# Climate Variability and Trends in Ecosystem Services in the Nilgiri Biosphere Reserve

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# Climate Variability and Trends in Ecosystem Services in the Nilgiri Biosphere Reserve

**Technical Report**

*Prepared by*

**Foundation for Ecological Research, Advocacy and Learning (FERAL)**

**and**

**National Centre for Biological Sciences (NCBS)**

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# Executive summary

The Nilgiri Biosphere Reserve (NBR) is the first biosphere reserve established in India in 1986. The region is noted for its rich biodiversity. It houses about 3500 species of flowering plants, out of which 1500 are endemic to the Western Ghats. The fauna includes over 100 species of mammals, 550 birds, 30 reptiles and amphibians, 300 butterflies, and a large number of invertebrates. NBR covers an area of 5500 km$^2$ and shows a large gradient in rainfall, temperature, and elevation. These gradients have given rise to diverse vegetation types which range from scrub and thorn forests to deciduous forests to wet evergreen forests, and from dry savanna grasslands to high altitude wet grasslands. The high biodiversity, wide range of forest types, and human diversity led to its inscription as a biosphere reserve with the objective of preserving biodiversity, promoting ecologically sustainable development, and to provide facilities for research, monitoring, education, and training. This largely addressed the loss of biodiversity concerns in the early 1980s. The climatic and vegetation gradients within the NBR makes it an ideal site to understand the historical trends in ecosystem services and their response to changing climatic conditions. More importantly it will fill gaps in our knowledge about the functioning of tropical forests due to climatic vagaries.

This report has five sections which covers trends and variability in climatic factors and its impacts on ecosystem services using gridded and remotely sensed data products. We used spatially explicit dynamic models to understand the trends in the response variable and to also understand the relationship between the response variable and climatic variables, and how it evolves over time.

The annual rainfall in the NBR varies from 900 mm to 6500 mm, and has an elevation gradient ranging from 300 m to 2500 m mean sea level. The mean annual temperature ranges from 15 °C to 28 °C. Our results from the analysis of coarse scale historical gridded data products show that the average rainfall across the NBR during the South West Monsoon (SWM) has witnessed a significant decline (-41.5 mm/decade) with a corresponding reduction in the number of rain days (-5 days/decade) during the period 1951–2007. However, the quantum of rainfall and rainy days during the North East Monsoon (NEM) has seen a slight increase since the 1980’s. The mean annual temperature over this region has also witnessed a significant increase (0.16 °C/decade) during the period 1961–2015. Our results from the spatially explicit dynamic models suggest that 53.6% of the NBR has witnessed a decline in the quantum of rainfall received during the SWM with a small percentage of area (14.3%) showing increasing rainfall trends. Nearly 10% of this landscape has witnessed an increase in rainfall during the NEM. Nearly half of the NBR (53.4%) has witnessed a

decline in the annual number of intense rain events. The entire landscape has witnessed an increase in temperature, which is in line with future climate change predictions. Hopwever, the trends in historical rainfall are contrary to large scale model predictions which indicate increase in rainfall totals with high levels of uncertainty. The remotely sensed rainfall and temperature products, which were used to understand the trends in ecosystem services in the last two decades, showed similar trends as the historical dataset.

We studied trends in annual net primary productivity (ANPP), which is the amount of carbon assimilated in terrestrial biomass. The net effect of photosynthesis and respiration determines the net primary productivity of plants. Changes in the ambient air temperature, water availability, nutrient uptake, and atmospheric $CO_2$ concentrations have direct effect on net photosynthesis, which subsequently drives the net primary productivity. With increasing temperatures and declining rainfall there is a concern that periods of drought are increasing and water stress will have a major impact on the ANPP. Hence in this study, we analysed ANPP as a function of water stress, which is a combined effect of temperature and water availability. Water stress was calculated as a function of difference between precipitation (water input) and potential evapotranspiration (water loss). Our results show that large parts (94%) of the NBR did not show any significant trend in water stress. However, 84% of the NBR experienced a decrease in the ANPP due to the long term influence of water stress, with evergreen and deciduous forests experiencing a decline up to 90%. Majority of the landscape showed a transition from increasing to declining trend in the ANPP from 2008 onwards. The magnitude of the ANPP–water stress index was weak suggesting that water stress alone might not be a significant driver of productivity in the NBR. We found that the regions at higher elevations (> 1000 m) were experiencing the greatest decline in the ANPP in the NBR. The influence of water stress on the ANPP showed an increasing positive trend in the drier low altitude forest types, like the dry deciduous forests and savannas, over the past two decades.

Tropical forests display synchrony and periodicity in leaf fall, leaf flush, flowering, and fruiting. These phenological changes in the plants that occur at the species and community level have profound influences on vegetation productivity. The changes in temperature and precipitation can affect the plant’s physiology, which in turn influence the plant’s phenology. Warming climates have been widely recognized to advance vegetation phenology. However, the delayed responses of vegetation phenology to rising temperature and rainfall variability are poorly understood, especially in tropical forests.

Using a time series of remotely sensed vegetation indices, the vegetation growth period and vegetation biomass growth was calculated to explore climate phenological linkages in the NBR. In addition we looked at vegetation greening/browning trends and their relationship with climatic variables. Results from our spatially explicit analysis showed that there was no considerable difference in the percentage of areas witnessing increase or decrease in the length of the growing period across all land use land cover (LULC) types. The percentage area within NBR witnessing an increase in vegetation growth was higher than areas undergoing decline across all LULC types. Trends in greening and browning showed a net greening in the NBR. Rainfall has a positive influence on growth period, except in the wetter forests where it was negative or close to zero. This influence was found to be increasing in recent times and was higher than the influence of temperature across all LULC categories and across the elevational zones. Temperature had a negative influence on the growth period across all vegetation and elevation zones, except in the lower elevation dry deciduous forests with the influence becoming positive in recent years. Rainfall and temperature have a similar magnitude in their influence on vegetation growth, the influence of rainfall was increasing in areas above the altitude of 900 m. Whereas, the influence of temperature on vegetation growth was increasing at lower elevations. The influence of rainfall on greening remained stable across all elevation and land use land cover types except for moist deciduous forests in the lower and mid elevation zones which has witnessed a consistent decline in sensitivity. Temperature showed no directional trend on greening/browning across LULC categories. However, the influence of temperature was higher than that of rainfall, especially in dry deciduous forests, savannas, and grasslands.

Hydrological services refer to a range of regulatory and provisioning services including evapo-transpiration, discharge as stream flows, soil moisture retention, mitigation of water damage, and recharge of ground water. These water services are arguably the most important services and an alteration in these services will directly affect fresh water, terrestrial ecosystems, and also human well-being. Recent research has found that climate change has drastically altered some of these hydrological processes and services globally. Understanding the influence of climate variability on these services is essential for developing effective watershed management plans and adapting to changing climate for future well-being of humans. To understand the impacts of climatic variables on hydrological services we analysed the trends in blue water availability in the NBR as a function of time-varying temperature and rainfall. Blue water refers to the amount of water available as surface flows and groundwater and which is available for irrigation, domestic purposes, power generation, and maintaining ecological flows.

The results indicate an increase in blue water upto 2015–2016 and a decrease thereafter. Our results show that large parts of the NBR remain stable with respect to the trend in blue water after accounting for the effects of temperature and rainfall. Only 6.75% of the area in the Nilgiris witnessed a declining trend, while a significant increase was observed in 37.93% of the area. Among different vegetation types considered, agricultural landscapes, showed maximum increase in blue water (60%), followed by savannas (53%). Blue-water trends in deciduous forests were found to be more sensitive to change in temperature, while in evergreen forests, the trends were sensitive to rainfall patterns.

Land use land cover change is known to affect a wide range of ecosystem services including hydrological and carbon services. We used a time series of tree cover data rather than hard classified vegetation maps to determine changes between LULC categories in the NBR. In addition to climatic variables, understanding and identifying areas undergoing rapid deforestation and/or degradation could be a key in monitoring ecosystem services and developing regional climate resilience plans. Our results indicate that, majority of the areas in the Nilgiris, remained stable with a net increase in tree cover over the last two decades. A significant decrease in tree cover was noted in 6.52% of the area in the Nilgiris, while a significant increase in tree cover was observed in 11.37% of the area. Among different vegetation types considered, savannas showed the largest gains in area (24%) as well as the least losses (1%) in tree cover suggesting an expansion of woody vegetation into these grass dominated landscapes. Agriculture also showed one of the highest gains in tree cover (23%) suggesting a change in land management practice in the landscape. Evergreen and moist deciduous forests showed more losses than gains compared to all other LULC types in the NBR. LULC changes, regional climatic variable, and other non-climatic factors had greater influence on carbon sequestration compared to phenology and hydrological services.

In the absence of long term ecological studies, the results presented here, based on remotely sensed data, are novel and provide information on trends in different tropical ecosystem services and their response to changes in climatic factors in the NBR. While the different ecosystem services showed varying response to precipitation and temperature, the differences in response between wetter and drier vegetation types emerges across all ecosystem services that were included in this study. We provide results on areas that are undergoing rapid changes in terms of ecosystem services and their response to a changing temperature and rainfall. These results can feed into conservation planning, developing regional climate resilience plans, and also aid in our understanding of regional to global scale vegetation dynamics, which are required to improve models of climate biosphere interactions.

# Table of Contents

# Assessment of climate variability and trends in the Nilgiri Biosphere Reserve

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## Highlights

- South West monsoon (SWM) rainfall and number of rain days has decreased since 1951 over the NBR.
- An increase in North East monsoon (NEM) since 1980’s is evident across the NBR.
- The annual mean temperature has increased throughout the NBR at a rate of 0.16 $^{0}$C/decade since 1961.
- A strong positive influence of La Nina was bserved on the SWM rainfall totals, which has declined in recent decades.
- The influence of IOD on the SWM rainfall totals has been declining over the years.

## Abstract

The Western Ghats, one of the 36 global biodiversity hotspots, supports a high human population and underpins ecosystems of global significance. Understanding emerging trends and drivers of rainfall and temperature is of importance for managing the natural wealth and also to stakeholders who depend on ecosystem services that are provided by this mountainous landscape. The key teleconnections which drive rainfall in India are El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). Temperature is known to be driven by ENSO, and a second set of drivers that include aerosols and land-use change. We use spatially explicit time-varying models to understand the dynamic influence of ENSO and IOD on rainfall during the South West Monsoon (SWM) and North East monsoon (NEM) and annual counts of intense rain events (IREs) from 1951 to 2007 across the Niligiri Biosphere Reserve (NBR). The same approach was used to understand the influence of ENSO on annual mean temperature from 1961 to 2015. Our results showed that the spatially averaged SWM rainfall totals across the NBR has declined since 1951 (-41.5 mm/decade). The spatially averaged trends showed an increase in rainfall totals from the 1980’s during the NEM. The number of IREs declined in the NBR over the years. The results also suggested that wetter regions of the NBR were getting drier and drier regions were getting wetter. The annual mean temperature increased throughout the biosphere reserve (0.16 $^{0}$C/decade). The spatially explicit

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results indicate that nearly half of the NBR experienced declining trends in SWM rainfall totals. Large parts of the NBR showed no significant trends in the NEM rainfall totals, while the IREs declined in nearly half of the NBR. The entire biosphere reserve showed an increase in the annual mean temperature. The historical trend, which seems to contradict climate predictions, indicates wetter conditions which could lead to greening with warming in the future. Understanding the response of natural ecosystems and their services to changing climatic variables is of interest to researchers, ecologists, and planners. In addition, it will also help in identifying areas that have witnessed transformations due to climate variability.

## Introduction

The Western Ghats is a biodiversity-rich region and is one of the 36 global biodiversity hotspots (Mittermeier et al., 2011; Myers et al., 2000). The variability in topography, soil, and rainfall has resulted in a wide variety of forest types ranging from wet evergreen and semi-evergreen forests in the higher elevations and along the western slopes to dry deciduous and scrub formations at the lower elevation and along the eastern slopes. The varying climatic and vegetation types support more than 4000 species of flowering plants (38% endemic), 508 species of birds (4% endemic), 208 species of fishes (53% endemic), 157 species of reptiles (62% endemic), 127 species of mammals (12% endemic), and 127 species of amphibians (68% endemic) (Daniels, 2001; Johnsingh, 2001; N. C. Nair & Daniel, 1986). Several new species in lesser-studied taxa continue to be discovered, suggesting a lack of systematic inventories across this large landscape and also highlighting the rich biodiversity and high levels of endemism.

The Western Ghats mountain chain lies almost perpendicular to the low level jet stream and hence receives about three times the average rainfall in India. The onset of the South West Monsoon (SWM) also occurs in this region, and thus it plays a key role in regulating the climate in India through regional climate modulations. Therefore, detecting changes in the rainfall in the Western Ghats is necessary to identify changes in regional climate. Studies have shown an overall decline in the average rainfall in recent decades throughout India (Krishnan et al., 2013; Kumar et al., 2011). However, certain parts of the country are witnessing an increase in rainfall (Guhathakurta & Rajeevan, 2008) and in the frequency of extreme rain events (Guhathakurta et al., 2011). Here, we examine the features of rainfall received and reasons for the observed rainfall patterns in the Nilgiri Biosphere Reserve (NBR), located in the southern part of the Western Ghats. In addition to rainfall, we also examine long-term trends in temperature, which along with rainfall, plays an important role in determining regional ecosystem processes and services (Clinton et al., 2014; Heisler-White et al., 2009; Osland et al., 2016; Traill et al., 2010).

The NBR was established in 1986 and was the first biosphere reserve in India (Daniels, 1996). It covers an area of 5000 $km^2$ and includes eight Protected Areas including four Tiger Reserves. The NBR experiences a large variation in the annual rainfall, which varies from 500 mm to 7000 mm, received in a short span of 3–4 months during the SWM. The eastern parts of the biosphere reserve also receives rain from the North East monsoon (NEM). The NBR displays an elevation gradient that ranges from 300 m to 2500 m above mean sea level. Thus, there is an altitudinal and east-west gradient in rainfall wherein, the eastern slopes and plains receive lower rainfall when compared to the windward western slopes of the Ghats. The altitudinal gradient and north-south east-west aspects in the NBR further results in large variations in the mean annual temperature which ranges from 15 °C to 28 °C. An earlier study suggests that over the past 100 years there has been significant variation in both rainfall and temeprature in the NBR. A multi-decadal declining trend in rainfall was observed in the NBR region and the rainfall declined between 100 mm and 250 mm along with a reduction in the number of rainy days over the past 100 years (Ramachandra & Bharath, 2020). On the other hand, an increase in temperature of 0.25–0.5 °C has been obseved in the NBR region (Ramachandra & Bharath, 2020).

The gradients in rainfall, elevation, and temperature have given rise to diverse vegetation types in the NBR landscape. However, this landscape has undergone drastic modifications over the years with natural vegetation being replaced by commercial plantations, agriculture, and construction of dams (Ramachandra & Bharath, 2020). In many areas, natural ecosystems have been invaded by exotic plants (Prasad, 2012; Rajput et al., 2019; Ramaswami & Sukumar, 2013; Sivakumar et al., 2018). Additionally, active timber operations, extensive extraction of fuelwood, grazing, and frequent forest fires have degraded the forest vegetation. These large scale land use/land cover (LULC) changes along with increasing climate variability will not only affect the functioning of the ecosystems but also the lives and livelihoods of millions of people who depend on this biosphere reserve. Several perennial rivers originate in the NBR. Understanding rainfall and temperature variabilities is important for understanding ongoing changes and developing regional management plans for this landscape.

The key drivers of the monsoon are El Nino Southern Osciallation (ENSO), specifically La Nina, and Indian Ocean Dipole (IOD), besides the solar cycle (Krishnaswamy et al., 2015; Roy & Collins, 2015). The role of ENSO and IOD on rainfall has been well documented (Ashok et al., 2001, 2007; Endris et al., 2019; Hrudya et al., 2021; Meyers & Cai, 2011; Pillai et al., 2021). However, very few studies have looked at the spatial variation in these trends. The positive IOD phase is known to significantly reduce the impacts of El Nino on the Indian monsoon (Ashok et al., 2001, 2004). Furthermore, in the water deficit state of Tamil Nadu, the vegetation in the Western Ghats contributes 25–40% of the water, through evapotranspiration, to the rainfall recieved during the SWM. This contribution reaches 50% during deficit monsoon years or dry spells within a season (Paul et al., 2016). Similarly, temperature is known to be driven by ENSO (Chiang & Sobel, 2002; Donat et al., 2014; Wu et al., 2010). Several ecosystem services including net primary productivity and water-cycles in tropical forests are very sensitive to temperature and rainfall variabilities (Phillips et al., 2009; Sullivan et al., 2020). Hence, understanding the aggregated and spatially explicit historical trends and drivers of the monsoon rains and temperature in the Western Ghats is of great interest to scientists, the Government, and other stakeholders in relation to future projections and LULC changes. In this study, we explore the trends and patterns of rainfall characteristics in the NBR over the period 1951–2007, and temperature trends from 1961 to 2015, which can have significant long-term implications for regional climate change.

