Investigating the impact of climate change, land use change, and their interactions on forest loss in India

Doctor of Philosophy

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Alice Haughan

Date: 14/10/2021

Covid impact statement

The production of this thesis was impacted by the Covid-19 pandemic. During the pandemic lockdowns substantial care requirement of a family member impacted the time that I could spend on my PhD and my mental capacity to output good-quality work.

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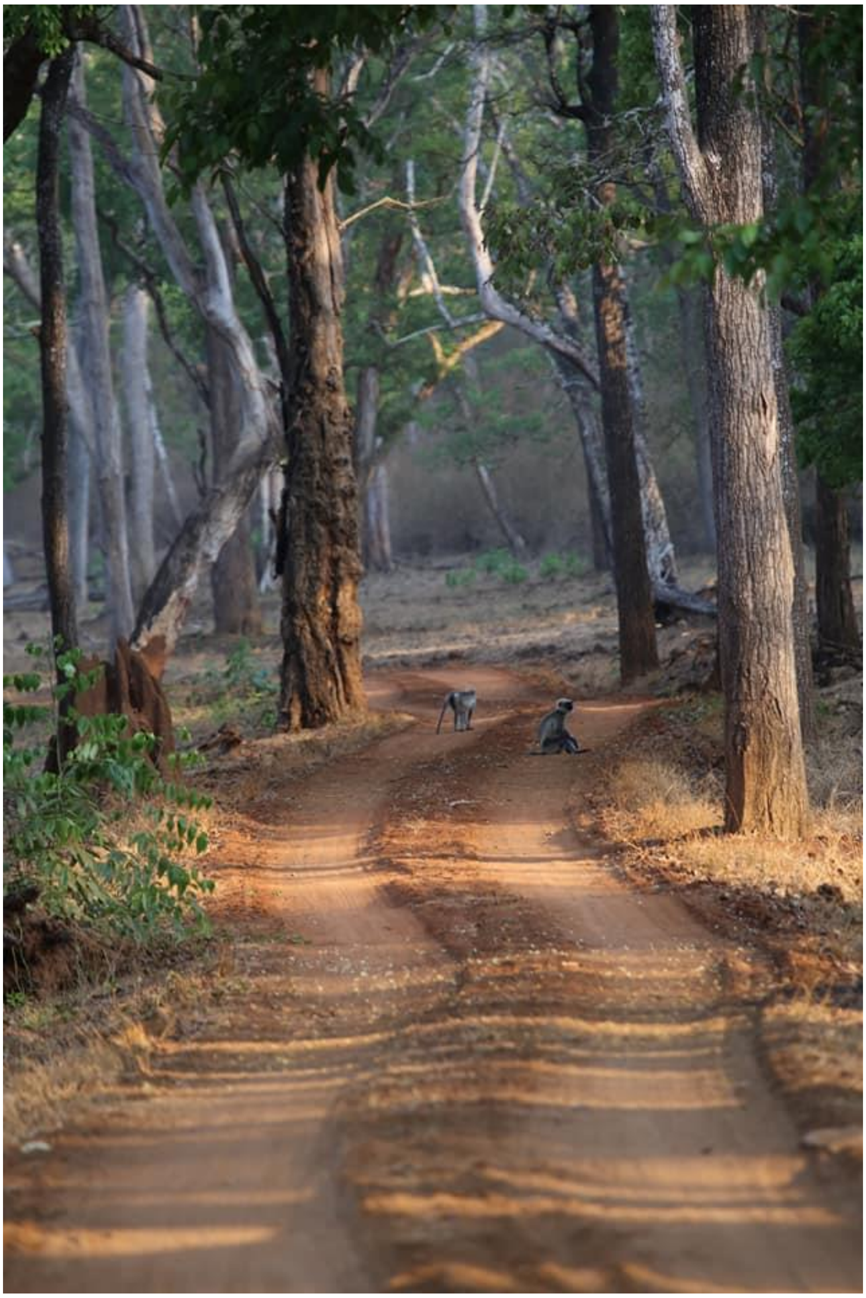
Abstract

Climate and land use change are the two main drivers of biodiversity loss worldwide. Forests, particularly tropical forests, host a disproportionate amount of terrestrial biodiversity. However, there remains a substantial research bias towards temperate regions and Amazonia when assessing the joint impacts of climate and land use change. Climate and land use change have been shown to interact, leading to complex and unexpected ecological responses, as such this bias could be leading to a misrepresentation of the threats to tropical forests across Asia and Africa. India, a country not previously considered, presents a unique opportunity to explore the potential for interactions between the two drivers. India is predicted to experience increases in temperature, variable rainfall and prevalence of extreme events, at the same time as rapid population expansion. Analysis of forest trends in the country were prevalent in the 1990's and the primary driver of loss was agricultural expansion. However, there are substantial knowledge gaps including the recent trends in forest change and the current primary driver of forest loss. Additionally, the effects of climate change on forests in the country have been largely overlooked. This thesis uses global datasets and mixed modelling approaches to explore the effects of climate change, land use change and their interactions across India during 1995-2019. Results show, for the first time, that climate change has played a role in forest loss in India, however, the predominant driver of forest loss remains agricultural-driven land use changes. This research provides the first evidence of a synergistic interaction between drought and land use change in the country, where the two drivers are leading to a greater area of forest loss. This research aslo significantly contributes to the increased knowledge of the drivers of forest loss in India and highlights a concerning interaction that is predicted to worsen with time. These results have key implications for future management of the forests, which do not currently take climate change into account, and highlight that interactions between climate and land use change are occurring in Asian tropical forests.

Chapter 1: Introduction



Black-footed grey langurs on the forest roads within Nagarhole Wildlife Sanctuary, India. The reserve is a key part of the largest protected area in Southern India and contains predominantly moist deciduous forests.

Source: Alice Haughan (Author's own)

1. Introduction

1.1 The impact of climate and land use change on biodiversity

Humans interact with the biotic and abiotic environment around them in many ways and have dramatically altered biodiversity levels on Earth over time (IPBES, 2019). This has manifested as changes in ecosystem distribution, composition and functioning, as well as changes in climatic conditions that have ultimately led to negative consequences for biodiversity and life on Earth (Hoskins et al., 2016; Lambin et al., 2001; Newbold et al., 2016; Roy et al., 2013). Biodiversity is declining at a significant rate on a global scale due to anthropogenic causes, and while there are several pathways by which these declines may occur, climate and land use change are known to be two of the major drivers of loss (Brodie, 2016; Heller & Zavaleta, 2009; IPBES, 2019; Pautasso, 2012). Changes in land use and increasing land degradation can directly impact species richness and abundance (Camacho et al., 2021; Hill et al., 2018; Newbold et al., 2015), alter effectiveness of key ecosystem functions (Bhattacharyya et al., 2015; Cardinale et al., 2012; Mina et al., 2017), and even alter local climates, changing the relationship between humans and the natural system (Lambin et al., 2001;Foley et al., 2005; Roy et al., 2013; Niyogi et al., 2018). Land use changes often affect species' capability to adapt and react to other threats, and can facilitate or prohibit movement to more suitable habitats (Guo et al., 2018; Newbold et al., 2016, 2015; Oliver & Morecroft, 2014).

Alongside land use changes, climate changes are the second major driver of biodiversity declines worldwide (IPBES, 2019; Ostberg et al., 2015). Climate change is accelerating beyond natural fluctuations resulting in new, unpredictable and sometimes extreme climatic conditions that many species have not encountered before (IPCC, 2021; Watson, 2014). Globally warming temperatures, intensification of rainfall regimes, melting of glaciers and sea-level rise have all been recorded and these changes are expected to intensify in the near future (IPCC, 2021; Kirilenko & Sedjo, 2007; Sivakumar et al., 2005). Species adaptation and ability to relocate to suitable environments will determine survival (Pautasso, 2012; Pecl et al., 2017). This in turn will have impacts on local ecosystem composition and functioning (Grimm et al., 2013; Weiskopf et al., 2020). Changes in climate can alter biodiversity by modifying conditions from the optimal required by species to survive and function (Aubry-Kientz et al., 2019; Garcia et al., 2014). As species begin to move from unfavourable to more favourable areas, ecosystem composition in both locations will likely change, adapting to functioning with an altered composition of species (Descombes et al., 2020; Pecl et al., 2017). This could result in changes in the ecosystem functions including key processes such as the carbon and water cycles (Foley et al., 2005; Pecl et al., 2017; Weiskopf et al., 2020). There is consensus that climate change will cause a global redistribution of species, the extent of which has consequences for all ecosystems, as well as human populations, and remains poorly understood (Guo et al., 2018; Hansen et al., 2001; IPBES, 2019; Pecl et al., 2017).

The speed at which climate changes are occurring is also a concern (Brito-Morales et al., 2018; Corlett & Westcott, 2013; Kosanic et al., 2019; Loarie et al., 2009). If climate changes occur too quickly species migration and adaptation may not be fast enough, whereas species acclimation or extinction in response to climate change could be more likely (Devictor et al., 2012; Hoffmann & Sgrò, 2011; Radchuk et al., 2019). Studies employing a metric called climate velocity, which estimates a speed at which species will need to travel to reach a similar climate, have shown that many species may need to quickly traverse large distances to keep pace with their current climate niche (Hiddink et al., 2012; Loarie et al., 2009). Small-ranged, endemic and less mobile species are likely to be most at risk, including many species in the tropics (Carroll et al., 2015; Sandel et al., 2011; Schloss et al., 2012; Tewksbury et al., 2008). A study by Schloss et al. (2012) focusing on the Western Hemisphere estimated that 39% of mammals may not be able to keep pace with projected climate changes. The study found that in the Amazon many mammal species are only capable of migrating at a speed around 1km per year but that the pace of climate change that they will experience will be eight times this.

Increasingly shown in the literature is evidence that habitat loss and land use change often impact species well before the impacts of climate change are felt (Boit et al., 2016; Ostberg et al., 2015). However, research also suggests that climate change effects are putting mounting pressure on biodiversity, and the impact of climate change is predicted to equal or exceed that of land use change by 2070 (Mantyka-pringle et al., 2012; Newbold, 2018). A study by Ostberg et al. (2015), found that over the course of the last three hundred years the impact of land use change on our ecosystems has reached thirteen times what it used to be; however, within the past 100 years alone climate change has reached the same level of impact on our ecosystems, and is now the most prominent effect on 60% of terrestrial land. This has prompted considerable concern that climate changes are accelerating too fast for species to react (Lenoir et al., 2020; Radchuk et al., 2019; Ye et al., 2018). Further to this, there is evidence of a 'climatic debt' where species have a lagged response to climate change that has not materialised yet and as such we may be underestimating the long-term effects of climate change on species extinctions (Bertrand et al., 2016; Devictor et al., 2012).

1.2 The prevalence of climate-land use interactions and their impact on biodiversity

Investigations into the impacts of climate change and land use change on species have been frequently studied in isolation, but the scientific community is becoming aware of the potential for interactions between the two that could result in a different impact than predicted by studies quantifying their individual impacts (Brodie, 2016; Côté et al., 2016; Oliver et al., 2016; Sirami et al., 2017). It is generally thought that the risk of species and population extinctions may be greatly increased in areas where threats, such as climate and land use change, interact (Northrup et al., 2019; Oliver et al., 2016). For example, it is estimated that 24% of global terrestrial land has experienced major biogeochemical and structural changes due to the combined impacts of land use change and climate change (Ostberg et al., 2015) and that interactions between the two stressors could result in a 20% reduction in the richness of species assemblages across much of terrestrial land by 2070 (Newbold, 2018). Combined effects or interactions are also thought to affect ecosystem structure and functioning through homogenisation of ecological communities (Grimm et al., 2013; Ye et al., 2018; Newbold et al., 2019). Since the majority of ecological studies focus on single-stressor effects, there is concern that adaptation and mitigation strategies will not be effective if they do not take into account the combinations of stressor effects (Côté et al., 2016; Darling & Côté, 2008).

Interactions between ecosystem stressors can be complex and multidimensional (Côté et al., 2016; Gissi et al., 2021; Orr et al., 2020). Land use and climate change have been shown to both ameliorate and exacerbate the other’s effects on species and ecosystems. For example, changes in land use and fragmentation of habitats can act as barriers to species migration in response to climate change (Hansen et al., 2001; Oliver et al., 2017; Oliver & Morecroft, 2014; Robillard et al., 2015) and, conversely, stress caused by climate change can reduce the resilience of species to land use changes (Brodie et al., 2012; He et al., 2019). Mantyka-Pringle et al., (2015) found that rising temperatures led to a 43% increase in the global vulnerability of bird species to habitat loss. In this instance, climate change exacerbated the effect of land use change on birds. While Schloss et al., (2012) found that the presence of human-modified areas required species to migrate 0.8 km faster per year in order to track their climate niche, and so land use changes exacerbated the effect of climate changes. Synergies between climate and land use change have been shown to increase abundance of invasive species (Manzoor et al., 2021), pests (Grünig et al., 2020; Zhang et al., 2018) and disease (Ebi et al., 2007; Patz et al., 2008; Young et al., 2017), all of which could have negative consequences for native species and human populations. Climate changes are also likely to result in an expansion of some species’ ranges as more areas become suitable habitat while other species ranges will contract, which could have implications for forests (Pautasso, 2012; Ye et al., 2018). Brodie (2016) showed that projected climate changes in Southeast Asia will increase the climatically suitable areas of oil palm plantations, in some cases to higher elevations where forest species have been protected from cropland expansions in the past. The interactions between climate and land use change in this scenario are predicted to reduce the environmentally suitable mammal habitat by 47% on average, with some species experiencing a 90% reduction in range size. These are examples of synergies between the two drivers, however, there is also evidence that one driver could lessen the effects of another on species. For example, Warren et al., (2001) found that the positive effects of warming, through range expansions, for butterfly species in the UK were dampened by the negative effect of habitat loss on the species, resulting in overall declines of distribution with a particularly strong effect on specialist species. Whereas a study by Mantyka-Pringle et al., (2019), found that increasing temperatures in prairie wetland ecosystems in Canada reduced the negative effects of agricultural intensification on insectivorous birds, possibly by increasing food abundances. Overall, the evidence suggests that climate and land use changes can have multiple varying effects on biodiversity depending on the type of interaction, the location on the globe and the species or ecosystem in question (França et al., 2020; Frishkoff et al., 2016; Mantyka-Pringle et al., 2019; Mantyka-Pringle et al., 2012; Newbold et al., 2020).

The evidence strongly suggests that not taking interactions into account could result in under- or over-estimating the impacts of stressors on biodiversity leading to false future trajectories of biodiversity loss and less effective management or policy strategies (Brodie, 2016; Newbold et al., 2019; Sirami et al., 2017). It is therefore important that there is a drive towards understanding how these stressors may interact with each other and the impacts that the joint associations might have on species and ecosystems (Darling & Côté, 2008; Didham et al., 2007). The number of studies investigating the interactions between land use and climate change, and their effects on biodiversity, are still scarce (Ahmed et al., 2016; Sirami et al., 2017) and it is likely that interactions are more prevalent than originally thought (Mantyka-Pringle et al., 2015).

Despite developing an understanding of interactions like these essential to evaluating the risk a species may be under, it remains quite difficult to analyse the interacting effects of climate and land use changes. The reasons for this are well researched in a review by Oliver & Morecroft (2014), which highlights both the difficulties in understanding climate and land use change interactions, as well as the current geographic bias. Oliver % Morecroft (2014) pose that the main reasons for this difficulty are that firstly, the actual mechanisms behind interactions are often not well understood due to the high-level of complexity in the interaction. Secondly, many habitat and climate variables can be confounding especially with socio-economic variables, leading to correlations that might not be the main cause of species loss. Thirdly, interactions between land use change and climate change are likely to be highly diverse across even small areas and so generalisations about how a species might respond to an interaction are not likely to be accurate. Studies need to be developed with a mechanistic understanding of the interaction to ensure effects are reasonably attributed to climate and/or land use change (Oliver & Morecroft, 2014; Schafer & Piggot, 2018), an appreciation that the interaction can have varied effects from the expected additive effect (Cote et al., 2016), as well as ensuring spatial autocorrelation is accounted for, and that sufficient, concurrent trend data is available for all variables (Oliver & Morecroft, 2014).

1.3 The importance of tropical forests for humans and biodiversity

Forests are globally important ecosystems for supporting high levels of biodiversity as well as providing ecosystem services such as regulation of the water cycle and carbon capture benefits (FAO, 2020; McDowell, 2018; Turubanova et al., 2018; Wani et al., 2012). Land use change and climate change remain the largest drivers of forest loss worldwide (Asner et al., 2010; FAO, 2020; McDowell et al., 2018). However, research on climate change, and in particular its interactions with land use change, tend to have a geographical bias towards temperate regions (Armstrong et al., 2016; Asner et al., 2010; França et al., 2020b; Riordan et al., 2015). Subsequently, relatively little is known about how interactions manifest in forests at low latitudes, particularly tropical and sub-tropical regions (Asner et al., 2010; Jetz et al., 2007) despite predictions that interaction effects on biodiversity will be more severe in tropical regions (Newbold et al., 2020).

Tropical forests are the most diverse terrestrial ecosystems on the planet (Barlow et al., 2018; França et al., 2020). It is thought that they harbour two thirds of global terrestrial biodiversity, a large proportion (>80%) of globally threatened species (Luther et al., 2020), and a significant number of endemic species (Barlow et al., 2018; França et al., 2020). There is a wealth of studies on the importance of tropical forests to biodiversity across the biome which have shown that when forests are lost or degraded, species often face reductions in abundance and diversity (Alroy, 2017; Camacho et al., 2021; Hansen et al., 2020), range shifts (França et al., 2020; Larsen, 2012), and even local extinctions (Boekhout Van Solinge, 2010; Schleuning et al., 2016). For example, Sodhi & Brook (2006) predicted that deforestation in Southeast Asia will lead to an 80% reduction in vertebrate species by 2100 and, as a result of the high levels of endemism in this region, this would mean global extinctions of several species. As such, tropical forests are integral ecosystems for the protection of biodiversity on the globe. They also have key functions in maintaining soil structure and increasing resilience of the ecological communities within them to extreme events (Anderegg et al., 2018; Betts et al., 2018). Tropical forests also provide vital support for local people and their livelihoods (FAO, 2020; IPBES, 2019). Around 820 million people live in tropical forests, many of which live below the poverty line with a strong reliance on forest resources for income (FAO, 2020). Tropical forests provide direct resources such as food, fuel, building materials, medicinal plants and fodder for rural communities as well as indirect benefits through increased protection from extreme events, and ecosystem services such as pollination (Brookhuis & Hein, 2016; FAO, 2020; IPBES, 2019). Despite their known importance, tropical forests continue to be lost at a rapid rate globally (Laurance, 2013; Lewis et al., 2015; Song et al., 2018;

Turubanova et al., 2018), between 2010-2015, 32 million hectares of tropical forest were lost worldwide (IPBES, 2019).

1.4 The impact of climate, land use change, and their interactions on tropical forests

Land use changes, primarily associated with agricultural expansion and commodity production, are known to be the primary driver of tropical forest loss (Boekhout Van Solinge, 2010; Curtis et al., 2018; Manchego et al., 2017; Staal et al., 2020). IPBES (2019) reported that half of the global agricultural expansion that occurred between 1980 and 2000 resulted in a direct loss of tropical forests. In addition, FAO (2020) reported that during 2000-2010, 40% of tropical deforestation was attributable to large-scale agriculture, with a further 33% to subsistence agriculture. In the Amazon during 2000-2013, more than 72% of deforestation was a direct result of cropland and pasture expansion (Libonati et al., 2021). Cropland expansion can result in large areas of forest being removed, and in the tropics, this is often for slash-and-burn agriculture. These methods not only remove large amounts of biomass, and cause loss of habitat for species, but if ill-managed can result in accidental removal of more forest than intended due to difficulty controlling the spread of the fire (Brando et al., 2014; Carmenta et al., 2013; Field et al., 2009; Laurance, 2003). Cropland expansions can also affect forests on a much smaller scale, acting on forest edges and removing small areas of trees at a time (Gascon et al., 2000; Ordway & Asner, 2020). Other drivers of forest loss are often related to human activities that do not result in a complete removal of forest but increase degradation, and fragmentation over time. On a large scale, these tend to be timber extraction from logging companies, mining, and road development (Hosonuma et al., 2012; Kleinschroth & Healey, 2017; Wright, 2010). On a smaller scale, collection of forest resources such as fodder and fuelwood, as well as use of the forest understory for livestock grazing, contribute to forest degradation as well as increasing forest susceptibility to further exploitation (Chitale et al., 2020; FAO, 2020; Hosonuma et al., 2012). The level of degradation and fragmentation of forests can affect the services and biodiversity they provide (Betts et al., 2022; Liu et al., 2018; Wilson et al., 2015). Where intact forests have been shown to harbour much higher levels of species diversity and abundances, and a greater provision of ecosystem services, compared to fragmented forests (Betts et al., 2019; Gibson et al., 2011; Sharp et al., 2019). However, fragmented forests, which are often thought of as less valuable and given lower protection status, remain an integral refuge for many species and if left to regenerate have been shown to reach similar levels of biodiversity (Edwards et al., 2011; González del Pliego et al., 2016). Changes in forest coverage can also impact local and global climate. For example, Betts (2007) reported that a reduction in forest extent in the Amazon, predominantly caused by drought, led to an additional 25% reduction in precipitation over the Amazon Basin. Reductions in forest cover have been shown to result in increasing temperatures (Gogoi et al., 2019; Kayet et al., 2016;

Nayak et al., 2021), reductions in precipitation (Betts et al., 2004; Leite-Filho et al, 2021) and increased incidence of fire (Libonati et al., 2021).

Though deforestation remains the primary cause of tropical forest loss (FAO, 2020; Manchego et al., 2017), studies have also shown climate change to be an important driver (França et al., 2020; McDowell et al., 2018; Siyum, 2020). Studies investigating the impact of climate change on tropical forests are scarce in comparison to their temperate counterparts, despite several studies indicating that generally tropical species may be at greater risk from climate changes than temperate species due to their narrower climatic tolerances (Deutsch et al., 2008; Newbold et al., 2020; Tewksbury et al., 2008). However, so far temperature increases, reductions or increasingly variable rainfall, and extreme events such as drought, fire and lightning have all been linked to changes in the distribution of tropical forests, reductions in forest area, tree mortality and reductions in growth (Aubry-Kientz et al., 2019; Field et al., 2009; McDowell, 2018). Loss of forest area and tree mortality as a result of climate change effects have also been shown to result in reductions of forest fauna, with possible repercussions for ecosystem functioning (Dundas et al., 2021; França et al., 2020; Larsen, 2012). For example, increased mortality of trees in the Amazon forest as a result of El-Nino related drought and fire in 2015-16 resulted in a reduction in the abundance of dung beetles and rates of dung removal and seed dispersal (França et al., 2020).

Evidence suggests that the responses of different regions, forest types and individual tree species to climate changes can be highly diverse (Allen, 2017; Jimenez et al., 2018; McDowell et al., 2018; Rifai et al., 2019). Currently most studies have focused on the effects of increasing temperatures and drought events on forests, due to the importance of water availability to the functioning of the ecosystem, alongside relative ease of delineating the effects of one extreme event on forests compared to long-term changes in climate. This covers the sensitivity of tree species to drought, i.e., the effect that a hazard has on the tree or forest. However, the vulnerability of a forest system to a stressor such as climate change is thought to be impacted by three key components; sensitivity, adaptive capacity and exposure (though some argue that exposure should be discussed separately as it is an external factor and not intrinsic to the system) (Sharma & Ravindranath, 2019). Sensitivity being the direct or indirect effect of the hazard of an organism, adaptive capacity being the capability of the organism to adjust to the stressors (either by adapting or moving), and exposure relating to an organism being in a location that is affected by an external stressor (Sharma & Ravindranath, 2019). It is also worth considering that each of these components can manifest at different points in the hazard timeline e.g., risk-related factors such as exposure can be clear before the event, whilst sensitivity is often determined during or immediately after the event, and adaptive capacity can become clear after the event (Lecina-Diaz et al., 2020). To understand how vulnerable tropical forests are to climate change, we need to understand how each one of these components is impacted by a stressor. In the literature, studies assessing the effect of climate change on tropical forests often focus on one of these components (Lecina-Diaz et al., 2020) but they are not always related back to the vulnerability framework and as such it is difficult to ensure that each system has enough information on each component to understand overall vulnerability. There is also a need to be more consistent in the usage of 'vulnerability' in the literature as it is sometimes used to refer to just one component of vulnerability, typically exposure (Sharma & Ravindranath, 2019; Lecina-Diaz et al., 2020)

Tree species response to drought is largely determined by the position on the moisture gradient (Aguirre-Gutiérrez et al., 2020; Engelbrecht et al., 2007; Meir et al., 2018), where species found in drier regions tend to be more resilient to the effects of drought than wetter-affiliated species (Browne et al., 2021; Meir et al., 2018; Pulla et al., 2015). A study by Browne et al., (2021) found a 25-57% increase in mortality of seedlings in wet tropical forests compared to mortality in dry forests. There also seems to be higher resilience of deciduous species to drought and increasing temperatures compared to evergreen species, and distributions of deciduous forest types are expected to expand under drying conditions. This has been found across the biome in the Amazon (Allen et al., 2017; Esquivel-Muelbert et al., 2019), West African (Aguirre-Gutiérrez et al., 2020) and Asian tropical forests (Fan et al., 2012; Suresh et al., 2010). Aguirre-Gutierrez et al. (2020) reported that the effects of climate change have led to a reduction in the diversity of tree types in tropical forests due to the varied capabilities of forest types to deal with changes. This homogenisation of tropical diversity in response to climate changes has been shown in other studies and prompts concerns for the functioning of the forests and the ecosystem services they provide (Newbold et al., 2019; Nobre et al., 2016). Drought has also been found to disproportionately affect larger trees (Bennett et al., 2015; Meir et al., 2018; Phillips et al., 2010), resulting in an opening up of the canopy, reduction in litterfall and soil biota changes with negative repercussions for biodiversity (Bennett et al., 2015; Nepstad et al., 2007). Though decreases in precipitation and drought events are generally associated with negative effects on forests, increases in temperature have been shown to have both positive and negative effects on tropical tree species. For example, studies have shown that increasing temperatures can lead to an extension of the growth season (Grimm et al., 2013; Yang et al., 2018). However, rising temperatures have also been shown to increase mortality, reduce growth rates and decrease productivity of tropical tree species (Allen et al., 2010; Siyum, 2020; Sullivan et al., 2020). Recently, climate changes including increasing temperatures, variable precipitation and changes in the photoperiod have been shown to modify the phenology of vegetation in tropical forests (Butt et al., 2015; Lima et al., 2021; Yadav & Yadav, 2008), resulting in a delay in flowering and leaf fall, which in turn can disrupt ecosystem services forests provide such as pollination, seed dispersal and soil-related services (Butt et al., 2015; Gunarathne & Perera, 2014; Weiskopf et al., 2020).

Due to the long generation times of many tree species will migrate and adapt at much slower rates than mobile species. This factor, coupled with the narrow temperature gradients characteristic in the tropics, makes the speed of climate change a concern for tropical forests (Bertrand et al., 2011; Corlett & Westcott, 2013; Feeley et al., 2012). Plant species will not be able to migrate to more favourable climates by individual movement like many animal species, but instead will rely on seed dispersal and the survival of new seedlings at the leading edge of the climatic niche (Bell et al., 2014; Bullock, 2013; Corlett & Westcott, 2013; Nathan et al., 2011). The latter creates a slow shift in the direction of the moving climate niche but if generation times are long, this process could take many decades. Studies employing the climate velocity metric have shown that the speeds at which climate is changing are not possible for tree species to catch up with and would require rapid adaptation or acclimation in-situ (Corlett & Westcott, 2013; Dobrowski & Parks, 2016; Nathan et al., 2011; Zhu et al., 2012).

Tropical regions are expected to get warmer with increasingly variable precipitation and an increased incidence of extreme events (IPCC, 2021). Future scenarios of climate change predict severe impacts on mortality and distribution of tropical forests (McDowell et al., 2018; Newbold, 2018; Sullivan et al., 2020; Wright, 2010) and it is expected that changes to climatic patterns will begin to have a bigger effect in the tropics than land use change (Newbold, 2018; Ostberg et al., 2015). Therefore, improving our understanding of how forests across the tropical biome respond to climate change is key to understanding the threat the forest, and the species that rely on it as habitat, are under. Though research into the climate effects on tropical forests is increasing, there is still substantial uncertainty that needs to be addressed and there have been calls for an increased focus on this in the literature (Bonebrake, 2013; Brodie et al., 2012; Siyum, 2020; Zhou et al., 2013).

Like many ecosystems, tropical forests are expected to be particularly susceptible to interactions between climate change and land use change (Bonebrake, 2013; Newbold et al., 2019). Some findings suggest that interactions between the two drivers could lead to a 60% reduction in forest coverage in the Amazon by 2050 (Nobre et al., 2016). Studies so far have predominantly shown that climate changes, particularly warming and drying conditions along with drought episodes, can increase the vulnerability (using the IPCC definition detailing an increase in sensitivity and a reduction in adaptive capacity) of forests to human disturbances such as habitat degradation (IPCC, 2019; Mantyka-Pringle et al., 2015). Degraded forests are generally more vulnerable to stressors and many of the interactive effects outlined in the literature involve climate effects worsened by forest degradation (Ewers & Banks-Leite, 2013; Grimm et al., 2013; Hansen et al., 2001). For example, Qie et al., (2019) reported greater mortality and halted succession of trees caused by droughts in degraded forests compared to primary forests in Malaysia. Similar findings in the Amazon showed that degraded forests experienced greater water stress and reductions in productivity as a result of temperature increases compared to primary forests (Longo et al., 2020) and were more vulnerable to invasive species (Nobre et al., 2016). Studies have found that a reduction in forest cover and an increase in fragmentation also reduce forest species capabilities to migrate in response to climate change (Senior et al., 2019). The interaction appears to have a cyclical nature, where drought-derived thinning of the forest has increased accessibility to hunters, loggers, as well as invasive species, leading for further degradation (Brook et al., 2008). Fire damage, often as a result of escaped agricultural fires from slash and burn farming, has also been shown to be exacerbated by dry conditions in drought years, leading to a greater spread and intensity of fire and increased forest loss (Libonati et al., 2021; Nobre et al., 2016). Additionally, large-scale deforestation in the Amazon has reduced precipitation, a change that could increase the chance of drought stress on forests in the future (Leite-Filho et al., 2021; Nobre et al., 2016; Spracklen & Garcia-Carreras, 2015). Forest reductions leading to increasing local temperatures and reduced precipitation, often as a result of a reduction in evapotranspiration and a loss of canopy cover, have been shown in other studies (Kweka et al., 2016; Lawrence & Vandecar, 2014; Li et al., 2016; Paul et al., 2018), highlighting a detrimental feedback loop between deforestation, climate change and drought prevalence in forests. Interactions between the two drivers in tropical forests also affect the species that live in the forests.

It is thought that land use change coupled with a warming and drying climate will act synergistically in the redistribution of tropical forests. This is a result of the narrow temperature gradient found in tropical systems coupled with the slow adaptation and range shifts of tree species (Feeley et al., 2012), which reduces the capability of species to migrate latitudinally with climate. Instead, studies have predicted that range shifts to higher elevations where conditions may be more tolerable is one possible way that tropical tree species will track climate (Brodie et al., 2017; Feeley et al., 2012; Morueta-Holme et al., 2015; Rehm, 2014). However, because land use pressures on forests tend to be greater at lower elevations, and the same climate changes that are shifting tree distributions to higher elevations may also allow croplands to expand to higher elevations (Brodie, 2016), as a result there is predicted to be a synergistic effect of climate change and land use change pushing tropical tree species to higher elevations and increasing tree loss at lower elevations (Colwell et al., 2008; Guo et al., 2018). Though uncommon in the literature, there is some evidence to suggest that climate and land use change can ameliorate each other's impact in tropical forests. For example, forest degradation can result in a thinning of the forest which has been shown to reduce the impact of drought on forests, reducing competition for resources and benefitting early successional trees (Ovenden et al., 2021).

Given the evidence, species and ecosystem's ability to respond and adapt to climate change may be directly linked to how humans respond to climate change. As climate changes occur, human populations or individuals often modify land management decisions to adapt and ensure survival in uncertain climatic and economic futures (Harvey et al., 2018; Lei et al., 2016; Zaveri et al., 2020), as some land uses are better suited and more profitable under various climate scenarios (Shi et al., 2018). In lower income areas, particularly in the tropics, land use changes often occur out of necessity to ensure protection of human livelihoods particularly in times of climate or economic stress. Climate changes such as variable rainfall and incidences of drought have been shown to reduce crop production putting farmers under stress and reducing income (Desbureaux & Damania, 2018; IPCC, 2019; Lei et al., 2016). Forests can often offer cheap and readily accessible resources to diversify income, more fertile soils for agriculture following slash and burn (Benhin, 2006), as well as fuelwood and fodder resources. For example, collecting fuelwood has been shown to reduce smallholder famer's household expenditure by $450 compared to buying from the market (Davidar et al., 2008). Therefore, during times of declining crop yields there can be greater degradation of nearby forests (Desbureaux & Damania, 2018; Zaveri et al., 2020).

Whether the interactions have negative or positive effects on species appears to depend largely on the type of climate change, the region, forest type and the level of human disturbance (Brodie et al., 2012; Brook et al., 2008). However, currently the majority of climate and interaction studies in tropical forests focus on the Amazon (FAO & ITTO, 2011; Jimenez et al., 2018; Rifai et al., 2019). Whilst the research focusing on the Amazon has provided a good base of knowledge of the kind of effects climate changes can have on tropical forests our knowledge is limited in other regions, such as Africa and Asia, and in particular South Asia (Kumar & Scheiter, 2019; Thang et al., 2020). Due to the high variation in responses between climate changes, forest types and disturbance levels (Asner et al., 2010; FAO & ITTO, 2011; Liu et al., 2017) there is likely to be a large diversity in responses of tropical forests to climate across the tropical biome, and subsequently a varied set of interactions between the two drivers (Brodie et al., 2012; Turubanova et al., 2018). The current geographical bias hinders our understanding of how climate affects the tropical forest biome as a whole.

1.5 Indian forests as a model study system

Asian tropical forests account for 19% of the global tropical forest area (Benhin, 2006). The forests here have some of the highest rates of deforestation (Deb et al., 2018; Kumar & Scheiter, 2019) whilst harbouring a lower amount of remaining forest cover and higher population densities than other regions (Kumar & Scheiter, 2019; Laurance, 2007). Some studies have predicted that Asia could see a loss of 75% of its original forest cover and a 50% reduction in its biodiversity by 2100 (Sodhi et al., 2004).

South Asia, and India in particular, are a relatively overlooked tropical system in terms of the impacts of climate and land use change on forests and their associated biodiversity, but India is predicted to experience relatively high pressures from both climate and land use changes in the near future (Jimenez et al., 2018; Newbold et al., 2019; Sunderland et al., 2015; Venter et al., 2016). Forests in India are known to harbour high levels of biodiversity and four of 36 global biodiversity hotspots - areas with high endemic plant diversity but < 30% of their native habitat remaining - are within India's forested ecosystems (Brooks et al., 2002). Indo-Burma, which has the second highest deforestation rate of the global hotspots, and the Western Ghats are two of the most threatened hotspots on the planet, and all of India's hotspots have at least part of their area under high or very high human pressures (Venter et al., 2016). The country is an important reservoir of global species diversity, harbouring ~8% of all known species on 2.4% of the land area, and nearly 50% of global aquatic species are found here (CBD, 2018; Choudhary et al., 2022). It is also important for medicinal products, and it's thought that around 60-80% of the population of India use forest species as a primary source of healthcare (UNDP, 2012). Globally, it ranks fifth in rates of reptile endemism, and tenth in rank for bird endemism, highlighting the importance of the country to global biodiversity (CBD, 2018). As well as being one of the important historical origins of many of our current crop varieties, making it an important reservoir for new varieties (CBD, 2018). In particular, diversity in India's forests is of great importance to not only global biodiversity, but the ecosystem services it provides for human survival and economy (Ninan & Kontoleon, 2016). Millions of people rely on India's forests for food, fuel and timber, as well as these forests being attributed to absorbing ~11% of India's GHG emissions (CBD, 2018). India's forests are home to several charismatic species that are important for international tourism and global conservation funding, such as the Bengal Tiger and Asiatic Elephant (Johnsingh & Joshua, 1994; Barua et al., 2010; Barua et al., 2011).

The unusually high numbers of endemics have been attributed to the diversity and extent of its tropical forest cover (Sunderland et al., 2015). Over 74% of India's forests are tropical forests, predominantly dry and moist deciduous species, a further 6% are sub-tropical forests, and the remainder are a mix of plantation species (8%), temperate (6%) and alpine species (2%) (FSI 2019) (Table 1).

Table 1| The extent and diversity of forest types in India according to the Forest Survey of India Report (2019)

Forest Type	Percent of total forest area
Tropical Wet Evergreen	2.66
Tropical Semi-Evergreen	9.44

Tropical Moist Deciduous	17.96
Tropical Dry Deciduous	41.58
Tropical Thorn	2.77
Tropical Dry Evergreen	0.12
Littoral and Swamp	0.74
Subtropical Broadleaved Hill	4.34
Subtropical Pine	2.40
Subtropical Dry Evergreen	0.02
Montane Wet Temperate	2.71
Himalayan Moist Temperate	3.41
Himalayan Dry Temperate	0.75
Sub-Alpine and Alpine	2.50
Plantation	8.60

Due to inaccessibility of spatial data on forest types from the Forest Survey of India, this study utilises land cover maps from the European Space Agency using the FAO classification system (ESA CCI Land Cover project (v2.0.7 1995-2015) and EC C3S Land Cover project (v2.1.1 2016-2019)). Figure 1 shows the distribution of forest types across the country using this classification at the start of the study period used in this thesis (1995). Figure 2 shows the distribution of land cover classes across the country, also in 1995, to show the distribution of forests in relation to other extensive land classes, particularly cropland.

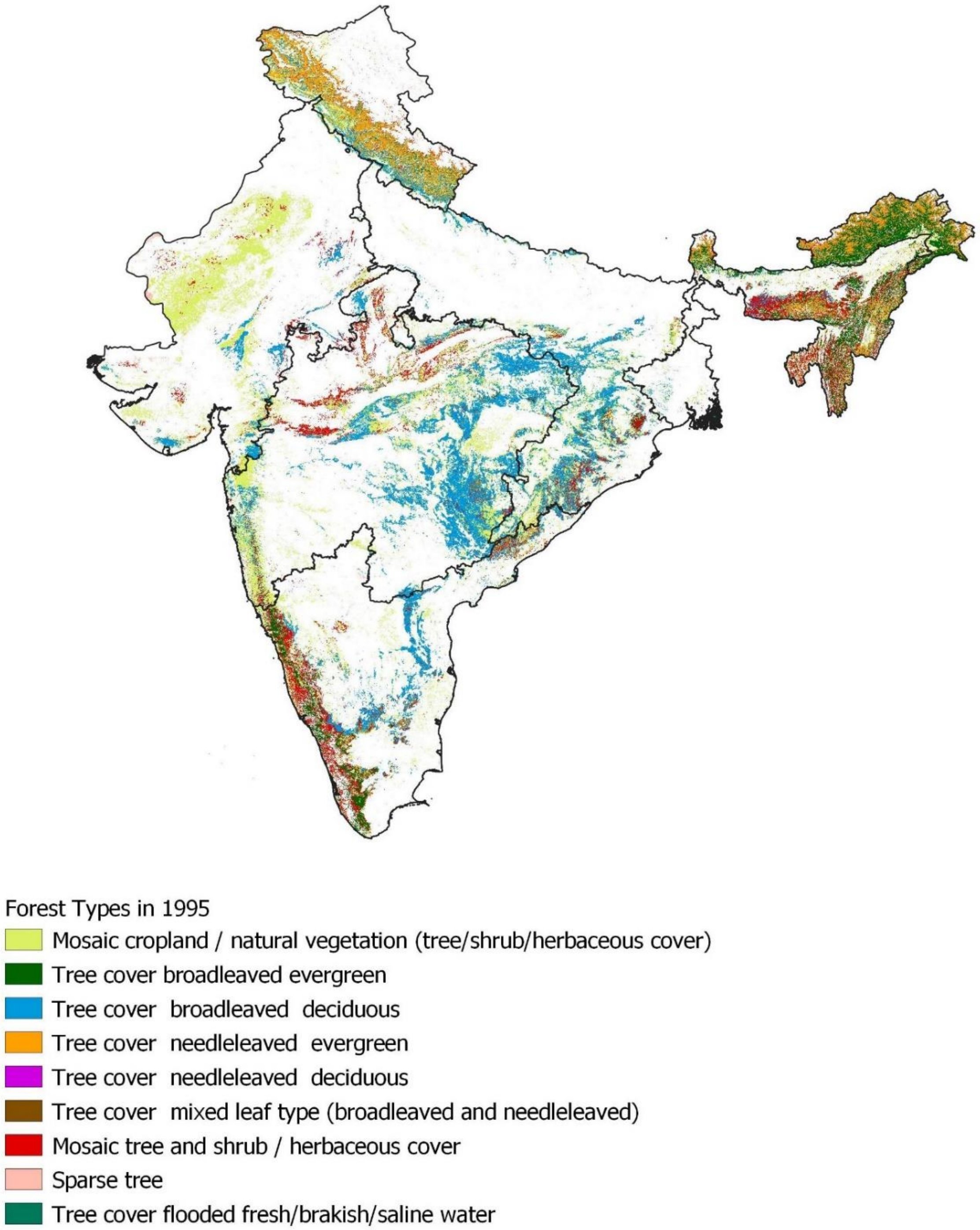


Figure 1| The distribution of different forest types across India in 1995. Land cover classification of ESA CCI Land Cover project (v2.0.7 1995-2015) and EC C3S Land Cover project (v2.1.1 2016-2019) utilising the FAO classification system.

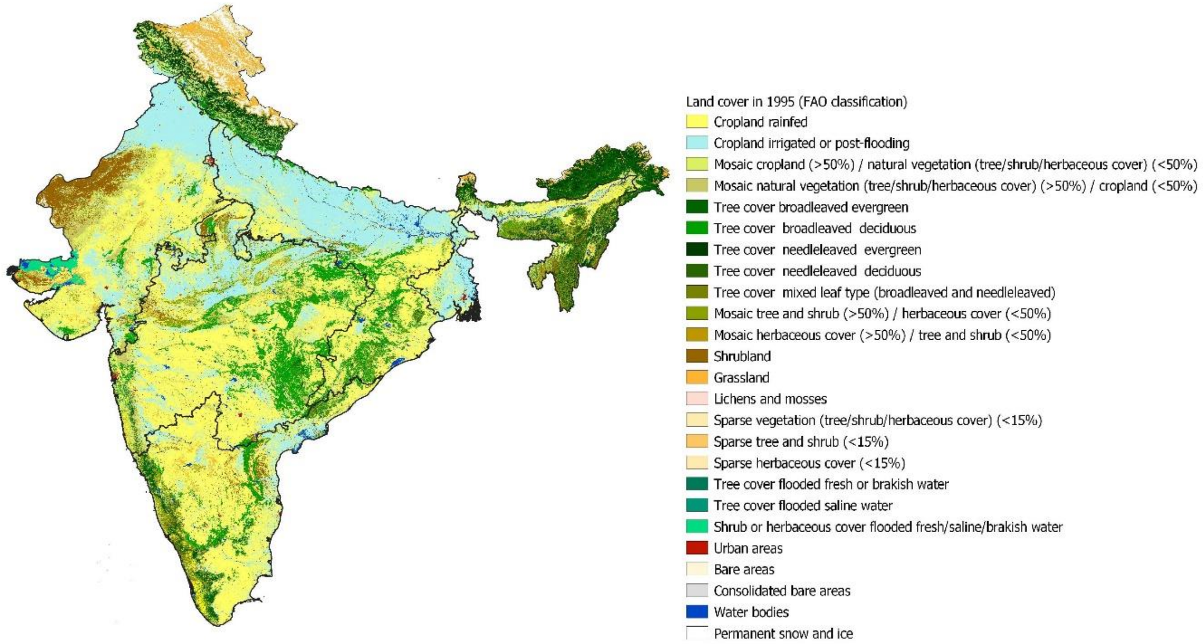


Figure 2| Land cover map of India in 1995. Land cover classification of ESA CCI Land Cover project (v2.0.7 1995-2015) and EC C3S Land Cover project (v2.1.1 2016-2019) utilising the FAO classification system.

Historically, forests in this country have very high rates of loss, with 0.77% of forest lost every year between 1930 and 1975 and 28% of forest lost between 1930-2013 (Sudhakar Reddy et al., 2016). The highest rates of loss tend to be reported in the Northeast region where much of the country's remaining forest cover is located (FSI, 2019; Lele & Joshi, 2009), with 65% of total forest loss between 2005-2008 reported in this region (Chaturvedi et al., 2011). Past forest loss has largely been attributed to expansions in cropland, with contributions from other drivers such as logging, mining, plantations (Giriraj et al., 2008; Kundu et al., 2015; Padalia et al., 2019; Reddy et al., 2013; Roy & Giriraj, 2008) and fuelwood and fodder collection (Arjunan et al., 2005; Davidar, 2007; FSI, 2019). The threat of land use change to forests in the country is expected to increase in the future due to the continued rapid growth of the population, the increased demand for food resources and the reliance of the country on agricultural development (Bhattacharyya et al., 2015; Delzeit et al., 2016; Hinz et al., 2020). Crop production is predicted to grow by 55% between 2010 and 2030 (Hinz et al., 2020). However, a reduction in studies in recent decades has resulted in an uncertainty around the extent of forest loss and its relationship with land use change.

To date, the effects of climate change on past forest loss have been largely overlooked within India (Kumar & Scheiter, 2019). However, a number of recent studies have begun to consider the effects of future climate changes on the distribution of forests and have predicted that climate is likely to have a significant effect on forests in the future (Deb et al., 2018; Gopalakrishnan et al., 2011; Ravindranath et al., 2011; Sharma et al., 2017). Chaturvedi et al., (2011) reported that there is likely to be a redistribution of forests in the country in response to changing distributions of rainfall, where Western Central India is expected to see an expansion of forests, but Northwest forests and those in the Northern Western Ghats will become increasingly exposed to detrimental climate changes (with an increased vulnerability to forest loss). Several studies also predict a change in the distribution of forest types with future climate changes, for example, Ravindranath et al., (2005) predicted an expansion of drier forest types in the Northwest alongside a change towards wetter forest types in the Northeast of the country in response to changing rainfall patterns. Like other tropical regions, India is predicted to experience increases of temperature, highly variable precipitation, especially during the monsoon and increasing incidences and strength of extreme events, such as flooding and drought, resulting in severe conditions that many species have not experienced before (Chaturvedi et al., 2011; IPCC, 2019; Kumar & Scheiter, 2019; Sharma & Mujumdar, 2017). The monsoon climate (responsible for 80% of annual precipitation) also makes the country more vulnerable to climate changes than other areas of the tropics due to the heavy reliance by both natural and human systems on the seasonal rainfall (Arjun, 2013; Deb Burman et al., 2020; Goswami, 2005; Mishra, 2019).

Despite a dearth of studies focusing on interactions between climate and land use change in India's forests, research on future scenarios highlight that fragmentation and land use change is likely to increase vulnerability of forests to climate changes (Chaturvedi et al., 2011; Deb et al., 2018; Gopalakrishnan et al., 2011; Kumar & Scheiter, 2019). This premise is also supported by several global studies highlighting that forest biodiversity in South Asia will be highly affected by the combined stressors (Newbold, 2018; Newbold et al., 2019). Given the role climate is suspected to play in future loss, the current trajectory of climate change in the country, and findings from other tropical regions, it is likely that climate change has contributed to forest losses in the past in India and that interactions with land use changes will be occurring. This presents a key gap in our understanding of the drivers of forest loss and may result in inaccurate projections of future loss if its past role is not properly understood.

India presents a unique opportunity to explore the potential for interactions between the two significant drivers, in a country not previously considered. Focusing on Indian forests has the potential to increase knowledge of the drivers of forest loss in the country, as well as a greater understanding of the drivers of tropical forest loss, and their interactions, in an underrepresented region of the tropics. This study therefore has the potential to better understand implications for forest protection, and consideration of multiple drivers may enable more informed management strategies in the future that better protect the forests. Since Indian biodiversity and agriculture are intrinsically linked with the forest this thesis also has implications beyond the extent of forest loss, to biodiversity conservation and human livelihoods.

1.6 Thesis aims and structure

In light of these research gaps, this thesis aims to increase understanding of the effects of climate change, land use change and their interactions on forests in India.

Overall objectives:

1. To evaluate the degree to which climate changes have played a role in India's forest loss in the past 20 years
2. To assess the extent of land use change contributions to forest loss in India in the past 20 years
3. To ascertain whether there is evidence of a climate-land use change interaction impacting forest loss in the country

The following provides a brief outline of the thesis chapters created to address these objectives, and this is further illustrated in Figure 3:

Chapter 2:

Chapter 2 linked to objective one, investigates whether climate change has contributed to the extensive forest losses in India in the past. It uses temporal trends of precipitation and temperature to assess whether these trends have contributed to forest loss between 2001 and 2018. It also employs an emerging metric, climate velocity, that encompasses climate change over space and time and is yet to be widely used. This chapter is crucial to broadening the scope of literature around this topic, which has to date not considered climate change as a driver of forest loss in the past within India. The chapter acts as a key foundation to the thesis aiming to form an understanding of how one of the two main stressors of interest materialises in the country.

The key questions addressed in this chapter are:

1. Has climate change contributed to past forest loss in India?
2. Are there seasonal and regional variations in the climate-forest loss relationship in the country?
3. Are Indian forests exposed to high and/or overlapping climate velocities and is forest loss greater in these areas?

4. Can climate velocity provide additional understanding of forest’s risk to climate change?

Chapter 3:

Chapter 3 focuses on the second objective of the thesis and assesses how land use and land cover change have affected forests in the country. It aims to understand the trends in forest losses and gains, addresses questions around whether agriculture remains the primary cause of forest loss and provides understanding of the vulnerability of different regions and forest types to deforestation. It looks at a 1995-2019 time period where there has been reduced focus on the trends in forest loss or the role of land use change in the literature and contributes knowledge that supports understanding of forest change in the country. It also provides key information to address the thesis objectives around land use change.

The key questions addressed in this chapter are:

1. How has the area of forest changed over time?
2. What specific land uses or land cover types are associated with the greatest forest losses?
3. Are the drivers of loss different for different forest types and regions?

Chapter 4:

Chapter 4 aims to understand the effect of drought on forests and whether there is evidence to suggest that interactions are occurring with land use change. Focusing on the Northeast region during the period 1995-2019, this chapter assesses forest changes over five precipitation deficit years. It aims to increase understanding of the combined threat of drought and land use change to forests in the region by exploring the spatial extent of forest loss during drought years, quantifying the major types of forest lost, and assessing the key land use and land cover changes associated with forest loss. The chapter importantly addresses the third objective of the thesis to consider the combined effects of climate and land use change in India’s tropical forests.

The key questions addressed in this chapter are:

1. Do precipitation deficits result in a higher probability of forest loss?
2. Is forest loss attributed to anthropogenic land use changes more prevalent in the wetter areas of a drought?

Chapter 5:

This chapter summarises the overall findings of the thesis along with outlining how the research contributes to the wider body of evidence and what the findings mean practically for the protection of forests and biodiversity in India now and in the future. The chapter then explores the limitations associated with the research and highlights remaining knowledge gaps and key areas for future research focus.

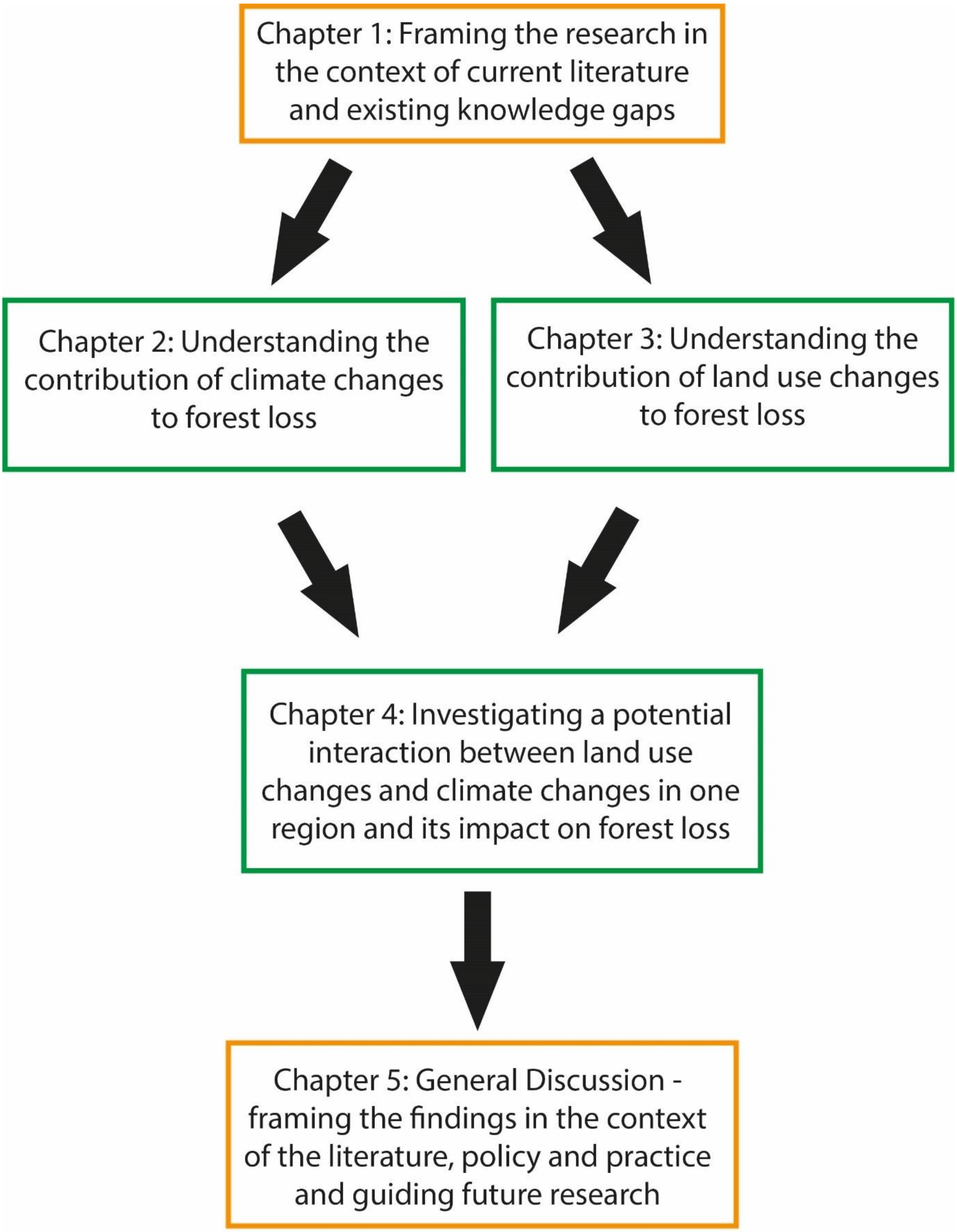


Figure 3| Flow diagram illustrating the structure of the thesis. Chapters where primary data is analysed are shown in a green outline whereas introductory and discussion chapters are shown with an orange outline.

1.7 Methodological considerations – Data use and spatial resolution

When spatially analysing trends over large areas and longer periods of time, there can be difficulties with acquiring appropriate datasets. Typically, there is a trade-off between temporal and spatial resolution of satellite datasets, where the datasets with the smallest temporal resolution have a lower spatial resolution and vice versa. For analysing changes in forest distribution, it would be preferable to have the highest spatial resolution (so we can the smallest changes in forest edge loss) and a fairly small temporal resolution (so that at least seasonal changes important in forest growth are captured). The difficulty acquiring appropriate resolution data for both climate change and land use change is well documented and can be a key barrier to effective research in India (Kumar et al., 2018; Gia et al., 2019). Though satellite data is improving all the time, and we now have access to temporal resolutions of sub-hourly and spatial resolutions of > 1 metre, it is still hard to find free, accessible data that covers large time periods with high spatial resolutions, particularly when looking for a regional focus. Regional datasets are often better due to their more specific calibrations from the region of interest that can make them more accurate than global datasets. However, obtaining high quality, long-term satellite data for India for this thesis proved difficult, mainly due to paywalls on climate data and lack of long term data collection on land use change. For these reasons, this thesis uses globally available free datasets that span the required temporal period and have a reasonable spatial resolution to capture the changes in forest coverage. There are two main considerations about the data used in this thesis that I would like to highlight and discuss here:

Firstly, in Chapter 2, I use the Global Forest Change Dataset by Hansen et al., (2013). This is a highly cited dataset with publications in high ranking journals (e.g., Curtis, et al., 2018; Hansen, et al., 2020; Harris, et al., 2021; Moffette, et al., 2021) and is used as the primary data for the global platform, Global Forest Watch (https://www.globalforestwatch.org/map/). Despite known limitations around this dataset in terms of its capability to distinguish between natural and plantation forests (critiqued well in Tropek et al., 2014), this dataset is the only dataset available that specifically focuses on forest loss with the temporal and spatial coverage required to do this analysis. This dataset worked well when used alongside climate data in Chapter 2. However in Chapter 3, where I introduce land cover data to assess changes in land cover over time, the Hansen GFC dataset could no longer be used as it was found to match up poorly with the land cover data. There were instances where what was recorded as tree cover by the Hansen dataset was recorded as shrubland by the land cover dataset. Therefore, these two datasets could not be used in conjunction, and so in Chapter 3, I had to rely on the land cover data to assess both land cover changes and forest changes. Finding errors and incompatibility between satellite-derived data sources is common as the field continues to develop and aims to provide better coverage across the globe temporally and spatially. This incompatibility in data sources resulted in different findings of forest cover change between Chapters 2 and 3 which is discussed in detail in Chapter 5.

Secondly, throughout this thesis I use the freely available global dataset on temperature and precipitation developed by the Climate Research Unit (CRU) (https://crudata.uea.ac.uk/cru/data/hrg/). This dataset has a spatial resolution of 0.5 degrees (~50km x 50km grid squares) and there are instances where the climate for a district in India is derived from an average of two grid squares due to the small size of some of the districts in the country. Most freely available large scale climate datasets at this time are not able to provide better resolution that this or would compromise on temporal resolution. For example, the NOAA CMAP data (https://psl.noaa.gov/data/gridded/data.cmap.html) has good temporal resolution (1979-2022) but is only available at 2.5 degrees coverage, or at 0.25 degrees spatial resolution but only until the year 2006. WorldClim (https://www.worldclim.org/data/index.html) has excellent spatial resolution (~1km) but does not have annual or monthly data at the time of analysis (though it now does at 20km resolution), and IMD Pune (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html) have a 0.25 degree long-term precipitation dataset (1901-2018) but only have temperature data at 1 degree spatial resolution. Accessing high resolution temperature data was particularly challenging and the CRU dataset used in this thesis provided both a good temporal and spatial resolution for temperature and precipitation. The CRU climate dataset is a widely used dataset with both high temporal and spatial resolution precipitation and temperature data and is, importantly, freely available. As far as I am aware, it is the only accessible dataset with the temporal and spatial resolution capable for conducting this analysis and this is the reason it was chosen for the thesis.

