Climate change impacts on tropical forests: Identifying risks for tropical Asia

Article *in* Journal of Tropical Forest Science · April 2018
DOI: 10.26525/jtfs2018.30.2.182194

4 authors, including:

Jiban Chandra Deb
University of New Brunswick

Nathalie Butt
The University of Queensland

https://doi.org/10.26525/jtfs2018.30.2.182194

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

Deb JC[1, 4, *], Phinn S[1], Butt N[2] & McAlpine CA[3]

[1]The University of Queensland, Remote Sensing Research Centre, School of Earth and Environmental Sciences, Brisbane 4072, Australia
[2]The University of Queensland, ARC Centre of Excellence for Environmental Decisions and School of Biological Sciences, Brisbane 4072, Australia
[3]The University of Queensland, School of Earth and Environmental Sciences and Centre for Biodiversity and Conservation Science, Brisbane 4072, Australia
[4]Shahjalal University of Science and Technology, Department of Forestry and Environmental Science, School of Agriculture and Mineral Sciences, Sylhet-3114, Bangladesh

**j.deb@uq.edu.au*

Submitted 7 March 2017; accepted 21 September 2017

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. This study reviewed the available evidence of climate change impacts on tropical forests. We selected 85 studies based on two selection criterias and recorded the impacts of climate change on different areas of tropical forests. The majority of the studies examined climate change impacts on forest structure and composition (72%), with few considering phenology (8%). This study focused on tropical Asian forests because of their high biodiversity values and their vulnerability to the interacting threats of forest fragmentation and climate change. The difference map (2080–2100 compared with 1980–2000) indicates a significant acceleration of mean warming (5–9 °C) and increase in mean precipitation (0.5–1 mm day^{-1}) in the Himalayan Highlands, Tibetan Plateau and arid regions of South Asia. Based on this review, two issues were posed to direct future tropical forest research: (1) effect of climate change on the extinction risk of tropical trees and (2) integration of climate change risks into forest policy and management.

Keywords: Climate extremes, forest disturbance, forest fragmentation, species composition, species distribution, phenology

INTRODUCTION

Projected changes in climate will produce significant shifts in the distribution and abundance of many forest tree species (Dale & Rauscher 1994). Climate change affects forest ecosystems through changes in mean temperature and rainfall, and frequency and severity of weather and climate extremes, such as wildfires, storms, cyclones (hurricanes or typhoons) and drought (Garcia et al. 2014). These impacts are broadly characterised as changes in species distribution, forest composition (relative abundance of species), forest structure and flowering and fruiting phenology (Thuiller et al. 2008, Grimm et al. 2013, Butt et al. 2015). Rising temperatures increase the frequency and magnitude of extreme events (e.g. extreme storms or cyclones), and changes in seasonality, along with anthropogenic disturbances such as plantations, clearing and deliberate burning, which alter the structure and function of forest ecosystems (Grimm et al. 2013, Seidl et al. 2017). Climate change-induced shifts in plant distributions determines 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 key drivers of variability (e.g. El Niño Southern Oscillation, African Intertropical Convergence Zone) are often associated with extreme climate 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 as recently occurred in the Amazonian rainforest (Allen et al. 2010, 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). 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 (Malhi & Phillips 2004). However, they are now under unprecedented threat from deforestation and degradation and accelerating climate change (Pacifici et al. 2015). The Intergovernmental Panel on Climate Change (IPCC) projected that tropical forest ecosystems are likely to be significantly impacted by climate change (IPCC 2014). 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) due to clearing, with an annual increment of forest loss of 2101 km^2 year^{-1}. Although the extent of forest cover loss is highest in South American tropical forests (approximately 16% of global forest cover loss), tropical Asia are experiencing the highest rates of loss (e.g. Indonesia exhibited the largest increase in forest loss by 1021 km^2 year^{-1} 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 °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 (Figure 1). 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 (Dudgeon & Corlett 1994, Corlett & Lafrankie-Jr 1998). In the aseasonal tropics, drought occurs at supra-annual

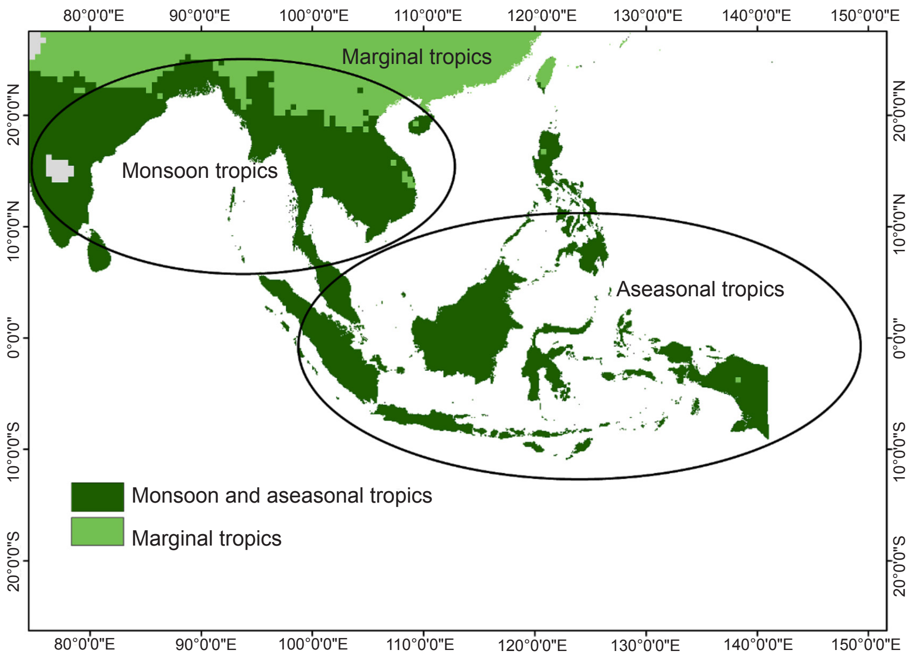

Figure 1 The extent of the major climatic zones of tropical Asia: marginal tropics (area indicated as light green colour), monsoon tropics (covers mostly South Asian region; dark green colour and indicated by ellipse curve), and aseasonal tropics (covers mostly the Southeast Asian regions; dark green colour and indicated by ellipse curve) (Corlett & Lafrankie-Jr 1998)

