1999 to 2009 (Carter et al. 2013). The distribution range of all these large mammals across tropical Asia is not limited to Protected Areas (PAs) and areas outside PAs are subject to development projects that may be a problem for the conservation of these mammals (Sathyakumar 2006).

The findings of our study inform the suitability of habitats for these threatened large mammals in different climatic scenarios inside and outside the PAs and can inform conservation planning. Our models predict more than 50% of climatically suitable habitat conditions for all species will occur outside of their natural habitats (Figures 5.4-7 and Figures D5.1-4). Different efforts to reduce habitat degradation outside PAs, and to increase the number and/or area of PAs considering the habitat range of these species, would be highly beneficial for species conservation (IUCN 2016). For instance, China, India, and several other countries have already established a number of PAs within the range of Asiatic black bears (Chape et al. 2003). In addition, establishing travel corridors between existing PAs could also be an option to account for the projected shifts in the distributions of mammal habitat under global climate change, and facilitate species' movement (Chape et al. 2003). The future distributions of the Asian elephant and Bengal tiger depend upon the conservation of large areas of suitable habitat by securing additional habitat, as their distribution is now highly clumped in disjunct areas (Puyravaud et al. 2016; Walston et al. 2010).

Habitat suitability models that predict the impact of climate change on species distributions frequently contrast scenarios of unconstrained and no dispersal with the caveat that, in reality, most species will show a range of dispersal distances which fall between these two assumptions (Broennimann et al. 2006). Therefore, the importance of dispersal in enabling species to keep pace with changing climates could be a useful tool for conservation planning. However, the quantitative descriptions of dispersal for the studied species were not included in the models due to the lack of robust data. The shifts in the distribution of the threatened large mammals' suitable climate space revealed in this study could be used to inform assisted migration as a management strategy for aiding species in reaching newly suitable locations as climate changes (Hällfors et al. 2016). Poaching, hunting and human-wildlife conflicts also increase the extinction risks of mammals. Although these variables were not included in our models, the conservation needs of the threatened large mammals may vary depending on the intensity of these variables. For instance, if poaching is worse in some areas, then different conservation measures would be needed, such as improved legislation and law enforcement regarding poaching, hunting and human-wildlife conflicts. Monitoring of conservation interventions as part of adaptive management, and reliable estimation of population size and trends, are also required for the success of mammal conservation (IUCN, 2016). In addition, increasing connectivity of suitable habitats between PAs that are too small to maintain viable populations in isolation, as well as conservation outside PAs, would be beneficial for mammal conservation in tropical Asia (Trisurat et al. 2012).

5.5 Conclusions

Most studies on mammal habitat suitability in Asian countries focus on the local scale and do not consider the entire distribution ranges of the species. This can hinder conservation efforts. However, habitat suitability models can assess the vulnerability of threatened Asian mammals with patchy distributions in different ecosystems and in areas that have undergone extensive disturbance. The findings of our models can inform conservation planning for these threatened large mammals under global climate change. We recommend that proper habitat management of the existing protected areas, and increasing the number and connectivity of protected areas could reduce the extinction risks of these threatened mammals. Future research should focus on the spatial prediction of these mammals within and outside of protected areas, looking for previously unrecorded populations, prey density, poaching incidents, dispersal capabilities of species, and conflicts with humans, updating models and planning for conservation.

CHAPTER 6

SYNTHESIS AND RECOMMENDATIONS

This chapter revisits the main findings of the thesis and discusses their implications for biodiversity conservation and forest management. Limitations of the studies are also presented and the directions for future works are suggested.

No paper publication is associated with this chapter

6.1 Overview

Tropical Asian forests encompass several biodiversity hotspots and species-rich ecoregions, and are likely to experience significant changes during this century due to projected increase in temperature, precipitation and extreme climate events (IPCC 2014). Several studies investigated the likely climate change impacts on species distribution at local scale (e.g., Chitale & Behera 2012; Gopalakrishnan et al. 2011). Without considering the entire distribution ranges of the species can hinder conservation efforts at global/continental scale. This thesis has investigated the potential impacts of climate change on continental-scale distributions of different taxa (e.g., Dipterocarps, Teak, large mammals) across tropical Asia in order to inform the development of effective strategies for biodiversity conservation under global climate change. To explore the current knowledge and understanding of climate change impacts on tropical Asian forests, I reviewed the existing literature for all tropical regions, and presented the projected changes in mean climate and climate extremes to identify potential future climate threats to the diverse and species-rich ecoregions of tropical Asia. I applied species distribution models to link species occurrences to bioclimatic and environmental data over large spatial scales in tropical Asia. This allowed the estimation of species' ecological requirements, and accordingly, to predict future suitable climate space for species, or their extinction risks. The key findings, limitations, and recommendations that come out of this thesis are presented below, following the general flow of the thesis.

6.2 Main findings and outcomes

This subsection is arranged by restating the PhD objectives, following the main findings and outcomes of each objectives.

Objective 1: Climate change impacts on tropical forests: identifying risks for tropical Asia

In this research chapter, I presented a global meta-analysis that assessed the effect of climate change on tropical forest vegetation. The analysis revealed that the impacts of climate change on tropical forests fell mainly into one of three broad categories: (1) changes in the plant species' distribution; (2) changes in forest stand dynamics, including changes in forest cover, structure and composition; and (3) changes in tree phenology. Most of the studies focussed on South and Central America (*n*=26) followed by South Asia (*n*=24) and Africa (*n*=15). The species-rich ecoregions of tropical Asia are particularly vulnerable to climate change due to the projected increase in temperature and precipitation variability, and extreme climate events in the region. The limited number of continental scale studies in tropical Asia can hinder the understanding of climate change impacts and associated conservation efforts, and based on this review, two research questions were posed to address these questions in the thesis: (1) how does climate change affect extinction risk for tropical trees and animals?; and (2) how can climate change risks be integrated into forest policy and management?

Objective 2: The impact of climate change on the distribution of two threatened Dipterocarp trees

In this research chapter, I modelled and quantified the climatically suitable habitat conditions for two ecologically and economically important and threatened Dipterocarp trees Sal and Garjan, distributed over a wide region in tropical Asian countries using a climate envelop modelling tool 'MaxEnt' (The Maximum Entropy algorithm). The models identified annual precipitation as the key bioclimatic variable for explaining the current and future distributions of Sal and Garjan and predicted that the suitable habitat conditions for both Sal and Garjan will decline by 2070 under RCP4.5 and RCP8.5. The models identified the vulnerable habitats of Sal and Garjan where artificial regeneration should be undertaken for forest restoration. In addition, attention should be paid to enabling the natural regeneration of the trees in the sites calculated as high risk. Assisted migration of species can also be adopted as a conservation strategy into the climatically suitable habitats.

Objective 3: Climatic-induced shifts in the distribution of Teak (Tectona grandis) in tropical Asia: implications for forest management and planning

In this study, I developed a species distribution model for Teak using a range of available data sets across its entire native distribution in tropical Asia, and its non-native distribution in Bangladesh using MaxEnt (maximum entropy). The results suggest that changes in annual precipitation, precipitation seasonality and annual mean actual evapotranspiration may result in shifts in the distributions of Teak across tropical Asia. Land use/land cover and elevation were important variables for the distributions of native and non-native Teak in tropical Asia. The findings of this study are globally significant as Teak is one of the most valuable tropical hardwood species in the international timber market. The extent of natural Teak forests from India through Myanmar, Laos and Thailand is shrinking due to deforestation and the local impacts of global climate change. Taking a predictive approach to understanding how climate change drives Teak distributions is a major advance. Long rotation Teak is not capable of adapting to rapidly changing climates and therefore, the findings of the study can be used to inform the following: forest risk assessment and management; conservation of critical Teak habitats; shortening the rotation period of Teak in the sites calculated as high risk; biological invasion that may occur due to its cultivation in non-native ranges, and direct management aimed at preventing, eliminating or minimizing biological invasion and their effects.

Objective 4: Increasing climate stress on tropical forests reveals greater extinction risk for threatened large mammals

In this chapter, I developed habitat suitability models for four large threatened mammals (Asiatic black bear, Asian elephant, Western hoolock gibbon and Bengal tiger), across their entire distributions in Asia. I found that changes in annual precipitation, annual mean temperature, precipitation and temperature seasonality, land use/land cover and elevation features of landscapes could reduce suitable habitat for these large mammals and therefore increase their extinction risks. The recommendations made from this study in order to reduce extinction risk include increasing the number and connectivity of protected areas, as well as strengthening legislation and law enforcement regarding poaching, hunting and human-wildlife conflicts.

6.3 Underlying causes of biodiversity loss in tropical Asia: climate change or LULC change or combined effects?

Tropical Asia is a known global hotspot of biodiversity and endemism, and the ecosystems across the region are threatened by an array of drivers such as land use change, habitat loss, climate change, and other biotic factors (Hughes 2017). It is difficult to predict the effects of these global change drivers on biodiversity due to their complex interaction (Asner et al. 2010; Brook et al. 2008; Mantyka-Pringle et al. 2014). Furthermore, there is no robust dataset available on the projections of LULC change, soil properties, logging activities, hunting, poaching, human-wildlife conflicts, and other biotic variables such as competition, predator, and dispersal mechanism that can be utilised in the models to predict the continental-scale range shifts of species (e.g., Wang et al. 2016). However, it has been reported that including the static variables (considered as the important driving factors of the species) in the models along with the dynamic climate variables performed better or no worse than excluding them (Stanton et al. 2012). This thesis has addressed this issue and employed several static variables such as LULC (Arino et al. 2012), elevation (Hijmans et al. 2005), MGVF (Broxton et al. 2014), and AET (Trabucco & Zomer 2010), along with dynamic climate variables (Hijmans et al. 2005) in the MaxEnt models to predict the continental-scale distribution of several plants and animals species in tropical Asia. The results suggest that the relative contribution of climate change variables is more than LULC variable for the distribution of Dipterocarp Sal and Garjan species as well as for the threatened large mammals in tropical Asia. In contrast, the LULC is the main regulatory factor for the distribution of timber species teak. However, the accuracy of the modelling results may be influenced by several factors. For instance, environmental data frequently require manipulation before using in species distribution models, and this often involves resampling data to a coarser or finer resolution. The LULC data used in this thesis was aggregated from 300 m to 1 km in order to match the spatial resolution of climate and other data. Inconsistencies are apparent for some of the maps of suitable habitat due to the aggregation of LULC data to a coarser resolution. In addition, different predictor variables were not used in the models (e.g., soil, tree physiological variables, logging intensity, and biotic factors for tree distribution while hunting, poaching, and human-wildlife conflicts for mammal distribution). The models calibrated with different dynamic climate and environmental variables that more closely align in spatial resolution may have different findings to this thesis and therefore requiring further exploration.