***Study area***

The NBR, the first biosphere reserve to be established in India is spread across three south Indian states, Karnataka, Kerala, and Tamil Nadu, covering an area of 5000 $km^2$. The landscape has eight Protected Areas including four Tiger Reserves. The NBR is home to several indigenous tribes including the Kadu Kurubas, Jenu Kurubas, Poojary, Todas, Kotas, Badagas, Irulas, Kurumbas, Paniyas, Adiyans, Edanadan Chettis, Cholanaickens, Allar, Malayan, and Mullu Kurumba. It is also an abode to a large number of threatened large mammals like the tiger (*Panthera tigris*), leopard (*Panthera pardus*), dholes (*Cuon alpinus*), Asian elephant (*Elephas maximus*), gaur (*Bos gaurus*), Nilgiri tahr (*Nilgiritragus hylocrius*), sambar (*Rusa unicolor*), and the Nilgiri marten (*Martes gwatkinsii*). NBR is also known for the many endemic species of plants and animals. About 3300 flowering plants have been reported from this landscape of which 132 are endemic to NBR (Shobha Kumari, 2015).

The NBR receives an annual rainfall between 500 mm and 7000 mm. The elevation gradient in this landscape ranges from 300 m to 2500 m mean sea level and the mean annual temperature ranges from 150 °C to 280 °C. The elevation, rainfall, and temperature gradients have given rise to diverse vegetation types including thorns/savanna woodlands, dry and moist deciduous forests, low elevation evergreen forests and montane-rain-forests (shola), and high-altitude grasslands (S. S. C. Nair et al., 1977). A large part of this landscape has witnessed rapid changes in the land use and

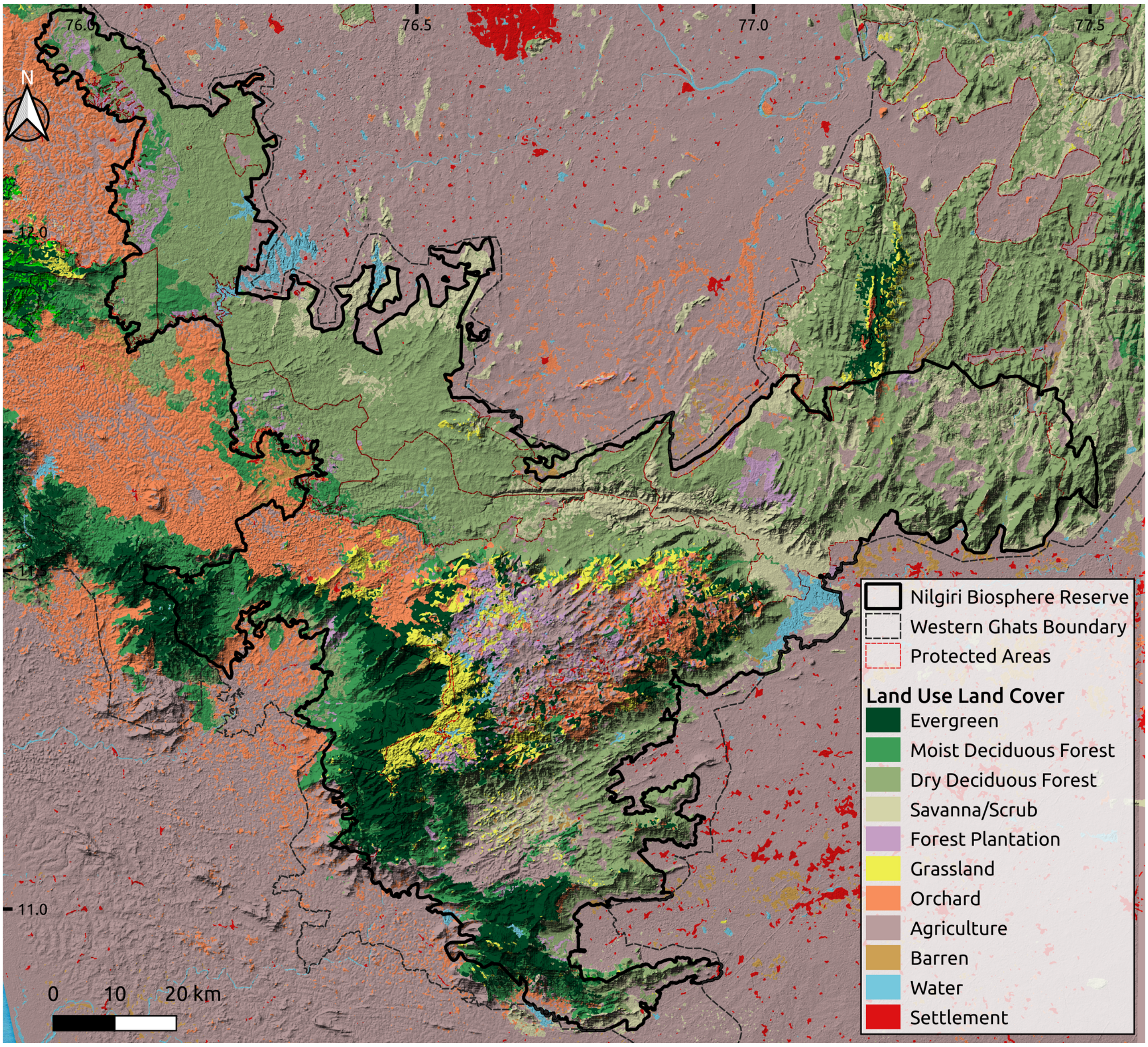

*Figure 1: Land use Land cover map of the Nilgiri Biosphere Reserve (modified from Roy et al. 2015).*

land cover types, which started in the 1800s (Joshi et al., 2018; Satish et al., 2014; Srinivasan et al., 2012). Vast stretches of lowland forests, grasslands, and montane forests (shola) have been converted into commercial plantations of tea (*Camellia sinensis*) and coffee (*Coffea arabica*), and forestry plantations of teak (*Tectona grandis*), wattle (*Acacia spp.*), blue gum (*Eucalyptus spp.*), and prosopis (*Prosopis juliflora*). This conversion continued until the late 1990s. Some of the introduced species like wattle (*Acacia mearnsii* and *Acacia dealbata*) and prosopis, and other exotic shrubs like broom-grasses (*Cytisus scoparius* and *Ulex europaeus*) and lantana (*Lantana camara*) have invaded natural ecosystems (Joshi et al., 2018; Prasad, 2012; Rajput et al., 2019; Ramaswami & Sukumar, 2013; Sivakumar et al., 2018). This landscape also witnesses regular forest fires (Kodandapani et al., 2004).

The NBR forms an important catchment area for peninsular India. Several major tributaries of the river Kaveri such as Bhavani, Moyar, Kabini, and other rivers like Chaliyar and Punampuzha originate and have their catchment areas within NBR. As many as seven mega hydro-electric power projects are present in the Kundah, Pykara, Avalanche, Bhavani, and Moyar basins (http://117.252.14.242/rbis/india_information/hydropower.htm).

## Methods

In India the period June to September is defined as the SWM and the period October to December as the NEM, even though the period where bulk of the annual rain is received in any year can vary considerably (Krishnan et al., 2013). Moisture for the SWM and NEM originates from the adjacent oceans and seas and the entire country receives 88% of the annual total rainfall between June and November and almost all extreme rain events, including cyclonic storms, are confined to this period. December rainfall is often dominated by non-monsoonal precipitation pattern based on moisture originating outside the Asian region, driven by the Westerlies (Winstanley, 1973). We used spatially explicit time-varying models to understand the dynamic influence of ENSO and IOD on rainfall during the SWM and NEM and annual counts of intense rain events (IREs) from 1951 to 2007. The same approach was used to understand the influence of ENSO on annual mean temperature from 1961 to 2015.

### *Data*

We used the NINO4 (average SST over 160°E to 150°W and 5°S to 5°N), an ENSO index based on the Extended Reconstructed SST dataset (ERSSTv3). Studies have shown this region to have a stronger teleconnection with the SWM, based on which, this index was chosen (Kumar et al., 2006). The sign of the index was reversed to give a positive correlation with the SWM rainfall. Positive values correspond to La Nina, which is associated with higher SWM rainfall. The IOD index is the difference in anomalies in sea surface temperature (SST) between the western (50°E to 70°E and 10°S to 10°N) and eastern (90°E to 110°E and 10°S to 0°S) tropical Indian Ocean (Saji et al., 1999). The indices were defined for the period June–Septmeber, October–December, and annually and are based on the ERSSTv3 dataset. The indices were obtained from http://iridl.ldeo.columbia.edu/.

For the period 1951–2007, we used the freely available daily gridded APHRODITE rainfall dataset (http://aphrodite.st.hirosaki-u.ac.jp/download/), the only long-term, continent scale, high resolution daily product, which is now being used to determine changes in Asian monsoon precipitation (Yatagai et al., 2012). This dataset is based on a superior spherically based interpolation procedure

(Willmott et al., 1985) and has a well described quality control protocol (Yatagai et al., 2012). Intense Rain Events (IRE) for each year was computed as the number of days for which rainfall for a given grid cell exceeded the 90$^{th}$ percentile rainfall per day. Number of rainy days for each monsoonal season was defined as days where the rainfall was 2.5 mm/day or more (IMD). To analyse the trends in temperature for the period 1961–2015 we used the freely available daily mean temperature 0.25° gridded product (http://aphrodite.st.hirosaki-u.ac.jp/download/) (Yasutomi et al., 2011).

### *Analysis*

A spatially explicit version of dynamic models was used to analyse rainfall-La Nina/IOD relationships for each grid cell. For every APHRODITE grid cell, we constructed the time-series of the SWM and NEM rainfall totals, square-root of the annual counts of IRE, and the square-root of the number of rainy days along with the corresponding average NINO4 and IOD index values for the same period. In these models the regression parameters, the time-varying intercept or level ($\beta 0_t$), and the regression slopes ($\beta 1_t$,$\beta 2_t$) change with time for every APHRODITE grid cell.

The dynamic regression of monsoon totals and IRE counts against the covariates for each grid for the period 1951–2007 yielded 57 time-varying intercepts and slopes. Finally, we estimated the Sen slope, a robust measure of monotonic trend (Sen, 1968), for the original time-series as well as time-varying intercept and the regression slopes for La Nina and IOD. P-values were estimated to map areas with significant ($p < 0.1$) monotonic trends.

The models we fitted were:

$$Rainfall_t = \beta 0_t + \beta 1_t LaNina_t + \beta 2_t IOD_t + e_t,$$

where Rainfall$_t$ is the SWM and NEM rainfall totals in each year, $\beta 0_t$ is the time-varying intercept or level, $\beta 1_t$,$\beta 2_t$ are the regression slopes which change with time, and $e_t$ is the time-varying error.

$$\text{Square-root } [CountsRainyDays_t] = \beta 0_t + \beta 1_t LaNina_t + \beta 2_t IOD_t + e_t,$$

where square-root of annual counts of rainy days is the number of rainy days during SWM and NEM in each year.

$$\text{Square-root } [CountsIRE_t] = \beta 0_t + \beta 1_t LaNina_t + \beta 2_t IOD_t + e_t,$$

where square-root of annual counts of IRE was the response variable.

$$Temperature_t = \beta 0_t + \beta 1_t ENSO_t + e_t,$$

where the annual mean temperature was the response variable and the untransformed ENSO index was used as the explanatory variable.

## Results

Averaged across the NBR, there is a significant decline (-41.5 mm/decade) in the SWM rainfall totals (Fig. 2a; $p < 0.001$) for the period 1950–2007. A significant decline in the number of rainy days (-5 days/decade) during the SWM was observed for the same time period, and the decline is more pronounced since the 1970s (Fig. 2b; $p < 0.05$). We found a strong positive influence of La Nina on the SWM rainfall totals. However, it has been declining in recent decades (Fig. 3a). Similarly, IOD's influence on the SWM rainfall totals has been declining over the years (Fig. 3b). We found a decline in the influence of both La Nina and IOD on IREs, however, the influence of La Nina remained positive (Figs. 3e-f).

The rainfall totals and number of rainy days during the NEM showed a non-significant increase (3.06 mm/decade) across the NBR (Figs. 2c&d; $p > 0.9$ and $p > 0.6$, respectively). Furthermore, the annual frequency of IREs in the NBR showed a declining trend (Fig. 2e; $p < 0.01$; -16 events/decade). The annual mean temperature for the period 1961–2015 showed a significant increase in the NBR (Fig. 2f; $p < 0.001$; 0.16 °C/decade). We found a positive influence of La Nina on the NEM rainfall totals, especially since the 1990s (Fig. 3c), while a decline in the IOD's influence on the NEM rainfall totals was observed since the 1990s (Fig. 3d).

Unlike the spatially averaged trends, which indicated declining rainfall trends, the spatially explicit trends in rainfall totals after accounting for the changing influence of La Nina and IOD showed areas with increasing and decreasing rainfall. The spatially explicit results suggest that wetter regions have been getting drier and drier regions have been witnessing an increase in rainfall over time. Nearly 53.6% of the NBR has declining trends and only 14.3% of the biosphere reserve is witnessing an increase in the SWM rainfall (Fig. 4a, Table 1). Major declines in the SWM rainfall totals was noticed in the western part of the NBR covering Nagarhole, Bandipur, Waynad, Mudumalai, and parts of the Nilgiris. On the other hand, the eastern part of the biosphere reserve around Satyamangalam Tiger Reserve experienced a slight increase in the SWM rainfall totals. A declining trend in the number of rainy days during the SWM was noted in the southwest part (32.1%) of the NBR, while an increase of 25% was noted in the eastern part (Fig. 4b, Table 1).

Areas showing declines in the SWM rainfall totals were associated with areas where the influence of La Nina was decreasing, and areas with increase in rainfall totals were associated with regions where the influence of both La Nina and IOD were increasing. For the same season, the number of rainy days was seen to increase where IOD's influence was increasing. Further, some parts on the southeast region of the study area showed coherence with increasing influence of La Nina (Fig. 5).

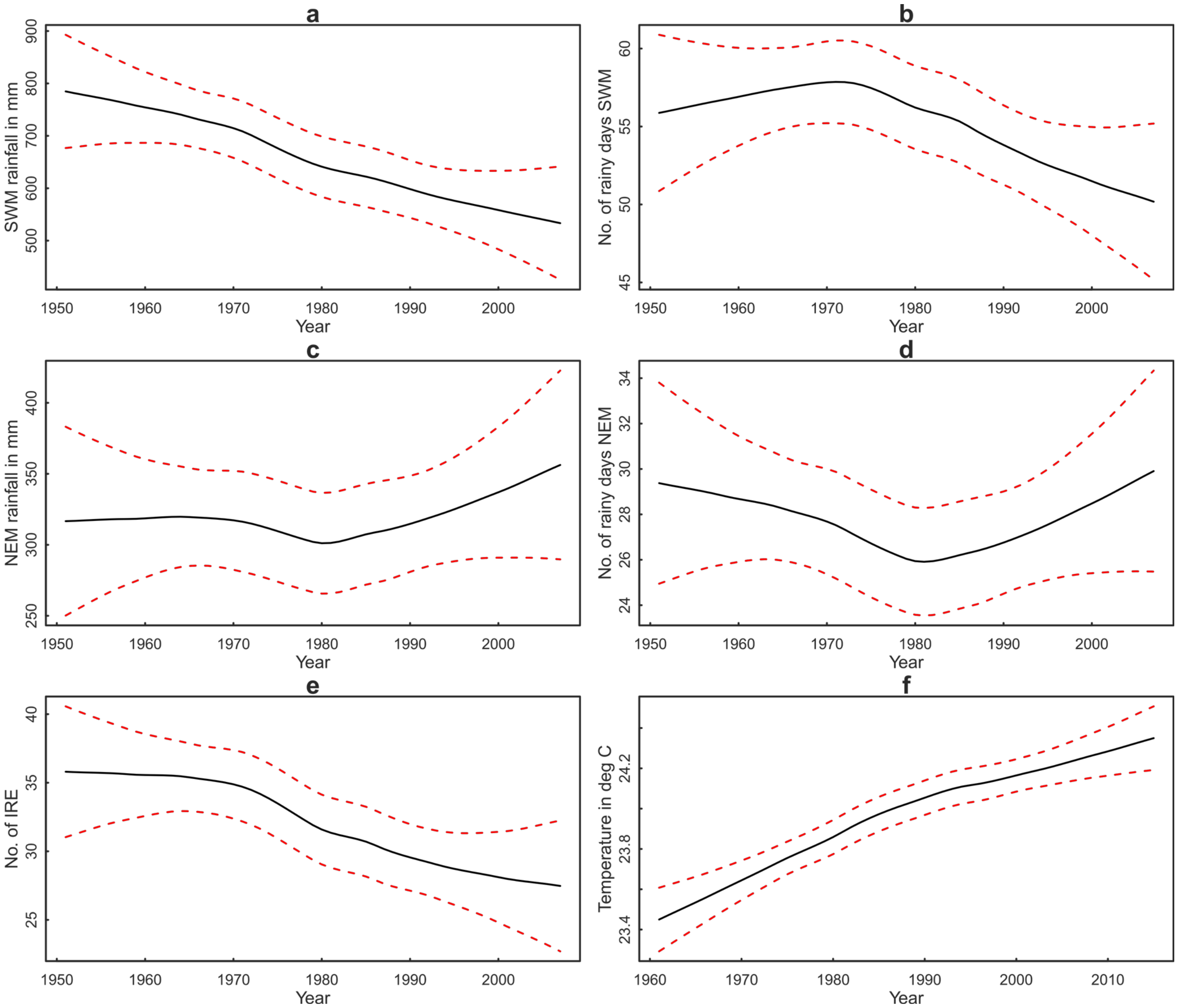


*Figure 2: Spatially averaged trends in rainfall and temperate in the Nilgiri Biosphere Reserve a) declining trend in the South West Monsoon (SWM) rainfall totals; b) declining trend in the number of rainy days during the SWM; c) increasing trend in the North East Monsoon (NEM) rainfall totals in recent decades; d) trend in the number of rainy days during the NEM; e) declines in intense rainfall events; f) increasing trend in the annual mean temperature.*

In the case of the NEM, large parts of the NBR (~89%) showed no significant change in rainfall totals and 10.7% of the area showed an increasing trend in the rainfall totals around the western and southern boundaries (Fig. 4c, Table 1). The number of rainy days during the NEM increased in 17.9% of the landscape and 10.7% of the reserve showed a decline (Fig. 4d, Table 1). Spatially explicit trends in La Nina and IOD did not match either the spatial trends in NEM rainfall totals or the decline in the number of rainy days. Increase in the number of rainy days was associated with a decrease in the influence of IOD (Fig. 5). This is contrary to what is known about the role of IOD on the NEM rainfall totals.