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). 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) (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, Deb et al. 2017a). In tropical Asia, most of the forests are degraded and fragmented due to widespread conversion of forests for agriculture (Ashton et al. 2014). As a result, the vulnerability of tropical Asian forests to climate change is enhanced (Laurance 2004, Sodhi et al. 2010), and understanding its impacts on tropical Asian forests is a priority for their conservation.

This paper reviews and synthesises the available evidence for climate change impacts on tropical vegetation. The findings for tropical Asia and other tropical regions are discussed with focus on tropical Asian forests because of their high biodiversity values and their vulnerability to the interacting threats of forest fragmentation and climate change. Projected climate change and climate extreme events and their likely impacts on tropical Asian forests are reviewed. The review provides a synthesis of research findings and identifies two important areas for further research.

MATERIALS AND METHODS

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, and forest fragmentation and climate change. The search covered the period 1900–2016, including studies published until May 2016, using all databases. The University of Queensland (UQ) Library database and Google Scholar search engine were also used for all available years. In addition, the reference lists of the retrieved papers were reviewed, in order to search for additional papers. The search yielded over 5,000 papers, but most of them were irrelevant. For instance, most of the climate change-related studies were on socio-economic perspectives, forest fauna or policy governance, and were excluded from the study. Only peer-reviewed articles were considered, written in English, focusing on tropical and subtropical forest ecosystems (i.e., South Asia, Southeast Asia, South America, Central America, Africa and Australia), and met the following criterias: (1) the article must be an original study and not a review or synthesis, and (2) the article must have addressed the potential impacts of climate change on forest structure and composition, plant species distribution and phenology, in tropical or subtropical regions. A total of 85 studies were selected and forest types, locations, landscape structure and climate change impacts on different areas of forests (Appendix 1) were recorded.

RESULTS

Climate change impacts on tropical forests

The majority of the reviews focussed on South and Central America (n = 26) followed by South Asia (n = 24) and Africa (n = 15) (Table 1). The same number of studies (n = 10) were found from Australia and Southeast Asia (Table 1, Figure 2). Most studies reported the response of forest trees to climate change (Appendix 1). The impacts of climate change on tropical forests fell mainly into one of three broad categories: (1) changes in the plant species distribution (Saatchi et al. 2008, Gopalakrishnan et al. 2011), (2) changes in forest stand dynamics, including changes in forest cover, structure and composition (Anadon et al. 2014) and (3) changes in tree phenology (Gunarathne & Perera 2014). The temporal trend of publications indicates that

Table 1 Summary of the number of studies that explained climate change impacts on tree species distribution, phenology, forest structure and composition in 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

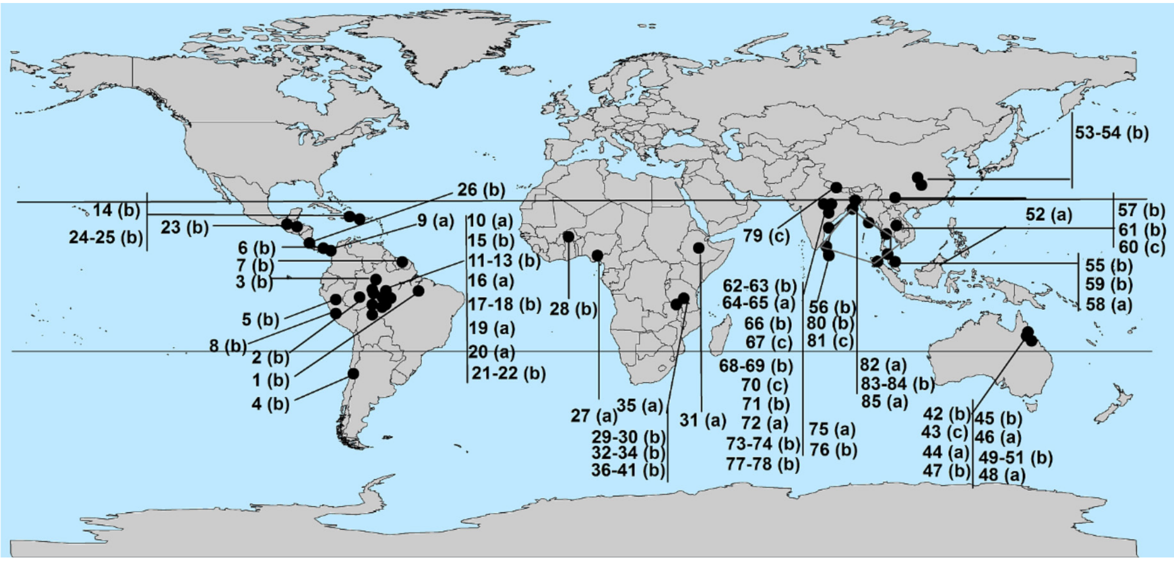

Figure 2 The geographic locations of 85 studies on forest-climate interactions in fragmented tropical landscapes reviewed in this paper (the two straight line indicate the boundary of tropical regions); numbers refer to reviewed papers (Appendix 1) and location of the studies; letters in parentheses after reference number refer to climate change impacts on forest plants studied: (a) species distribution, (b) forest structure and composition and (c) phenology

climate change research in all tropical regions has increased over the last decade (Figure 3). In the following sub-sections, the findings of climate change impacts on tropical Asian forests and other tropical regions are discussed.