6.4 Implications for biodiversity conservation

A prerequisite for conservation planning is to categorise the forest sites of high conservation value and those with high vulnerability to global climate change (Myers et al. 2000; Olson & Dinerstein 1998). The Sal, Garjan and Teak are valuable timber trees and their forests have important biodiversity features, and are facing current and future threats from climate change (Chapters 3, 4 and 5). Bioclimatic models can be used to categorize the natural habitats of these trees as low to high risk under changing climates to inform conservation planning. For example, plantations of these trees should not be introduced to sites calculated as high risk under future climates, and should be replaced with other species assessed as more suitable under those climatic conditions. These trees are long rotation species and their rotation period can also be shortened in different sites according to the level of risk posed by climate change. The models predicted some areas as climatically suitable for species outside of their native ranges. As a conservation strategy, assisted migration may be possible for aiding these species in reaching newly suitable locations as climate changes (Hällfors et al. 2016). Climate space suitability models for Asiatic black bear, Asian elephant, Western hoolock gibbon, and Bengal tiger predicted more than 50% of climatically suitable habitat conditions for all species will occur outside of their natural habitats, but not all of the areas are designated as protected areas. The findings of this study can be used to identify the climatically suitable habitats for these threatened large mammals inside and outside of protected areas and inform conservation planning. Although not all areas and actions identified as being important to biodiversity conservation in tropical Asia will be protected, the outcomes of this thesis can be used for conservation prioritization of the species that reflect a real-world decision-making process.

6.5 Management recommendations

The large predicted shifts in their distribution will have major consequences for the Sal, Garjan and Teak dominated ecosystems and all related/dependent fauna and flora. Climatic-induced changes in species distribution will result in the absence of particular species in some ecosystems and this will affect the persistence of associated species. Therefore, proper guidelines need to be formulated for sustainable forest management under changing climates. These long rotation species have the potential to sequester more carbon than atmosphere and are important for ecosystem functioning (e.g., Pan et al. 2011). Therefore, small changes in their distributions can have large implications in terms of carbon storage as they are distributed over a large area in Asia (e.g., Sal forests cover 11 million ha in India, Bangladesh, and Nepal; the natural Teak of India, Myanmar, Laos and Thailand is estimated to cover over 29 million ha). Results from this thesis emphasize the importance of carbon storage through restoration of native forests and sustainable land management practices in tropical Asia. Large mammals are important biotic components in terms of ecosystem health. Increasing climate stress on tropical forests may lead them to become extinct locally or regionally. Different efforts such as the development of forest policy incorporating climate change issues, the imposition of logging bans in the natural forests to reduce deforestation and degradation, the declaration of more reserve forests as protected areas, and the improvement of legislation and law enforcement regarding poaching, hunting and human-wildlife conflicts are essential for better protection of these mammals and to reduce their extinction risks.

My research highlights that a paradigm shift is required to include more proactive planning and a focus on processes rather than patterns for the management of forests in tropical Asia. Understanding the effects of climate change on species and forest ecosystems has critical implications for our ability to support and incorporate climate change adaptation measures into policy development and management responses in tropical Asia. Both ‘climate change mitigation’ and ‘adaptation to climate change’ strategies required for responding to climate change impacts in tropical Asia. The ‘gain’ and ‘no change’ in climatic space in different ecoregions for Sal, Garjan, and Teak identified in this study can be considered as potential climate change refugia, as these species grow in a wide range of climates and may also be able to adapt to new climatic conditions (i.e. novel climates). The adaptive potential of the threatened large mammals to the novel climatic conditions (i.e. suitable habitat conditions) can also be considered as a management strategy to reduce their extinction risks. My research identified that ‘land use change’ or deforestation variable is an important factor along with other bioclimatic variables for the distribution of species in tropical Asia. Different strategies to avoid both climate change and human induced land cover changes either directly or indirectly in tropical Asia are: control of greenhouse gas emissions by reducing use of fossil fuels; reducing harvesting of large trees for short turnover products; planting rapidly growing native trees or enhancing their carbon sequestration potential; and restoring the degraded or deforested habitats for wildlife.

6.6 Limitations and future research directions

The research presented in this thesis presents potential climate change effects on several species' distributions in tropical Asia. Each research chapter highlights some important future research needs by addressing the limitations related to the methods and results. The correlative approach of species distribution modelling used in this thesis projects species' response to bioclimatic and environmental factors in tropical Asia. However, using a more mechanistic approach that allows the inclusion of tree physiological factors can be incorporated in future modelling analyses.

The species occurrence data were compiled from a variety of sources (e.g., field data, Global Biodiversity Information Facility database, IUCN spatial data, and published literature records). Therefore, higher number of species occurrence records may be included in the relatively well known areas (e.g., distribution of Dipterocarp trees are relatively well known across India, Bangladesh, Nepal, and Myanmer) compared to other native ranges. However, the sampling bias layer used in the models respresents a close approximation of the actual species' distributions. The presence/absence data of studied species for the entire distribution in tropical Asia is not available, and therefore MaxEnt (maximum entropy) algorithm was used in this thesis for modelling changes in species distribution. Different variables considered as important factors (e.g., logging pressure, soils, competition, dispersal capabilities, poaching, human-wildlife conflicts, roads etc.) were not included in the distribution modelling due to the lack of robust data. However, these should be incorporated in future analysis. This thesis forms the basis for the study on climate change impacts on tropical Asian forests at continental scale. Future research should focus on previously unrecorded populations, updating models and datasets such as collecting presence/absence data of species, improving bias corrections, exploring other methodologies (e.g., biomod2, random forest) and comparing the model performances to describe the potential impacts of climate change. In addition, the combined effects of climate change and land use change interactions need to be incorporated in future modelling studies.

In order to support effective conservation decisions, the following three topics should be the focus of urgent further research in tropical Asia:

1. Most Asian Dipterocarps remain in evergreen forests (mostly in aseasonal areas). A few species of *Shorea* and *Dipterocarpus* live in fire climax dry Dipterocarp woodlands (Appanah & Turnbull, 1998) among which two species (*Shorea robusta*, and *Dipterocarpus turbinatus*) have been addressed in this work. Future research should focus on more Dipterocarp trees in the aseasonal tropical areas (i.e., the ecoregions of Southeast Asian countries) at the continental scale that will explore their vulnerability to global climate change.

2. Climatic-induced shifts in the distribution of Teak (*Tectona grandis*) across its entire natural distribution in tropical Asia and non-native distributions in Bangladesh were modelled in this thesis. Future research should focus on using different modelling approaches and Teak forest management practices in other countries. According to Kollert & Cherubini (2012), Teak was introduced to 38 countries and the area of planted Teak forests is estimated to be 4.4 million ha, of which 83% is in Asia, 11% in Africa, and 6% in tropical America.
3. Habitat suitability models for four threatened large mammals (Asiatic black bear, Asian elephant, Western hoolock gibbon and Bengla tiger) and their conservation importance were discussed in this work. Future research should focus on more mammal species (especially the endangered species according to the IUCN red list of threatened species) in the species-rich ecoregions and biodiversity hotspots of tropical Asia to inform their conservation planning.

6.7 Conclusion

The world's biodiversity is facing a very uncertain future from global climate change and other extinction drivers such as habitat loss, land use change and anthropogenic disturbances. Although projected impacts of climate change on species distributions are well studied across the world, climate change studies in tropical Asia are very limited, mostly focus on the local scale, and often do not consider the entire distribution ranges of the species assessed. This thesis has addressed this gap by modelling the distributions of several species under changing climates, and provides a scientific basis for developing adaptive strategies in forest management in tropical Asia. The analyses presented in this thesis provide some initial clues to the consequences of climate change in Asia. These findings can be tested more thoroughly by exploring more methodologies with the collection of presence/absence data of species, incorporating more predictor variables in the models, such as tree physiological variables, land use change variables, hunting, poaching, and wildlife conflicts with human variables.

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APPENDICES

Chapter 2

Table A2.1 Summary of climate change impacts on tree species distribution, phenology, forest structure and composition for each of the 85 studies reviewed

Location	Continent/Region	Forest types	Landscape structure	Impacted areas of forest	Factors responsible	References
Brazil	South America	Tropical rainforest, savannah, subtropical, grassland	Fragmented	Forest structure and composition	Climate change	1. Raghunathan *et al*. 2015
Amazon	South America	Tropical Amazon	Fragmented	Forest structure and composition	Climate change	2. Olivares *et al*. 2015
Brazil	South America	Tropical Amazon	Fragmented	Forest dynamics and composition	Climate change	3. Laurance *et al*. 2014
Chile	South America	Tropical rainforest	Fragmented	Vegetation cover change	Biophysical and anthropogenic disturbances	4. Schulz *et al*. 2011
Peru	South America	Tropical rainforest	Fragmented	Tree diversity and aboveground carbon	Climate change and anthropogenic disturbances	5. Gonzalez *et al*. 2014
Brazil	South America	Amazon forests	Fragmented	Forest biomass	Climate change and anthropogenic stressors	6. Fearnside 2004
French Guiana	South America	Tropical moist forests	Fragmented	Canopy fragmentation, stand structure	Climate change	7. Rutishauser *et al*. 2011
Peru	South America	Tropical montane cloud forests	Fragmented	Tree diversity and functional characteristics	Climate change	8. Ledo *et al*. 2009
Panama	South America	Tropical forest	Fragmented	Changes in tree species abundance	Climate change	9. Condit *et al*. 1996
Amazonia	South America	Amazon forests	Fragmented	Changes in tree diversity and distributions	Climate change	10. Miles *et al*. 2004
Amazon	South America	Rainforests	Fragmented	Dieback of the Amazon rainforest	Climate change	11. Malhi *et al*. 2009 and 12. Boulton *et al*. 2013
Amazon	South America	Tropical forests	Fragmented	Forest cover change	Climate change	13. Nobre *et al*. 1991
Puerto Rico	South America	Tropical forests	Not reported	Forest structure and composition	Climate extremes	14. O'Brien *et al*. 2015
Amazon	South America	Tropical forests	Fragmented	Forest biomass	Climate change	15. Phillips *et al*. 1998
Amazon	South America	Tropical forests	Fragmented	Shifts in species distribution	Climate change	16. Vieira *et al*. 2015
Amazon	South America	Tropical forests	Fragmented	Forest carbon dynamics	Climate extremes	17. Doughty *et al*. 2015
Amazon	South America	Tropical forests	Fragmented	Drying and vegetation stress	Climate change	18. Roy 2011
Amazon	South America	Tropical forests	Not reported	Tree diversity and distribution	Climate change	19. Saatchi *et al*. 2008
Costa Rica	Central America	Rainforests	Not reported	Forest structure and dynamics	Climate extremes	20. Silva *et al*. 2013
Brazil	South America	Tropical forests	Fragmented	Tree species distribution	Climate change	21. Rodriguez *et al*. 2015
Amazon	South America	Tropical forests	Fragmented	Plant species composition	Climate change	22. Punyasena *et al*. 2008
Amazon	South America	Tropical forests	Fragmented	Amazon biomass	Climate change	23. Almeida Castanho *et al*. 2016
America	Central America	Tropical and Subtropical	Fragmented	Forest structure and composition	Climate change	24. Anado′n *et al*. 2014