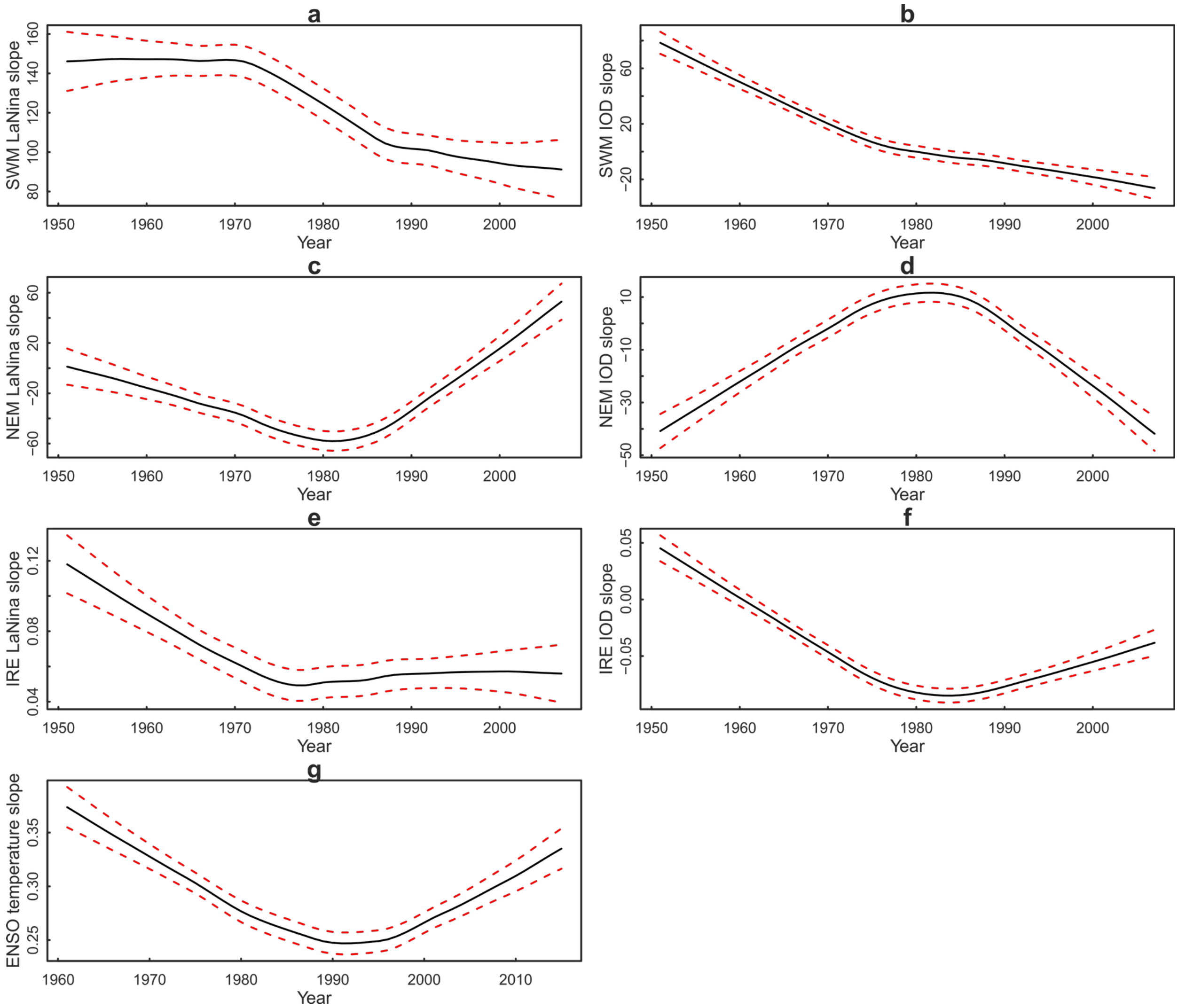


*Figure 3: The time-varying slope of rainfall/temperature-teleconnections: (a) La Nina had a strong positive influence on the South West Monsoon (SWM) rainfall totals. However, this influence has been declining in recent decades; (b) Influence of the Indian Ocean Dipole (IOD) on SWM rainfall totals witnessed a declining trend; (c) La Nina had a positive influence on NEM rainfall totals, especially since the 1990s; (d) IOD's influence on NEM rainfall totals witnessed a declining trend since the 1990s; (e-f) The influence of La Nina and IOD on intense rain events showed a decline, however, the influence of La Nina remained positive; (g) El Nino Southern Oscillation (ENSO) had a strong positive influence on the annual mean temperature; although this influence declined until 1990, it increased thereafter.*

The spatially explicit trend in IREs was found to be declining in nearly half (53.6%) of the NBR and a small fraction of the landscape showed an increasing trend (Fig. 4e, Table 1). Areas witnessing a decline in IREs were associated with an increasing influence of La Nina.

All areas of the NBR showed an increase in the annual mean temperature (Figs. 2f, 4f, Table 1). We found a strong positive influence of ENSO on the annual mean temperature. This influence showed a declining trend from 1960 to1990s, and an increasing trend in more recent decades (Fig. 3g).

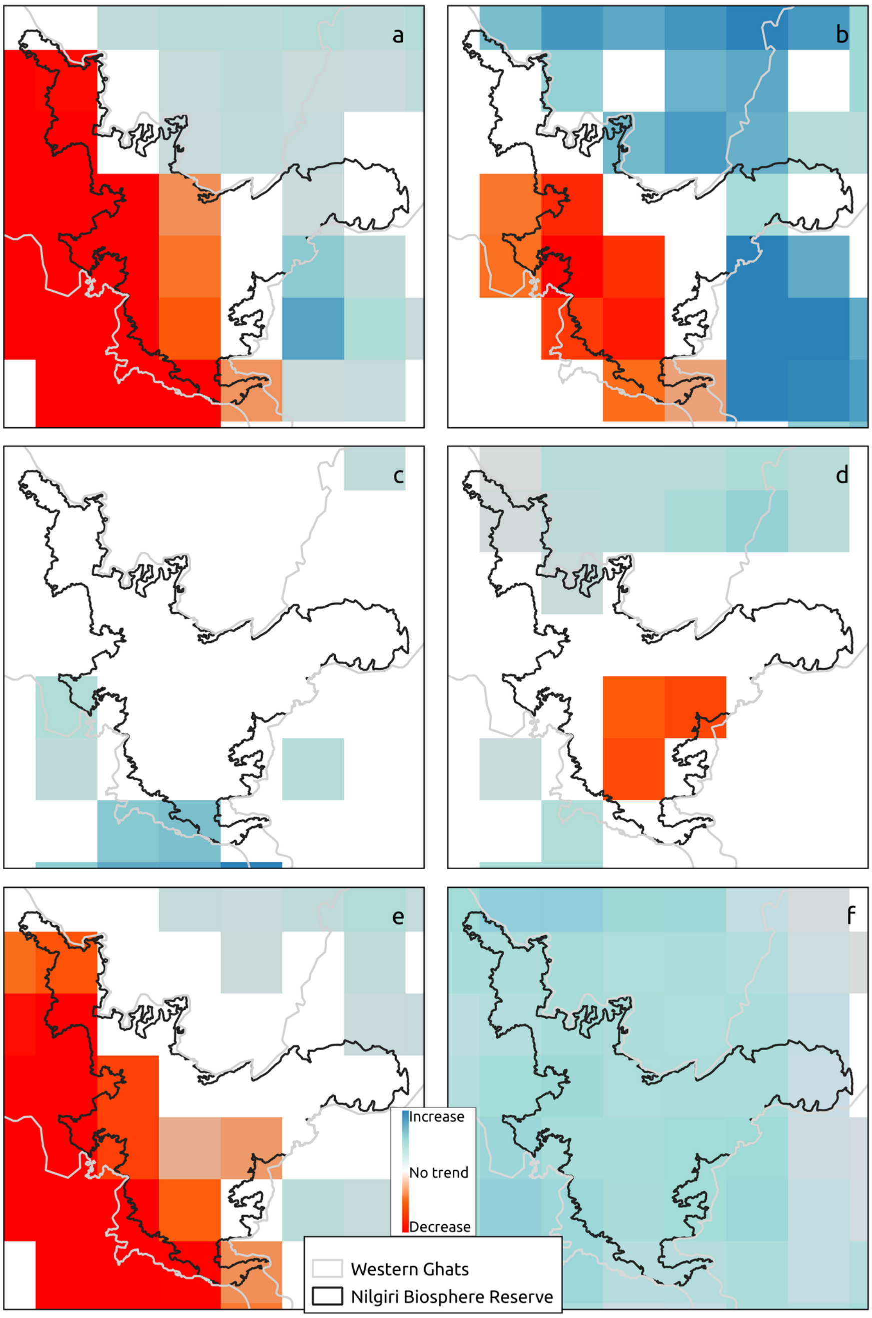


*Figure 4: Spatially explicit trends of the time-varying intercept from dynamic regression model with La Nina and Indian Ocean Dipole (IOD) as covariates and the South West Monsoon (SWM) annual total rainfall, North East Monosoon (NEM) annual total rainfall, and annual mean temperature as response variables in the Nilgiri Biosphere Reserve (NBR): (a) Nearly 53.6% of the NBR showed a significant decline in the annual SWM rainfall while only 14.3% of the area showed an increase; (b) a decline in the number of rainy days during SWM was observed in 32.1% of the NBR while there was an increase in 25% of the landscape; (c) Large parts of the NBR (~89%) showed no significant change in the NEM rainfall totals. Only 10.7% of the NBR showed an increasing trend in the NEM rainfall totals around the western and southern boundaries; (d) The number of rainy days during the NEM increased in 17.9% of the landscape and 10.7% of the reserve showed a decline; (e) Intense rain events declined in nearly half (53.6%) of the NBR; (f) trend of time-varying intercept from dynamic regression model with La Nina as covariates and annual mean temperature as response variable showed an increase in temperature throughout the landscape.*

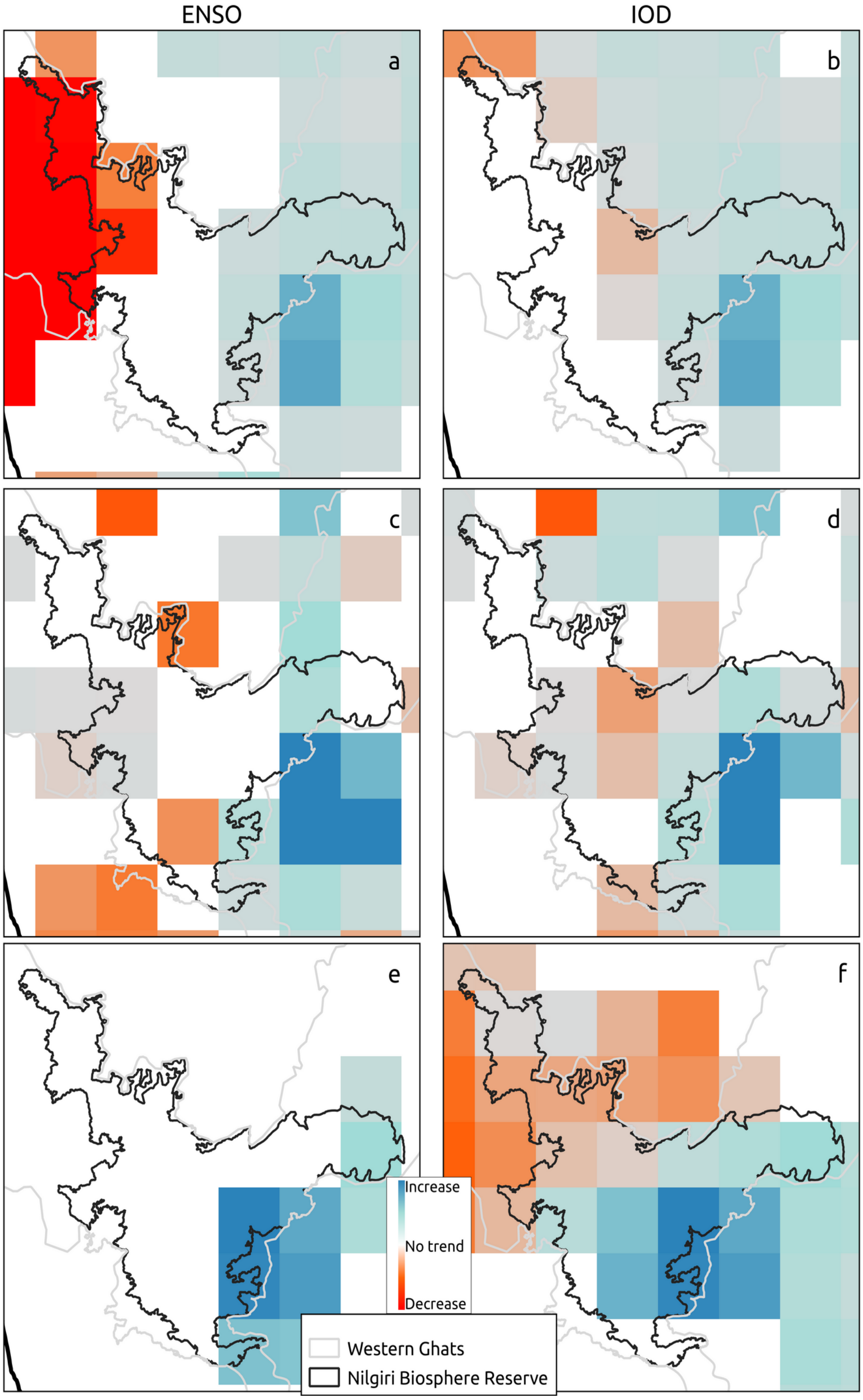


*Figure 5.1: Spatially explicit trends of the time-varying slopes from dynamic regression models showed the relationship between the response variable and La Nina and Indian Ocean Dipole (IOD) in the Nilgiri Biosphere Reserve (NBR): The influence of (a) La Nina on the South West Monsoon (SWM) rainfall increased in 28.6% and decreased in 32.1% of the NBR, (b) IOD on the SWM rainfall increased in 32.1% and decreased in 17.9% of the NBR, (c) La Nina on the number of rainy days during the SWM increased in 28.6% and decreased in 17.9% of the NBR, (d) IOD on the number of rainy days during the SWM increased in 39.3% and decreased in 17.9% of the NBR, (e) La Nina on the North East Monsoon (NEM) rainfall increased in 21.4% and decreased in 0% of the NBR, (f) IOD on the NEM rainfall increased in 35.7% and decreased in 46.4% of the NBR.*