Changes in species distributions

The search revealed 17 studies that met the search criterias (Figure 2), 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 1). Two recent studies in India found that 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 (Remya et al. 2015, Priti et al. 2016). 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 (regionally limited cooperation and slower adaptation of

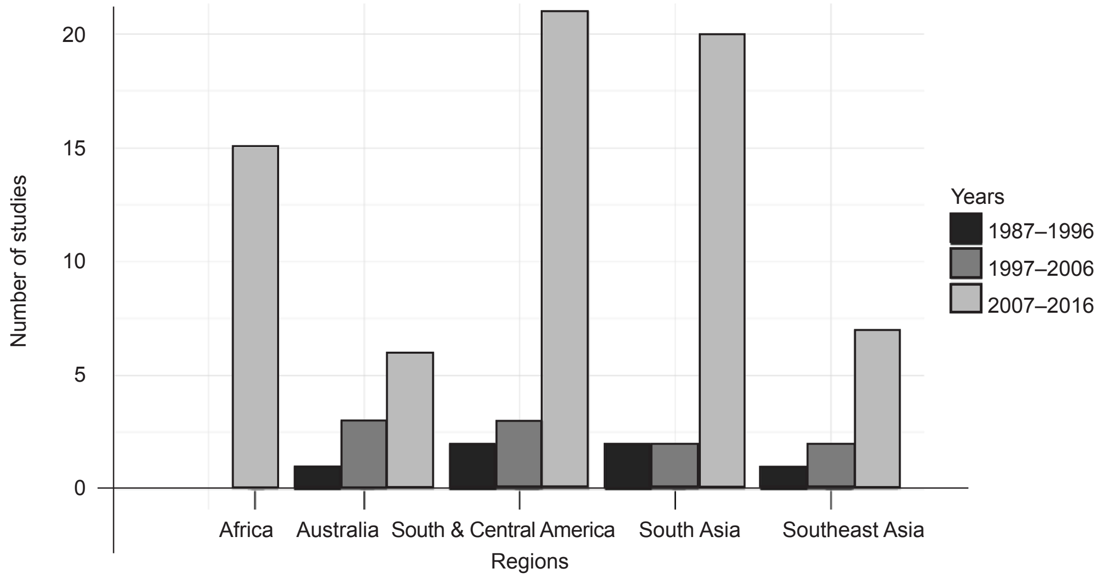

Figure 3 The temporal pattern of the studies by regions that were selected for review in our study; the results suggest that most of the climate change studies were conducted in the last decade in all regions

new technologies with an unstabilised population growth) and B2 (regionally limited ecological development), Special Report on Emissions Scenarios (SRES) 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).

Changes in forest structure and composition

Most studies (21 in tropical Asia and 40 in other tropical regions) reported climate change impacts on forest vegetation dynamics and species abundance in all tropical regions (Appendix 1). 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 forest (Margrove et al. 2015). Land use conversion (Sukumar et al. 1995) and population pressure (Srivastava et al. 2015) were recognised 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 resulting from dams are among the major disturbances threatening the world's largest single block of Sundarbans mangrove forests in Bangladesh (Pethick & Orford 2013).

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 (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. It was 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).

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 (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 (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* (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 recognised as a key mechanism for *Manilkara hexandra*, 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 recognised 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 (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). The review revealed very few studies of climate change impacts on tree phenology in all tropical regions and supports the need for the study (Appendix 1).

Observed climate change in tropical Asia

Tropical Asia is highly vulnerable to climate change. The observed climate trends and variability in tropical Asia are 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. 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. 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. 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 increased by 22 mm per decade, while rainfall from extreme rain days increased by 10 mm per decade. 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. In Peninsular Malaya, total rainfall and the frequency of wet days decreased during the southwest monsoon season, but rainfall intensity increased. On the other hand, total rainfall, the frequency of extreme rainfall events and rainfall intensity increased in the peninsula during northeast monsoon (IPCC 2014).

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 three Representative Concentration Pathways i.e., RCP 4.5, RCP 6.0 and RCP 8.5 will be significant, with an increase of 5–9 °C in the Himalayan Highlands, Tibetan