Table A2.1 – continued

Location	Continent/Region	Forest types	Landscape structure	Impacted areas of forest	Factors responsible	References
Puerto Rico	Central America	Tropical forests	Fragmented	Canopy loss and forest dynamics	Climate change	25. Shiels *et al*. 2014 26. Shiels & González 2014
Africa	Africa	Tropical mountains	Fragmented	Shifts in tree distributions	Climate change	27. Jacob *et al*. 2015
Burkina Faso	Africa	Tropical forests	Fragmented	Forest cover change	Land use change, climate change	28. Ouedraogo *et al*. 2010
Africa	Africa	Tropical forests	Fragmented	Forest vegetation	Climate change	29. Delire *et al*. 2008
Africa	Africa	Tropical forests	Fragmented	Forest vegetation	Climate change	30. Scheiter & Higgins 2009
Ethiopia	Africa	Tropical forests	Fragmented	Plant species distribution	Climate change	31. Kreyling *et al*. 2010
Africa	Africa	Tropical forests	Fragmented	Forest vegetation	Climate change	32. Ivory *et al*. 2012
Africa	Africa	Rainforests	Fragmented	Forest vegetation	Global warming	33. James *et al*. 2013
Africa	Africa	Tropical forests	Fragmented	Forest vegetation	Climate change	34. Asefi-Najafabady & Saatchi 2013
Africa	Africa	Mangrove forests	Fragmented	Species distribution	Sea Level Rise	35. Yang *et al*. 2014
Africa	Africa	Tropical forests	Fragmented	Forest vegetation	Climate change	36. Groner *et al*. 2015
Africa	Africa	Tropical forests	Fragmented	Shifts in forest vegetation	Climate change	37. Jung *et al*. 2016
Africa	Africa	Tropical forests	Fragmented	Shifts in forest vegetation	Climate change	38. Pienaar *et al*. 2015
Ethiopia	Africa	Montane forests	Fragmented	Forest dynamics	Climate change	39. Hiltner *et al*. 2016
Ethiopia	Africa	Tropical forests	Fragmented	Forest vegetation distribution	Climate extremes	40. Van Breugel *et al*. 2016
Africa	Africa	Tropical forests	Fragmented	Palm species vulnerability	Climate change	41. Blach-Overgaard *et al*. 2015
Northeast Queensland	Australia	Rainforests	Not reported	Vegetation pattern	Climate change	42. Ostendorf *et al*. 2001
Queensland	Australia	Tropical forests	Fragmented	Vegetation phenology	Climate change	43. Ma *et al*. 2013
Queensland	Australia	Tropical forests	Fragmented	Tree species distribution	Climate change	44. Powell *et al*. 2010
Australia	Australia	Tropical forests	Fragmented	Forests vulnerability	Climate change	45. Murphy *et al*. 2014
Queensland	Australia	Tropical forests	Not reported	Flowering phenology	Climate extremes	46. Hopkins & Graham 1987
Queensland	Australia	Tropical forests	Not reported	Plant species vulnerability	Climate change	47. Fordham *et al*. 2012
Australia	Australia	Tropical and other forest ecosystems	Fragmented	Tree species distribution	Climate change	48. Butt *et al*. 2013
Queensland	Australia	Tropical forests	Fragmented	Forest vulnerability	Climate change	49. Hilbert *et al*. 2001
Australia	Australia	Tropical forests	Fragmented	Forests vulnerability	Climate change	50. Williams *et al*. 2003
Queensland	Australia	Tropical forests	Fragmented	Forest carbon stock	Climate change	51. Zimmermann *et al*. 2015
China	East Asia	Tropical forests	Not reported	Woody species distribution	Climate change	52. Zhang *et al*. 2014
East Asian regions	East Asia	Tropical forests	Not reported	Vegetation cover change	Climate change	53. Cho *et al*. 2015
East Asian regions	East Asia	Tropical forests	Fragmented	Land use and forest cover change	Climate change	54. Xu *et al*. 2015
Malaysia	Southeast Asia	Dipterocarp forest	Fragmented	Tree mortality	Climate change	55. Margrove *et al*. 2015

Table A2.1 – continued

Location	Continent/Region	Forest types	Landscape structure	Impacted areas of forest	Factors responsible	References
Asian countries	East Asia	Mangrove forests	Fragmented	Forest dynamics	Climate change, anthropogenic disturbances	56. Giri *et al*. 2008
Thailand	Southeast Asia	Deciduous	Fragmented	Stomatal conductance of trees, forest ecosystem functioning	Climate change	57. Igarashi *et al*. 2015
Malaysia	Southeast Asia	Rainforest	Fragmented	Tree distributions	Climate change	58. Fangliang *et al*. 1997
Malaysia	Southeast Asia	Rainforest	Fragmented	Tree mortality, forest structure	Climate change	59. Woods 1989
Malaysia	Southeast Asia	Tropical forests	Not reported	Flowering phenology	Climate extremes	60. Numata *et al*. 2003
Thailand	Southeast Asia	Pine forests	Fragmented	Stand dynamics	Climate change	61. Zimmer & Baker 2009
India	South Asia	Deciduous forest	Fragmented	Tree mortality	Climate change	62. Suresh *et al*. 2010
India	South Asia	Tropical forests	Fragmented	Shifts in forest types	Climate change	63. Ravindranath *et al*. 2006
India	South Asia	Deciduous forests	Fragmented	Species distribution	Climate change	64. Remya *et al.* 2015
India	South Asia	Deciduous forests	Fragmented	Species distribution	Climate change	65. Priti *et al.* 2016
India	South Asia	Deciduous forests	Fragmented	Dipterocarps extinction	Climate change	66. Shukla *et al.* 2013
India	South Asia	Tropical forests	Not reported	Flowering phenology	Climate change	67. Gaira *et al*. 2014
India	South Asia	Tropical forest	Fragmented	Shifts in vegetation	Climate change	68. Chaturvedi *et al*. 2011
India	South Asia	Deciduous and evergreen	Fragmented	Forest vegetation change	Climate change and anthropogenic stressors	69. Ravindranath & Sukumar 1998
India	South Asia	Tropical dry forest	Not reported	Flowering phenology of trees	Climate change	70. Kushwaha *et al*. 2011
India	South Asia	Deciduous forests	Fragmented	Species diversity and community structure	Climate change	71. Kushwaha & Nandy 2012
India	South Asia	Tropical forests	Not reported	Tree species distribution	Climate change	72. Gopalakrishnan *et al*. 2011
India	South Asia	Tropical forests	Not reported	Forest vegetation and landscape dynamics	Climate extremes	73. Kumaran *et al*. 2014
India	South Asia	Mangrove forests	Fragmented	Mangrove vegetation changes	Climate change, anthropogenic disturbances	74. Srivastava *et al*. 2015
India	South Asia	Deciduous forests	Fragmented	Tree species distribution	Climate change	75. Chitale & Behera 2012
India	South Asia	Tropical forests	Fragmented	Biome boundary shifts	Climate change	76. Chakraborty *et al.* 2013
India	South Asia	Tropical forests	Fragmented	Forest structure and composition	Climate change	77. Mehta *et al.* 2014
India	South Asia	Montane forests	Fragmented	Forest ecosystems	Climate change, land use conversions	78. Sukumar *et al*. 1995
Nepal	South Asia	Montane forests	Not reported	Vegetation cover, phenology	Climate change	79. Mainali *et al*. 2015
Sri Lanka	South Asia	Tropical forests	Fragmented	Forest Distribution	Climate change	80. Somaratne & Dhanapala 1996
Sri Lanka	South Asia	Tropical forests	Not reported	Tree phenology	Climate change	81. Gunarathne & Perera 2014
Bangladesh	South Asia	Freshwater swamp forests	Fragmented	Tree species distribution	Climate change	82. Deb *et al.* 2016

Table A2.1 – continued

Location	Continent/Region	Forest types	Landscape structure	Impacted areas of forest	Factors responsible	References
Bangladesh	South Asia	Mangrove forests	Fragmented	Dynamics of Sundarbans	Sea Level Rise	83. Pethick & Orford 2013
Bangladesh	South Asia	Mangrove forests	Fragmented	Forests vulnerability	Sea Level Rise	84. Rahman *et al.* 2011
Bangladesh	South Asia	evergreen forests	Fragmented	Tree distribution	Climate change	85. Sohel *et al.* 2016

Chapter 3

Table B3.1 The natural distribution of the two Dipterocarp trees can be categorized in the following eco-regions of the South and Southeast Asia.

Dipterocarp Species/Forests	Eco-regions/Climatic regions
Shorea robusta	- Upper Gangetic Plains Moist Deciduous Forests - Chhota-Nagpur Dry Deciduous Forests - Eastern Highlands Moist Deciduous Forests - Lower Gangetic Plains Moist Deciduous Forests - Northern Dry Deciduous Forests
Dipterocarpus turbinatus	• Brahmaputra Valley Semi-Evergreen Forests • Cardamom Mountains Rain Forests • Luang Prabang Montane Rain Forests • Meghalaya Subtropical Forests • Mizoram-Manipur-Kachin Rain Forests • Northern Annamites Rain Forests • Lower Gangetic Plains Moist Deciduous Forests • Northern Khorat Plateau Moist Deciduous Forests • Southern Annamites Montane Rain Forests • Southeastern Indochina Dry Evergreen Forests

Table B3.2 The result of correlation test of the 19 environmental variables initially selected for the MaxEnt models.