1.8 References

Aguirre-Gutiérrez, J., et al., (2020). Long-term droughts may drive drier tropical forests towards increased functional, taxonomic and phylogenetic homogeneity. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-16973-4

Ahmed, K. F., et al., (2016). Potential impact of climate and socioeconomic changes on future agricultural land use in West Africa. *Earth System Dynamics*, *7*(1), 151–165. https://doi.org/10.5194/esd-7-151-2016

Allen. (2017). Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes?. *Environmental Research Letters*, 12(2). https://doi.org/10.1088/1748-9326/aa5968

Allen, C. D., 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*(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Allen, K., et al., (2017). Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes? *Environmental Research Letters*, *12*(2), 023001. https://doi.org/10.1088/1748-9326/AA5968

Alroy, J. (2017). Effects of habitat disturbance on tropical forest biodiversity. *Proceedings of the National Academy of Sciences*, *114*(23), 6056–6061. https://doi.org/10.1073/PNAS.1611855114

Anderegg, et al., (2018). Hydraulic diversity of forests regulates ecosystem resilience during drought. *Nature, 561*(7724), 538–541. https://doi.org/10.1038/s41586-018-0539-7

Arjun, K. M. (2013). Indian Agriculture-Status, Importance and Role in Indian Economy. *International Journal of Agriculture and Food Science Technology*, 4(4), 343–346

Arjunan, M., Puravaud, J., & Davidar, P. (2005). The impact of resource collection by local communities on the dry forests of the Kalakad-Mundanthurai Tiger Reserve. *Tropical Ecology*, *46*(2).

Armstrong, E., et al., (2016). The Role of CO 2 and Dynamic Vegetation on the Impact of Temperate Land-Use Change in the HadCM3 Coupled Climate Model, *Earth Interactions*, *20*(10). https://doi.org/10.1175/EI-D-15-0036.1

Asner, G. P., Loarie, S. R., & Heyder, U. (2010). Combined effects of climate and land-use change on the future of humid tropical forests. *Conservation Letters*, *3*(6), 395–403. https://doi.org/10.1111/j.1755-263X.2010.00133.x

Aubry-Kientz, et al.,. (2019). Temperature rising would slow down tropical forest dynamic in the Guiana Shield. *Scientific Reports*, *9*(1), 1–8. https://doi.org/10.1038/s41598-019-46597-8

Barlow, J., et al., (2018). The future of hyperdiverse tropical ecosystems. *Nature*, *559*(7715), 517–526. https://doi.org/10.1038/s41586-018-0301-1

Barua, M., et al., 2010. Mutiny or Clear Sailing? Examining the role of the Asian Elephant as a Flagship Species. Human Dimensions of Wildlife, 15(2), 145-160

Barua et al., 2011. Defining Flagship uses is critical for flagship selection: A critique of the IUCN climate change flagship fleet. AMBIO, 40, 431-435

Bell, D. M., Bradford, J. B., & Lauenroth, W. K. (2014). Early indicators of change: divergent climate envelopes between tree life stages imply range shifts in the western United States. *Global*

Ecology and Biogeography, *23*(2), 168–180. https://doi.org/10.1111/GEB.12109

Benhin, J. K. A. (2006). Agriculture and Deforestation in the Tropics: A Critical Theoretical and Empirical Review. AMBIO: A Journal of the Human Environment, *35*(1), 9–16. https://doi.org/10.1579/0044-7447-35.1.9

Bennett, A. C., et al., (2015). Larger trees suffer most during drought in forests worldwide. *Nature Plants*, *1*(10), 1–5. https://doi.org/10.1038/nplants.2015.139

Bertrand, R., et al., (2011). Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, *479*(7374), 517–520. https://doi.org/10.1038/nature10548

Bertrand, R., et al., (2016). Ecological constraints increase the climatic debt in forests. *Nature Communications*, *7*(1), 1–10. https://doi.org/10.1038/ncomms12643

Betts, M. G., et al., (2018). Old-growth forests buffer climate-sensitive bird populations from warming. *Diversity and Distributions*, *24*(4), 439–447. https://doi.org/10.1111/ddi.12688

Betts, M. G., et al., (2019). Extinction filters mediate the global effects of habitat fragmentation on animals. *Science*, *366*(6470), 1236–1239. https://doi.org/10.1126/SCIENCE.AAX9387

Betts, M., et al., (2022). Forest degradation, not loss, drives widespread avian population declines. *Nature Ecology and Evolution*. https://doi.org/10.21203/rs.3.rs-686817/v1

Betts, R. A., et al., (2004). The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and Applied Climatology*, *78*(1), 157–175. https://doi.org/10.1007/S00704-004-0050-Y

Bhattacharyya, R., et al.,. (2015). Soil Degradation in India: Challenges and Potential Solutions. *Sustainability*, *7*(4), 3528–3570. https://doi.org/10.3390/SU7043528

Boekhout Van Solinge, T. (2010). Deforestation Crimes and Conflicts in the Amazon. *Crit Crim*, *18*, 263–277. https://doi.org/10.1007/s10612-010-9120-x

Boit, A., et al., (2016). Large-scale impact of climate change vs. land-use change on future biome shifts in Latin America. *Global Change Biology*, *22*(11), 3689–3701. https://doi.org/10.1111/GCB.13355

Bonebrake, T. C. (2013). Conservation implications of adaptation to tropical climates from a historical perspective. *Journal of Biogeography*, *40*(3), 409–414. https://doi.org/10.1111/JBI.12011

Brando, P. M., et al., (2014). Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proceedings of the National Academy of Sciences*, *111*(17), 6347–6352. https://doi.org/10.1073/PNAS.1305499111

Brito-Morales, I., et al., (2018). Climate Velocity Can Inform Conservation in a Warming World. *Trends in Ecology and Evolution*, 33(6):441-457. https://doi.org/10.1016/j.tree.2018.03.009

Brodie, J. F. (2016). Synergistic effects of climate change and agricultural land use on mammals. *Frontiers in Ecology and the Environment*, *14*(1), 20–26. https://doi.org/10.1002/16-0110.1

Brodie, J. F., et al., (2017). Lowland biotic attrition revisited: body size and variation among climate change 'winners' and 'losers.' *Proceedings of the Royal Society B: Biological Sciences*, *284*(1847). https://doi.org/10.1098/RSPB.2016.2335

Brodie, J., Post, E., & Laurance, W. F. (2012). Climate change and tropical biodiversity: a new focus. *Trends in Ecology & Evolution*, *27*(3), 145–150. https://doi.org/10.1016/J.TREE.2011.09.008

Brook, B. W., Sodhi, N. S., & Bradshaw, C. J. A. (2008). Synergies among extinction drivers under global change. *Trends in Ecology and Evolution*. https://doi.org/10.1016/j.tree.2008.03.011

Brookhuis, B. J., & Hein, L. G. (2016). The value of the flood control service of tropical forests: A case study for Trinidad. *Forest Policy and Economics*, *62*, 118–124. https://doi.org/10.1016/J.FORPOL.2015.10.002

Brooks, T. M., et al., (2002). Habitat Loss and Extinction in the Hotspots of Biodiversity. *Conservation Biology*, *16*(4), 909–923. https://doi.org/10.1046/J.1523-1739.2002.00530.X

Browne, L., et al., (2021). Increased mortality of tropical tree seedlings during the extreme 2015–16 El Niño. *Global Change Biology*, *27*(20), 5043–5053. https://doi.org/10.1111/GCB.15809

Bullock, J. M. (2013). Plant dispersal and the velocity of climate change. *Dispersal Ecology and Evolution*, 366–377. https://doi.org/10.1093/ACPROF:OSO/9780199608898.003.0029

Butt, N., et al., (2015). Cascading effects of climate extremes on vertebrate fauna through changes to low-latitude tree flowering and fruiting phenology. *Global Change Biology*, *21*(9), 3267–3277. https://doi.org/10.1111/gcb.12869

Camacho, L. F., Barragán, G., & Espinosa, S. (2021). Local ecological knowledge reveals combined landscape effects of light pollution, habitat loss, and fragmentation on insect populations. *Biological Conservation*, *262*, 109311. https://doi.org/10.1016/J.BIOCON.2021.109311

Cardinale, B. J., et al., (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*(7401), 59–67.

https://doi.org/10.1038/nature11148

Carmenta, R., et al., (2013). Shifting Cultivation and Fire Policy: Insights from the Brazilian Amazon. *Human Ecology*, 41, 603-614. https://doi.org/10.1007/s10745-013-9600-1

Carroll, C., et al., (2015). Biotic and Climatic Velocity Identify Contrasting Areas of Vulnerability to Climate Change. *PLOS ONE*, *10*(10), e0140486. https://doi.org/10.1371/JOURNAL.PONE.0140486

CBD (2018). India's Sixth National Report to the Convention of Biological Diversity. Accessible at: https://chm.cbd.int/database/record?documentID=241351

Chaturvedi, R. K., et al.,. (2011). Impact of climate change on Indian forests: A dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change*, *16*(2), 119–142. https://doi.org/10.1007/s11027-010-9257-7

Chaudhary, A., et al., (2022). Subnational assessment of threats to Indian biodiversity and habitat restoration opportunities. *Environmental Research Letters*, 17(5)

Chitale, V. S., et al., (2020). Understanding socio-ecological drivers of fuelwood dynamics and their impact in Churia hills of Nepal. *Tropical Ecology*, *61*(1), 76–83. https://doi.org/10.1007/s42965-020-00069-7

Colwell, R. K., et al., (2008). Global Warming, Elevational Range Shifts, and Lowland Biotic Attrition in the Wet Tropics. *Science*, *322*(5899), 258–261. https://doi.org/10.1126/science.1162547

Corlett, R. T., & Westcott, D. A. (2013). Will plant movements keep up with climate change? *Trends in Ecology and Evolution*, 28(8), 482-488. https://doi.org/10.1016/j.tree.2013.04.003

Côté, I. M., Darling, E. S., & Brown, C. J. (2016). Interactions among ecosystem stressors and their importance in conservation. *Proceedings of the Royal Society B: Biological Sciences*. https://doi.org/10.1098/rspb.2015.2592

Curtis, P. G., et al., (2018). Classifying drivers of global forest loss. *Science*, *361*(6407), 1108–1111. https://doi.org/10.1126/science.aau3445

Darling, E. S., & Côté, I. M. (2008). Quantifying the evidence for ecological synergies. *Ecology Letters*. https://doi.org/10.1111/j.1461-0248.2008.01243.x

Davidar. (2007). Forest degradation in the Western Ghats biodiversity hotspots: Resource collection, livelihood concerns and sustainability. *Current Science*, 93(11), 1573-1578

Davidar, P., Arjunan, M., & Puyravaud, J. P. (2008). Why do local households harvest forest products?

A case study from the southern Western Ghats, India. *Biological Conservation*, *141*(7), 1876–1884. https://doi.org/10.1016/J.BIOCON.2008.05.004

Deb Burman, et al., (2020). The effect of Indian summer monsoon on the seasonal variation of carbon sequestration by a forest ecosystem over North-East India. *SN Applied Sciences 2020 2:2*, *2*(2), 1–16. https://doi.org/10.1007/S42452-019-1934-X

Deb, J. C., et al., (2018). Climate change impacts on tropical forests: identifying risks for tropical Asia. *Journal of Tropical Forest Science*, *30*(2), 182–194. https://doi.org/10.26525/JTFS2018.30.2.182194

Delzeit, R., et al., (2016). Addressing future trade-offs between biodiversity and cropland expansion to improve food security. *Regional Environmental Change*, *17*(5), 1429–1441. https://doi.org/10.1007/S10113-016-0927-1

Desbureaux, S., & Damania, R. (2018). Rain, forests and farmers: Evidence of drought induced deforestation in Madagascar and its consequences for biodiversity conservation. *Biological Conservation*, *221*, 357–364. https://doi.org/10.1016/J.BIOCON.2018.03.005

Descombes, P., et al., (2020). Novel trophic interactions under climate change promote alpine plant coexistence. *Science*, *370*(6523), 1469–1473. https://doi.org/10.1126/SCIENCE.ABD7015

Deutsch, C. A., et al., (2008). Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences*, *105*(18), 6668–6672. https://doi.org/10.1073/PNAS.0709472105

Devictor, V., et al., (2012). Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, *2*(2), 121–124. https://doi.org/10.1038/nclimate1347

Didham, R. K., et al., (2007). Interactive effects of habitat modification and species invasion on native species decline. *Trends in Ecology and Evolution*, 22(9), 489-496 https://doi.org/10.1016/j.tree.2007.07.001

Dobrowski, S. Z., & Parks, S. A. (2016). Climate change velocity underestimates climate change exposure in mountainous regions. *Nature Communications*, *7*(1). https://doi.org/10.1038/ncomms12349

Dundas, S. J., et al.,. (2021). Some like it hot: Drought-induced forest die-off influences reptile assemblages. *Acta Oecologica*, *111*, 103714. https://doi.org/10.1016/J.ACTAO.2021.103714

Ebi, K. L., et al., (2007). Climate change-related health impacts in the Hindu Kush-Himalayas.

EcoHealth, *4*(3), 264–270. https://doi.org/10.1007/S10393-007-0119-Z

Edwards, D. P., et al., (2011). Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1702), 82–90. https://doi.org/10.1098/RSPB.2010.1062

Engelbrecht, B. M. J., et al., (2007). Drought sensitivity shapes species distribution patterns in tropical forests. *Nature*, *447*(7140), 80–82. https://doi.org/10.1038/nature05747

Esquivel-Muelbert, A., et al., (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, *25*(1), 39–56. https://doi.org/10.1111/GCB.14413

Ewers, R. M., & Banks-Leite, C. (2013). Fragmentation Impairs the Microclimate Buffering Effect of Tropical Forests. *PLoS ONE*, *8*(3). https://doi.org/10.1371/JOURNAL.PONE.0058093

Fan, Z.-X., et al., (2012). Hydraulic conductivity traits predict growth rates and adult stature of 40 Asian tropical tree species better than wood density. *Journal of Ecology*, *100*(3), 732–741. https://doi.org/10.1111/J.1365-2745.2011.01939.X

FAO. (2020). *The State of the World's Forests 2020*. FAO and UNEP. https://doi.org/10.4060/ca8642en

FAO & ITTO (2011). The State of Forests in the Amazon Basin, Congo Basin and Southeast Asia. Summit of the Three Rainforest Basins report. Food and Agriculture Organisation of the United Nations and the International Tropical Timber Organisation. Accessed at: http://www.fao.org/3/i2247e/i2247e00.pdf

Feeley, K. J., Rehm, E. M., & Machovina, B. (2012). perspective: The responses of tropical forest species to global climate change: acclimate, adapt, migrate, or go extinct? *Frontiers of Biogeography*, *4*(2). https://doi.org/10.21425/F5FBG12621

Field, R. D., van der Werf, G. R., & Shen, S. S. P. (2009). Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nature Geoscience*, *2*(3), 185–188. https://doi.org/10.1038/ngeo443

Foley, J. A., et al.,. (2005). Global Consequences of Land Use. *Science*, *309*(5734), 570-574

França, F. M., et al., (2020). Climatic and local stressor interactions threaten tropical forests and coral reefs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794), 20190116. https://doi.org/10.1098/rstb.2019.0116

França, F. M., et al., (2020). El Niño impacts on human-modified tropical forests: Consequences for dung beetle diversity and associated ecological processes. *Biotropica*, *52*(2), 252–262. https://doi.org/10.1111/BTP.12756

Frishkoff, L. O., et al., (2016). Climate change and habitat conversion favour the same species. *Ecology Letters*, 19(9), 1081-1090. https://doi.org/10.1111/ele.12645

FSI (2019). State of the Forest Report, 2019. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

Garcia, R. A., et al., (2014). Multiple dimensions of climate change and their implications for biodiversity. *Science*. 344(6183). https://doi.org/10.1126/science.1247579

Gascon, C., Williamson, G. B., & Da Fonseca, G. A. B. (2000). Receding forest edges and vanishing reserves. *Science*, *288*(5470), 1356–1358. https://doi.org/10.1126/SCIENCE.288.5470.1356

Gibson, L., et al., (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, *478*(7369), 378–381. https://doi.org/10.1038/NATURE10425

Giriraj, A., et al., (2008). Modelling Spatial and Temporal Forest Cover Change Patterns (1973-2020): A Case Study from South Western Ghats (India). *Sensors*, *8*(10), 6132–6153. https://doi.org/10.3390/s8106132

Gissi, E., et al., (2021). A review of the combined effects of climate change and other local human stressors on the marine environment. *Science of The Total Environment*, *755*, 142564. https://doi.org/10.1016/J.SCITOTENV.2020.142564

Gogoi, P. P., et al., (2019). Land use and land cover change effect on surface temperature over Eastern India. *Scientific Reports*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-45213-z

González del Pliego, P., et al., (2016). Thermally buffered microhabitats recovery in tropical secondary forests following land abandonment. *Biological Conservation*, *201*, 385–395. https://doi.org/10.1016/J.BIOCON.2016.07.038

Gopalakrishnan, R., et al.,. (2011). Climate change and Indian forests. *Current Science*, 101 (3), 348.

Goswami, B. N. (2005). South Asian monsoon. *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, 19–61. https://doi.org/10.1007/3-540-27250-X_2

Grimm, N. B., et al., (2013). The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and the Environment*, 11(9), 474-482. https://doi.org/10.1890/120282

Grünig, M., et al., (2020). Crop and forest pest metawebs shift towards increased linkage and suitability overlap under climate change. *Communications Biology*, *3*(1), 1–10. https://doi.org/10.1038/s42003-020-0962-9

Gunarathne, R. & Perera, G. A. D. (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*(1), 63–73.

Guo, F., Lenoir, J., & Bonebrake, T. C. (2018). Land-use change interacts with climate to determine elevational species redistribution. *Nature Communications,* 9. https://doi.org/10.1038/s41467-018-03786-9

Hansen, A. J., et al., (2001). Global Change in Forests: Responses of Species, Communities, and BiomesInteractions between climate change and land use are projected to cause large shifts in biodiversity. *BioScience*, *51*(9), 765–779. https://doi.org/10.1641/0006-3568(2001)051[0765:gcifro]2.0.co;2

Hansen, M. C., et al., (2013). High-resolution global maps of 21st Century forest cover change. *Science*, 342(6160), 850-853

Hansen, M. C., et al., (2020). The fate of tropical forest fragments. *Science Advances*, *6*(11), 8574–8585. https://doi.org/10.1126/sciadv.aax8574

Harris, N.L., et al. (2021). Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change.* **11,** 234–240

Harvey, C. A., et al., (2018). Climate change impacts and adaptation among smallholder farmers in Central America. *Agriculture & Food Security*, *7*(1), 1–20. https://doi.org/10.1186/S40066-018-0209-X

He, X., et al.,. (2019). The Effects of Interaction between Climate Change and Land-Use/Cover Change on Biodiversity-Related Ecosystem Services. *Global Challenges*, *3*(9), 1800095. https://doi.org/10.1002/GCH2.201800095

Heller, N. E., & Zavaleta, E. S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, 142(1), 14-32 https://doi.org/10.1016/j.biocon.2008.10.006

Hiddink, J. G., et al., (2012). Keeping pace with climate change: what can we learn from the spread of Lessepsian migrants? *Global Change Biology*, *18*(7), 2161–2172. https://doi.org/10.1111/J.1365-2486.2012.02698.X

Hill, S. L. L., et al., (2018). Worldwide impacts of past and projected future land-use change on local species richness and the Biodiversity Intactness Index. *BioRxiv*, 311787. https://doi.org/10.1101/311787

Hinz, R., et al., (2020). Agricultural Development and Land Use Change in India: A Scenario Analysis of Trade-Offs Between UN Sustainable Development Goals (SDGs). *Earth's Future*, *8*(2), e2019EF001287. https://doi.org/10.1029/2019EF001287

Hoffmann, A. A., & Sgrò, C. M. (2011). Climate change and evolutionary adaptation. *Nature*, *470*(7335), 479–485. https://doi.org/10.1038/nature09670

Hoskins, A. J., et al., (2016). Downscaling land-use data to provide global 30″ estimates of five land-use classes. *Ecology and Evolution*, *6*(9), 3040–3055. https://doi.org/10.1002/ece3.2104

Hosonuma, N., et al., (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, *7*(4), 044009. https://doi.org/10.1088/1748-9326/7/4/044009

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services. https://doi.org/10.5281/ZENODO.3553579

IPCC. (2019). Summary for Policymakers — Special Report on Climate Change and Land. Retrieved February 3, 2021, from https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

IPCC. (2021). The Physical Science Basis Summary for Policymakers Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: https://www.ipcc.ch/report/ar6/wg1/

Jetz, W., Wilcove, D. S., & Dobson, A. P. (2007). Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds. *PLoS Biology*, *5*(6), e157. https://doi.org/10.1371/journal.pbio.0050157

Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)].

Jimenez, J. C., et al., (2018). Spatio-temporal patterns of thermal anomalies and drought over tropical forests driven by recent extreme climatic anomalies. *Philosophical Transactions of the Royal*

Society B: Biological Sciences, *373*(1760). https://doi.org/10.1098/RSTB.2017.0300

Johnsingh, A.J.T. & Joshua, J. (1994). Conserving Rajaji and Corbett National Parks - the elephant as a flagship species. *Oryx*, 28(2)

Kayet, N., et al., (2016). Spatial impact of land use/land cover change on surface temperature distribution in Saranda Forest, Jharkhand. *Modeling Earth Systems and Environment*, *2*(3), 1–10. https://doi.org/10.1007/S40808-016-0159-X

Kirilenko, A. P., & Sedjo, R. A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Sciences*, *104*(50), 19697–19702. https://doi.org/10.1073/PNAS.0701424104

Kleinschroth, F., & Healey, J. R. (2017). Impacts of logging roads on tropical forests. *Biotropica*, *49*(5), 620–635. https://doi.org/10.1111/BTP.12462

Kosanic, A., et al., (2019). Climate change and climate change velocity analysis across Germany. *Scientific Reports*, *9*(1), 2196. https://doi.org/10.1038/s41598-019-38720-6

Kumar, D., & Scheiter, S. (2019). Biome diversity in South Asia - How can we improve vegetation models to understand global change impact at regional level? *Science of The Total Environment*, *671*, 1001–1016. https://doi.org/10.1016/J.SCITOTENV.2019.03.251

Kundu, S. S., et al., (2015). Shifting Cultivation Dynamics in Barak Basin of Northeast India: A geospatial approach. *International Journal of Advancement in Earth and Environmental Sciences* 3 (2), 21-29

Kweka, E. J., Kimaro, E. E., & Munga, S. (2016). Effect of Deforestation and Land Use Changes on Mosquito Productivity and Development in Western Kenya Highlands: Implication for Malaria Risk. *Frontiers in Public Health*, *0*, 238. https://doi.org/10.3389/FPUBH.2016.00238

Kumar, M., et al., (2018). Dynamic forest vegetation models for predicting impacts of climate change on forests: An Indian perspective. *Indian Journal of Forestry*, 41(1), 1-12

Lambin, E. F., et al., (2001). The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change*, *11*, 261–269.

Larsen, T. H. (2012). Upslope Range Shifts of Andean Dung Beetles in Response to Deforestation: Compounding and Confounding Effects of Microclimatic Change. *Biotropica*, *44*(1), 82–89. https://doi.org/10.1111/J.1744-7429.2011.00768.X

Laurance, W. F. (2003). Slow burn: the insidious effects of surface fires on tropical forests. *Trends in Ecology & Evolution*, *18*(5), 209–212. https://doi.org/10.1016/S0169-5347(03)00064-8

Laurance, W. F. (2007). Forest destruction in tropical Asia. *Current Science*, *93*(11), 1544–1550. Retrieved from http://www.jstor.org/stable/24099083

Laurance, W. F. (2013). Emerging Threats to Tropical Forests. *Treetops at Risk: Challenges of Global Canopy Ecology and Conservation*, 71–79. https://doi.org/10.1007/978-1-4614-7161-5_5

Lawrence, D., & Vandecar, K. (2014). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, *5*(1), 27–36. https://doi.org/10.1038/nclimate2430

Lecina-Diaz, J. et al., (2020). Characterising forest vulnerability and risk to climate-change hazards. *Frontiers in Ecology and the Environment*, 19(2), 126-133

Lei, Y., Zhang, H., Chen, F., & Zhang, L. (2016). How rural land use management facilitates drought risk adaptation in a changing climate — A case study in arid northern China. *Science of The Total Environment*, *550*, 192–199. https://doi.org/10.1016/J.SCITOTENV.2016.01.098

Leite-Filho, A. T., et al., (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications*, *12*(1), 1–7. https://doi.org/10.1038/s41467-021-22840-7

Lele, N., & Joshi, P. K. (2009). Analyzing deforestation rates, spatial forest cover changes and identifying critical areas of forest cover changes in North-East India during 1972–1999. *Environmental Monitoring and Assessment*, *156*(1–4), 159–170. https://doi.org/10.1007/s10661-008-0472-6

Lenoir, J., et al., (2020). Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, *4*(8), 1044–1059. https://doi.org/10.1038/s41559-020-1198-2

Lewis, S. L., Edwards, D. P., & Galbraith, D. (2015). Increasing human dominance of tropical forests. *Science*, 349(6250), 827-832. https://doi.org/10.1126/science.aaa9932

Li, Y., et al., (2016). The role of spatial scale and background climate in the latitudinal temperature response to deforestation. *Earth System Dynamics*, *7*(1), 167–181. https://doi.org/10.5194/ESD-7-167-2016

Libonati, R., et al., (2021). Twenty-first century droughts have not increasingly exacerbated fire season severity in the Brazilian Amazon. *Scientific Reports*, *11*(1), 1–13. https://doi.org/10.1038/s41598-021-82158-8

Lima, D. F., et al., (2021). Phenological responses to climate change based on a hundred years of herbarium collections of tropical Melastomataceae. *PLoS ONE*, *16*(5). https://doi.org/10.1371/journal.pone.0251360

Liu, et al., (2018). How does habitat fragmentation affect the biodiversity and ecosystem functioning relationship? *Landscape Ecology*, *33*(3), 341–352. https://doi.org/10.1007/S10980-018-0620-5

Liu, et al., (2017). Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño. *Science*, *358*(6360). https://doi.org/10.1126/SCIENCE.AAM5690

Loarie, S. R., et al., (2009). The velocity of climate change. *Nature*, 462(7276), 1052–1055. https://doi.org/10.1038/nature08649

Longo, M., et al., (2020). Impacts of Degradation on Water, Energy, and Carbon Cycling of the Amazon Tropical Forests. *Journal of Geophysical Research: Biogeosciences*, 125(8), e2020JG005677. https://doi.org/10.1029/2020JG005677

Luther, D., et al., (2020). Global assessment of critical forest and landscape restoration needs for threatened terrestrial vertebrate species. *Global Ecology and Conservation*, 24, e01359. https://doi.org/10.1016/J.GECCO.2020.E01359

Manchego, C. E., et al., (2017). Climate change versus deforestation: Implications for tree species distribution in the dry forests of southern Ecuador. *PLoS ONE*, *12*(12). https://doi.org/10.1371/JOURNAL.PONE.0190092

Mantyka-Pringle, C., et al., (2019). Antagonistic, synergistic and direct effects of land use and climate on Prairie wetland ecosystems: Ghosts of the past or present? *Diversity and Distributions*, 25(12), 1924–1940. https://doi.org/10.1111/DDI.12990

Mantyka-pringle, C. S., Martin, T. G., & Rhodes, J. R. (2012). Interactions between climate and habitat loss effects on biodiversity: A systematic review and meta-analysis. *Global Change Biology*, 18(4), 1239-1252. https://doi.org/10.1111/j.1365-2486.2011.02593.x

Mantyka-Pringle, C. S., et al.,. (2015). Climate change modifies risk of global biodiversity loss due to land-cover change. *Biological Conservation*, 187. https://doi.org/10.1016/j.biocon.2015.04.016

Manzoor, S. A., Griffiths, G., & Lukac, M. (2021). Land use and climate change interaction triggers contrasting trajectories of biological invasion. *Ecological Indicators*, 120, 106936. https://doi.org/10.1016/J.ECOLIND.2020.106936

McDowell, N., et al., (2018). Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, 219(3), 851-869. https://doi.org/10.1111/nph.15027

McDowell, N. G. (2018). Deriving pattern from complexity in the processes underlying tropical forest drought impacts. *New Phytologist*, 219(3), 841–844. https://doi.org/10.1111/nph.15341

Meir, P., et al., (2018). Short-term effects of drought on tropical forest do not fully predict impacts of repeated or long-term drought: gas exchange versus growth. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760). https://doi.org/10.1098/RSTB.2017.0311

Mina, M., et al., (2017). Future ecosystem services from European mountain forests under climate change. *Journal of Applied Ecology*, *54*(2), 389–401. https://doi.org/10.1111/1365-2664.12772

Mishra, A. K. (2019). Quantifying the impact of global warming on precipitation patterns in India. *Meteorological Applications*, 26(1), 153-160. https://doi.org/10.1002/met.1749

Moffette, F., et al. (2021). The impact of near-real-time deforestation alerts across the tropics. *Nature Climate Change* **11,** 172–178

Morueta-Holme, N., et al.,. (2015). Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt. *Proceedings of the National Academy of Sciences*, 112(41), 12741–12745. https://doi.org/10.1073/PNAS.1509938112

Nathan, R., et al., (2011). Spread of North American wind-dispersed trees in future environments. *Ecology Letters*, *14*(3), 211–219. https://doi.org/10.1111/J.1461-0248.2010.01573.X

Nayak, S., et al., (2021). Influence of the Changes in Land-Use and Land Cover on Temperature over Northern and North-Eastern India. *Land*, *10*(1), 52. https://doi.org/10.3390/LAND10010052

Nepstad, D. C., et al., (2007). Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology*, *88*(9), 2259–2269. https://doi.org/10.1890/06-1046.1

Newbold, T. (2018). Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1881). https://doi.org/10.6084/m9

Newbold, T., et al., (2019). Climate and land-use change homogenise terrestrial biodiversity, with consequences 1 for ecosystem functioning and human well-being 2 3. *Emerging Topics in Life Sciences*, *3*(2), 207–219. Retrieved from https://bit.ly/2ssbjWu.

Newbold, T., et al., (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science*, *353*(6296), 288–291. https://doi.org/10.1126/science.aaf2201

Newbold, T., et al., (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*(7545), 45–50. https://doi.org/10.1038/nature14324

Newbold, T., et al., (2020). Tropical and Mediterranean biodiversity is disproportionately sensitive to land-use and climate change. *Nature Ecology & Evolution*, *4*(12), 1630–1638. https://doi.org/10.1038/s41559-020-01303-0

Ninan, K.N. & Kontoleon, A., (2016). Valuing forest ecosystem services and disservices - case study of a protected area in India. *Ecosystem Services*, 20, 1-14.

Niyogi, D., et al., (2018). The Impact of Land Cover and Land Use Change on the Indian Monsoon Region Hydroclimate. In: Vadrevu, K., Ohara, T., Justice, C. (eds) Land-Atmospheric Research Applications in South and Southeast Asia. Springer Remote Sensing/Photogrammetry. Springer, Cham. https://doi.org/10.1007/978-3-319-67474-2_25

Nobre, C. A., et al., (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences*, *113*(39), 10759–10768. https://doi.org/10.1073/PNAS.1605516113

Northrup, J. M., et al., (2019). Synergistic effects of climate and land-use change influence broad-scale avian population declines. *Global Change Biology*, *25*(5), 1561–1575. https://doi.org/10.1111/GCB.14571

Oliver, I., et al.,. (2016). Additive and synergistic effects of land cover, land use and climate on insect biodiversity. *Landscape Ecology*, 31, 2415-2431. https://doi.org/10.1007/s10980-016-0411-9

Oliver, T. H., et al., (2017). Large extents of intensive land use limit community reorganization during climate warming. *Global Change Biology*, *23*(6). https://doi.org/10.1111/gcb.13587

Oliver, T. H., & Morecroft, M. D. (2014). Interactions between climate change and land use change on biodiversity: Attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, 5(3), 317-335. https://doi.org/10.1002/wcc.271

Ordway, E. M., & Asner, G. P. (2020). Carbon declines along tropical forest edges correspond to heterogeneous effects on canopy structure and function. *Proceedings of the National Academy of Sciences*, *117*(14), 7863–7870. https://doi.org/10.1073/PNAS.1914420117

Orr, J. A., et al., (2020). Towards a unified study of multiple stressors: divisions and common goals across research disciplines. *Proceedings of the Royal Society B*, *287*(1926). https://doi.org/10.1098/RSPB.2020.0421

Ostberg, S., et al., (2015). Three centuries of dual pressure from land use and climate change on the biosphere. *Environmental Research Letters*, 10(4). https://doi.org/10.1088/1748-9326/10/4/044011

Ovenden, T. S., et al., (2021). Life after recovery: Increased resolution of forest resilience assessment sheds new light on post-drought compensatory growth and recovery dynamics. *Journal of Ecology*, 109(9), 3157-3170. https://doi.org/10.1111/1365-2745.13576

Padalia, H., et al., (2019). Assessment of historical forest cover loss and fragmentation in Asian elephant ranges in India. *Environmental Monitoring and Assessment*, *191(802)*. https://doi.org/10.1007/s10661-019-7696-5

Patz, J. A., et al., (2008). Disease Emergence from Global Climate and Land Use Change. *Medical Clinics of North America*, *92*(6), 1473–1491. https://doi.org/10.1016/J.MCNA.2008.07.007

Paul, S., et al., (2018). Moisture Supply From the Western Ghats Forests to Water Deficit East Coast of India. *Geophysical Research Letters*, *45*(9), 4337–4344. https://doi.org/10.1029/2018GL078198

Pautasso, M. (2012). Observed impacts of climate change on terrestrial birds in Europe: An overview. *Italian Journal of Zoology*, 79(2), 296-314. https://doi.org/10.1080/11250003.2011.627381

Pecl, G. T., et al., (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, *355*(6332). https://doi.org/10.1126/science.aai9214

Phillips, O. L., et al., (2010). Drought–mortality relationships for tropical forests. *New Phytologist*, *187*(3), 631–646. https://doi.org/10.1111/J.1469-8137.2010.03359.X

Pulla, S., et al., (2015). Assessing the resilience of global seasonally dry tropical forests. *International Forestry Review*, *17*(2), 91–113. https://doi.org/10.1505/146554815815834796

Qie, L., et al., (2019). Drought cuts back regeneration in logged tropical forests. *Environmental Research Letters*, *14*(4), 045012. https://doi.org/10.1088/1748-9326/AB0783

Radchuk, V., et al., (2019). Adaptive responses of animals to climate change are most likely insufficient. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-10924-4

Ravindranath, N. H., et al., (2005). Impact of climate change on forests in India. *Current Science*, 90(3), 354-361. https://doi.org/10.2307/24091869

Ravindranath, N. H., et al., (2011). Climate change vulnerability profiles for North East india. *Current Science*, *101*(3), 384–394.

Reddy, S., Dutta, K., & Jha, C. S. (2013). Analysing the gross and net deforestation rates in India. *Current Science*, 105 (11), 1492-1500

Rehm, E. M. (2014). Rates of upslope shifts for tropical species depend on life history and dispersal mode. *Proceedings of the National Academy of Sciences*, *111*(17), E1676–E1676. https://doi.org/10.1073/PNAS.1403417111

Rifai, S. W., Li, S., & Malhi, Y. (2019). Coupling of El Niño events and long-term warming leads to pervasive climate extremes in the terrestrial tropics. *Environmental Research Letters*, *14*(10), 105002. https://doi.org/10.1088/1748-9326/AB402F

Riordan, E. C., et al., (2015). Threats of future climate change and land use to vulnerable tree species native to Southern California. *Environmental Conservation*, 42(2), 127-138. https://doi.org/10.1017/S0376892914000265

Robillard, C. M., et al., (2015). Facilitating climate-change-induced range shifts across continental land-use barriers. *Conservation Biology*, *29*(6), 1586–1595.

Roy, & Giriraj. (2008). Land Use and Land Cover Analysis in Indian Context. *Journal of Applied Sciences*, *8*(8), 1346–1353. https://doi.org/10.3923/jas.2008.1346.1353

Roy, P. S., et al., (2013). Forest Fragmentation in India. *Current Science*, *105*(6), 774–780.

Sandel, B., et al., (2011). The influence of Late Quaternary climate-change velocity on species endemism. *Science*, *334*(6056), 660–664. https://doi.org/10.1126/science.1210173

Schafer & Piggot (2018). Advancing understanding and prediction in multiple stressor research through a mechanistic basis for null models. *Global Change Biology*, 24, 1817-1836

Schleuning, M., et al., (2016). Ecological networks are more sensitive to plant than to animal extinction under climate change. *Nature Communications*, 7, 13965. https://doi.org/10.1038/ncomms13965

Schloss, C. A., Nuñez, T. A., & Lawler, J. J. (2012). Dispersal will limit ability of mammals to track climate change in the Western Hemisphere, *PNAS, 109*(22), 8606-8611. https://doi.org/10.1073/pnas.1116791109

Senior, R. A., Hill, J. K., & Edwards, D. P. (2019). Global loss of climate connectivity in tropical forests. *Nature Climate Change*, *9*(8), 623–626. https://doi.org/10.1038/s41558-019-0529-2

Sharma, J., et al., (2017). Vulnerability of Forests in India: A National Scale Assessment. *Environmental Management*, *60*(3), 544–553. https://doi.org/10.1007/s00267-017-0894-4

Sharma, S., & Mujumdar, P. (2017). Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India, *Nature Scientific Reports*, 7, 15582.

https://doi.org/10.1038/s41598-017-15896-3

Sharma, J. & Ravindranath, N.H., (2019). Applying IPCC 2014 framework for hazard-specific vulnerability assessment under climate change. *Environmental Research Communications*, 1(5)

Sharp, A. C., et al., (2019). Tropical logging and deforestation impacts multiple scales of weevil beta-diversity. *Biological Conservation*, *234*, 172–179. https://doi.org/10.1016/J.BIOCON.2019.03.024

Shi, G., Jiang, N., & Yao, L. (2018). Land Use and Cover Change during the Rapid Economic Growth Period from 1990 to 2010: A Case Study of Shanghai. *Sustainability*, *10*(2), 426. https://doi.org/10.3390/su10020426

Sirami, C., et al., (2017). Impacts of global change on species distributions: obstacles and solutions to integrate climate and land use. *Global Ecology and Biogeography*, *26*(4), 385–394. https://doi.org/10.1111/geb.12555

Sivakumar, M. V. K., Das, H. P., & Brunini, O. (2005). Impacts of Present and Future Climate Variability and Change on Agriculture and Forestry in the Arid and Semi-Arid Tropics. *Climatic Change*, *70*(1–2), 31–72. https://doi.org/10.1007/s10584-005-5937-9

Siyum, Z. G. (2020). Tropical dry forest dynamics in the context of climate change: syntheses of drivers, gaps, and management perspectives. *Ecological Processes*, *9*(1), 1–16. https://doi.org/10.1186/S13717-020-00229-6

Sodhi, N. S., & Brook, B. W. (2006). Southeast Asian biodiversity in crisis. Cambridge University Press.

Sodhi, N. S., et al., (2004). Southeast Asian biodiversity: an impending disaster. *Trends in Ecology & Evolution*, *19*(12), 654–660. https://doi.org/10.1016/J.TREE.2004.09.006

Song, X. P., et al., (2018). Global land change from 1982 to 2016. *Nature Letters*. 560, 639-643 https://doi.org/10.1038/s41586-018-0411-9

Spracklen, D. V., & Garcia-Carreras, L. (2015). The impact of Amazonian deforestation on Amazon basin rainfall. *Geophysical Research Letters*, *42*(21), 9546–9552. https://doi.org/10.1002/2015GL066063

Staal, A., et al., (2020). Feedback between drought and deforestation in the Amazon. *Environmental Research Letters*, *15*(4), 044024. https://doi.org/10.1088/1748-9326/AB738E

Sudhakar Reddy, C., et al., (2016). Quantification and monitoring of deforestation in India over eight decades (1930–2013). *Biodiversity and Conservation*, *25*(1), 93–116. https://doi.org/10.1007/s10531-015-1033-2

Sullivan, M. J. P., et al., (2020). Long-term thermal sensitivity of Earth's tropical forests. *Science*, *368*(6493), 869–874. https://doi.org/10.1126/SCIENCE.AAW7578

Sunderland, T., et al., (2015). Global dry forests: a prologue. *International Forestry Review*, *17*(2), 1–9. https://doi.org/10.1505/146554815815834813

Suresh, H. S., Dattaraja, H. S., & Sukumar, R. (2010). Relationship between annual rainfall and tree mortality in a tropical dry forest: Results of a 19-year study at Mudumalai, southern India. *Forest Ecology and Management*, *259*(4), 762–769. https://doi.org/10.1016/J.FORECO.2009.09.025

Tewksbury, J. J., Huey, R. B., & Deutsch, C. A. (2008). Putting the heat on tropical animals. *Science*, 320(5881), 1296-1297.

Thang, T. H., Thu, A. M., & Chen, J. (2020). Tree species of tropical and temperate lineages in a tropical Asian montane forest show different range dynamics in response to climate change. *Global Ecology and Conservation*, *22*, e00973. https://doi.org/10.1016/J.GECCO.2020.E00973

Tropek, R. et al. (2014). Comment on "High-resolution global maps of 21st Century forest cover change". Technical comment. *Science*, 344 (6187), 981.

Turubanova, S., et al., (2018). Ongoing primary forest loss in Brazil, Democratic Republic of the Congo, and Indonesia. *Environmental Research Letters*, *13*(7), 074028. https://doi.org/10.1088/1748-9326/AACD1C

UNDP (2012). *Mainstreaming conservation and sustainable use of medicinal plant diversity in three Indian states: project profile of Uttarakhand.* Accessible at https://www.undp.org/india/publications/mainstreaming-conservation-and-sustainable-use-medicinal-plant-diversity-three-indian-states-project-profile-uttarakhand

Venter, O., et al., (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications*, *7*(1), 1–11. https://doi.org/10.1038/ncomms12558

Wani, A. A., et al., (2012). Carbon Sequestration Potential of Indian Forestry Land Use Systems-A Review. *Nature and Science*, 10(12).

Watson, J. E. M. (2014). Human responses to climate change will seriously impact biodiversity conservation: It's time we start planning for them. *Conservation Letters*, 7(1), 1-2. https://doi.org/10.1111/conl.12083

Weiskopf, S. R., et al., (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of the Total Environment*, 733, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

Wilson, M. C., et al., (2015). Habitat fragmentation and biodiversity conservation: key findings and future challenges. *Landscape Ecology*, *31*(2), 219–227. https://doi.org/10.1007/S10980-015-0312-3

Wright, M.,(2001). Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature*, *414*(6859), 65–69. https://doi.org/10.1038/35102054

Wright, S. J. (2010). The future of tropical forests. *Annals of the New York Academy of Sciences*, 1195(1), 1-27

Yadav, R. K., & Yadav, A. S. (2008). Phenology of selected woody species in a tropical dry deciduous forest in Rajasthan, India. *Tropical Ecology*, *49*(1), 25–34.

Yang, J., et al., (2018). Amazon drought and forest response: Largely reduced forest photosynthesis but slightly increased canopy greenness during the extreme drought of 2015/2016. *Global Change Biology*, *24*(5), 1919–1934. https://doi.org/10.1111/GCB.14056

Ye, X., et al., (2018). Impacts of future climate and land cover changes on threatened mammals in the semi-arid Chinese Altai Mountains. *Science of the Total Environment*, 612, 775-787. https://doi.org/10.1016/j.scitotenv.2017.08.191

Young, H. S., et al., (2017). Interacting effects of land use and climate on rodent-borne pathogens in central Kenya. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1722). https://doi.org/10.1098/RSTB.2016.0116

Zaveri, E., Russ, J., & Damania, R. (2020). Rainfall anomalies are a significant driver of cropland expansion. *Proceedings of the National Academy of Sciences*, *117*(19), 10225–10233. https://doi.org/10.1073/PNAS.1910719117

Zhang, W., et al., (2018). Multidecadal, county-level analysis of the effects of land use, Bt cotton, and weather on cotton pests in China. *Proceedings of the National Academy of Sciences*, *115*(33), E7700–E7709. https://doi.org/10.1073/PNAS.1721436115

Zhou, X., et al.,. (2013). An imperative need for global change research in tropical forests. *Tree Physiology*, *33*(9), 903–912. https://doi.org/10.1093/TREEPHYS/TPT064

Zhu, K., Woodall, C. W., & Clark, J. S. (2012). Failure to migrate: lack of tree range expansion in response to climate change. *Global Change Biology*, *18*(3), 1042–1052. https://doi.org/10.1111/J.1365-2486.2011.02571.X

Chapter 2: Determining the role of climate change in India’s past forest loss

Nohsngithiang Falls in the East Khasi Hills district, Meghalaya. The most populous district in Meghalaya, with a large area of tropical and subtropical broadleaved forest. It is one of the wettest places on Earth.

Source: @twobirdsbreakingfree/instagram.com

2.1 Abstract

Tropical forests in India have declined at an alarming rate, with extensive literature focusing on the high contributions of agricultural expansions to deforestation, while the effects of climate change have largely been overlooked. Climate change effects, such as increasing temperatures, drought and flooding have already occurred, and are projected to worsen. Climate velocity, a metric that accounts for spatial heterogeneity in climate, can help identify contiguous areas under greater climate stress and potential climate refuges in addition to traditional temporal trends. Here, we examined the relative contribution of climate changes to forest loss in India during the period 2001-2018, at two spatial (regional and national) and two temporal (seasonal and annual) scales. This includes, for the first time, a characterisation of climate velocity in the country. Our findings show that annual forest loss increased substantially over the 17 years, with the majority of forest loss occurring in the Northeast region. Decreases in temporal trends of temperature and precipitation were most associated with forest losses but there was large spatial and seasonal variation in the relationship. In every region except the Northeast, forest losses were correlated with faster velocities of at least one climate variable but overlapping areas of high velocities were rare. Our findings indicate that climate changes have played an important role in India's past forest loss, but likely remain secondary to other factors at present. We stress concern for climates velocities recorded in the country, reaching 97km yr^{-1}, and highlight that understanding the different regional and seasonal relationships between climatic conditions and forest distributions will be key to effective protection of the country's remaining forests as climate change accelerates.

2.2 Introduction

Forests are being destroyed at an alarming rate globally (Hansen et al., 2001; Haddad et al., 2015; Song et al., 2018; FAO & UNEP 2020), despite their importance for human wellbeing and the maintenance of planetary ecosystems. Tropical forests, home to a disproportionate amount of the world's biodiversity, are experiencing some of the largest declines (Hansen et al., 2013; Song et al., 2018; IPBES, 2019; França et al., 2020). Land use change is the leading cause of forest declines worldwide (Ostberg et al., 2015; Choe and Thorne, 2017; FAO & UNEP, 2020; WWF, 2020) with recent estimates suggesting that only 24% of tropical forests are still intact (Lewis, Edwards, & Galbraith, 2015). In addition, there is increasing concern regarding the impacts of climate change, with research suggesting that its effects are already eclipsing those of land use change on 60% of the global land surface (Ostberg et al., 2015). Though this is not yet the case in tropical forests, the contribution of climate change effects in tropical forests is increasing (Ostberg et al., 2015; IPCC, 2019; WWF, 2020). Despite this, research into its effects on forest loss are limited, particularly in the tropics.

Impacts of climate change are often largely dependent on geographic location and interactions between climate variables (Allen et al., 2010; Brito-Morales et al., 2018; Maracchi, Sirotenko, & Bindi, 2005) but have been shown to both positively and negatively affect forest growth, mortality, productivity and distribution, alongside impacting the capability to deal with other stressors like drought and fire (IPCC, 2019; Ovenden et al., 2021). Temperature increases are by far the most commonly studied climate driver of forest mortality (Chen et al., 2011; Seidl et al., 2017; Heikkinen et al., 2020; Maringer et al. 2021) and have been shown to directly impact forest distribution and growth (Garcia et al., 2014; Lenoir and Svenning, 2015). Changes in precipitation have also been shown to affect forest survival, most commonly precipitation decreases (Aiba & Kitayama, 2002; Bennett et al., 2015; Chen et al.,, 2017; Phillips et al., 2009; Taccoen et al., 2019; Zhang et al., 2017), but the relationships are often complex, and can be highly dependent on regional and seasonal changes (Bateman et al., 2016; Seidl et al., 2017), forest type, previous conditions, and phenotypical adaptations of species (Das et al., 2013; Greenwood et al., 2017; McDowell, 2018). Tree mortality from climate change is often linked to drought induced hydraulic failure (McDowell et al., 2018) but indirect effects such as increased forest susceptibility to pests and diseases (Lindner et al., 2010; Seidl et al., 2017; Stralberg et al., 2015), contributing to human decisions surrounding land use change and resource extraction (IPBES, 2018), among other pathways, also occur. There is also some evidence to suggest that even climate changes that support tree growth, through increased CO_2 fertilisation and light exposure, can lead to mortality, as increased growth can result in greater competition for resources (Huete et al., 2006; McDowell et al., 2018; Saleska et al., 2007).

Typically, studies assess the risk of temporal trends in climate variables, but the spatial heterogeneity of climate in the area where a species is found can also be important in species survival under climate change. Climate velocity (Loarie et al., 2009) is a metric that encompasses the spatial heterogeneity in climate in the surrounding area. The creators of the first climate velocity metric, Loarie et al., (2009) and others since, theorised that areas where climate is changing quickly, and similar climates are further away, will be at greater risk to climate change (García Molinos et al., 2019; Garcia et al., 2014; Hamann et al., 2015; Loarie et al., 2009). The metric provides an additional dimension to climate risk, and subsequently high velocities have been linked to reductions and redistributions in small-ranged species (Sandel *et al.*, 2011), marine taxa (García Molinos et al., 2016), birds (Bateman et al., 2016) and trees (Bateman et al., 2016; Liang et al.,, 2018; Nadeau & Fuller, 2015; Sandel et al., 2011), and areas of low velocities have been hailed potential climate refuges (Brito-Morales *et al.*, 2018; Heikkinen *et al.*, 2020).

Due to the complexities of the metric there have been some criticisms of its usefulness and confusion over the conclusions that can be drawn from it (Dobrowski & Parks, 2016; Hamann et al., 2015). However, equally when used appropriately, climate velocity estimates may be an important component for identifying areas most at risk to the effects of climate change, providing a dimension that temporal trends cannot (Loarie et al., 2009; Garcia et al., 2014; Heikkinen et al., 2020).

Currently there is a strong bias in the literature of climate-forest systems towards northern temperate regions, particularly for velocity studies, and less is known about the relationship in the tropics (Lenoir and Svenning, 2015; Seidl et al., 2017; Brito-Morales et al., 2018; França, et al., 2020). Drawing conclusions about the effect of climate change in tropical regions is often more complex that the temperate counterparts, in part due to a large variety of forest types, adaptations and microclimates, and a lower availability of high quality data (McDowell, 2018). In the past, many studies have focused on Amazonia (Giardina et al., 2018; Huete et al., 2006; Nepstad et al., 2007; Saleska et al., 2007), where deforestation rates are the highest, but evidence suggests that responses across tropical regions may be highly diverse (Asner et al., 2010; McDowell, 2018; Wagner et al., 2014).

India is in the top ten countries in the world for forest cover (FAO & UNEP, 2020). Forests, primarily tropical and sub-tropical, cover 20% of the country's land mass (Ravindranath et al., 2005). It is one of the most biodiverse countries in the world, representing 11% of the world's flora and encompassing four biodiversity hotspots (Chitale et al., 2014) (Figure S8). The country has experienced large-scale forest loss for decades, which has been extensively studied, with land use changes largely cited as the major cause of forest declines (Jha et al., 2000; Lele et al., 2009; Reddy et al., 2013; Roy et al., 2013). Increased demand for crop productions, commercial livestock rearing, timber extraction, rapidly increasing populations and an emerging economy, are all known to be putting high pressure on forests, alongside cultural practices of shifting cultivation (Lele & Joshi, 2009; Wani et al., 2012). Large proportions of the population directly rely on forests for their survival and livelihoods, and in particular, fuelwood and fodder collection are major sources of domestic energy and income for tens of thousands of villages (Roy et al., 2013; Sharma et al., 2015). Whereas the effect of land use changes on forest loss have been a key focus in the literature in the past (Davidar et al., 2010; Gupta, 2007; Lele & Joshi, 2009; Roy et al., 2013), there has been little focus on the potential role of climate change. Ascertaining climate's role in the country's past forest loss could help predict the future stability of forests in the face of increasing change, as well as aiding effective management strategies for current forest conservation. Due to the unique variation in climate driven by two monsoon systems (Krishnan et al., 2020), India is likely to experience a range of different climate changes and is therefore an ideal country to study the effects of climate change, including velocity, on tropical forest systems.

Climate change in India has been evident for many years and numerous studies have described a consistent pattern of warming (Dash et al., 2011; Mishra, 2019; Rao et al., 2016; Ravindranath et al., 2011; Rupa Kumar et al., 2006), more frequent high-intensity rain events, higher maximum temperatures (Krishnan et al., 2020), warmer winters and a lower confidence in the timing of the monsoon which is critical for India's agricultural-driven economy (Dash et al., 2011; Ravindranath et al., 2011). Research that focuses on the relationship between climate change and forest loss in India, has almost always analysed the potential threats of *future* climate change on forests through global vegetation models (Brown & Pearce, 1994; Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Kumar et al., 2018; Ravindranath et al., 2005; Sharma et al., 2017; Upgupta et al., 2015), but none so far have considered velocity. Existing studies have predicted climate change to have strong influences on forest cover, consistently predicting a shift to wetter forest types and a loss of drier forest types in response to a generally warmer and wetter climate in the future, noting precipitation thresholds to be particularly important (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Ravindranath et al., 2005; Ravindranath & Sukumar, 1998). Some regions are predicted to gain forests, whilst others, to lose forest (Chaturvedi et al., 2011; Ravindranath et al., 2005). Areas of highest vulnerability are those with projected increases in temperature but decreases in precipitation (Chaturvedi et al., 2011). Past research has generally predicted the Himalayan forests, northern Western Ghats and North-western regions to be most at risk to climate change effects due to a combination of forest intactness, forest type, and climate change exposure (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Upgupta et al., 2015). Whereas, forests in the north-eastern region and southern Western Ghats are expected to be less vulnerable due to being predominantly composed of tropical moist forests which are likely to expand in range, alongside higher levels of intactness and species richness (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Ravindranath et al., 2005).

While these projections provide useful foresight into potential at-risk areas, there is a clear gap in our understanding of the distribution of climatic effects in areas of high forest loss in the past which could help inform future predictions. Additionally, mapping and analysing the distribution in climate velocity in a country could be crucial for conservation strategies to support in-situ adaptation, by limiting other stressors, considering potential strategies for relocating or aiding limited dispersal to less affected areas.

This study aims to characterise the relationship between climate change and India's past forest loss and explores the relative importance of drivers other than the well-documented effects of land use change. It aims to map and analyse climate velocities in India for the first time, and critically assess the usefulness of this metric in providing additional understanding of risks to forests in India. Given current evidence, we expect climate changes, such as declining precipitation and temperature increases, to be correlated with areas of high forest loss but expect considerable seasonal and regional variation due to the diversity in climate and geography across the country, which we account for in our methodology. In terms of climate velocity, though previous analyses have been largely confined to higher latitude studies, evidence from these and coarser-scale global analyses lead us to expect forest loss will be greater in areas of higher climate velocity where forests are more exposed to faster changes in climate or where high velocities of multiple variables overlaps.

The key questions addressed in this manuscript are:

1. Has climate change contributed to forest loss in India between 2001-2018?
2. Are there seasonal and regional variations in the climate-forest loss relationship in the country?
3. Are Indian forests exposed to high and/or overlapping climate velocities and is forest loss greater in these areas?
4. Can climate velocity provide additional understanding of forest's risk to climate change?

2.3 Methods

2.3.1 Forest Loss

Records of annual forest loss were obtained from the Hansen Global Forest Change v1.6 dataset (GFC) (Hansen et al., 2013) for the period 2001-2018 at a spatial resolution of ~30m, within the Google Earth Engine interface (Gorelick, et al., 2017). The GFC data takes the form of a binary record of loss (1) or no loss (0) for each pixel in the area of interest and records all trees above 5m in height. District level totals of forest loss (km²) were generated and subsequently analysed in RStudio (version 3.6.2). Any districts with less than a total of 0.1km² forest cover were excluded to avoid any noise in the Hansen GFC data. This resulted in a total of 13 districts (of 577) being excluded from the analyses, predominantly from the arid and xeric shrubland regions of the Northwest (Supplementary Table S1). In addition to those removed for low levels of forest cover, island union territories were excluded due to potential differences between island and land mass effects of climate in addition to concern over the accuracy of the datasets used on small island states.

2.3.2 Climate data

Global raster datasets of total monthly precipitation (mm) and monthly mean temperature (°C) from the Climate Research Unit (CRU TS v. 4.03) were obtained at 0.5 x 0.5 degree resolution (~112km^2), covering the years 2001-2018. The selected period was chosen to align with the availability of GFC data. Climate datasets were averaged to create a data point for each district. Regional datasets were also created by compiling districts belonging to each of the six monsoon regions outlined by the Indian Institute of Tropical Meteorology (www.tropmet.res.in); Northeast (NE), Northwest (NW), Central Northwest (CNE), West Central (WC), Peninsular (PEN), and Hilly region, composed of the East Hilly Region (EHR) and the West Hilly Region (WHR) (Figure S1). The monthly data was aggregated to create a dataset of total annual precipitation by calculating, for each raster cell in each year, the sum of the monthly values. Mean annual temperatures were then created by averaging a cells value across all months.

For the seasonal analysis, data was collated from the monthly climate rasters and averages of mean temperature and total precipitation calculated for each season at both national and regional spatial scales. The seasons are those used by the Indian Meteorological Department (http://www.imdpune.gov.in/Weather/Reports/glossary.pdf) and most commonly found in the literature for national scale studies of India. These were monsoon (June-September), post-monsoon (October-December), winter (January-February), and pre-monsoon (March-May). It is important to note that, despite these being the standard national seasons, the climate of each season varies considerably by region (Figure S2, S3).

2.3.3 Calculating climate velocity

Gradient-based climate velocity was calculated in R using the gVoCC package and the integrated functions; SpatGrad and TempTrend following the methodology for local climate velocity outlined in García Molinos et al., (2019) and based off the original calculation by Loarie et al., (2009). The TempTrend function calculates the temporal trend by performing linear regressions of the variable against time for each individual cell. This was calculated for both the annual and seasonal averages. The temporal trends were used in the climate velocity metric but also as a separate variable in the models. The SpatGrad function calculates spatial gradients for each cell by determining the magnitude of the differences in the climate variable over its neighbouring (3x3) cells. In order to avoid the potential of infinite velocities caused by spatial gradients of zero (Hamann et al., 2015; Loarie et al., 2009), a value of 0.1 was added to all the data points. Climate velocity was then calculated by dividing the temporal trend by the spatial gradient. An average climate velocity for each variable was calculated per district by taking the mean magnitude from all the cells present in a district's boundary using the zonal statistics function in QGIS v3.8.2. Each district was an individual data point used in the models.