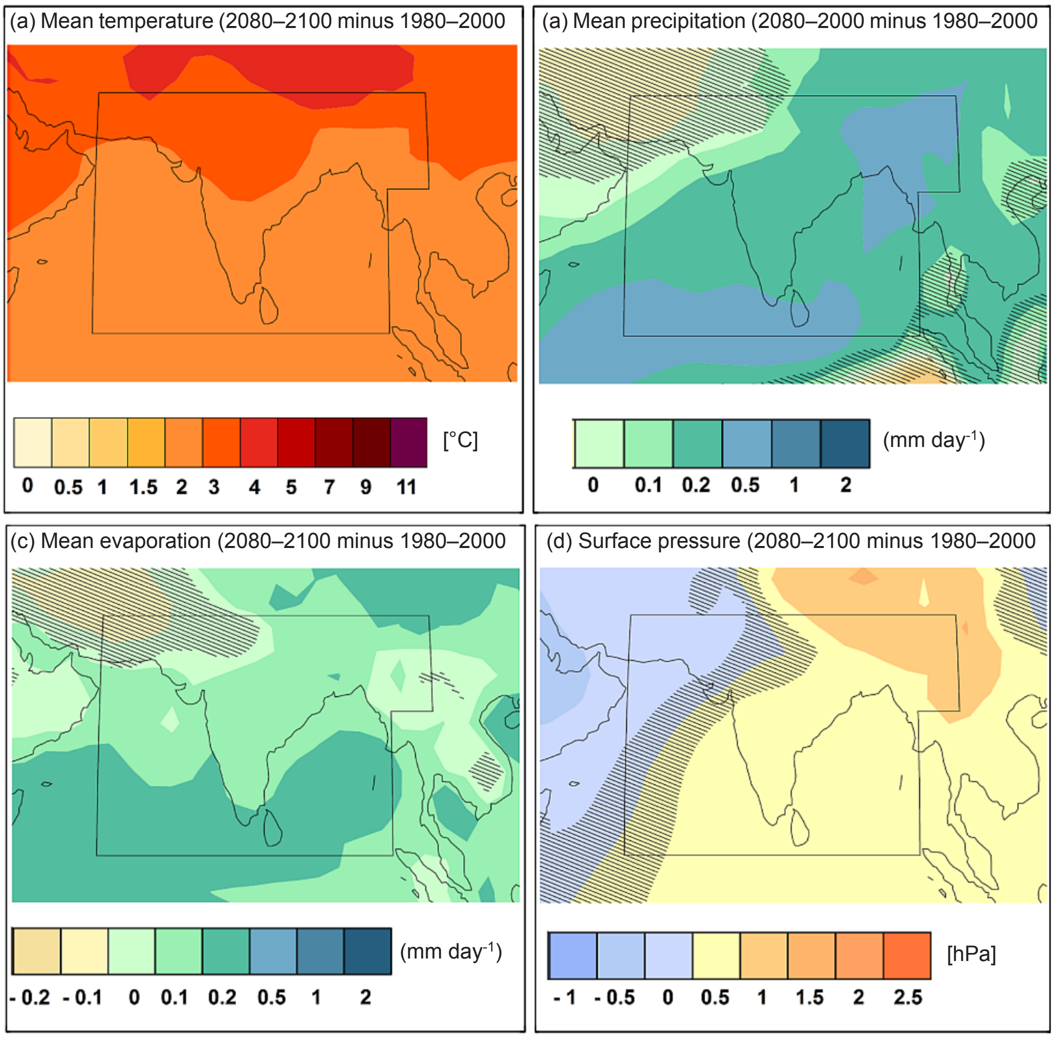

Figure 4 Projected increases in four climatic parameters for South Asia: (a) mean temperature (Celsius), (b) mean precipitation (mm day^{-1}), (c) mean evaporation and (d) mean air surface pressure at sea level (hPa); CMIP5 (IPCC AR5) climate data for mean of RCP4.5, RCP6.0 and RCP8.5 scenarios, 2080–2100 compared with 1980–2000 for South Asia

Plateau and arid regions of South Asia (Figure 4a). Similarly, mean precipitation is likely to increase in the Tibetan Plateau and Bangladesh (Figure 4b). 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 4c). The air pressure at sea level is projected to increase by 0.5–2 hPa by 2100, with a significant increase for Bangladesh (Figure 4d).

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). 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 5. The simple precipitation intensity index indicates that the annual mean rainfall for South Asia will increase by 0.5–2 mm per day (Figure 5a), 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 5b). 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 5c, d). The