Variables	BIO1	BIO2	BIO3	BIO4	BIO5	BIO6	BIO7	BIO8	BIO9	BIO10	BIO11	BIO12	BIO13	BIO14	BIO15	BIO16	BIO17	BIO18	BIO19
BIO1	1.00	0.05	0.33	-0.43	**0.86**	**0.90**	-0.20	**0.92**	**0.93**	**0.93**	**0.95**	0.09	0.14	-0.16	0.35	0.13	-0.21	-0.17	0.01
BIO2	0.05	1.00	-0.37	0.58	0.46	-0.32	**0.83**	0.18	0.06	0.29	-0.15	-0.60	-0.41	-0.44	0.61	-0.44	-0.48	-0.43	-0.29
BIO3	0.33	-0.37	1.00	**-0.87**	-0.06	0.62	**-0.79**	0.14	0.38	0.03	0.57	0.31	0.16	0.22	-0.38	0.16	0.19	0.04	0.29
BIO4	-0.43	0.58	**-0.87**	1.00	0.02	**-0.74**	**0.90**	-0.19	-0.43	-0.09	-0.68	-0.47	-0.31	-0.15	0.39	-0.33	-0.13	-0.13	-0.21
BIO5	**0.86**	0.46	-0.06	0.02	1.00	0.59	0.30	**0.84**	**0.82**	**0.97**	0.69	-0.24	-0.08	-0.32	0.62	-0.10	-0.38	-0.43	-0.11
BIO6	**0.90**	-0.32	0.62	**-0.74**	0.59	1.00	-0.59	**0.73**	**0.86**	**0.71**	**0.98**	0.29	0.25	0.02	0.04	0.24	-0.02	-0.07	0.16
BIO7	-0.20	**0.83**	**-0.79**	**0.90**	0.30	-0.59	1.00	-0.02	-0.20	0.14	-0.47	-0.58	-0.37	-0.35	0.58	-0.39	-0.36	-0.34	-0.29
BIO8	**0.92**	0.18	0.14	-0.19	**0.84**	**0.73**	-0.02	1.00	**0.81**	**0.92**	**0.80**	0.04	0.10	-0.19	0.45	0.10	-0.22	-0.07	-0.07
BIO9	**0.93**	0.06	0.38	-0.43	**0.82**	**0.86**	-0.20	**0.81**	1.00	**0.87**	**0.90**	0.05	0.11	-0.14	0.35	0.09	-0.19	-0.28	0.07
BIO10	**0.93**	0.29	0.03	-0.09	**0.97**	**0.71**	0.14	**0.92**	**0.87**	1.00	**0.79**	-0.11	0.02	-0.24	0.56	0.00	-0.30	-0.29	-0.06
BIO11	**0.95**	-0.15	0.57	-0.68	0.69	**0.98**	-0.46	**0.80**	**0.90**	**0.79**	1.00	0.23	0.21	-0.08	0.16	0.21	-0.13	-0.12	0.09
BIO12	0.09	-0.60	0.31	-0.47	-0.24	0.29	-0.58	0.04	0.05	-0.11	0.23	1.00	**0.90**	**0.71**	-0.21	**0.94**	**0.75**	**0.71**	**0.73**
BIO13	0.14	-0.41	0.16	-0.31	-0.08	0.25	-0.37	0.10	0.11	0.02	0.21	**0.90**	1.00	0.11	0.13	**0.98**	0.14	0.55	0.35
BIO14	-0.16	-0.44	0.22	-0.15	-0.32	0.02	-0.35	-0.19	-0.14	-0.24	-0.08	**0.71**	0.11	1.00	-0.49	0.14	**0.94**	0.29	0.30
BIO15	0.35	0.61	-0.38	0.39	0.62	0.04	0.58	0.45	0.35	0.56	0.16	-0.21	0.13	-0.49	1.00	0.07	-0.52	-0.28	-0.13
BIO16	0.13	-0.44	0.16	-0.33	-0.10	0.24	-0.39	0.10	0.09	0.00	0.21	**0.94**	**0.98**	0.14	0.07	1.00	0.18	0.61	0.30
BIO17	-0.21	-0.48	0.19	-0.13	-0.38	-0.02	-0.36	-0.22	-0.19	-0.30	-0.13	**0.75**	0.14	**0.94**	-0.52	0.18	1.00	0.36	0.31
BIO18	-0.17	-0.43	0.04	-0.13	-0.43	-0.07	-0.34	-0.07	-0.28	-0.29	-0.12	**0.71**	0.55	0.29	-0.28	0.61	0.36	1.00	0.00
BIO19	0.01	-0.29	0.29	-0.21	-0.11	0.16	-0.29	-0.07	0.07	-0.06	0.09	**0.73**	0.35	0.30	-0.13	0.30	0.31	0.00	1.00

Table B3.3 The full names of CMIP5 Global Climate Models used in the analysis.

Model Name	Modelling Centre (or Group)	Institute ID
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
HadGEM2-ES	Met Office Hadley Centre (contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (INPE)

Table B3.4 Summary of the relative contribution of all variables used in the MaxEnt models and their percent contribution to each model.

Variables	**Description**	**Contribution to MaxEnt models (%)**					
		Shorea robusta			*Dipterocarpus turbinatus*		
		GCM-1	GCM-2	GCM-3	GCM-1	GCM-2	GCM-3
BIO1	Annual Mean Temperature	12.7	14.3	12.5	9.2	7.9	10.6
BIO2	Mean Diurnal Range (Mean of monthly (max temp – min temp))	3.6	4.7	3.5	11.1	11.3	9
BIO4	Temperature Seasonality (standard deviation *100)	11.2	10.6	11.6	12.2	11.7	12.3
BIO12	Annual Precipitation	39.9	37.5	40.2	22.8	23.2	22.4
BIO15	Precipitation Seasonality (Coefficient of Variation)	8.5	8.5	11.8	3.6	4	3.4
ELV	Elevation	7.5	8	6.9	25.4	25.9	26.4
AET	Actual Evapotranspiration	6	4	4.7	0.7	0.7	0.7
LULC	Land use/land cover	1.4	1.5	1.5	8.7	8.7	9
MGVF	Maximum Green Vegetation Fraction	9.8	10.8	10.8	6.4	6.6	6.2

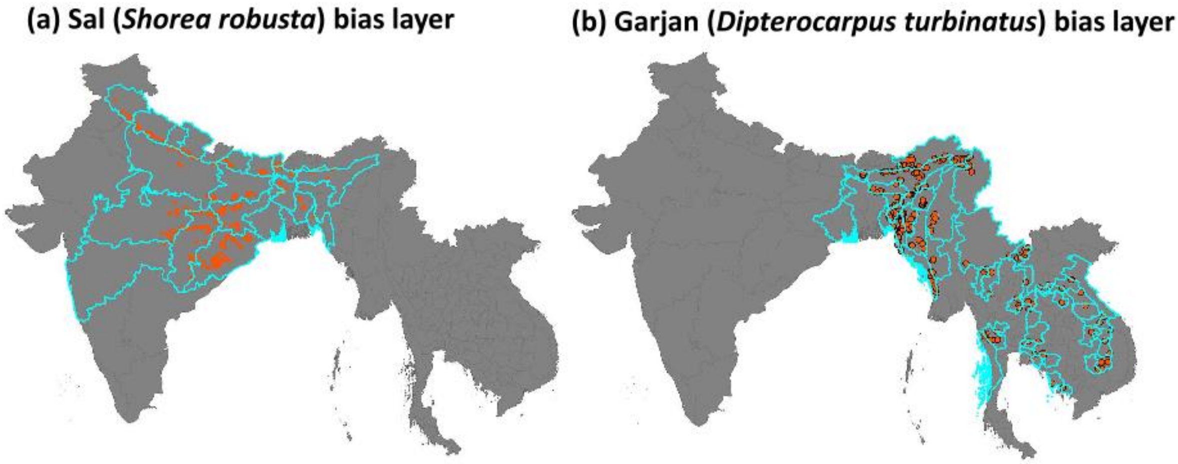
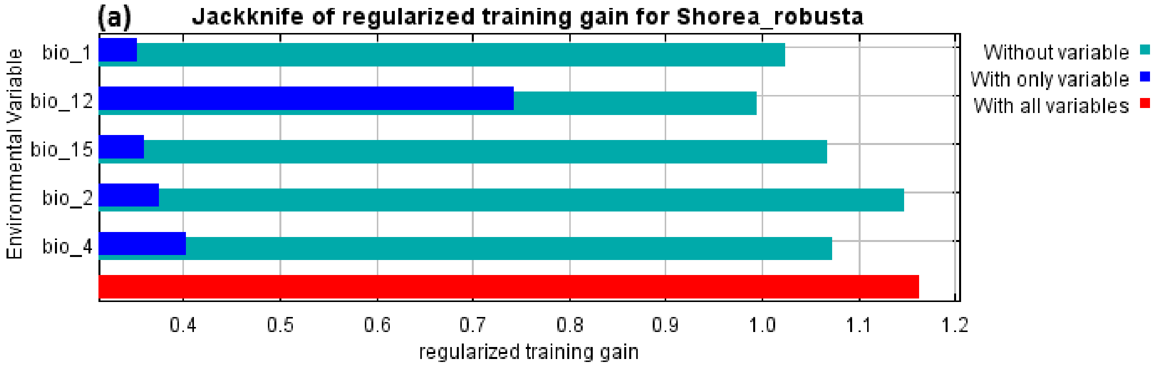


Figure B3.1. The bias layer created for the (a) Sal (*Shorea robusta*) and (b) Garjan (*Dipterocarpus turbinatus*) species to limit the background points to the occurrence areas for the species.

GCM 1


(a) Jackknife of regularized training gain for Shorea_robusta

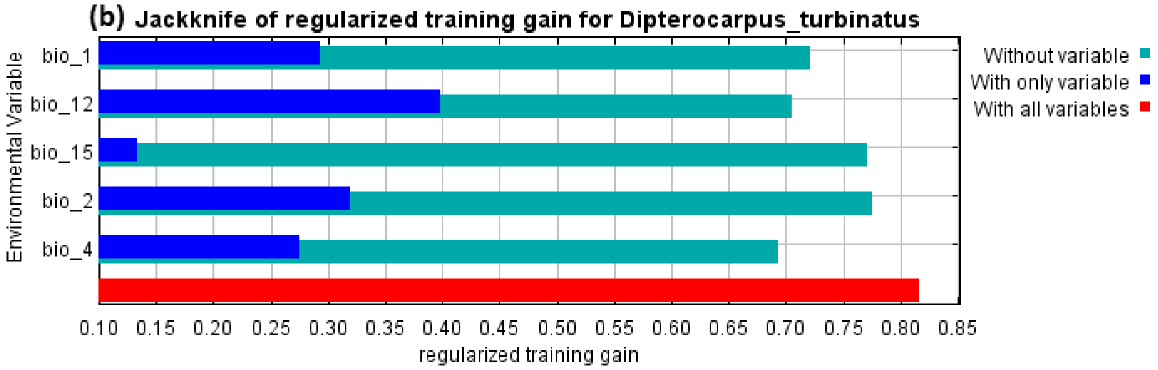

(b) Jackknife of regularized training gain for Dipterocarpus_turbinatus

Figure B3.2. The jackknife test results for environmental variables: (a) *Shorea robusta* model, and (b) *Dipterocarpus turbinatus* model. The graph depicts the training gain of each variable if the model was run in isolation, and compares it to the training gain with all the variables. Annual precipitation (BIO12) was the most significant variable with highest gain when used in isolation for both models.