It is important to note that climate velocity can be both negative and positive - the direction of the effect is taken from the temporal trend, and it is the magnitude that relates to the velocity. So, a large negative precipitation velocity indicates a faster reduction in precipitation over time, and a large positive precipitation velocity indicates a faster increase in precipitation. Smaller velocities indicate slower changes. Therefore, positive relationships between forest loss and climate velocity could equally represent greater forest loss at faster positive velocities or slower negative velocities, whereas negative relationships represent greater forest loss at faster negative velocities or slower positive velocities.

2.3.4 Population density as a proxy for human pressures

Human pressures, particularly land use changes, are regularly cited as a primary cause of forest loss in India. To account for the effects of these, a proxy of population density was included as an explanatory variable (Cimatti et al., 2021; Kok, 2004; Milanesi et al, 2017). Population density has been shown to have a large effect on land use changes in India in the past, particularly relating to forest cover, agriculture and urban areas (Kale et al., 2016; Palchoudhuri et al., 2015). Whilst population density does not explicitly account for other human pressures such as infrastructure and demand for forest resources, and indices such as the 'Human Influence Index' (https://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-influence-index-geographic) may be better able to capture the breadth of human pressures, population density data is available on the temporal and spatial scale fitting this chapter whereas other indices are temporally and spatially limited. For example, the Human Influence Index has a temporal availability of 1995-2004 which would be too short for this analysis.

Data on population density (people per km^2) for the years 2000 and 2020 was obtained from SEDAC's GPWv4.11 dataset at a spatial resolution of 30 arc-seconds (~$1km^2$ at the equator). Population density change over the 20-year period was calculated on a cell by cell basis by subtracting the final year's values from the first year. Cells with positive values represented an increase in population density over time and cells with a negative value, a decrease. Mean values of population density change were calculated for each district from this cell level data. The data was only available in 5-year increments thus the years 2000 and 2020 were selected to match the forest loss data as closely as possible (Figure S4).

2.3.5 Modelling the impact of climate change on forest loss

Linear mixed-effects models were developed using the nlme package in R to assess the relationship of the climate variables on forest loss at both the national and regional level. Firstly, a null model comprising of the response variable (forest loss in km^2) and a random effect of the State (political boundary), was created as a basis for model generation. The state that the forest belonged to was considered to affect the level of forest loss due to the individual forest policies between states, subsequently districts in the same state are likely to be more similar.

Eight models were created in total: four at the national scale and four at the regional scale. Within these, two included temperature and precipitation velocity as the explanatory variable, with one using annual and the other using seasonal data. The second two models included the temporal trends of temperature and precipitation as the explanatory variables, again one using annual data and the other seasonal data. All models included population density change as an explanatory variable and state as a random effect. In all models, the explanatory variables were standardized to account for the large variation in scale and a gaussian spatial autocorrelation structure was used to account for spatial autocorrelation detected in the data (Moran's I $p<0.001$) which was shown to adequately account for the autocorrelation with a further Moran's I test on the model residuals (Moran's I $p>0.05$).

2.4 Results

2.4.1 National and regional trends in forest loss

Forest loss increased substantially during the study period (2001-2018), escalating from annual losses of 647km^2 to a peak of 2,503km^2 lost in 2017, shortly followed by a slight decline to ~1,900km^2 in 2018 (Figure S5). Over the course of the 2001-2018 study period, a total of 20,472km^2 of forest was lost, accounting for 7.34% of India's forest cover in 2001. The Northeast region contributed a significant proportion of the loss, in the last five years of the study losses here were over four times that of the other regions (Figure 1 & Figure S6). Three key areas of high forest losses were identified, these were; 1) the combined regions of the NE and EHR, 2) the nexus of the CNE, WC and PEN regions, and 3) a few districts in the northern Western Ghats (PEN region). All experienced losses greater than 20km^2 over the time period (Figure S8).

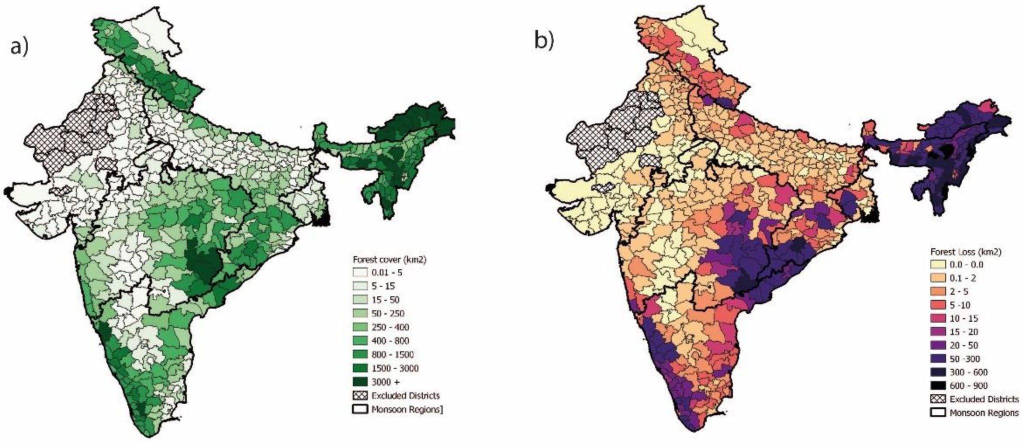


Figure 1| (a) Forest cover in km^2 of each district in India, Jammu and Kashmir, and Ladakh in the year 2000. (b) The total forest lost in each district between the years 2001-2018 in km^2. Much of the forest cover is located in the Northeast and along the east and southwestern coasts. Total forest loss is greatest in the Northeast, central west coast and southwestern areas, where forest cover is also high.

2.4.2 National and regional trends in climatic variables

Precipitation

Annual-based temporal trends showed increases in precipitation of ~5-10mm yr^{-1} for much of the country, with some notable exceptions in districts in the northeast and southern areas of the country (Figure 2). Annual trends were largely driven by substantial increases recorded in the monsoon season, and the remaining three seasons showed mean decreases in precipitation (Figure S10). The same trend was found for velocities, where at times monsoon velocities reached twice the speed of other seasons (Figure 3), while the other seasons were, on the whole, getting drier but at a slower rate. Annual velocities ranged from -13 – 34 km yr^{-1} (Table S2), with the fastest velocities found in districts bordering the WC and CNE regions. Seasonal velocities ranged from -97 – 41 km yr^{-1}. The fastest velocities were found in the pre-monsoon (-) and monsoon seasons (+). The NE and EHR experience the largest negative precipitation velocities (largely between -5 and -20 km yr^{-1}), showing a rapid drying trend. The most extreme velocity recorded in the study of -97.59 km yr^{-1} was located in the East Khasi Hills district of the NE region during the pre-monsoon season. Patterns of seasonal precipitation velocity were generally complex with many regions experiencing both positive and negative precipitation velocities at different points in the year (Figure 3).

Temperature

Based on annual temperature temporal trends, the majority of the country warmed at a rate around 0.025-0.050^{o}C yr^{-1}, with notable exceptions of some CNE and NE districts where temperature was cooling at the same rate (Figure 2). Seasonal analyses showed the fastest warming to be in the winter season where some districts exceeded increases of 0.051°C yr^{-1}. There were no occurrences of temperature reductions in the monsoon season. In all other seasons, there was a significant cooling patch in the CNE and NE regions, which was most expansive in the post-monsoon and winter seasons. Seasonal variation was greater for precipitation than temperature with many regions experiencing the same temperature trends year-round e.g., PEN and EHR regions experienced warming year round, reaching +0.045°C yr^{-1} at its fastest in the post-monsoon. Annual-based temperature velocities ranged between -0.321-0.298 km yr^{-1} (Table S2) and followed a similar patterning to the temporal trends. The monsoon season showed widespread warming, but the highest positive velocities rotated around the country throughout the year resulting in high but seasonal exposure to fast positive velocities in much of the North, West and South (Figure 4). The fastest negative velocities of -0.4 km yr^{-1} were located in the CNE and NE region. Temperature velocities were much slower than those recorded for precipitation.

2.4.3 The influence of spatial gradients on climatic trends

Spatial gradients differed between temperature and precipitation variables as well as between seasons, leading to a variety of differences in temporal trends and velocities between the two variables (Table S3). Patterning in velocities often matched those of their temporal trend counterparts, but velocity magnitudes were found to be greatly affected by spatial gradients. In some cases, trends were reversed due to the influence of spatial gradients. For example, a dampening of the negative pre-monsoon precipitation temporal trend in the NE due to a high spatial gradient alongside an exacerbation of a positive temporal trend in the southern CNE region led to a different relationship between pre-monsoon precipitation and forest loss in the temporal trend and velocity models. Effects of spatial gradients were more evident for precipitation than temperature which had lower spatial heterogeneity in climate. Spatial gradients of temperature did not exceed 0.4°C/km consistently resulting in velocities with higher values than temporal trends (spatial gradients >1 would result in smaller velocities).

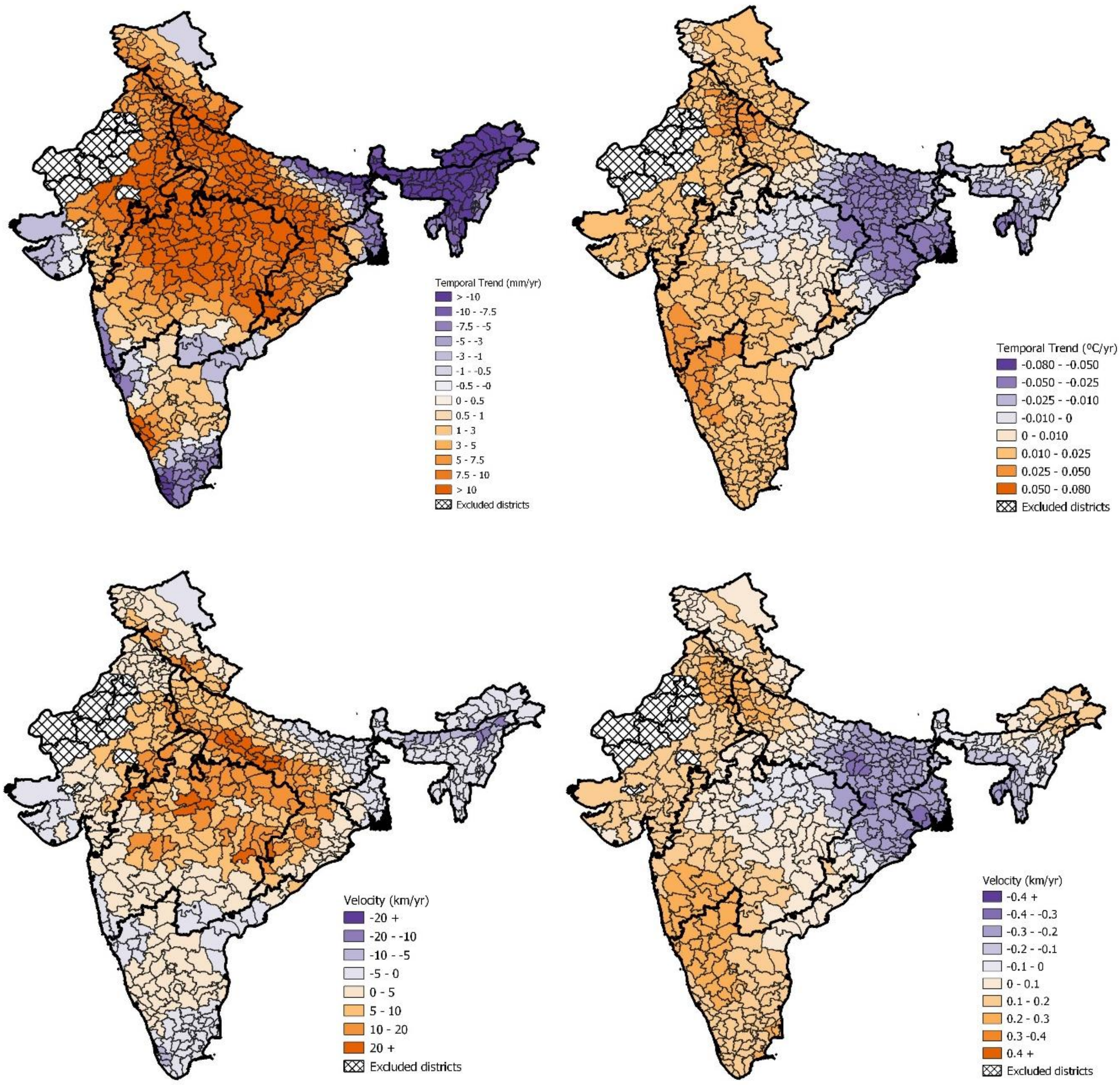


Figure 2| Annual based precipitation (top left image) and temperature temporal trends (top right) and precipitation (bottom left image) and temperature velocities (km yr^{-1}) (bottom right) across the districts of India, with the outlines of the monsoon regions. Hatched districts are those that have been excluded from the study.

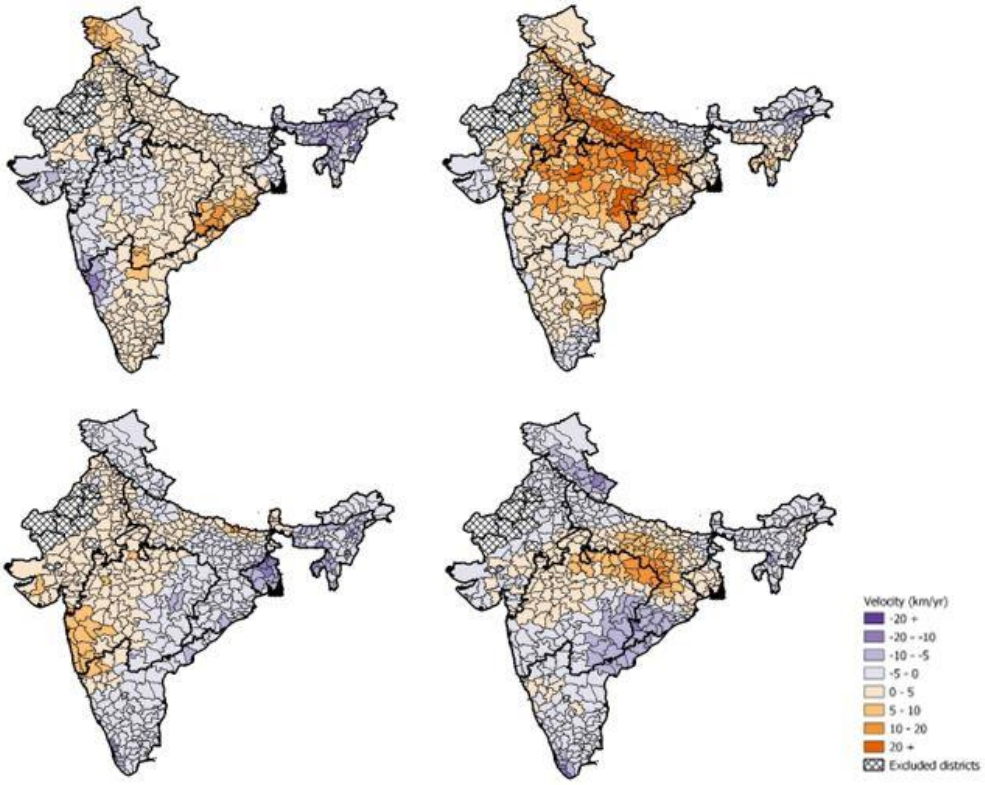


Figure 3 | Seasonal precipitation velocities in km yr^{-1} of each district for the time period 2001-2018. In a clockwise direction the seasons depicted are as follows: pre-monsoon, monsoon, post-monsoon and winter. The black outlines show the borders of the monsoon regions.

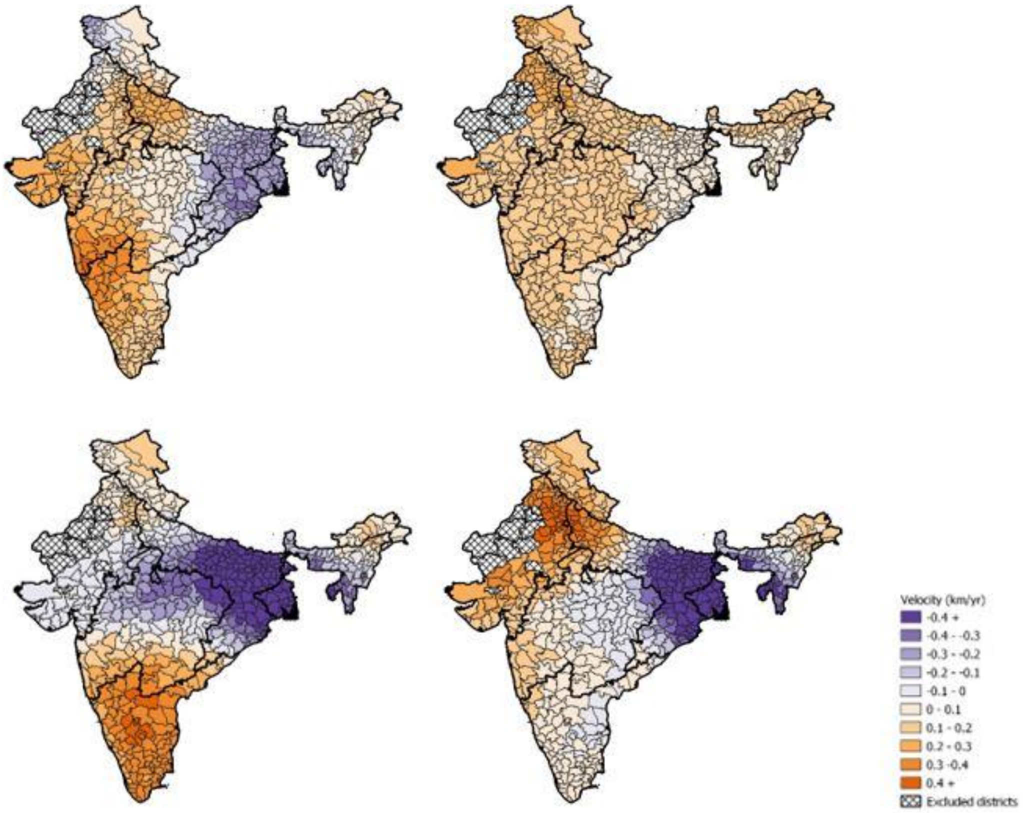


Figure 4| Seasonal temperature velocities in km yr^{-1} of each district for the time period 2001-2018. In a clockwise direction the seasons depicted are as follows: pre-monsoon, monsoon, post-monsoon and winter. The black outlines show the borders of the monsoon regions.

2.4.4 National models

At the national scale, there was no effect of annual-based climate change on forest loss. However, there was a significant effect from eight seasonal variables: velocities of monsoon (-) and winter temperatures (+), pre-monsoon (+) and winter precipitation (+), and temporal trends of monsoon (-), pre-monsoon (-) and winter temperatures (+) and pre-monsoon precipitation (-) (Table 1). Notably, the post-monsoon season was not a driver of forest loss at the national scale. For temperature, the negative effect direction seen in the models for the monsoon season relates to smaller increases in temperature since there were no decreases in temperature during this season.

In the regional models, climate was found to significantly affect forest loss in every region. Some regions were more affected than others, e.g., the Northwest region (Table 2 & 3), and each region had different compositions of climate trends that affected forest loss. The correlation between declines or lower values of monsoon temperatures and increases in forest losses was consistent across the models but other variables showed trends of both negative and positive effect directions depending on season and location.

Table 1 | National scale seasonal models of the effects of climate velocity and temporal trends on national forest loss, accounting for population density. The response variable tested in each model was forest loss (km^2). The explanatory variables were the eight seasonal climate variables and population density change between 2000-2020 (people per km^2).

Model	Significant fixed effect variables	Estimate	T	p
Seasonal velocity	Pre-monsoon precipitation	0.088	2.128	0.033
	Winter precipitation	-0.121	-2.225	0.026
	Monsoon temperature	-0.335	-4.007	<0.001
	Winter temperature	0.384	2.363	0.018
Seasonal temporal trends	Pre-monsoon precipitation	-0.251	-3.544	<0.001
	Pre-monsoon temperature	-0.341	-2.395	0.016
	Monsoon temperature	-0.383	-3.863	<0.001
	Winter temperature	0.507	3.027	0.002
	Population density change	-0.083	-2.381	0.017

Table 2| Regional scale seasonal models of the effects of climate velocities on regional forest loss accounting for population density. The response variable tested in each model was forest loss (km^2). The explanatory variables for each model were the precipitation velocity and temperature velocity of each of the four seasons (eight climate variables in total) and population density change between 2000-2020 (people per km^2).

Model	Significant fixed effect variables	Estimate	T	p
NE	No significant variables	NA	NA	NA
CNE	Pre-monsoon precipitation	0.831	5.438	<0.001
NW	Monsoon precipitation	0.295	2.414	0.018
	Monsoon temperature	-0.634	-3.267	0.001
	Post-monsoon temperature	0.674	3.258	0.001
WC	Post-monsoon temperature	0.670	2.279	0.024
PEN	Post-monsoon temperature	-0.463	-3.799	<0.001
Hilly	Post-monsoon precipitation	-0.589	-3.087	0.003
	Winter precipitation	0.571	3.565	0.001
	Monsoon temperature	-0.594	-2.553	0.014

Table 3| Regional scale seasonal models of the effects of climatic temporal trends on regional forest loss. The response variable tested in each model was forest loss (km^2). The explanatory variables for each model were the precipitation and temperature temporal trends of each of the four seasons (eight climate variables in total) and population density change between 2000-2020 (people per km^2).

Model	Significant fixed effect variables	Estimate	T	p
NE	Monsoon temperature	-0.626	-2.353	0.021
	Population density change	-0.242	-2.076	0.041
CNE	No significant variables	NA	NA	NA
NW	Pre-monsoon precipitation	0.588	2.706	0.008
	Monsoon precipitation	0.275	2.028	0.046
	Winter precipitation	-1.206	-3.153	0.002
	Pre-monsoon temperature	0.533	2.245	0.027
	Winter temperature	-0.639	-2.517	0.014
WC	Post-monsoon precipitation	-0.680	-2.96	0.003
PEN	Monsoon temperature	-0.542	-2.222	0.029
	Post-monsoon temperature	-0.459	-2.715	0.008
Hilly	No significant variables	NA	NA	NA

2.4.5 Population Density Change

Generally, population density increased across India during 2000-2020. Density changes ranged from -45 – 4,000 people per km^2, with an average increase of 200 people per km^2. The highest increases were found in the North of the country, mainly the Central North-Eastern region. Only eleven districts in the country experienced a reduction in population density during the period (Figure S4).

Population density change did not have a significant effect on forest loss in the annual-based national models, but there was a negative correlation between density change and forest loss in the seasonal models. In the regional models, there was also a significant negative correlation between population density change and forest loss in the Northeast region.

2.4.6 The extent of overlapping climate velocities

In addition to the velocities of temperature and precipitation being highly variable across the country and between seasons, they had very different spatial configurations. Overlaps between high (top 10% of values) velocities of precipitation and temperature were rare with only two instances occurring within high forest loss areas (Figure 5). The first, and largest, instance was in the Northern Western Ghats which experienced both high velocities of precipitation declines, and temperature increases during the pre-monsoon season. The second instance occurred in the NE region where high velocities of declining precipitation overlapped with high velocities of declining temperature during the post-monsoon season. In both the annual and winter data no overlaps of high velocity areas were recorded. Though overlaps were rare, many areas of high forest loss experience singular high velocities over the period.

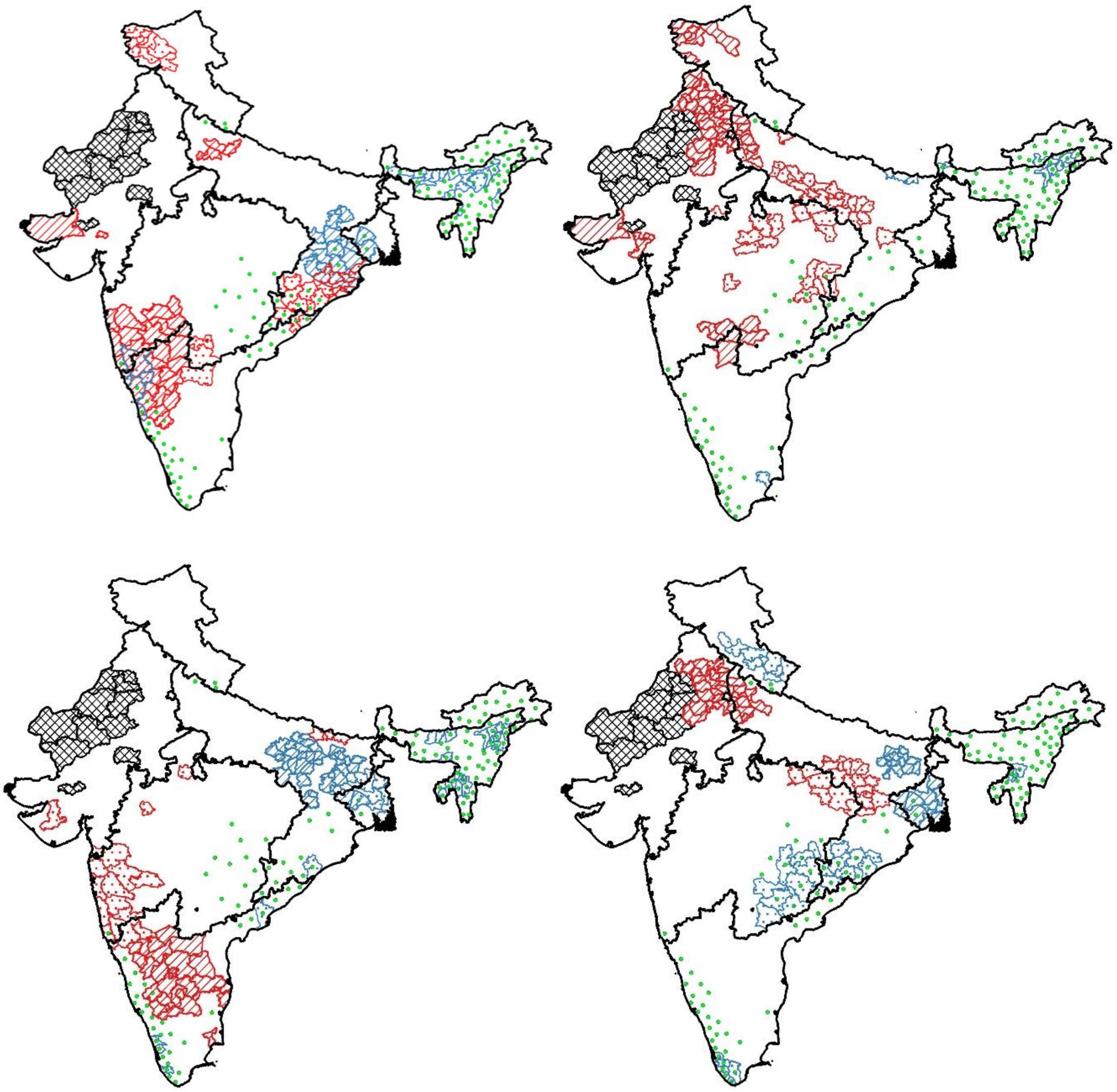


Figure 5| Overlaps between districts containing the 10% fastest climate velocities and the highest forest losses (>20km^2). Positive velocities are depicted in red and negative velocities depicted in blue. Hashed districts represent temperature velocities and dots represent precipitation. Districts with the highest levels of forest loss over the time period are shown in green. In a clockwise direction the seasons depicted are as follows: pre-monsoon, monsoon, post-monsoon and winter. The black outlines show the borders of the monsoon regions.

2.5 Discussion

This study indicates that climate change has played a significant role in India’s forest loss, a contribution that has previously been overlooked. This study highlights the complexities of climate change effects on forests in India, the emerging climatic trends that may cause risks to forests in the future and analyses the relevance of velocity metrics in tropical forest systems. Here, the findings are discussed in relation to the research questions.

Has climate change contributed to past forest loss in India?

Our analyses show that there are significant correlations between both temporal trends and velocities of climate variables with increased forest loss in India. Unexpectedly, and contrary to the literature, temperature decreases and slower warming were generally correlated with greater forest loss, despite much of the country warming up to 0.051°C yr^{-1} and given the known detrimental effects that warmer temperatures can pose to forests through drought stress (Bonan, 2008; Chaturvedi et al., 2011; Gopalakrishnan et al., 2011). Though the mechanism behind this relationship is unknown, as deforestation and encroachment have been prevalent in India for many years, much of the forest exists at higher elevations where temperatures tend to be cooler. The trend is also likely affected by high forest loss in the NE and CNE where there is an anomalous cooling patch, thought to be caused by a growing aerosol haze (Ross et al., 2018). Many studies contrastingly predict temperature increases in these regions and expect forests to be adept at coping with warming (Chaturvedi et al., 2011; Ravindranath et al., 2005), our research suggests a re-evaluation of the climate threats to forests in this region given the substantial cooling. Although cooler temperatures in the tropics are not thought to be a direct threat to forests, there is the potential for indirect effects caused by additional pressure on people in the region e.g., reducing agricultural yields or inducing additional fuelwood collection.

Relationships between precipitation and forest loss were also common in both the national and regional models, though the trends were highly variable both regionally and seasonally. Precipitation decreases and faster velocities were most associated with increased losses. This trend was strongest in the NE, EHR and Northern Western Ghats, but did not appear as a correlate of forest loss in the respective regional models as drying spots occurred on the borders between regions. Precipitation increases were also associated with increased loss in some regions. This has been found in other studies (Maringer et al., 2020; Neumann et al., 2017) and although appearing counterintuitive it can arise due to increased competition after forest growth spurts (Condit et al., 2004; McDowell, 2018) and the decoupling between precipitation and soil moisture which, in areas of groundwater depletion like NW India, is common (Zaveri et al., 2016; Condon and Maxwell, 2019).

Mapping of trends in areas of high forest loss (<20km^2) in the country revealed that most experienced reductions in precipitation, particularly during the post-monsoon and winter seasons, and year round in the NE and EHR regions. This is concerning for future forest persistence, with adequate precipitation and soil moisture often critical for forest growth (Seidl et al., 2017). The models in this study are unlikely to capture these trends due to the regional separations. These findings also contradict previous studies that predict the NE region to get wetter and generally positive effects of climate on forest growth in the region (Chaturvedi et al., 2011). Additionally, many areas of the country experienced warming winter temperatures coupled with reduced precipitation. Of particular concern are the Western Ghats area and the Hilly region, both areas of conservation importance and high endemism. These results support previous studies detailing forests in these regions to be a high risk of climate change effects in the future (Chaturvedi et al., 2011; Ravindranath et al., 2005; Sharma et al., 2015; Upgupta et al., 2015). Importantly, though warming and drying conditions were most common in high loss areas, not all experience this type of climate change. The nexus between the CNE, WC and PEN hotspot at times is both cooling and getting wetter.

Are there seasonal and regional variations in the climate-forest loss relationship in the country?

Regionally the way climate affected forest loss varied greatly, both in the amount of exposure to different variables and in the effect directions of relationships. Forests in some regions, such as the NW, had a greater variety of climate variables correlated with forest loss. Here, high seasonal variation in the climate variables associated with forest loss could require different strategies for conservation throughout the year to tackle potential winter droughts and summer flooding. With some of the lowest amounts of forest cover in the country due to its aridity, even small losses have large implications for overall forest cover. These analyses support predictions of the high vulnerability of remaining NW forests to climate changes (Chaturvedi et al., 2011; Das & Behera, 2019; Gopalakrishnan et al., 2011). The NE, where loss is highest, was only associated with one climate variable. This region is thought to be largely resilient to projected climate changes due to lower exposure, and more resilient forest types (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011). Known for its high levels of shifting cultivation and agricultural encroachment (Lele et al., 2008; Lele & Joshi, 2009), land use change and other factors likely still play a main role in forest loss here.

Every season appeared as a correlate of forest loss in the models and there was no clear dominant season that affected forest loss. The diversity in seasonal contributions to forest loss between regions highlights the diversity found in climate and forest type across the country and illustrates the array of challenges forests in the country could face if seasons show diverging trends.

Precipitation trends fluctuated more than temperature throughout the year, varying greatly by season, which species may find harder to adapt to than a unidirectional climate change. Interestingly, the fastest velocities and largest changes in precipitation occurred in different seasons (pre-monsoon and monsoon) to those of temperature (post-monsoon and winter). Though this result could provide seasonal respite from overlapping high velocities it could mean that forests are exposed to potential year round climate stress. In addition, the analyses revealed several occurrences where adjacent seasons had diverging trends that may upset processes of growth and reproduction, as existing evidence shows that seasonal climate patterns can impact plant phenology in subsequent seasons (Chen., X et al., 2017; Cook et al., 2012; Harvey et al., 2019; Laube et al., 2013).

For management strategies to be effective, they will need to be able to evolve with the seasons, be regionally specific and account for difficult transition periods. The variation found in this study provides evidence for a need for a diverse range of strategies not only throughout the country but also throughout the year.

Are Indian forests exposed to high and overlapping climate velocities and is forest loss greater in these areas?

Forests were exposed to high velocities of both climate variables, and faster velocities were found to be correlated with areas of higher forest losses in the models. However, faster velocities did not always denote more forest loss. A key example of this is the relationship between negative monsoon temperature velocities and increased loss. With no occurrences of declining monsoon temperatures, only lower increases, velocities must be indicative of slower increases in temperature. As such, it is likely that high velocities are not sole determinants of forest loss. Though the relationship between higher velocities and forest loss is not always detrimental, it is promising that no high forest areas had year-round exposure to high velocities. Further research is needed to understand when high velocities become detrimental to forests.

Encouragingly, overlaps of fast climate velocities of temperature and precipitation were uncommon and generally covered small areas. This supports other studies that have shown spatial heterogeneity in temperature and precipitation velocities (Garcia et al., 2014; Heikkinen et al., 2020). The exception in the Northern Western Ghats, could be concerning due to increased drought and fire risk in an area that covers seven protected areas within a biodiversity hotspot, and is already threatened by encroachment by agriculture and extensive fragmentation (Jha et al., 2000; Sharma et al., 2015). In addition, all three of the forest loss hotspots identified by this study received singular high velocities at some point during the year, with the Northeast and eastern Hilly regions experiencing some of the fastest negative precipitation velocities in every season. This prolonged exposure to rapid changes in climate could mean that species here are under additional pressure to move or adapt to climate sooner. The Northeast and eastern Hilly regions host some of the most biodiverse forests in the country (Chatterjee et al., 2006; Lele & Joshi, 2009) and fast velocities of changing climate here to add stress to species already experiencing high levels of threat from land use change (Lele & Joshi, 2009; Ramakrishnan, 2007).

Precipitation velocities in India's forests, generally ~5-10km yr^{-1}, were much larger than those recorded for temperature, which were 0.6km yr^{-1} at their fastest. These precipitation velocities are likely unattainably fast even for far more mobile species than trees, which under ideal conditions are expected to move a kilometre a year at best (Corlett & Westcott, 2013). The velocities recorded for precipitation in India (annual mean at 3.98km yr^{-1}) are high compared to other studies including the global mean of 0.22 km yr^{-1} (Kosanic et al., 2019; Loarie et al., 2009; Vanderwal et al., 2013). However, velocities of temperature in the country (annual mean at 0.029km yr^{-1}) are much lower than the global average of 0.42km yr^{-1} (Loarie et al., 2009; Vanderwal et al., 2013). Our results, suggest that precipitation velocities may be greater in the tropics than those in temperate regions but the same may not be true for temperature. For species capable of tracking climate, precipitation velocities could be a great concern as the speeds in which species would need to travel to reach their preferred climate may be too quick to traverse.

Can climate velocity provide additional understanding of a forest's risk to climate change?

This study found the metric of climate velocity to provide additional information compared to traditional temporal trend analysis as it provides a measure of, and a suggested repercussion of, the spatial variability in the climate variable of interest. Different relationships between climate change and forest loss were found in India due to the effect of the spatial gradient and, if forests respond in the way that the velocity mechanism expects, climate velocity should be an important component of management plan for protecting India's forests. The metric has been used in the past to assess the vulnerability of areas to future climate change and the utility of protected areas in the future (Arafeh-Dalmau et al., 2020; Fuentes-Castillo et al., 2020). Areas where climate velocity is low are likely to be key refuges for many species in the future and management strategies should take this into account and ensure these low velocity areas are as protected from multiple threats as possible. Additionally, climate velocity can identify areas that are climatically heterogenous and are key refuge areas for species. Ensuring that there are corridors between high velocity, spatially homogenous areas, and low velocity, heterogenous refuges could help many species transition between climatically unsuitable or rapidly changing areas to more suitable, refuge sites as well as ensuring protected areas are large enough to provide a variety of climate conditions for species (Brito-Morales et al., 2018). The majority of the protected areas in India do not fall within the high velocity areas for either precipitation or temperature (Figures 5 & S8). This is promising as they lie in potential refuge areas for species and the protected area status may relieve pressures from other stressors such as land use change. Many of the areas with a higher coverage of protected areas, such as the Western Ghats, are also in mountainous, and therefore climatically heterogenous landscapes, offering more protection (Brito-Morales et al., 2018; Loarie et al., 2009). However, it is concerning that there appears to be few protected areas in locations of high climate velocities, such as the central areas of the PEN region and the PEN, WC & CNE nexus. The lack of protected areas across these more exposed locations could mean that there are not the ecological corridors available for species to adjust their distribution safely with climate change. India's National Biodiversity Target 6 aimed to have 20% of the country's land area covered by protected areas by 2020 (CBD, 2018). According to the ENVIS reports (ENVIS, 2020), India fell short of this target in 2020 reaching just 5% coverage in protected areas (including areas protected under lower protection status such as Wildlife Reserves). The results from our study could help to inform placement of new protected areas to reach the 20% target with climate change trajectories in mind.

We find climate velocity to be a valuable metric, especially when used at a large scale where it can identify areas where the speed of climate change could be a concern for species persistence. However, this metric is known to lack biological realism at present and there are several caveats to its efficacy in indicating species vulnerability to climate change (Brito-Morales et al., 2018; Carroll et al., 2015; Hamann et al., 2015) . In particular, we note concerns around comparing temperature and precipitation velocities. Absolute values of precipitation will usually be much higher than temperature but their values are not comparable in terms of effect on species. Additionally, the fastest velocity in this study, -97kmyr^{-1}, was located on a mountain plateau, a small area of low spatial gradients but surrounded by a myriad of valleys (potential climate refuges). We stress that a key area of future study should be assessing the biologically realism of the spatial gradient aspect of climate velocity metrics specifically for forests before using this metric to obtain realistic estimates of forest species risk. We also stress that this metric should be integrated with more biologically realistic parameters if used in future modelling studies.

Despite these caveats, the metric has provided additional information on the general climate risk of a region not possible from conventional temporal trend data. It highlights areas of continuous homogenous climate which may have reduced opportunities for species to find climate refuges, particularly evident for temperature in India where the spatial gradient was considerably lower. This can be useful in planning areas for long-term conservation (Heikkinen et al., 2020; Loarie et al., 2009). It is also meaningful when considering the breadth of species reliant and relied on by tropical forests that are capable of moving to more climatically suitable, available areas.

Methodological considerations and future directions

This study provides novel insight into the potential climate variables leading to forest loss in a tropical-subtropical system with a uniquely national focus. However, there are associated limitations that are highlighted below to enable improvements in future studies.

The use of population density as a land use proxy

Previous studies have shown human pressures, such as increasing land use changes, as a major causes for forest declines in India (Gupta, 2007; Meiyappan et al., 2017; Padalia et al., 2019; Sudhakar Reddy et al., 2016) and a link between population density and land use changes associated with forest loss (Kale et al., 2016; Palchoudhuri et al., 2015). Higher population densities were expected to increase pressure on forest resources leading to more loss. However, our results, using the proxy of population density, do not support this. Although higher population densities are likely to put additional pressure on forest resources, many densely populated areas have little forest cover left resulting in loss occurring further from the source of the demand, geographically uncoupling the relationship between population density and demand on forest resources. Forest encroachment has also been linked to other socio-economic drivers such as out-migration of labourers and infrastructure such as irrigation facilities (Meiyappan et al., 2017). As population density does not account for these factors and showed a relatively small effect on forest loss in the models, the contribution of other human pressures e.g., land use change and infrastructure, to forest loss trends remains an open question. Future studies will aim to investigate the relative contributions of both human pressures and climate change in conjunction to forest loss in India. Metrics such as the 'Human Influence Index', developed by SEDAC CIESEN (https://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-influence-index-geographic) may better capture the trends needed by this analysis as they account for a range of anthropogenic factors including population pressure, human land use and infrastructure, and human access (e.g., roads and rivers). Currently the dataset only spans 1995-2004, a temporal length that is too short to support the timescale of this analysis currently, and quite a large spatial resolution (1km) but should be a consideration for future studies alongside developing similar metrics with a longer temporal scale and smaller spatial scale that can capture the variety of human pressures.

The importance of spatial and temporal scale

These analyses find that trends are misleading when focusing solely on annual climate averages. This is particularly the case for precipitation, where seasonal variation is masked in annual averages by strong opposing monsoonal trends. Focusing solely on annual averages in this study result in concluding no effect of climate on forest loss in India. This has repercussions such as underestimating future projected losses, dismissing interactions with other stressors and missed opportunities for protection. We stress that in countries with high seasonality, using seasonal data is necessary at the very least.

We also highlight the importance of utilising an appropriate spatial scale in large-scale analyses. The results obtained for national and regional models differed greatly in this study. Use of regional models highlighted large variation in climate drivers of loss across India but also separated climatic trends and contiguous areas of forest. This is of particular concern in the border districts of the CNE, WC and PEN regions which contained contiguous areas of high forest loss and homogenous climatic trends, but which were segregated in the regional models, potentially lessening the impact of climate trends observed.

Lag times and contribution of plantation forests

Forests often have lagged responses to changes in climate (Bertrand et al., 2011; Tei & Sugimoto, 2018). However, these can be highly variable between species and there is no clear consensus on the length of such lags (Bertrand et al., 2011; Corlett & Westcott, 2013; Kosanic et al., 2019; Liang et al., 2018). Therefore, it was difficult to account for without detailed context-specific information at the species-level and as such lags were not considered in this study. The forest data used in this study also does not discriminate between natural and plantation forests, a known concern with forest data in India (Puyravaud et al., 2010). Some losses recorded in this study are possibly due to harvesting of tree plantations and not natural forests. Future studies would benefit greatly from the creation of forest cover maps that can distinguish between natural and plantation forests (Puyravaud et al., 2010).

Conclusions

We show, for the first time, that climate change has played a role in past forest loss in India and provide the first characterisation of climate velocity in the country. We highlight a concern for future forest loss due to emerging drying trends and the locations and magnitude of singular high velocities in India’s remaining forest strongholds. This study highlights the issues around spatial and temporal scales leading to misrepresentation of climatic contributions to forest losses, particularly in ecologically and climatically diverse systems like India. Although this study shows climate to contribute to India’s forest loss, it also supports that other stressors, particularly land use change, likely still play a major role. As climate changes become more extreme, an understanding of how stressors interact will be of paramount importance in preserving India’s forest and biodiversity. In light of this, future studies should aim to quantify different aspects of the climate-forest relationship in India, particularly the response of different tree species to climate, prevalence of extreme events e.g., drought, interactions between climate and other stressors, the lag time, and the effects of climate-related forest loss on other aspects of biodiversity within the country. Studies, such as this, where other drivers of forest loss are explored can help to inform conservation policy and practice on a national and regional level, leading to more successful and cost-effective management programmes, especially as climate changes become more prevalent.

2.6 References

Aiba, S. I. and Kitayama, K. (2002) 'Effects of the 1997-98 El Niño drought on rain forests of Mount Kinabalu, Borneo', *Journal of Tropical Ecology*, 18(2), pp. 215–230

Allen, C. D. *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(4), pp. 660–684

Arafeh-Dalmau, N., et al. (2020). Incorporating climate velocity into the design of climate-smart networks of protected areas. *Methods in Ecology and Evolution,* 12(10), 1969-1983

Asner, G. P., Loarie, S. R. and Heyder, U. (2010) 'Combined effects of climate and land-use change on the future of humid tropical forests', *Conservation Letters*, 3(6), pp. 395–403

Bateman, B. L. *et al.* (2016) 'The pace of past climate change vs. potential bird distributions and land use in the United States', *Global Change Biology*, 22(3), pp. 1130–1144

Bennett, A. C. *et al.* (2015) 'Larger trees suffer most during drought in forests worldwide', *Nature Plants*, 1(10), pp. 1–5

Bertrand, R. *et al.* (2011) 'Changes in plant community composition lag behind climate warming in lowland forests', *Nature*, 479(7374), pp. 517–520

Bonan, G. B. (2008) 'Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests', *Science*, 320(5882), pp. 1444-1449

Brito-Morales, I. *et al.* (2018) 'Climate Velocity Can Inform Conservation in a Warming World', *Trends in Ecology and Evolution*, 33(6), pp.441-457

Brown, K. and Pearce, D. W. (1994) *The causes of tropical deforestation: the economic and statistical analysis of factors giving rise to the loss of the tropical forests*. UBC Press. ISBN:9780774805117.

Carroll, C. *et al.* (2015) 'Biotic and climatic velocity identify contrasting areas of vulnerability to climate change', *PLoS ONE*, 10(10), e0142024

CBD (2018). India's Sixth National Report to the Convention of Biological Diversity. Accessible at: https://chm.cbd.int/database/record?documentID=241351

Chaturvedi, R. K. *et al.* (2011) 'Impact of climate change on Indian forests: A dynamic vegetation modeling approach', *Mitigation and Adaptation Strategies for Global Change*, 16(2), pp. 119–142

Chen, I. C. *et al.* (2011) 'Rapid range shifts of species associated with high levels of climate warming', *Science*, 333(6045), pp. 1024–1026

Chen, X., Wang, L., & Inouye, D. (2017). Delayed response of spring phenology to global warming in subtropics and tropics. *Agricultural and Forest Meteorology*, 234-235, pp. 222-235

Chen, Y. *et al.* (2017) 'Assessing the effectiveness of China's protected areas to conserve current and future amphibian diversity', *Diversity and Distributions*, 23(2), pp. 146–157

Chitale, V. S., Behera, M. D. and Roy, P. S. (2014) ‘Future of endemic flora of biodiversity hotspots in India’, *PLoS ONE*, 9(12), e115264.

Choe, H. and Thorne, J. H. (2017) ‘Integrating Climate Change and Land Use Impacts to Explore Forest Conservation Policy’, *Forests*, 8(9), pp. 321

Cimatti, M. *et al.* (2021) ‘Large carnivore expansion in Europe is associated with human population density and land cover changes’, *Diversity and Distributions*, 27(4), pp. 602–617

Cook, B.I., Wolkovich, E.M., & Parmesan, C. (2012). Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, 109(23), 9000-9005

Condit, R. *et al.* (2004) 'Tropical forest dynamics across a rainfall gradient and the impact of an El Niño dry season', *Journal of Tropical Ecology*, 20(1), pp. 51-72

Condon, L. E. and Maxwell, R. M. (2019) ‘Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion’, *Science Advances*, 5(6), pp. 4574–4593

Corlett, R. T. and Westcott, D. A. (2013) ‘Will plant movements keep up with climate change?’, *Trends in Ecology and Evolution*, 28(8), pp. 482–488

Das, A. J. *et al.* (2013) ‘Climatic Correlates of Tree Mortality in Water- and Energy-Limited Forests’, *PLoS ONE*, 8(7), e69917

Das, P. and Behera, M. D. (2019) ‘Can the forest cover in India withstand large climate alterations?’, *Biodiversity and Conservation*, 28(8–9), pp. 2017–2033

Dash, S. K. *et al.* (2011) ‘Characteristic changes in the long and short spells of different rain intensities in India’, *Theoretical and Applied Climatology*, 105(3), pp. 563–570

Davidar, P. *et al.* (2010) ‘Assessing the extent and causes of forest degradation in India: Where do we stand?’, *Biological Conservation*, 143(12), pp. 2937–2944

Dobrowski, S. Z. and Parks, S. A. (2016) ‘Climate change velocity underestimates climate change exposure in mountainous regions’, *Nature Communications*, 7(12349)

ENVIS (2020). Protected Areas of India. ENVIS centre on Wildlife Protected Areas. Accessible at: http://www.wiienvis.nic.in/Database/Protected_Area_854.aspx

França, F. M., Benkwitt, C. E., Peralta, G., Robinson, James P.W., *et al.* (2020) ‘Climatic and local stressor interactions threaten tropical forests and coral reefs’, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375(1794), 20190116

Fuentes-Castillo, T., Hernández, H.J. & Pliscoff, P. (2020). Hotspots and ecoregion vulnerability driven by climate change velocity in Southern South America. *Regional Environmental Change,* 20 (27). doi: 10.1007/s10113-020-01595-9

García Molinos, J. *et al.* (2016) ‘Climate velocity and the future global redistribution of marine biodiversity’, *Nature Climate Change*, 6(1), pp. 83–88

García Molinos, J. *et al.* (2019) ‘VoCC: An r package for calculating the velocity of climate change and related climatic metrics’, *Methods in Ecology and Evolution*, 10 (12), pp.2195-2202

Garcia, R. A. *et al.* (2014) ‘Multiple dimensions of climate change and their implications for biodiversity’, *Science*, 344(6183)

Giardina, F. *et al.* (2018) 'Tall Amazonian forests are less sensitive to precipitation variability', *Nature Geoscience*, 11(6), pp. 405–409

Gopalakrishnan, R. *et al.* (2011) 'Climate change and Indian forests', *Current Science,* 101(3), pp.348-355

Greenwood, S. *et al.* (2017) 'Tree mortality across biomes is promoted by drought intensity, lower wood density and higher specific leaf area', *Ecology Letters*, 20(4), pp. 539-553

Gupta, H. K. (2007) 'Deforestation and Forest Cover Changes in the Himachal Himalaya, India', *International Journal of Ecology and Environmental Sciences*, 33(2-3), pp.207-218

Haddad, N. M. *et al.* (2015) 'Habitat fragmentation and its lasting impact on Earth's ecosystems', *Science Advances*, 1(2), pp. e1500052–e1500052

Hamann, A. *et al.* (2015) 'Velocity of climate change algorithms for guiding conservation and management', *Global Change Biology*, 21(2), pp. 997–1004

Hansen, A. J. *et al.* (2001) 'Global Change in Forests: Responses of Species, Communities, and BiomesInteractions between climate change and land use are projected to cause large shifts in biodiversity', *BioScience*, 51(9), pp. 765–779

Hansen, M. C. *et al.* (2013) 'High-resolution global maps of 21st-century forest cover change', *Science*, 342(6160), pp. 850–853

Harvey, J.E., et al. (2019). Tree growth influenced by warming winter climate and summer moisture availability in northern temperate forests. *Global Change Biology*, 26(4), 2505-2518

Heikkinen, R. K. *et al.* (2020) 'Fine-grained climate velocities reveal vulnerability of protected areas to climate change', *Scientific Reports*, 10(1), pp. 1–11

Huete, A. R. *et al.* (2006) 'Amazon rainforests green-up with sunlight in dry season', *Geophysical Research Letters*, 33(6), pp. L06405

Jha, C. S., Dutt, C. B. S. and Bawa, K. S. (2000) 'Deforestation and land use changes in Western Ghats, India', *Current Science*, 79(2), pp. 231–238

Kale, M. P. *et al.* (2016) 'Land-use and land-cover change in Western Ghats of India', *Environmental Monitoring and Assessment*, 188(7) pp. 387

Kok, K. (2004) 'The role of population in understanding Honduran land use patterns', *Journal of Environmental Management*, 72(1–2), pp. 73–89

Kosanic, A. *et al.* (2019) 'Climate change and climate change velocity analysis across Germany', *Scientific Reports*, 9(1), pp. 2196

Krishnan, R. *et al.* (2020) 'Assessment of climate change over the Indian region: A report of the ministry of earth sciences (MOES), government of India', *Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India*. Springer Singapore, pp. 1–226

Kumar, M., Singh, H. and Kalra, N. (2018) 'Dynamic forest vegetation models for predicting impacts of climate change on forests: An Indian perspective Modeling Climate Change Impact on Agriculture and Developing Mitigation'*, Indian Journal of Forestry,* 41(1), pp.1-12

Laube, J., et al. (2013). Chilling outweighs photoperiod in preventing precocious spring development. *Global Change Biology*, 20(1), 170-182

Lele, N. and Joshi, P. K. (2009) ‘Analyzing deforestation rates, spatial forest cover changes and identifying critical areas of forest cover changes in North-East India during 1972–1999’, *Environmental Monitoring and Assessment*, 156(1–4), pp. 159–170

Lele, N., Joshi, P. K. and Agrawal, S. P. (2008) ‘Assessing forest fragmentation in northeastern region (NER) of India using landscape matrices’, *Ecological Indicators*, 8(5), pp. 657–663

Lenoir, J. and Svenning, J. C. (2015) ‘Climate-related range shifts - a global multidimensional synthesis and new research directions’, *Ecography*, 38(1), pp. 15–28

Lewis, S. L., Edwards, D. P. and Galbraith, D. (2015) ‘Increasing human dominance of tropical forests’, *Science*, 349(6250), pp. 827–832

Liang, Y. *et al.* (2018) ‘How disturbance, competition, and dispersal interact to prevent tree range boundaries from keeping pace with climate change’, *Global Change Biology*, 24(1), pp.e335-e351

Lindner, M. *et al.* (2010) ‘Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems’, *Forest Ecology and Management,* 259(4), pp.698-709

Loarie, S. R. *et al.* (2009) ‘The velocity of climate change’, *Nature*, 462(7276), pp. 1052–1055

Maracchi G., Sirotenko O., Bindi M. (2005) Impacts of Present and Future Climate Variability on Agriculture and Forestry in the Temperate Regions: Europe. In: Salinger J., Sivakumar M., Motha R.P. (eds) Increasing Climate Variability and Change. Springer, Dordrecht. ISBN: 978-1-4020-3354-4

Maringer, J. *et al.* (2020) ‘Ninety-five years of observed disturbance-based tree mortality modeled with climate-sensitive accelerated failure time models’, *European Journal of Forest Research*, 140(3), pp. 255–272

McDowell, N. *et al.* (2018) ‘Drivers and mechanisms of tree mortality in moist tropical forests’, *New Phytologist*, 219(3), pp. 851–869

McDowell, N. G. (2018) ‘Deriving pattern from complexity in the processes underlying tropical forest drought impacts’, *New Phytologist*, 219(3), pp. 841–844

Meiyappan, P. *et al.* (2017) ‘Dynamics and determinants of land change in India: integrating satellite data with village socioeconomics’, *Regional Environmental Change*, 17, pp.753-766

Milanesi, P. *et al.* (2017) ‘European human-dominated landscapes provide ample space for the recolonization of large carnivore populations under future land change scenarios’, *Ecography*, 40(12), pp. 1359–1368

Mishra, A. K. (2019) ‘Quantifying the impact of global warming on precipitation patterns in India’, *Meteorological Applications*, 26(1), pp.153-160

Nadeau, C. P. and Fuller, A. K. (2015) ‘Accounting for multiple climate components when estimating climate change exposure and velocity’, *Methods in Ecology and Evolution*, 6(6), pp. 697–705

Nepstad, D. C. *et al.* (2007) ‘Mortality of large trees and lianas following experimental drought in an Amazon forest’, *Ecology*, 88(9), pp. 2259–2269

Neumann, M. *et al.* (2017) ‘Climate variability drives recent tree mortality in Europe’, *Global Change Biology*, 23(11), pp. 4788–4797

Ostberg, S. *et al.* (2015) ‘Three centuries of dual pressure from land use and climate change on the biosphere’, *Environmental Research Letters*, 10(4), 044011

Ovenden, T. S. *et al.* (2021) ‘Life after recovery: Increased resolution of forest resilience assessment sheds new light on post-drought compensatory growth and recovery dynamics’, *Journal of Ecology*, 109(9), pp. 3157-3170

Padalia, H. *et al.* (2019) ‘Assessment of historical forest cover loss and fragmentation in Asian elephant ranges in India’, *Environmental Monitoring and Assessment*, 19(Suppl 3): 802

Palchoudhuri, Y., Roy, P. S. and Srivastava, V. K. (2015) ‘A New Socio–economic Index for Modelling Land Use and Land Cover Change’, *Journal of Land and Rural Studies*, 3(1), pp. 1–28

Phillips, O. L. *et al.* (2009) ‘Drought sensitivity of the amazon rainforest’, *Science*, 323(5919), pp. 1344–1347

Puyravaud, J. P., Davidar, P. and Laurance, W. F. (2010) ‘Cryptic destruction of India’s native forests’, *Conservation Letters*, 3(6), pp.390-394

QGIS.org (2019). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.org

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Ramakrishnan, P. S. (2007). Traditional forest knowledge and sustainable forestry: A north-east India perspective. *Forest Ecology and Management*, *249*(1-2), 91-99.

Rao, C. A. R. *et al.* (2016) 'A district level assessment of vulnerability of Indian agriculture to climate change', *Current Science*, 110(10), pp.1939-1946

Ravindranath, N. H. *et al.* (2005) ‘Impact of climate change on forests in India’, *Current Science*, 90(3), pp.354-361

Ravindranath, N. H. *et al.* (2011) ‘Climate change vulnerability profiles for North East india’, *Current Science*, 101(3), pp. 384–394.

Ravindranath, N. H. and Sukumar, R. (1998) ‘Climate change and tropical forests in India’, *Climatic Change*, 39, pp. 563–581

Reddy, C. S. *et al.* (2013) ‘National assessment of forest fragmentation in India: Landscape indices as measures of the effects of fragmentation and forest cover change’, *Ecological Engineering*, 60, pp. 453–464

Ross, R. S. *et al.* (2018) ‘Decadal surface temperature trends in India based on a new high-resolution data set’, *Scientific Reports*, 8(7452)

Roy, P. S. *et al.* (2013) ‘Forest Fragmentation in India’, *Current Science*, 105(6), pp. 774–780.

Rupa Kumar, K. *et al.* (2006) ‘High-resolution climate change scenarios for India for the 21st Century’, *Current Science*, 90(3), pp. 334–345.