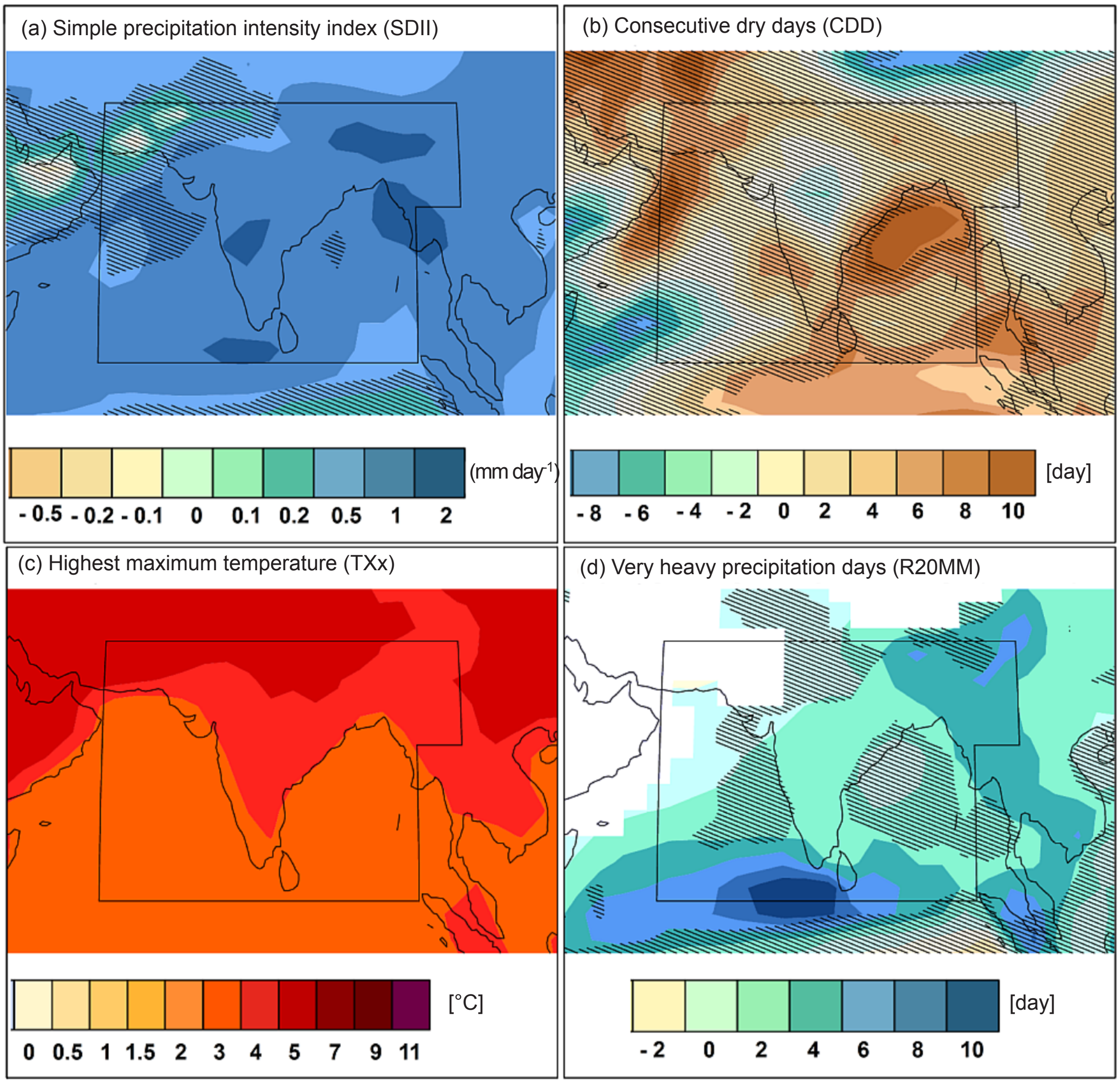

Figure 5 Projected increases in selected climate extreme indices under the RCP 8.5 climate scenario for South Asia: (a) simple precipitation intensity index (mm day^{-1}), (b) maximum number of consecutive dry days per year, (c) value of daily maximum temperature (Celsius), (d) very heavy precipitation days with daily precipitation > 20 mm, days year^{-1}; CMIP 5 climate extremes ensemble data, 2080–2100 compared with 1980–2000 for South Asia (http://climexp.knmi.nl/plot_atlas_form.py)

projected climate extreme indices for South Asia indicate that Bangladesh will experience a significant increase in all indices by 2100.

Potential risks for tropical Asian forests

In tropical Asia, climate change impacts on many plants and animal species is likely 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 (IPCC 2014, Deb et al. 2016). The composition and geographic distribution of forest ecosystems will change as the individual species respond to new climate conditions (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 (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 6).

More frequent extreme events such as storms, floods, inter-annual and decadal climate variations, as well as large-scale circulation changes such as the 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 run-off 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.

DISCUSSION

The 85 reviewed studies document a wide variety of climate change impacts on tropical forests (Appendix 1). The impacts varied considerably, depending on the forest type, structural and floristic composition, disturbance

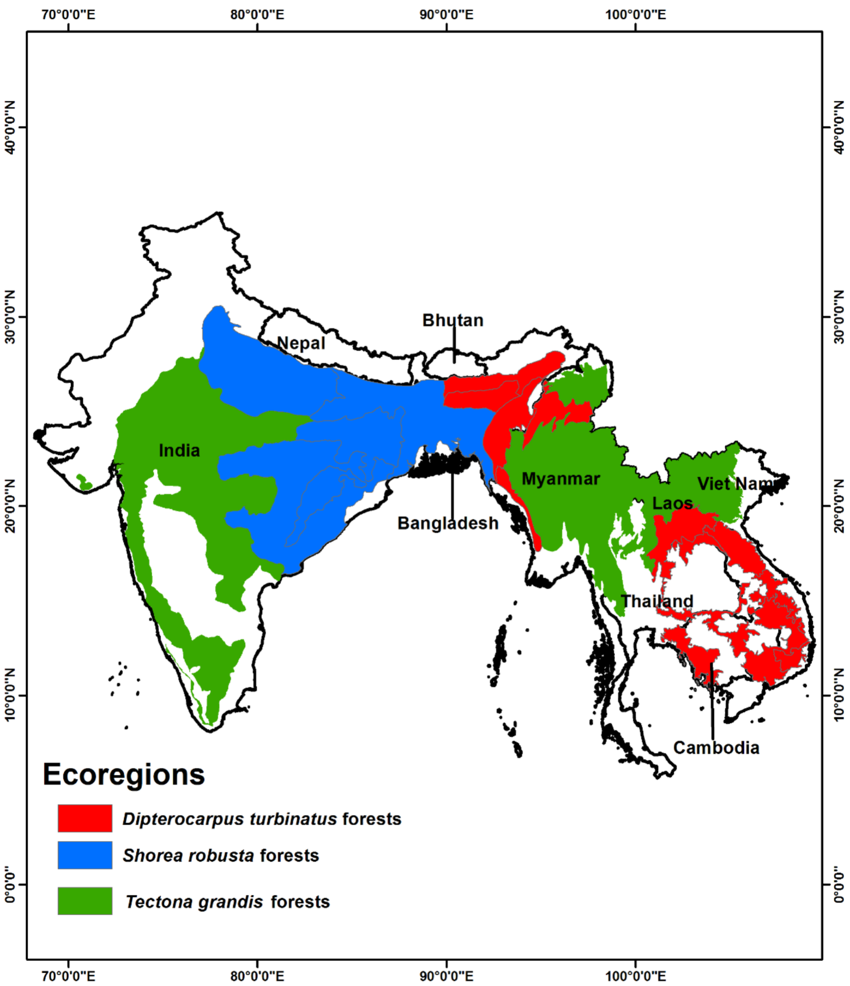

Figure 6 The distribution of three major deciduous tree species (*Dipterocarpus turbinatus*, *Shorea robusta* and *Tectona grandis*) across different ecoregions of tropical Asia; the tree distributions data were compiled from a variety of sources i.e., fieldwork, Global Biodiversity Information Facility 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