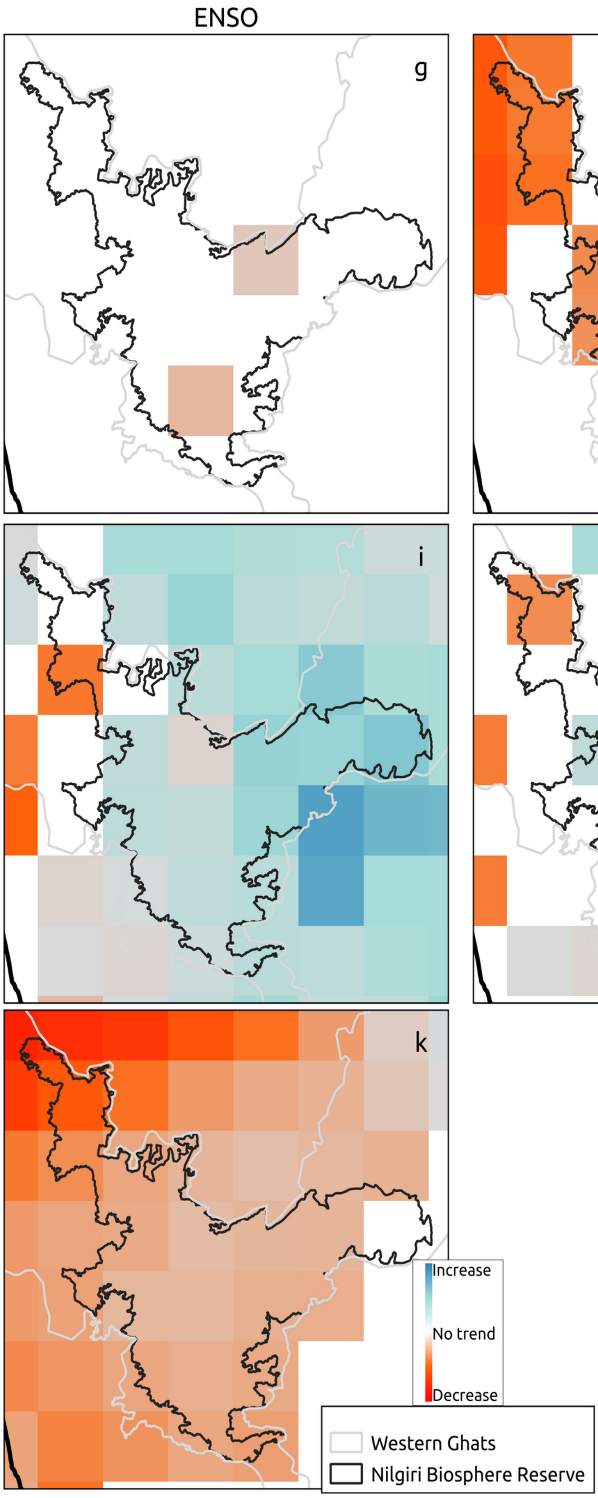

*Figure 5.2: Spatially explicit trends of the time-varying slopes from dynamic regression models showed the relationship between the response variable and La Nina and Indian Ocean Dipole (IOD) in the Nilgiri Biosphere Reserve (NBR): The influence of (g) La Nina on the number of rainy days during the North East Monsoon (NEM) increased in 0% and decreased in 7.1% of the NBR, (h) IOD on the number of rainy days during the NEM increased in 0% and decreased in 46.4% of the NBR, (i) La Nina on the number of intense rain events increased in 67.9% and decreased in 10.7% of the NBR, (j) IOD on the number of intense rain events increased in 28.6% and decreased in 7.1% of the NBR, (k) El Nino Southern Oscillation (ENSO) on the annual mean temperature increased in 2.4% and decreased in 49.6% of the NBR.*

*Table 1: Percentage of the Nilgiri Biosphere Reserve witnessing significant trends in rainfall and temperature. SWM, South West Monsoon; NEM, North East Monsoon; IRE, Intense rainfall events*

| | Increasing trend | Declining trend |
|---|---|---|
| SWM annual rainfall total | 14.3% | 53.6% |
| No. of rainy days SWM | 25.0% | 32.1% |
| NEM annual rainfall total | 10.7% | 0.0% |
| No. of rainy days NEM | 17.9% | 10.7% |
| IRE | 3.6% | 53.6% |
| Annual mean temperature | 100.0% | 0.0% |

## Discussion

Understanding emerging trends and drivers of rainfall and temperature is important for managing the natural wealth and is useful to stakeholders who depend on ecosystem services that are provided by forested landscapes. We studied spatial variabilities and long-term trends in rainfall and temperature and the dynamic influence of ENSO and IOD on these trends in the NBR. We found a decreasing trend in the SWM rainfall total and a reduction in the number of rainy days during the SWM. On the other hand, there was an increase in the NEM rainfall total and a corresponding increase in the number of rainy days during the NEM in the study area. Further, a reduction in the number of IREs was observed. The spatially explicit trends suggested a reduction in rainfall in the wetter parts and an increase in the drier parts of the landscape. We found La Nina and IOD to influence the number of rainy days and rainfall totals during SWM in NBR. The mean annual temperature in NBR witnessed a significant increase.

The spatially averaged trends suggested an overall decrease in SWM—the annual SWM rainfall totals decreased by a magnitude of 41.5 mm/decade. A recent study in the Western Ghats suggests a decline in rainfall by 100 mm–250 mm over the past 100 years in this landscape (Ramachandra & Bharath, 2020) and attributed this decline to increased deforestation rates. Varikoden et al. (2019) also showed that rainfall has been declining in the Western Ghats, including the NBR and the region south of the NBR, and attributed this decline to the northward movement of low-level jet (LLJ) stream from 10°N to 15°N. This shift in the LLJ is triggered by an abnormal increase in the surface temperature of the northern Arabian Sea and the tropospheric temperature in north India in the recent decades (Varikoden et al., 2019).

In our study, we found that the larger teleconnections have greater influence on the SWM total rainfall and the number of rainy days. The declining trend in SWM rainfall is attributed to the declining influence of La Nina and IOD (Fig. 3). The spatially explicit analysis of rainfall trends suggested a decrease in SWM in 53.6% of the NBR landscape while an increase was noticed in 14.3% of the area. This decline in rainfall was mainly associated with a declining influence of La Nina, whereas, the increasing trend was associated with the increasing influence of both La Nina and IOD (Fig. 3).

Our study revealed a greater reduction in the number of rainy days which declined by 5 days/decade during the SWM in the landscape. Other studies also suggest similar declines in the number of rainy days in the NBR region (Guhathakurta et al., 2011; Ramachandra & Bharath, 2020). Spatially explicit analysis suggests a decline in the number of rainy days during SWM in 32.1% of the study area while there was an increase in 25% of the landscape over the years. The number of rainy days during the SWM showed an increase where IOD's influence was increasing. Our results suggest that the influence of ENSO is more prominent on rainfall in the NBR compared to the influence of IOD. This result is in contrast to findings from other studies that suggest a more prominent influence of IOD over ENSO on the Indian monsoon for the rest of the country in recent years (Ashok et al., 2001, 2004; Ashok & Saji, 2007; Ashrit et al., 2001; Ihara et al., 2008; Izumo et al., 2010; Krishnaswamy et al., 2015; Kumar et al., 1999; Ummenhofer et al., 2011). Our findings emphasise the need for regional rainfall and forecast models.

Our results showed a non-significant increase in the NEM rainfall totals (3.06 mm/decade) across the NBR, especially since the 1980s. This is attributed to the increasing influence of La Nina and a declining influence of IOD around the same time period. This is consistent with earlier studies which have shown a significant positive correlation with ENSO and a weaker relationship between the IOD and the NEM rainfall totals (Geethalakshmi et al., 2009). Similar seasonal variations in the influence of ENSO and IOD on rainfall have been observed in other parts of the world (King et al., 2014; Risbey et al., 2009).

The spatially explicit analysis of rainfall trends suggested that 10% of the NBR landscape is witnessing an increase in rainfall totals during the NEM. However, there is no spatial correlation between trends in the NEM rainfall and trends in the influence of teleconnections. This suggests that other local and regional drivers also play a role in changing the rainfall regime in the NBR. Studies have suggested a greater influence of deforestation on rainfall and temperature changes in the Western Ghats (Ramachandra & Bharath, 2020).

Our results showed an increasing trend in the annual mean temperature in the NBR—the spatially aggregated results for the last five decades showed an increase of 0.16 °C/decade. ENSO has a positive influence on temperature. However, its influence has witnessed a decline from 1960s to 1990s and an increase since the 1990s (Fig. 3g). The spatially explicit results showed that the entire NBR has witnessed an increase in temperature, which is in line with climate predictions made for the area (Collins et al., 2013). However, the influence of ENSO on the annual mean temperature has declined in a large part of the NBR, suggesting that there are other drivers contributing to the increase in temperature. Other studies have shown that the temperatures have increased between 0.25 °C and 0.5 °C in a century in and around the NBR and attribute the observed increase to LULC changes (Ramachandra & Bharath, 2020).

Rainfall in India and the associated high intensity rain events are largely confined within the period June to November and are governed by the SWM and NEM, each with their spatially coherent signatures (Kripalani & Kumar, 2004). Both these Monsoons have distinct, complex, and evolving relationship with the two main ocean-atmosphere phenomena, the ENSO and IOD (Ashok et al., 2004; Saji et al., 1999). La Nina, the positive phase of ENSO, is often beneficial for the SWM, especially in the latter half (Gill et al., 2015; Xavier et al., 2007). Positive IOD helps mitigate the negative effects of El Nino on the Indian Monsoon and is linked to extreme rain events in non-El Nino years (Ashok et al., 2004). The NEM, which is most active in October and November, is usually retarded by La Nina, and has a weaker link with the IOD (Geethalakshmi et al., 2009; Kripalani et al., 2003; Kripalani & Kumar, 2004). However there is concern that warming of oceans and atmospheres may be changing the spatial and temporal influence of these phenomena in complex ways (Krishnaswamy et al., 2015; Roxy et al., 2015). Potential changes to ENSO resulting from climate change may have far reaching impacts through atmospheric teleconnections. Future simulations showed that while more land may be affected by ENSO, with respect to rainfall and temperature, the existing teleconnections may not be simply strengthened. Rainfall in India has been declining since the 1950s, even as intense rains have become more frequent (Bollasina et al., 2011; Goswami et al., 2006; Krishnan et al., 2013). These processes are linked to global warming, teleconnections such as La Nina and IOD, and warming of the Indian Ocean relative to the land (Ashok et al., 2004; Cherchi & Navarra, 2013; Kumar et al., 1999; Roxy et al., 2015; Saji et al., 1999; Turner & Annamalai, 2012). They are also linked to a second set of drivers including aerosols and land-use change (Bollasina et al., 2011; Douglas et al., 2006; Kishtawal et al., 2010). There is increasing concern in India on the damage from variability of rainfall and its extremes (Ghosh et al., 2012; Singh et al., 2014).

Like in other regions in India, the changing influence of these teleconnection on rainfall in the NBR has major implications for agriculture and cropping patterns, management of reservoirs, and also for the functioning and maintenance of natural ecosystems (Antonelli et al., 2018; Sintayehu, 2018; Traill et al., 2010). However, historical trends for rainfall seem to contradict global climate predictions for rainfall, which indicate wetter conditions that could lead to greening with warming in the future (Collins et al., 2013). Hence, development of regional climate models that consider historical trends in climate and regional drivers of climate variabilities is of immediate need. Our study provides critical information on areas that have witnessed transformations due to climate variability. Understanding climatic trends in the recent past in the NBR is of high importance as palaeoenvironmental history, since the last glacial maximum, indicate that three different contrasting trajectories of rainfall and temperature led to the expansion of forests and grassland in the Nilgiris (Caner et al., 2007). Historical climatic trends coupled with land use changes will not only help in understanding how forests and their ecosystem services in this biosphere reserve have fared in the recent past, but will also help understand future trajectories under different climate change scenarios.

## References

Antonelli, A., Kissling, W. D., Flantua, S. G. A., Bermúdez, M. A., Mulch, A., Muellner-Riehl, A. N., Kreft, H., Linder, H. P., Badgley, C., Fjeldså, J., Fritz, S. A., Rahbek, C., Herman, F., Hooghiemstra, H., & Hoorn, C. (2018). Geological and climatic influences on mountain biodiversity. *Nature Geoscience*, *11*(10), 718–725. https://doi.org/10.1038/s41561-018-0236-z

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., & Yamagata, T. (2007). El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research*, *112*(C11), C11007.

Ashok, K., Guan, Z., Saji, N. H., & Yamagata, T. (2004). Individual and combined influences of ENSO and the Indian Ocean dipole on the Indian summer monsoon. *Journal of Climate*, *17*(16), 3141–3155.

Ashok, K., Guan, Z., & Yamagata, T. (2001). Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophysical Research Letters*, *28*(23), 4499–4502.

Ashok, K., & Saji, N. H. (2007). On the impacts of ENSO and Indian Ocean dipole events on sub-regional Indian summer monsoon rainfall. *Natural Hazards*, *42*(2), 273–285. https://doi.org/10.1007/s11069-006-9091-0

Ashrit, R. G., Kumar, K. R., & Kumar, K. K. (2001). ENSO-monsoon relationships in a greenhouse warming scenario. *Geophysical Research Letters*, *28*(9), 1727–1730.

Bollasina, M. A., Ming, Y., & Ramaswamy, V. (2011). Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *Science*, *334*(6055), 502–505.

Caner, L., Seen, D. L., Gunnell, Y., Ramesh, B. R., & Bourgeon, G. (2007). Spatial heterogeneity of land cover response to climatic change in the Nilgiri highlands (Southern India) since the last glacial maximum. *The Holocene*, *17*(2), 195–205. https://doi.org/10.1177/0959683607075833

Cherchi, A., & Navarra, A. (2013). Influence of ENSO and of the Indian Ocean Dipole on the Indian summer monsoon variability. *Climate Dynamics*, *41*(1), 81–103. https://doi.org/10.1007/s00382-012-1602-y

Chiang, J. C. H., & Sobel, A. H. (2002). Tropical Tropospheric Temperature Variations Caused by ENSO and Their Influence on the Remote Tropical Climate. *Journal of Climate*, *15*(18), 2616–2631. https://doi.org/10.1175/1520-0442(2002)015<2616:TTTVCB>2.0.CO;2

Clinton, N., Yu, L., Fu, H., He, C., & Gong, P. (2014). Global-scale associations of vegetation phenology with rainfall and temperature at a high spatio-temporal resolution. *Remote Sensing*, *6*(8), 7320–7338. https://doi.org/10.3390/rs6087320

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., Wehner, M. F., Allen, M. R., Andrews, T., Beyerle, U., Bitz, C. M., Bony, S., & Booth, B. B. B. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013 - The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.*, 1029–1136.

Daniels, R. J. R. (1996). *The Nilgiri Biosphere reserve: A review of conservation status with recommendations for a holistic approach to management, India*.

Daniels, R. J. R. (2001). Endemic fishes of the Western Ghats and the Satpura hypothesis. *Current Science*, *81*(3), 240–244.

Donat, M. G., Peterson, T. C., Brunet, M., King, A. D., Almazroui, M., Kolli, R. K., Boucherf, D., Al-Mulla, A. Y., Nour, A. Y., Aly, A. A., Nada, T. A. A., Semawi, M. M., Dashti, H. A. A., Salhab, T. G., Fadli, K. I. E., Muftah, M. K., Eida, S. D., Badi, W., Driouech, F., … Shekaili, M. N. A. (2014). Changes in extreme temperature and precipitation in the Arab region: Long-term trends and variability related to ENSO and NAO. *International Journal of Climatology*, *34*(3), 581–592. https://doi.org/10.1002/joc.3707

Douglas, E. M., Niyogi, D., Frolking, S., Yeluripati, J. B., Pielke, R. A., Niyogi, N., Vörösmarty, C. J., & Mohanty, U. C. (2006). Changes in moisture and energy fluxes due to agricultural land use and irrigation in the Indian Monsoon Belt. *Geophysical Research Letters*, *33*(14). https://doi.org/10.1029/2006GL026550

Endris, H. S., Lennard, C., Hewitson, B., Dosio, A., Nikulin, G., & Artan, G. A. (2019). Future changes in rainfall associated with ENSO, IOD and changes in the mean state over Eastern Africa. *Climate Dynamics*, *52*(3), 2029–2053. https://doi.org/10.1007/s00382-018-4239-7

Geethalakshmi, V., Yatagai, A., Palanisamy, K., & Umetsu, C. (2009). Impact of ENSO and the Indian Ocean Dipole on the north-east monsoon rainfall of Tamil Nadu State in India. *Hydrological Processes*, *23*(4), 633–647. https://doi.org/10.1002/hyp.7191

Ghosh, S., Das, D., Kao, S.-C., & Ganguly, A. R. (2012). Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes. *Nature Climate Change*, *2*(2), 86–91. https://doi.org/10.1038/nclimate1327

Gill, E. C., Rajagopalan, B., & Molnar, P. H. (2015). Sub-Seasonal Variations in Spatial Signatures of ENSO on the Indian Summer Monsoon from 1901-2009. *Journal of Geophysical Research: Atmospheres*, 2015JD023184. https://doi.org/10.1002/2015JD023184

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science*, *314*(5804), 1442–1445.

Guhathakurta, P., & Rajeevan, M. (2008). Trends in the rainfall pattern over India. *International Journal of Climatology*, *28*(11), 1453–1469.

Guhathakurta, P., Sreejith, O., & Menon, P. A. (2011). Impact of climate change on extreme rainfall events and flood risk in India. *Journal of Earth System Science*, *120*(3), 359–373. https://doi.org/10.1007/s12040-011-0082-5

Heisler-White, J. L., Blair, J. M., Kelly, E. F., Harmoney, K., & Knapp, A. K. (2009). Contingent productivity responses to more extreme rainfall regimes across a grassland biome. *Global Change Biology*, *15*(12), 2894–2904. https://doi.org/10.1111/j.1365-2486.2009.01961.x

Hrudya, P. H., Varikoden, H., & Vishnu, R. (2021). A review on the Indian summer monsoon rainfall, variability and its association with ENSO and IOD. *Meteorology and Atmospheric Physics*, *133*(1), 1–14. https://doi.org/10.1007/s00703-020-00734-5

Ihara, C., Kushnir, Y., Cane, M. A., & Kaplan, A. (2008). Timing of El Niño–Related Warming and Indian Summer Monsoon Rainfall. *Journal of Climate*, *21*(11), 2711–2719. https://doi.org/10.1175/2007JCLI1979.1

Izumo, T., de Boyer Montegut, C., Luo, J.-J., Behera, S. K., Masson, S., & Yamagata, T. (2010). *Role of the Somalia-Oman upwelling and ENSO on Indian monsoon rainfall variability*. 11448. https://ui.adsabs.harvard.edu/abs/2010EGUGA..1211448I

Johnsingh, A. (2001). The Kalakad-Mundanthurai Tiger Reserve: A global heritage of biological diversity. *Current Science, 80*(3), 378–388.