Saleska, S. R. *et al.* (2007) ‘Amazon forests green-up during 2005 drought’, *Science*, 318(5850), pp. 612

Sandel, B. *et al.* (2011) ‘The influence of Late Quaternary climate-change velocity on species endemism.’, *Science,* 334(6056), pp. 660–4

Seidl, R. *et al.* (2017) ‘Forest disturbances under climate change’, *Nature Climate Change*, 6, pp.395-402

Sharma, J. *et al.* (2015) ‘Assessing “inherent vulnerability” of forests: a methodological approach and a case study from Western Ghats, India’, *Mitigation and Adaptation Strategies for Global Change*, 20(4), pp. 573–590

Sharma, J. *et al.* (2017) ‘Vulnerability of Forests in India: A National Scale Assessment’, *Environmental Management*, 60(3), pp. 544–553

Song, X. P. *et al.* (2018) ‘Global land change from 1982 to 2016’, *Nature*, 560, pp. 639–643

Stralberg, D. *et al.* (2015) ‘Conservation of future boreal forest bird communities considering lags in vegetation response to climate change: a modified refugia approach’, *Diversity and Distributions*, 21(9), pp. 1112–1128

Sudhakar Reddy, C. *et al.* (2016) ‘Quantification and monitoring of deforestation in India over eight decades (1930–2013)’, *Biodiversity and Conservation*, 25(1), pp. 93–116

Taccoen, A. *et al.* (2019) ‘Background mortality drivers of European tree species: Climate change matters’, *Proceedings of the Royal Society B: Biological Sciences*, 286(1900)

Tei, S. and Sugimoto, A. (2018) ‘Time lag and negative responses of forest greenness and tree growth to warming over circumboreal forests’, *Global Change Biology*, 24(9), pp. 4225–4237

Upgupta, S. *et al.* (2015) ‘Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India’, *Climate Risk Management*, 10, pp. 63–76

Vanderwal, J. *et al.* (2013) ‘Focus on poleward shifts in species’ distribution underestimates the fingerprint of climate change’, *Nature Climate Change*, 3(3), pp. 239–243

Wagner, F. *et al.* (2014) ‘Pan-Tropical Analysis of Climate Effects on Seasonal Tree Growth’, *PLoS ONE*, 9(3), pp. e92337

Wani, A. A. *et al.* (2012) 'Carbon Sequestration Potential of Indian Forestry Land Use Systems-A Review', *Nature and Science*, 10(12), pp.78-85

Zaveri, E. *et al.* (2016) ‘Invisible water, visible impact: Groundwater use and Indian agriculture under climate change’, *Environmental Research Letters*, 11(8), pp. 084005

Zhang, Q. *et al.* (2017) ‘Relationship of Climatic and Forest Factors to Drought- and Heat-Induced Tree Mortality’, *PLOS ONE*, 12(1), pp. e0169770

Zhang, Y. *et al.* (2010) ‘The response of soil moisture content to rainfall events in semi-arid area of Inner Mongolia’, *Procedia Environmental Sciences*, 2, pp. 1970–1978

2.7 Supplementary Material

Table S1| List of excluded districts due to having less than 0.1km^2 of forest cover at the start of the study period

District	State	District Area (km^2)	Forest cover (km^2)	Forest loss (km^2)	Percent of total forest cover lost (%)
Churu	Rajasthan	17075.11777	0	0	0
Jaisalmer	Rajasthan	38637.6099	0	0.002054	0
Bikaner	Rajasthan	26965.39559	0	0.002723	0
Jodhpur	Rajasthan	22842.40267	4.49E-04	0.015823	1.00E+02
Patan	Gujarat	6026.347964	0.0016362	0.011306	100
Barmer	Rajasthan	28372.88001	0.0028321	0.006959	100
Hanumangarh	Rajasthan	8912.642101	0.006607	0.01745	100
Nagaur	Rajasthan	17676.90422	0.012381	0.015812	100
Yanam	Puducherry	31.65915537	0.0436975	0	0
Sirsa	Haryana	4236.292792	0.0721095	0.022118	30.67348159
Hyderabad	Telangana	178.6037918	0.0725725	0.024237	33.3963124
Bhilwara	Rajasthan	10469.55369	0.0764671	0.039023	51.03189784
Ganganagar	Rajasthan	11679.58236	0.0856024	0.104419	100

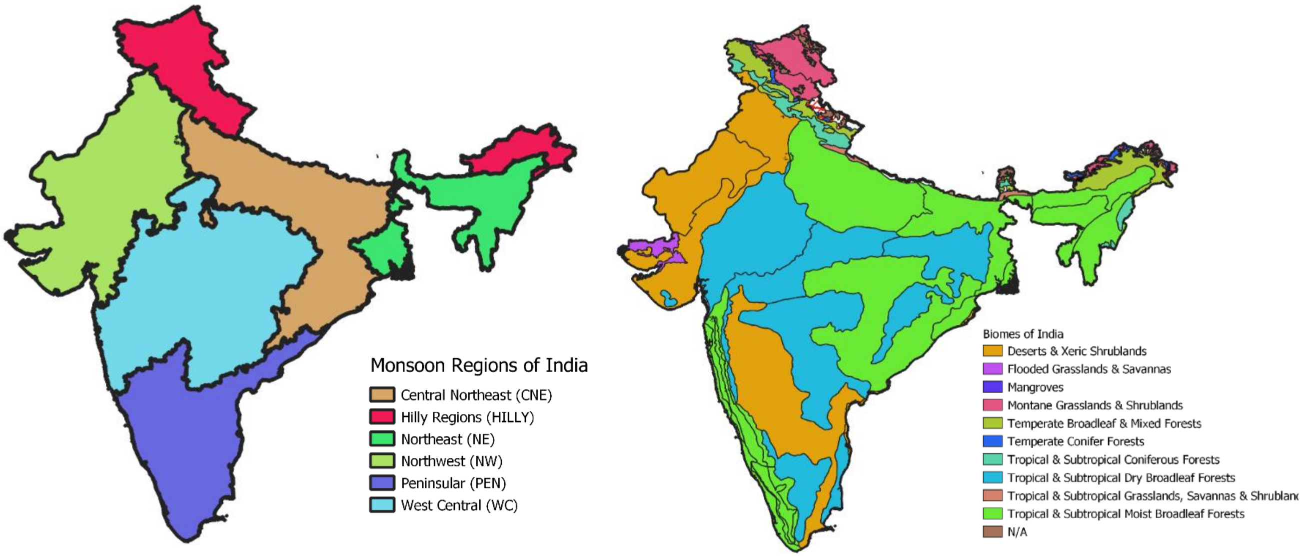


Figure S1| Left panel: The six monsoon regions used in my study; Northeast (NE), Northwest (NW), Central Northeast (CNE), West Central (WC), Peninsular (PEN) & Hilly. The map was created to display the Homogenous Monsoon Regions of India outlined by the Indian Institute of Tropical Meteorology. **Right panel:** The ecological biomes of India. Most of India is located in the biomes of Tropical and Subtropical Moist Broadleaf forests, Dry Broadleaf forests and Deserts and Xeric Shrublands. The map is a clipped version of the global extent created by Dinerstein et al., (2017)

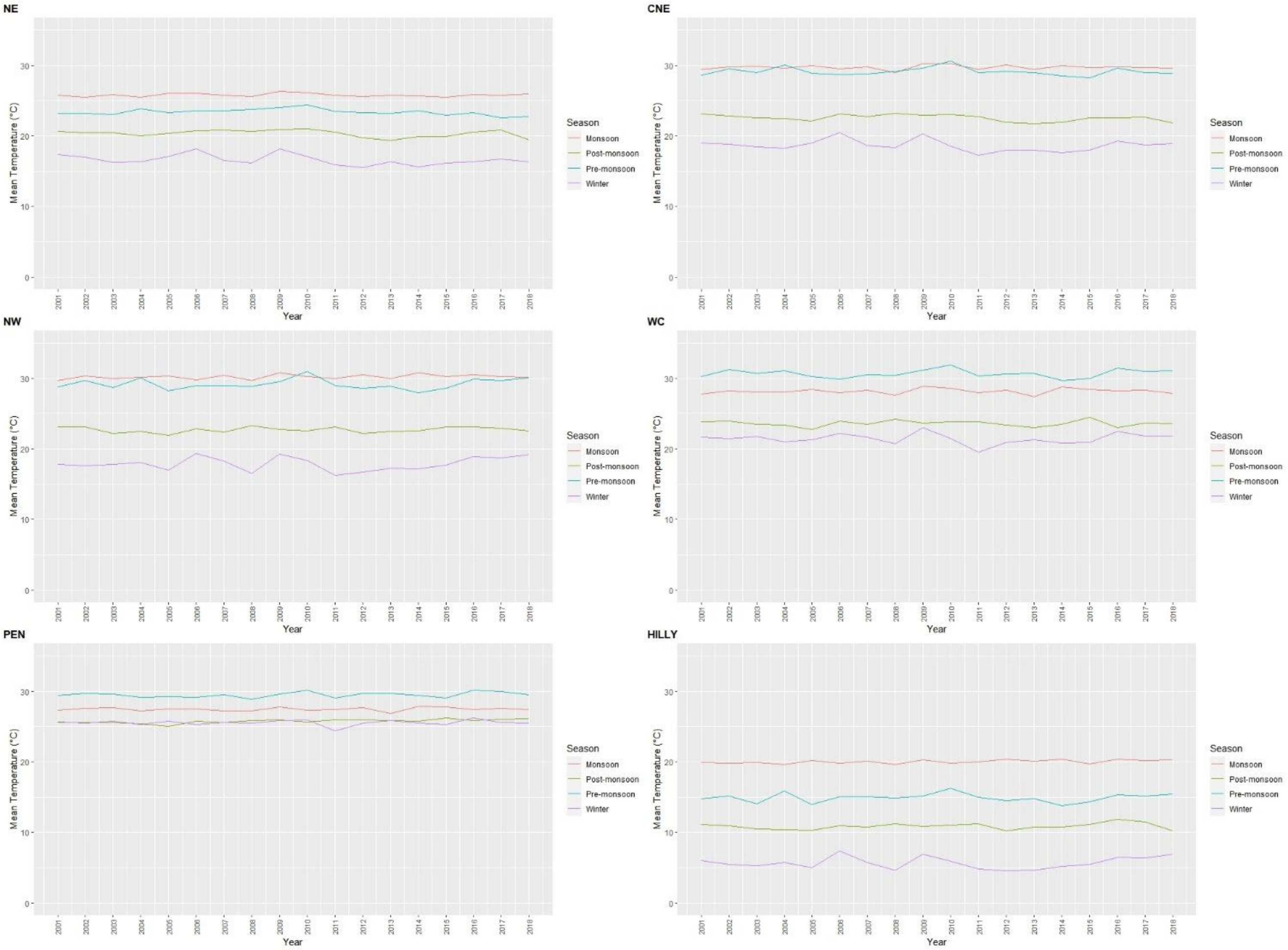


Figure S2|Trends in seasonal mean temperature (^{O}C) across all six monsoon regions for the time period 2001-2018. Different seasons are depicted as individual lines; monsoon (red), post-monsoon (green), pre-monsoon (blue) and winter (purple)

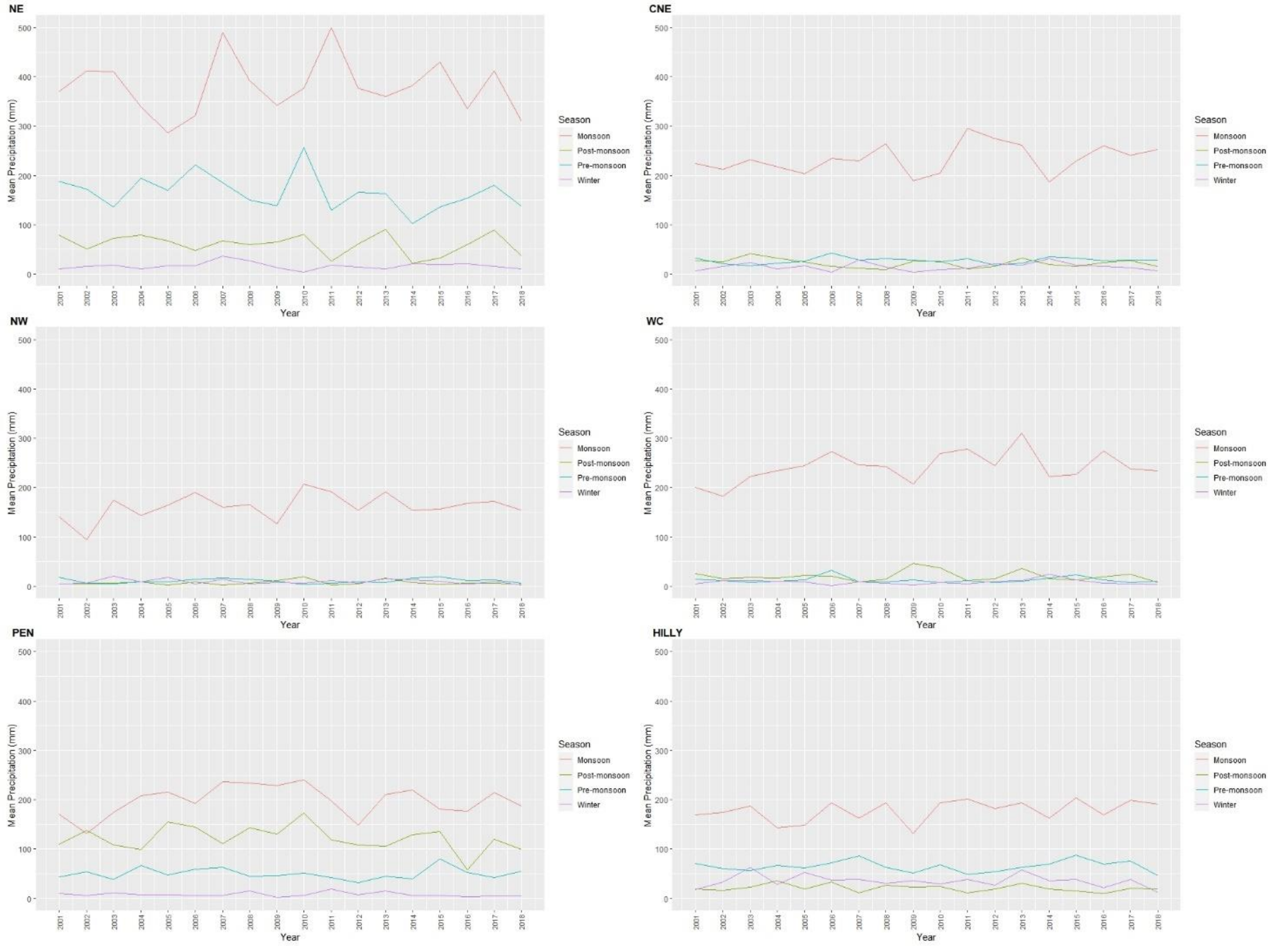


Figure S3| Trends in seasonal total precipitation (mm) across all six monsoon regions for the time period 2001-2018. Different seasons are depicted as individual lines; monsoon (red), post-monsoon (green), pre-monsoon (blue) and winter (purple)

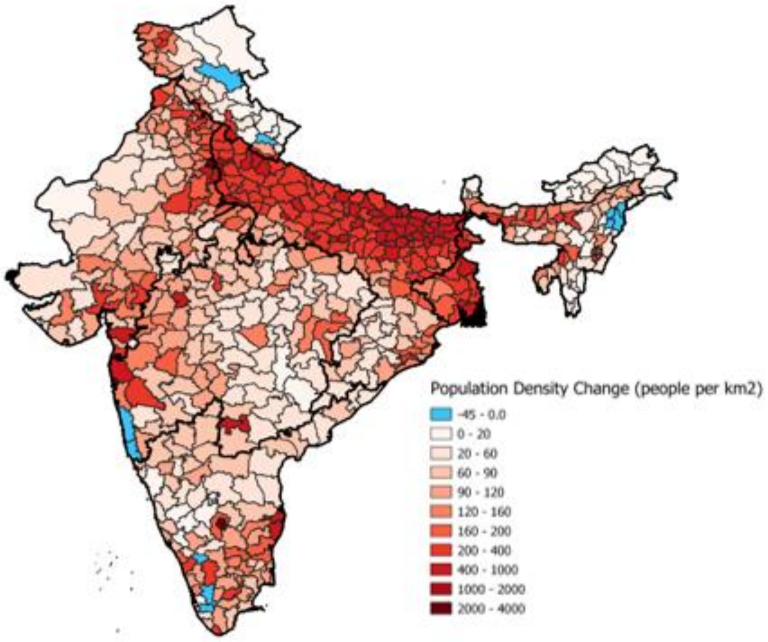


Figure S4 | Population density change (people per km^2) between the years 2000-2020 in the districts of India. The thick black lines show the borders of the monsoon regions.

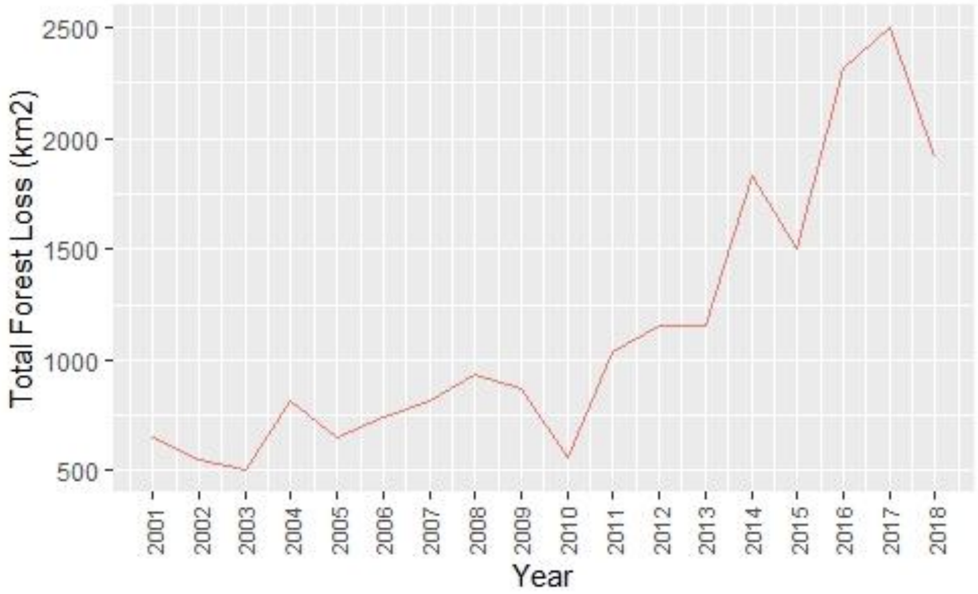


Figure S5| The increase in total annual forest loss on a national level between the years 2001-2018 in km^2

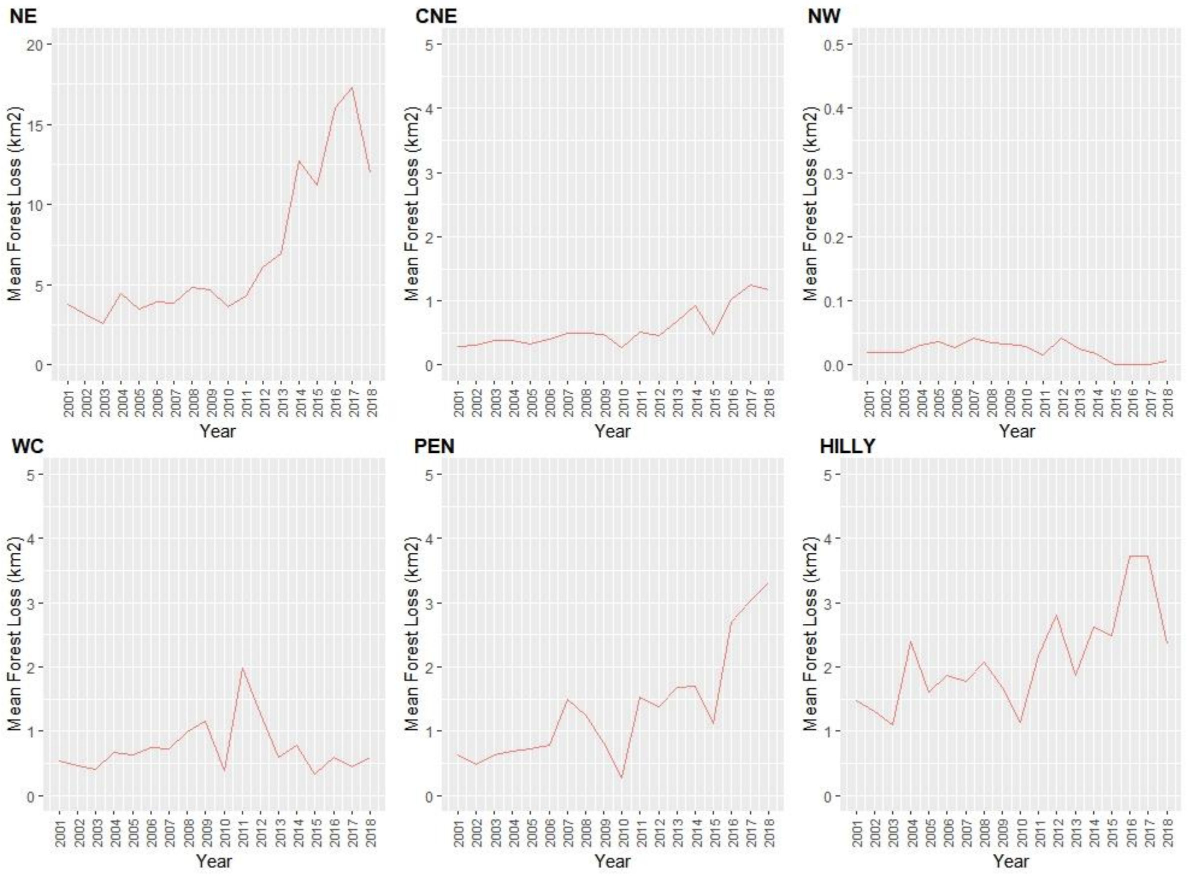


Figure S6| The mean annual forest loss per district per year in the monsoon region of India between the years 2001-2018. Note the difference in axis range (y-axis), used to ensure trends could be seen clearly.

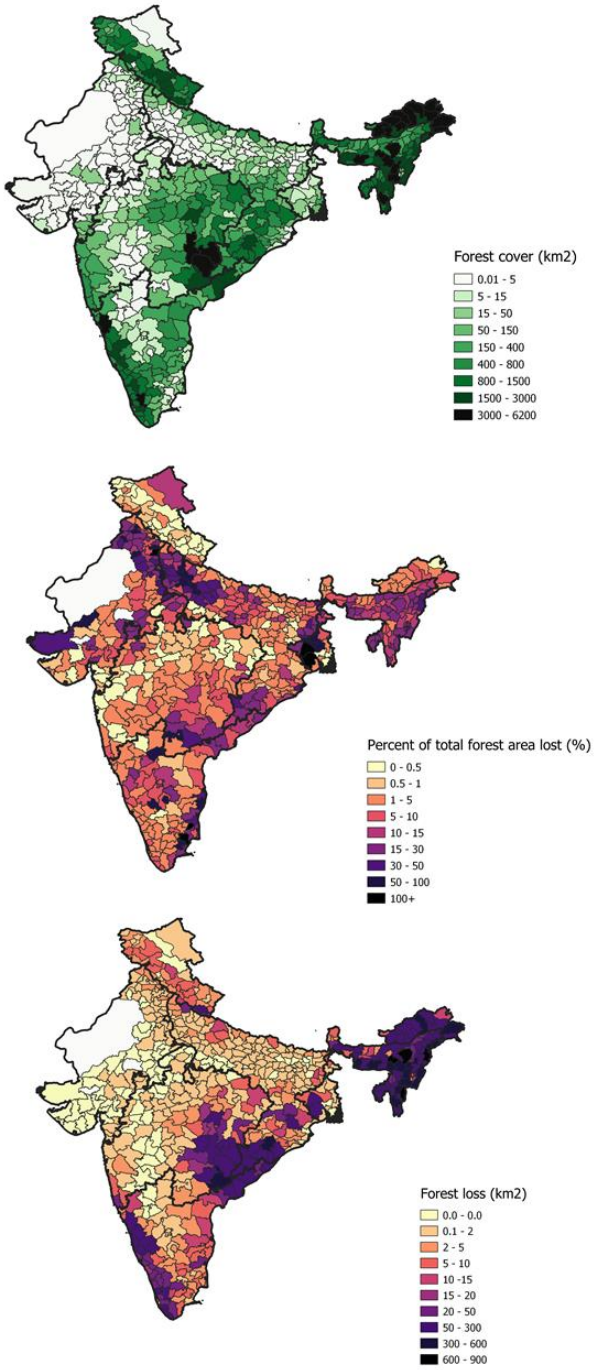


Figure S7| Top panel: The forest cover in km^2 of each district in India in the year 2000. Middle panel: The percent of each district's forest cover that was lost between the years 2001-2018. Bottom panel: The total forest lost in each district between the years 2001-2018 in km^2. Much of the country's forest cover is located in the Northeast and along the east and southwestern coasts. The highest percentage of forest cover lost are spread across the country with hotspots in the Northwest and Northeast. Total forest loss is greatest in the Northeast, central west coast and southwestern areas, where forest cover is also high.

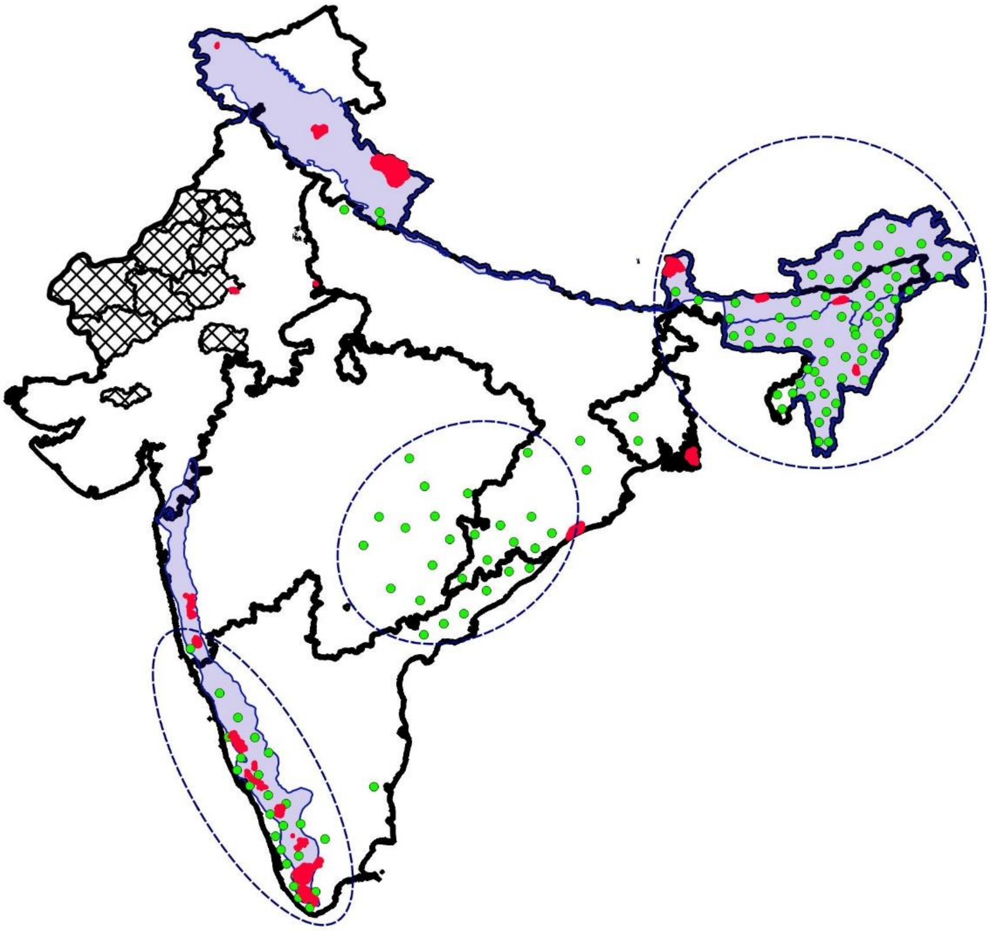


Figure S8| Districts with forest losses >20km^2 during the time period 2001-2018. Green dots indicate the central point of a district that had a forest loss area greater than 20km^2 during the time period 2001-2018. The three areas of high forest loss are highlighted with blue circles. Protected areas are marked in red (UNEP-WCMC & IUCN, 2021). Biodiversity hotspots are marked as blue filled in areas (Hoffman, et al., 2016). The map is split up into the homogenous monsoon regions and hashed districts display those excluded from the study.

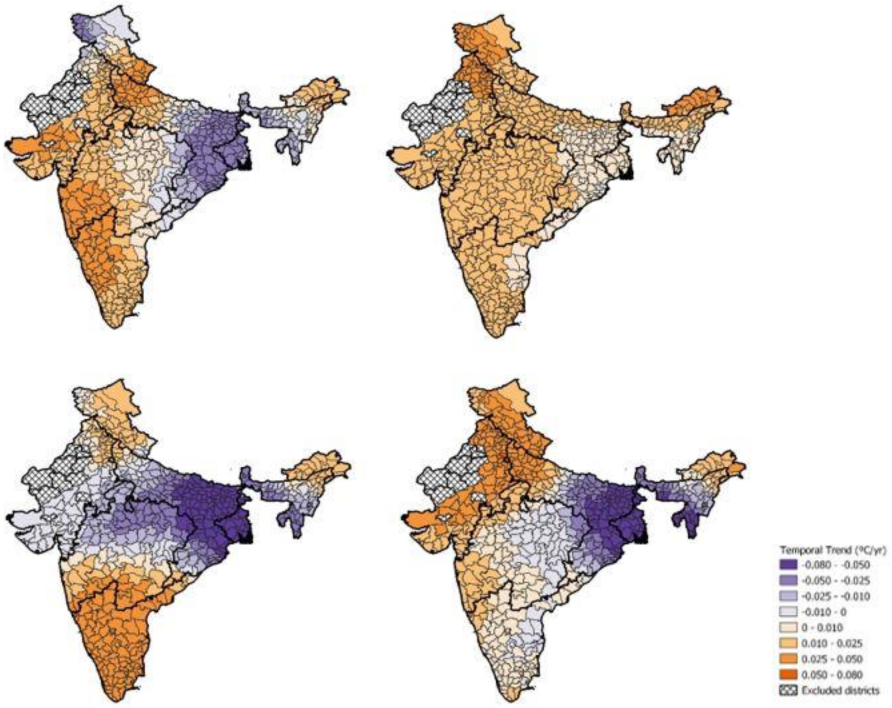


Figure S9| Seasonal temperature temporal trends in ^{0}C/year of each district for the time period 2001-2018. In a clockwise direction the seasons depicted are as follows; pre-monsoon, monsoon, post-monsoon and winter. The black outlines show the borders of the monsoon regions.

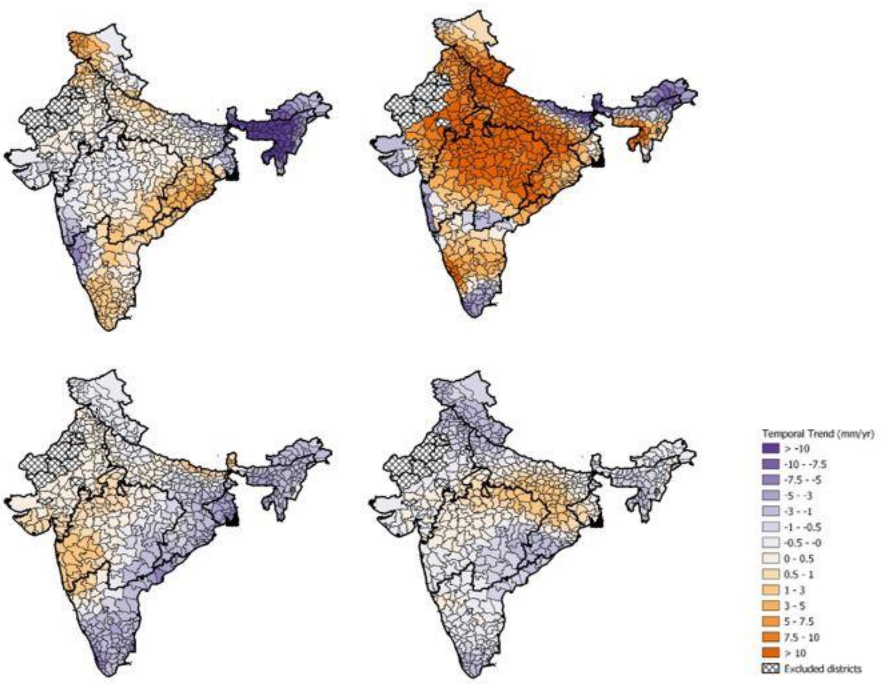


Figure S10| Seasonal precipitation temporal trends in mm/year of each district for the time period 2001-2018. In a clockwise direction the seasons depicted are as follows: pre-monsoon, monsoon, post-monsoon and winter. The black outlines show the borders of the monsoon regions

Table S2| The range and average values of precipitation and temperature velocities of annual and seasonal variables.

Season	Range of Precipitation Velocities	Mean	Range	Range of Temperature Velocities	Mean	Range
Annual	-13.752 – 34.320	3.981	48.072	-0.321 – 0.298	0.029	0.619
Monsoon	-10.152 – 41.388	4.881	51.54	-0.010 – 0.272	0.118	0.282
Post-monsoon	-14.550 – 11.254	-0.903	25.804	-0.725 – 0.440	-0.090	1.165
Pre-monsoon	-97.586 – 13.086	-0.008	110.672	-0.334 – 0.403	0.042	0.737
Winter	-16.458 – 19.034	-0.589	35.492	-0.606 – 0.489	-0.025	1.095

Table S3| The range and mean values of precipitation and temperature spatial gradients between seasons

Season	Temperature Range (Mean)	Precipitation Range (Mean)
Pre-Monsoon	0.1-0.38 (0.128)	0.1-4.63 (0.549)
Monsoon	0.1-0.33 (0.125)	0.1-19.40 (2.271)
Post-Monsoon	0.1-0.36 (0.126)	0.1-5.13 (0.383)
Winter	0.1-0.36 (0.127)	0.1-2.30 0.203)

Chapter 3: Dynamics of forest change and the contribution of agricultural development to forest loss in India

A tea plantation within the Nilgiris, Western Ghats, India.

Source: Alice Haughan (Author's own)

3.1 Abstract

India has experienced high rates of forest loss for decades, largely as a result of commodity-driven deforestation related to agriculture. Past studies marked a decline in deforestation by the early 1990's, however, few studies have characterised forest change on a large scale following this and little is known about whether agriculture is still the main cause of forest loss in the country. This research examines the trends in forest change across India during the period 1995-2019, at two spatial scales: national and regional. Land cover change detection analysis was used to create spatial datasets of land use change and forest loss and gains. Linear mixed effects models were used to investigate the relationship between forest loss and types of land cover conversions to ascertain whether loss was predominantly associated with agricultural-based land cover changes, or other land cover types. The chapter further uses the data to characterise which forest types are most at risk to different land cover changes as well as which have gained the most area coverage over the time period. The findings show that despite losing 6.2% of its forest cover over the 24 years, India is experiencing net increases in forest cover by the 2015-2019 period. Large increases in forest cover, in all regions, during the 2015-2019 period overrode net losses that were predominant prior to 2015. Forest loss was not consistent across regions, and in contrast to previous studies, these results indicate that forests in the West Central region were most at risk. Forests in this region continuously experienced the highest losses, losing >1,583km^2 more forest than the next worst affected region. Forest loss was not consistent across forest types, where broadleaved deciduous forests lost disproportionately more forest cover. Agriculture-based land use changes (particularly mosaic cropland) were the primary cause of forest loss across the country, but their contribution declined over time. There was a notable shift towards increases of forest being lost to natural land covers which provide novel indications that the primary cause of forest loss is changing to natural land covers such as mosaic vegetation, shrub and grasslands. Our findings have potentially positive implications for forest cover and biodiversity in the country as forest cover increases but we stress concern over the level of forest loss still occurring, despite gains. We further highlight the importance of regular monitoring of forests at different spatial scales and suggest that forests in different regions and of different types will require different management strategies to conserve them. Understanding the trends and causes of forest change in recent years will help to better protect India's remaining forest resources, upon which high levels of biodiversity and rural population depend on.

3.2 Introduction

India has experienced high rates of forest loss for decades (Lele et al., 2008; Roy et al., 2013). Between 1930 and 1975, an average of 4,700km^2 of forest were lost per year - a gross annual rate of loss of 0.77% (Sudhakar Reddy et al., 2016). More recent estimates from the early 1990's reflect a continued but lower loss rate of 0.35% (Meiyappan et al., 2017). After the 1980 Forest Conservation Act and other attempts by the Government throughout the late 80's and early 90's to promote intensification of agriculture alongside reforestation (Gupta, 2007; Sudhakar Reddy et al., 2016), the rate of forest loss was further reduced, dropping to a rate of 0.07% during 1995-2005, and with evidence of reforestation occurring in some areas (Adhikari et al., 2015; Kundu et al., 2015; Padalia et al., 2019). Most regions in the country showed lower deforestation rates by 2005, with the exception of the northeast where forest loss remained high (Sudhakar Reddy et al., 2016). Despite these changes, deforestation is still occurring at unsustainable levels, and at a faster rate than reforestation (Adhikari et al., 2015; Puyravaud et al., 2010; Sudhakar Reddy et al., 2016), and many forests continue to display increasing levels of fragmentation (Wakeel et al., 2005; Pandit et al., 2007; Roy et al., 2013).

India's forests are notable for their high levels of biodiversity and endemism (Chitale et al., 2014; Lele et al., 2008). The country is home to four of the world's global biodiversity hotpots as well as important refuges for populations of charismatic species such as Bengal tiger and Indian Elephant (Padalia et al., 2019; Puyravaud et al., 2010). Approximately 247 million people are dependent on India's forests for survival (World Bank, 2005; FSI 2019) with two-thirds of the population relying on fuelwood for cooking (Davidar et al., 2010; Puyravaud et al., 2010) and forest products such as food, fuelwood, fodder, and timber being the sole income for many rural inhabitants. Forest loss in India has been shown to directly negatively impact biodiversity (Raman, 2006; Pandit et al., 2007), and reduce the numbers of medicinal and economically important species (Pandit et al., 2007; Roy et al., 2013), and fuelwood and fodder yield (Wakeel et al., 2005). While reductions in forest coverage can improve accessibility across regions, loss has led to increased risk of desertification, flooding and local climate change in the country (Bhattacharjee & Behera, 2017; Nayak & Mandal, 2019; Sen et al., 2004).

Land use change is recognised as the primary cause of forest loss, and the types of land cover that replace forests vary across the country (Wakeel et al., 2005; Sudhakar Reddy et al., 2016). While shifting cultivation, logging and mining play a large role in the Northeast; expansion of plantations and agriculture are significant in the Western Ghats and Himalayas; and agriculture, logging, and infrastructure development are the leading causes of forest loss in the Deccan plateau (Kundu et al., 2015; Lele & Joshi, 2009; Reddy et al., 2013). Nationwide, cropland expansion and shifting cultivation are recognised to be the biggest drivers of forest loss (Gupta, 2007; Meiyappan et al., 2017; Padalia et al., 2019; Sudhakar Reddy et al., 2016). Meiyappan et al., (2017) showed that, nationally, forest was predominantly lost to cropland expansion and was more at risk in areas where agricultural yields were low, due to lack of irrigation facilities, soil degradation and a shortage in agricultural workers. Lower yields led to communities seeking out more land to cultivate alongside alternative incomes, often at the expense of forests and their resources, this has been shown as a concern on a global scale (FAO, 2020). Agriculture is likely to remain a significant driver of loss considering that as an industry it accounts for 14%-20% of GDP (Bana & Gautam, 2014; Zaveri et al., 2016), employs >50% of India's workforce, and it is the primary income source for 70% of rural households in the country (FAO, 2020). It is clear that forest loss in the country is intrinsically linked to the welfare of agriculture in rural communities.

Recent evidence suggests that certain types of forest are disproportionately lost (Wakeel et al., 2005; Puyravaud et al., 2010). Roy et al., (2013) focused on forest fragmentation at the national scale and found that sub-tropical dry evergreen forests and mixed formations had some of the lowest levels of fragmentation, potentially as a result of increased institutional and social protection, and the prevalence of this forest type in inaccessible locations. On the other hand, moist deciduous and dry deciduous forests had some of the largest percentage of their coverage under medium to high fragmentation. Several forest types with high fragmentation, such as tropical broad-leaved and dry deciduous forests, harboured high levels of endemism and are important for biodiversity (Roy et al., 2013; Utkarsh et al., 1998; Wright, 2010). Contrastingly, other studies have also shown disproportionate losses in different types of evergreen forests. For example, in the southern state of Tamil Nadu, most loss has occurred in tropical dry evergreen forests along the coasts (Puyravaud et al., 2010). In central Himalaya, due to the revenue that pine resin provides the local government, pine forests (needle-leaved evergreen) were found to be more intact and better protected than oak (broadleaved evergreen) forests and evidence suggests that generally broad-leaved forest types are more at risk due to their versatility in produce (fuelwood, timber & fodder) and the suitability of these forest types for livestock rearing (Singh et al, 2016; Wakeel et al., 2005). Future predictions for forest type distributions in the country predict a general shift from tropical dry deciduous species to tropical wet evergreen species, as well as an increase in the distribution of wetter forest types in response to a predicted warmer and wetter climate across much of the country (Chaturvedi et al., 2011; Ravindranath et al., 2005). To date, most studies considering forest type have been small-scale regional studies, and the last national study to consider forest type when assessing human-driven forest losses focused on loss during only two seasons in 2005-2006 (Roy et al., 2013). Since different types of forest support different species, harbour different levels of biodiversity and have different extents in the country, the identity of forest being lost is a key knowledge gap that needs to be addressed to determine threats to biodiversity. Since climate changes are predicted to impact certain forest types, an understanding of the types at risk from land use changes will facilitate understanding of which types are threatened by multiple stressors.

Currently, there is substantial regional bias in studies focusing on forest changes within India. A high proportion of studies are conducted in areas with high forest cover and biodiversity, such as the Western Ghats, Himalayas, and particularly the Northeast region where ~25% of India's forest cover is located alongside some of the highest rates of loss, despite remaining largely inaccessible until the 1990s (Kant and Katwal, 2003; Lele et al., 2008; Lele and Joshi, 2009; FSI 2019). Analyses of deforestation trends in other areas of the country are sporadic. Central regions, the Deccan Plateau, and Eastern Ghats have been largely overlooked, despite containing important habitat corridors and high levels of forest fragmentation (Padalia et al., 2019). These regions also tend to have lower protected coverage and subsequently have increased vulnerability (Puyravaud et al., 2010), as well as having been subject to extreme forest loss for a long time due to being in more populous regions, but are under-represented in the deforestation literature. Several small-scale (district or watershed) studies during the early 1990s and 2000s (Reddy et al. 2013; Meiyappan et al., 2017) investigate rates of deforestation displaying high variability across the country; for instance, a review by Reddy et al. (2013) showed some Northeast districts to have a net deforestation rate of 0.90-5.29% per year, the Himalayas a net deforestation rate between 0.13-0.69%, the Western Ghats between 0.04-1.34% and the Deccan peninsula 0.19-3.2%, but highlighted that different methodologies between studies often result in widely dissimilar estimates. These small-scale studies provide useful insights into regional gaps in the knowledge of forest loss trends but do not scale up to show the dynamics of forest changes in the country at larger scales (e.g., national) and limit our understanding of where forests are currently at risk.

Research on the extent of national forest loss has been declining and very little has focused on forest change in recent periods. Many studies took place during the peak of the forest loss and just after the 1980 Forest Conservation Act was enacted. This produced a wealth of literature on India's forest loss between 1990-2005 and many recent studies still focus on this period (Adhikari et al., 2015; et al., 2000; Meiyappan et al., 2017; Wakeel et al., 2005). However, the number of studies on forest loss in the country have been declining and very few have investigated land use changes underpinning forest loss in the last 10 years. The most recent study, which looks at forest change between 1930-2013, showed that deforestation rates were still high but declining with time, finding that agriculture remained the primary cause of forest loss across the country in the later periods (Sudhakar Reddy et al., 2016). In that study, Sudhaker Reddy et al., (2016) recorded a 28% loss in forest coverage between 1930 and 2013, but with considerably lower average annual rates of loss at 0.07% by the period 1995-2005, and 0.05% during 2005-2013.

The only regular source of forest data in India is the biennial State of the Forest report conducted by the Forest Survey of India. These reports have shown net increases in forest cover nationally and across many areas of the country since 2013, owing to reforestation schemes (FSI 2017, 2019). There has, however, been longstanding controversy over the accuracy of these reports, which regularly monitor the forest but struggle to distinguish between natural forests and plantations, several of the reports attributed many forest gains to increases in plantations (e.g., FSI 2001, 2017) which are known to have lower conservation value (Horák et al., 2019; Kanowski et al., 2005; Martello et al., 2018; Phommexay et al., 2011). Many are concerned that these reports currently over-inflate the forest cover and subsequently, the relevance of the FSI reports are disputed in relation to conservation of natural forests (Ravindranath et al., 2005; Puyravaud et al., 2010; Roy and Joshi, 2010; Sudhakar Reddy et al., 2016).

The lack of recent studies, the existence of regional bias and focus on small scale research has resulted in only minimal understanding of forest change on a national scale (in which policies often act on) in recent times. Questions remain around whether deforestation rates are still slowing, whether the main cause is still agriculture-based, and if certain types are forest are at greater risk. This research aims to answer the following questions:

1. How has the area of forest changed over 24 years between 1995 and 2019?
2. What land covers are associated with greater forest losses?
3. Are the drivers of loss different for different forest types and geographical regions?

Following trends in the literature, we hypothesise that forest losses will be decreasing across the country, whilst forest gains will be increasing. Due to the high dependence on agriculture, and the historical risk agricultural expansion poses to forests in the country, we predict that conversion to agriculture will remain the largest cause of forest losses. As the type of forest present is often highly location-dependent and each type can provide different material benefits to people, we predict that the proportion of forest lost will not be consistent across forest types. Finally, due to differing social and economic stressors alongside differing extents of forest cover, we predict that forest loss will not be homogenous across regions.

3.3 Methods

3.3.1 Quantifying forest change

Global land cover data was obtained from the ESA CCI Land Cover project (v2.0.7 1995-2015) and EC C3S Land Cover project (v2.1.1 2016-2019) at the spatial resolution of 300m. The land cover data was clipped to the borders of India using QGIS (version 3.16.0). The EC C3S product was designed to be consistent with the ESA CCI dataset and as such, both iterations of the land cover product utilise the FAO Land Cover Classification System (Di Gregorio, 2016) (see Table S1). Land cover change was then defined for a full 24-year study period (1995-2019) and also five-year intervals; 1995-1999, 2000-2004, 2005-2009, 2010-2014, 2015-2019 & 1995-2019 (full study period) using the Land Cover Change function from the Semi-Automatic Classification Plugin (v 6.4.5) (Congedo, 2021) in QGIS. Periods of five years were chosen to capture changing general trends while avoiding smaller inter-annual fluctuations. Pixels where forest had been lost or gained were extracted from the land cover data using 'Reclassify by table' function from the QGIS Raster Analysis toolbox.

The geographic coordinates (centre of the pixel of interest), administrative divisions of state and district, monsoon region, forest type, and the land cover change category associated with the change, were extracted for each forest loss and gain pixel using the QGIS Point Sampling Tool. The categories of land cover change were later simplified from those outlined in the FAO classification system into eight categories: cropland, mosaic cropland (part cropland, part tree/shrub/herbaceous cover), natural mosaics (part tree/shrub, part herbaceous cover), urban areas, other tree types, shrub and grasslands & water bodies. The full details of this reclassification are available in Table S1.

Aggregated metrics were then calculated, firstly, the total forest loss and total forest gain areas per district. This is the total area lost (or gained) without taking into account forest gains (or losses). As a rule, where '(total) forest loss' or '(total) forest gain' is mentioned, this is what is being referred to. Secondly, the *net* change in forest cover for each district was calculated and aggregated nationally and regionally. The net change is defined as the total forest gains minus the total forest losses, resulting in a representative change in forest cover accounting for both losses and gains. Where net change, is reported it is labelled as such to distinguish it from the total area lost or gained.

Finally, rates of forest loss and gain for each of the periods at two spatial scales (national and regional) were calculated following the methodology from Puyravaud (2003) and using the formula:

$$r = \frac{1}{t2 - t1} x \; ln \frac{a2}{a1}$$

where r is the annual rate of loss or gain, t1 is the first year of the period, t2 is the last year of the period, and a1 and a2 are the total losses or gains at time t1 and t2 respectively.

Climate is highly variable across the country, and this has considerable impact on the distribution of forest type and land cover (Kumar & Scheiter, 2019). To account for this, regional data was based on the breakdown of the country into homogeneous monsoon regions, Regional boundaries were sourced from Indian Institute of Tropical Meteorology for the six regions: Central Northeast (CNE), Northeast (NE), Northwest (NW), West Central (WC), Peninsular (PEN) and Hilly regions (Figure S1).

Analyses focused on mainland states and districts with >0.1 km^2 of total forest cover (Table S2). Subsequently, thirteen districts, predominantly from the arid and xeric shrubland regions of the Northwest, and island union territories were excluded. These 13 excluded districts covered a land area that accounted 5.73% of the total land area in the study and 0.0001% of the country's forest cover. In addition to those removed for low levels of forest cover.

In the previous chapter, forest loss data was obtained from the Global Forest Change dataset (Hansen et al., 2013). However, when used in conjunction with the land cover data for this analysis discrepancies between forest classification and other land cover categories (particularly shrubland) in the two datasets made them incompatible, and hence the land cover data was used for both forest change and other land cover change. The differences between these two datasets are discussed in more detail in the thesis discussion.

3.3.2 Determining the land use changes driving forest loss

Linear mixed effects models were used to understand the relationship between forest loss and land cover conversion type. These models included total area of forest lost (km^2) to each land cover type per district as the response variable alongside a categorical explanatory variable of the type of land cover that forest had been lost to. A nested random effect of District within State was included within the models to account for the expected similarities in effects occurring within the same districts and states of the country (as in Meiyappan et al., 2017). An offset of the area of forest cover (km^2) in the start year (1995) was included to account for the differences in the original area of forest coverage. The response variable was log-transformed due to a high amount of skew in the data and the offset was subsequently logged to match the response. Model selection was based on ANOVA, AIC and analysis of diagnostic plots.

Land cover types with less than 10 data points were excluded from the models as parameters estimated with less than this number of data points are unlikely to be able to produce reasonable effect sizes and statistical power (Harrell , 2015). This resulted in the NW region being excluded from the models as well as the 'Water bodies' land cover category in the NE and Hilly regions. Model residuals were tested for spatial autocorrelation using the function 'moran.mc' from the package spdep (v. 1.5) in R, which calculated a Moran's I statistic for the residuals and subsequently found no spatial autocorrelation in the residuals of any of the models (Table S3).

All models were conducted in R studio using R version 4.0.3 and the package lme4.

3.4 Results

3.4.1 Characterising forest loss and its relationship with forest gain

While forest loss has occurred from 1995 to 2019 in India, there has been a greater area of forest gains. Both losses and gains were high in the first five years of the study and declined until 2014, after which rose in area again but gains substantially more so than losses.

Over the course of the 24-year period (1995-2019), forest loss totalled an area of 28,549km^2, equal to 6.29% of the country's 1995 forest coverage. A large proportion, 49.8%, occurred in the first five years (1995-1999) (Figure 1). The average annual rate of loss across the 24-year period was 0.26% of the 1995 forest cover (~1,189 km^2 per year, Table S4). The fastest annual rate of loss occurred in the 1995-1999 period (0.62%) and the slowest in the 2005-2009 period (0.09%). Nationally, forest gains totalled an area of 34,387 km^2, with half of this gained in the last five years of the study (2015-2019) where the area of forest gained was more than twice the amount of forest lost in the same five-year period. Between 2000 and 2014, forest gains declined and at a faster rate that forest losses (Figure 1). The average rate of forest gain across the 24 years was 0.32% per year with the fastest rate occurring in the last period, 2015-2019 (0.83%) and the slowest in the 2010-2014 period (0.04%).

In three of the five periods, the area of forest loss was greater than the area of forest gain. However, over the 24-years, the country shows a net gain in forest cover of 5,838km^2 (0.05%), mostly in response to the large forest gains occurring in the final period.

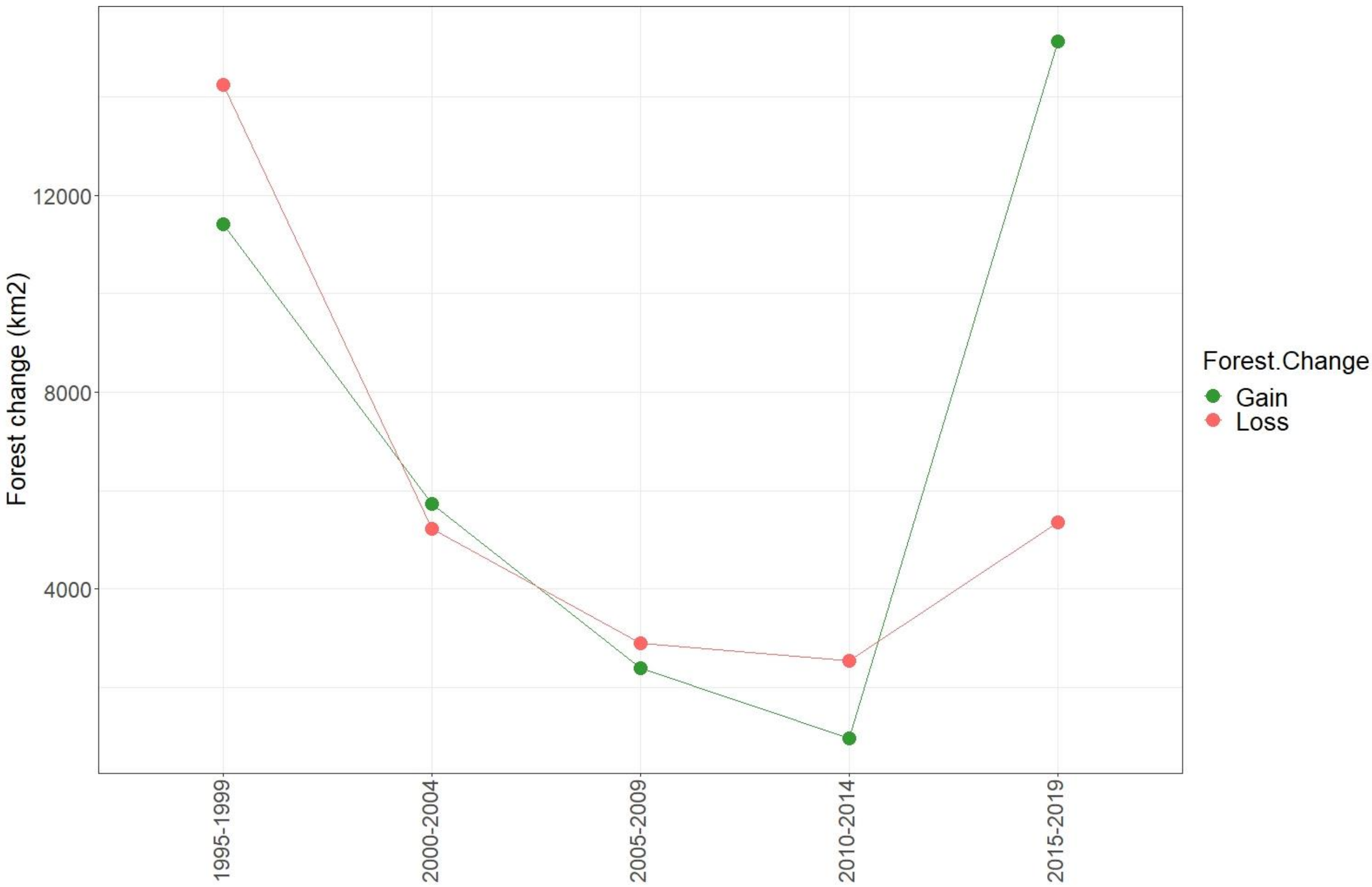


Figure 1| The total area size (km^2) of forest gains (green) and forest losses (red) in each of the five periods of the study at the national scale.

Area size of forest loss varied greatly between the monsoon regions but was most notable in the WC and CNE regions. The WC region lost the greatest area of forest over the 24 years, losing 9,146 km^2 (7.6% of its 1995 forest cover), whilst the CNE region lost the highest percentage of its original forest cover, losing 12.0% over the 24 years (7.9% of which occurred in the first five years) but had a lower areal loss of 7,563 km^2. The NW and NE regions experienced the lowest areal losses (NW: 443km^2 & NE: 1,736km^2) and NE and Hilly regions had the lowest percentage losses (NE: 2.9% & Hilly: 3.7%). Annual rates of forest loss differed between regions with the fastest annual rate of loss (0.50%) in the CNE region and the lowest annual rate of loss (0.12%) in the NE region. Most regions showed a decline in the area of forest lost through the first three periods (1995-2009) before either a levelling off or slight increase by the last period. The WC region, however, showed a substantial increase in forest loss during this later period (Figure 2).

In addition to having the second smallest area of forest losses, the NE also had the greatest area of forest gains among the six regions. Here, 8,116km^2 of forest was gained (~338km^2 per year) over the 24-year period, half of which occurred in the first period (1995-1999). The NW region, which also saw low forest losses, had the smallest area of forest gains (1,207.8km^2) but this was an annual average gain of 0.43% of its 1995 forest cover which was high compared to the national average. The Hilly region had the lowest rate of gain, gaining on average 0.19% of its 1995 forest cover per year. The greatest increases in net regional forest cover predominantly occurred during the last five years of the study in the 2015-2019 period, with the exception NE region where increases were higher in the first period (Figure 2).