history and phenology. Although the spatial and temporal scales of the studies varied, projected climate change and its interaction with land use change are the greatest overall threat to tropical biodiversity (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). 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 4 & 5).

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, Raghunathan et al. 2015). Disturbances such as hurricanes, cyclones and typhoons significantly affect forest structure and species composition in Central America (Anadon et al. 2014, Shiels & Gonzalez 2014). In Africa, biomass and vegetation phenology will be significantly affected due to global climate change (Scheiter & Higgins 2009). In the following section, two key issues are posed which act as a guide for further research based on the findings of the current review, contemporary ecological theory and forest policy issues.

Issue 1: Effect of climate change on the extinction risk of tropical trees

Recent climate change has resulted shifts the distribution and abundance of plant species (Thomas et al. 2004, Deb et al. 2017a, Deb et al. 2017b). Several lines of research suggest that climate change could become a major cause of species extinction over the 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 conservation planning (for example forest restoration) under future climates. As tropical forests contain at least half of all earth's species, which 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 the tropical Asian regions assessed the impacts of climate change on vegetation cover (Table 1, Appendix 1). However, the responses of species' distributions and phenologies to climate change have not been investigated in all tropical regions. 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 and 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 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.

Issue 2: Integration of climate change risks into forest policy and management

Forests have significant potential for climate change mitigation as their life cycles range from decades to centuries. It has been estimated that the world's forests sequester one fourth of annual carbon emission. However, the forest sector contributes 17.4% of greenhouse gas 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). Much greater efforts are needed to decarbonise globally, and in other ways accelerate the transition to a future which sees global temperatures capped at or below the level agreed to in the 2015 Paris climate Accord.

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 paper 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. Researchers working in tropical regions should link vegetation datasets with projected climate change for better understanding of the relationships between them.

CONCLUSION

This review throws light on forest-climate interactions in the tropics, with a focus on Asia. This region has not been rigorously investigated, or has been overlooked, in many empirical studies. It is imperative that tropical forests are given greater consideration by ecologists, government agencies and conservationists to ensure that these forests receive appropriate attention for the biodiversity and ecological values they represent, both now and in the future. Research should test the likely climate change impacts on vegetation in different tropical regions to form a basis for comparisons and meaningful conclusions.

SUPPORTING INFORMATION

Appendix 1 which contains the summary of the data set used for this study can be viewed at: https://espace.library.uq.edu.au/view/UQ:686262. Doi: 10.14264/uql.2017.814

ACKNOWLEDGEMENTS

This research was funded by IPRS and UQ Centennial Scholarship. The authors would also like to acknowledge the Research Grant from School of SEES, UQ.

REFERENCES

Ahmed AU, Siddiqi NA & Choudhuri RA. 1999. Vulnerability of forest ecosystems of Bangladesh to climate change. Pp 93–111 in Huq S et al. (eds) *Vulnerability and Adaptation to Climate Change for Bangladesh.* Springer Netherlands, Dordrecht.

Allen CD, Macalady AK, Chenchouni H et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259: 660–684.

Anadon JD, Sala OE & Maestre FT. 2014. Climate change will increase savannas at the expense of forests and treeless vegetation in tropical and subtropical Americas. *Journal of Ecology* 102: 1363–1373.

Appanah S & Turnbull JM. 1998. *A Review of Dipterocarps: Taxonomy, Ecology and Silviculture.* CIFOR, Indonesia.

Ashton MS, Goodale UM, Bawa KS, Ashton PS & Neidel JD. 2014. Restoring working forests in human dominated landscapes of tropical South Asia: an introduction. *Forest Ecology and Management* 329: 335–339.

Bertin RI. 2008. Plant phenology and distribution in relation to recent climate change. *The Journal of the Torrey Botanical Society* 135: 126–146.

Boulton CA, Good P & Lenton TM. 2013. Early warning signals of simulated Amazon rainforest dieback. *Theoretical Ecology* 6: 373–384.

Braatz S, Rametsteiner E, Thunberg J & Cartographers. 2011. *Climate Change for Forest Policy-Makers. An Approach for Integrating Climate Change in Forest Programmes in Support of Sustainable Forest Management.* FAO, Rome.

Breshears DD, Cobb NS, Rich PM et al. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America* 102: 15144–15148.

Brook BW, Sodhi NS & Bradshaw CJ. 2008. Synergies among extinction drivers under global change. *Trends in Ecology and Evolution* 23: 453–460.

Butt N, Pollock LJ & Mcalpine CA. 2013. Eucalypts face increasing climate stress. *Ecology and Evolution* 3: 5011–5022.

Butt N, Seabrook L, Maron M, Law BS, Dawson TP, Syktus J & Mcalpine CA. 2015. Cascading effects of climate extremes on vertebrate fauna through changes to low-latitude tree flowering and fruiting phenology. *Global Change Biology* 21: 3267–3277.