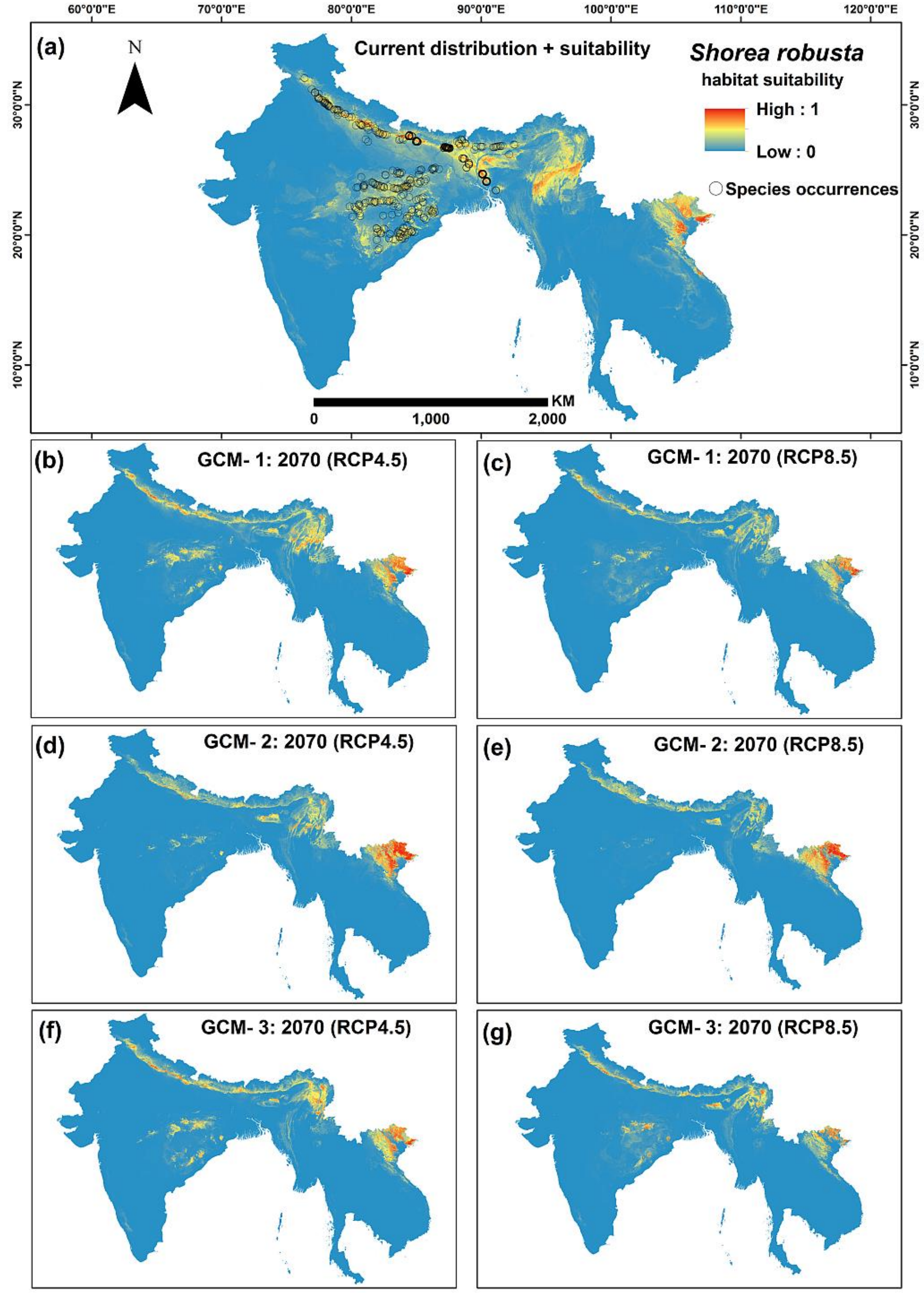


Figure B3.3. Modelling results of *S. robusta* species including all environmental variables for three GCMs: (a) current distribution and suitability; (b-c) scenarios for CGM 1; (d-e) scenarios for GCM 2; and (f-g) scenarios for GCM 3.

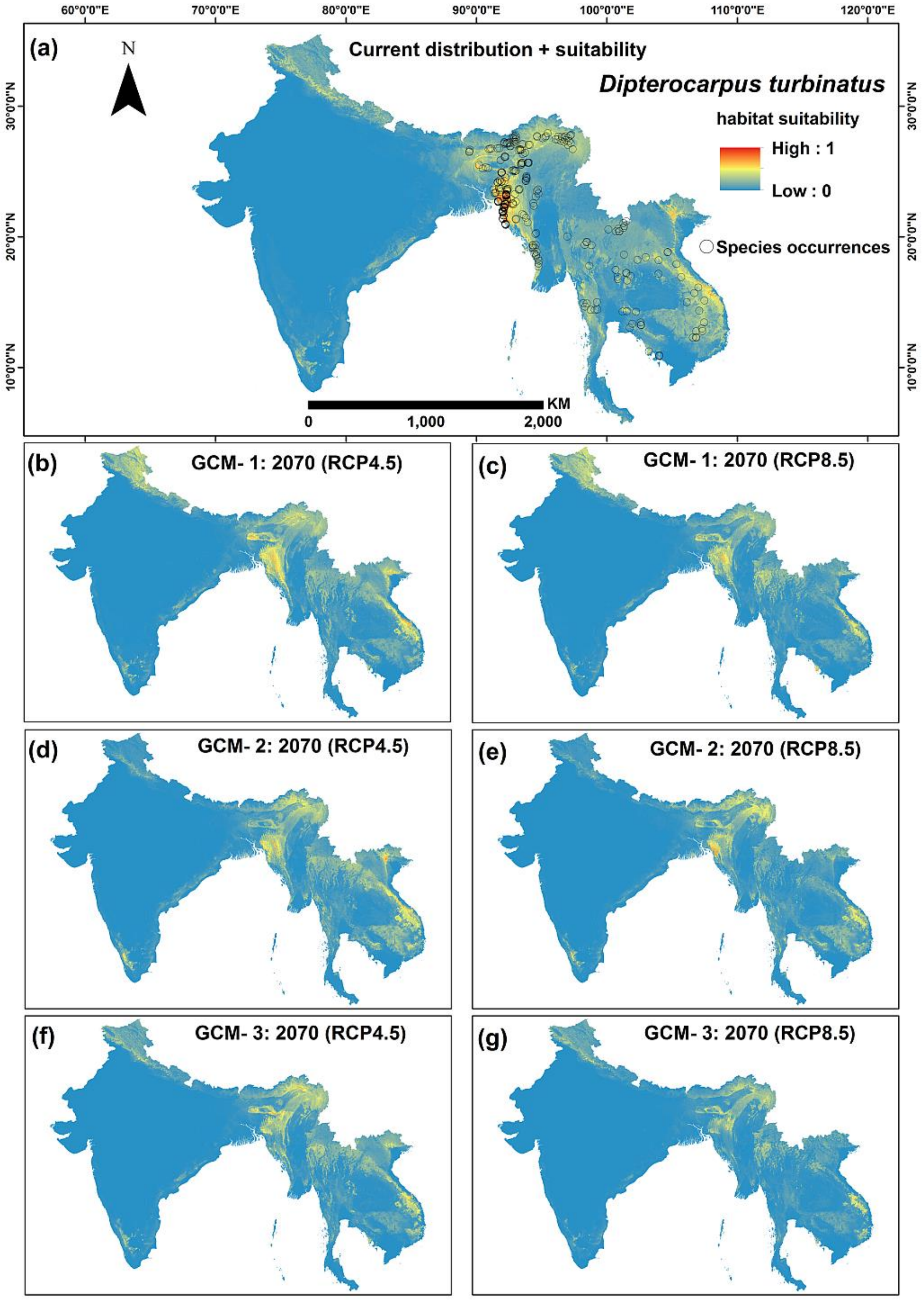


Figure B3.4. Modelling results of *D. turbinatus* species including all environmental variables for three GCMs: (a) current distribution and suitability; (b-c) scenarios for CGM 1; (d-e) scenarios for GCM 2; and (f-g) scenarios for GCM 3.

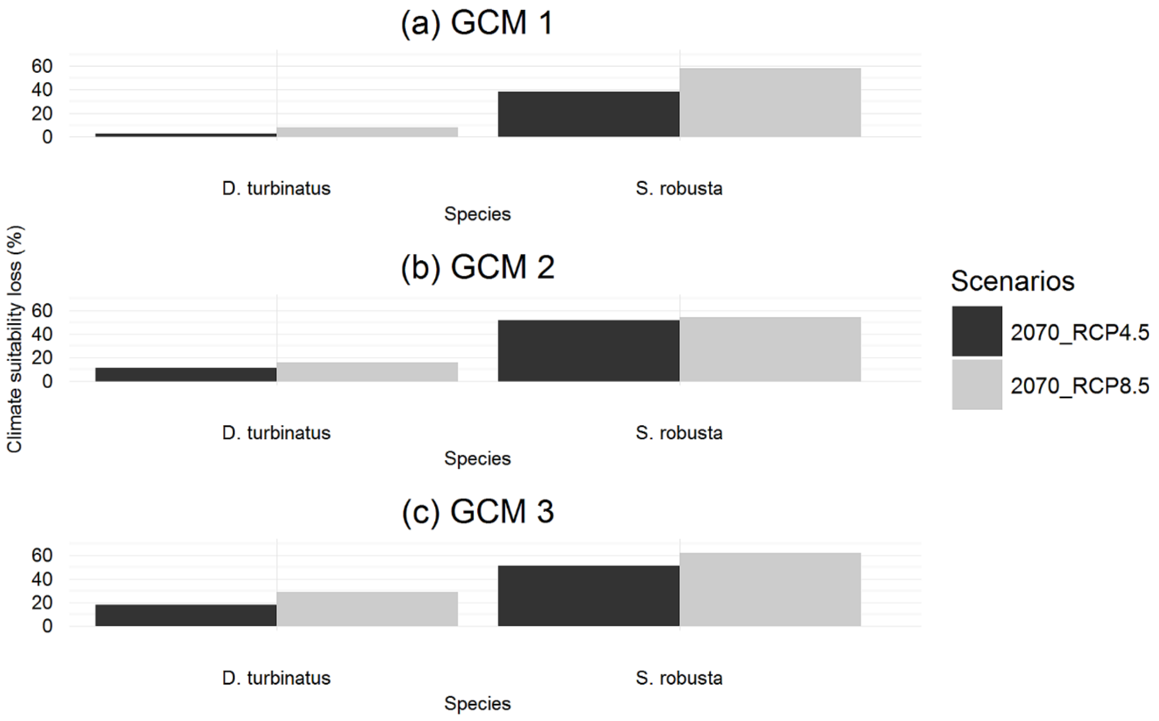


Figure B3.5. The modelling results which included all variables suggest that both *S. robusta* and *D. turbinatus* species are likely to lose suitable climate space by 2070.

Chapter 4

Table C4.1 The details of the 23 environmental variables primarily selected for the models. After a multicollinearity test, nine and eleven variables were used for native and non-native distributions respectively

Variables	Description	Resolution	Used in MaxEnt Models	
			Native	Non-native
BIO1	Annual Mean Temperature	1 km	√	√
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	1 km	√	×
BIO3	Isothermality (BIO2/BIO7) (* 100)	1 km	×	√
BIO4	Temperature Seasonality (standard deviation *100)	1 km	√	√
BIO5	Max Temperature of Warmest Month	1 km	×	×
BIO6	Min Temperature of Coldest Month	1 km	×	×
BIO7	Temperature Annual Range (BIO5-BIO6)	1 km	×	×
BIO8	Mean Temperature of Wettest Quarter	1 km	×	×
BIO9	Mean Temperature of Driest Quarter	1 km	×	√
BIO10	Mean Temperature of Warmest Quarter	1 km	×	×
BIO11	Mean Temperature of Coldest Quarter	1 km	×	×
BIO12	Annual Precipitation	1 km	√	√
BIO13	Precipitation of Wettest Month	1 km	×	×
BIO14	Precipitation of Driest Month	1 km	×	√
BIO15	Precipitation Seasonality (Coefficient of Variation)	1 km	√	√
BIO16	Precipitation of Wettest Quarter	1 km	×	×
BIO17	Precipitation of Driest Quarter	1 km	×	×
BIO18	Precipitation of Warmest Quarter	1 km	×	×
BIO19	Precipitation of Coldest Quarter	1 km	×	×
ELV	Digital Elevation Model (m) (SRTM)	1 km	√	√
LULC	Land use/land cover	1 km	√	√
MGVF	Maximum Green Vegetation Fraction	1 km	√	√
AET	Actual Evapotranspiration	1 km	√	√

Table C4.2 The natural distribution of the *Tectona grandis* forests can be categorized in the following eco-regions of the South and Southeast Asia