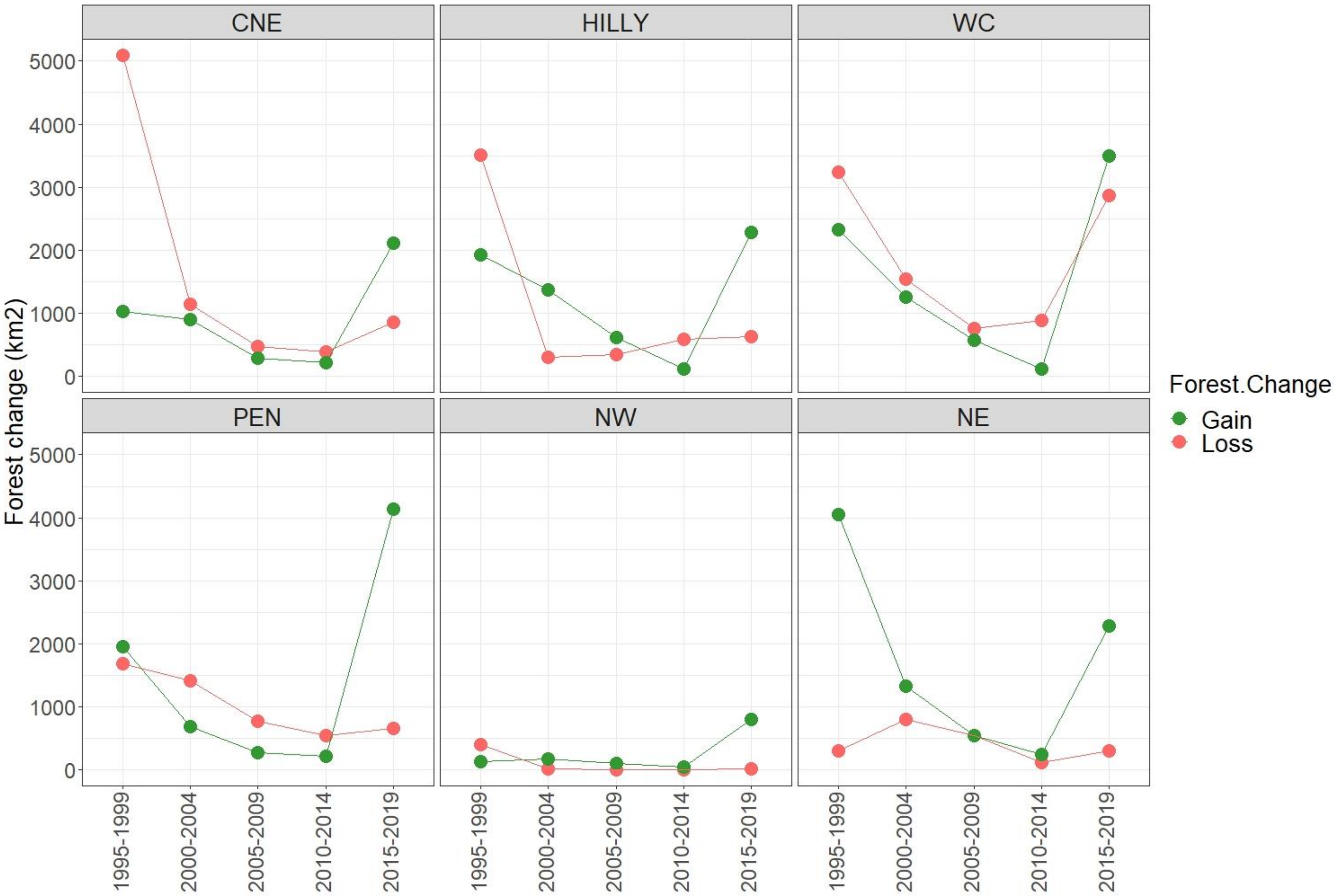
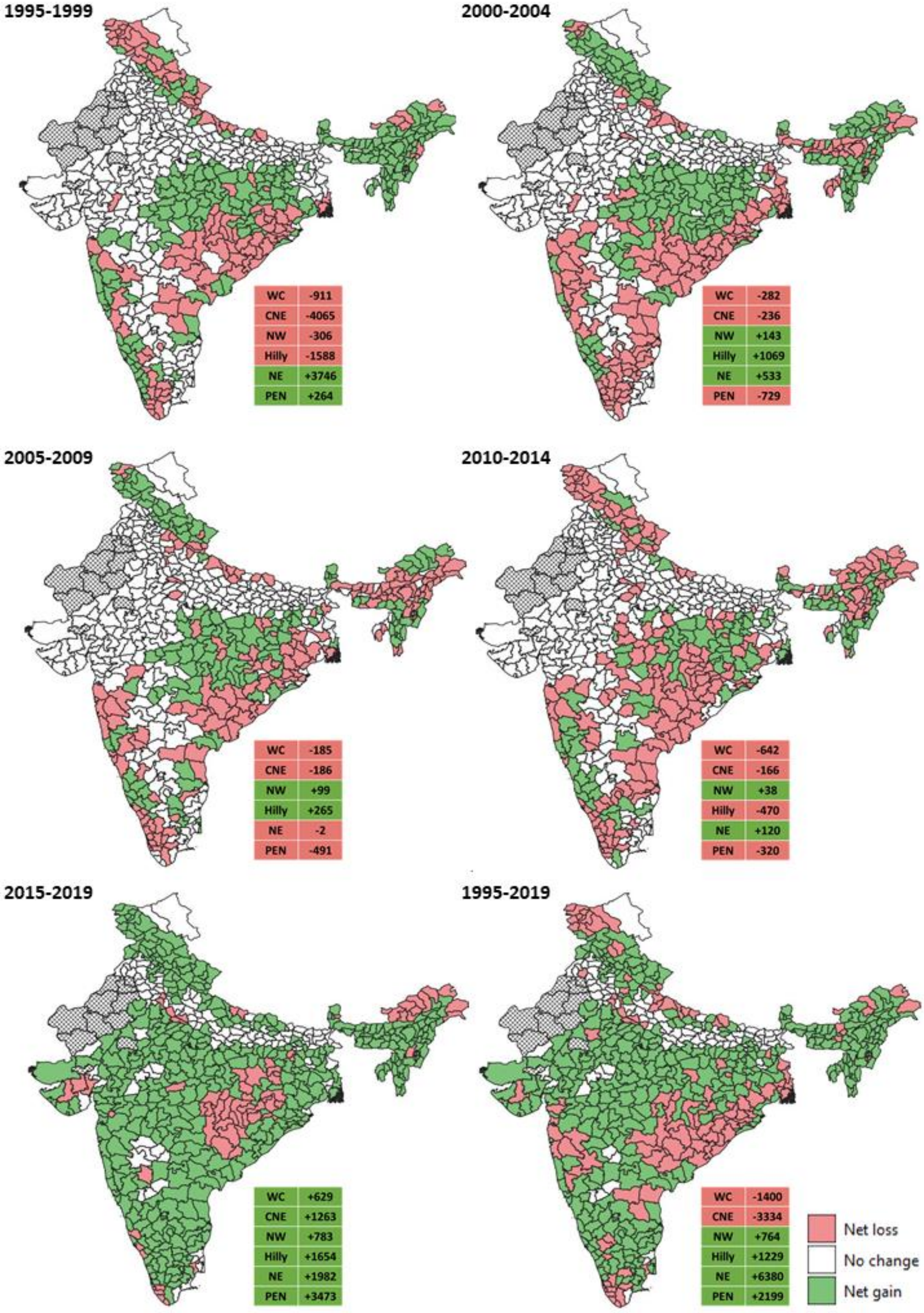


Figure 2| The total area size (km^2) of forest gains (green) and forest losses (red) in each of the five periods of the study for each monsoon region.

Prior to the 2015-2019 period, all regions were experiencing net losses, with the exception of the NE and the NW which experienced net gains in most periods (Figure 3 & Table S5). The substantial increase in forest gains in the final period of the study coupled with comparatively reduced losses resulted in all regions experiencing net increases in forest cover in the final period. Over the 24-year period of the study, four regions experienced net increases in forest cover whereas two regions, WC and CNE, experienced net reductions in forest cover (Figure 3 & Table S5). Net rates of change over the 24-year period varied regionally, ranging from -0.22% per year in the CNE to +0.44% per year in the NE (Table S4).



1995-1999

WC	-911
CNE	-4065
NW	-306
Hilly	-1588
NE	+3746
PEN	+264

2000-2004

WC	-282
CNE	-236
NW	+143
Hilly	+1069
NE	+533
PEN	-729

2005-2009

WC	-185
CNE	-186
NW	+99
Hilly	+265
NE	-2
PEN	-491

2010-2014

WC	-642
CNE	-166
NW	+38
Hilly	-470
NE	+120
PEN	-320

2015-2019

WC	+629
CNE	+1263
NW	+783
Hilly	+1654
NE	+1982
PEN	+3473

1995-2019

WC	-1400
CNE	-3334
NW	+764
Hilly	+1229
NE	+6380
PEN	+2199

Figure 3| District-based net forest change across six periods: 1995-1999, 2000-2004, 2005-2009, 2010-2014, 2015-2019 & 1995-2019. Districts where there was a net loss in forest over the period of time are shown in red, net gains are shown in green, and districts with no change in the area of forest coverage are shown in white. Black outlines display district boundaries and excluded districts are shown in a hashed pattern. Tables within the figure show the net change in forest (km^2) for each region in the same period as its accompanying map.

There was considerable variation in the trends of net forest change (forest gains minus losses) within districts across the country. For the regions with the largest net losses across the 24-year period, WC and CNE, this trend was primarily driven by a homogeneous collection of districts bordering the two regions (shown in red in Figure 4). These districts had net losses substantially higher than the surrounding districts and contrastingly, most districts within the two regions tended towards low net gains. The Hilly region, despite generally showing net increases in forest cover in all periods, contained a small number of districts with some of the highest net losses, centred in the Western portion of the region. However, these are inconspicuous when averaging over the region due to the relatively high forest gains in the southerly portion of the region (Figure 4).

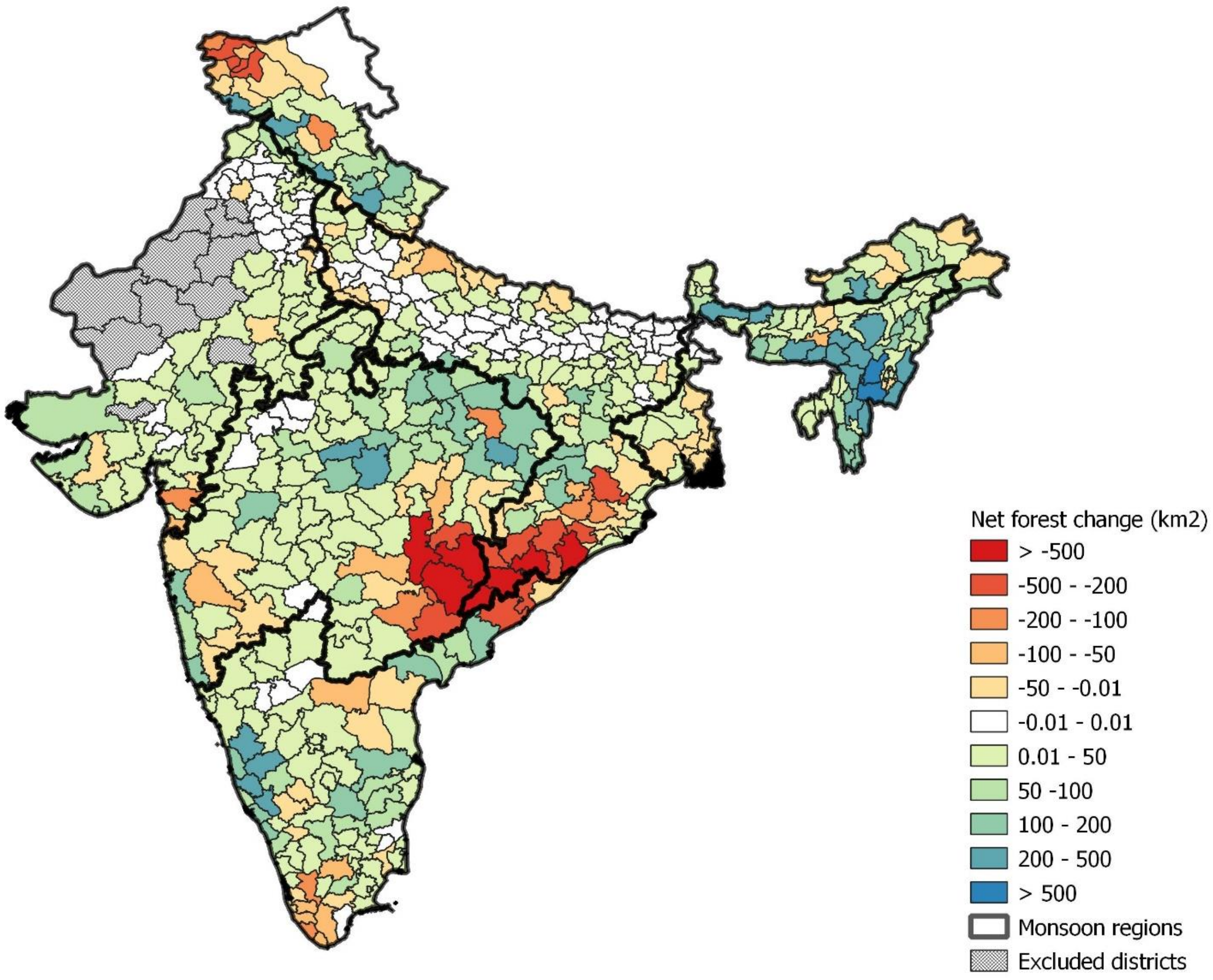


Figure 4| District-based net forest change (km^2) during the 1995-2019 study period. Black outlines show the monsoon regions, hashed areas show districts excluded from the analysis due to low forest cover. Districts shown in orange or red depict areas of net forest losses, where the area (km^2) of forest lost was greater than the area of forest gained over the period. Districts shown in green and blue depict areas of net forest increases (gains), where the area (km^2) of forest increases was greater than the area of forest lost over the period.

3.4.2 Investigating the contribution of different land use changes to forest loss

During the 24-year study period, land cover changes associated with agriculture (mosaic cropland and cropland) were responsible for 58.9% of all forest losses. Forest to mosaic cropland conversions accounted for 11,844km^2 (41.4%) of forest loss across the country, followed by conversion to natural mosaics (30.1%), and cropland (17.5%). Conversion to shrubland, urban, water and other forest types accounted for the remaining 10.8% of loss (Figure 5).

Whilst conversion to mosaic cropland, cropland and natural mosaics remained the top three contributors to forest loss throughout the first three periods accounting for >84% of all loss, both cropland and mosaic cropland reduced in their contributions over time, whilst natural mosaics and shrubland increased. By the 2010-2014 period, cropland and mosaic cropland accounted for 36% of the loss, whereas natural mosaics and shrubland accounted for 55%. This was a 34% reduction in the contribution of cropland-based land cover types to forest losses compared to the previous periods. During 2015-2019 there was a slight increase in the contributions of cropland and mosaic cropland (driven by increases in mosaic cropland), however, this was still lower, at 42%, than the contributions of natural mosaics and shrublands which was 56% (Figure 5).

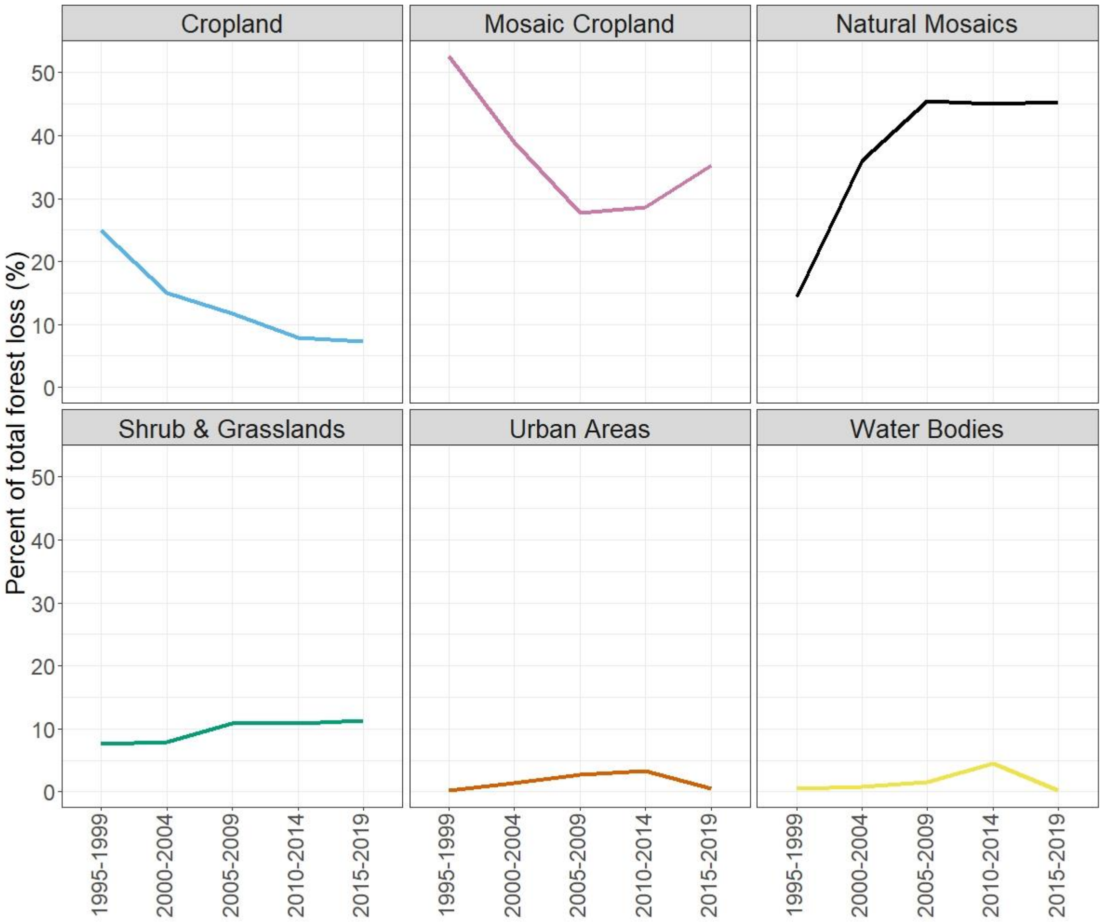


Figure 5| Percentage of national forest loss to different land covers categorised by period.

The types of land cover associated with forest loss varied regionally (Figure 6). Over the 24-years, natural mosaics and mosaic cropland had similar contributions to forest losses in the CNE, HILLY and WC regions. Whereas, in the PEN and NE region, contributions of natural mosaics to forest losses were much greater than mosaic cropland. In five of the six regions, conversion of forest to urban areas and water bodies was rare but in the NW they had considerably higher contributions to forest loss. Conversion of forest to croplands was also common in this region and associated with the majority of loss in the first two periods and the last period.

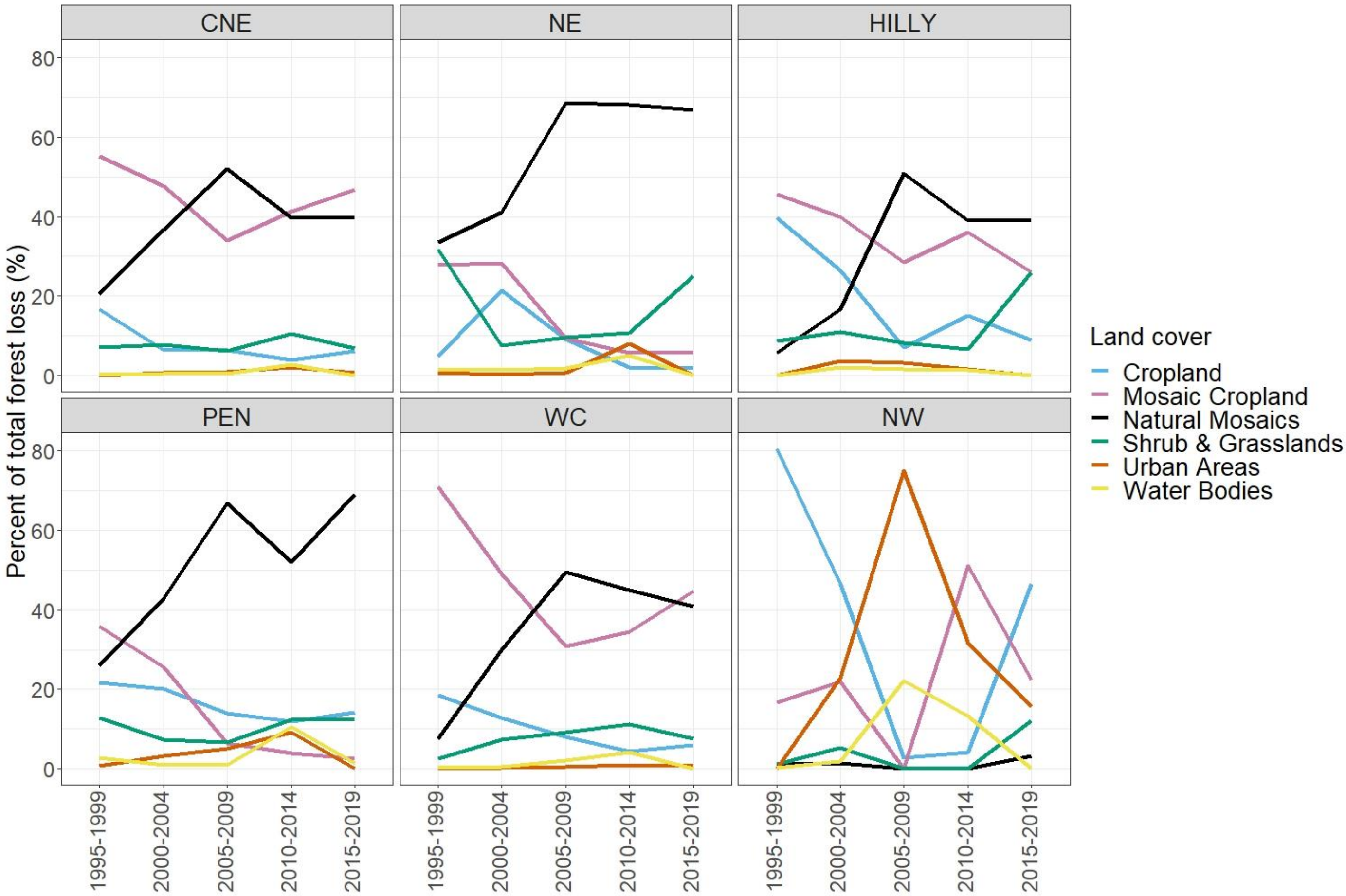
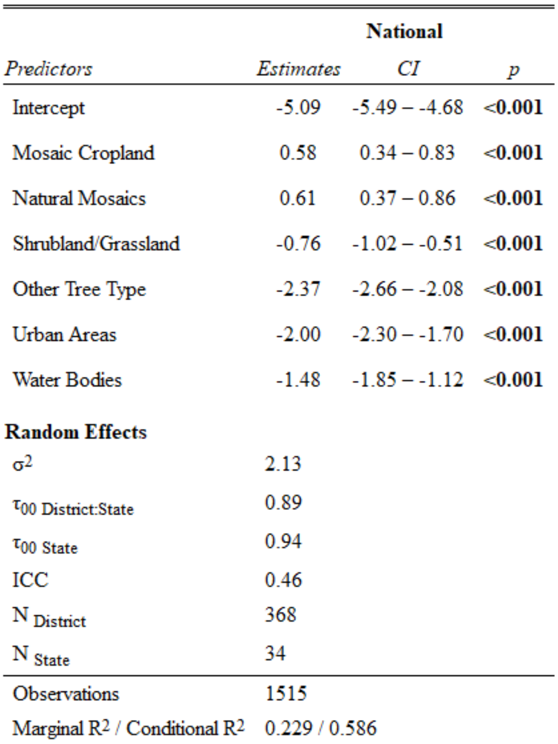


Figure 6| Percentage of forest loss to different land covers categorised by period in each monsoon region

Results from the linear mixed effects models at the national scale revealed that there was significantly more forest lost to mosaic cropland and natural mosaics than to other categories over the 24-year period (Table 1), but that these two main drivers did not contribute to significantly different amounts of loss (contrast estimate: -0.02, SE: 0.122, t: -0.219, p: >0.05) (Table S6). Conversion of forest to cropland was the third largest contributor to forest loss in the country (Table 1). The fixed effects in this model explained 23.1% of the variance, with 58.1% explained by the random effects (Table 1).

Table 1| Linear mixed effects model output of the relationship between area of forest cover lost (km^2) in a district to seven land cover predictors. The intercept represents the land cover category of cropland. Significant p-values are shown in bold.



	National		
Predictors	*Estimates*	*CI*	*p*
Intercept	-5.09	-5.49 – -4.68	**<0.001**
Mosaic Cropland	0.58	0.34 – 0.83	**<0.001**
Natural Mosaics	0.61	0.37 – 0.86	**<0.001**
Shrubland/Grassland	-0.76	-1.02 – -0.51	**<0.001**
Other Tree Type	-2.37	-2.66 – -2.08	**<0.001**
Urban Areas	-2.00	-2.30 – -1.70	**<0.001**
Water Bodies	-1.48	-1.85 – -1.12	**<0.001**
Random Effects			
σ^2	2.13		
τ_{00} District:State	0.89		
τ_{00} State	0.94		
ICC	0.46		
$N_{District}$	368		
N_{State}	34		
Observations	1515		
Marginal R^2 / Conditional R^2	0.229 / 0.586		

Conversion to mosaic cropland, natural mosaics and full cropland conversions were consistently the land cover types with the largest contributions to forest loss across all regions. Mosaic cropland resulted in more forest loss than natural mosaics and cropland in Hilly and CNE regions, whereas conversion to natural mosaics caused the majority of forest loss in PEN and NE regions (Table 2). Conversion to mosaic cropland in the WC region resulted in a higher model estimate for forest loss but this was not significantly different from forest loss to natural mosaics (Table S7). Fixed effects in the regional models accounted for between 10.8% and 36.4% of the variation in the response variable (Table 2). The NW region was the only region where conversion to full cropland resulted in the largest amount of forest losses with little contribution from other categories but was excluded from the models for having too few data points.

Table 2| Regional model output of the relationship between forest loss (log km^2) per district and seven land cover predictors in each of the six monsoon regions. The intercept represents the land cover category of cropland. Significant p-values are shown in bold. Gaps in the table occur where there are <10 instances of a predictor in a region. These results remain on the log scale.

	NE			CNE			WC			PEN			HILLY		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
Intercept	-5.77	-6.55 – -4.99	**<0.001**	-4.97	-6.04 – -3.89	**<0.001**	-5.65	-6.40 – -4.89	**<0.001**	-4.91	-5.46 – -4.36	**<0.001**	-5.33	-6.25 – -4.41	**<0.001**
Mosaic Cropland	0.15	-0.39 – 0.69	0.584	1.29	0.79 – 1.79	**<0.001**	1.13	0.64 – 1.62	**<0.001**	-0.39	-0.92 – 0.13	0.140	0.90	0.39 – 1.42	**0.001**
Natural Mosaics	1.14	0.59 – 1.68	**<0.001**	0.50	-0.01 – 1.01	0.054	0.38	-0.12 – 0.89	0.139	1.19	0.67 – 1.70	**<0.001**	0.08	-0.44 – 0.60	0.768
Shrubland/Grassland	-0.14	-0.72 – 0.45	0.644	-0.89	-1.45 – -0.34	**0.002**	-1.09	-1.60 – -0.57	**<0.001**	-0.73	-1.26 – -0.20	**0.007**	-0.70	-1.22 – -0.18	**0.009**
Other Tree Type	-1.94	-2.59 – -1.29	**<0.001**	-3.25	-3.93 – -2.58	**<0.001**	-2.50	-3.23 – -1.77	**<0.001**	-2.22	-2.79 – -1.66	**<0.001**	-2.18	-2.73 – -1.63	**<0.001**
Urban Areas	-1.92	-2.55 – -1.30	**<0.001**	-1.81	-2.58 – -1.03	**<0.001**	-2.28	-3.00 – -1.56	**<0.001**	-1.73	-2.35 – -1.11	**<0.001**	-2.87	-3.46 – -2.28	**<0.001**
Water Bodies				-2.45	-3.28 – -1.61	**<0.001**	-1.56	-2.17 – -0.96	**<0.001**	-0.96	-1.67 – -0.24	**0.009**			
Random Effects															
σ^2	1.97			1.84			1.92			1.85			1.69		
τ_{00}	0.58 District:State			0.73 District:State			1.11 District:State			1.58 District:State			0.24 District:State		
	0.80 State			1.08 State			0.48 State			0.07 State			0.83 State		
ICC	0.41			0.50			0.45			0.47			0.39		
N	75 District			76 District			74 District			63 District			51 District		
	8 State			5 State			6 State			5 State			5 State		
Observations	290			274			312			302			267		
Marginal R^2 / Conditional R^2	0.254 / 0.561			0.348 / 0.671			0.284 / 0.608			0.247 / 0.603			0.364 / 0.610		

3.4.3 Understanding the extent of forest loss for different forest types

By far the largest forest losses across the 24-year period were in broadleaved deciduous (closed to open >15%) forests (Table S8). This type of forest lost 19,149km^2, which was twice the amount of the next category needle-leaved evergreen (closed to open >15%), which lost 5,910km^2. For broadleaved deciduous (closed to open >15%) forests this equates to a loss of 7.4% and for needle-leaved evergreen (closed to open >15%) forests it equated to 5.2% loss of their 1995 forest coverage. These are also the highest percentage losses of forest cover across the forest types.

Broadleaved deciduous (closed to open >15%), also had the highest gains amounting to 19,289km^2 (7.4% of 1995 coverage), resulting in net gains overall. The forest type with the second largest gains of

8,591km^2 (8.4% of its 1995 coverage) was broadleaved evergreen (closed to open >15%) forest. The largest percentage increases were found in needle leaved deciduous (closed >40%) forests which saw a 195% increase in coverage, alongside incurring no losses. This increase occurred exclusively in the 2015-2019 period before which no change occurred in this forest type, and it is worth noting that this corresponded to only a 15km^2 increase in area. Prior to 2015, the forest type with substantially larger percentage increases in forest coverage than any other forest type was flooded saline forests, which saw a 15% increase in area between 1995-2014.

Most forest types increased in area over the 24-years, after accounting for both losses and gains. The forest types that experienced the largest net gains were broadleaved evergreen (closed to open >15%) and needle leaved deciduous (closed to open >15%) forest types, which experienced net gains of 4,895km^2 and 325km^2. Though these values have very different meanings in terms of expansion of these forest types, where broadleaved evergreen (closed to open >15%) expanded by 8.4% but needle leaved deciduous (closed to open >15%) forests expanded by 45%. Only two forest types experienced net losses over the 24-years, these were broadleaved deciduous (closed >40%) and needle leaved evergreen (closed >40%), losing 20km^2 and 0.18 km^2 respectively.

It is important to note that broadleaved deciduous (closed to open >15%), needle-leaved evergreen (closed to open >15%), and broadleaved evergreen (closed to open >15%) forests, which have the highest forest loss and gains, also constitute the largest coverage of forest, accounting for 96.3% of India's forest cover.

Regionally, the major type of forest lost was broadleaved deciduous (closed to open >15%); in half of the regions (CNE, NW, WC) 90-96% of the loss was from this category of forest. The NE and Hilly regions predominantly lost forest from different types: the NE lost mostly from broadleaved evergreen (closed to open >15%) accounting for ~46% of total loss and Hilly region predominantly lost needle leaved evergreen (closed to open >15%) forests accounting for ~71% of total loss. The PEN region predominantly lost broadleaved evergreen (closed to open >15%) and broadleaved deciduous (closed to open >15%), 44% and 41% of the region's total loss, respectively.

There was also an interesting trend in the types of land cover that different forest types were lost to, and land use categories did not contribute evenly to losses across forest types. The two forest types with the largest losses, broadleaved deciduous (closed to open >15%) and needle-leaved evergreen (closed to open >15%) forests had the highest contributions of agricultural land uses to loss. For both types, croplands and mosaic croplands contributed to >64% of their losses. The only other forest type which lost predominantly to agricultural land uses was broadleaved deciduous (closed >40%) forest where 73% of loss in this type could be attributed to cropland and mosaic croplands. This type of forest was one of the only types to still be experiencing net losses. Other forest types lost <35% to agricultural land uses and mainly lost coverage to urban areas and shrublands.

3.5 Discussion

This study aimed to characterise forest change during the period 1995-2019, to assess the primary cause of forest loss, as well as to investigate whether different forest types and geographical regions were experiencing disproportionate forest changes. These findings show that although rates of forest loss remain concerning in India, areas of forest gain are more numerous, and the country has been experiencing overall net gains between 2015-2019. Conversion of forest to mosaic-cropland was the primary cause of loss across the period, indicating that agriculture remains the biggest contributor to forest loss in the country. The study also found that forest losses were not distributed evenly across forest types and regions. The study provides detailed information on forest changes during a period currently unaccounted for in the literature and provides novel indications of a shift in drivers of forest loss over time in India.

These analyses provide supportive evidence to past studies showing that forest loss continued to decline post-1995 (Roy et al. 2013; Sudhakar Reddy et al., 2016). Despite reductions in forest losses, there was a net decline in forest nationally in three of the five periods. This is largely due to forest gains reducing faster and on a larger scale than losses, e.g., in 2010-2014 losses reduced by 12.3% but gains reduced by 59.7%. This is surprising considering India’s commitments to reforestation over this period and the average annual net gains of 0.4% reported by the FSI over this time (FSI, 1995; FSI 2015). However, rapid increases in forest gains compared to losses during the 2015-2019 period resulted in overall net increases of 0.05% in forest cover over the 24 years of the study. These net increases and lower rates of forest loss suggest that forest policies may be starting to take effect, but the tendency towards small increases in losses in half of the regions by the final period, is concerning. Our analyses estimate that India lost ~6.3% of its original forest cover over the 24 years of the study. Though comparative studies (of a similar length of time) are limited, a study by Jha et al., (2000) showed a 25.6% loss in forest cover in the 20 years preceding this study (1973-1995). We show a considerable reduction in the forest loss in more recent times in comparison. The study by Jha et al., (2000) focused on quantifying forest loss across the Western Ghats area (part of our Peninsular region), which in this chapter we show to be experiencing net forest increases across most of its districts during the last 10 years. This further shows the importance, and need, for more frequent recent research on changes in India’s forest coverage since the trajectory and magnitude appear to be changing rapidly.

The net change in forest cover reported in this study (+0.05%) is also small compared to the FSI reports of the same period. Though FSI do not publish rates of change, using the forest cover estimates for two years we can estimate the annual rate of change to be +1.09% between 1995 and 2019 (FSI, 1995; FSI 2019) but are similar in scale to past research in the country, which showed a net change of 0.05% during 2005-2007 (Sudhakar Reddy et al., 2016). For forest research in India, it has been common to record large differences in rates of change between studies due to differences in the definition of forest and the resolution of data used (Reddy et al., 2013). In addition, several studies have criticised the efficacy of the FSI reports in producing a representative rate of forest change and over-inflation of forest change is a concern in these reports (Puyravaud et al., 2010; Roy & Joshi, 2010). Overall, nationally these analyses show trends of a net increase in forest cover and a greater rate of gain compared to losses which is potentially positive for biodiversity protection in the country and could be a sign that conservation policies are beginning to work.

Interestingly, most forest gains over the 24 years were a result of loss of shrubland, which has been found in other studies (Sudhakar Reddy et al., 2016; Tian et al., 2014) and is thought to be a response to government advocated schemes targeting wastelands and degraded forest areas for afforestation (Sudhakar Reddy et al., 2016). Though increases in forest coverage are likely to be beneficial to many species, it raises concern for the conservation of species specific to shrubland habitats, shrublands and grasslands have been shown to be globally at high risk (Bremer & Farley, 2010; Newbold et al., 2016). Furthermore, the interplay between forest losses and gains is important in reaching target amounts of forest cover but forest gains may not provide the same benefits, at least in the short term, to biodiversity that were provided by the lost forest especially if a different forest type is gained (Coleman et al., 2021; Kimberley et al., 2019; Puyravaud et al., 2010; Watts et al., 2020). The best insurance for biodiversity remains the maintenance and future survival of old-growth forests where possible (Gibson et al., 2011).

Regionally, the rates of forest losses and gains were highly variable and support the chapter hypothesis that regional variation would be found. The two regions where forest is most threatened are the WC and CNE regions both of which experienced large net losses over the 24-year period and consistently in the first 20-years. The WC and CNE regions also have some of the highest percentage losses and the highest rates of loss across the 24-year period at 0.32 % (WC) and 0.50% (CNE). A review paper analysing previous estimates from smaller-scale studies in the areas of high loss in these regions found annual rates of loss in these regions between 0.19-3.2 (Deccan Peninsular, WC) and 0.74-1.83 (Odisha, CNE) (Reddy et al., 2013). Our rates are similar in comparison and on the lower end which is unsurprising given the reductions in loss seen over the last 24 years. These two regions are often overlooked in regional studies in favour of the more biodiversity rich Northeast and Western Ghats areas, despite them containing large tracts of tiger and elephant habitats (NTCA, 2018). They are also key agricultural zones where maintenance of natural forest cover could play a role in ensuring soil stability and water retention to prevent agricultural losses in the future. Another region where the rate of forest loss is concerning is the Hilly region. Despite this region generally showing increases in forest cover and lower rates of loss, when visualising the area of forest change on the district level it was clear that there are several districts in the Western part of the region that have experienced some of the largest net declines in forest cover. This has been found in other studies of this region where deforestation is markedly higher in the Western portion than the East due to higher population densities (Pandit et al. 2007). Our results contrast with earlier reports of highest levels of forest loss in the NE region (Lele et al., 2008; Lele & Joshi, 2009; S. Reddy et al., 2013) and suggest that in recent years it is one of the least affected areas of the country. In these analyses, this region experienced the largest net increase in forest cover and had the lowest percentage loss of original cover, losing 2.9% between 1995 and 2019.

This study analysed recent forest change trends across India, showing that agriculture-based land use changes are still largely responsible for forest loss across India during the period 1995-2019. This supports the chapter hypothesis and earlier studies showing the importance of agriculture in forest change (Gupta, 2007; Meiyappan et al., 2017; Padalia et al., 2019). However, despite agriculture-based land cover changes accounting for 59% of the forest loss across the 24-years, the majority of loss was not as a result of complete conversion of forest to cropland and more forest was lost to mosaic cropland conversions and natural mosaic conversions, nationally and in all but one of the regions. The only region where conversion to cropland was associated with the largest amounts of losses was in the NW region but due to this region containing very low levels of forest cover, this could not be confirmed in the models. Distinction between the two types of croplands, mosaic cropland and cropland, is important because mosaic cropland, retaining a proportion of natural vegetation, likely supports a higher level of biodiversity and forest intactness (depending on the proportion of natural vegetation remaining) than full conversion to cropland (Roy et al. 2013; Anand et al., 2010; Haddad et al., 2015; Oliver et al., 2016; Raman, 2006). This finding also likely supports previous research which has shown that many areas of forest that are lost to agriculture-based land cover conversions in India are due to shifting cultivation, encroachment and small-scale agriculture (Lele et al., 2008; Meiyappan et al., 2017).

The findings also show previously undetected indications that the main cause of loss is changing with time, identifying a shift towards forest loss driven by conversion to natural mosaics, shrubland and grasslands which by the final period account for a larger proportion of the loss compared to agriculture-based conversions. This is the first documented shift in the main driver of national forest loss away from agriculture in the country, though increases in the contributions of shrubland conversions to forest loss have been found in previous studies (Meiyappan et al., 2017; Sudhakar Reddy et al., 2016). This study cannot identify the casual factors behind this shift, but it is possibly a success of the country's national forest policies reducing forest losses from large-scale agricultural expansions (Tian et al., 2014; National Forest Policy, 1988). The location of the remaining forests could also be a factor since it is likely that much of the cultivatable land has already lost its forest cover and the remaining forests are in harder to reach locations or those less suitable for growing crops (J. J. Liu & Slik, 2014). Many areas where the practice of shifting cultivation is present often have areas of shrubland in between cropping phases due to the start of forest regrowth which could be contributing to this trend (Kant & Katwal, 2003; Lele et al., 2008). The unique patterning and shortening rotational cycles of shifting cultivation practices (Kundu et al., 2015; Nikhil Lele & Joshi, 2009) could also result in an under-estimation of the effect of agriculture if it is classed instead as natural mosaics or shrubland. Without further information from ground-based and social surveys, alongside repeated studies from this time period, is it difficult to conclude why this shift from agriculture-based forest loss is occurring, and whether it will continue given slight increases in agriculture-based contributions in the final period of the study.

The highest areal and percent coverage losses of forest were consistently found in the most prolific forest type nationally, broadleaved deciduous (closed to open >15%), and this was also the case in half of the regions. This supports previous studies which find broadleaved deciduous forests to be at high risk to human exploitation in India (Coleman et al., 2021; Ramprasad et al., 2020; Wakeel et al., 2005). This forest type also had disproportionately higher losses as a result of agricultural conversions. However, encouragingly they also experienced the largest increases in forest area and are expected to be more resilient to a warming and drying climate (Aguirre-Gutiérrez et al., 2020; Esquivel-Muelbert et al., 2019; Suresh et al., 2010). The high increases in broadleaved area may also be due to its selection for afforestation programs in some areas. These programmes sometimes use broadleaved genera such as Eucalyptus, Quercus and Acacia because of the high yields of timber, fuelwood and fodder they provide which could reduce pressure for resources on old-growth forests (Kesari & Rangan, 2010; Köhlin & Parks, 2001; Ramprasad et al., 2020). Between 1995-2014, the largest percent coverage increases of a forest type were in flooded saline forests, which saw a 12% net increase in coverage which was over twice that of any other forest type. Net increases of this forest type were seen in all regions and could be an indicator of increased conservation or of sea-level rise. The increase in flooded forest area in India has been found in other studies and has been primarily attributed to restoration activities in place to tackle sea level rise on India's coasts (Ghorai et al., 2016; Murthy et al., 2015; Prasad et al., 2017).

Interestingly, there is considerable mismatch between the types of forest being lost and gained across the study period. Firstly, though most forest types experienced net gains in coverage on the national level, there were differences in the magnitude of these gains between types. For example, needle-leaved evergreen lost 5.2% of its 1995 coverage and gained 5.3%, leading to a net gain of around 0.1%. In contrast, broadleaved evergreen forests lost 3.6% of coverage but gained 8.4%. Secondly, at the regional scale there were mismatches between the types of forest lost and gained. For example, the Central Northeast region predominantly lost forest from the broadleaved deciduous forest type but gained needle-leaved deciduous forests. Whereas the Hilly region predominantly gained broadleaved deciduous forests and lost needle-leaved evergreen forests. These regional differences between types of forests being lost and gained can be overlooked when looking at national totals depicting mainly gains in all forest types. However, differences in climate, habitat types, predation, and food, among many factors, mean that both different types of forests and forests in different areas, protect different species (Karanth et al., 2010; Utkarsh et al., 1998) and so losing forest in one area and gaining in another is likely to impact biodiversity. This is particularly concerning in regions such as the WC and CNE which lost a lot of forest and experienced lower forest gains. Additionally, the shift in the different types of forest being gained compared to those being lost could be due to natural causes such as climate, due certain species being more competitive in the successional stages of new forest growth or to reforestation preferences (Alexander et al., 2015; Asher & Bhandari, 2021). Relocation of some types of forest is expected across the country in response to climate change (Chitale et al., 2014; Deb et al., 2017; Ravindranath & Sukumar, 1998). For example, many regions will be more favourable to drought-tolerant species and previously dry regions may become more hospitable to forest growth where precipitation increases are projected (Ravindranath & Sukumar, 1998; Sharma et al., 2017). In these instances, potential reforestation schemes could plan for future climate change effects on species by reforesting in regions that may have more favourable climate in the future or by using tree species better suited to the changing climate. This future-proofing of the forest could, if appropriate habitat corridors are ensured, protect species that might otherwise suffer under climate change. Due to increasing human pressures on the land, reforestation and afforestation schemes are also likely to be limited in where they have access to land and may not have the luxury of choice of forest type and location of the afforestation which could be contributing to the observed mismatches (Coleman et al., 2021; Ramprasad et al., 2020).

Chapter 2, which also assessed forest loss across the country during a similar time period (though covering 2001-2018 rather than 1995-2019), showed different trends in forest loss than those found in this chapter, and it is worth highlighting the extent of these differences and the potential reasoning for this. In Chapter 2, the analysis used a different dataset for forest change (Global Forest Change by

Hansen et al., 2013) than this chapter which used the ESA CCI land cover product. The Chapter 2 analysis found forest loss in India to be extensive between 2001-2018, averaging 1,204km^2 per year. Whereas, using the data from this chapter for as similar time period as possible (2000-2019), loss is estimated at 766km^2 per year. This is still extensive but a much reduced rate. Furthermore, the two datasets showed differing locations of concern for forest loss, since Chapter 2 showed the NE to have the greatest rate of loss, but this chapter showed drastically lower forest loss in comparison, and for the CNE and WC regions to have the greatest areas of loss. The differences seem to lie in the classification of shrubland and forest pixels, where the Global Forest Change dataset used in Chapter 2 tends to classify more pixels as forest than the CCI land cover dataset. Some of the forest pixels classified as forest in the Global Forest Change dataset are classified as shrubland in the CCI land cover dataset likely due to the similar composition of vegetation and hence likely a similar spectral signature making it hard to distinguish between the two. It is concerning to see such a disparity between two regularly used datasets which could result in a misunderstanding of the magnitude of the problem, as well as leading to different management strategies between the regions without a true understanding of which needs greater protection. This is discussed further in Chapter 5.

This study has provided novel insights into the scale and main drivers of forest loss in recent times in India. However, there are some key limitations and areas of future study that are necessary to further this work. Firstly, the study would benefit from a locally derived land cover classification instead of relying on a global dataset which is likely to have more errors and misclassifications on a local scale (Liu et al., 2018; Pérez-Hoyos et al., 2017). This could also provide greater confidence in the classification given the disparity between datasets discussed earlier. Further analysis should be undertaken to measure the accuracy of these classifications for India, since the scale of the data may be masking smaller scale transitions in land cover possibly resulting in an underestimation of loss. As such, the study was constrained by lack of available and accessible data classified for India which is commonly cited as a problem (Davidar et al., 2010; Pandit et al., 2007; Tsarouchi, Mijic, Moulds, & Buytaert, 2014) and a lack of comparable studies. Secondly, further local knowledge is needed to ascertain the exact causes of loss beyond solely what the land has been converted to. Understanding the underlying drivers of conversion to these land cover types is essential for mitigating forest loss in the future. The same conversion type can be driven by completely different drivers e.g. conversion to natural mosaics could be due to shifting cultivation, logging, other local uses of the forest products such as villages with a main trade around wood products (Meiyappan et al., 2017).

Overall, this study presents a much needed analysis of the trends of forest change in India in the two most recent decades. The study importantly highlights a shift towards net forest increases in recent years but cautions over increases in forest losses in recent years. The study concludes that conversion of forest to agricultural-based land cover remains the primary concern for forests across the 24-years, but also highlights a potential novel shift towards increases in contributions of natural-based land cover in the future. More research needs to be done to comparatively assess this period, to examine the consequential effects on biodiversity and the mechanisms behind the changes in these broad land cover types. This study paints an encouraging picture for the conservation of forests in India following extensive net increases in forest cover in recent years. However, in order to maintain India's high levels of biodiversity and forest cover, appropriate land cover planning on both a national and regional level will be necessary and as such, recent research such as this on the trajectory and main contributors to forest loss is much needed. The findings suggest that additional conservation action is needed to reduce forest loss within the West Central and Central Northeast regions of the country, the areas with the greatest forest losses, and to account for disproportionate losses to broadleaved deciduous forests.

3.6 References

Adhikari, S., Southworth, J., & Nagendra, H. (2015). Understanding forest loss and recovery: a spatiotemporal analysis of land change in and around Bannerghatta National Park, India. *Journal of Land Use Science*, *10*(4), 402–424. https://doi.org/10.1080/1747423X.2014.920425

Aguirre-Gutiérrez, J., et al., (2020). Long-term droughts may drive drier tropical forests towards increased functional, taxonomic and phylogenetic homogeneity. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-16973-4

Alexander, J. M., Diez, J. M., & Levine, J. M. (2015). Novel competitors shape species' responses to climate change. *Nature*, *525*(7570), 515–518. https://doi.org/10.1038/nature14952

Anand, M. O., et al., (2010). Sustaining biodiversity conservation in human-modified landscapes in the Western Ghats: Remnant forests matter. *Biological Conservation*, *143*(10), 2363–2374. https://doi.org/10.1016/j.biocon.2010.01.013

Asher, M., & Bhandari, P. (2021). Mitigation or Myth? Impacts of Hydropower Development and Compensatory Afforestation on forest ecosystems in the high Himalayas. *Land Use Policy*, *100*, 105041. https://doi.org/10.1016/J.LANDUSEPOL.2020.105041

Bana, R. S. (2014). Soybean based cropping systems. *Indian Journal of Agronomy*. 59(2), 179-190

Bhattacharjee, K., & Behera, B. (2017). Forest cover change and flood hazards in India. *Land Use Policy*, *67*, 436–448. https://doi.org/10.1016/j.landusepol.2017.06.013

Bremer, L. L., & Farley, K. A. (2010). Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. *Biodiversity and Conservation*, *19*(14), 3893–3915. https://doi.org/10.1007/S10531-010-9936-4

Chaturvedi, R. K., et al., (2011). Impact of climate change on Indian forests: A dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change*, *16*(2), 119–142. https://doi.org/10.1007/s11027-010-9257-7

Chitale, V. S., Behera, M. D., & Roy, P. S. (2014). Future of endemic flora of biodiversity hotspots in India. *PLoS ONE*, *9*(12). https://doi.org/10.1371/journal.pone.0115264

Coleman, E. A., et al., (2021). Limited effects of tree planting on forest canopy cover and rural livelihoods in Northern India. *Nature Sustainability*, 1–8. https://doi.org/10.1038/s41893-021-00761-z

Congedo, L (2021). Semi-automatic classification plugin: A python tool for the download and processing of remote sensing images in QGIS. *Journal of Open Source Software*. 6(64) 3172.

Davidar, P., et al., (2010). Assessing the extent and causes of forest degradation in India: Where do we stand? *Biological Conservation*, *143*(12), 2937–2944. https://doi.org/10.1016/j.biocon.2010.04.032

Deb, J. C., et al., (2017). Climatic-Induced Shifts in the Distribution of Teak (Tectona grandis) in Tropical Asia: Implications for Forest Management and Planning. *Environmental Management*, *60*(3), 422–435. https://doi.org/10.1007/s00267-017-0884-6

Di Gregorio, A. (2016). *Land Cover Classification System : Classification concepts. Software version 3*. Retrieved from http://www.fao.org/3/a-i5232e.pdf

Esquivel-Muelbert, A., et al., (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, *25*(1), 39–56. https://doi.org/10.1111/GCB.14413

FAO. (2020). *The State of the World's Forests 2020*. *The State of the World's Forests 2020*. FAO and UNEP. https://doi.org/10.4060/ca8642en

FSI (1995). State of the Forest Report, 1995. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

FSI (2001). State of the Forest Report, 2001. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

FSI (2015). State of the Forest Report, 2015. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

FSI (2017). State of the Forest Report, 2017. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

FSI (2019). State of the Forest Report, 2019. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

Ghorai, D., Mahapatra, M., & Paul, A. K. (2016). Application of Remote Sensing and GIS Techniques for Decadal Change Detection of Mangroves along Tamil Nadu Coast, India. *Journal of Remote Sensing & GIS*, *7*(1), 42–53.

Gibson, L., et al., (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, 478(7369), 378–381. https://doi.org/10.1038/NATURE10425

Gupta, H. K. (2007). Deforestation and Forest Cover Changes in the Himachal Himalaya, India. *International Journal of Ecology and Environmental Sciences,* 33 (2).

Haddad, N. M., et al., (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, *1*(2), https://doi.org/10.1126/sciadv.1500052

Hansen, M. C., et al., (2013). High-resolution global maps of 21st Century forest cover change. *Science*, 342(6160), 850-853

Harrell , F. E. (2015). *Regression Modeling Strategies*. Springer Series in Statistics. Springer Cham. https://doi.org/10.1007/978-3-319-19425-7

Horák, J., et al., (2019). Green desert?: Biodiversity patterns in forest plantations. *Forest Ecology and Management*, *433*, 343–348. https://doi.org/10.1016/J.FORECO.2018.11.019

Jha, C. S., Dutt, C. B. S., & Bawa, K. S. (2000). Deforestation and land use changes in Western Ghats, India. *Current Science*, *79*(2), 231–238.

Kanowski, J., Catterall, C. P., & Wardell-Johnson, G. W. (2005). Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *Forest Ecology and Management*, *208*(1–3), 359–372.

Kant, P., & Katwal, R. P. S. (2003). Exploring possibilities of reforestation of forest lands exposed to encroachment and shifting cultivation in the North Eastern India through clean development mechanisms. Published in the Proceedings of the National Workshop on Technological Innovations and Research Advancements for Application in Joint Forest Management held at

ICFRE, Dehradun, February 3 & 4, 2003, pages 153 - 159

Karanth, K. K., et al., (2010). The shrinking ark: Patterns of large mammal extinctions in India. *Proceedings of the Royal Society B: Biological Sciences*, 277, 1971-1979. https://doi.org/10.1098/rspb.2010.0171

Kesari, V., & Rangan, L. (2010). Development of Pongamia pinnata as an alternative biofuel crop — current status and scope of plantations in India. *Journal of Crop Science and Biotechnology*, *13*(3), 127–137. https://doi.org/10.1007/S12892-010-0064-1

Kimberley, A., Bullock, J. M., & Cousins, S. A. O. (2019). Unbalanced species losses and gains lead to non-linear trajectories as grasslands become forests. *Journal of Vegetation Science*, *30*(6), 1089–1098. https://doi.org/10.1111/JVS.12812

Köhlin, G., & Parks, P. J. (2001). Spatial variability and disincentives to harvest: Deforestation and fuelwood collection in South Asia. *Land Economics*, *77*(2), 206–218. https://doi.org/10.2307/3147090

Kumar, D., & Scheiter, S. (2019). Biome diversity in South Asia - How can we improve vegetation models to understand global change impact at regional level? *Science of The Total Environment*, *671*, 1001–1016. https://doi.org/10.1016/J.SCITOTENV.2019.03.251

Kundu, S. et al., (2015). Shifting cultivation dynamics in Barak basin of North East India: A Geospatial Approach. *International Journal of Advancement in Earth and Environmental Sciences* 3(2), 21-29

Lele, N., Joshi, P. K., & Agrawal, S. P. (2008). Assessing forest fragmentation in northeastern region (NER) of India using landscape matrices. *Ecological Indicators*, *8*(5), 657–663.

Lele, Nikhil, & Joshi, P. K. (2009). Analyzing deforestation rates, spatial forest cover changes and identifying critical areas of forest cover changes in North-East India during 1972–1999. *Environmental Monitoring and Assessment*, *156*(1–4), 159–170.

Liu, J. J., & Slik, J. W. F. (2014). Forest fragment spatial distribution matters for tropical tree conservation. *Biological Conservation*, *171*, 99–106.

Liu, X., et al., (2018). Comparison of country-level cropland areas between ESA-CCI land cover maps and FAOSTAT data. *International Journal of Remote Sensing. 39*(20), 6631–6645.

Martello, F., et al., (2018). Homogenization and impoverishment of taxonomic and functional diversity of ants in Eucalyptus plantations. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-20823-1

Meiyappan, P., et al., (2017). Dynamics and determinants of land change in India: integrating satellite data with village socioeconomics. *Regional Environmental Change*, 17, 753-766. https://doi.org/10.1007/s10113-016-1068-2

Murthy, I. K., et al. (2015). Mangrove Area Assessment in India: Implications of Loss of Mangroves. *J Earth Sci Clim Change*, *6*, 280. https://doi.org/10.4172/2157-7617.1000280

Nayak, S., & Mandal, M. (2019). Impact of land use and land cover changes on temperature trends over India. *Land Use Policy*, *89*. https://doi.org/10.1016/j.landusepol.2019.104238

National Forest Policy (1988). Ministry of Environment and Forests. Government of India. New Delhi. Accessed at: http://asbb.gov.in/Downloads/National%20Forest%20Policy.pdf

Newbold, T. et al. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science*, *353*(6296), 291–288.

Oliver, I., et al. (2016). Additive and synergistic effects of land cover, land use and climate on insect biodiversity. *Landscape Ecology*, 31, 2415-2431. https://doi.org/10.1007/s10980-016-0411-9

Padalia, H., et al. (2019). Assessment of historical forest cover loss and fragmentation in Asian elephant ranges in India. *Environmental Monitoring and Assessment*, *191*. https://doi.org/10.1007/s10661-019-7696-5

Pandit, M. K., et al. (2007). Unreported yet massive deforestation driving loss of endemic biodiversity in Indian Himalaya. *Biodiversity and Conservation*, *16*(1), 153–163. https://doi.org/10.1007/s10531-006-9038-5

Pérez-Hoyos, A., et al. (2017). Comparison of Global Land Cover Datasets for Cropland Monitoring. *Remote Sensing*, *9*(11), 1118. https://doi.org/10.3390/RS9111118

Phommexay, P., et al. (2011). The impact of rubber plantations on the diversity and activity of understorey insectivorous bats in southern Thailand. *Biodiversity and Conservation*, *20*(7), 1441–1456. https://doi.org/10.1007/S10531-011-0036-X

Prasad, P. R. C., Karuna, C. V. L., & Kumari, J. A. (2017). Evaluating mangroves of Krishna Wildlife Sanctuary in relation to the general status of mangroves in Andhra Pradesh, India. *International Journal of Environmental Studies*, *74*(2), 214–229. https://doi.org/10.1080/00207233.2017.1283939

Puyravaud (2003). Standardising the calculation of the annual rate of deforestation. *Forest Ecology and Management*. 177, 593-596

Puyravaud, J. P., Davidar, P., & Laurance, W. F. (2010). Cryptic destruction of India's native forests. *Conservation Letters*, 3, 390-394. https://doi.org/10.1111/j.1755-263X.2010.00141.x

QGIS.org (2019). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.org

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Raman, T. R. S. (2006). Effects of habitat structure and adjacent habitats on birds in tropical rainforest fragments and shaded plantations in the Western Ghats, India. *Biodiversity and Conservation*, *15*(4), 1577–1607. https://doi.org/10.1007/s10531-005-2352-5

Ramprasad, V., Joglekar, A., & Fleischman, F. (2020). Plantations and pastoralists: Afforestation activities make pastoralists in the Indian Himalaya vulnerable. *Ecology and Society*, *25*(4), 1–12. https://doi.org/10.5751/ES-11810-250401

Ravindranath, N. H., et al. (2005). Impact of climate change on forests in India. *Current Science*, 90(3), 354-361. https://doi.org/10.2307/24091869

Ravindranath, N. H., & Sukumar, R. (1998). Climate change and tropical forests in India. *Climatic Change*, 39, 563-581. https://doi.org/10.1023/a:1005394505216

Reddy, C. S., et al. (2013). National assessment of forest fragmentation in India: Landscape indices as measures of the effects of fragmentation and forest cover change. *Ecological Engineering*, *60*, 453–464. https://doi.org/10.1016/j.ecoleng.2013.09.064

Reddy, S., Dutta, K., & Jha, C. S. (2013). Analysing the gross and net deforestation rates in India. *Current Science*. 105 (11), 1492-1500

Roy, P. S., & Joshi, P. K. (2010). Forest cover assessment in north-east India--the potential of temporal wide swath satellite sensor data (IRS-1C WiFS). *International Journal of Remote Sensing*, 23(22), 4881-4896. https://doi.org/10.1080/01431160110114475

Roy, P. S., et al., (2013). Forest Fragmentation in India. *Current Science*, *105*, (*6*), 774–780.

Sen, O. L., et al., (2004). Impact of Indochina Deforestation on the East Asian Summer Monsoon. *Journal of Climate*, *17*(6), 1366–1380. https://doi.org/10.1175/1520-0442(2004)017<1366:IOIDOT>2.0.CO;2

Shankar Raman, T. R., & Sukumar, R. (2002). Responses of tropical rainforest birds to abandoned plantations, edges and logged forest in the Western Ghats, India. *Animal Conservation*, *5*(3), 201–216. https://doi.org/10.1017/S1367943002002251

Sharma, J., et al., (2017). Vulnerability of Forests in India: A National Scale Assessment. *Environmental Management*, *60*(3), 544–553. https://doi.org/10.1007/s00267-017-0894-4

Singh, T., Singh, A., & Dangwal, L. R. (2016). Impact of overgrazing and documentation of wild fodder plants used by Gujjar and Bakerwal Tribes of district Rajouri (J&K), India. *Journal of Applied and Natural Science*, *8*(2), 804–811.