Joshi, P. P., Murthy, I. K., Hegde, G. T., Sathyanarayan, V., Bhat, S., Patil, V., Esteves, T., & Ravindranath, N. H. (2018). Biophysical quantification of biodiversity and ecosystems services of forest ecosystems in the Western Ghats: A case study of Uttara Kannada District, India. *Journal of Forestry Research, 29*(3), 735–748. https://doi.org/10.1007/s11676-017-0488-2

King, A. D., Klingaman, N. P., Alexander, L. V., Donat, M. G., Jourdain, N. C., & Maher, P. (2014). Extreme Rainfall Variability in Australia: Patterns, Drivers, and Predictability. *Journal of Climate*, *27*(15), 6035–6050. https://doi.org/10.1175/JCLI-D-13-00715.1

Kishtawal, C. M., Niyogi, D., Tewari, M., Pielke Sr, R. A., & Shepherd, J. M. (2010). Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology, 30*(13), 1908–1916.

Kodandapani, N., Cochrane, M. A., & Sukumar, R. (2004). Conservation Threat of Increasing Fire Frequencies in the Western Ghats, India. *Conservation Biology*, *18*(6), 1553–1561. https://doi.org/10.1111/j.1523-1739.2004.00433.x

Kripalani, R. H., & Kumar, P. (2004). Northeast monsoon rainfall variability over south peninsular India vis-à-vis the Indian Ocean dipole mode. *International Journal of Climatology, 24*(10), 1267–1282.

Krishnan, R., Sabin, T. P., Ayantika, D. C., Kitoh, A., Sugi, M., Murakami, H., Turner, A. G., Slingo, J. M., & Rajendran, K. (2013). Will the South Asian monsoon overturning circulation stabilize any further? *Climate Dynamics*, *40*(1), 187–211. https://doi.org/10.1007/s00382-012-1317-0

Krishnaswamy, J., Vaidyanathan, S., Rajagopalan, B., Bonell, M., Sankaran, M., Bhalla, R. S., & Badiger, S. (2015). Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. *Climate Dynamics*, *45*(1), 175–184. https://doi.org/10.1007/s00382-014-2288-0

Kumar, K. K., Kamala, K., Rajagopalan, B., Hoerling, MartinP., Eischeid, JonK., Patwardhan, S. K., Srinivasan, G., Goswami, B. N., & Nemani, R. (2011). The once and future pulse of Indian monsoonal climate. *Climate Dynamics*, *36*(11–12), 2159–2170. https://doi.org/10.1007/s00382-010-0974-0

Kumar, K. K., Rajagopalan, B., & Cane, M. A. (1999). On the Weakening Relationship Between the Indian Monsoon and ENSO. *Science*, *284*(5423), 2156–2159. https://doi.org/10.1126/science.284.5423.2156

Meyers, G., & Cai, W. (2011). Understanding feedback mechanisms of the Indo-Pacific Ocean climate system. *Eos, Transactions American Geophysical Union*, *92*(31), 260–260. https://doi.org/10.1029/2011EO310004

Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., & Gascon, C. (2011). Global Biodiversity Conservation: The Critical Role of Hotspots. In F. E. Zachos & J. C. Habel (Eds.), *Biodiversity Hotspots: Distribution and Protection of Conservation Priority Areas* (pp. 3–22). Springer. https://doi.org/10.1007/978-3-642-20992-5_1

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858. https://doi.org/10.1038/35002501

Nair, N. C., & Daniel, P. (1986). floristic diversity of the Western Ghats and its conservation: A review. *Proceedings. Animal Sciences - Indian Academy of Sciences*. https://agris.fao.org/agris-search/search.do?recordID=US201301429491

Nair, S. S. C., Nair, P. V., Sharatchandra, H. C., & Gadgil, M. (1977). An ecological reconnaissance of the proposed Jawahar National Park India. *The Journal of the Bombay Natural History Society*, *74*, 401–435.

Osland, M. J., Enwright, N. M., Day, R. H., Gabler, C. A., Stagg, C. L., & Grace, J. B. (2016). Beyond just sea-level rise: Considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. *Global Change Biology*, *22*(1), 1–11. https://doi.org/10.1111/gcb.13084

Paul, S., Ghosh, S., Oglesby, R., Pathak, A., Chandrasekharan, A., & Ramsankaran, R. (2016). Weakening of Indian Summer Monsoon Rainfall due to Changes in Land Use Land Cover. *Scientific Reports*, *6*(1), 32177. https://doi.org/10.1038/srep32177

Pillai, P. A., Ramu, D. A., & Nair, R. C. (2021). Recent changes in the major modes of Asian summer monsoon rainfall: Influence of ENSO-IOD relationship. *Theoretical and Applied Climatology*, *143*(3), 869–881. https://doi.org/10.1007/s00704-020-03454-3

Prasad, A. E. (2012). Landscape-scale relationships between the exotic invasive shrub Lantana camara and native plants in a tropical deciduous forest in southern India. *Journal of Tropical Ecology*, *28*(1), 55–64. https://doi.org/10.1017/S0266467411000563

Rajput, N., Baranidharan, D. K., Vijayabhama, D. M., & Sawant, A. (2019). Ecological impact of Prosopis juliflora on the habitat conditions of blackbuck in Sathyamangalam tiger reserve, Tamil Nadu, India. *Journal of Entomology and Zoology Studies*, 6.

Ramachandra, T. V., & Bharath, S. (2020). Carbon Sequestration Potential of the Forest Ecosystems in the Western Ghats, a Global Biodiversity Hotspot. *Natural Resources Research*, *29*(4), 2753–2771. https://doi.org/10.1007/s11053-019-09588-0

Ramaswami, G., & Sukumar, R. (2013). Long-Term Environmental Correlates of Invasion by Lantana camara (Verbenaceae) in a Seasonally Dry Tropical Forest. *PLOS ONE*, *8*(10), e76995. https://doi.org/10.1371/journal.pone.0076995

Risbey, J. S., Pook, M. J., McIntosh, P. C., Wheeler, M. C., & Hendon, H. H. (2009). On the Remote Drivers of Rainfall Variability in Australia. *Monthly Weather Review*, *137*(10), 3233–3253. https://doi.org/10.1175/2009MWR2861.1

Roxy, M. K., Ritika, K., Terray, P., Murtugudde, R., Ashok, K., & Goswami, B. N. (2015). Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nature Communications*, *6*(1), 7423. https://doi.org/10.1038/ncomms8423

Roy, I., & Collins, M. (2015). On identifying the role of Sun and the El Niño Southern Oscillation on Indian Summer Monsoon Rainfall. *Atmospheric Science Letters*, *16*(2), 162–169. https://doi.org/10.1002/asl2.547

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature*, *401*(6751), 360–363. https://doi.org/10.1038/43854

Singh, D., Tsiang, M., Rajaratnam, B., & Diffenbaugh, N. S. (2014). Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nature Clim. Change*, *4*(6), 456–461.

Sintayehu, D. W. (2018). Impact of climate change on biodiversity and associated key ecosystem services in Africa: A systematic review. *Ecosystem Health and Sustainability*, *4*(9), 225–239. https://doi.org/10.1080/20964129.2018.1530054

Sivakumar, K., Rawat, G. S., Badola, R., Adhikari, B. S., & Kamalakannan, B. (2018). *Study on ecological and socio-economic impact of invasive species, Prosopis juliflora and Lantana camara, and their removal from forest, common and fallow land of Tamil Nadu.* [Technical Report]. Wildlife Institute of India.

Traill, L. W., Lim, M. L. M., Sodhi, N. S., & Bradshaw, C. J. A. (2010). Mechanisms driving change: Altered species interactions and ecosystem function through global warming. *Journal of Animal Ecology*, *79*(5), 937–947. https://doi.org/10.1111/j.1365-2656.2010.01695.x

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Clim. Change*, *2*(8), 587–595. https://doi.org/10.1038/nclimate1495

Ummenhofer, C. C., Gupta, A. S., Li, Y., Taschetto, A. S., & England, M. H. (2011). Multi-decadal modulation of the El Niño–Indian monsoon relationship by Indian Ocean variability. *Environmental Research Letters*, *6*(3), 034006. https://doi.org/10.1088/1748-9326/6/3/034006

Varikoden, H., Revadekar, J. V., Kuttippurath, J., & Babu, C. A. (2019). Contrasting trends in southwest monsoon rainfall over the Western Ghats region of India. *Climate Dynamics*, *52*(7), 4557–4566. https://doi.org/10.1007/s00382-018-4397-7

Willmott, C. J., Rowe, C. M., & Philpot, W. D. (1985). Small-Scale Climate Maps: A Sensitivity Analysis of Some Common Assumptions Associated with Grid-Point Interpolation and Contouring. *The American Cartographer*, *12*(1), 5–16. https://doi.org/10.1559/152304085783914686

Winstanley, D. (1973). Recent Rainfall Trends in Africa, the Middle East and India. *Nature*, *243*(5408), 464–465. https://doi.org/10.1038/243464a0

Wu, R., Yang, S., Liu, S., Sun, L., Lian, Y., & Gao, Z. (2010). Changes in the relationship between Northeast China summer temperature and ENSO. *Journal of Geophysical Research: Atmospheres*, *115*(D21). https://doi.org/10.1029/2010JD014422

Xavier, P. K., Marzin, C., & Goswami, B. N. (2007). An objective definition of the Indian summer monsoon season and a new perspective on the ENSO–monsoon relationship. *Quarterly Journal of the Royal Meteorological Society*, *133*(624), 749–764. https://doi.org/10.1002/qj.45

Yasutomi, N., Hamada, A., & Yatagai, A. (2011). Development of a long-term daily gridded temperature dataset and its application to rain/snow discrimination of daily precipitation. *Global Environ. Res*, *15*, 165–172.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., & Kitoh, A. (2012). APHRODITE: Constructing a Long-Term Daily Gridded Precipitation Dataset for Asia Based on a Dense Network of Rain Gauges. *Bulletin of the American Meteorological Society*, *93*(9), 1401–1415. https://doi.org/10.1175/BAMS-D-11-00122.1

# Declining trend in Annual Net Primary Productivity and its response to water stress

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## Highlights

- 84% of the NBR experienced a decrease in the Annual Net Primary Productivity (ANPP) due water stress, with evergreen and deciduous forests experiencing a decline up to 90%.
- Areas of the NBR at altitudes higher than 1000 m experienced the highest decline in ANPP.
- Majority of the landscape showed a transition from increasing to declining trend in ANPP from 2008 onwards.
- The magnitude of ANPP–water stress index was weak suggesting that water stress alone might not be a significant driver of productivity in the NBR.
- The influence of water stress on ANPP showed an increasing positive trend in the drier low-altitude forest types, like dry deciduous forests and savannas, over the past two decades.

## Abstract

Tropical forests have the highest net primary productivity constituting a major carbon sink in the Earth's biosphere. Increase in atmospheric temperature and variation in precipitation due to climate change can impose constraints on the productivity of tropical forests. Increase in temperature induces higher water saturation levels in the atmosphere leading to higher evapotranspiration stress in plants. Furthermore, higher variation in precipitation can extend the dry season causing water stress in plants. In the recent decades, Nilgiri Biosphere Reserve (NBR) has been experiencing a decrease in the number of rainy days and a prolonged dry season. Hence, it is important to understand productivity–water stress relationships to predict future trends in the vegetation productivity in the NBR. We studied spatial and temporal trends and the relationship between the annual net primary productivity (ANPP) and water stress, as defined by the Standard Precipitation–Evapotranspiration Index (SPEI), an index of water stress, using dynamic linear models. The positive values of SPEI depict higher plant available water, whereas negative values depict water deficit and lower plant available water. Overall, 34% of the NBR experienced a decline in ANPP and this decline increased to 84% after accounting for the effects of water stress. In evergreen,

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moist deciduous, and dry deciduous forests, the ANPP declined in over 90% of the area. The ANPP increased during the period 2001–2007, but declined drastically after 2008, resulting in an overall decline in the ANPP over the period 2001–2019. The magnitude of the ANPP–water stress index was weak suggesting that water stress alone might not be a significant driver of productivity in the NBR. We found high temporal variation in the influence of water stress across land use land cover and altitudinal zones—ANPP continued to decline in drier low altitude regions, which experienced a positive and increasing trend in plant available water. Whereas, ANPP in the wetter higher altitude regions experienced a negative and declining sensitivity to the SPEI. This further suggests that the drier regions, in addition to water stress are vulnerable to other local stressors which are affecting ANPP.

## Introduction

Tropical forests contain 25% of the global terrestrial biosphere's carbon with 33% of the terrestrial net primary production (Bonan, 2008). In the current scenario of climate change, increased atmospheric $CO_2$ concentrations can increase the photosynthetic capability of plants. This process can accelerate the growth rate of plants, sequestering the atmospheric $CO_2$ to the terrestrial biosphere and thus reducing the $CO_2$ concentrations in the atmosphere (Cernusak et al., 2013). This negative feedback in the atmosphere–biosphere interactions is highly influenced by the tropical forests as they have the highest net primary productivity compared to all other forest and land use types (Bonan, 2008; Malhi et al., 2000). However, tropical forests are sensitive to environmental conditions like temperature and plant available water (Phillips et al., 2009; Sullivan et al., 2020). How future climate change will affect net primary productivity and the corresponding carbon sequestration in tropical forests remains uncertain (Cox et al., 2000).

Tropical forests are influenced by global monsoon patterns. Global monsoons are predicted to increase in its mean and variability over the Southeast Asian region and these monsoonal dynamics are strongly correlated to increasing temperatures (Chen et al., 2020; Loo et al., 2015). However, future climate change scenarios predict that the evapotranspiration demand will be higher than precipitation, suggesting an increase in temperature without equivalent increase in precipitation (Kao & Ganguly, 2011). Hence, future climate will be warmer and will have variable precipitation, which indicates that plants will experience a higher evapotranspiration demand. The rate of increase in temperature and associated environmental stresses can be greater than the global average in higher elevation regions, as these regions have been experiencing a high rate of increase in temperatures over the past few decades (Rangwala & Miller, 2012). A comprehensive examination of current trends and relationships of net primary productivity with climate variables in tropical forests can provide crucial insights about their primary production rate and the dynamics of tropical biomass carbon stocks and its persistence.

The sensitivity of tropical forests to inter- and intra-annual fluctuations in climate depends on the physiology of the trees at the species level. Plants acclimatize to warming climatic conditions by increasing their net photosynthesis through reduction in respiration rates (Ow et al., 2008; Wang et al., 2020). The ability of plants to persistently recalibrate their physiological optima to the surrounding environment can be a major determinant of tropical biomass carbon. Additionally, changes in demographic rates and shifts in the species richness play an important role in determining long term vegetation productivity (Brown et al., 1997; Fauset et al., 2012). Tropical forests are distributed over steep elevation gradients, which adds to the variation in their response to environmental fluctuations. Accounting for the spatial and temporal variations in the net primary productivity to abiotic conditions—mainly, temperature and water stress—can improve the prediction of carbon stocks in the tropical regions for different future climate change scenarios.

There is growing evidence of a higher influence of temperature induced water stress on photosynthetic activity and productivity (Kumarathunge et al., 2020). The role of warming-induced drought stress is evident in recent studies that have analysed drought impacts on net primary production and tree mortality (Linares & Camarero, 2012; Martinez-Vilalta et al., 2008; McGuire et al., 2010; A. P. Williams et al., 2011). Empirical studies have demonstrated that higher temperatures increase drought stress and enhance forest mortality under precipitation shortages (Adams et al., 2009). Climate change models predict an increase in temperature and it has consequences for drought like conditions, with an increase in water demand due to evapotranspiration. Thus, this depicts a negative co-variation between temperature and plant available water at regional scales (Mantgem et al., 2009; C. A. Williams et al., 2012). Examining the sensitivity of the annual net primary productivity (ANPP) to water stress, which includes temperature data in their formulation, would provide a simple, yet holistic understanding of the vegetation–climate interactions for tropical regions. In India, the tropical forest areas in the Nilgiri Biosphere Reserve (NBR) has been identified as one of the vulnerable regions for climate change (Ravindranath et al., 2006). This region has been experiencing a consistent decline in precipitation and an increase in temperature over the past few decades (Refer Fig. 2 on page 9). These climatic conditions can induce water stress conditions but their effect on vegetation can be scale dependent (Fatichi et al., 2016). Examining the current trends and relationships between primary productivity and water stress at an annual scale can help in understanding the sensitivity of the NBR to climate change. In this study, we assessed the long term spatial and temporal trends of ANPP and its sensitivity to water stress in different land uses and across elevation gradients in the NBR.