Natural Distributions	Eco-regions/Climatic regions in Asia
Tectona grandis	- Chin Hills-Arakan Yoma Montane Forests
	- Central Deccan Plateau Dry Deciduous Forests
	- Irrawaddy Moist Deciduous Forests
	- Kayah-Karen Montane Rain Forests
	- North Western Ghats Moist Deciduous Forests
	- North Western Ghats Montane Rain Forests
	- Northern Indochina Subtropical Forests
	- Northern Thailand-Laos Moist Deciduous Forests
	- Northern Triangle Subtropical Forests
	- South Western Ghats Moist Deciduous Forests
	- Irrawaddy Dry Forests
	- Khathiar-Gir Dry Deciduous Forests
	- Narmada Valley Dry Deciduous Forests
	- South Deccan Plateau Dry Deciduous Forests

Table C4.3 The training and test AUC values and standard deviation for training (75%) and test (25%) data of the five replicated models and their averages for both the native and non-native teak distribution models

Tectona grandis distribution ranges	Models	Training AUC	Test AUC	AUC Standard Deviation
Native	Model-1	0.839	0.840	0.014
	Model-2	0.844	0.807	0.016
	Model-3	0.843	0.823	0.014
	Model-4	0.850	0.785	0.016
	Model-5	0.843	0.813	0.016
	Averages	0.844	0.813	0.051
Non-native	Model-1	0.973	0.973	0.005
	Model-2	0.974	0.975	0.005
	Model-3	0.975	0.958	0.012
	Model-4	0.974	0.975	0.005
	Model-5	0.974	0.969	0.006
	Averages	0.974	0.970	0.007

Table C4.4 The projected changes in climate space for the different ecoregions of natural teak in South and Southeast Asia

Climatic scenarios	**Changes in climate space in different ecoregions**		
	Gain	**Loss**	**No change**
2050 (RCP6.0)	- Northern Thailand-Laos Moist Deciduous Forests - Irrawaddy Dry Forests - Khathiar-Gir Dry Deciduous Forests	- Central Deccan Plateau Dry Deciduous Forests - Irrawaddy Moist Deciduous Forests - Northern Indochina Subtropical Forests - Northern Triangle Subtropical Forests - South Western Ghats Moist Deciduous Forests - Narmada Valley Dry Deciduous Forests - South Deccan Plateau Dry Deciduous Forests	- Chin Hills-Arakan Yoma Montane Forests - Kayah-Karen Montane Rain Forests - North Western Ghats Moist Deciduous Forests - North Western Ghats Montane Rain Forests
2070 (RCP6.0)	- Central Deccan Plateau Dry Deciduous Forests - Kayah-Karen Montane Rain Forests - Northern Thailand-Laos Moist Deciduous Forests - Irrawaddy Dry Forests - Khathiar-Gir Dry Deciduous Forests - Narmada Valley Dry Deciduous Forests	- Irrawaddy Moist Deciduous Forests - Northern Indochina Subtropical Forests - Northern Triangle Subtropical Forests - South Western Ghats Moist Deciduous Forests - South Deccan Plateau Dry Deciduous Forests	- Chin Hills-Arakan Yoma Montane Forests - North Western Ghats Moist Deciduous Forests - North Western Ghats Montane Rain Forests
2050 (RCP8.5)	- Northern Thailand-Laos Moist Deciduous Forests - Irrawaddy Dry Forests - Khathiar-Gir Dry Deciduous Forests - Narmada Valley Dry Deciduous Forests	- Chin Hills-Arakan Yoma Montane Forests - Central Deccan Plateau Dry Deciduous Forests - Irrawaddy Moist Deciduous Forests - Northern Indochina Subtropical	- Kayah-Karen Montane Rain Forests - North Western Ghats Moist Deciduous Forests - North Western Ghats Montane Rain Forests

		Forests - Northern Triangle Subtropical Forests - South Western Ghats Moist Deciduous Forests - South Deccan Plateau Dry Deciduous Forests	
2070 (RCP8.5)	- Central Deccan Plateau Dry Deciduous Forests - Kayah-Karen Montane Rain Forests - Northern Thailand-Laos Moist Deciduous Forests - Irrawaddy Dry Forests - Khathiar-Gir Dry Deciduous Forests - Narmada Valley Dry Deciduous Forests	- Irrawaddy Moist Deciduous Forests - North Western Ghats Moist Deciduous Forests - North Western Ghats Montane Rain Forests - Northern Indochina Subtropical Forests - Northern Triangle Subtropical Forests - South Western Ghats Moist Deciduous Forests - South Deccan Plateau Dry Deciduous Forests	- Chin Hills-Arakan Yoma Montane Forests

Table C4.5 The projected changes in climate space in the different teak plantations of Bangladesh

Climatic scenarios	**Changes in climate space in different forests in Bangladesh**		
	Gain	**Loss**	**No change**
2050 (RCP6.0)	- Chunati Wildlife Sanctuary - Fasiakhali Wildlife Sanctuary - Himchari National Park - Medhakachhapia National Park - Teknaf Wildlife Sanctuary - Bangabanfhu Safari Park Coxbazar	- Lawachara National Park - Khadimnagar National Park - Satchari National Park - Rema Kalenga Wildlife Sanctuary - Tilagorh Eco Park	- Hajarikhil Wildlife Sanctuary - Baroiyadhala National Park - Dudpukuria-Dhopachari Wildlife Sanctuary - Kaptai National Park
2070 (RCP6.0)	- Chunati Wildlife Sanctuary - Fasiakhali Wildlife Sanctuary - Himchari National Park - Medhakachhapia National Park - Teknaf Wildlife Sanctuary - Khadimnagar National Park - Bangabanfhu Safari Park Coxbazar - Tilagorh Eco Park	- Hajarikhil Wildlife Sanctuary - Baroiyadhala National Park - Dudpukuria-Dhopachari Wildlife Sanctuary - Kaptai National Park - Lawachara National Park - Satchari National Park - Rema Kalenga Wildlife Sanctuary	-
2050 (RCP8.5)	- Chunati Wildlife Sanctuary - Fasiakhali Wildlife Sanctuary - Himchari National Park - Medhakachhapia National Park - Teknaf Wildlife Sanctuary - Khadimnagar National Park - Bangabanfhu Safari Park Coxbazar - Tilagorh Eco Park	- Hajarikhil Wildlife Sanctuary - Baroiyadhala National Park - Dudpukuria-Dhopachari Wildlife Sanctuary - Kaptai National Park - Lawachara National Park - Satchari National Park - Rema Kalenga Wildlife Sanctuary	-
2070 (RCP8.5)	- Chunati Wildlife Sanctuary - Fasiakhali Wildlife Sanctuary - Himchari National Park - Medhakachhapia National Park - Teknaf Wildlife Sanctuary - Khadimnagar National Park - Bangabanfhu Safari Park Coxbazar - Tilagorh Eco Park	- Hajarikhil Wildlife Sanctuary - Baroiyadhala National Park - Dudpukuria-Dhopachari Wildlife Sanctuary - Kaptai National Park	- Lawachara National Park - Satchari National Park - Rema Kalenga Wildlife Sanctuary

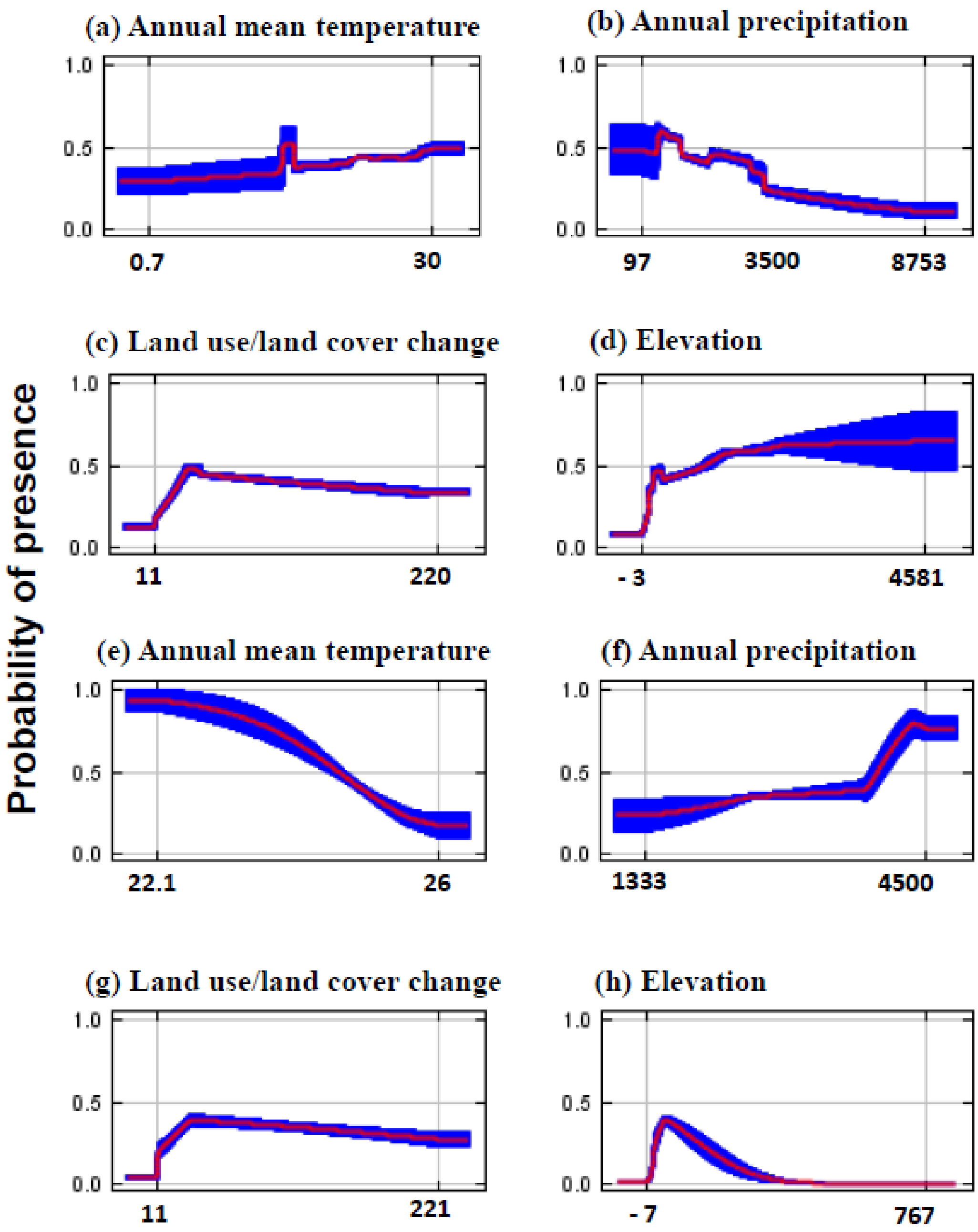


Figure C4.1 The response curves of *Tectona grandis* to the annual mean temperature and annual precipitation with two most important variables Land use/land change and Elevation (a-d represents the model for native distribution and e-h represents for non-native distributions). The curves show the mean response of the 5 replicated model runs (red) and the mean +/- one standard deviation (blue). The unit of x-axis in the figures ‘a’ and ‘e’ is in ^{0}C and in the figures ‘b’ and ‘f’ is in mm. The unit of elevation (figures ‘d’ and ‘h’) is in m (SRTM)