Sudhakar Reddy, C., et al., (2016). Quantification and monitoring of deforestation in India over eight decades (1930–2013). *Biodiversity and Conservation*, *25*(1), 93–116. https://doi.org/10.1007/s10531-015-1033-2

Suresh, H. S., Dattaraja, H. S., & Sukumar, R. (2010). Relationship between annual rainfall and tree mortality in a tropical dry forest: Results of a 19-year study at Mudumalai, southern India. *Forest Ecology and Management*, *259*(4), 762–769. https://doi.org/10.1016/J.FORECO.2009.09.025

Tian, H., et al., (2014). History of land use in India during 1880–2010: Large-scale land transformations reconstructed from satellite data and historical archives. *Global and Planetary Change*, *121*, 78–88. https://doi.org/10.1016/J.GLOPLACHA.2014.07.005

Tsarouchi, G. M., et al., (2014). Historical and future land-cover changes in the Upper Ganges basin of India. *International Journal of Remote Sensing*, *35*(9), 3150–3176. https://doi.org/10.1080/01431161.2014.903352

Utkarsh, G., Joshi, N. V, & Gadgil, M. (1998). On the patterns of tree diversity in the Western Ghats of India. *Current Science*, *75*(6).

Wakeel, A., et al., (2005). Forest management and land use/cover changes in a typical micro watershed in the mid elevation zone of Central Himalaya, India. *Forest Ecology and Management*, *213*(1–3), 229–242. https://doi.org/10.1016/J.FORECO.2005.03.061

Watts, K., et al., (2020). Ecological time lags and the journey towards conservation success. *Nature Ecology & Evolution*, *4*(3), 304–311. https://doi.org/10.1038/s41559-019-1087-8

World Bank (2005). India: Unlocking Opportunities for Forest-Dependent People in India, Volume 1, Main Report. The World Bank Group. Washington. Accessed at: https://openknowledge.worldbank.org/handle/10986/8416

Wright, S. J. (2010). The future of tropical forests. *Annals of the New York Academy of Sciences*, 1195(1), 1-27.

Zaveri, E., et al., (2016). Invisible water, visible impact: Groundwater use and Indian agriculture under climate change. *Environmental Research Letters*, *11*(8), 084005. https://doi.org/10.1088/1748-9326/11/8/084005

3.7 Supplementary material

Table S1| Summary of the FAO Land Cover Classification System used by the ESA CCI Land Cover Dataset with the simplified categories generated for analysing land cover change across India.

FAO Land Cover Classification System Types	Simplified categories
Cropland rainfed	Cropland
Cropland rainfed - Herbaceous cover	
Cropland rainfed - Tree or shrub cover	
Cropland irrigated or post-flooding	
Mosaic cropland (>50%) / natural vegetation (tree/shrub/herbaceous cover) (<50%)	Mosaic cropland
Mosaic natural vegetation (tree/shrub/herbaceous cover) (>50%) / cropland (<50%)	
Tree cover broadleaved evergreen closed to open (>15%)	Tree cover
Tree cover broadleaved deciduous closed to open (>15%)	
Tree cover broadleaved deciduous closed (>40%)	
Tree cover broadleaved deciduous open (15-40%)	
Tree cover needleleaved evergreen closed to open (>15%)	
Tree cover needleleaved evergreen closed (>40%)	
Tree cover needleleaved evergreen open (15-40%)	
Tree cover needleleaved deciduous closed to open (>15%)	
Tree cover needleleaved deciduous closed (>40%)	
Tree cover needleleaved deciduous open (15-40%)	
Tree cover mixed leaf type (broadleaved and needleleaved)	
Tree cover flooded fresh or brakish water	
Tree cover flooded saline water	
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Natural mosaics
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	
Shrubland	Shrubland & Grassland
Shrubland evergreen	
Shrubland deciduous	
Grassland	
Urban areas	Urban areas
Lichens and mosses	Sparse/Bare
Sparse vegetation (tree/shrub/herbaceous cover) (<15%)	
Sparse tree (<15%)	
Sparse shrub (<15%)	
Sparse herbaceous cover (<15%)	
Bare areas	
Consolidated bare areas	
Unconsolidated bare areas	
Water bodies	Water/snow
Permanent snow and ice	
Shrub or herbaceous cover flooded fresh/saline/brakish water	

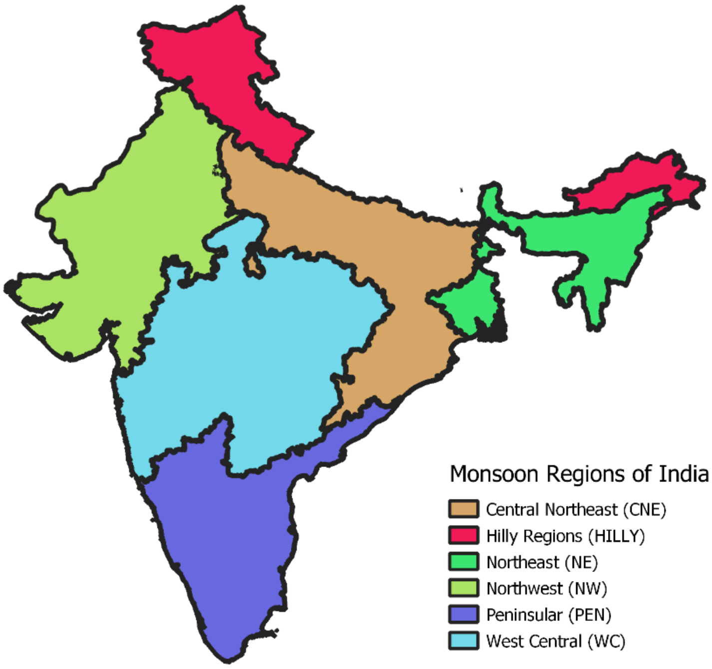


Figure S1| The six homogenous monsoon regions of India as defined by the Indian Institute of Tropical Meteorology: Northeast (NE), Northwest (NW), Central Northeast (CNE), West Central (WC), Peninsular (PEN) & Hilly

Table S2| List of excluded districts due to having less than 0.1km^2 of forest cover at the start of the study period

District	State	District Area (km^2)	Forest cover (km^2)	Forest loss (km^2)	Percent of total forest cover lost (%)
Churu	Rajasthan	17,075	0	0	0
Jaisalmer	Rajasthan	38,637	0	0.002	0
Bikaner	Rajasthan	26,965	0	0.002	0
Jodhpur	Rajasthan	22,842	0.0004	0.015	100
Patan	Gujarat	6,026	0.001	0.011	100
Barmer	Rajasthan	28,372	0.003	0.006	100
Hanumangarh	Rajasthan	8,912	0.006	0.017	100
Nagaur	Rajasthan	17,676	0.012	0.015	100
Yanam	Puducherry	31	0.043	0	0
Sirsa	Haryana	4,236	0.072	0.022	30.67
Hyderabad	Telangana	178	0.072	0.024	33.39
Bhilwara	Rajasthan	10,469	0.076	0.039	51.03
Ganganagar	Rajasthan	11,679	0.085	0.104	100

Table S3| Moran's I statistic and p-values from the test on model residuals for spatial autocorrelation. Moran's I values are between -1 (negative spatial autocorrelation) and +1 (positive spatial autocorrelation). The closer a value is to -1 or +1 the stronger the spatial autocorrelation. A Moran's I above 0.5 is considered an indication of strong spatial autocorrelation. A significant p-value indicates that the residuals are more spatially clustered than would be expected if spatial processes were random. The NW region is excluded here as no model was run on this data.

Region	Moran's I statistic	p-value
CNE	0.036	0.135
NE	0.001	0.445
HILLY	-0.057	0.919
PEN	-0.053	0.931
WC	-0.06	0.958
NW	NA	NA
National	-0.016	0.816

Table S4| Annual rates of loss and gain and net annual rate of change for each monsoon region and nationally. Net rate of change is the average annual percentage change of forest over the 24-year period (1995-2019). Rate of loss/gain is the average annual percentage of 1995 forest coverage lost/gained over the 24-year period.

Region	Loss	Gain	Net rate of change
CNE	0.5	0.28	-0.22
HILLY	0.15	0.19	0.04
NE	0.12	0.56	0.44
NW	0.16	0.43	0.27
PEN	0.32	0.47	0.15
WC	0.32	0.27	-0.05
National	0.26	0.32	0.05

Table S5| Regional net forest change (km^2) in each period. Net losses are highlighted in red and net gains in green.

Period	NE	PEN	WC	HILLY	CNE	NW
1995-2000	3746.7	264.1	-911.1	-1588.5	-4065.3	-306
2000-2005	533.9	-729.8	-282.6	1069.5	-236.1	143.6
2005-2010	-2.8	-491.5	-185.1	265.8	-186.9	99.9
2010-2015	120.2	-320.9	-642.2	-470.8	-166.1	38.3
2015-2019	1982.3	3473.4	629.5	1654.1	1263.6	783
1995-2019	6380.4	2199.2	-1400.5	1229.5	-3334.6	764.5

Table S6| Comparison of estimated marginal means of the response for each land cover type in the National model using Tukey post-hoc comparison (emmeans package in R).

Contrast	**Estimate**	**SE**	**df**	**t ratio**	**p value**
Cropland - Mosaic Cropland	-0.5845	0.123	1199	-4.74	< 0.0001
Cropland - Natural Mosaics	-0.6113	0.125	1202	-4.875	< 0.0001
Cropland - Shrubland & Grassland	0.7622	0.13	1199	5.857	< 0.0001
Cropland - Other Tree Type	2.3704	0.15	1211	15.816	< 0.0001
Cropland - Urban areas	2.001	0.154	1315	12.984	< 0.0001
Cropland - Water Bodies	1.4844	0.188	1319	7.896	< 0.0001
Mosaic Cropland - Natural Mosaics	-0.0267	0.122	1196	-0.219	**1**
Mosaic Cropland - Shrubland & Grassland	1.3467	0.127	1204	10.568	< 0.0001
Mosaic Cropland - Other Tree Type	2.955	0.148	1212	20.007	< 0.0001
Mosaic Cropland - Urban Areas	2.5856	0.152	1328	16.987	< 0.0001
Mosaic Cropland - Water Bodies	2.069	0.186	1319	11.11	< 0.0001
Natural Mosaics - Shrubland & Grassland	1.3735	0.129	1198	10.664	< 0.0001
Natural Mosaics - Other Tree Type	2.9817	0.149	1209	20.043	< 0.0001
Natural Mosaics - Urban Areas	2.6123	0.154	1315	16.992	< 0.0001
Natural Mosaics - Water Bodies	2.0957	0.188	1319	11.146	< 0.0001
Shrubland & Grassland - Other Tree Type	1.6082	0.152	1204	10.566	< 0.0001
Shrubland & Grassland - Urban Areas	1.2388	0.158	1319	7.858	< 0.0001
Shrubland & Grassland - Water Bodies	0.7222	0.191	1319	3.788	0.003
Other Tree Type - Urban Areas	-0.3694	0.174	1298	-2.128	**0.3366**
Other Tree Type - Water Bodies	-0.886	0.206	1306	-4.303	< 0.001
Urban Areas - Water Bodies	-0.5166	0.208	1350	-2.488	**0.1645**

Table S7| Resultant p-values from the comparison of estimated marginal means (EMMs) of the response for each land cover type in the regional models using Tukey post-hoc comparison (emmeans package in R). P-values indicating a non-significant difference in the EMMs of forest lost to land cover conversion types are shown in red.

Contrast	PEN	CNE	NE	WC	HILLY
Cropland - Mosaic_cropland	0.76	< 0.001	0.99	< 0.001	0.009
Cropland - Natural_mosaics	< 0.001	0.46	< 0.001	0.76	0.99
Cropland - Shrubland_Grassland	0.11	0.03	0.99	0.001	0.09
Cropland - Tree_cover	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cropland - Urban areas	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cropland - Water_snow	0.12	< 0.001	NA	< 0.001	NA
Mosaic_cropland - Natural_mosaics	< 0.001	0.03	0.002	0.06	0.02
Mosaic_cropland - Shrubland_Grassland	0.89	< 0.001	0.9	< 0.001	< 0.001
Mosaic_cropland - Tree_cover	< 0.001	0	< 0.001	< 0.001	0
Mosaic_cropland - Urban areas	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mosaic_cropland - Water_snow	0.73	< 0.001	NA	< 0.001	NA
Natural_mosaics - Shrubland_Grassland	< 0.001	< 0.001	< 0.001	< 0.001	0.04
Natural_mosaics - Tree_cover	0	0	< 0.001	< 0.001	< 0.001
Natural_mosaics - Urban areas	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Natural_mosaics - Water_snow	< 0.001	< 0.001	NA	< 0.001	NA
Shrubland_Grassland - Tree_cover	< 0.001	< 0.001	< 0.001	0.004	< 0.001
Shrubland_Grassland - Urban areas	0.04	0.31	< 0.001	0.03	< 0.001
Shrubland_Grassland - Water_snow	0.99	0.008	NA	0.74	NA
Tree_cover - Urban areas	0.77	0.03	1	0.99	0.23
Tree_cover - Water_snow	0.02	0.62	NA	0.27	NA
Urban areas - Water_snow	0.47	0.88	NA	0.58	NA

Table S8| Net change (km^2) for each forest type in each region between **1995 & 2019**. Cells highlighted in red represent net declines in the extent of a forest type and highlights in green represent net increases in the extent of the forest type. NA represents where there was no loss or gain of forest in that region, whereas '0' represents no net change in coverage.

Forest Type	WC	PEN	CNE	NE	NW	HILLY
Broadleaved deciduous closed (>40%)	-0.45	-33.48	-63.27	-7.2	69.3	15.03
Broadleaved deciduous closed to open (>15%)	-1797.48	1359.45	-3188.97	978.3	540.9	2247.21
Mixed leaf type (broadleaved & needle leaved)	0	0	0	0	0	17.73
Needle leaved deciduous closed (>40%)	0	0	0	0	0	15.66
Needle leaved deciduous closed to open (>15%)	119.7	0	76.05	0.36	73.98	55.17
Needle leaved evergreen closed (>40%)	0	0	0	0	-0.18	0
Needle leaved evergreen closed to open (>15%)	115.56	197.82	-213.12	1399.05	56.79	-1386.54
Needle leaved evergreen open (>15%)	0	0	0	0	0	0
Broadleaved evergreen closed to open (15-40%)	98.01	541.26	1.35	3980.88	10.98	262.71
Flooded saline	64.17	134.19	53.37	28.98	12.78	2.52

Table S9| Net change (km^2) for each forest type in each region between **1995 & 2015**. Cells highlighted in red represent net declines in the extent of a forest type and highlights in green represent net increases in the extent of the forest type. NA represents where there was no loss or gain of forest in that region, whereas '0' represents no net change in coverage.

Forest Type	WC	PEN	CNE	NE	NW	HILLY
Broadleaved deciduous closed (>40%)	-1.17	0.54	14.85	2.25	67.68	192.69
Broadleaved deciduous closed to open (>15%)	-2072.16	-1856.70	-4719.33	-266.76	-236.79	-220.05
Mixed leaf type (broadleaved & needle leaved)	NA	NA	NA	NA	NA	0.18
Needle leaved deciduous closed (>40%)	NA	NA	NA	NA	NA	0
Needle leaved deciduous closed to open (>15%)	1.80	0.99	3.60	7.92	5.58	0.09
Needle leaved evergreen closed (>40%)	NA	NA	NA	NA	-0.18	-0.45
Needle leaved evergreen closed to open (>15%)	-144.18	-210.15	-36.90	649.71	32.40	-1614.51
Needle leaved evergreen open (>15%)	NA	NA	NA	NA	NA	0
Broadleaved evergreen closed to open (15-40%)	147.06	601.29	48.06	3972.78	2.52	909.09
Flooded saline	47.61	183.51	35.28	32.22	104.31	8.91

Chapter 4: Do precipitation deficits affect forest susceptibility to land use change?

Rice paddy planting near Chennai, India

Source: ADM Institute for the Prevention of Postharvest Loss via Flickr (https://www.flickr.com/photos/phlinstitute/)

4.1 Abstract

Climate changes such as increasing temperatures and variable rainfall are predicted to have major effects on future forest distribution in India. However, the effect of climate changes on Indian forests has been largely overlooked. The increasing incidence of drought in the country is particularly concerning since droughts are known to have direct negative impacts on tropical forests. At present, studies assessing the effect of droughts on forests in India are lacking. In other regions, drought events have been shown to interact synergistically with land use changes to result in increased tropical forest losses. India's rural populations rely heavily on agriculture for their livelihoods and droughts could have serious implications for agriculture in the country. The primary cause of forest loss is agriculture-driven land use change and drought-stress on this agriculture could result in further indirect effects on forests. The effect of interactions between land use change and droughts on forest coverage have not been investigated in India before. This research aims to address two key knowledge gaps; whether drought events have led to increased forest losses and whether there is evidence of an interaction with land use change. The study uses spatial auto-logistic models to assess the relationship between forest loss and five past drought events in Northeast India. Findings indicate an increased probability of forest loss with drought events in the region alongside evidence to suggest an interaction with land use changes. Probability of forest loss was found to increase in the less severe areas of a drought, where agriculture is more likely to succeed. Our findings indicate that droughts in Northeast India are having both direct and indirect effect on forest loss and demonstrates an interactive effect of climate and land use changes on forests in the region for the first time. With climate projections predicting increased drought in the future, alongside a greater demand for agricultural products from a growing population, research considering both the direct and indirect effects of climate change on forests will be critical for accurately predicting the effects on forests. The study also provides evidence to suggest that inclusion of climate-related effects on forests will help to create more realistic and effective conservation strategies for forests in the future.

4.2 Introduction

The reasons behind forest loss are often multi-faceted and location dependent (Curtis et al., 2018). The main cause of forest loss globally is increasing commodity-driven land use change, most prominently as a result of agricultural expansion (Curtis et al., 2018; FAO & UNEP, 2020), but there are often other factors such as extreme climatic events (e.g., drought and floods), disease, and pests (Allen et al., 2010; Clark et al., 2016). Recent studies have found that drivers of forest loss can interact with each other to produce combined effects that are different from those projected in models considering only one driver. Interaction effects between drivers of forest loss are often overlooked, particularly in the tropics (Barlow et al., 2018; França et al., 2020; Guo et al., 2018; Laurance & Useche, 2009). However, considering these interactions could help to better predict effects of global changes on forests and lead to more effective management strategies (Côté et al., 2016; Kulakowski et al., 2011; Mantyka-Pringle et al., 2015; Oliver & Morecroft, 2014). Tropical forests are facing high levels of degradation and conversion to other land uses. These losses of forest cover often result in particularly large reductions in specialist and endemic forest species but can also alter the provision of forest ecosystem services such as pollination, and the carbon and water cycle (Brookhuis & Hein, 2016; França et al., 2020; Giam, 2017; Pandit et al., 2007; Rosa et al., 2016). The effects of land use change on tropical forest have been studied for decades but there is increased concern about how interactions with escalating climatic changes could affect forest survival and functioning (Allen et al., 2015; Barlow et al., 2018; McDowell et al., 2018; Nobre et al., 2016; Siyum, 2020).

Research considering the joint effects of climate and land use changes in tropical forests is still scarce. The majority of studies have focused on the interaction between drought and forest degradation in the Amazon. Increases in the incidences of drought are a major concern for forest survival (Allen et al., 2010; Clark et al., 2016) and trees are known to be affected by drought directly through hydraulic failure. This is where gas enters the water transport system and disrupts flow of water to the leaves (Choat et al., 2012; Hanson & Weltzin, 2000). The evidence so far suggests that all forest biomes are likely to be vulnerable to drought stress (Choat et al., 2012) but that the most severe effects may be felt in tropical wet forests which tend to lack the structural adaptations to cope with water stress (Browne et al., 2021; Fauset et al., 2012; McDowell, 2018; Pulla et al., 2015). Drought often increases mortality of individual trees leading to a reduction in canopy cover (Betts, 2007; Choat et al., 2018; Meir et al., 2015). This can result in biodiversity reductions and a change in the provisioning of ecosystem services (Dundas et al., 2021; França et al., 2020; Larsen, 2012). Drought affects forest types and species differently, with some more capable than others of surviving drought events (Saleska et al., 2007; Siyum, 2020). Wet evergreen forest types are reported to be at increased risk to drought effects due to their high-water needs and year-round foliage, whereas deciduous species and dry-affiliated types are suspected to be more resilient to drought (Allen et al., 2017; Asner, Loarie, & Heyder, 2010; Pulla et al., 2015).

Defining drought

It is important to note that drought is defined, and calculated, in numerous ways. In general terms drought is defined as a ‘prolonged absence or marked deficiency of precipitation’, ‘a deficiency of precipitation that results in water shortage for some activity or for some group’, or a ‘period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance' by the IPCC 4th assessment report (Trenberth et al., 2007; Trenberth et al. 2014)). This generally centres around a reduction in precipitation from the norm and is commonly referred to as meteorological drought, but some definitions imply a wider, and often specific, effect on a system e.g., impacting human activities or vegetation. This is where confusion arises over what drought is. Most studies that use the term 'drought' to refer to meteorological drought, agricultural drought, or occasionally ecological drought. However, these differ in both their definition and measurement considerably, and have different implications for the impacted system (Duan & Mei, 2014; Trenberth et al., 2014). Agricultural drought differs from meteorological drought generally due to the inclusion of a measure of soil moisture to capture whether the drought is sufficient enough to impact the water availability to crops (Trenberth et al., 2014). Ecological drought is a more recent concept and is still defined in many different ways (Slette et al., 2019). However, generally, it is defined as 'a reduction in rainfall or a change in the timing or distribution of rainfall that has the potential to directly impact community- or ecosystem-level plant or microbial processes' (Allen et al., 2017). It is different from meteorological or agricultural drought as it does not see drought through a human-centric lens. For this, data on soil moisture is typically included as well as a good understanding of the system being studied to be aware of what species' tolerances to drought might be. However, it is an emerging concept and there is currently no standardised metric that is readily used, though metrics are being developed all the time (e.g., Jiang et al., 2021). There are many constraints with more tailored drought metrics like this as they rely on a good understanding of the system and species that are present there. For example, a drought could directly impact a short rooted species but have little effect on a long rooted species or could impact evergreen species but not deciduous species (Hasselquist et al., 2010; Paz et al., 2015). Therefore, classifying an ecological drought can be difficult (Jiang et al., 2021).

A recent review paper by Slette et al., (2019) found that most ecology papers define drought as simply dry or differs from normal and avoid using standardised metrics. This could be due to temporal inconsistencies in metrics available or a lack of knowledge on how to apply the metrics, and a lack of understanding and data available on ecological drought (Slette et al., 2019). Many standardised indices have been created to help capture the multiple components of drought e.g., PDSI and SPI which are typically used to quantify meteorological drought, either measuring precipitation and temperature (former) or just precipitation (latter). Another common metric is the SPEI which takes into account evapotranspiration as well as is more typically used for measuring agricultural drought. However, standardised indices can be harder to implement as they often require access to regular long-term high resolution datasets.

Interactions

In addition to the direct effect of drought on tropical forests, drought can interact with land use change to increase susceptibility of forests to negative effects as well as impacting their adaptive capacity e.g., by increasing stand density. The two drivers have been shown to act synergistically resulting in further loss of forest (Laurance & Williamson, 2001; Qie et al., 2019; Staal et al., 2020). For example, Longo et al. (2020) found that degraded forests were more likely to be under water stress and experience declines in productivity in comparison to primary forests. Brando et al., (2014) conducted an experiment in the Amazon showing that drought and human degradation increased fire outbreaks in forests. Another study finds that synergies between drought and land use expansion are likely to further increase prevalence of forest fires under future scenarios (Le Page et al., 2017).

Currently, the geographic bias in studies on climate and land use interactive effects in tropical forests is limiting our understanding of how these interactive effects may manifest across the biome. Previous studies have shown that there is a large variation in climate change, land use change and how these changes might interact across different regions (Asner et al., 2010; Brodie et al., 2012; Turubanova et al., 2018). As such, more research is needed to characterise these interactions in less studied forests such as those in Africa and South Asia (Kumar & Scheiter, 2019; Thang et al., 2020).

Case study: India

In India, rates of forest loss occur at high, unsustainable levels, despite being lower than their historical averages and this has a direct effect on the biodiversity of the country (Davidar et al., 2010; Puyravaud, Davidar, & Laurance, 2010). Indian forests are currently lost at a rate around 1.5-2.7% per year (Sheth et al., 2020). Like other tropical regions, land use changes, predominantly related to agriculture, are known to be the main cause of forest loss in India (Chakraborty et al., 2018; Mahato et al.,, 2021; Wakeel et al., 2005). Agriculture is one of the most important industries in in the country and is responsible for between 14%-20% of its GDP (Bana & Gautam, 2014; Zaveri et al., 2016) as well as ~70% of rural communities depending on it for survival (Kala, 2017). Forest losses are often incurred from expanding existing agricultural land and encroaching on forest edges alongside full clearance of forests for new croplands (Chakraborty et al., 2018; Mahato et al., 2021; Meiyappan et al., 2017). The traditional practice of shifting cultivation, particularly prevalent in the Northeast of the country, have led to large areas of forest loss (Tripathi et al., 2016, FSI, 2019). In the past shifting cultivation has been a relatively sustainable practice, allowing forests time to regrow, but in recent years due to soil degradation, loss of financial security and climate variability there has been a noticeable shortening of the regrowth periods which has resulted in more forest loss and a patchwork of shrubland, forest and bare areas (Lele et al., 2008; Teegalapalli & Datta, 2016). The forests in which shifting cultivation take place are also often protected from other land use changes due to topographical inaccessibility and less fertile soils (Teegalapalli & Datta, 2016). Other land use changes such as expansion of urban areas, building of reservoirs, logging and clearing of forest areas for livestock rearing also contribute to deforestation in the country (Meiyappan et al., 2017). While harvesting of forest products, e.g., collection of fuelwood and fodder, for heating of homes, food, livestock feed and making crafts, contribute to forest fragmentation (Bhatt & Sachan, 2004; Davidar et al., 2008; Lele et al., 2008).

So far, the effects of land use change have been the primary focus of research exploring deforestation in the country but there are likely to be other contributing factors. A particular concern is the rate in which India is experiencing changes in climate. A study by Gogoi et al., (2019) found that in the Eastern state of Odisha, the mean temperature had increased by 0.3°C between 1981 and 2010, with the fastest warming occurring in the last decade. The occurrence of droughts has also increased substantially over the country in the recent decade (Auffhammer et al., 2011; Kala, 2017; Sharma & Mujumdar, 2017). The monsoon rains have become highly variable in the timing of their arrival and the provision of rainfall (Dash et al., 2011; Guhathakurta et al., 2015; Paul et al., 2018; Ramesh & Goswami, 2007; Turner & Annamalai, 2012). Precipitation deficits are particularly damaging during the monsoon season when more than 80% of the annual rainfall normally occurs (Mishra, 2020). This is because it is the main growing season for natural vegetation as well as being vital for crop production, e.g., more than half of rice production in the country occurs during the monsoon season (Auffhammer et al., 2011). Precipitation deficits in this season also have significant effects on the productivity of crops throughout the year (Zaveri et al., 2016). A study by Kala (2017) found that over 330 million people across the country had been affected by a drought in 2016 caused by two years of deficit monsoons. The study further reported that Cherrapunji, renowned as one of the wettest places on Earth, had recently faced drought for over six months, and in 2015-2018 India experienced its longest drought in 150 years (Mishra, 2020). These changes in climate are likely to be affecting the country's forests but have rarely been considered, and there is yet to be a study looking at the effects of climate change on past forest distribution on a national scale.

Studies that have considered the effects of climate change on India's forests have estimated the effects of future climate change on forest distributions. These studies have found that >30% of forest areas may see a shift in distribution in response to climate changes (Gopalakrishnan et al., 2011; Upgupta et al., 2015). The Himalayan states, e.g., Arunachal Pradesh, the Western Ghats and central areas are projected to experience the largest changes in forest cover with marked reductions in forest cover and a shift in forest type from deciduous to evergreen species with increasing precipitation (Chaturvedi et al., 2011). Across the country increases in temperature coupled with variable precipitation leading to an increased prevalence of drought is also a key concern (Chaturvedi et al., 2011; Mishra, 2019; Ravindranath et al., 2005). Many of these studies highlight a concern over the future effects of climate changes on forests in India and call for more studies to assess the effects on forest survival (Kumar & Scheiter, 2019; Sharma et al., 2015). Some also express concern that increased land use changes could worsen the effects of climate (Deb et al., 2018; Gopalakrishnan et al., 2011; Upgupta et al., 2015). However, to date, there are no studies assessing the impacts of droughts on forests in India. There remains a significant lack of understanding of how climate changes are impacting forests and whether interactions with land use changes are occurring.

Despite the lack of research on the impact of drought on forests in the country, there has been a wealth of studies assessing the effects on droughts on agriculture and human health (Algur et al., 2021; Bana, 2014; Bandyopadhyay et al., 2020; Ravindranath et al., 2011). These have found that the effects of drought on agriculture in the country can be severe, increasing the probability of crop failure, reducing agricultural profits and making crops more vulnerable to pests and diseases (Bana & Gautam, 2014). For example, Auffhammer et al., (2011) found that the monsoon drought in 2009 resulted in a decline in rice yield of 14% and these effects are projected to worsen in the future (Fishman, 2016; Ravindranath et al., 2011). Vulnerability of people to droughts in India is likely to be high due to the large proportion of low-income smallholder farmers who have a strong dependence on agriculture (Bhatta & Aggarwal, 2015; Harvey et al., 2014; Jamshidi et al., 2019; Xu et al., 2020). As such the effects of drought are often felt throughout the community having far reaching societal impacts such as reduction in education, a rise in health issues, polluted water supplies, a disproportionate effect on women and a rise in farmer suicides (Algur et al., 2021; Bana & Gautam, 2014; Bandyopadhyay et al., 2020). Adaptation strategies to drought effects on agricultural livelihoods vary greatly depending on factors such as household income, education, and infrastructure (Harvey et al., 2018). Some farmers expand their fields to increase profit on less profitable land, some migrate to cities or other areas to seek more guaranteed employment, and others look to diversify their income sources often using forest resources e.g., collecting fodder for livestock and wood for crafting furniture (Bana, 2014; Belay et al., 2017; Harvey et al., 2018; Lei et al., 2016; Li et al., 2021; Meiyappan et al., 2017; Ramprasad et al., 2020)

Considering the impact of drought, the evidence of interactions with land use change, the climate change projections for India and the strong impact of drought on cropland in the country, it is highly likely that Indian forests could not only be directly affected by drought but also indirectly via shifts in agricultural and associated land uses. During drought years, the pressure on forests is likely to increase as farmers require more land to make the same profits, require land that is experiencing less drought, and potential diversification of income often centring around the use of forest products. There could, therefore, be a synergy between precipitation deficits and land use changes in India with implications for how and where forest is lost.

The Northeast (NE) region of India has had some of the highest rates of forest loss in the past (Pandit et al., 2007; Sheth et al., 2020). The region is a key refuge for a large proportion of India's remaining forests and as such is an important region in terms of biodiversity and species endemism (Chitale, Behera, & Roy, 2014; FSI, 2019; Narwade et al., 2011; Sheth et al., 2020). The practice of shifting cultivation in this region has caused large amounts of loss often resulting in mosaic habitats with poor species composition (Kundu et al., 2015; Lele & Joshi, 2009). The region now has 30% of its forest cover under high pressure from increasing land use changes (Lele & Joshi, 2009).The region has some of the lowest population densities in the country with 82% of the population living in rural areas (Ravindranath et al., 2011). Agriculture is the main source of income for much of the region, particularly in Assam & Meghalaya. The main crop is rice, which accounts for 84% of cultivated area (Parida & Oinam, 2015). Due to the high-water demand of rice crops, alongside generally poor infrastructure and lack of irrigation facilities in most districts, the region's primary livelihood is particularly vulnerable to drought (Das et al., 2009; Ravindranath et al., 2011) and farmers in the region are often less equipped to deal with drought when it occurs (Parida & Oinam, 2015; Ravindranath et al., 2011). The high drought vulnerability is also likely to be aggravated by the relative wetness of the region compared to other areas of the country which makes both its water-intensive agriculture and forest types much less capable of dealing with drought stress (Ravindranath et al., 2011). The heightened vulnerability of agriculture in the region increases the probability that farmers will need to diversify their incomes to account for losses during drought years. This could increase pressure on the surrounding forests. This vulnerability, along with the high contributions of agriculture-based land use changes to forest loss in the region (Lele et al., 2008; Padalia et al., 2019; Srivastava et al., 2002), and the increased prevalence of drought (IPCC, 2019; Ravindranath et al., 2011) make this region an ideal location to study the relationship between precipitation deficits and human land use change on forests in the country.

Understanding the multiple causes of forest losses is vital for the protection of specific habitats, preservation of biodiversity, and the viability of ecosystem services that are crucial to the country's main income from agriculture. Given that extreme events are likely to worsen including increased exposure to drought events, understanding the relationships between drought, land use change and forest loss will be critical to make informed decisions that can better protect Indian forests. As such, this study aims to understand how forests in NE India are affected by drought, explicitly investigating the links between this driver and land use change. Considering the above, I predict that more forest loss is expected in areas experiencing precipitation deficits during the monsoon season due to the direct impact on trees through water stress, and associated factors, such as increased fire risk, but also that there will be an additional effect from land use change. However, because people are likely to respond by relocating or expanding agriculture, I predict forest loss to direct, natural causes will be more likely in the driest areas during a drought but forest loss from indirect effects through land use change to be more likely in the wetter areas that remain suitable for growing crops, looking after livestock and supporting human livelihoods.

This study uses the meteorological definition of drought (as a difference from the average) since the focus is on understanding the response of large forest areas rather than specific species (where additional information could be collected to look at ecological drought).

It is important to consider that there are multiple drivers behind the vulnerability and susceptibility of trees or forests to stressors like climate change. Vulnerability frameworks highlight that vulnerability to drought stems from three key components; sensitivity, adaptive capacity and exposure (Lecina-Diaz et al., 2020; Sharma & Ravindranath, 2019). This highlights that the exposure, magnitude and length of time that the species is in the vicinity of the stressor drivers vulnerability, as well as the importance of a species' characteristics that might affect how susceptible it is to the stressor e.g., deciduousness, and the adaptive capacity of the species e.g., faster reproduction or ability to change root structure (Hasselquist et al., 2010; Paz et al., 2015). Here, we talk about the exposure of forests to drought events, as well as the possibility of the susceptibility being impacted by proximity to land use change. We predict that the prevalence of land use change will lead to an increase in susceptibility of forests to drought in areas that may have been less exposed. It is important that there are many other aspects that contribute to the susceptibility of forests to drought, including their deciduousness, their size, among other factors and here we do not measure the adaptive capacity of species to these drought events.

In this study I aim to answer the following main questions:

1. Do precipitation deficits result in a higher probability of forest loss?
2. Is forest loss attributed to anthropogenic land use changes more prevalent in the wetter areas of a drought?

Further to these questions, this chapter aims to increase understanding of the threat of drought and land use change to forests in the region by exploring the spatial extent of forest loss during drought years, quantifying the major types of forest lost, and assessing the key land use and land cover changes associated with forest loss.

4.3 Methods

4.3.1 Data acquisition

Land cover

Global land cover data was obtained from the ESA CCI Land Cover project (v2.0.7 1992-2015) and EC C3S Land Cover project (v2.1.1 2015-2019) at five-year increments for the period 1995-2019, at the spatial resolution of 300m. Five-year increments were chosen to capture the changing trend over time while minimising the effect of smaller inter-annual fluctuations. The data was clipped to the borders of the Northeast region of India using QGIS (version 3.16.0). The EC C3S product was designed to be consistent with the ESA CCI dataset and as such, both iterations of the land cover product utilise the FAO Land Cover Classification System (Di Gregorio, 2016) which is outlined in Table S1.

Mean precipitation

Total monthly precipitation (mm) was obtained from TerraClimate dataset at a resolution of 4km. The data was aggregated using the Climate Engine tool (https://app.climateengine.org/climateEngine) to create a total precipitation for each 4km cell for the monsoon season (June-September) for each year of the study 1992-2019. The monsoon months used (June-September) are those defined by the Indian Meteorological Department (http://www.imdpune.gov.in/Weather/Reports/glossary.pdf).

Human population density

Population density data at the resolution of ~5km was obtained from SEDAC CIESIN for the period 2000-2020. The data availability of 5-year increments meant that not every year of the study had an associated population density dataset thus, the closest timepoint was extracted for each forest loss point in each year. Population density in this dataset represented the number of people per km^2. Population density was included because it was considered a key factor in influencing land use change (Kale et al., 2016; Palchoudhuri et al., 2015).

4.3.2 Quantifying forest loss and its associated land use types

Land use land cover (LULC) change rasters were created from the annual land cover maps using the Land Cover Change function from the Semi-Automatic Classification Plugin (v 6.4.5) (Congedo Luca, 2020) in QGIS. Rasters of forest loss for each year were created by masking out all pixels of land cover change that did not result in forest loss using the ‘Reclassify by table’ function from the QGIS Raster Analysis toolbox. Rasters of forest cover were also created for each year by using the same method on the original land cover maps and masking out any pixels that were not classified as forest for each year.

These rasters of forest loss and forest cover were then converted to point data, where each point represents a one pixel of forest loss or cover equal to an area of $0.09km^2$.

For each forest loss point, the land use or land cover type that replaced the forest after it was lost and the type of forest that was lost was extracted using the Point Sampling tool in QGIS. The category that the forest was lost to was simplified to either anthropogenic land uses (grouping cropland, mosaic croplands, and urban areas. Table S1) or natural land covers (natural mosaics, shrubland, grasslands and different tree types). Note that these natural categories could hide human-caused degradation of the forest e.g., from harvesting of products, but detection of these processes is not possible with the available data.

Forest areas converted to water bodies, sparse and bare areas were not considered in the analysis as it could not be certain whether these were human driven e.g., reservoir development, or natural e.g., flooding.

4.3.3 Creation of precipitation metrics

We created two metrics from the precipitation data to quantify for each forest loss point **a)** the difference in monsoon precipitation from the 30-year average for that forest point, hereafter referred to as temporal change or P_{time} and **b)** the difference in monsoon precipitation from the average for the district that the forest loss point is in, hereafter referred to as spatial change or P_{area}.

P_{time} provides a measure of how different the precipitation was, when the forest point was lost, to the average precipitation that point received in the past. It is a measure of how dry or wet that point is compared to its own 30-year average. Whereas P_{area}, is a measure of how dry or wet a forest loss point was compared to those around it. It uses the average precipitation for the same monsoon season for the district that the point is located in as a comparison.

P_{time} was created by subtracting the precipitation from each year from a raster containing the 30-year averages using the Raster Calculator in QGIS. P_{area} was created by obtaining the precipitation of the forest point when the forest was lost and subtracting this by the average precipitation of the district that it the point is located within. This was done using the extract() function in R to get the precipitation data for each point and then using simple math code to subtract the precipitation column from a column containing district averages.

4.3.4 Selection of focal precipitation deficit years

There is no official designation of drought years for the Northeast region of India, so I used available research papers to define the following precipitation deficit periods: 2000-2001, 2005-2006, 2009-

2011, 2013 and 2016-2018 (Das et al., 2009; Parida & Oinam, 2015; Mishra, 2019). I then examined the precipitation deficit trends in my own data identifying those years with the highest precipitation deficits that matched the drought periods outlined in the literature. This resulted in five years identified as focal: 2001, 2005, 2009, 2013, and 2017. The analysis in this chapter focuses on a meteorological definition of drought, as a difference from the norm or a 'precipitation deficit'. Within this chapter I use 'drought' and 'precipitation deficit' interchangeably but I am referring to a difference from the baseline period (the 30 years before the study – 1960-1990). This method has been used elsewhere, most relevantly by the Indian Meteological Department (e.g., Parida & Oinam, 2015). The general definition of drought and other drought definitions are discussed in detail in the introduction to the chapter.

Standard procedures for measuring drought such as using one standard deviation away from the mean were not possible with this region due to the extreme variability in rainfall. Using this method with one or two standard deviations away from the mean resulted in no years being classed as drought years. The mean for total monsoon precipitation in the region was 1,394mm, with a standard deviation of +/- 637mm. Similarly, traditionally used drought metrics such as the Palmer Drought Severity Index were not appropriate because they often work well on long timescales (>12 months) but do not capture short-term drought well (Dai et al., 2019), they also often require soil moisture data which we did not have access to. Using a 'difference from the mean' approach enabled a simple analysis to capture how deficits in precipitation could impact forest cover.

4.3.5 Modelling the effect of two precipitation metrics on the probability of forest loss

Two logistic regression models were used to determine the relationship between a binary response variable, two climate metrics (tested separately) and population density.

The first model examined whether across the full 30 years of data that we had access to (1990-2019), forest loss was more likely to occur in areas that were experiencing precipitation deficits in the monsoon i.e., a negative value in the P_{time} metric. The response variable in this model was binary, where '0' represented forest pixels that remained unchanged and '1' represented pixels where forest was lost. The second model focused on the key precipitation deficit years and aimed to understand whether forest loss to land use change was more likely to occur in areas that were wetter than those around them i.e., a positive value in the P_{area} metric. For these models, areas that were not in a precipitation deficit were excluded from the model. The response variable in this model was a binary metric where '0' represented forest lost to natural land uses and '1' represented forest was lost to land use change.

Both logistic models were run using the lme4 package in R. Before modelling, the correlation between the predictor variables were checked and there were no concerning correlations found (Pearson correlation coefficient < 0.3). After models were run, variance inflation factors were also used to check for multicollinearity and all returned values <2.5 reflecting no issues.

Following logistic regression, the model residuals were checked for spatial autocorrelation using the 'lm.morantest' function in R. Where spatial autocorrelation was found, identified by a significant Moran's I value, an auto-logistic model was used instead of a logistic regression to account for the autocorrelation found. This model used a spatial autocovariate, appearing as an additional predictor variable, termed 'lag rate', in the model, that takes the spatial autocorrelation present in the data into account through creation of a spatial weights matrix (see Augustin, et al., 1996; Betts et al., 2017). The spatial autocovariate was created using the spdep package in R. These models were checked for spatial autocorrelation again and found to adequately account for the spatial relationships.

4.4 Results

4.4.1 Distribution of precipitation deficits across the five focal years

Distribution of precipitation deficits ranged widely across the five focal years; 2001, 2005, 2009, 2013, and 2017 (Figure 1). The most widespread drought occurred in 2005, where a large proportion of the region experienced deficits greater than 250mm, an 18% reduction from the regional average for the season. The year 2005 also experienced the largest deficit across the five years of 2,629mm which occurred in the East Khasi Hills district of Meghalaya. Notably, in 2005 and 2009, no areas showed precipitation surplus (more rain than the 30-year average. Figure 2A). The most severe deficits, in terms of intensity, generally occurred in the states of Assam and Meghalaya.

Areas of forest loss were highly variable across the region between the deficit years and did not seem to correlate with areas of high forest cover or high population density (Figure 2B & C). West Bengal is the most populous state, with an average of 1,145 people per km^2, followed by Assam with an average of 425 people per km^2. Arunachal Pradesh contained the most forest cover at 69,504km^2. Forest cover was typically higher where population density was lower (Figure 2). There were also clear instances where areas of high forest loss occurred in a precipitation surplus. Examples of these are the States of Sikkim and its border with northern West Bengal seen in the top left promontory in 2001 on Figure 1, and the States of Mizoram and Tripura in the southeast of the region in 2017.

Generally, forest loss associated with human land use and natural land cover changes did not have spatially distinct distributions. The exception being that loss in the State of West Bengal was wholly related to human land use changes in every year (Figure S1).

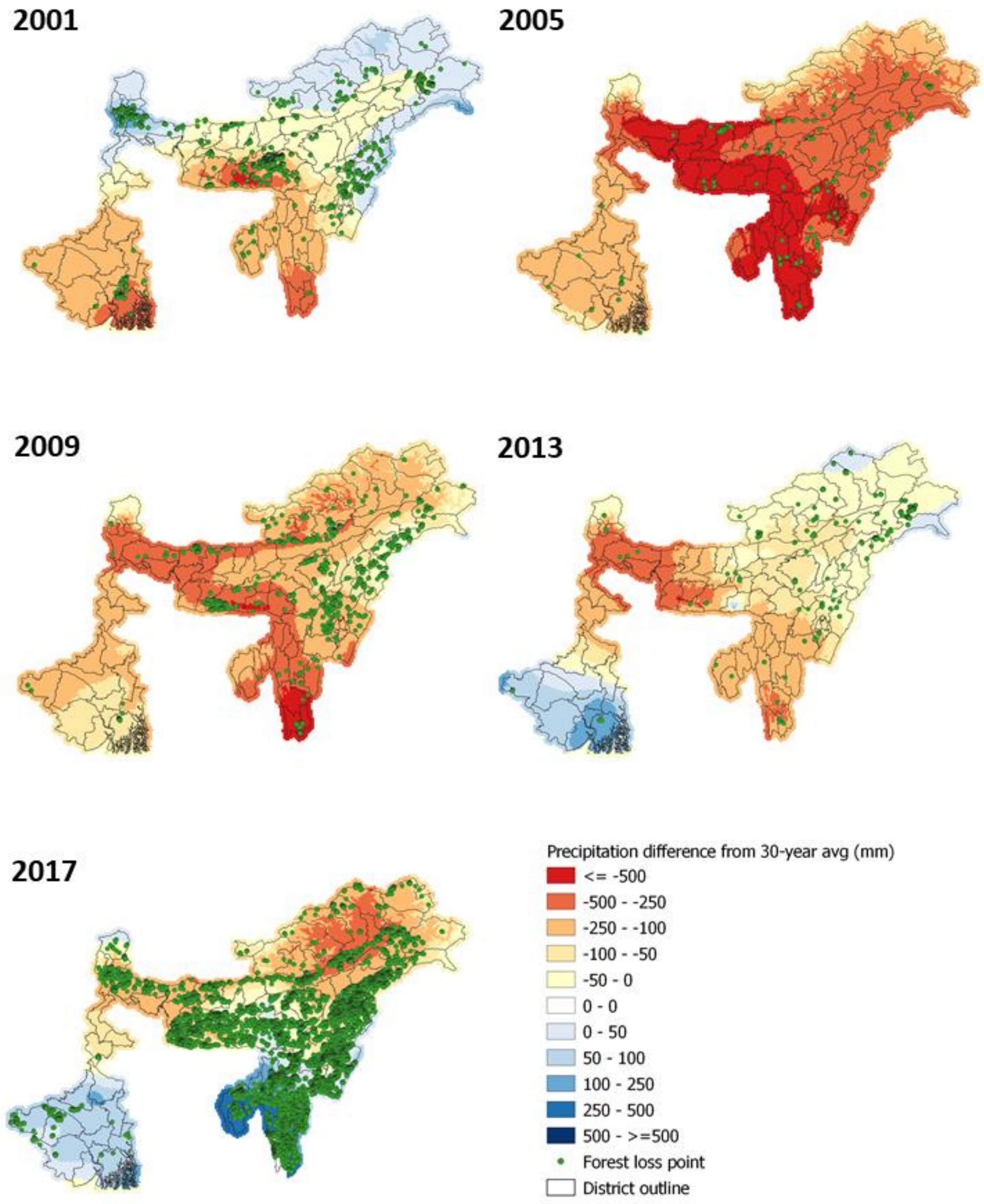


Figure 1| Precipitation difference from a 30-year average (1990-2019) in each focal rainfall deficit year. Redder areas signify a more severe deficit of rainfall. Outlines of administrative districts are shown in black, and locations of forest loss shown in green.

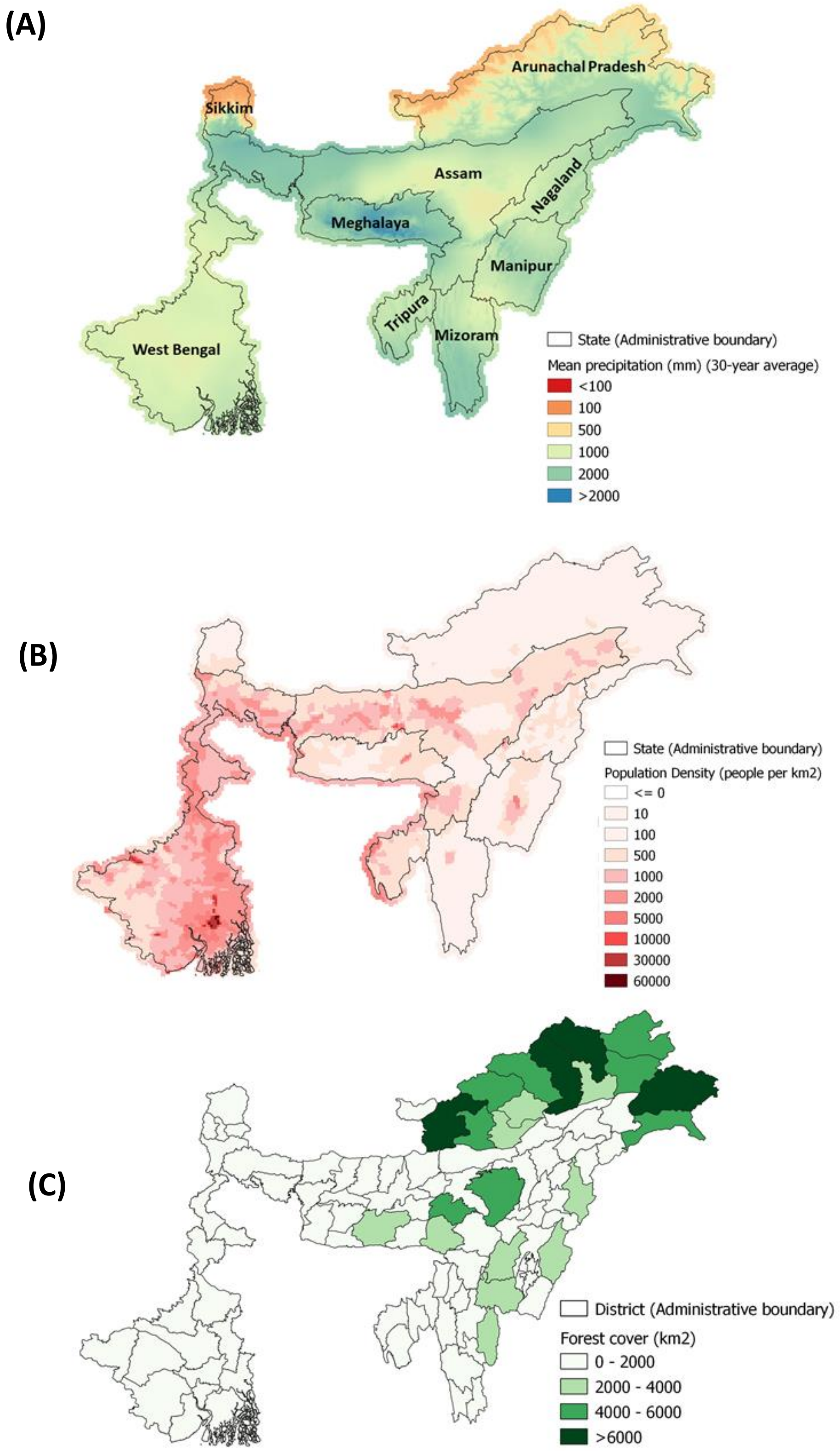


Figure 2| A) Average precipitation over a 30-year period (1990-2019) in millimetres. State boundaries are shown in black. Areas with a higher average precipitation over the period are shown in blue. B) Population density (people per km^2) across the region. State boundaries are shown in black. Areas with higher population densities are shown in a darker red. **C)** Forest cover (km^2) per district. District boundaries are shown in black. Districts with a larger coverage of forest cover appear in a darker green.

4.4.2 Exploring the distribution of forest loss within the climate space

Qualitatively, there was a clear relationship between the two climate variables of interest and amount of forest loss in the precipitation deficit years (Figure 3). In every year there was more loss in areas experiencing precipitation deficits, and in the wetter areas of this deficit. In 2005 and 2009, the entire region experienced precipitation deficits but the trend remained that those losses were greatest where the deficit was lowest.

In every year, a higher proportion of forest loss was associated with natural land cover changes than human land use changes, this contribution was increased in the later three years compared to the earlier years of 2001 and 2005 (Table 1).

Table 1| Contributions of anthropogenic land use and natural land cover categories to total loss in each focal precipitation deficit year. In all years there was a higher contribution of losses associated with natural land uses.

Year	Total loss (points)	Human land uses (%)	Natural land cover (%)
2001	6599	49.9%	50.1%
2005	698	40.7%	59.3%
2009	2665	18.1%	81.9%
2013	758	36.1%	63.9%
2017	16486	33.6%	66.4%

Of the loss attributed to human land use change, a larger proportion of the loss was consistently found in areas that were drier than the 30-year average (negative P_{time}) and wetter than their district's average (positive P_{area}), in each year (Table 2). This could indicate that these conditions may be preferred for human land use changes, whether this is a result of where people tend to live or where forest areas are more desirable for cropland is uncertain. The difference in contributions of human land use changes to these two categories of climate space increased with time. Similarly, forest losses associated with natural land conversions were also more likely in areas that had negative P_{time} and positive P_{area}, but these contributions declined with time.

Table 2| The percentage of loss attributed to human and natural land changes in each area of the climate space shown in Figure 3. 'BL' represents the bottom-left quadrant of Figure 3 where areas are drier than the 30-year average and drier than the district average, 'BR' represents the bottom-right quadrant where areas are drier than the 30-year average and wetter than the district average. The remaining percentages show the amount of loss in the top quadrants where areas are not in a precipitation deficit (i.e., positive P_{time}). Numbers in red show the difference in the percentage of loss occurring in drier areas of the districts compared to wetter areas for both land change groups.

	Human				Natural		
Year	BL	BR	Remaining (Top)		BL	BR	Remaining (Top)
2001	26.5%	38.9% (+12.4)	**34.6%**		22.4%	56.9% (+34.5)	**20.7%**
2005	50.0%	50.0% (+0)	**0%**		35.5%	64.4% (+28.9)	**0%**
2009	30.9%	69.1% (+38.2)	**0%**		40.9%	59.1% (+18.2)	**0%**
2013	12.7%	80.3% (+67.6)	**7.0%**		46.3%	43.6% (-2.7)	**10.1%**
2017	29.3%	44.5% (+15.2)	**26.2%**		32.6%	30.8% (-1.8)	**36.6%**

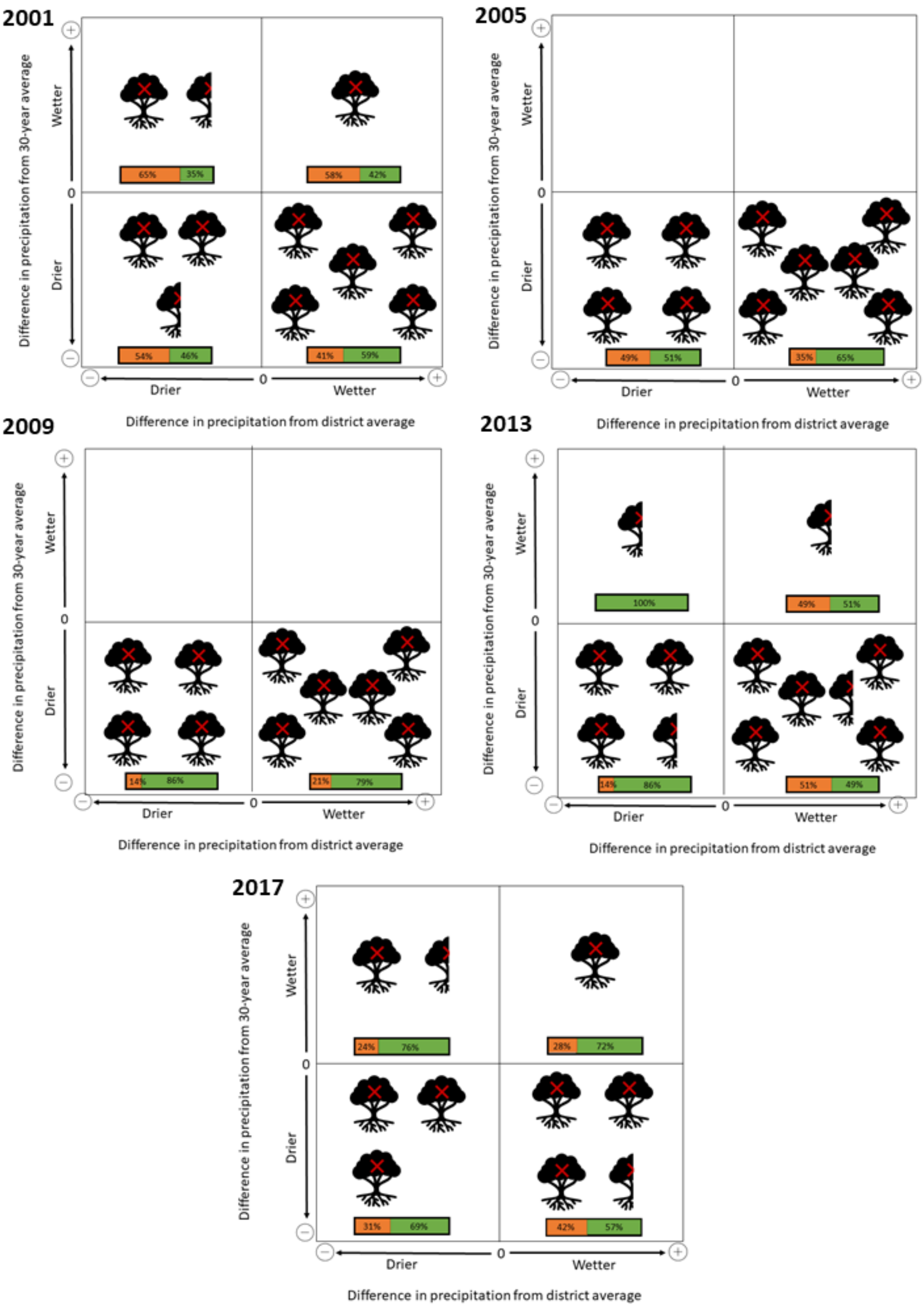


Figure 3| Representation of the relationship between the two climate variables; P_{time} (difference in precipitation from the 30-year average) and P_{area} (difference in precipitation from the district average), and the effect on forest loss. Each tree represents 10% of overall forest loss i.e., a quadrant with 4 trees shows that 40% of the total forest loss occurred in those conditions. Percentages were rounded to the nearest 5% for visual clarity. Percentage bars within each quadrant display the proportion of forest loss in that quadrant that is related to a change in land use that is classified as 'human' or 'natural', where human is shown in orange.