## Methods

### *Vegetation Carbon*

We used MOD17A3HGF Version 6 Annual Net Primary Productivity data for the time period of 2001–2019 at a spatial resolution of 500 m. Using the quality control layer supplied along with the ANPP data, pixels with low or no cloud cover were considered good quality pixels and selected for further analysis, which accounted for 90% of the pixels within NBR.

### *Water Stress*

We calculated the Standard Precipitation–Evapotranspiration Index (SPEI) as an indicator of water stress (Vicente-Serrano et al., 2010). SPEI is the difference between precipitation and potential evapotranspiration (PET). The SPEI combines the sensitivity of Palmer Drought Severity Index to changes in evaporation demands caused by temperature fluctuations and trends. It is simple to calculate and possess the multi-temporal nature of the Standardised Precipitation Index (Vicente-Serrano et al., 2010), a widely used precipitation based drought index. We used Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for calculating the monthly precipitation. MODIS MOD16A2 Version 6 product was used to derive the monthly PET (See Annexure I for steps followed to preprocess the PET dataset). The monthly time series of precipitation and PET data were used to calculate the annual SPEI using the R package ‘spei’. The positive values of SPEI depict water excess (higher plant available water), whereas negative values depict water deficit (lower plant available water).

### *Data analysis*

The spatially explicit temporal relationship between the ANPP and SPEI was evaluated using a dynamic linear model (DLM) at the pixel level. The trend analysis on the time-varying intercepts indicates the increase or decrease in the ANPP due to water stress. Similarly, the trend in time-varying slope values from DLM indicate the change in sensitivity of the ANPP to water stress. A Sen’s slope analysis (Sen, 1968) was used to determine significant monotonic trends. Additionally, we conducted a segmented regression on the time-varying intercept values. The significant breakpoint year and the temporal trend in the ANPP intercept values before and after the breakpoint were noted (See Annexure II for details).

The time-varying slope from the DLM was examined for different forest types/land uses along an elevation gradient. The NBR was classified into four altitudinal zones: < 450 m, 450 m–900 m, 900 m–1500 m, and > 1500 m. The median values of the time-varying slopes was calculated for different land uses and examined to understand the relationship over different altitudinal zones. Further, the distribution of the Sen's slope of the time-varying slope was examined for each altitudinal zones in every land use category. This analysis would help understand the variation in the strength and direction of sensitivity of the ANPP with water stress in different land uses and altitudinal zones.

To derive an overall understanding about the influence of water stress in determining the annual primary productivity across the NBR, the trends in the time-varying intercept and slope values were evaluated for altitudinal bins of 200 m.

Generally, ANPP is hypothesized to have a positive relationship with SPEI, as water stress directly inhibits the photosynthetic capacity of plants. Since the positive values of SPEI depict higher plant available water, a positive relationship of ANPP with SPEI was hypothesized at a regional scale.

## Results

The total ANPP in the NBR from 2001 to 2019 varied between 0.251 GtC/ha/y – 0.354 GtC/ha/y. Of this, on an average, the evergreen forests (1.29 ± 0.17 $kgC/m^2/y$) showed the highest ANPP followed by moist deciduous forests (1.23 ± 0.23 $kgC/m^2/y$) and dry deciduous forests (1.00 ± 0.18 $kgC/m^2/y$) (Fig. 1). The majority of the region did not show any significant change in the ANPP (63.81%), while the rest of the region showed a negative trend (34.17%). Large parts (96%) of the landscape remained stable with respect to trends in SPEI.

The results from the DLM showed that nearly 90% of the NBR has witnessed a decline in the ANPP (Fig. 2). This was seen across all land use types and was due to the influence of water stress. The average rate at which the ANPP declined across vegetation types was -3.2 $gC/m^2/y$ for the period 2001–2019.

Evergreen, moist deciduous, and dry deciduous forests showed a decline in the ANPP in over 90% of their area. Overall, 84% of the NBR experienced a decline in the ANPP after accounting for the long term effect of SPEI.

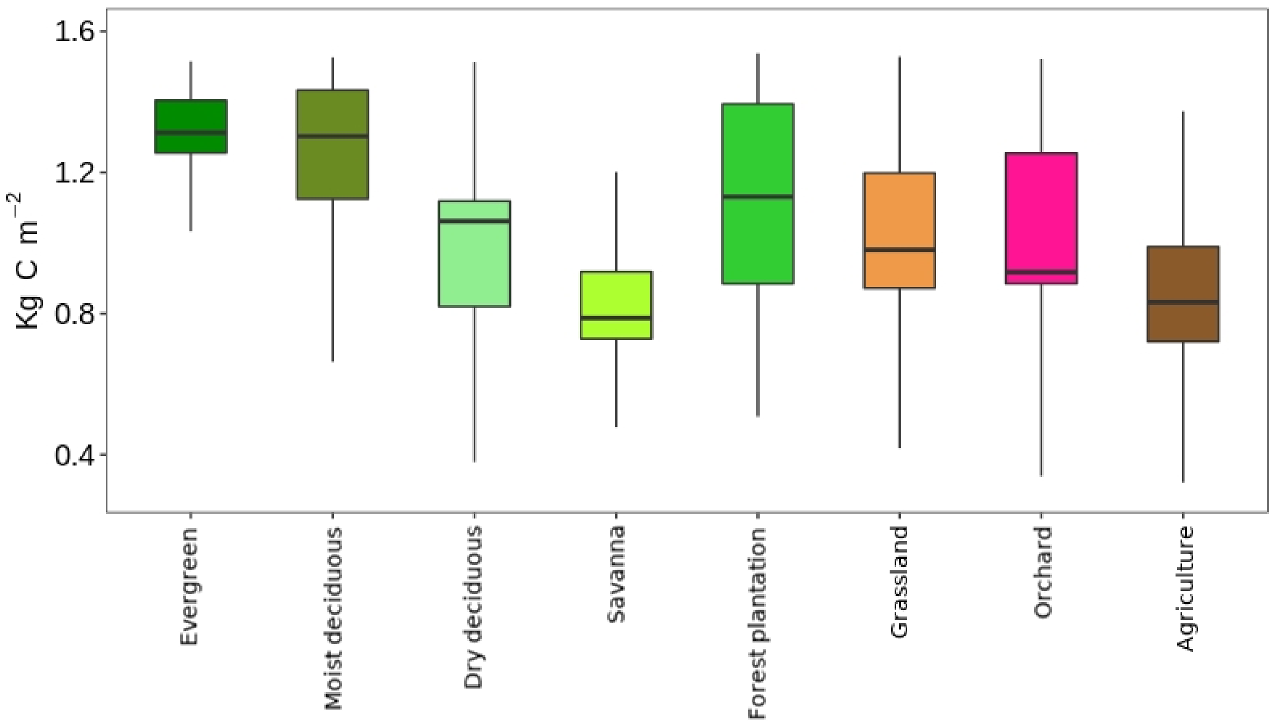


*Figure 1: Spatial variation in the ANPP in different land uses. Evergreen and moist deciduous forests showed the highest ANPP. Forest plantations, orchards, and agriculture, which were supplied with additional water and nutrients by humans, showed high variation in ANPP.*

The monotonic trends of the time-varying slopes showed a positive relationship between ANPP and SPEI in 36.5% of the NBR, while a negative relationship was seen in 27.47% of the landscape.

Across different land use land cover categories, dry deciduous (48.3%) and savannas (61.3%) showed relatively higher percentage of area where SPEI had a positive linear influence on ANPP. Contrastingly, evergreen (20.5%) and moist deciduous forests (14.4%) showed very low percentage of area with positive relationship between ANPP and SPEI (Table 1).

The segmented regression analysis showed that the majority of the region experienced a transition in the ANPP in the period 2008–2012 (Fig. 3a; Fig. 4). The analysis of the distribution of slope showed significant difference between the slope values before and after the breakpoint year. The NBR landscape experienced increased productivity before the break (Mean slope value: 0.002 ± 0.003). However, after the breakpoint, the mean slope values were negative (-0.008 ± 0.005), indicating that the ANPP had declined steeply in recent years (Fig. 3b).

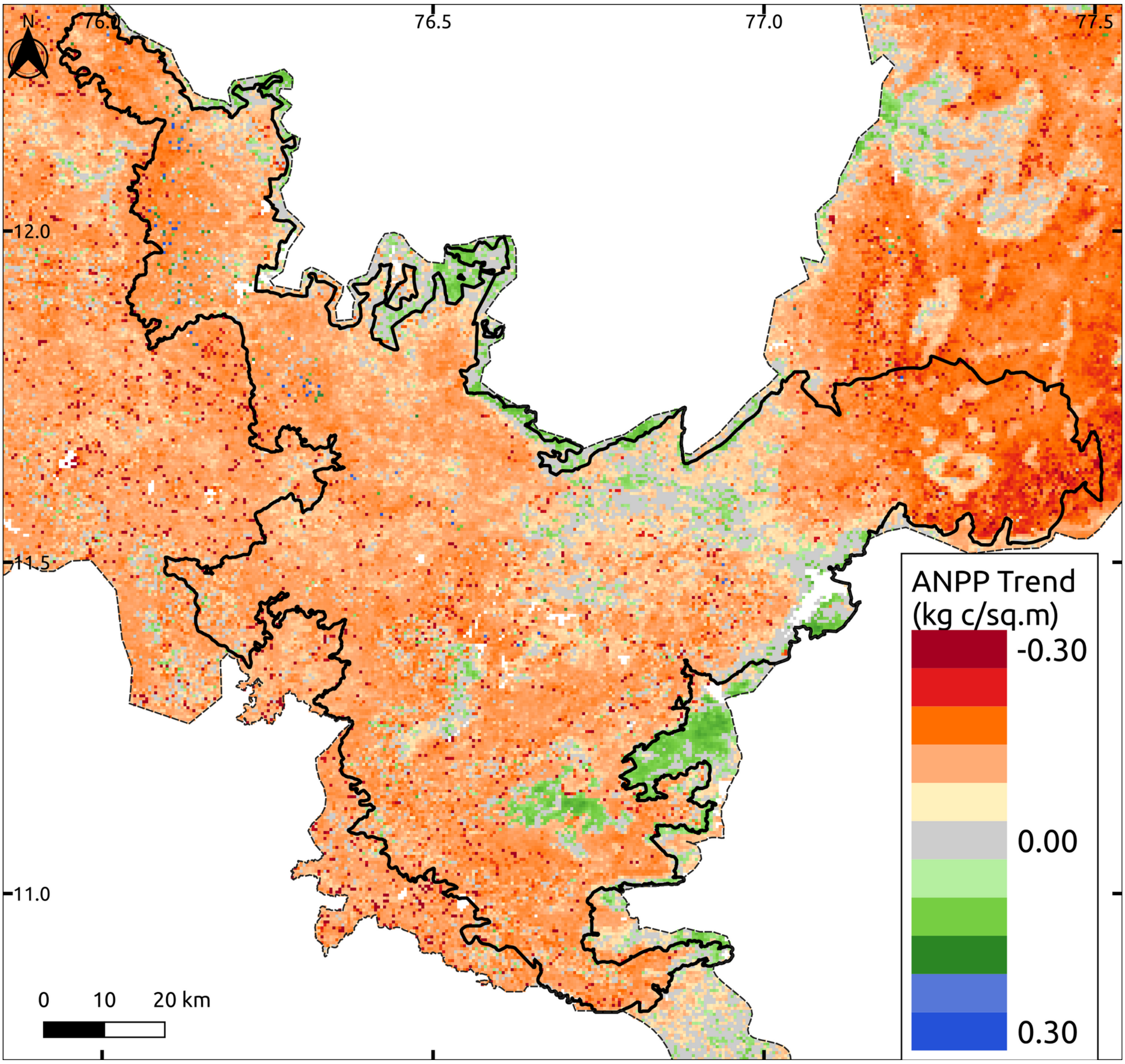

*Figure 2: The trend in the time-varying intercept values from the dynamic linear models shows that the majority of the region witnessed a significant decline in ANPP over the period 2001–2019 due to long term changes in SPEI.*

*Table 1: The time-varying intercept from the linear models suggest the increase or decrease in the annual net primary productivity (ANPP) due to water stress (using the Standard Precipitation–Evapotranspiration Index (SPEI)) in NBR. Similarly, the time-varying slope values of the linear models indicate changes in the sensitivity of the ANPP to water stress. The first two columns give the percentage of area showing an increase or a decrease in the ANPP due to water stress in the different land use types in the Nilgiri Biosphere Reserve (NBR). The last two columns gives the percentage of area showing an increase or a decrease in the sensitivity of ANPP to water stress across different land use types in the NBR.*

| **Landuse** | $\widehat{ANPP}$ | | **ANPP~SPEI** | |
|---|---|---|---|---|
| | **%Decrease** | **%Increase** | **%Decrease** | **%Increase** |
| Evergreen | 89.45 | 2.31 | 44.22 | 20.48 |
| Moist Deciduous | 94.30 | 1.78 | 43.90 | 14.37 |
| Dry Deciduous | 90.70 | 2.44 | 17.05 | 48.31 |
| Savanna | 67.06 | 11.24 | 5.99 | 61.34 |
| Plantation | 94.35 | 2.44 | 50.70 | 19.46 |
| Grassland | 81.33 | 5.00 | 42.41 | 25.38 |
| Orchard | 96.67 | 0.70 | 45.57 | 15.75 |
| Agriculture | 68.99 | 13.82 | 26.64 | 36.31 |

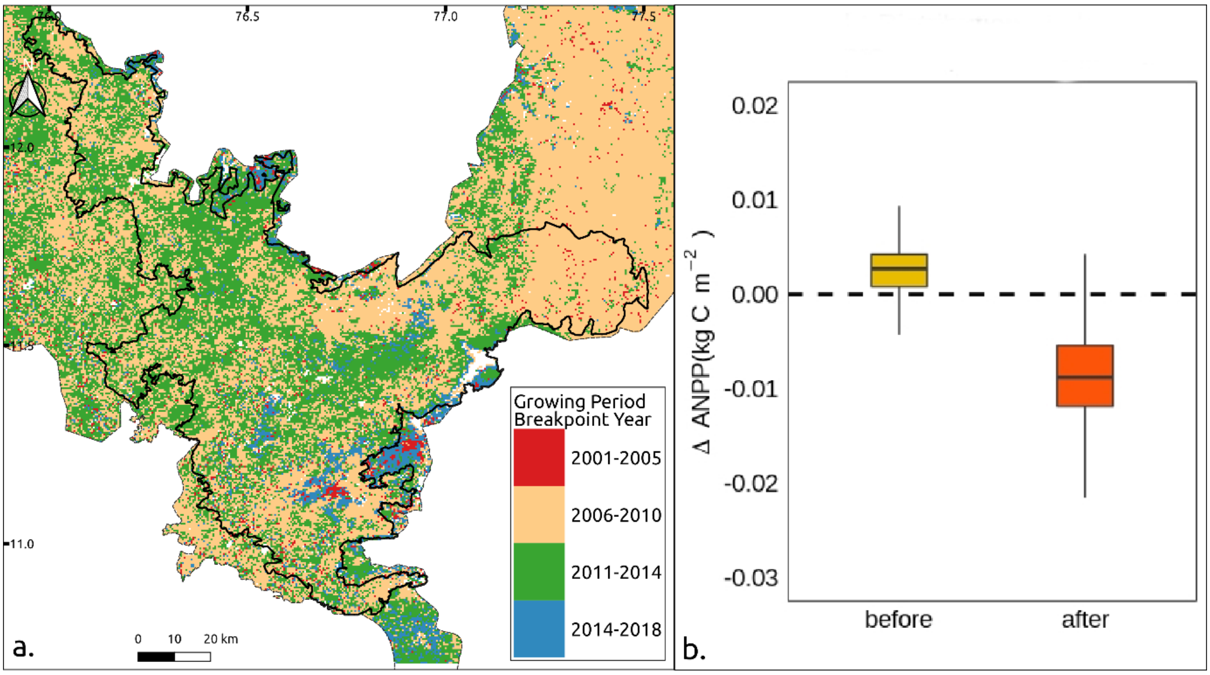


*Figure 3: Segmented regression analysis of the time-varying intercept values from the dynamic linear model analysis. a) Distribution of the breakpoint year in the NBR suggests that the majority of the region experienced a transition in the ANPP in the period 2006–2014; b) Distribution of slope values before and after the breakpoint suggests that the ANPP has decreased significantly in the recent years.*