Chapter 5

Table D5.1 Distribution range, habitat and ecology and major threats of the four threatened Asian mammals (IUCN 2016)

Species	Distribution range	Habitat and ecology	Major threats
Ursus thibetanus	Afghanistan, Bangladesh, Bhutan, Cambodia, China, India, Iran, Japan, Korea, Laos, Myanmar, Nepal, Pakistan, Russia, Taiwan, Thailand, Viet Nam	- Both broad-leaved and coniferous forests. - Foods include succulent vegetation (shoots, forbs and leaves) in spring, insects and a variety of trees and shrub-borne fruits in summer and nuts in autumn. - The diet also contains meat from mammalian ungulates.	- Habitat loss due to logging, expansion of human settlements, roadway networks etc. - Global climate change - Hunting for skins, paws and gall bladders.
Elephas maximus	Bangladesh, Bhutan, Cambodia, China, India, Indonesia, Laos, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand, Viet Nam	- Grassland, tropical evergreen, semi-evergreen, moist deciduous, dry deciduous and dry thorn forests including cultivated and secondary forests and scrublands. - One of the last few mega-herbivores still extant on earth. - They need to consume large quantities of food per day. - The diet contains a variety of plants (82 species and 60 species in India and Sri Lanka respectively). - Annual diet is dominated by grass (84%). - Flagship species or keystone species for their important ecological role and impact on the environments.	- Habitat loss, degradation and forest fragmentation which are driven by an expanding human population. - Global climate change - Increasing conflicts between humans and elephants when elephants eat or trample crops. - Poaching is a major threat to elephants in Asia.
Hoolock hoolock	Bangladesh, India, Myanmar	- Tropical evergreen, semi-evergreen, rainforests, mixed deciduous and subtropical broadleaf hill forests. - Frugivorous species, with ripe fruits composing a majority of its diet. - An important disperser of undigested seeds from large and small fruit-bearing trees.	- Combined effects of habitat loss, fragmentation, human interference and hunting. - Global climate change - Shifting cultivation and large scale hunting for food and medicinal properties by the ethnic groups

Species	Distribution range	Habitat and ecology	Major threats
Panthera tigris tigris	Bangladesh, Bhutan, India, Nepal	- Tropical evergreen, dry deciduous, moist deciduous, mangrove, subtropical and temperate uplands and alluvial grasslands. - Wild pigs and deer of various species are the two prey types that make up the bulk of the tiger's diet, and in general tigers require a good population of these species in order to survive and reproduce. - The diet contains birds, fish, rodents, insects, amphibians, reptiles in addition to other mammals such as primates and porcupines. - Tigers can also take ungulate prey much larger than themselves, including large bovids (Water Buffalo, Gaur, Banteng), elephants and rhinos. - A top predator which is at the apex of the food chain and maintains the balance between prey herbivores and the vegetation upon which they feed. - Play an important role in the health and diversity of an ecosystem. Therefore, its presence in the forests is an indicator of the well-being of the ecosystem.	- Poaching for illegal trade in high-value tiger products including skins, bones, meat and tonics is a primary threat to tigers. - Conversion of forest land to agriculture and silviculture, commercial logging, and human settlement are the main drivers of tiger habitat loss. - Global climate change

Table D5.2 The 23 environmental variables primarily selected for the models. After a multicollinearity test, nine variables were used for modelling the distributions of the mammals

Variables	Description	Resolution	Used in MaxEnt Models
BIO1	Annual Mean Temperature	1 km	√
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	1 km	√
BIO3	Isothermality (BIO2/BIO7) (* 100)	1 km	√
BIO4	Temperature Seasonality (standard deviation *100)	1 km	√
BIO5	Max Temperature of Warmest Month	1 km	×
BIO6	Min Temperature of Coldest Month	1 km	×
BIO7	Temperature Annual Range (BIO5-BIO6)	1 km	×
BIO8	Mean Temperature of Wettest Quarter	1 km	×
BIO9	Mean Temperature of Driest Quarter	1 km	×
BIO10	Mean Temperature of Warmest Quarter	1 km	×
BIO11	Mean Temperature of Coldest Quarter	1 km	×
BIO12	Annual Precipitation	1 km	√
BIO13	Precipitation of Wettest Month	1 km	×
BIO14	Precipitation of Driest Month	1 km	×
BIO15	Precipitation Seasonality (Coefficient of Variation)	1 km	√
BIO16	Precipitation of Wettest Quarter	1 km	×
BIO17	Precipitation of Driest Quarter	1 km	×
BIO18	Precipitation of Warmest Quarter	1 km	×
BIO19	Precipitation of Coldest Quarter	1 km	×
ELV	Digital Elevation Model (m) (SRTM)	1 km	√
LULC	Land use/land Cover	1 km	√
MGVF	Maximum Green Vegetation Fraction	1 km	√
AET	Actual Evapotranspiration	1 km	×

Table D5.3 The threshold independent ROC tests for mammals' species. The AUC values of both models ('climatic' and 'all variables') have good discrimination ability in accurately identifying the potential distribution of all mammals' species across tropical Asia.

Species	AUC	
	Climatic variables	All variables
Ursus thibetanus	0.86	0.87
Elephas maximus	0.77	0.80
Hoolock hoolock	0.75	0.77
Panthera tigris tigris	0.80	0.83

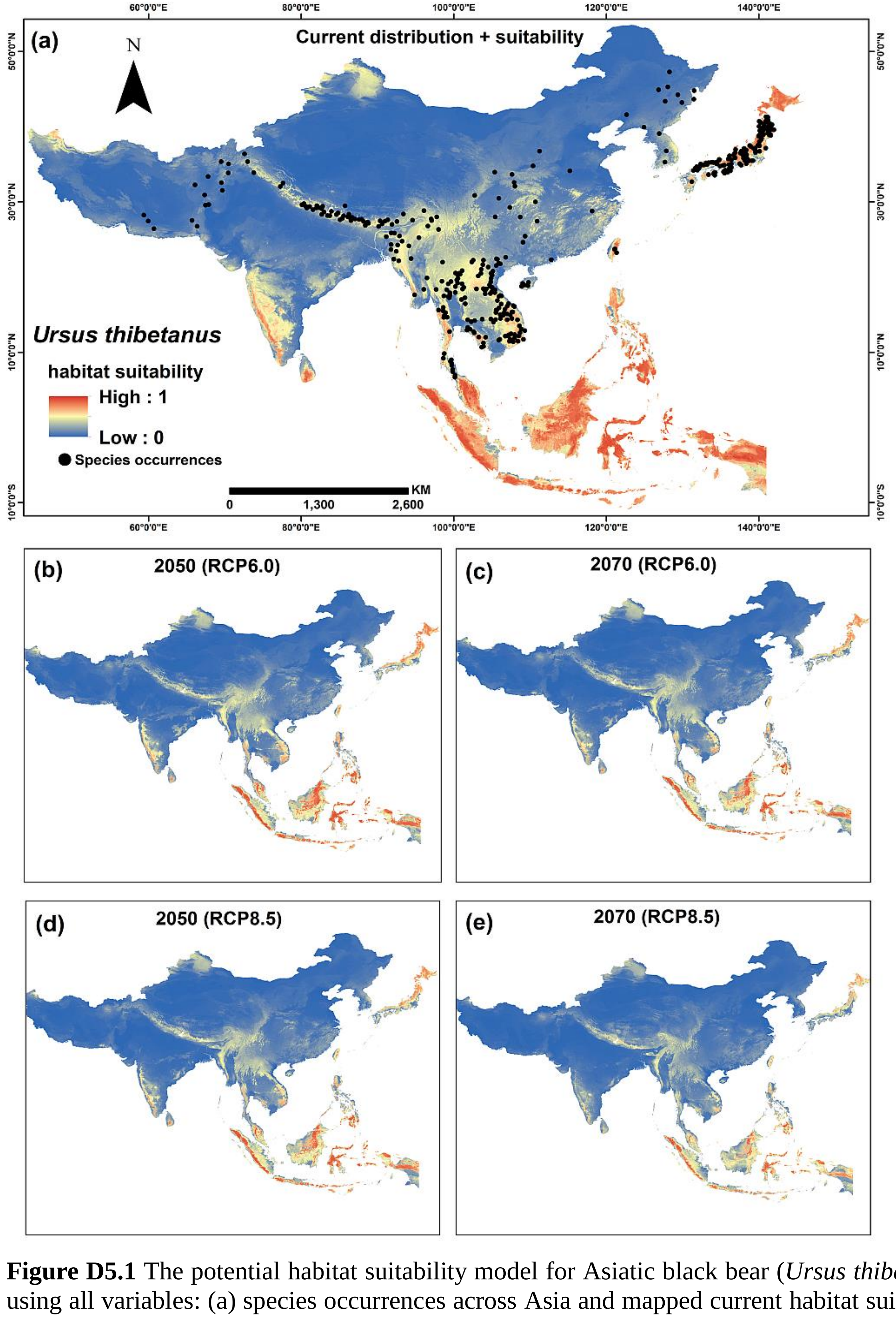


Figure D5.1 The potential habitat suitability model for Asiatic black bear (*Ursus thibetanus*) using all variables: (a) species occurrences across Asia and mapped current habitat suitability for bear; and (b-e) the four projected habitat suitability for bear in different scenarios. Changes in annual precipitation, precipitation and temperature seasonality, annual mean temperature and elevation features may influence the distribution of Asiatic black bear.