4.4.3 Temporal change in forest loss and analysis of the land use associated with loss

Forest loss did not consistently increase over time, but it was greatest in the last deficit year (2017) (Table 1). Loss in this year was greater than all other deficit years combined and accounted for 36.7% of the total loss in the region between 1995-2019.

Across the five precipitation deficit years, the forest type with consistently the highest percentage losses was 'broadleaved evergreen closed to open'. 51% of forest losses were from this category, followed by 34% from the forest type 'broadleaved deciduous closed to open'. Both forest types remained those with the largest losses for human and natural land changes, however, broadleaved evergreen closed to open forests were favoured by natural land cover changes where they accounted for 63% of all losses, and broadleaved deciduous closed to open forests were favoured by human land use changes, accounting for 54% of losses (Table S1).

Conversion to natural mosaics was the primary cause of loss over the five deficit years (51.5% of loss over the 5 years), followed by conversion to mosaic croplands (24.4% of loss over the 5 years). Among the losses associated with natural land cover changes, conversions to natural mosaics were associated with >78% of forest losses in every year, with the second biggest contributor being shrubland. Among human-related forest losses, mosaic croplands replaced 37-57% of the forest and was the most common land use conversion each year. An exception to this was in the year 2005, where the largest contributor was irrigated croplands. Over time, a shift towards increased forest losses associated with natural land covers was detected.

4.4.4 Model results

Do precipitation deficits result in a higher probability of forest loss?

The P_{time} model revealed forest loss to be significantly less likely in areas that were wetter than their 30-year average (estimate = -2.58e-04, std err= 1.42e-05, z=-18.28, p =<0.0001). In particular, the model predicted a 1% lower risk of forest loss for each 10 mm increase in precipitation over the 30-year average.

Is forest loss attributed to anthropogenic land use changes more prevalent in the wetter areas of a drought?

In the P_{area} model, there was a consistently positive effect between P_{area} and the probability of forest being associated with human land use changes, indicating a higher likelihood of forest loss in areas that were wetter than the district average. However, there was also a significant interaction between P_{area} and population density in every year except 2009 (Table 3), such that at higher population densities there was a greater probability of forest loss associated with human land use change in areas with a greater precipitation deficit. In 2009, there was a significant effect of both population density and P_{area} on the probability of forest being lost to a certain land use type but no interaction.

Model residuals were tested for spatial autocorrelation, and autocorrelation was found in every model except 2009 (Moran's I: observed=0.58, expected=-0.92, variance=1.67, p=0.12). The spatial autocorrelation detected was positive in every case indicating that data points closer together in space were more likely to be similar than those further away.

Employing auto-logistic models with a lag variable to account for the spatial autocorrelation resulted in the interactions in three of the four (2009 not included) models becoming no longer significant. The interaction remained significant in the year 2001 (Table 3). Subsequently, P_{area} no longer showed a significant effect on whether forest loss was more likely to be associated with human or natural land use changes in two of the years; 2005 and 2017. The effect of population density remained significant in all years, with a positive effect direction. This indicates that increases in population density resulted in an increased likelihood of forest loss being associated with human land use changes. There remained a significant effect of P_{area} in 2001 and 2013 in a positive effect direction, indicating that wetter areas increased the likelihood of forest loss being associated with human land use changes (Table 3).

Table 3 | Logistic and auto-logistic model outputs for each precipitation deficit year. Non-significant effects are highlighted in red. AIC values for each model are shown after predictor variables. The predictor variable ‘Lag rate’ in the auto-logistic models corresponds to the addition of a spatial lag variable to account for spatial autocorrelation in the residuals of the model.

		Logistic model				Auto-logistic model			
Year	Predictor variables	Estimate	Std Err	Z	P	Estimate	Std Err	Z	P
2001	Intercept	-0.83	0.04	-16.8	<0.001	-8.87	0.23	-37.69	<0.001
	Lag rate	NA	NA	NA	NA	5.73	0.15	36.83	<0.001
	Precipitation difference	1.56E-03	1.63E-04	9.58	<0.001	6.25E-04	2.23E-04	2.8	0.005
	Population density	2.59E-03	2.00E-04	12.97	<0.001	1.05E-03	2.57E-04	4.11	<0.001
	Interaction	-1.22E-05	1.21E-06	-10.12	<0.001	-4.37E-06	1.50E-06	-2.91	0.003
	AIC	5780				AIC	3170		
2005	Intercept	2.23	0.19	-11.61	<0.001	-8.84	0.58	-15.1	<0.001
	Lag rate	NA	NA	NA	NA	5.41	0.41	13.21	<0.001
	Precipitation difference	3.88E-03	5.83E-04	6.66	<0.001	1.34E-03	7.59E-04	1.77	0.07
	Population density	8.56E-03	8.41E-04	10.17	<0.001	2.61E-03	9.53E-04	2.73	0.006
	Interaction	-1.92E-05	3.27E-06	-5.88	<0.001	-6.44E-06	4.08E-06	-1.58	0.11
	AIC	698				AIC	393		
2009	Intercept	-2.75	0.1	-26.04	<0.001	/	/	/	/
	Lag rate	NA	NA	NA	NA	/	/	/	/
	Precipitation difference	2.29E-03	2.81E-04	8.13	<0.001	/	/	/	/
	Population density	7.24E-03	5.61E-04	12.89	<0.001	/	/	/	/
	Interaction	-3.58E-06	2.50E-06	-1.43	0.15	/	/	/	/
	AIC	2020							
2013	Intercept	-2.23	0.19	-11.38	<0.001	-9.04	0.66	-13.68	<0.001
	Lag rate	NA	NA	NA	NA	5.53	0.46	11.93	<0.001
	Precipitation difference	4.79E-03	3.62E-04	13.23	<0.001	1.11E-03	4.75E-04	2.33	0.01
	Population density	4.57E-03	8.51E-04	5.37	<0.001	3.25E-03	1.25E-03	2.59	0.009
	Interaction	-1.43E-05	3.51E-06	-4.09	<0.001	-2.80E-06	4.45E-06	-0.63	0.53
	AIC	640				AIC	407		
2017	Intercept	-1.09	0.03	-35.49	<0.001	-8.31	0.13	-61.63	<0.001
	Lag rate	NA	NA	NA	NA	5.39	0.09	58.42	<0.001
	Precipitation difference	3.34E-04	9.70E-05	3.44	<0.001	8.66E-05	1.26E-04	0.68	0.49
	Population density	2.53E-03	1.09E-04	23.23	<0.001	4.07E-04	1.01E-04	4.01	<0.001
	Interaction	1.78E-06	4.33E-07	4.12	<0.001	3.55E-07	5.20E-07	0.68	0.49
	AIC	13774				AIC	7717		

4.5 Discussion

This study provides the first assessment of an interactive effect between a climate driver and land use change on forest loss in India. The findings provide evidence for a combined effect of drought and land use change on the distribution of forest loss in the Northeast region of India. Precipitation deficits increased the probability of forest loss in the region, but smaller precipitation deficits resulted in an increased probability of forest loss to land use change. Broadleaved evergreen forests saw the largest losses during the precipitation deficits years; however, the findings of this study show that broadleaved deciduous forests were at a greater risk from land use changes than any other forest type. Overall, this chapter contributes to an increased understanding of the relationship between precipitation deficits and forest loss in Northeast India, as well as providing evidence of interactive effects between precipitation deficits and land use change. The research also increases the broader knowledge of interactions between these two drivers in the South Asian area of the tropical forest biome, a severely understudied area in terms of climate-land interactions.

In this study, a greater probability of forest loss was found in areas experiencing a precipitation deficit. These findings supported the first prediction of the study as well as studies from other tropical regions which have shown increased mortality of tropical trees in response to precipitation deficits (McDowell et al., 2018; Meir et al., 2015; Phillips et al., 2010). The majority of forest in the Northeast region is tropical wet deciduous and evergreen forests which have been shown to be particularly prone to drought stress (Browne et al., 2021; Esquivel-Muelbert et al., 2019), and the prevalence of this forest type is likely to have exacerbated the effects of the drought. The effect of drought on the forests in this region is concerning as the Northeast forests are of national importance, harbouring a large proportion of the country's remaining intact forest they are a key refuge for biodiversity and many endemic species (Karanth et al.,2009; Lele & Joshi, 2009). The region is also considered to be at relatively low-risk for climate effects due to its high biodiversity, contiguous forest cover and projections of increased rainfall. Studies assessing the future climate effects on forests in India have predicted the region to be more resilient and potentially see positive effects of climate change on its forests (Chaturvedi et al., 2011; Gopalakrishnan et al., 2011; Ravindranath et al., 2005). This is primarily as a result of predicted increases in both precipitation and temperature without taking into account potential extreme events on the forests in the future, including droughts, which are predicted to increase in incidence and severity (Kala, 2017; Sharma & Mujumdar, 2017). Climate change is rarely considered a current threat to forests in India in the literature or policy documents and often referred to as a future threat, however, the findings in this chapter suggest that this is an oversight and that not accounting for the drought effects on forest distribution in the region could lead to a greater forest loss than expected currently. This chapter finds that the Northeast region may be more affected by climate extremes than previously considered. Assessing the effects of these events on forests in India is necessary to ensure more accurate predictions of forest vulnerability in the future.

This study also found evidence of an interaction between precipitation deficits and land use change, where land-use change driven forest losses were more likely to occur in the wetter areas of a drought. This supports the second prediction of the study as well as supporting studies from other regions that have shown interactions between drought and land use changes (Longo et al., 2020; Qie et al., 2019). In this chapter the majority of land-use change driven forest losses were as a result of conversion of forest to mosaic croplands. As water resources are integral to crop production it is possible that conversion of forest to cropland mainly occurred in locations with a smaller precipitation deficit because these areas had the best chance of crop success during a drought. The findings have key implications for the future of the region's forests since both an increasing incidence of drought and further agriculture expansion are predicted to occur (Hinz et al., 2020; IPCC, 2019; Mishra, 2019; Sharma & Mujumdar, 2017). The interaction found in this chapter provides an opportunity to better understand the mechanisms behind forest loss in the region and could lead to more accurate predictions of forest loss in the future. This not only has implications for improving forest and biodiversity conservation strategies but also for climate change mitigation strategies. This is because vegetation losses in the country have been shown to lead to localised warming (Gogoi et al., 2019; Nayak & Mandal, 2019), increased incidences of drought (Roy & Hirway, 2007), flooding (Bhattacharjee & Behera, 2017), and changes in the monsoon (Sen et al., 2004). Considering interactions between forest loss drivers could lead to more accurate predictions of vegetation loss and therefore, a better understanding of the feedback effects on climate change.

It is notable that an interaction between precipitation deficits and land use change was not found in every deficit year i.e., P_{area} was not a significant driver in every model. The two years in which the interaction was not significant showed unique attributes that could have contributed to a difference in trend. For instance, 2005 had the largest precipitation deficits of any year. Much of the major cropland growing areas, such as Assam and Meghalaya, experienced a worse drought than the rest of the region. The lowest number of forest losses across the five years were also recorded in this year. It is possible that the severe deficits meant that conversions to cropland were not viable in 2005. In 2017, the region experienced the most extensive forest losses which appeared independent of the precipitation deficit trend. Though analysis of forest loss trends during the last decade in India is scarce, reports of increased forest loss in India during 2016, 2017 and 2018 have been found global datasets (Global Forest Watch, 2021), and the Northeastern states are shown to be experiencing net losses during these years in governmental reports (FSI, 2017, 2019). The global assessments attribute the large losses during this time to increases in as forestry particularly in the states of Mizoram and Manipur. Whereas the governmental reports attribute the losses to shifting cultivation practices and development projects. As such, it remains uncertain why there was such a rapid increase in loss compared to previous years, but it is not likely to be directly a result of the drought. The precipitation deficit in 2017 was one of the least severe, however, a previous study by Mishra (2019) reported repeated drought occurrences during this period which could have an accumulating effect (Rajsekhar & Gorelick, 2017; Zhao et al., 2020). The accumulation of effects from multiple years of drought may have contributed to the increased forest loss in this year but would not have been picked up in this study.

The distribution of the largest precipitation deficits across the region in this study also prompts concern for both forest conservation and human livelihoods. The largest deficits occurred in the states of Assam and Meghalaya, which have been previously identified as particularly vulnerable to drought (Ravindranath et al., 2011). These states are key agricultural areas with a high proportion of the population dependent of agriculture (Amoako Johnson & Hutton, 2014) but they also have ecologically important forests and several nationally important protected areas, such as Kaziranga National Park (Sheth et al., 2020). The East Khasi Hills district in Meghalaya experienced a 188% rainfall deficit in 2005, compared to the regional average for the season. This district is one of the wettest places on Earth. If extreme deficits like this occur regularly, it is likely that this will put considerable stress on the district's tropical wet forests that are currently reliant on consistent heavy rainfall. There would also be consequences for agriculture as both Meghalaya and Assam are typically reliable areas for crop growth and local farmers have limited experience and infrastructure to deal with drought conditions (Parida & Oinam, 2015). Precipitation in these states feed into the Brahmaputra River, part of larger river system which provides resources for a population of 780 million people (Whitehead et al., 2018) which is vitally important for the country's crop production, so deficits in this area are likely to have far-reaching effects.

Across all precipitation deficit years, natural mosaics and mosaic croplands were the major drivers of forest loss. This is likely to be encouraging for forest biodiversity compared to if forest were being predominantly lost to cropland or urban areas. The remaining forest cover in the mosaic habitats could provide vital refuge for forest species and allow them to persist despite the loss of the wider contiguous habitat (Bhagwat et al., 2008; Udawatta et al., 2019), though this might not be the case for the most sensitive species (Keinath et al., 2017; Leal et al., 2012; Magura et al., 2001). The network of forest patches in the mosaic may also allow some maintenance of ecosystem services compared to complete conversion to another land cover type. However, fragmented forests are also likely to harbour lower levels of diversity and reduced functioning than intact forest cover, with an increased likelihood of further degradation (Haddad et al., 2015; Tracewski et al., 2016). The majority (80%) of forest losses were from broadleaved forest types, with broadleaved evergreen forests losing a larger area than broadleaved deciduous forests. The susceptibility of evergreen forests to drought conditions has been found in other tropical regions, where deciduous and dry-affiliated species are expected to expand in range in the place of evergreens (Aguirre-Gutiérrez et al., 2020; Chaturvedi et al., 2011; Esquivel-Muelbert et al., 2019). Despite broadleaved evergreen forests losing a larger area of forest, the loss of broadleaved deciduous forests could be more alarming given their lower areal extent at the start of the study. In 2000, broadleaved deciduous forests accounted for only 13% of forest cover, whereas broadleaved evergreen forests accounted for 57%. The findings in this chapter show that broadleaved deciduous forests were disproportionately favoured by human-driven losses, likely due to this type providing good harvests of fuelwood and fodder (Coleman et al., 2021; Wakeel et al., 2005). Previous studies have identified deciduous forests in the Northeast as most at risk to human degradation (Srivastava et al., 2002; Wakeel et al., 2005). In contrast, broadleaved evergreen forests were more likely to be lost to natural land cover changes which could be indicative of their greater susceptibility to drought effects (Ratnam et al., 2019; Vico et al., 2017). The finding that these two forest types are susceptible to different drivers is concerning in the context of the interaction found because it could mean that a larger area and diversity of forest is lost when droughts and land use changes impact the same area.

The results of this study produce compelling evidence that both extreme precipitation deficits and land use changes can impact forests in the Northeast region of India. The two drivers are likely to be acting synergistically to result in more extensive forest loss that the drivers acting alone. The evidence presented here supports a drive towards understanding how these drivers are interacting within the country and what this means for forests and biodiversity. There are four immediate research directions that would appropriately follow the evidence presented here.

1) Factors not considered in this study namely soil type, soil moisture levels, agricultural preferences i.e., rainfed, irrigation or shifting cultivation, as well as the distribution of protected areas, are likely to impact the susceptibility of these forests to drought and land use interactions. The ways in which these factors alter the risk of forests to drought and land use change stressors, including whether these factors alter how interactions between the two manifest, should be further explored. For example, higher baseline soil moisture levels may buffer forests from the negative effects of drought causing the

direct effects of the drought to be less severe which could increase the capability of the forest to deal with other stressors such as degradation (Aguirre-Gutiérrez et al., 2020; Meir et al., 2015).

2) Further research is needed to understand whether there is an accumulating effect of droughts in this region. Accumulating effects have been found to exacerbate forest loss in other regions (Rajsekhar & Gorelick, 2017; Zhao et al., 2020). This is concerning for the Northeast region due to the increase in occurrence of droughts and the short time periods between the precipitation deficit years identified in this study. This is especially a concern during the later years where multiple dry years were found in other research (Mishra, 2019) and could be leading to a larger effect of forests not correlated with one extreme year. Understanding whether there is a cumulative effect of drought in Northeast India could be crucial in halting such high forest losses in the future, where additional protection may be required. Other researchers have noted that India's policies tend to be reactive to extreme events like drought, where action is mobilised when droughts become severe and start having visible effects (Bandyopadhyay et al., 2020; Prabhakar & Shaw, 2007; Wilhite et al., 2014). If there is an accumulating effect over multiple years of drought, this is likely going unnoticed.

3) Quantifying the point at which drought causes stress on humans specifically in this region is also vitally important to increasing our understanding of the mechanistic drivers behind land use change driven forest losses. Exploring whether there is a threshold for drought stress on different populations in the region could facilitate better awareness of forest vulnerability in different areas. This threshold could also better inform management strategies which could use this threshold to support forest conservation in advance using climate projections. This information could also be used in conjunction with projected population and land use changes to predict where forests might be lost in the future.

4) There is recent evidence to suggest that the long-term effects of drought on forests and their associated species may be different from the short-term effects (Meir et al. 2018, Ovenden, 2021). For example, (Nepstad et al., (2007), found that loss of large trees in a drought had long term effects on litter fall, soil conditions and a reduction in biodiversity that was not observed in the short-term. There could also be a lagged response in the effects of forest loss on species resulting in a 'debt' that becomes apparent at a later stage (Meir et al. 2018, Bertrand et al. 2016). However, other studies have shown an increase in tree growth following a drought in some species up to nine years after the event (Ovenden 2021). Thus the long-term effects could be more positive than in apparent by the short-term changes in terms of forest survival and biodiversity in the future even if individual trees are lost (Meir et al., 2018; Ovenden et al., 2021). Further research assessing the effects of these droughts on forest coverage, tree mortality, and the associated biodiversity over a longer period of time is needed to ascertain the long-term effects of these droughts on the Northeast region's forests.

There are some key considerations that should be taken into account when interpreting the results of this chapter. Firstly, there may be a lag in the time taken for the impact of drought on both humans and forests (Wu et al., 2015; Zhao et al., 2020; Phillips et al. 2009). This was not accounted for in the study as it can be hard to quantify and likely to be different for natural and human drivers of loss as well as different locations along the soil moisture gradient (Meir et al. 2018, Ovenden, 2021). The presence of repeated droughts in this region and during the period of study also complicated this, as introducing a lag effect could make it difficult to differentiate between loss caused by a current vs previous drought (Rajsekhar & Gorelick, 2017). A four-year lag was initially considered in this study however, these difficulties prevented its inclusion in the chapter. Secondly, the precipitation deficit years informed by the literature are predominantly based on agricultural or meteorological drought which are not designed to capture the stress that forests may experience. Employing metrics assessing vegetation condition indices and soil moisture can help to ascertain whether forests are experiencing drought stress and these methods should be employed in future studies specifically assessing the losses attributed to natural land use changes following this study. Finally, across the deficit years more loss was attributed to natural land cover changes than land use changes. This could be indicative of the additional stress that the forests are under due to the precipitation deficits leading to an increase in mortality, but further research is needed to evaluate whether this is the causal factor. This is because the study design only distinguishes definitive human-related causes from other types of land cover change. Thus, climatic causes of forest loss such as drought stress and fire, cannot be distinguished from human-driven activities that do not result in conversion to cropland or urban areas like harvesting of forest products, plantations, livestock rearing or logging. For example, the practice of shifting cultivation, which can be fairly robust to drought (Teegalapalli & Datta, 2016), results in a mosaic of forest and shrubland which appear as a ‘natural’ transition in this analysis but is human-driven. As such, this study is likely to be underestimating the proportion of forest lost to anthropogenic influences. This was expected and could not be accounted for without higher resolution data and on-the-ground surveys to better classify the land use changes associated with these losses.

Despite its limitations, this study is the first to consider how an interaction between drought and land use change is affecting forests in the country. It bridges two main knowledge gaps, the first being how droughts affect forest coverage in the Northeast region of the country and the second of whether interactions between these two drivers are leading to increased forest losses. This study provides novel findings on both knowledge gaps which will contribute to a better understanding of forest vulnerability in the Northeast region. The research challenges previous studies that predict the region to be resilient to climate effects and recommends future studies and conservation policies take into account the effect of extreme climatic events, and their interactions with land use change, on the forests of the region. The study finds for the first time in the country that drought increases the probability of forest loss and that there can be a relationship between precipitation deficits and the spatial distribution of forest loss associated with human land use changes in the Northeast region of India. The study provides evidence to show that the coupling of these two stressors threaten a larger area of forest, and diversity of forest types, than either driver acting alone. The research presented here provides an important starting point for assessing potential interactions between drivers of forest loss in India, an interaction that has been overlooked in the past. Without accounting for likely relationships between drivers and actively considering new ones, we risk inadequately protecting the forest resources and placing sole accountability on the agricultural community to reduce losses. With climate projections showing increased drought in the future, this research stresses the importance of considering the direct and indirect effects of climate change on forests in future studies and provides information that could inform the creation of more holistic and effective protection of forest resources, whilst recognising that forest protection schemes will need to go hand in hand with ensuring adequate food provisions and economic well-being.

4.6 References

Aguirre-Gutiérrez, J., et al. (2020). Long-term droughts may drive drier tropical forests towards increased functional, taxonomic and phylogenetic homogeneity. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-16973-4

Algur, K. D., Patel, S. K., & Chauhan, S. (2021). The impact of drought on the health and livelihoods of women and children in India: A systematic review. *Children and Youth Services Review*, *122*, 105909. https://doi.org/10.1016/J.CHILDYOUTH.2020.105909

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), 1–55. https://doi.org/10.1890/ES15-00203.1

Allen, C. D., 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*(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Allen, K., et al. (2017). Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes? *Environmental Research Letters*, *12*(2), 023001. https://doi.org/10.1088/1748-

9326/AA5968

Amoako Johnson, F., & Hutton, C. W. (2014). Dependence on agriculture and ecosystem services for livelihood in Northeast India and Bhutan: vulnerability to climate change in the Tropical River Basins of the Upper Brahmaputra. *Climatic Change*, *127*(1), 107–121. https://doi.org/10.1007/S10584-012-0573-7

Asner, G. P., Loarie, S. R., & Heyder, U. (2010). Combined effects of climate and land-use change on the future of humid tropical forests. *Conservation Letters*, *3*(6), 395–403. https://doi.org/10.1111/j.1755-263X.2010.00133.x

Auffhammer, M., Ramanathan, V., & Vincent, J. R. (2011). Climate change, the monsoon, and rice yield in India. *Climatic Change*, *111*(2), 411–424. https://doi.org/10.1007/S10584-011-0208-4

Augustin, N. H., Mugglestone, M. A., & Buckland, S. T. (1996). An Autologistic Model for the Spatial Distribution of Wildlife. *The Journal of Applied Ecology*, *33*(2), 339. https://doi.org/10.2307/2404755

Bana, R. S. (2014). Soybean based cropping systems. *Indian Journal of Agronomy*. 59(2), 179-190

Bandyopadhyay, N., Bhuiyan, C., & Saha, A. K. (2020). Drought mitigation: Critical analysis and proposal for a new drought policy with special reference to Gujarat (India). *Progress in Disaster Science*, *5*. https://doi.org/10.1016/J.PDISAS.2019.100049

Barlow, J., et al., (2018). The future of hyperdiverse tropical ecosystems. *Nature*, *559*(7715), 517–526. https://doi.org/10.1038/s41586-018-0301-1

Belay, A., et al., (2017). Smallholder farmers’ adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *Agriculture & Food Security*, *6*(1), 1–13. https://doi.org/10.1186/S40066-017-0100-1

Betts, M. G., et al., (2017). Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature*, *547*(7664), 441–444. https://doi.org/10.1038/nature23285

Betts, R. (2007). Implications of land ecosystem-atmosphere interactions for strategies for climate change adaptation and mitigation. *Tellus, Series B: Chemical and Physical Meteorology*, 59(3), 602-615. https://doi.org/10.1111/j.1600-0889.2007.00284.x

Bhagwat, S. A., et al., (2008). Agroforestry: a refuge for tropical biodiversity? *Trends in Ecology & Evolution*, *23*(5), 261–267. https://doi.org/10.1016/J.TREE.2008.01.005

Bhatt, B. P., & Sachan, M. S. (2004). Firewood consumption pattern of different tribal communities in Northeast India. *Energy Policy*, *32*(1), 1–6. https://doi.org/10.1016/S0301-4215(02)00237-9

Bhatta, G. D., & Aggarwal, P. K. (2015). Coping with weather adversity and adaptation to climatic variability: a cross-country study of smallholder farmers in South Asia. *Climate and Development*, *8*(2), 145–157. https://doi.org/10.1080/17565529.2015.1016883

Bhattacharjee, K., & Behera, B. (2017). Forest cover change and flood hazards in India. *Land Use Policy*, *67*, 436–448. https://doi.org/10.1016/j.landusepol.2017.06.013

Brando, P. M., et al., (2014). Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proceedings of the National Academy of Sciences*, *111*(17), 6347–6352. https://doi.org/10.1073/PNAS.1305499111

Brodie, J., Post, E., & Laurance, W. F. (2012). Climate change and tropical biodiversity: a new focus. *Trends in Ecology & Evolution*, *27*(3), 145–150. https://doi.org/10.1016/J.TREE.2011.09.008

Brookhuis, B. J., & Hein, L. G. (2016). The value of the flood control service of tropical forests: A case study for Trinidad. *Forest Policy and Economics*, *62*, 118–124. https://doi.org/10.1016/J.FORPOL.2015.10.002

Browne, L., et al., (2021). Increased mortality of tropical tree seedlings during the extreme 2015–16 El Niño. *Global Change Biology*, *27*(20), 5043–5053. https://doi.org/10.1111/GCB.15809

Chakraborty, K., et al., (2018). Recognizing the rapid expansion of rubber plantation - A threat to native forest in parts of northeast India. *Current Science*, *114*(1), 207–213. https://doi.org/10.18520/CS/V114/I01/207-213

Chaturvedi, R. K., et al., (2011). Impact of climate change on Indian forests: A dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change*, *16*(2), 119–142. https://doi.org/10.1007/s11027-010-9257-7

Chitale, V. S., Behera, M. D., & Roy, P. S. (2014). Future of endemic flora of biodiversity hotspots in India. *PLoS ONE*, *9*(12). https://doi.org/10.1371/journal.pone.0115264

Choat, B., et al., (2018). Triggers of tree mortality under drought. *Nature*, *558*(7711), 531–539. https://doi.org/10.1038/s41586-018-0240-x

Choat, B., et al., (2012). Global convergence in the vulnerability of forests to drought. *Nature*, *491*(7426), 752–755. https://doi.org/10.1038/nature11688

Clark, J. S., et al., (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, *22*(7), 2329–2352. https://doi.org/10.1111/gcb.13160

Coleman, E. A., et al., (2021). Limited effects of tree planting on forest canopy cover and rural livelihoods in Northern India. *Nature Sustainability*, 4, 997-1004. https://doi.org/10.1038/s41893-021-00761-z

Congedo, L (2021). Semi-automatic classification plugin: A python tool for the download and processing of remote sensing images in QGIS. *Journal of Open Source Software*. 6(64) 3172.

Côté, I. M., Darling, E. S., & Brown, C. J. (2016). Interactions among ecosystem stressors and their importance in conservation. *Proceedings of the Royal Society B: Biological Sciences*, 282(1824). https://doi.org/10.1098/rspb.2015.2592

Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, *361*(6407), 1108–1111. https://doi.org/10.1126/science.aau3445

Dai, Aiguo & National Center for Atmospheric Research Staff (Eds.). Last modified 12 Dec 2019. “The Climate Data Guide: Palmer Drought Severity Index (PDSI).” Retrieved from https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi

Das, A., et al., (2009). Climate change in Northeast India: recent facts and events - worry for agricultural management. ISPRS Archives XXXVIII-8/W3 Workshop Proceedings: Impact of Climate Change on Agriculture.

Dash, S. et al., (2011). Characteristic changes in the long and short spells of different rain intensities in India. *Theoretical and Applied Climatology*, *105*(3), 563–570. https://doi.org/10.1007/s00704-011-0416-x

Davidar, P., Arjunan, M., & Puyravaud, J. P. (2008). Why do local households harvest forest products? A case study from the southern Western Ghats, India. *Biological Conservation*, *141*(7), 1876–1884. https://doi.org/10.1016/J.BIOCON.2008.05.004

Davidar, P., et al., (2010). Assessing the extent and causes of forest degradation in India: Where do we stand? *Biological Conservation*, *143*(12), 2937–2944. https://doi.org/10.1016/j.biocon.2010.04.032

Deb, J. C., et al., (2018). Climate change impacts on tropical forests: identifying risks for tropical Asia. *Journal of Tropical Forest Science*, *30*(2), 182–194.

https://doi.org/10.26525/JTFS2018.30.2.182194

Di Gregorio, A. (2016). *Land Cover Classification System : Classification concepts. Software version 3*. http://www.fao.org/3/a-i5232e.pdf

Duan & Mei (2014). Comparison of meteorological, hydrological and agricultural drought responses to climate change and uncertainty assessment. *Water Resources Management*, 28, 5039-5054

Dundas, S. J., et al., (2021). Some like it hot: Drought-induced forest die-off influences reptile assemblages. *Acta Oecologica*, *111*, 103714. https://doi.org/10.1016/J.ACTAO.2021.103714

ESA. Land Cover CCI Product User Guide Version 2. Tech. Rep. (2017). Available at: maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

ESA C3S. Land Cover CCI Product User Guide (2016-2019): https://datastore.copernicus-climate.eu/documents/satellite-land-cover/D5.3.1_PUGS_ICDR_LC_v2.1.x_PRODUCTS_v1.1.pdf

Esquivel-Muelbert, A., et al., (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, *25*(1), 39–56. https://doi.org/10.1111/GCB.14413

Fauset, S., et al., (2012). Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. *Ecology Letters*, *15*(10), 1120–1129. https://doi.org/10.1111/J.1461-0248.2012.01834.X

Fishman, R. (2016). More uneven distributions overturn benefits of higher precipitation for crop yields. *Environmental Research Letters*, *11*(2), 024004. https://doi.org/10.1088/1748-9326/11/2/024004

França, F. M., et al., (2020). El Niño impacts on human-modified tropical forests: Consequences for dung beetle diversity and associated ecological processes. *Biotropica*, *52*(2), 252–262. https://doi.org/10.1111/BTP.12756

FSI (2017). State of the Forest Report, 2017. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

FSI (2019). State of the Forest Report, 2019. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

Giam, X. (2017). Global biodiversity loss from tropical deforestation. *Proceedings of the National Academy of Sciences*, *114*(23), 5775–5777. https://doi.org/10.1073/PNAS.1706264114

Gogoi, P. P., et al., (2019). Land use and land cover change effect on surface temperature over

Eastern India. *Nature Scientific Reports*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-45213-z

Gopalakrishnan, R., et al., (2011). Climate change and Indian forests. *Current Science,* 101(3), 348-355

Guhathakurta, P., et al., (2015). Observed changes in southwest monsoon rainfall over India during 1901-2011. *International Journal of Climatology*, *35*(8), 1881–1898. https://doi.org/10.1002/joc.4095

Guo, F., Lenoir, J., & Bonebrake, T. C. (2018). Land-use change interacts with climate to determine elevational species redistribution. *Nature Communications*, 9(1315). https://doi.org/10.1038/s41467-018-03786-9

Haddad, N. M., et al., (2015). Habitat fragmentation and its lasting impact on Earth’s ecosystems. *Science Advances*, *1*(2), e1500052–e1500052. https://doi.org/10.1126/sciadv.1500052

Hasselquist et al., (2010). Water relations of evergreen and drought-deciduous trees along a seasonally dry tropical forest chronosequence. *Oecologia*, 164, 881-890

Hanson, P. J., & Weltzin, J. F. (2000). Drought disturbance from climate change: Response of United States forests. *Science of the Total Environment*, *262*(3), 205–220. https://doi.org/10.1016/S0048-9697(00)00523-4

Harvey, C. A., et al., (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1639). https://doi.org/10.1098/RSTB.2013.0089

Harvey, C. A., et al., (2018). Climate change impacts and adaptation among smallholder farmers in Central America. *Agriculture & Food Security*, *7*(1), 1–20. https://doi.org/10.1186/S40066-018-0209-X

Hinz, R., et al., (2020). Agricultural Development and Land Use Change in India: A Scenario Analysis of Trade-Offs Between UN Sustainable Development Goals (SDGs). *Earth’s Future*, *8*(2), e2019EF001287. https://doi.org/10.1029/2019EF001287

IPCC. (2019). Summary for Policymakers — Special Report on Climate Change and Land. Retrieved February 3, 2021, from https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

Jamshidi, O., et al., (2019). Vulnerability to climate change of smallholder farmers in the Hamadan province, Iran. *Climate Risk Management*, *23*, 146–159. https://doi.org/10.1016/J.CRM.2018.06.002

Jiang et al., (2021). A novel index for ecological drought monitoring based on ecological water deficit. *Ecological Indicators*, 129, 107804

Kala, C. P. (2017). Environmental and Socioeconomic Impacts of Drought in India: Lessons for Drought Management. *Applied Ecology and Environmental Sciences*, *5*(2), 43–48. https://doi.org/10.12691/AEES-5-2-3

Kale, M. P., et al., (2016). Land-use and land-cover change in Western Ghats of India. *Environmental Monitoring and Assessment*, 188(7), 387. https://doi.org/10.1007/s10661-016-5369-1

Karanth, K. K., et al.,. (2009). Patterns and determinants of mammal species occurrence in India. *Journal of Applied Ecology*, 46(6), 1189-1200. https://doi.org/10.1111/j.1365-2664.2009.01710.x

Keeley et al., (2018). New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, 13(7), 073002

Keinath, D. A., et al., (2017). A global analysis of traits predicting species sensitivity to habitat fragmentation. *Global Ecology and Biogeography*, *26*(1), 115–127. https://doi.org/10.1111/GEB.12509

Kulakowski, D., Bebi, P., & Rixen, C. (2011). The interacting effects of land use change, climate change and suppression of natural disturbances on landscape forest structure in the Swiss Alps. *Oikos*, *120*(2), 216–225. https://doi.org/10.1111/j.1600-0706.2010.18726.x

Kumar, D., & Scheiter, S. (2019). Biome diversity in South Asia - How can we improve vegetation models to understand global change impact at regional level? *Science of The Total Environment*, *671*, 1001–1016. https://doi.org/10.1016/J.SCITOTENV.2019.03.251

Kundu, S. S., et al., (2015). Shifting cultivation dynamics in Barak bason of North east India - A geospatial approach. *International Journal of Advancement in Earth and Environmental Sciences* 3 (2), 21-29

Larsen, T. H. (2012). Upslope Range Shifts of Andean Dung Beetles in Response to Deforestation: Compounding and Confounding Effects of Microclimatic Change. *Biotropica*, *44*(1), 82–89. https://doi.org/10.1111/J.1744-7429.2011.00768.X

Laurance, W. F., & Useche, D. C. (2009). Environmental Synergisms and Extinctions of Tropical Species. *Conservation Biology*, *23*(6), 1427–1437. https://doi.org/10.1111/J.1523-1739.2009.01336.X

Laurance, W. F., & Williamson, G. B. (2001). Positive Feedbacks among Forest Fragmentation, Drought, and Climate Change in the Amazon. *Conservation Biology*, *15*(6), 1529–1535. https://doi.org/10.1046/J.1523-1739.2001.01093.X

Le Page, Y., et al., (2017). Synergy between land use and climate change increases future fire risk in Amazon forests. *Earth Syst. Dynam*, *8*, 1237–1246. https://doi.org/10.5194/esd-8-1237-2017

Leal, I. R., et al., (2012). Effects of habitat fragmentation on ant richness and functional composition in Brazilian Atlantic forest. *Biodiversity and Conservation*, *21*(7), 1687–1701. https://doi.org/10.1007/S10531-012-0271-9

Lecina-Diaz, J. et al., (2020). Characterising forest vulnerability and risk to climate-change hazards. *Frontiers in Ecology and the Environment*, 19(2), 126-133

Lei, Y., et al., (2016). How rural land use management facilitates drought risk adaptation in a changing climate — A case study in arid northern China. *Science of The Total Environment*, *550*, 192–199. https://doi.org/10.1016/J.SCITOTENV.2016.01.098

Lele, N., Joshi, P. K., & Agrawal, S. P. (2008). Assessing forest fragmentation in northeastern region (NER) of India using landscape matrices. *Ecological Indicators*, *8*(5), 657–663. https://doi.org/10.1016/J.ECOLIND.2007.10.002

Lele, Nikhil, & Joshi, P. K. (2009). Analyzing deforestation rates, spatial forest cover changes and identifying critical areas of forest cover changes in North-East India during 1972–1999. *Environmental Monitoring and Assessment*, *156*(1–4), 159–170. https://doi.org/10.1007/s10661-008-0472-6

Li, C., et al., (2021). Recent changes in cropland area and productivity indicate unsustainable cropland expansion in Malawi. *Environmental Research Letters*, *16*(8), 084052. https://doi.org/10.1088/1748-9326/AC162A

Longo, M., et al., (2020). Impacts of Degradation on Water, Energy, and Carbon Cycling of the Amazon Tropical Forests. *Journal of Geophysical Research: Biogeosciences*, *125*(8), e2020JG005677. https://doi.org/10.1029/2020JG005677

Magura, T., Ködöböcz, V., & Tóthmérész, B. (2001). Effects of habitat fragmentation on carabids in forest patches. *Journal of Biogeography*, *28*(1), 129–138. https://doi.org/10.1046/J.1365-2699.2001.00534.X

Mahato, R., et al., (2021). Assessing the tropical forest cover change in northern parts of Sonitpur and Udalguri District of Assam, India. *Nature Scientific Reports*, *11*(1), 1–11. https://doi.org/10.1038/s41598-021-90595-8

Mantyka-Pringle, C. S., et al., (2015). Climate change modifies risk of global biodiversity loss due to land-cover change. *Biological Conservation*, *187*. https://doi.org/10.1016/j.biocon.2015.04.016

McDowell, N., et al., (2018). Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, 219(3), 851-869. https://doi.org/10.1111/nph.15027

McDowell, N. G. (2018). Deriving pattern from complexity in the processes underlying tropical forest drought impacts. *New Phytologist*, *219*(3), 841–844. https://doi.org/10.1111/nph.15341

Meir, P., et al., (2018). Short-term effects of drought on tropical forest do not fully predict impacts of repeated or long-term drought: gas exchange versus growth. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760). https://doi.org/10.1098/RSTB.2017.0311

Meir, P., Mencuccini, M., & Dewar, R. C. (2015). Drought-related tree mortality: addressing the gaps in understanding and prediction. *New Phytologist*, *207*(1), 28–33. https://doi.org/10.1111/NPH.13382

Meir, P., et al., (2015). Threshold Responses to Soil Moisture Deficit by Trees and Soil in Tropical Rain Forests: Insights from Field Experiments. *BioScience*, *65*(9), 882–892. https://doi.org/10.1093/BIOSCI/BIV107

Meiyappan, P., et al., (2017). Dynamics and determinants of land change in India: integrating satellite data with village socioeconomics. *Regional Environmental Change*, 17, 753-766. https://doi.org/10.1007/s10113-016-1068-2

Mishra, A. K. (2019). Quantifying the impact of global warming on precipitation patterns in India. *Meteorological Applications*, 26(1), 153-160. https://doi.org/10.1002/met.1749

Mishra, V. (2020). Long-term (1870–2018) drought reconstruction in context of surface water security in India. *Journal of Hydrology*, 580. https://doi.org/10.1016/j.jhydrol.2019.124228

Narwade, S., et al., (2011). Literature based species occurrence data of birds of Northeast India. *ZooKeys*, *150*, 407–417. https://doi.org/10.3897/zookeys.150.2002

Nayak, S., & Mandal, M. (2019). Impact of land use and land cover changes on temperature trends over India. *Land Use Policy*, *89*. https://doi.org/10.1016/j.landusepol.2019.104238

Nepstad, D. C., et al., (2007). Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology*, *88*(9), 2259–2269. https://doi.org/10.1890/06-1046.1

Nobre, C. A., et al., (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences*, *113*(39), 10759–10768. https://doi.org/10.1073/PNAS.1605516113

Oliver, T. H., & Morecroft, M. D. (2014). Interactions between climate change and land use change on biodiversity: Attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, 5(3), 317-335. https://doi.org/10.1002/wcc.271

Ovenden, T. S., et al., (2021). Life after recovery: Increased resolution of forest resilience assessment sheds new light on post-drought compensatory growth and recovery dynamics. *Journal of Ecology*, 109(9), 3157-3170. https://doi.org/10.1111/1365-2745.13576

Padalia, H., et al.,. (2019). Assessment of historical forest cover loss and fragmentation in Asian elephant ranges in India. *Environmental Monitoring and Assessment*, *191*. https://doi.org/10.1007/s10661-019-7696-5

Palchoudhuri, Y., Roy, P. S., & Srivastava, V. K. (2015). A New Socio–economic Index for Modelling Land Use and Land Cover Change. *Journal of Land and Rural Studies*, *3*(1), 1–28. https://doi.org/10.1177/2321024914534051

Pandit, M. K., et al., (2007). Unreported yet massive deforestation driving loss of endemic biodiversity in Indian Himalaya. *Biodiversity and Conservation*, *16*(1), 153–163. https://doi.org/10.1007/s10531-006-9038-5

Parida, B. & Oinam (2015). Unprecedented drought in North East India compared to Western India. *Current Science*. 109 (11), 2121-2126

Paul, S., et al., (2018). Moisture Supply From the Western Ghats Forests to Water Deficit East Coast of India. *Geophysical Research Letters*, *45*(9), 4337–4344. https://doi.org/10.1029/2018GL078198

Paz et al., (2015). Root depth and morphology in response to soil drought: comparing ecological groups along the secondary succession in a tropical dry forest. *Oecologia*, 179, 551-561

Phillips, O. L., et al., (2010). Drought–mortality relationships for tropical forests. *New Phytologist*, *187*(3), 631–646. https://doi.org/10.1111/J.1469-8137.2010.03359.X

Prabhakar, S. & Shaw, R. (2007). Climate change adaptation implications for drought risk mitigation: a perspective for India. *Climatic Change*, *88*(2), 113–130. https://doi.org/10.1007/S10584-007-9330-8

Pulla, S., et al., (2015). Assessing the resilience of global seasonally dry tropical forests. *International Forestry Review*, *17*(2), 91–113. https://doi.org/10.1505/146554815815834796

Puyravaud, J. P., Davidar, P., & Laurance, W. F. (2010). Cryptic destruction of India’s native forests. *Conservation Letters*, 3, 390-394. https://doi.org/10.1111/j.1755-263X.2010.00141.x

Qie, L., et al., (2019). Drought cuts back regeneration in logged tropical forests. *Environmental Research Letters*, *14*(4), 045012. https://doi.org/10.1088/1748-9326/AB0783

QGIS.org (2019). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.org

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Rajsekhar, D., & Gorelick, S. M. (2017). Increasing drought in Jordan: Climate change and cascading Syrian land-use impacts on reducing transboundary flow. *Science Advances*, *3*(8). https://doi.org/10.1126/SCIADV.1700581

Ramesh, K. V., & Goswami, P. (2007). Reduction in temporal and spatial extent of the Indian summer monsoon. *GeoRL*, *34*(23), L23704. https://doi.org/10.1029/2007GL031613

Ramprasad V, et al., (2020). Plantations and pastoralists: Afforestation activities make pastoralists in the Indian Himalaya vulnerable. *Ecology and Society*, *25*(4), 1–12. https://doi.org/10.5751/ES-11810-250401

Ratnam, J., et al., (2019). Functional Traits of Trees From Dry Deciduous “Forests” of Southern India Suggest Seasonal Drought and Fire Are Important Drivers. *Frontiers in Ecology and Evolution*, 7(8). https://doi.org/10.3389/FEVO.2019.00008

Ravindranath, N. H., et al., (2005). Impact of climate change on forests in India. *Current Science*, 90(3). https://doi.org/10.2307/24091869

Ravindranath, N. H., et al.,. (2011). Climate change vulnerability profiles for North East india. *Current Science*, *101*(3), 384–394.

Rosa, I. M. D., et al., (2016). The Environmental Legacy of Modern Tropical Deforestation. *Current Biology*, *26*(16), 2161–2166. https://doi.org/10.1016/J.CUB.2016.06.013

Roy, A., & Hirway, I. (2007). Multiple Impacts of Droughts and Assessment of Drought Policy in Major Drought Prone States in India Centre for Development Alternatives. *Project Report submitted to The Planning Commission, Government of India, New Delhi.* Accessible at: https://niti.gov.in/planningcommission.gov.in/docs/reports/sereport/ser/stdy_droght.pdf

Roy, P. S., et al., (2013). Forest Fragmentation in India. *Current Science*, *105*, *6*, 774–780.

Saleska, S. R., et al., (2007). Amazon forests green-up during 2005 drought. *Science*, *318*(5850), 612. https://doi.org/10.1126/science.1146663

Sen, O. L., et al., (2004). Impact of Indochina Deforestation on the East Asian Summer Monsoon. *Journal of Climate*, *17*(6), 1366–1380. https://doi.org/10.1175/1520-0442(2004)017<1366:IOIDOT>2.0.CO;2

Sharma, J., et al., (2015). Assessing “inherent vulnerability” of forests: a methodological approach and a case study from Western Ghats, India. *Mitigation and Adaptation Strategies for Global Change*, *20*(4), 573–590. https://doi.org/10.1007/s11027-013-9508-5

Sharma, S., & Mujumdar, P. (2017). Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India. *Nature Scientific Reports*, 7(15582). https://doi.org/10.1038/s41598-017-15896-3

Sharma, J. & Ravindranath, N.H., (2019). Applying IPCC 2014 framework for hazard-specific vulnerability assessment under climate change. *Environmental Research Communications*, 1(5)

Sheth, C., Datta, A., & Parashuram, D. (2020). Persistent loss of biologically-rich tropical forests in the Indian Eastern Himalaya. *BioRxiv*, 827360. https://doi.org/10.1101/827360

Siyum, Z. G. (2020). Tropical dry forest dynamics in the context of climate change: syntheses of drivers, gaps, and management perspectives. *Ecological Processes*, *9*(1), 1–16. https://doi.org/10.1186/S13717-020-00229-6

Slette et al., (2019). How ecologists define drought, and why we should do better. *Global Change Biology*, 25(10), 3193-3200

Srivastava, S., et al., (2002). Assessment of large-scale deforestation in Sonitpur district of Assam. *Current Science*, 1479-1484.

Staal, A., et al., (2020). Feedback between drought and deforestation in the Amazon. *Environmental Research Letters*, *15*(4), 044024. https://doi.org/10.1088/1748-9326/AB738E

Teegalapalli, K., & Datta, A. (2016). Shifting to settled cultivation: Changing practices among the Adis in Central Arunachal Pradesh, north-east India. *Ambio*, 45(5), 602-612. https://doi.org/10.1007/s13280-016-0765-x

Thang, T. H., Thu, A. M., & Chen, J. (2020). Tree species of tropical and temperate lineages in a tropical Asian montane forest show different range dynamics in response to climate change.

Global Ecology and Conservation, *22*, e00973. https://doi.org/10.1016/J.GECCO.2020.E00973

Tracewski, Ł., et al., (2016). Toward quantification of the impact of 21st-century deforestation on the extinction risk of terrestrial vertebrates. *Conservation Biology*, *30*(5), 1070–1079. https://doi.org/10.1111/COBI.12715

Trenberth, K. E. et al. in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. et al.) 235–336 (IPCC, Cambridge Univ. Press, 2007)

Trenberth et al., (2014). Global warming and changes in drought. *Nature Climate Change*, 4, 17-22

Tripathi, S. K., et al., (2016). Perspectives of Forest Biodiversity Conservation in Northeast India High Altitude Phytodiversity and Impacts of Climate Variability at Ecosystem and Species Level in Garhwal Himalaya (Uttarakhand) using Geospatial Techniques. *Journal of Biodiversity, Bioprospecting and Development*, 3(2). https://doi.org/10.4172/2376-0214.1000157

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, *2*(8), 587–595. https://doi.org/10.1038/nclimate1495

Turubanova, S., et al., (2018). Ongoing primary forest loss in Brazil, Democratic Republic of the Congo, and Indonesia. *Environmental Research Letters*, *13*(7), 074028. https://doi.org/10.1088/1748-9326/AACD1C

Udawatta, R. P., Rankoth, L., & Jose, S. (2019). Agroforestry and Biodiversity. *Nature Sustainability*, *11*(10), 2879. https://doi.org/10.3390/SU11102879

Upgupta, S., et al., (2015). Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India. *Climate Risk Management*, *10*, 63–76. https://doi.org/10.1016/j.crm.2015.08.002

Vico, G., et al., (2017). How competitive is drought deciduousness in tropical forests? A combined eco-hydrological and eco-evolutionary approach. *Environmental Research Letters*, *12*(6), 065006. https://doi.org/10.1088/1748-9326/AA6F1B

Wakeel, A., et al., (2005). Forest management and land use/cover changes in a typical micro watershed in the mid elevation zone of Central Himalaya, India. *Forest Ecology and Management*, *213*(1–3), 229–242. https://doi.org/10.1016/J.FORECO.2005.03.061

Whitehead, P. G., et al., (2018). Modelling impacts of climate change and socio-economic change on the Ganga, Brahmaputra, Meghna, Hooghly and Mahanadi river systems in India and Bangladesh. *Science of The Total Environment*, *636*, 1362–1372.

https://doi.org/10.1016/J.SCITOTENV.2018.04.362

Wilhite, D. A., Sivakumar, M. V. K., & Pulwarty, R. (2014). Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, *3*, 4–13. https://doi.org/10.1016/J.WACE.2014.01.002

Wu, D., et al., (2015). Time-lag effects of global vegetation responses to climate change. *Global Change Biology*, *21*(9), 3520–3531. https://doi.org/10.1111/gcb.12945

Xu, X., et al., (2020). Climate change vulnerability assessment for smallholder farmers in China: An extended framework. *Journal of Environmental Management*, *276*, 111315. https://doi.org/10.1016/J.JENVMAN.2020.111315

Zaveri, E., et al., (2016). Invisible water, visible impact: Groundwater use and Indian agriculture under climate change. *Environmental Research Letters*, *11*(8), 084005. https://doi.org/10.1088/1748-9326/11/8/084005

Zhao, A., et al., (2020). Evaluating the cumulative and time-lag effects of drought on grassland vegetation: A case study in the Chinese Loess Plateau. *Journal of Environmental Management*, *261*, 110214. https://doi.org/10.1016/J.JENVMAN.2020.110214

4.7 Supplementary Information

Table S1|Summary of the FAO Land Cover Classification System used by the ESA CCI Land Cover Dataset with the simplified categories generated for analysing land cover change across India.

FAO Land Cover Classification System Types	Simplified categories
Cropland rainfed	Cropland
Cropland rainfed - Herbaceous cover	
Cropland rainfed - Tree or shrub cover	
Cropland irrigated or post-flooding	
Mosaic cropland (>50%) / natural vegetation (tree/shrub/herbaceous cover) (<50%)	Mosaic cropland
Mosaic natural vegetation (tree/shrub/herbaceous cover) (>50%) / cropland (<50%)	
Tree cover broadleaved evergreen closed to open (>15%)	Tree cover
Tree cover broadleaved deciduous closed to open (>15%)	
Tree cover broadleaved deciduous closed (>40%)	
Tree cover broadleaved deciduous open (15-40%)	
Tree cover needleleaved evergreen closed to open (>15%)	
Tree cover needleleaved evergreen closed (>40%)	
Tree cover needleleaved evergreen open (15-40%)	
Tree cover needleleaved deciduous closed to open (>15%)	
Tree cover needleleaved deciduous closed (>40%)	
Tree cover needleleaved deciduous open (15-40%)	
Tree cover mixed leaf type (broadleaved and needleleaved)	
Tree cover flooded fresh or brakish water	
Tree cover flooded saline water	
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Natural mosaics
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	
Shrubland	Shrubland & Grassland
Shrubland evergreen	
Shrubland deciduous	
Grassland	
Urban areas	Urban areas
Lichens and mosses	Sparse/Bare
Sparse vegetation (tree/shrub/herbaceous cover) (<15%)	
Sparse tree (<15%)	
Sparse shrub (<15%)	
Sparse herbaceous cover (<15%)	
Bare areas	
Consolidated bare areas	
Unconsolidated bare areas	
Water bodies	Water/snow
Permanent snow and ice	
Shrub or herbaceous cover flooded fresh/saline/brakish water	

Figure S1| The distribution of forest losses associated with human land use changes (orange) and natural land use changes (purple) in each of the focal precipitation deficit years. Black outlines show the administrative borders of States within the Northeast region of India. Each point represents a pixel of forest loss.

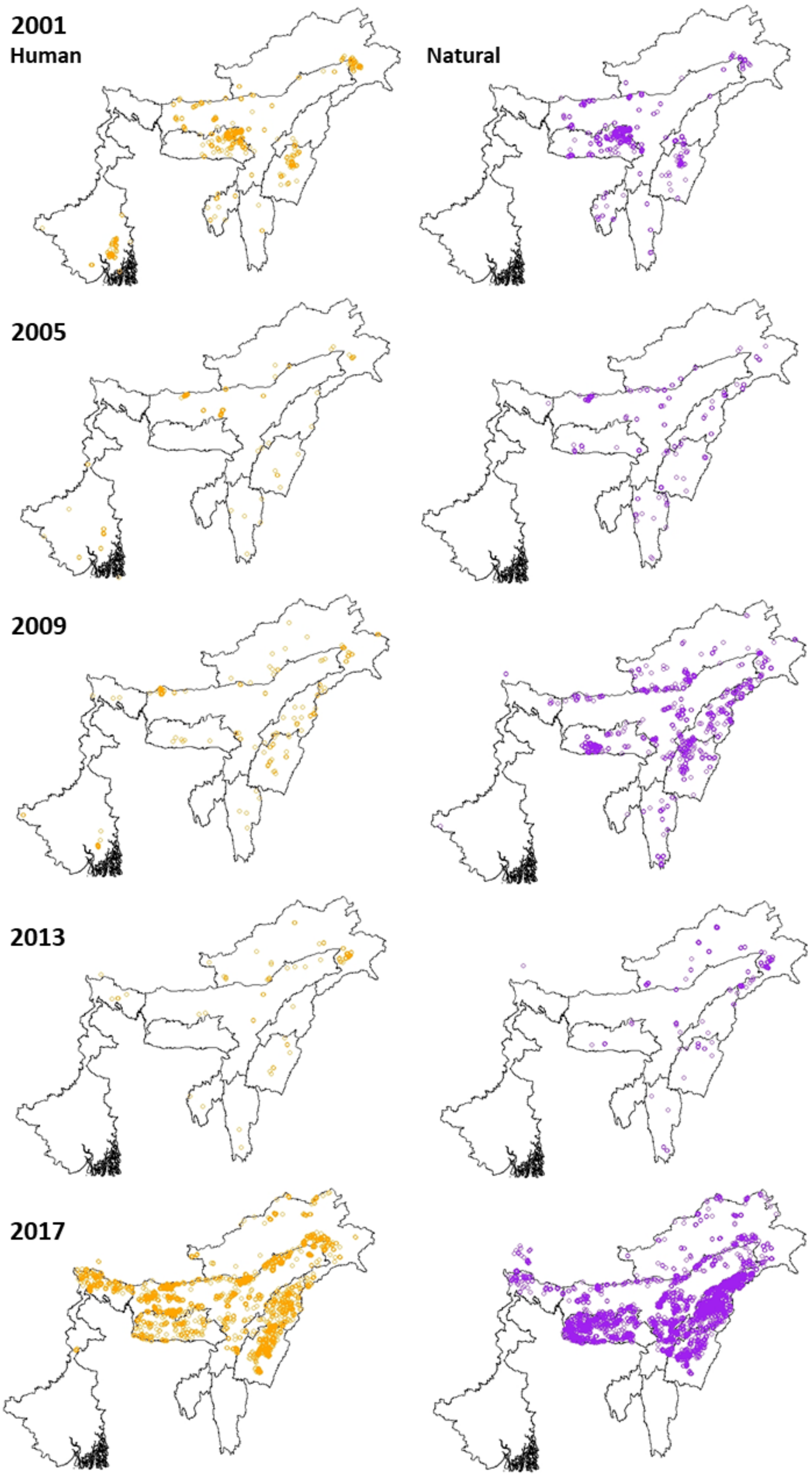


Table S1| The percentage of each forest type lost overall during the five precipitation deficit years. The table displays the percentage contributions of each forest type to human land use change forest losses (Column 2, LUC), to natural land cover change forest losses (Column 3, LCC) and finally the contribution of each forest type to total forest loss over the years (Column 4).

Forest Type	Percentage of LUC loss	Percentage of LCC loss	Percentage of total loss
Broadleaved evergreen closed to open (>15%)	30.19	63.64	51.51
Broadleaved deciduous closed to open (>15%)	54.48	23.64	34.82
Broadleaved deciduous closed (>40%)	0.19	0.09	0.13
Broadleaved deciduous open (15-40%)	0.00	0.00	0.00
Needleleaved evergreen closed to open (>15%)	13.26	12.61	12.85
Needleleaved evergreen closed (>40%)	0.00	0.00	0.00
Needleleaved evergreen open (15-40%)	0.00	0.00	0.00
Needleleaved deciduous closed to open (>15%)	0.00	0.01	0.00
Needleleaved deciduous closed (>40%)	0.00	0.00	0.00
Needleleaved deciduous open (15-40%)	0.00	0.00	0.00
Mixed leaf type (broadleaved and needleleaved)	0.00	0.00	0.00
Flooded fresh or brakish water	0.00	0.00	0.00
Flooded saline water	1.88	0.02	0.69

Chapter 5: General Discussion

Pockets of trees within the densely inhabited southern city of Madurai, India

Source: Alice Haughan (Author's own)

Tropical and sub-tropical forests are one of the most biodiverse ecosystems on the planet supporting two thirds of global biodiversity on just 15.8% of terrestrial land surface (França et al., 2020; Giam, 2017). Climate and land use change are the primary drivers of tropical forest loss, but evidence suggests that the effects of these two drivers on forest loss differ between regions (Hosonuma et al., 2012; Jimenez et al., 2018; Rifai et al., 2019; Turubanova et al., 2018; Vancutsem et al., 2021). As a result the ways in which they interact are likely to differ between regions as well (Mantyka-pringle et al., 2012; Oliver & Morecroft, 2014). Climate and land use changes are intertwined in their effects on systems, and it is important to increase understanding of how these two drivers individually and jointly impact forests across the tropical biome. This is crucial for ascertaining realistic vulnerability profiles of tropical forests and their associated species as well as underpinning effective and informed protection measures. In the evidence to date, a geographic bias has resulted in a key knowledge gap of how these stressors may interact to affect forests in South Asia, and India in particular (Kumar & Scheiter, 2019). Further there were substantial knowledge gaps in the country including: how climate change has impacted past forest loss, the land use change drivers associated with forest loss in recent decades, and a dearth of evidence of climate-land use interactions affecting forests in the country. This thesis aimed to address these knowledge gaps and to contribute to a better understanding of these key drivers on an understudied region of the tropical forest biome. This research provides the first assessment of the contribution of climate change to past forest loss in India, maps climate velocity (i.e., the rate of change of climate over space and time) for the first time in the country, updates a recent gap in our understanding of the land use change drivers associated with loss, and finally provides the first evidence of a joint climate-land use effect on India's forests.