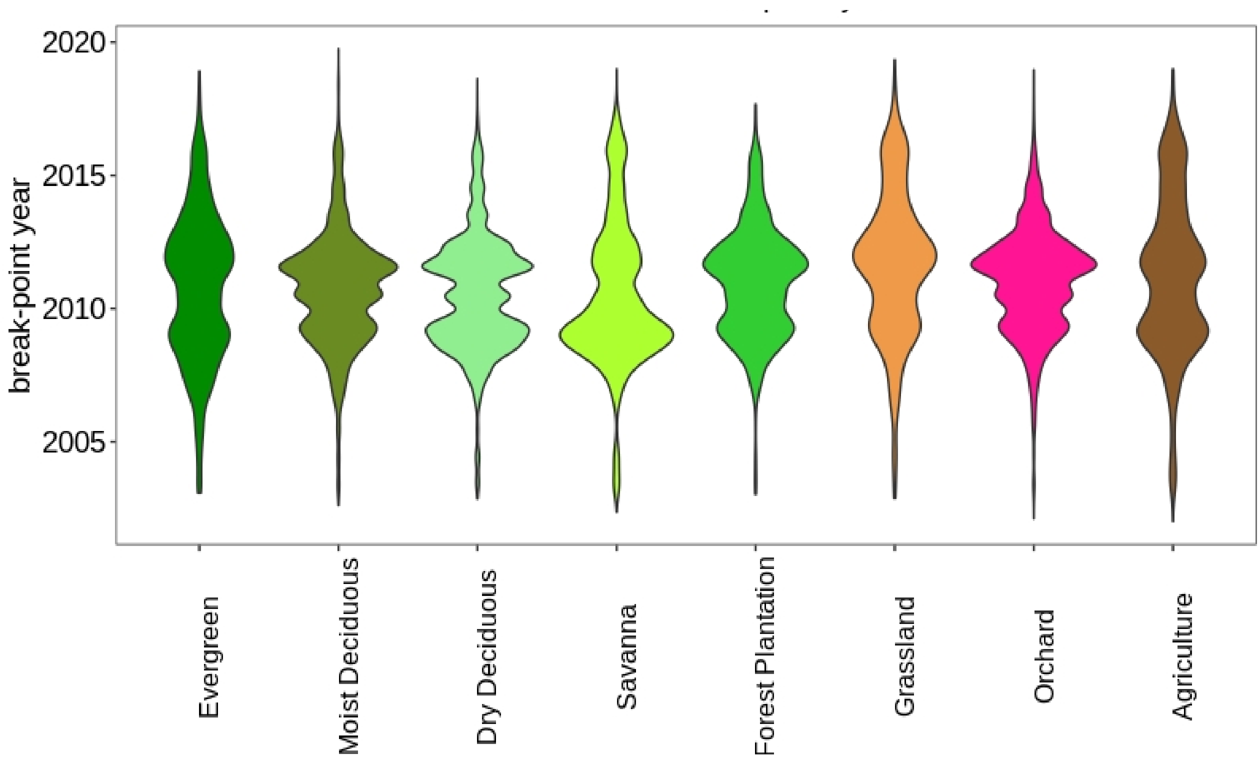

*Figure 4: The distribution of breakpoint year of the time-varying intercept has predominantly occurred between 2008 and 2012 for all land uses. The width of the violin plot depicts the distribution of the breakpoint year.*

The annual median of the time-varying slope, measuring the strength of the relationship of the ANPP to SPEI, varied across land uses and over different altitudinal zones (Fig. 5). Although a large parts of the NBR showed a declining trend in ANPP due to the water stress, the strength of this relationship was very weak (Fig. 5). The wettter forest types, evergreen and moist deciduous forests, showed a negative relationship between ANNP and SPEI, especially in the mid and high elevations of the NBR. On the other hand, the drier formatations, dry decidous forest and savannas, showed increasing sensitivity to SPEI in the 450 m–900 m elevation range. High elevation forest plantations, orchards, and grasslands showed a negative relationship between ANPP and the SPEI index. Agriculture, which was mainly distributed in the lower altitudes, showed an increasing sensitivity to SPEI. These results show that the temporal relationship between ANPP and SPEI varies over different land uses and elevation gradient.

Trends in the time-varying intercepts was consistently negative for all altitudes with the highest negative value for altitudes between 1000 m and 1600 m (Fig. 6a). The breakpoint analysis showed that the ANPP intercept was declining in the post break period (Fig. 4b) and hence, the variation in the median values of trends in the post break period was further analysed (Fig. 6b). The results showed a negative trend in the ANPP across all elevation ranges, but higher negative trends were found at elevations between 1000 m and 1600 m (Fig. 6b). There was also a weak altitudinal effect on the ANPP–SPEI relationship, which transitioned from a positive to a negative relationship along the elevation gradient (Fig. 6c).

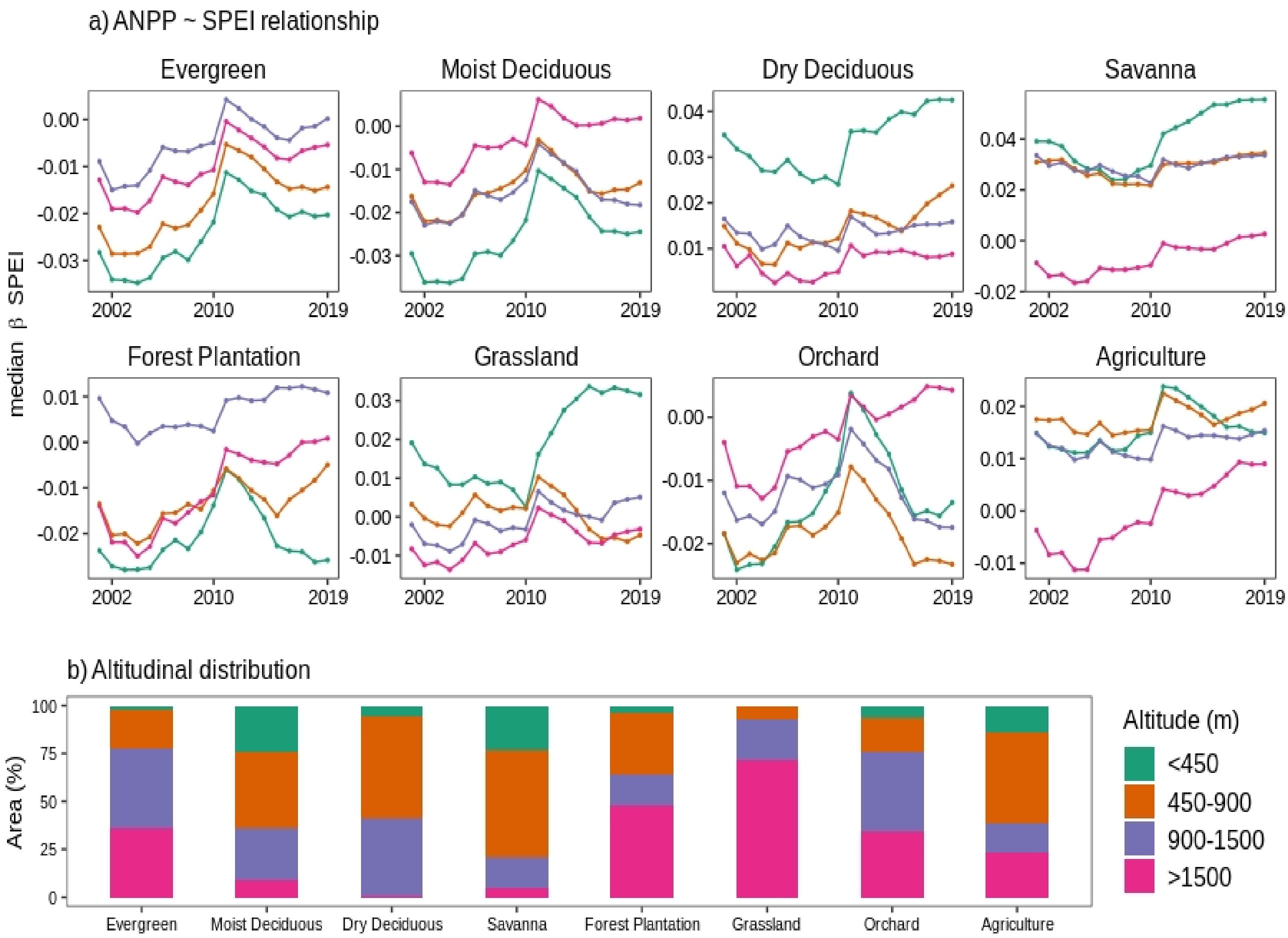


*Figure 5: Altitudinal variation in the time-varying relationship between ANPP and SPEI over different land uses. Slope values indicate the direction and magnitude of the sensitivity of ANPP to SPEI. a) Annual median slope values show a weak relationship along with high temporal variation in different land uses. Evergreen and moist deciduous forests show declining negative sensitivity whereas the dry deciduous and savannas show increasing positive sensitivity to water stress; b) Distribution of land uses in different altitudinal zones. Evergreen and moist deciduous forests, plantations, orchards, and grasslands are mainly present in the higher altitudes. Savanna and dry deciduous areas occur in the mid-altitude areas while agriculture is mainly seen in the low altitudes.*

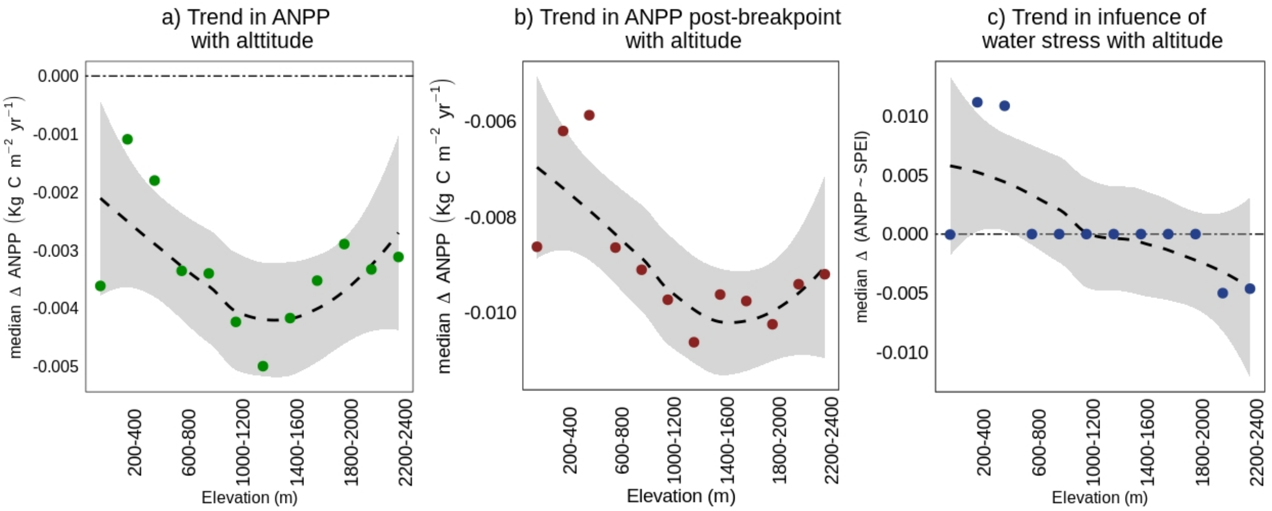


Figure 6: Variation in the temporal trends in the ANPP and ANPP–SPEI relationship along elevation gradient. a) Median Sen's slope for time-varying ANPP intercept is consistently negative for all altitudes with the highest negative value for altitudes *between* 1000 m–1600 m; b) Median slope value post breakpoint is consistently negative for all altitudes. Higher elevation ranges have greater negative slope values; c) Median Sen's slope for time-varying ANPP–SPEI relationship shows a *zero* slope except for mid-elevation range (800 m–2000 m), depicting a consistent and weak influence of SPEI over ANPP in most of the elevation ranges.

## Discussion

In this study, we evaluated the spatially explicit temporal trends and relationship between the net primary productivity and a water stress index (SPEI) at an annual scale for the time period 2001–2019. These relationships were examined for different land use land cover types along the elevation gradient. Physiologically, we expected a positive relationship between ANPP and SPEI as higher values of SPEI indicate water excess, which aids plant productivity. Nearly three-fourths of the landscape did not show any significant trends in the ANPP in the past two decades. Similarly, there were no discernable trends in the water stress index across the landscape (96%) for the same time period. However, the DLM model with covariates improved our predictive capability and indicated that nearly 90% of the NBR has been undergoing changes in the ANPP due to water stress, even when the strength of ANPP – SPEI relationship was very weak.

NBR experienced an increase in the ANPP in early 2000, but this trend transitioned to decline in the period 2008–2012. The relationship between ANPP and SPEI showed increasing positive association for the drier land cover types, like the dry deciduous forests and the savanna, which are mainly present at lower altitudes (< 900 m). However, this relationship was negative for wetter land cover types, like the evergreen and moist deciduous forests and high elevation grasslands and orchards, which moved towards a zero value (i.e., towards a lower influence of water stress on the ANPP) in more recent years.

The temporal trend of the time-varying intercept of the ANPP for the entire time period and post breakpoint years showed a consistent negative slope for all elevation ranges, with the highest negative slope for elevations between 1000 m and 1600 m indicating that the highest decline in the ANPP occurred at this elevation range. The temporal trend in the ANPP–SPEI relationship showed that the relationship was consistent in the majority of the elevation ranges, but only higher altitude regions were experiencing a decline in the influence of SPEI over ANPP.

Tropical forests show high sensitivity to extended dry periods (Phillips et al., 2009), but they also exhibit a non-linearity in their relationship to temperature and water availability (Sullivan et al., 2020). The decline in ANPP in the wetter land uses at higher elevations is associated with a negative relationship with the water stress index. However, dry deciduous forests and savannas and land uses, mainly distributed over lower elevations, showed a decline in the ANPP with increase in SPEI, which was contrary to our *apriori* hypothesis. Thus, our results clearly highlight how the influence of SPEI varies across elevation and different land uses. One of the main reasons for this high variation in response to water stress is due to the variation of hydraulic traits in different forest types (Anderegg, 2015; Anderegg et al., 2019). For example, evergreen forests follow isohydric strategies to maintain hydraulic balance to cope with water stress conditions (Fisher et al., 2006) and as the region experiences good precipitation and is relatively less water limited, the influence of water stress would be negligible. Hence, our results reinforce that water management strategies and hydraulic traits of plants can play an important role in determining the productivity response to environmental stresses.

The results also highlight that water stress might not be a limiting factor in this landscape as the strength of the ANPP–SPEI relationship is not very high. In addition to water stress, other local climatic factors and anthropogenic influences might be playing a more important role, either independently or in tandem with water stress. This is further strengthened with high residual effect, which was examined in detail (See pages 93 - 108). A main limitation of this analysis was that the evaluation of these temporal trends was done at an annual scale, and does not capture the seasonal variation in water stress that can influence the productivity of forests. This can lead to results contrary to our expectations. As SPEI only captures the difference between precipitation and potential evapotranspiration, the access to sub-surface water for plants can increase water availability, which can have substantial influence on the ANPP. Hence, further investigations of the net primary productivity with water stress accounting for both water availability from precipitation and sub-surface water needs to be explored in greater detail.

The trends in the time-varying intercept values showed that the ANPP has been declining in the majority of the NBR landscape. These results are contrary to the global heuristic expectation that increased $CO_2$, in a possible future climate scenario, would likely increase the growth rate of plants, thus increasing the global net primary productivity (Ballantyne et al., 2012). The segmented regression analysis on the time-varying intercept showed that ANPP increased during the period 2001–2007, but in the recent years there has been a consistent and considerable decline. Similar trends of decline in peak biomass in the recent past has been observed in sub-tropical high-altitude forests in Africa, South America, and Central America (Krishnaswamy et al., 2014). In most areas of the study region, the ANPP transitioned from increasing to declining in the period 2008–2012. Furthermore, it is important to note that the breakpoint year in this landscape occurred in a spatially clustered manner. Thus, it is important to investigate whether there were drastic changes in the monsoonal patterns between 2008 and 2012 to get deeper insights about the drastic change in temporal trends in the ANPP.

In conclusion, this study shows that there is a recent decline in the ANPP across the NBR landscape. Although the ANPP shows some response to water stress in this landscape, this may not be a significant driver for productivity. Based on the strength of the relationship between ANPP and SPEI, water stress may not be a major concern for decline in productivity. Other local climatic factors, nitrogen degradation and soil nutrition availability (Fleischer et al., 2019), forest regrowth (Pan et al., 2011), changes in land use land cover, and other anthropogenic factors might be able to better explain the observed trends in ANPP in this landscape.