Chaturvedi RK, Gopalakrishnan R, Jayaraman M, Bala G, Joshi N, Sukumar R & Ravindranath N. 2011. Impact of climate change on Indian forests: a dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change* 16: 119–142.

Cleland EE, Chuine I, Menzel A, Mooney HA & Schwartz MD. 2007. Shifting plant phenology in response to global change. *Trends in Ecology and Evolution* 22: 357–365.

Condit R, Hubbell SP & Foster RB. 1996. Changes in tree species abundance in a neotropical forest: impact of climate change. *Journal of Tropical Ecology* 12: 231–256.

Corlett RT & Lafrankie-Jr JV. 1998. Potential impacts of climate change on tropical Asian forests through an influence on phenology. *Climatic Change* 39: 439–453.

Corlett RT & Westcott DA. 2013. Will plant movements keep up with climate change? *Trends in Ecology and Evolution* 28: 482–488.

Corlett RT. 1998. Frugivory and seed dispersal by vertebrates in the Oriental (Indomalayan) Region. *Biological Reviews of the Cambridge Philosophical Society* 73: 413–448.

Dale VH & Rauscher HM. 1994. Assessing impacts of climate change on forests: the state of biological modelling. *Climatic Change* 28: 65–90.

Dale VH, Joyce LA, Mcnulty S, et al. 2001. Climate change and forest disturbances. *BioScience* 51: 723–734.

Deb JC, Phinn S, Butt N & Mcalpine C. 2017a. The impact of climate change on the distribution of two threatened Dipterocarp trees. *Ecology and Evolution* 7: 2238–2248.

Deb JC, Phinn S, Butt N & Mcalpine C. 2017b. Climatic-induced shifts in the distribution of teak (*Tectona grandis*) in tropical Asia: Implications for forest management and planning. *Environmental Management* 60: 422–435.

Deb JC, Rahman HT & Roy A. 2016. Freshwater swamp forest trees of Bangladesh face extinction risk from climate change. *Wetlands* 36: 323–334.

Dudgeon D & Corlett R. 1994. *Hills and Streams: An Ecology of Hong Kong.* Hong Kong University Press, Hong Kong.

Gaira KS, Rawal RS, Rawat B & Bhatt ID. 2014. Impact of climate change on the flowering of Rhododendron arboretum in central Himalaya, India. *Current Science* 106: 1735–1738.

Gan J. 2004. Risk and damage of southern pine beetle outbreaks under global climate change. *Forest Ecology and Management* 191: 61–71.

Garcia RA, Cabeza M, Rahbek C & Araújo MB. 2014. Multiple dimensions of climate change and their implications for biodiversity. *Science* 344: 1247579.

Gonzalez P, Kroll B & Vargas CR. 2014. Tropical rainforest biodiversity and aboveground carbon changes and uncertainties in the Selva Central, Peru. *Forest Ecology and Management* 312: 78–91.

Gopalakrishnan R, Jayaraman M, Swarnim S, Chaturvedi RK, Bala G & Ravindranath N. 2011. Impact of climate change at species level: a case study of teak in India. *Mitigation and Adaptation Strategies for Global Change* 16: 199–209.

Grimm NB, Chapin III FS, Bierwagen B et al. 2013. The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and the Environment* 11: 474–482.

Gullison RE, Frumhoff PC, Canadell JG et al. 2007. Tropical forests and climate policy. *Science* 316: 985.

Gunarathne R & Perera G. 2014. Climatic factors responsible for triggering phenological events in Manilkara hexandra (Roxb.) Dubard., a canopy tree in tropical semi-deciduous forest of Sri Lanka. *Tropical Ecology* 55: 63–73.

Hansen MC, Potapov PV, Moore R et al . 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342: 850–853.

IPCC (Inter-Governmental Panel on Climate Change). 2014. *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Inter-Governmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jacob M, Annys S, Frankl A, De Ridder M, Beeckman H, Guyassa E & Nyssen J. 2015. Tree line dynamics in the tropical African highlands—identifying drivers and dynamics. *Journal of Vegetation Science* 26: 9–20.

Kaosa-ard A. 1977. *Physiological Studies of Sprouting of Teak (Tectona Grandis Linn. F.) Planting Stumps.* Australian National University, Canberra.

Kushwaha C, Tripathi S & Singh K. 2011. Tree specific traits affect flowering time in Indian dry tropical forest. *Plant Ecology* 212: 985–998.

Laurance WF, Andrade AS, Magrach A et al. 2014. Apparent environmental synergism drives the dynamics of Amazonian forest fragments. *Ecology* 95: 3018–3026.

Laurance WF. 2004. Forest-climate interactions in fragmented tropical landscapes. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 359: 345–352.

Ma X, Huete A, Yu Q et al . 2013. Spatial patterns and temporal dynamics in savanna vegetation phenology across the North Australian Tropical Transect. *Remote sensing of Environment* 139: 97–115.

Malhi Y & Phillips OL. 2004. Tropical forests and global atmospheric change: a synthesis. *Philosophical Transactions of the Royal Society B: Biological Sciences* 359: 549–555.

Malhi Y, Aragão LE, Galbraith D et al. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences* 106: 20610–20615.

Margrove JA, Burslem DF, Ghazoul J, Khoo E, Kettle CJ & Maycock CR. 2015. Impacts of an extreme precipitation event on Dipterocarp mortality and habitat filtering in a Bornean tropical rain forest. *Biotropica* 47: 66–76.