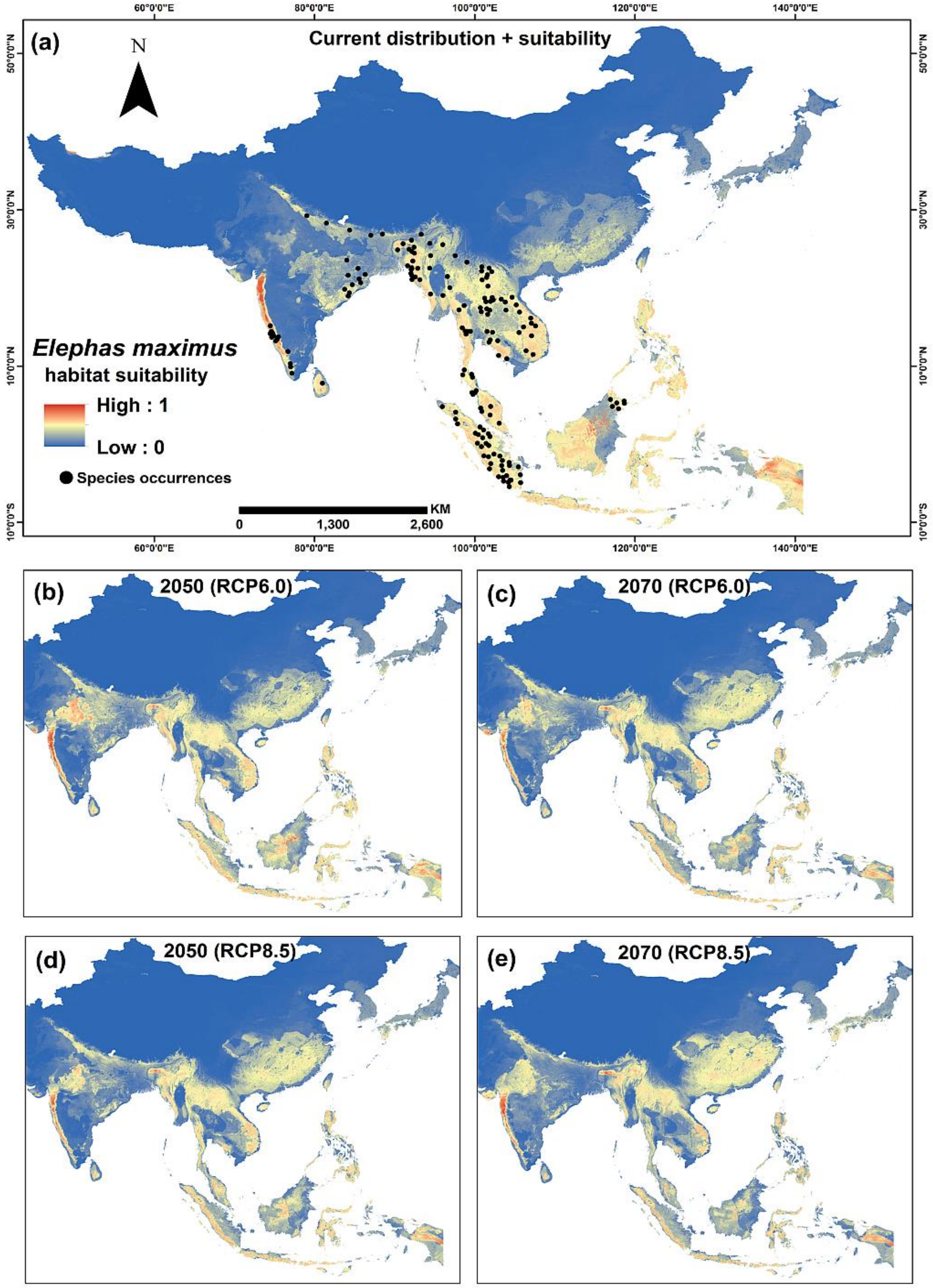


Figure D5.2 The predicted habitat suitability for Asian elephant (*Elephas maximus*) using all variables: (a) species occurrences across Asia and mapped current habitat suitability for elephant; and (b-e) the four projected habitat suitability for elephant in different scenarios. The key bioclimatic variables that influence the distribution of Asian elephant are annual precipitation, temperature seasonality, annual mean temperature, maximum green vegetation fraction and elevation features of the landscapes.

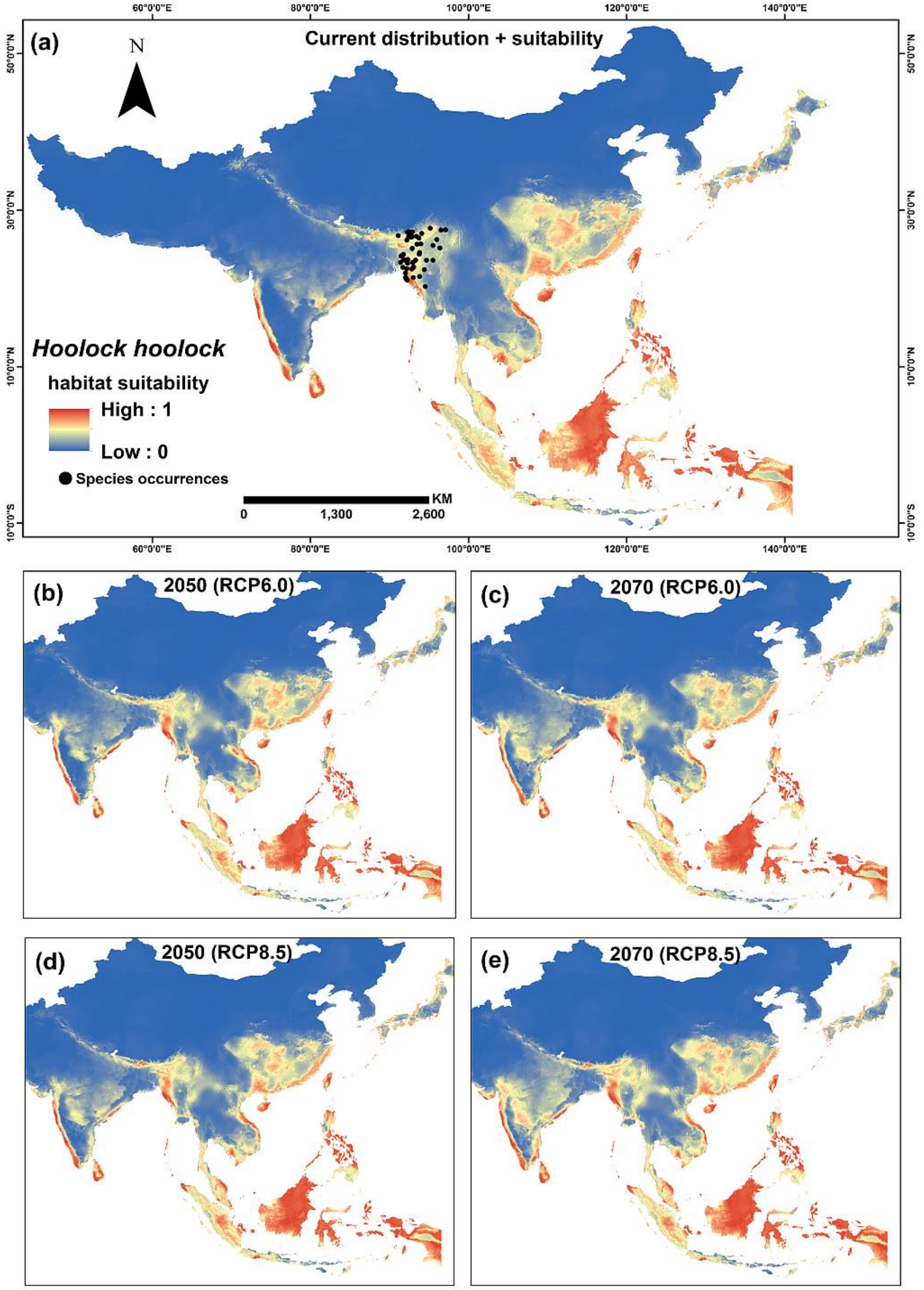


Figure D5.3 The projected habitat suitability for Western hoolock gibbon (*Hoolock hoolock*) using all variables: (a) species occurrences across Asia and mapped current habitat suitability for gibbon; and (b-e) the four projected habitat suitability for gibbon in different scenarios. Changes in the mean diurnal range, annual precipitation, isothermality, precipitation seasonality and elevation may influence the distribution of gibbon in Asia.

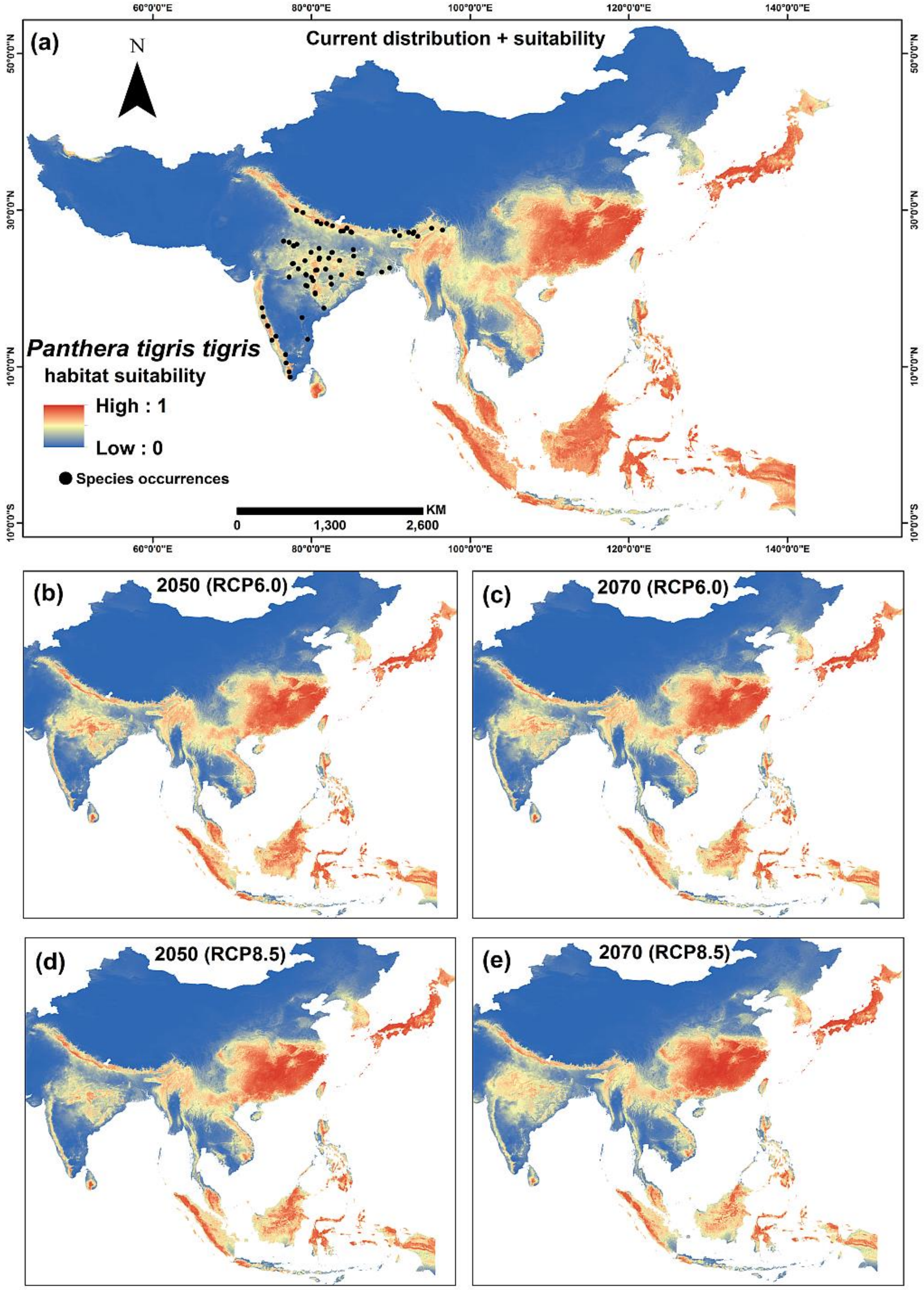


Figure D5.4 The potential habitat suitability for Bengal tiger (*Panthera tigris tigris*) using all variables: (a) species occurrences across Asia and mapped current habitat suitability for tiger; and (b-e) the four projected habitat suitability for tiger in different scenarios. The key bioclimatic variables that influence the distribution of tiger are annual precipitation; annual mean temperature, precipitation seasonality and land use/land cover.