The following sections of this chapter will synthesise these findings in relation to the core thesis objectives and summarise what these findings mean for policy and management practices.

5.1 Fundamental scientific findings

Is there evidence that climate changes have played a role in India's past forest loss?

In Chapter 2, assessment on different spatial and temporal scales revealed significant effects of climate, and the rate of climate change, on forest loss. In this chapter I found that increased forest losses were generally associated with decreases in temperature and precipitation, and faster climate velocities - however, there was considerable spatial variation across the country. In particular, forests in the Northwest region experienced a wider variety of climate threats, such as trends associated with temporal trends in the pre-monsoon and winter that were not seen in other regions. The regions with the lowest number of climate variables associated with loss were the Northeast and Central Northeast. This finding supports several previous predictions which have analysed the future effects of climate on India's forests and found the Northwest to be highly vulnerable to climate changes while the Northeast region is observed to be more resilient (Chaturvedi et al., 2011; Sharma et al., 2017). Generally, the reduced vulnerability of the Northeast compared to other regions is often attributed to its high diversity of species, more extensive forest cover, alongside predictions of precipitation and temperature increases which may be conducive to tree growth (Gopalakrishnan et al., 2011; Ravindranath et al., 2005; Sharma et al., 2017). In contrast, my research highlighted rapid decreases in precipitation across the region coupled with spatially distinct areas of temperature increases in the north of the region and temperature decreases in the south. Though contrasting most predicted changes for the Northeast region, these findings do agree with one study by Ravindranath et al., (2011) which showed the vulnerability of forests and cropland in this region to climate changes, mainly as a result of spatially variable trends in precipitation and an increase in the prevalence of drought. However, Ravindranath et al. do not include temperature changes. The diversity in predictions of climate effects on India's forests in the future compared to the findings of current trends in climate on forests found in this study is disconcerting. If forest policies are designing protection measures around future predictions without also considering current trends, forests could be inadequately protected from climate changes in the future. The most effective policies are likely to take into account from both current trends and future predictions.

The findings in this thesis support research from other tropical regions where declining precipitation and faster climate velocities have also been associated with increased forest losses (Aguirre-Gutiérrez et al., 2020; Allen, 2017; Brodribb et al., 2020; França et al., 2020). However, the finding that temperature decreases were associated with increased forest losses was unusual and contrasts with the several studies conducted in other regions which show increasing temperatures to be a primary concern for tropical forests (Aleixo et al., 2019; Aubry-Kientz et al., 2019; Slot & Winter, 2016). The different effect of temperature found between regions could be indicative of the different forest type assemblages and their different responses to climate. The primary forest type of the Amazon basin is tropical moist forests (FAO & ITTO, 2011), which are more prone to the negative effects of temperature increases than the predominantly tropical dry forests of India (Suresh et al., 2010). It is also possible that this result was driven by the severe cooling patch found in the high forest loss region of the Northeast, but further research is needed to ascertain whether the reduction in temperatures here have been a direct or indirect cause of forest loss. Previous studies have presented evidence of increased mortality of tropical species during extreme cold periods (Downing et al., 2016; Wang et al., 2016), including mortality of tropical trees (Abbas et al., 2017; Bojórquez et al., 2019), though these have been due to short term extreme events and not prolonged cooling. Further research is needed to explore this interesting finding, as tropical species are more likely to be susceptible to negative impacts of cooling, and as yet the effects of this cooling patch on species in this region has gone unexplored.

The findings of Chapter 2 also highlighted concerns that forests will not be able to reproduce quick enough to migrate and track the changes in climate or to adapt quick enough, due to the high velocities of temperature and precipitation outlined in this study. These findings echo concerns of other researchers about the ability of tropical tree species to succeed and occupy suitable climatic niches in the future (Bertrand et al., 2011; Corlett & Westcott, 2013; Dobrowski & Parks, 2016; Nathan et al., 2011). If species are unable to cope with the changes in climate through adaptation and migration due to the long generational times, acclimation will be the remaining option for species survival. Relatively little is known about the acclimation potential of tropical tree species since many are near their thermal limits, the conditions they will be exposed to in many cases do not exist yet. However, many studies suggest that climate changes will drive a loss of some tropical tree species and a homogenisation towards drought-tolerant species (Aguirre-Gutiérrez et al., 2020; Allen, 2017; Esquivel-Muelbert et al., 2019). This is supported by some findings in Chapter 3 and 4, where drought-tolerant deciduous species increased in area and were less likely to be lost to natural causes than evergreen species which may be less drought tolerant.

The research presented in this thesis has identified key areas of concern for forests undergoing climate change. The forests of the Eastern Hilly region, Northern Western Ghats and parts of the Northeast region are particularly concerning due to the trends found in this study towards precipitation decreases, temperature increases and fast velocities coupled with the already high levels of forest loss and the high biodiversity value of these regions (Roy et al., 2013; Sharma et al., 2015; Upgupta et al., 2015). For example, if the trends outlined in Chapter 2 continue, areas of the Northern Western Ghats, could experience a reduction in annual precipitation of 75mm, alongside a 0.5°C increase in temperature after 10 years. These changes would put substantial pressure on the tropical moist broadleaved forests that are present in this region, and drastically increase the likelihood of drought and fire events. The Northern Western Ghats have been highlighted as particularly at risk to climate change impacts if trends continue, more so than the Southern Western Ghats. Their vulnerability to climate change outlined in this study will likely be compounded by the high levels of human disturbance despite being part of India’s largest biodiversity hotspot (Blicharska et al., 2013). The forests here are less protected than areas of the Southern Western Ghats but harbour many species of conservation importance such as the pangolin, gaur, elephant and tiger (Choudhury, 2002; Katdare et al., 2021; Padalia et al., 2019).

The climate changes occurring in these forests are likely to be further exacerbated by the high rates of deforestation and interactions between the two could be leading to increased risk of tree loss, reductions in habitat connectivity and increased threat from invasive species. Interestingly, the trends in forest losses and contiguous areas of climatic change were often not well defined by the different monsoon regions and tended to span two or more regions, which is exemplified by these three high risk areas which all span multiple monsoon regions. As a result, it was useful in Chapter 2 to analyse the effects on both the national and regional scale to ensure trends that were broken up by the regional separations were still accounted for. This allowed detection of the extent of this cooling patch which extended through the Northeast region and parts of the Central Northeast region.

In addition to the temporal changes in climate found to be affecting forests in Chapter 2, this thesis also found an effect of extreme drought events on forest loss. Research in Chapter 4 revealed that increasing precipitation deficits in the Northeast region of India both directly led to a greater probability of forest loss and indirectly, via its effect on land use change. This research filled an important knowledge gap discussed in Chapter 2, where I highlighted that a greater understanding of the effects of extreme climatic events on forests in the country was also needed. This finding is explored further in a section below dedicated to the associated thesis objective.

The research undertaken in Chapters 2 and 4, has contributed greatly to the literature on threats to Indian forests by being the first study to assess the impact of climate change on past forest loss on a national scale and by providing a key baseline to model the impact of climate velocities for a range of future climate scenarios. The research also contributes to reducing knowledge gaps for the wider tropical forest biome by providing a better understanding of the spatial variability of impacts in an understudied tropical region. One of the key takeaways from this research is that we can use metrics like climate velocity to help design and modify protected area coverage to ensure that species and habitats remain connected, and as protected as possible, from the effects of future climate change (Keeley et al., 2018). This could mean ensuring habitat connectivity, through protected area coverage, from the Northern to the Southern Western Ghats, and as earlier discussed (in Chapter 2), a greater coverage of protected areas in the flatter regions that also experience high climate velocity such as the PEN, WC and CNE nexus.

The knowledge and data provided by these chapters could prove crucial to predicting more realistic estimates of forest change in the future when climate change is expected to worsen, as well as helping to inform more effective and holistic strategies of forest protection. Chapter 2 also achieved a key aim of this thesis, which was to characterise the effect of climate on forest change in India and provided a good foundation of knowledge enabling an interaction to be considered in Chapter 4.

How have land use changes contributed to forest loss in India in recent decades?

In Chapter 3, analyses of trends in forest loss and gain revealed that agriculture-based land use changes remain the primary cause of forest loss in India, supporting previous studies (Meiyappan et al., 2017; Padalia et al., 2019; Ramachandran et al., 2018; Roy et al., 2013). Similarly, to the effects of climate change, there were regional variations. Agricultural-related conversions of forests were more prevalent in the Central Northeast, West Central and Hilly regions and were least prevalent in Northeast and Peninsula regions. This was further supported by research in Chapter 4, which showed forest losses as a result of agricultural-related land use changes were less common than natural land cover changes in the Northeast region. This is likely due to the low population densities and poorer infrastructure for agriculture in this region and the greater dependence on shifting cultivation, small-scale agriculture, and harvesting of forest products for income which are less likely to lead to conversions of large areas of forest to agriculture (Johnson & Hutton, 2014; Kumar & Singh, 2012; Kumar et al., 2018; Lele et al., 2008). Conversion of forest to urban areas contributed very little to forest loss nationally, with the exception of the Northwest region. This was surprising, particularly in the densely populated region of Central Northeast. India's population is expanding at ~1% per year, which equates to an increase of 13 million people a year, with 35% of the population residing in urban areas (World Bank, 2021). However, several researchers have found that expansion of urban areas often comes at a cost to cropland and not forested areas, as croplands are likely to be the land use type nearest to urban edges (Hinz et al., 2020; Kale et al., 2016; Meiyappan et al., 2017). It would be interesting to see if there is an indirect effect of urban growth and encroachment of agriculture into forested areas, as this could be an additional pressure on human livelihoods that may have negative repercussions for forest cover.

The research in chapters 3 and 4, adds to a greater understanding of the dynamics of land use change and its impacts on forests in India by finding novel indications that the main cause of loss is shifting over time. Forest losses resulting from conversion to 'natural' land covers, such as natural mosaics, shrubland and grassland became more prevalent than conversion to agricultural land uses by the final period of the study. Further research is needed to understand what the causal drivers behind these conversions to other natural land covers are. This is because different management strategies would be required if the causal factor was climate change related, e.g., drought, compared to if it was due to human-driven degradation. This is a huge shift in the narrative of the causes of forest loss in India, which has thus far remained focused on agriculture as the major driver of loss. Forest protection policies and recommendations from past studies that revolve around reducing agricultural encroachment to reduce forest loss may need altering to ensure the protection for forests in the future. Since forest losses to cropland expansion have reduced over time, according to Chapter 3, it is likely that India's forest policies (e.g., The National Forest Policy, 1988 and The Green India Mission) have been more successful in their approach in recent years. Continuing to focus policies on reducing the tangible cause of agricultural expansion, e.g., lower yields from lack of access to technological and agricultural advances in crop management, may be easier than funding new research and policy changes to understand and mitigate for the proximal drivers of these 'natural' land transitions e.g., climate drivers such as drought. However, the research provided here strongly shows that policies will likely need to adapt to the evolving drivers of loss in order to remain effective in curbing forest loss.

The shift in cause of loss leads to further questions of the impact that this change will have on forest structure, function, and biodiversity. When agriculture was the primary cause of forest loss it is likely that encroachment on forest edges and clearing of large areas for new croplands was the primary spatial pattern in forest loss. Forest species would have been more at risk from edge effects, as well as loss and fragmentation of habitats. However, these 'natural' changes related to mosaic areas of trees and shrubs, and grasslands will likely have different impacts on forest species. Some may find the transition to these 'natural' land covers more manageable than complete conversion to cropland (Bhagwat et al., 2008; Udawatta et al., 2019), whereas forest specialist species might find the loss of contiguous forest cover intolerable (Keinath et al., 2017; Leal et al., 2012; Magura et al., 2001). It also will depend largely on the type of land cover that the forest has been lost to, where mosaics of trees and shrubs may support more biodiversity due to a larger diversity of habitats available, than a conversion to shrubland which could be a monoculture of shrub plantation such as tea or coffee. Further research is needed to understand how conversions of forests to these 'natural' land cover types is affecting the biodiversity across the country.

This work has contributed knowledge of more current threats to forests from human land use changes, after a reduction in published studies in India in recent years. This chapter achieved a key aim of our thesis which was to bring up to date the knowledge of land use drivers of forest loss in India.

Is there evidence of a climate-land use change interaction impacting forest loss in the country?

In Chapter 4, analysis of potential interactions between anthropogenic land use changes and drought indicated that combined effects of the two drivers are acting synergistically to increase the probability of forest loss in northeast India. Results showed that in some years the effect of drought on forests was exacerbated by the location of land use changes associated with agriculture and urban areas. During these years forests were more likely to be lost to human causes where drought conditions were less severe and where climatic conditions meant croplands could still be viable. This concurs with previous studies that indicate synergistic effects of land use change and drought on tropical forests (Le Page et al., 2017; Meir & Woodward, 2010; Staal et al., 2020). There was also a higher probability of forest loss in general under increasingly drier conditions, indicating a direct impact of drought on forests in the Northeast region of India. Forests, and tropical forests in particular, are highly susceptible to soil moisture stress (Clark et al., 2016; Engelbrecht et al., 2007; Greenwood et al., 2017; McDowell et al., 2018) and these findings align with studies undertaken in other areas of the biome such as the Amazon (Duffy et al., 2015; Phillips et al., 2009; Rowland et al., 2015), West Africa (Fauset et al., 2012), and Southeast Asia (Kumagai et al., 2009; Werner, 2003) that show a strong effect of drought on mortality of tropical tree species. The interaction found in this research is likely to be causing a larger area of forest loss than either stressor would be predicted to by itself, since the direct effects of drought are leading to forest loss in the driest areas and the indirect effects of drought, via land use change, are causing forest loss in the wetter areas of the drought (which might ordinarily survive the drought).

The forest types most at risk to loss in the drought years were broadleaved evergreen, followed by broadleaved deciduous which is consistent with the findings for this region in Chapter 3. The finding of a forest type response to drought was interesting because although studies in other tropical regions have also supported the increased loss of evergreen species in drought conditions due to the high water requirements of the forest type (Aguirre-Gutiérrez et al., 2020; Asner et al., 2010; Fauset et al., 2012), deciduous species are generally thought to be more resilient to drought effects (Fan et al., 2012; Ouédraogo et al., 2016; Suresh et al., 2010). Further consideration of findings in chapter 4 showed that the broadleaved evergreen forest type was more likely to be lost to natural land covers during the drought years, whereas the broadleaved deciduous forest type was more likely to be lost to human land use changes. This supports those previous studies and suggests that the direct impacts of drought were greater on evergreen species, but the indirect effects through land use change were greater on the deciduous type. Despite good ecological theory behind this finding, it is important to note however that we did not map the spatial proximity of the different forest types to densely populated areas. Therefore, it is possible that broadleaved deciduous forests were more likely to be lost to human land use changes simply because of spatial proximity to human populations. This should be explored in greater detail in future studies. It does appear that the interaction between drought and land use change in this case appears to be worsening the effect on broadleaved forests, where they are impacted by both the direct effects of land use change (shown in Chapter 3 and 4) as well as indirect effects of drought (shown in Chapter 4) and showed a much greater reduction in forest cover than needleleaved forest types.

Drought incidences and severity are expected to increase across the country (IPCC, 2021; Kala, 2017; Sharma & Mujumdar, 2017), as well as further expansion of cropland (Hinz et al., 2020). There is a strong likelihood that the effects of this interaction on the forest cover of this region will continue to result in large areas of forest loss in the coming years. This is turn, is likely to have negative repercussions for India's biodiversity. The Northeast region is often referred to as the last stronghold of India's forest cover and is an important area for biodiversity, but particularly for endemic and many flagship species important for conservation and tourism (Chatterjee, 2008; Ghosh-Harihar et al., 2019; Tripathi et al., 2016). The region is also predicted by many researchers to be the least affected by climate change in the future (Gopalakrishnan et al., 2011; Ravindranath et al., 2005; Sharma et al., 2017). If this is the case, interactions like this one between drought and land use change could have even stronger effects on forests in regions predicted to get much hotter and drier such as the Northern Western Ghats. Therefore, the findings of this interaction could be fortuitous in timing as it will provide a better understanding of the threats to forests in the Northeast region as these changes occur and could prompt further investigation into interactions in other areas of the country. The research presented across the three analytical chapters of this dissertation suggests that there are several important forest areas that are undergoing warming and drying climates, alongside substantial land use changes. Interactions between climate and land use change in these locations are undoubtedly leading to additional forest loss that is not yet predicted or accounted for in management plans. The key areas of concern presented across the chapters remain the Northeast region, the Northern Western Ghats, the Eastern Ghats and the Eastern Himalayan region.

The research presented here is the first study to examine the effects of an interaction between climate and land use in India, a knowledge gap that has been acknowledged as important for the country before (Kumar & Scheiter, 2019). These findings not only contribute to a greater understanding the of the joint effects of climate and land use change on the forests in Northeast India but also contribute to the global understanding of interactions in tropical regions. This research prompts further study of the spatial-temporal differences in climate-land use effects on forests across the tropical biome.

Trends in forest change in India

In addition to the three objectives outlined in the thesis, the research across the three chapters produced new analysis of the forest trends across the country at a national and regional scale which is much needed in the literature. The following section discusses the findings in relation to trends in forest cover.

Chapter 3 highlighted encouraging increases in reforestation and generally marked reductions in deforestation in recent years (2015-2019), compared to forest dynamics in the 1990's. The findings show overall net gains in forest cover in the final five years of the study and concur with other studies that have seen an increase in reforestation in recent years (Adhikari et al., 2015; Puyravaud et al., 2010; Reddy et al., 2013). The findings in this chapter suggest that long-running forest conservation policies in India may be succeeding in reducing forest losses and increasing forest cover. The increase in forest gains is likely have positive implications for tropical forest biodiversity. However, these benefits often take time to materialise, and it could be many years before new areas of forest cover replace the conservation value of the lost forests (Chazdon, 2008; Gries et al., 2012; Vesk et al., 2008; Wilson et al., 2010). The biodiversity gains associated with forest gains might also depend on the type of forest that is being planted or succeeding on the land (Coleman et al., 2021; Kanowski et al., 2005; Puyravaud et al., 2010). Reforestation programmes often use fast growing monocultures to increase forest area quickly as well as species which provide economic benefits (Coleman et al., 2021; Puyravaud et al., 2010). However, the resulting forest might be very different to the forest type that was lost and may not provide the same habitats and food resources to species (Brockerhoff et al., 2008; Kanowski et al., 2005). This is a concern in India following our findings in Chapter 3, where there were differences in the forest types which were lost and gained. Another concern is that these forest gains might be the result of increased spread of plantation forests which is common in India (Puyravaud et al., 2010). Monoculture plantations such as rubber, that are harvested regularly, are unlikely to provide conservation benefits to species (Martello et al., 2018; Phommexay et al., 2011). Therefore, urgent further research is needed to ascertain the conservation value of the extensive forest gains found in the country before assuming that these forest gains are beneficial to biodiversity, and to assess the scale of the extinction debt from the lost forests.

Despite the national net forest gains recorded, Chapter 3 also found forest losses to be occurring at concerning levels. The most extensive forest losses were in districts bordering the Central Northeast and West Central regions, which also experienced net forest losses during 1995-2019. The area of net forest loss included portions of the Northeastern Ghats, which are often overlooked, but include important habitat corridors for elephant and tiger populations which hold importance for biodiversity, ecosystem structure and function as well as increasing tourism revenue in the country (Padalia et al., 2019; Ramesh et al., 2020). The finding that most forest loss is occurring in these regions is in contrast to most previous literature on forest loss in India, which indicates the largest losses to be in the Northeast region (Lele & Joshi, 2009; FSI 2019). Though the findings support more recent research that highlights concern for the forests in the central regions of the country (Padalia et al., 2019; Puyravaud et al., 2010). It is important to note that the findings in Chapter 3 regarding reductions in forests losses also contrast with those I found in Chapter 2 in two main ways. Firstly, the research in Chapter 2 found that forest losses steadily increased in India from 2001 to 2017, after which they began to decline. In contrast, Chapter 3 found that forest losses declined between 2001 and 2014, after which they increased. Secondly, Chapter 2 found that the Northeast region experienced considerably higher forest losses than the other regions, whereas Chapter 3 found that the West Central and Central Northeast had the highest losses and the Northeast some of the lowest. The differences in forest loss found between the two chapters is likely due to the different datasets used, this is discussed further in section 5.3. The strong differences found between these two datasets is concerning as they are both widely used to assess land use changes and forest loss across the globe and could be resulting in substantially different reported trends in forest loss. Though both of the areas reported to have the highest forest losses in these chapters are important forest areas for the country, if the findings in Chapter 3 are correct there are likely to be serious failures in the focus of management strategies of forests in the country which focus heavily on maintaining forest resources in the Northeast.

5.2 Implications for policy and practice

India has been keen to set ambitious targets to mitigate the effects of climate change in the country and on a global scale. As part of its National Action Plan on Climate Change and the Green India Mission (Pandve, 2009), India has committed to increasing its forest cover to 33% (by an as yet undefined date). Further to this, as part of the United Nations Strategic Plan for Forests 2030 (FAO & UNSPF (2021), India committed to increasing forest coverage by 200,000ha per year. The results of this thesis suggest that India failed to reach its targets prior to 2015, when the country was experiencing a net loss in forest cover. However, in the five years between 2015 and 2019 the country has begun to make good contributions to its targets. Using data from Chapter 3, between 2015-2019, forest cover increased by 347,300 ha in the Peninsular region alone. This is a rapid increase in forest cover compared to previous years and may be indicative of India's forest policies beginning to work. At the current pace though, this still falls short of the 200,00 ha per year. If trends in net gain derived from the national level recorded in Chapter 3 during 1995-2019 remained stable (0.32%), it would take 35 years to reach the target of 33% forest cover (given the current forest cover is 21.67% of the land area (FSI, 2019)). However, if rates remain similar to those during the 2015-2019 period (+0.83% per year), it will take only 13 years to reach the target of 33%. However, as discussed earlier these net gains will need to come with reductions in forest loss if biodiversity is to be protected. The findings in Chapter 2, of rapid increases in forest losses nationally, and even those in Chapter 3 which point to an increase in forest loss in 2015-2019 highlight that India is not currently effective enough in reaching its targets to reduce deforestation. It also makes it unlikely to reach the Global Forest Goal 1, set out by the United Nations Strategic Plan for Forests 2030 to halt deforestation by 2030. National and local governments will need to change their strategies or improve implementation in order to reverse the trend in deforestation, which is perhaps of greater importance than reforestation for improving resilience of forests and their biodiversity to climate change in the short term.

As part of its National Mission on Strategic Knowledge for Climate Change, India has also committed to gaining a better understanding of climate and its impacts, and to develop adaptation and mitigation strategies. This commitment is further supported in the Nationally Determined Contributions submitted to the COP21 summit in 2015 addressing the country’s planned post-2020 climate actions. However, despite India’s impressive commitments and focus on climate change adaptation and mitigation, it remains focused on the use of forests as a climate mitigation strategy without assessing the impact of climate change on these important resources. The findings of this thesis suggest that this is an oversight. Climate change is having an effect on forest distribution in India and if reforestation schemes are to be successful, the effects of climate change on forests will need to be taken into account. However, reforestation schemes will not be enough to ensure survival of forest resources and conservation of existing forest alongside awareness of the potential shift in forest types will be critical to ensuring adequate protection of biodiversity and forest functioning. Recent analysis has also casted doubt on the climate mitigation potential of India’s afforestation programme (Coleman et al., 2021).

This thesis further provides evidence that conservation strategies need to be adapted to account for interactive effects of climate and land use change as well as a shift in the primary cause of forest loss away from agriculture. The research presented here provides a starting point to begin to account for the complexity of stressor interactions that undoubtedly impact forests in the country. It also increases the fundamental understanding of forest responses to climate and land use changes that will help inform future management strategies and to set more appropriate targets to limit forest loss in the face of climate change. Currently, India is in the process of creating a new National Forest Policy to replace the last, which was written in 1988. Therefore, this is a crucial time for policies to be considering the multiple threats that forests in the country face. Adaptable management strategies built from up-to-date research is even more important as the country faces unprecedented threats to economy and forests on multiple fronts due to large-scale impacts of the COVID-19 pandemic, climate change and biodiversity loss. The COVID-19 pandemic has resulted in a reduction of global GDP by 4.3% during 2020 which had a substantial impact on vulnerable populations, including rural communities who are often reliant on forest products (FAO & UNSPF, 2021). The pandemic in India resulted in a reduction in crops harvested and a reduction in wages for many small-scale farmers and livestock owners (Cariappa et al., 2021; Jaacks et al., 2021). The economic impacts of the pandemic on rural communities and farmers are likely to result in increased stress on forest resources. The research from Chapter 4 in this thesis hypothesised that where agriculture was more vulnerable to extreme events, this was likely to have negative impacts on nearby forests. This has been found in Bangladesh as a result of the pandemic, where deforestation and poaching of wildlife increased during the pandemic year of 2020 compared to the previous year (Rahman et al., 2021). The researchers of this paper concluded that this increased stress on the forests was as a result of the dependence of the local people on the forests during economic stress, lower surveillance of the forest, a severe reduction in tourism and the revenue to the Forest Department. As a result of this finding in Bangladesh and the knowledge collected by this thesis, it is recommended that studies are undertaken to assess the impact of the pandemic on forests across India as well as the impact on meeting currently proposed targets in light of this.

Finally, the findings in this thesis point towards a greater impact on some forest types than others, alongside previous research showing an increased likelihood of a homogenisation of forest types with climate change will have implications for the economy of the country. If distribution changes occur in major income-generating forest types, such as timber trees like Teak (*Tectona grandis*) then forest redistributions not only have an impact on biodiversity distributions but also on the distribution of wealth across the country (Deb et al., 2017).

There are key takeaway findings and novel analyses presented in this thesis that could be used to inform an adaptation plan for climate change at both the national and regional levels. Based off the literature and data analysed in this thesis, an adaptation plan for the country should focus on ensuring climate-wise connectivity (Keeley et al., 2018) of key habitats by connecting high climate velocity areas with low climate velocity areas, ensuring greater protection of forest in drought-prone areas whilst recognising the potential for a greater effect on forests and biodiversity from interactions between human land use change and drought, as well as mitigating the impacts of both agricultural expansion on natural forests and other overlooked drivers of land use change. Current adaptation plans relating to climate change, as discussed above, generally only relate to mitigation of climate impacts through reduction in CO2 by tree planting. Here, we highlight that adaptation plans can, and should be, much broader to ensure climate-wise connectivity and the best chance of maintaining biodiversity levels. This thesis highlights that different management approaches are needed in different regions, with different regions experiencing both different threats from climate change and land use change. As such, regional, as well as national adaptation plans should be generated to target the future and current impacts of climate change on forests in India, if forest coverage and its connection to biodiversity is important. This thesis has good applicability to aiding development of new adaptation plans for the country under climate change and importantly provides information on trends in climate velocity and drought on tropical forests which was currently missing from the literature. However, use of these analyses for policy making should also respect and understand that there was a different trajectory of forest loss found in two of these chapters that needs addressing with higher quality and more appropriate data that is ground-truthed in India to ensure its accuracy. Despite this, the contribution of maps of climate velocity, drought and both human- and ‘natural’-driven land use change has significant benefits for the development of future adaptation plans in the country.

5.3 Research limitations

There were several caveats associated with this study which are largely outlined within each chapter, however, there are some overarching limitations that impacted the production of this thesis as a whole, and these are outlined here.

As discussed in previous chapters the major limitation for this thesis was data availability and accessibility. This was pervasive across both of the main datasets required for this thesis, climate and land cover data. Though datasets of climate and land cover for India have been created in the past there were key barriers to their implementation in this study. The climate data, precipitation and temperature, was most intact and appropriate for this study as it was available on a station wide basis nationwide and with a high temporal coverage. However, accessibility was difficult due to the large scale of the data needed for the study and subsequently, the Indian Meteorological Department were unable to process my request for data as it went against their departmental policy, and to access state-wide data the cost associated would be prohibitively high. In terms of land cover data, despite recent efforts by researchers to create national land cover maps for India (Roy et al., 2015) which are available to access and download at large scales free of charge, the temporal coverage of this dataset is currently low with only 3 years of data at present. As a result, this thesis utilises well-known global datasets which have some classification limitations when focusing on a country-scale, such as a more generic list of land cover categories and a coarser resolution (Burivalova et al., 2015; Feng & Bai, 2019; Galiatsatos et al., 2020; Liu et al., 2018; Pérez-Hoyos et al., 2017).

Secondly, the forest data that was used in this thesis was from two different sources and at times showed conflicting results, particularly in the Northeast region of the country. For example, data from Hansen (Hansen et al., 2013) used in Chapter 2, indicated that forest loss increased substantially over time and the Northeast region had the highest amounts of loss, but in ESA CCI data (ESA CCI and EC C3S Land Cover project) used in Chapter 3, suggested that forest loss generally declined over time and the Northeast had some of the lowest amounts of loss. The Hansen data, used in Chapter 2, also underestimates the loss in the West Central and Central Northeast regions compared to the ESA CCI data used in Chapter 3. This could be due to the difference in definition of forest between the two datasets. When I further investigated the discrepancies between the two datasets in the Northeast region, it became apparent that many areas marked as forest loss in the Hansen dataset were marked as losses in shrubland in the ESA CCI dataset. This discrepancy between definitions of forest is frequently the cause of variable forest change reporting in India (Joshi et al., 2010; Puyravaud et al., 2010; Tian et al., 2014) and can drastically alter the conclusions made about the trajectory of forest loss. If the ESA CCI dataset is more accurate, by using the Hansen dataset we could be underestimating the vast losses of shrubland and if the Hansen dataset is correct, by using the ESA CCI data we are likely underestimating the forest loss. Both forests and shrubland habitat are critical for the survival of species in India and research is urgently needed to better understand the discrepancies outlined in this study. Without further research on national forest loss, or an investigation into the differences between the datasets using satellite imagery, it is not possible to conclude which dataset is more likely to be accurate. However, this thesis importantly highlights the differences that can arise from a variety of datasets and the importance of assessing the accuracy of global datasets for specific regions within data analysis. This is an important area of research for the country since the Forest Survey of India have also been reporting forest increases in many years that are disputed by some (Puyravaud et al., 2010; Roy & Joshi, 2010; Sudhakar Reddy et al., 2016). One solution would be co-creating data between the Forest Survey of India and independent researchers and making an established and widely supported open access dataset that is ground-truthed, to provide accurate information that has high spatial and temporal resolution.

Finally, the methodology used also had important implications for reporting forest trajectories in the country. In Chapter 2, I looked at the change in forest over periods of 5 years. Due to the length of the time period and the amount of information I collected from each point in terms of the land cover it used to be and the land cover it changed to, it made sense to compute these changes over periods of five years. However, this meant that the high amounts of loss observed during 2017 highlighted in Chapter 4 are at odds to the reduction in losses during 2015-2019 in Chapter 3. This large loss of forest area in 2017 is masked by looking at the 2015-2019 period in Chapter 3, in which there were large forest gains, and displays a critical point for the study of forest loss in a dynamically changing landscape like India. This finding highlights the importance of looking at changes at different time and spatial scales and is a key theme throughout this thesis. By looking at my results in Chapter 3 one would assume that the forest loss was reduced considerably since the earlier years of the study, but the methodology appears to have masked some of the worst forest loss that the Northeast region has seen.

5.4 Future research recommendations

There are several focal areas where I recommended directing future research as a result of the findings in this thesis.

1) Chapter 2 provides strong evidence to show that climate changes are having an effect on forests in India, but further research is needed to ascertain the causes of forest loss to the different climate trends in each region. Particularly interesting trends such as the temperature and precipitation decrease in the Northeast and the temperature increases and precipitation decreases in the Northern Western Ghats, both areas of important forest cover should be investigated further to understand the effects of these changes on forest cover and biodiversity within these forests if the trends continue.

2) The research from Chapter 3 and 4 prompt further study into ways to differentiate the natural causes of forests being converted to natural land covers from the human-driven changes as a result of forest degradation and shifting cultivation. In order to do this, studies could employ a soil moisture index alongside investigation into the threshold at which certain forest types in the region are likely to experience drought stress and combined these could reveal whether an area was likely to be lost to natural drought stress. Other natural hazards causing loss such as fire could also be mapped. In order to directly determine whether human degradation was the cause studies could use proximity of forest to villages as well as the socio-economic status and the primary occupation of the nearby population to imply whether forest degradation was likely. Ground-truthing and social surveys could be more accurate in determining the true casual factors but are likely to be costly and time-consuming.

3) Additional research is needed to understand the conservation implications for the forest gains documented in this thesis. The increase in forest gains could provide remarkable biodiversity benefits to the country if they are from established reforestation programmes focusing on re-establishing native forest or from natural succession of lost forest. However, if the forest gains are mainly from monoculture plantations, these are likely to have much lower benefits to biodiversity and as such the net gains detailed in this study may not result in much increase in the conservation value of forests in the country. Further research would need to identify the primary cause of these forest gains as a first step and also to investigate the effects on biodiversity of the concurrent loss of shrubland.

4) As demonstrated in Chapter 4, there is strong evidence to show that interactions between climate and land use are affecting forests in Northeast India. However, more information is needed to understand what this interaction means in the long-term for these forests and their biodiversity. Research should focus on quantifying a threshold for drought stress on crops, taking into account additional water sources farmers might have access to including groundwater storage via irrigation.

Information is needed to understand how people are going to respond to droughts and whether there is a tipping point for when they turn to forest resources for supplemental income, which could be different for rainfed and irrigated agriculture. Thresholds such as these, and of when forest types experience drought stress, can act as early warning signals to suggest when a forest might be under threat from natural or human-caused losses based off rainfall estimates. These thresholds alongside known correlates of forest loss such as proximity of forest edges to cropland, wealth, education level of region, and soil type could all help to predict the effect of this climate-land use interaction on forests in the future. These could also be used alongside different scenarios of land use and climate change to estimate where forest in the future may be most at risk.

5.5 Concluding remarks

The research presented here updates a long history of studies detailing the effects of land use change in India and through novel findings contributes new knowledge about the role of climate change, the spatial variability in climate velocity, a shift in land use changes and the role of climate-land use interactions on forest loss in India. It provides new evidence of an increase in forest gains which will help India reach it afforestation targets for mitigating climate change effects. However, it also highlights that forest loss is still pervasive and the effects of this loss may last for years to come. The research presented here demonstrates for the first time that interactions between climate and land use change are occurring in India's tropical forests, and it explores what this means for biodiversity and policy. This study provides a baseline for future studies to consider the effect of climate change and its interactions on forest loss and assures that this is essential to the protection of India's forest targets, biodiversity levels, and human well-being. Importantly, the increased understanding provided in this thesis will help to inform more realistic policies to protect India's important forest resources in the future.

The findings of this thesis also contribute to increased understanding of the role of climate, land use change, and their interactions on tropical forests in an underrepresented area of the biome. The thesis followed calls to increase of global understanding of how interactions between these two global change drivers are materialising in tropical forests and importantly, serves as a basis of evidence that interactions between these two drivers do occur in the tropical forests of South Asia. These findings come at a critical time as climate changes become more apparent and land use changes resulting in forest losses are still pervasive throughout tropical forests. The knowledge and discussion within this work has the potential to encourage further research, outlines clear paths for future studies, and provides knowledge that could lead to more informative policies and protection of tropical forests, which are of global importance.

5.6 References

Abbas, S., Nichol, J. E., & Fischer, G. A. (2017). Mapping and assessment of impacts of cold and frost on secondary forest in the marginally tropical landscape of Hong Kong. *Agricultural and Forest Meteorology*, *232*, 543–549. https://doi.org/10.1016/J.AGRFORMET.2016.10.008

Adhikari, S., Southworth, J., & Nagendra, H. (2015). Understanding forest loss and recovery: a spatiotemporal analysis of land change in and around Bannerghatta National Park, India. *Journal of Land Use Science*, *10*(4), 402–424. https://doi.org/10.1080/1747423X.2014.920425

Aguirre-Gutiérrez, J., et al., (2020). Long-term droughts may drive drier tropical forests towards increased functional, taxonomic and phylogenetic homogeneity. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-16973-4

Aleixo, I., et al., (2019). Amazonian rainforest tree mortality driven by climate and functional traits. *Nature Climate Change*, *9*(5), 384–388. https://doi.org/10.1038/S41558-019-0458-0

Allen, K., et al., (2017). Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes? *Environmental Research* Letters, 12(2). https://doi.org/10.1088/1748-9326/aa5968

Amoako Johnson, F., & Hutton, C. W. (2014). Dependence on agriculture and ecosystem services for livelihood in Northeast India and Bhutan: vulnerability to climate change in the Tropical River Basins of the Upper Brahmaputra. *Climatic Change*, *127*(1), 107–121. https://doi.org/10.1007/S10584-012-0573-7

Asner, G. P., Loarie, S. R., & Heyder, U. (2010). Combined effects of climate and land-use change on the future of humid tropical forests. *Conservation Letters*, *3*(6), 395–403. https://doi.org/10.1111/j.1755-263X.2010.00133.x

Aubry-Kientz, M., et al., (2019). Temperature rising would slow down tropical forest dynamic in the Guiana Shield. *Nature Scientific Reports*, *9*(1), 1–8. https://doi.org/10.1038/s41598-019-46597-8

Bertrand, R., et al., (2011). Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, *479*(7374), 517–520. https://doi.org/10.1038/nature10548

Bhagwat, S. A., et al., (2008). Agroforestry: a refuge for tropical biodiversity? *Trends in Ecology & Evolution*, *23*(5), 261–267. https://doi.org/10.1016/J.TREE.2008.01.005

Blicharska, M., et al., (2013). Safeguarding biodiversity and ecosystem services of sacred groves - Experiences from northern Western Ghats. *International Journal of Biodiversity Science,* *Ecosystem Services and Management*, *9*(4), 339–346. https://doi.org/10.1080/21513732.2013.835350

Bojórquez, A., et al., (2019). Understanding and predicting frost-induced tropical tree mortality patterns. *Global Change Biology*, *25*(11), 3817–3828. https://doi.org/10.1111/GCB.14775

Brockerhoff, E. G., et al., (2008). Plantation forests and biodiversity: oxymoron or opportunity? *Biodiversity and Conservation*, *17*(5), 925–951. https://doi.org/10.1007/S10531-008-9380-X

Brodribb, T. J., et al., (2020). Hanging by a thread? Forests and drought. *Science*, *368*(6488), 261–266. https://doi.org/10.1126/SCIENCE.AAT7631

Burivalova, Z., et al.,. (2015). Relevance of Global Forest Change Data Set to Local Conservation: Case Study of Forest Degradation in Masoala National Park, Madagascar. *Biotropica*, *47*(2), 267–274. https://doi.org/10.1111/BTP.12194

Cariappa, A. A., et al., (2021). Impact of COVID-19 on the Indian agricultural system: A 10-point strategy for post-pandemic recovery. *Outlook on Agriculture. 50*(1), 26–33.

Chatterjee, S. (2008). Biodiversity conservation issues of Northeast India. *International Forestry Review*, *10*(2), 315–324. https://doi.org/10.1505/IFOR.10.2.315

Chaturvedi, R. K., et al., (2011). Impact of climate change on Indian forests: A dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change*, *16*(2), 119–142. https://doi.org/10.1007/s11027-010-9257-7

Chazdon, R. L. (2008). Beyond deforestation: Restoring forests and ecosystem services on degraded lands. *Science*, *320*(5882), 1458–1460. https://doi.org/10.1126/SCIENCE.1155365

Choudhury, A. (2002). Distribution and conservation of the Gaur Bos gaurus in the Indian Subcontinent. *Mammal Review*, 32(3), 199-226.

Clark, J. S., et al., (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, *22*(7), 2329–2352. https://doi.org/10.1111/gcb.13160

Coleman, E. A., et al., (2021). Limited effects of tree planting on forest canopy cover and rural livelihoods in Northern India. *Nature Sustainability*, 4(11), 1-8. https://doi.org/10.1038/s41893-021-00761-z

Corlett, R. T., & Westcott, D. A. (2013). Will plant movements keep up with climate change? *Trends in*

Ecology and Evolution, 28(8), 482-488. https://doi.org/10.1016/j.tree.2013.04.003

Deb, J. C., et al., (2017). Climatic-Induced Shifts in the Distribution of Teak (Tectona grandis) in Tropical Asia: Implications for Forest Management and Planning. *Environmental Management*, *60*(3), 422–435. https://doi.org/10.1007/s00267-017-0884-6

Dobrowski, S. Z., & Parks, S. A. (2016). Climate change velocity underestimates climate change exposure in mountainous regions. *Nature Communications*, *7*(1). https://doi.org/10.1038/ncomms12349

Downing, J., Borrero, H., & Liu, H. (2016). Differential impacts from an extreme cold spell on Subtropical vs.Tropical specialist bees in southern Florida. *Ecosphere*, *7*(5). https://doi.org/10.1002/ecs2.1302

Duffy, P. B., et al., (2015). Projections of future meteorological drought and wet periods in the Amazon, *PNAS*, 112(43), 13172–13177. https://doi.org/10.1073/pnas.1421010112

Engelbrecht, B. M. J., et al., (2007). Drought sensitivity shapes species distribution patterns in tropical forests. *Nature*, 447(7140), 80–82. https://doi.org/10.1038/nature05747

ESA. Land Cover CCI Product User Guide Version 2. Tech. Rep. (2017). Available at: maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

ESA C3S. Land Cover CCI Product User Guide (2016-2019): https://datastore.copernicus-climate.eu/documents/satellite-land-cover/D5.3.1_PUGS_ICDR_LC_v2.1.x_PRODUCTS_v1.1.pdf

Esquivel-Muelbert, A., et al., (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, *25*(1), 39–56. https://doi.org/10.1111/GCB.14413

Fan, Z.-X., et al., (2012). Hydraulic conductivity traits predict growth rates and adult stature of 40 Asian tropical tree species better than wood density. *Journal of Ecology*, *100*(3), 732–741. https://doi.org/10.1111/J.1365-2745.2011.01939.X

FAO & ITTO, (2011). The State of Forests in the Amazon Basin, Congo Basin and Southeast Asia. Summit of the Three Rainforest Basins report. Food and Agriculture Organisation of the United Nations and the International Tropical Timber Organisation. Accessed at: http://www.fao.org/3/i2247e/i2247e00.pdf

FAO & UNSPF (2021). Strategic Plan for Forests 2030. The State of the World's Forests. FAO, Rome. Accessed at: https://www.un.org/en/desa/global-forest-goals-report-2021

Fauset, S., et al., (2012). Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. *Ecology Letters*, 15(10), 1120–1129. https://doi.org/10.1111/J.1461-0248.2012.01834.X

Feng, M., & Bai, Y. (2019). A global land cover map produced through integrating multi-source datasets. *Big Earth Data*, *3*(3), 191–219. https://doi.org/10.1080/20964471.2019.1663627

França, F. M., et al., (2020). Climatic and local stressor interactions threaten tropical forests and coral reefs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375(1794). https://doi.org/10.1098/rstb.2019.0116

França, F. M., et al., (2020). El Niño impacts on human-modified tropical forests: Consequences for dung beetle diversity and associated ecological processes. *Biotropica*, *52*(2), 252–262. https://doi.org/10.1111/BTP.12756

FSI (2019). State of the Forest Report, 2019. Forest Survey of India. Ministry of Environment, Forest & Climate Change, Government of India

Galiatsatos, N., et al., (2020). An Assessment of Global Forest Change Datasets for National Forest Monitoring and Reporting. *Remote Sensing*, *12*(11), 1790. https://doi.org/10.3390/RS12111790

Ghosh-Harihar, M., et al., (2019). Protected areas and biodiversity conservation in India. *Biological Conservation*, 237, 114-124. https://doi.org/10.1016/j.biocon.2019.06.024

Giam, X. (2017). Global biodiversity loss from tropical deforestation. *Proceedings of the National Academy of Sciences*, 114(23), 5775–5777. https://doi.org/10.1073/PNAS.1706264114

Gopalakrishnan, R., et al., (2011). Climate change and Indian forests. *Current Science*, 101(3), 348-355.

Greenwood, S., et al., (2017). Tree mortality across biomes is promoted by drought intensity, lower wood density and higher specific leaf area. *Ecology Letters*, *20*(4), 539–553. https://doi.org/10.1111/ele.12748

Gries, R., et al., (2012). Evaluating the impacts and conservation value of exotic and native tree afforestation in Cerrado grasslands using dung beetles. *Insect Conservation and Diversity*, *5*(3), 175–185. https://doi.org/10.1111/J.1752-4598.2011.00145.X

Hansen, M. C., et al., (2013). High-resolution global maps of 21st-century forest cover change. *Science*, *342*(6160), 850–853. https://doi.org/10.1126/science.1244693

Hinz, R., et al., (2020). Agricultural Development and Land Use Change in India: A Scenario Analysis of

Trade-Offs Between UN Sustainable Development Goals (SDGs). *Earth's Future*, *8*(2), e2019EF001287. https://doi.org/10.1029/2019EF001287

Hosonuma, N., et al., (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, *7*(4), 044009. https://doi.org/10.1088/1748-9326/7/4/044009

IPCC. (2021). The Physical Science Basis Summary for Policymakers Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Jaacks, L. M., et al., (2021). Impact of the COVID-19 pandemic on agricultural production, livelihoods, and food security in India: baseline results of a phone survey. *Food* Security, 13, 1–17. https://doi.org/10.1007/S12571-021-01164-W

Jimenez, J. C., et al., (2018). Spatio-temporal patterns of thermal anomalies and drought over tropical forests driven by recent extreme climatic anomalies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760). https://doi.org/10.1098/RSTB.2017.0300

Joshi, A. K., et al., (2010). National Forest Policy in India: Critique of Targets and Implementation. *Small-Scale Forestry*, 10(1), 83–96. https://doi.org/10.1007/S11842-010-9133-Z

Kala, C. P. (2017). Environmental and Socioeconomic Impacts of Drought in India: Lessons for Drought Management. *Applied Ecology and Environmental Sciences*, 5(2), 43–48. https://doi.org/10.12691/AEES-5-2-3

Kale, M. P., et al., (2016). Land-use and land-cover change in Western Ghats of India. *Environmental Monitoring and Assessment*, 188(7), 387. https://doi.org/10.1007/s10661-016-5369-1

Kanowski, J., Catterall, C. P., & Wardell-Johnson, G. W. (2005). Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *Forest Ecology and Management*, 208(1–3), 359–372. https://doi.org/10.1016/J.FORECO.2005.01.018

Katdare, B., et al.,. (2021). International Journal of Zoology Studies www.zoologyjournals.com Ant species consumed in diet as prey species by Indian pangolin (Manis crassicaudata) in northern Western Ghats of Maharashtra India. *International Journal of Zoology Studies*, 6(3), 36–40.

Keinath, D. A., et al., (2017). A global analysis of traits predicting species sensitivity to habitat fragmentation. *Global Ecology and Biogeography*, *26*(1), 115–127. https://doi.org/10.1111/GEB.12509

Kumagai, T., et al., (2009). Comparison of soil moisture dynamics between a tropical rain forest and a tropical seasonal forest in Southeast Asia: Impact of seasonal and year-to-year variations in rainfall. *Water Resources Research*, *45*(4). https://doi.org/10.1029/2008WR007307

Kumar, C., & Singh, S. P. (2012). Determinants of Agricultural Land Use Diversification in Eastern and Northeastern India. *Journal of Agriculture, Food Systems, and Community Development*, *3*(1), 73–98. https://doi.org/10.5304/jafscd.2012.031.004

Kumar, D., & Scheiter, S. (2019). Biome diversity in South Asia - How can we improve vegetation models to understand global change impact at regional level? *Science of The Total Environment*, 671, 1001–1016. https://doi.org/10.1016/J.SCITOTENV.2019.03.251

Kumar, M., Singh, H., & Kalra, N. (2018). Dynamic forest vegetation models for predicting impacts of climate change on forests: An Indian perspective. *Indian Journal of Forestry.* 41(1), 1-12

Le Page, Y., et al., (2017). Synergy between land use and climate change increases future fire risk in Amazon forests. *Earth Syst. Dynam*, *8*, 1237–1246. https://doi.org/10.5194/esd-8-1237-2017

Leal, I. R., et al., (2012). Effects of habitat fragmentation on ant richness and functional composition in Brazilian Atlantic forest. *Biodiversity and Conservation*, 21(7), 1687–1701. https://doi.org/10.1007/S10531-012-0271-9

Lele, N., Joshi, P. K., & Agrawal, S. P. (2008). Assessing forest fragmentation in northeastern region (NER) of India using landscape matrices. *Ecological Indicators*, *8*(5), 657–663. https://doi.org/10.1016/J.ECOLIND.2007.10.002

Lele, Nikhil, & Joshi, P. K. (2009). Analyzing deforestation rates, spatial forest cover changes and identifying critical areas of forest cover changes in North-East India during 1972–1999. *Environmental Monitoring and Assessment*, 156(1–4), 159–170. https://doi.org/10.1007/s10661-008-0472-6

Liu, X., et al.,. (2018). Comparison of country-level cropland areas between ESA-CCI land cover maps and FAOSTAT data. *International Journal of Remote Sensing*, 39(20), 6631–6645.

Magura, T., Ködöböcz, V., & Tóthmérész, B. (2001). Effects of habitat fragmentation on carabids in forest patches. *Journal of Biogeography*, *28*(1), 129–138. https://doi.org/10.1046/J.1365-2699.2001.00534.X

Mantyka-pringle, C. S., Martin, T. G., & Rhodes, J. R. (2012). Interactions between climate and habitat loss effects on biodiversity: A systematic review and meta-analysis. *Global Change Biology*, 18(4), 1239-1252. https://doi.org/10.1111/j.1365-2486.2011.02593.x

Martello, F., et al., (2018). Homogenization and impoverishment of taxonomic and functional diversity of ants in Eucalyptus plantations. *Nature Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-20823-1

McDowell, N., et al., (2018). Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, 219(3), 851-869. https://doi.org/10.1111/nph.15027

Meir, P., & Ian Woodward, F. (2010). Amazonian rain forests and drought: response and vulnerability. *New Phytologist*, *187*(3), 553–557. https://doi.org/10.1111/j.1469-8137.2010.03390.x

Meiyappan, P., et al., (2017). Dynamics and determinants of land change in India: integrating satellite data with village socioeconomics. *Regional Environmental Change*, 17, 753-766. https://doi.org/10.1007/s10113-016-1068-2

Nathan, R., et al., (2011). Spread of North American wind-dispersed trees in future environments. *Ecology Letters*, *14*(3), 211–219. https://doi.org/10.1111/J.1461-0248.2010.01573.X

Oliver, T. H., & Morecroft, M. D. (2014). Interactions between climate change and land use change on biodiversity: Attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, 5(3), 317-335. https://doi.org/10.1002/wcc.271

Ouédraogo, D.-Y., et al., (2016). The determinants of tropical forest deciduousness: disentangling the effects of rainfall and geology in central Africa. *Journal of Ecology*, 104(4), 924–935. https://doi.org/10.1111/1365-2745.12589

Padalia, H., et al., (2019). Assessment of historical forest cover loss and fragmentation in Asian elephant ranges in India. *Environmental Monitoring and Assessment*, 191(3), 802. https://doi.org/10.1007/s10661-019-7696-5

Pandve (2009). India's National Action Plan on Climate Change. *Indian journal of Occupational and Environmental Medicine*, 13(1):17-19

Pérez-Hoyos, A., et al.,. (2017). Comparison of Global Land Cover Datasets for Cropland Monitoring. *Remote Sensing*, *9*(11), 1118. https://doi.org/10.3390/RS9111118

Phillips, O. L., et al., (2009). Drought sensitivity of the amazon rainforest. *Science*, *323*(5919), 1344–1347. https://doi.org/10.1126/science.1164033

Phommexay, P., et al., (2011). The impact of rubber plantations on the diversity and activity of understorey insectivorous bats in southern Thailand. *Biodiversity and Conservation*, 20(7), 1441–1456. https://doi.org/10.1007/S10531-011-0036-X

Puyravaud, J. P., Davidar, P., & Laurance, W. F. (2010). Cryptic destruction of India's native forests. *Conservation Letters*, 3, 390-394. https://doi.org/10.1111/j.1755-263X.2010.00141.x

Rahman, M. S., et al.,. (2021). The COVID-19 pandemic: A threat to forest and wildlife conservation in Bangladesh? *Trees, Forests and People*, *5*, 100119. https://doi.org/10.1016/J.TFP.2021.100119

Ramachandran, et al.,. (2018). Long-term land use and land cover changes (1920–2015) in Eastern Ghats, India: Pattern of dynamics and challenges in plant species conservation. *Ecological Indicators*, 85, 21-36. https://doi.org/10.1016/j.ecolind.2017.10.012

Ramesh, T., et al., (2020). Patterns of livestock predation risk by large carnivores in India's Eastern and Western Ghats. *Global Ecology and Conservation*, 24, e01366. https://doi.org/10.1016/j.gecco.2020.e01366

Ravindranath, N. H., et al., (2005). Impact of climate change on forests in India. *Current Science*, 90(3). https://doi.org/10.2307/24091869

Ravindranath, N. H., et al., (2011). Climate change vulnerability profiles for North East india. *Current Science*, *101*(3), 384–394.

Reddy, S., Dutta, K., & Jha, C. S. (2013). Analysing the gross and net deforestation rates in India. *Current Science*. 105 (11), 1492-1500

Rifai, S. W., Li, S., & Malhi, Y. (2019). Coupling of El Niño events and long-term warming leads to pervasive climate extremes in the terrestrial tropics. *Environmental Research Letters*, *14*(10), 105002. https://doi.org/10.1088/1748-9326/AB402F

Rowland, L., et al., (2015). Death from drought in tropical forests is triggered by hydraulics not carbon starvation. *Nature*, 528(7580), 119–122. https://doi.org/10.1038/nature15539

Roy, P. S., et al., (2015). New vegetation type map of India prepared using satellite remote sensing: Comparison with global vegetation maps and utilities. *International Journal of Applied Earth Observation and Geoinformation*, 39, 142-159. https://doi.org/10.1016/j.jag.2015.03.003

Roy, P. S., & Joshi, P. K. (2010). Forest cover assessment in north-east India--the potential of temporal wide swath satellite sensor data (IRS-1C WiFS). *International Journal of Remote Sensing*, 23(22). https://doi.org/10.1080/01431160110114475

Roy, P. S., et al., (2013). Forest Fragmentation in India. *Current Science*, 105(6), 774–780.

Sharma, J., et al., (2015). Assessing “inherent vulnerability” of forests: a methodological approach and a case study from Western Ghats, India. *Mitigation and Adaptation Strategies for Global Change*, *20*(4), 573–590. https://doi.org/10.1007/s11027-013-9508-5

Sharma, J., et al., (2017). Vulnerability of Forests in India: A National Scale Assessment. *Environmental Management*, *60*(3), 544–553. https://doi.org/10.1007/s00267-017-0894-4

Sharma, S., & Mujumdar, P. (2017). Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India. *Nature Scientific Reports*, 7(15582). https://doi.org/10.1038/s41598-017-15896-3

Slot, M., & Winter, K. (2016). *The Effects of Rising Temperature on the Ecophysiology of Tropical Forest Trees*. In: Goldstein, G., Santiago, L. (eds). Tropical Tree Physiology. Tree Physiology, vol 6, Springer, Cham. https://doi.org/10.1007/978-3-319-27422-5_18

Staal, A., et al., (2020). Feedback between drought and deforestation in the Amazon. *Environmental Research Letters*, *15*(4), 044024. https://doi.org/10.1088/1748-9326/AB738E

Sudhakar Reddy, C., et al., (2016). Quantification and monitoring of deforestation in India over eight decades (1930–2013). *Biodiversity and Conservation*, *25*(1), 93–116. https://doi.org/10.1007/s10531-015-1033-2

Suresh, H. S., Dattaraja, H. S., & Sukumar, R. (2010). Relationship between annual rainfall and tree mortality in a tropical dry forest: Results of a 19-year study at Mudumalai, southern India. *Forest Ecology and Management*, *259*(4), 762–769. https://doi.org/10.1016/j.foreco.2009.09.025

Tian, H., et al., (2014). History of land use in India during 1880–2010: Large-scale land transformations reconstructed from satellite data and historical archives. *Global and Planetary Change*, *121*, 78–88. https://doi.org/10.1016/J.GLOPLACHA.2014.07.005

Tripathi, S. K., et al., (2016). Perspectives of Forest Biodiversity Conservation in Northeast India High Altitude Phytodiversity and Impacts of Climate Variability at Ecosystem and Species Level in Garhwal Himalaya (Uttarakhand) using Geospatial Techniques. *Journal of Biodiversity, Bioprospecting and Development*, 3(2). https://doi.org/10.4172/2376-0214.1000157

Turubanova, S., et al., (2018). Ongoing primary forest loss in Brazil, Democratic Republic of the Congo, and Indonesia. *Environmental Research Letters*, *13*(7), 074028. https://doi.org/10.1088/1748-9326/AACD1C

Udawatta, R. P., Rankoth, L., & Jose, S. (2019). Agroforestry and Biodiversity. *Nature Sustainability*, *11*(10), 2879. https://doi.org/10.3390/SU11102879

Upgupta, S., et al., (2015). Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India. *Climate Risk Management*, *10*, 63–76. https://doi.org/10.1016/j.crm.2015.08.002

Vancutsem, C., et al., (2021). Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Science Advances*, *7*(10). https://doi.org/10.1126/sciadv.abe1603

Vesk, P. A., et al., (2008). Time lags in provision of habitat resources through revegetation. *Biological Conservation*, *141*(1), 174–186. https://doi.org/10.1016/J.BIOCON.2007.09.010

Wang, X., et al., (2016, May 1). Greater impacts from an extreme cold spell on tropical than temperate butterflies in southern China. *Ecosphere*, 7(5), e01315. https://doi.org/10.1002/ecs2.1315

Werner, W. (2003). Toasted forests: Evergreen rain forests of tropical Asia under drought stress. *Discussion Papers 18732, University of Bonn, Center for Development Research (ZEF).* doi:10.22004/ag.econ.18732

Wilson, M. W., et al., (2010). Effects of growth stage and tree species composition on breeding bird assemblages of plantation forests. *Bird Study*, *53*(3), 225–236.

World Bank (2021): Population, total - India. The World Bank Group. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=IN. Accessed 12/09/2021