Mcgregor GR & Nieuwolt S. 1998. *Tropical Climatology: An Introduction to the Climates of the Low Latitudes.* John Wiley & Sons Ltd., Chichester.

Miles L, Grainger A & Phillips O. 2004. The impact of global climate change on tropical forest biodiversity in Amazonia. *Global Ecology and Biogeography* 13: 553–565.

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA & Kent J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.

Numata S, Yasuda M, Okuda T, Kachi N & Noor NSM. 2003. Temporal and spatial patterns of mass flowerings on the Malay Peninsula. *American Journal of Botany* 90: 1025–1031.

Pacifici M, Foden WB, Visconti P et al. 2015. Assessing species vulnerability to climate change. *Nature Climate Change* 5: 215–224.

Peel MC, Finlayson BL & Mcmahon TA. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* 11: 1633–1644.

Pethick J & Orford JD. 2013. Rapid rise in effective sea-level in southwest Bangladesh: its causes and contemporary rates. *Global and Planetary Change* 111: 237–245.

Powell M, Accad A, Austin MP, Choy SL, Williams KJ & Shapcott A. 2010. Predicting loss and fragmentation of habitat of the vulnerable subtropical rainforest tree *Macadamia integrifolia* with models developed from compiled ecological data. *Biological Conservation* 143: 1385–1396.

Priti H, Aravind N, Shaanker Ru & Ravikanth G. 2016. Modeling impacts of future climate on the distribution of Myristicaceae species in the Western Ghats, India. *Ecological Engineering* 89: 14–23.

Raghunathan N, François L, Huynen M-C, Oliveira LC & Hambuckers A. 2015. Modelling the distribution of key tree species used by lion tamarins in the Brazilian Atlantic forest under a scenario of future climate change. *Regional Environmental Change* 15: 683–693.

Rahman AF, Dragoni D & El-Masri B. 2011. Response of the Sundarbans coastline to sea level rise and decreased sediment flow: a remote sensing assessment. *Remote Sensing of Environment* 115: 3121–3128.

Remya K, Ramachandran A & Jayakumar S. 2015. Predicting the current and future suitable habitat distribution of *Myristica dactyloides* Gaertn. using MaxEnt model in the Eastern Ghats, India. *Ecological Engineering* 82: 184–188.

Saatchi S, Buermann W, Ter Steege H, Mori S & Smith TB. 2008. Modeling distribution of Amazonian tree species and diversity using remote sensing measurements. *Remote Sensing of Environment* 112: 2000–2017.

Scatena FN. 2001. Ecological rhythms and the management of humid tropical forests: examples from the Caribbean National Forest, Puerto Rico. *Forest Ecology and Management* 154: 453–464.

Scheiter S & Higgins SI. 2009. Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. *Global Change Biology* 15: 2224–2246.

Schwierz C, Davies HC, Appenzeller C, Liniger MA, Müller W, Stocker TF & Yoshimori M. 2006. Challenges posed by and approaches to the study of seasonal-to-decadal climate variability. *Climatic Change* 79: 31–63.

Seidl R, Thom D, Kautz M et al. 2017. Forest disturbances under climate change. *Nature Climate Change* 7: 395–402.

Shiels AB & González G. 2014. Understanding the key mechanisms of tropical forest responses to canopy loss and biomass deposition from experimental hurricane effects. *Forest Ecology and Management* 332: 1–10.

Shukla R & Ramakrishnan P. 1982. Phenology of trees in a sub-tropical humid forest in north-eastern India. *Vegetation* 49: 103–109.

Singh K & Kushwaha C. 2005. Emerging paradigms of tree phenology in dry tropics. *Current Science* 89: 964–975.

Sodhi NS, Koh LP, Brook BW & Ng PK. 2004. Southeast Asian biodiversity: an impending disaster. *Trends in Ecology and Evolution* 19: 654–660.

Sodhi NS, Koh LP, Clements R et al. 2010. Conserving Southeast Asian forest biodiversity in human-modified landscapes. *Biological Conservation* 143: 2375–2384.

Srivastava PK, Mehta A, Gupta M, Singh SK & Islam T. 2015. Assessing impact of climate change on Mundra mangrove forest ecosystem, Gulf of Kutch, western coast of India: a synergistic evaluation using remote sensing. *Theoretical and Applied Climatology* 120: 685–700.

Sukumar R, Suresh H & Ramesh R. 1995. Climate change and its impact on tropical montane ecosystems in southern India. *Journal of Biogeography* 1: 533–536.

Thomas CD, Cameron A, Green RE et al. 2004. Extinction risk from climate change. *Nature* 427: 145–148.

Ting S, Hartley S & Burns K. 2008. Global patterns in fruiting seasons. *Global Ecology and Biogeography* 17: 648–657.

Thuiller WC, Albert C, Araújo MB et al. 2008. Predicting global change impacts on plant species' distributions: future challenges. *Perspectives in Plant Ecology, Evolution and Systematics* 9: 137–152.

Woods P. 1989. Effects of logging, drought, and fire on structure and composition of tropical forests in Sabah, Malaysia. *Biotropica* 21: 290–298.

Yadav R & Yadav A. 2008. Phenology of selected woody species in a tropical dry deciduous forest in Rajasthan, India. *Tropical Ecology* 49: 25–34.

Zhang MG, Zhou ZK, Chen WY, Cannon CH, Raes N & Slik J. 2014. Major declines of woody plant species ranges under climate change in Yunnan, China. *Diversity and Distributions* 20: 405–415.