## References

Adams, H. D., Guardiola-Claramonte, M., Barron-Gafford, G. A., Villegas, J. C., Breshears, D. D., Zou, C. B., Troch, P. A., & Huxman, T. E. (2009). Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences*, *106*(17), 7063–7066. https://doi.org/10.1073/pnas.0901438106

Anderegg, W. R. L. (2015). Spatial and temporal variation in plant hydraulic traits and their relevance for climate change impacts on vegetation. *New Phytologist*, *205*(3), 1008–1014. https://doi.org/10.1111/nph.12907

Anderegg, W. R. L., Trugman, A. T., Bowling, D. R., Salvucci, G., & Tuttle, S. E. (2019). Plant functional traits and climate influence drought intensification and land–atmosphere feedbacks. *Proceedings of the National Academy of Sciences*, *116*(28), 14071–14076. https://doi.org/10.1073/pnas.1904747116

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P., & White, J. W. C. (2012). Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature*, *488*(7409), 70–72. https://doi.org/10.1038/nature11299

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Brown, J. H., Valone, T. J., & Curtin, C. G. (1997). Reorganization of an arid ecosystem in response to recent climate change. *Proceedings of the National Academy of Sciences*, *94*(18), 9729–9733. https://doi.org/10.1073/pnas.94.18.9729

Cernusak, L. A., Winter, K., Dalling, J. W., Holtum, J. A. M., Jaramillo, C., Körner, C., Leakey, A. D. B., Norby, R. J., Poulter, B., Turner, B. L., Wright, S. J., Cernusak, L. A., Winter, K., Dalling, J. W., Holtum, J. A. M., Jaramillo, C., Körner, C., Leakey, A. D. B., Norby, R. J., … Wright, S. J. (2013). Tropical forest responses to increasing atmospheric CO2: Current knowledge and opportunities for future research. *Functional Plant Biology*, *40*(6), 531–551. https://doi.org/10.1071/FP12309

Chen, Z., Zhou, T., Zhang, L., Chen, X., Zhang, W., & Jiang, J. (2020). Global land monsoon precipitation changes in CMIP6 projections. *Geophysical Research Letters*, *47*(14), e2019GL086902. https://doi.org/10.1029/2019GL086902

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, *408*(6809), 184–187. https://doi.org/10.1038/35041539

Fatichi, S., Pappas, C., & Ivanov, V. Y. (2016). Modeling plant–water interactions: An ecohydrological overview from the cell to the global scale. *WIREs Water*, *3*(3), 327–368. https://doi.org/10.1002/wat2.1125

Fauset, S., Baker, T. R., Lewis, S. L., Feldpausch, T. R., Affum-Baffoe, K., Foli, E. G., Hamer, K. C., & Swaine, M. D. (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

Fisher, R. A., Williams, M., Vale, R. L. D., Costa, A. L. D., & Meir, P. (2006). Evidence from Amazonian forests is consistent with isohydric control of leaf water potential. *Plant, Cell & Environment*, *29*(2), 151–165. https://doi.org/10.1111/j.1365-3040.2005.01407.x

Fleischer, K., Rammig, A., De Kauwe, M. G., Walker, A. P., Domingues, T. F., Fuchslueger, L., Garcia, S., Goll, D. S., Grandis, A., Jiang, M., Haverd, V., Hofhansl, F., Holm, J. A., Kruijt, B., Leung, F., Medlyn, B. E., Mercado, L. M., Norby, R. J., Pak, B., … Lapola, D. M. (2019). Amazon forest response to CO2 fertilization dependent on plant phosphorus acquisition. *Nature Geoscience*, *12*(9), 736–741. https://doi.org/10.1038/s41561-019-0404-9

Kao, S.-C., & Ganguly, A. R. (2011). Intensity, duration, and frequency of precipitation extremes under 21st-century warming scenarios. *Journal of Geophysical Research: Atmospheres*, *116*(D16). https://doi.org/10.1029/2010JD015529

Krishnaswamy, J., John, R., & Joseph, S. (2014). Consistent response of vegetation dynamics to recent climate change in tropical mountain regions. *Global Change Biology*, *20*(1), 203–215. https://doi.org/10.1111/gcb.12362

Kumarathunge, D. P., Drake, J. E., Tjoelker, M. G., López, R., Pfautsch, S., Vårhammar, A., & Medlyn, B. E. (2020). The temperature optima for tree seedling photosynthesis and growth depend on water inputs. *Global Change Biology*, *26*(4), 2544–2560. https://doi.org/10.1111/gcb.14975

Linares, J. C., & Camarero, J. J. (2012). From pattern to process: Linking intrinsic water-use efficiency to drought-induced forest decline. *Global Change Biology*, *18*(3), 1000–1015.

Loo, Y. Y., Billa, L., & Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, *6*(6), 817–823. https://doi.org/10.1016/j.gsf.2014.02.009

Malhi, Y., Grace, J., Malhi, Y., & Grace, J. (2000). Tropical forests and atmospheric carbon dioxide. *Trends in Ecology & Evolution*, *15*(8), 332–337. https://doi.org/10.1016/S0169-5347(00)01906-6

Mantgem, P. J. van, Stephenson, N. L., Byrne, J. C., Daniels, L. D., Franklin, J. F., Fulé, P. Z., Harmon, M. E., Larson, A. J., Smith, J. M., Taylor, A. H., & Veblen, T. T. (2009). Widespread increase of tree mortality rates in the Western United States. *Science*, *323*(5913), 521–524. https://doi.org/10.1126/science.1165000

Martinez-Vilalta, J., López, B. C., Adell, N., Badiella, L., & Ninyerola, M. (2008). Twentieth century increase of Scots pine radial growth in NE Spain shows strong climate interactions. *Global Change Biology*, *14*(12), 2868–2881.

McGuire, A. D., Ruess, R. W., Lloyd, A., Yarie, J., Clein, J. S., & Juday, G. P. (2010). Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: Dendrochronological, demographic, and experimental perspectives. *Canadian Journal of Forest Research*, *40*(7), 1197–1209. https://doi.org/10.1139/X09-206

Ow, L. F., Griffin, K. L., Whitehead, D., Walcroft, A. S., & Turnbull, M. H. (2008). Thermal acclimation of leaf respiration but not photosynthesis in Populus deltoides×nigra. *New Phytologist*, *178*(1), 123–134.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., & Hayes, D. (2011). A Large and Persistent Carbon Sink in the World's Forests. *Science*, *333*(6045), 988–993.

Phillips, O. L., Aragão, L. E. O. C., Lewis, S. L., Fisher, J. B., Lloyd, J., López-González, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C. A., Heijden, G. van der, Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T. R., Bánki, O., Blanc, L., Bonal, D., & Torres-Lezama, A. (2009). Drought sensitivity of the amazon rainforest. *Science*, *323*(5919), 1344–1347.

Rangwala, I., & Miller, J. R. (2012). Climate change in mountains: A review of elevation-dependent warming and its possible causes. *Climatic Change*, *114*(3), 527–547.

Ravindranath, N. H., Joshi, N. V., Sukumar, R., & Saxena, A. (2006). Impact of climate change on forests in India. *Current Science*, *90*(3), 8.

Sen, P. K. (1968). Estimates of the regression coefficient based on kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389.

Sullivan, M. J. P., Lewis, S. L., Affum-Baffoe, K., Castilho, C., Costa, F., Sanchez, A. C., Ewango, C. E. N., Hubau, W., Marimon, B., Monteagudo-Mendoza, A., Qie, L., Sonké, B., Martinez, R. V., Baker, T. R., Brienen, R. J. W., Feldpausch, T. R., Galbraith, D., Gloor, M., Malhi, Y., … Phillips, O. L. (2020). Long-term thermal sensitivity of Earth's tropical forests. *Science*, *368*(6493), 869–874. https://doi.org/10.1126/science.aaw7578

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, *23*(7), 1696–1718.

Wang, H., Atkin, O. K., Keenan, T. F., Smith, N. G., Wright, I. J., Bloomfield, K. J., Kattge, J., Reich, P. B., & Prentice, I. C. (2020). Acclimation of leaf respiration consistent with optimal photosynthetic capacity. *Global Change Biology*, *26*(4), 2573–2583.

Williams, A. P., Xu, C., & McDowell, N. G. (2011). Who is the new sheriff in town regulating boreal forest growth? *Environmental Research Letters*, *6*(4), 041004.

Williams, C. A., Reichstein, M., Buchmann, N., Baldocchi, D., Beer, C., Schwalm, C., Wohlfahrt, G., Hasler, N., Bernhofer, C., Foken, T., Papale, D., Schymanski, S., & Schaefer, K. (2012). Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers. *Water Resources Research*, *48*(6). https://doi.org/10.1029/2011WR011586

# Phenological responses to increasing temperature and declining rainfall

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## Highlights

- There was no considerable difference in the percentage of areas witnessing increase or decrease in the length of the growing season, vegetation growth and vegetation greening.
- Large parts of grasslands showed an increase in the vegetation growth period.
- The length of the growing period in drier vegetation showed a positive response to rainfall and a negative response to temperature.
- Rainfall and temperature have a similar magnitude in their influence on vegetation growth; temperature and rainfall had a negative influence in wetter forests and positive influence in drier forests.
- Eco-climatic distance showed that the Niligiri Biosphere Reserve witnessed a net greening.

## Abstract

Vegetation phenology is the periodic transitions in a plant's activity due to seasonal changes in climatic conditions. The phenological response of plants have profound influence on the hydrological cycle, biogeochemical cycles, and with the above and below ground trophic levels. The temporal changes in the vegetation phenology due to global warming has been well documented in temperate regions, but the tropical regions have not received similar attention. We examined the temporal variation of three phenological variables—vegetation growth period, vegetation growth, and eco-climatic distance, which is an index of deciduousness—and their relationship with temperature and precipitation, over the time period 2001–2018 in the Nilgiri Biosphere Reserve (NBR). We used dynamic linear models to understand the temporal changes in the phenology–climate relationships and these relationships were analyzed over an elevational gradient. Our results suggested almost equal proportion of areas with a significant increase (36% of area) and a decrease (33%) in the vegetation growth period in the NBR. A higher percentage of area showed an increase (44.5%) compared to decrease (26%) in vegetation growth. Analysis of eco-

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climatic distance trends suggested more vegetation greening (29%) compared to browning (17.5%) in the landscape. Vast areas of dry deciduous forests, savanna, forest plantations, and grasslands showed relatively higher percentage of area with increase in vegetation growth. The time-varying relationship between the phenological variables and climate variables varied considerably across land uses and altitudinal zones. The influence of precipitation on the phenological variables temporally increased in the altitude range of 800 m–1400 m. Regarding temperature, we found increasing sensitivity of vegetation period in the low altitude zone (< 800 m) and vegetation growth showed increasing sensitivity in the mid altitude zone (800 m–1400 m). Overall, precipitation had a positive influence and temperature had a negative influence on both vegetation period and growth, but the degree of influence varied between different land use and elevation range. Among natural land covers moist and dry deciduous forests and high altitude grasslands showed vegetation greening, while savanna showed browning in the landscape. Savanna vegetation showed an increasing response in eco-climatic distance to rainfall, while grasslands showed an increasing response to temperature. Overall drier regions, represented by dry deciduous forests and savanna, and high altitude grasslands showed majority of their area with increasing sensitivity to temperature, depicting a scenario where drier regions and high altitudes were more influenced by warming in the Tropical region of the NBR.

## Introduction

Phenology is the multiple transitions in plant activity, shifting through stages of dormancy, active growth, and senescence. The timing of these transitions in plant activity is in response to changes in the abiotic conditions caused by seasonality. The changes in plant activity due to seasonal changes directly influences biomass accumulation, transpiration, autotrophic respiration, soil processes like mineralization, and heterotrophic respiration (Barr et al., 2004; Cleland et al., 2007; Nord & Lynch, 2009). These periodic biological changes mediate feedbacks of terrestrial ecosystems with the earth's atmosphere and hence it is important to understand the climatic drivers of phenology (Peñuelas et al., 2009; White et al., 1997).

In the current context of climate change, increase in atmospheric $CO_2$ concentration has led to rise in global temperatures and variability in precipitation at a regional scale (Alexander et al., 2006; Hulme et al., 1999). Though experimental evidence suggests that the increase in $CO_2$ concentration does not induce any notable phenological changes (Herrick & Thomas, 2003; Norby et al., 2003); the changes in temperature and precipitation as a result of increased $CO_2$ concentration are reported to have a profound influence on vegetation phenology at both the regional and global scales

(Menzel & Fabian, 1999; Myneni et al., 1997). These changes in the climatic conditions are further amplified in higher altitude regions, which can induce additional variation in the vegetation-climate interactions (Gao et al., 2019; Krishnaswamy et al., 2014). Thus understanding variation in phenology with respect to changing climatic conditions on an elevation gradient over the past few decades will provide better insights of the role of phenology in mediating biosphere-atmosphere interactions.

Global studies have pointed out that global warming has led to the early onset of spring and extension of the vegetation growth period (Menzel et al., 2006; Myneni et al., 1997; Steltzer & Post, 2009). However, these results have been derived from temperate and boreal biomes where the thermal thresholds due to low temperatures for biological activities during spring and autumn is relaxed due to global warming (Linderholm, 2006). This heuristic explanation of phenology response to warming conditions cannot be directly applied to understand tropical ecosystems, as tropical regions do not experience high fluctuations in temperatures like the temperate biomes. This helps us to hypothesize that the tropical regions might be less sensitive to temperature changes and more responsive to precipitation (Reich, 1995). In the context of the Nilgiri Biosphere Reserve (NBR), a simplistic stronger relationship with precipitation might not hold true, as it is a heterogeneous landscape with different forest types and high plant diversity spread over elevations ranging between 80 m and 2500 m. It has been shown that the vegetation-climate relationship is uni-modal along the altitudinal gradient for temperate ecosystems (Trujillo et al., 2012); but no such generic relationships have been shown for tropical regions.

In this study, we try to advance our understanding about how changes in temperature and precipitation has influenced the phenology in the NBR over the past two decades. First, we extract two main phenology variables namely, vegetation growth period (hereafter referred to as growth period) and vegetation growth. The growth period corresponds to the length of the active vegetation period and vegetation growth refers to the total photosynthetic activity contributing to net primary productivity that occurred from the onset of spring to dormancy during autumn. We also evaluated trends in eco-climatic distance, which captures the floristic and biodiversity attributes of forest types spread over a moisture gradient (Krishnaswamy et al., 2009). The eco-climatic distance helps us to monitor if the vegetation is increasingly becoming deciduous due to increased frequency of droughts that are being reported in the tropical forests (Condit et al., 1996). Overall, the trends in the vegetation period, vegetation growth, and eco-climatic distance can help us understand the phenological trends in vegetation occurring in the NBR. Specifically, we examined the spatial and temporal variations in the phenology–temperature and phenology–precipitation relationships over different altitude zones over the past two decades. The phenology–climate relationships were evaluated over an elevation gradient to understand the most sensitive altitudinal zones in the NBR. Based on past studies we expected the growth period, vegetation growth, and greening to increase with increasing rainfall and temperature.

## Methods

### *Phenology datasets*

We used MODIS MCD12Q2v006 dataset to calculate the phenology variables. There are four main phenology events: spring green-up, maturity, autumn senescence, and dormancy (Richardson et al., 2010)(Richardson et al., 2010). The MODIS MCD12Q2v006 dataset uses Enhanced Vegetation Index (EVI) to track the annual temporal variation in plant biomass and all the above mentioned phenological events have been calculated in reference to the peak biomass. The spring green-up and maturity correspond to 90% and 50% of the peak biomass levels during the phase where the vegetation biomass reaches peak biomass. Similarly, autumn senescence and dormancy correspond to 50% and 90% of the peak biomass during the phase where the vegetation biomass is declining after reaching peak biomass. After plants reach senescence, there is a drastic decline in the quality and quantity of leaves and thus does not represent the active photosynthetic period of plants (Lichtenthaler & Babani, 2004). Hence, the period between the maturity and senescence have saturated levels of leaf surface area, representing active photosynthetic duration in the annual cycles of plant activity. The vegetation biomass during the vegetation spring green-up and dormancy represent the annual vegetation growth.

$$vegetation\,growth\;period = Dormancy\;date - maturity\;date\,(days)$$

$$vegetation\,growth = \int_{greenup}^{dormancy} EVI \times dt$$

The units for the vegetation growth period is days, whereas, vegetation growth is an unit-less index depicting the gross primary productive capability of the vegetation. The phenological variables calculated at the pixel level were checked for their quality. We used the pixel reliability layer to select only those pixels which were either designated as ‘Best’ or ‘Good’ quality levels.

Eco-climatic distance was calculated as the Mahalanobis distance in multi-dimensional space from a reference set of evergreen sites in the Western Ghats. To derive and analyze eco-climatic distances, we defined the year starting from October and ending in April, which corresponds with the hydrological year (June to May) and for each year the following bands were derived: Median

EVI for each year for the months October–April; this represents the overall green biomass irrespective of the changes that occur annually. The coefficient of variation (CV) represents the seasonal change in green biomass, which will differ between vegetation types (e.g., dry deciduous and wet evergreen) and would be a measure of the degree of deciduousness. The Sen's slope from October to April, which represents the progressive decline in the moisture and green biomass from the wettest to the driest months.

Using the derived bands, the average and covariance matrix (together referred to as the environmental center) for the reference sites was calculated for the first year in the time series. We then calculated the mahalanobis distance of each raster cell to the environmental center of the reference evergreen sites. The derived distance band indicates how far a given pixel is with respect to the reference evergreen sites in terms of overall biomass or greenness, deciduousness, and loss in green biomass from the wettest to the driest months. The environmental center from the first year was applied across the time series of derived bands to calculate the time series of eco-climatic distances. This will reflect the changes across vegetation types with respect to evergreen class at the beginning of the time series. Greater the eco-distance value, more deciduous will be the site, and vice versa.

We used daily rainfall data available from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset  (Funk et al., 2015) to derive annual total rainfall data. We derived annual mean temperature dataset by using the MODIS eight day land surface temperature product (MOD11A2).

***Data analysis***

To understand the individual influence of temperature and precipitation on phenology in the NBR, we conducted multivariate dynamic linear model (DLM) analysis to understand the time-varying relationship of the growth period, vegetation growth, and eco-climatic distance with temperature and precipitation.

$$GrowthPeriod_t = \beta 0_t + \beta 1_t \, AnnualPrecipitation_t + \beta 2_t \, AnnualMeanTemperature_t + e_t$$

$$VegetationGrowth_t = \beta 0_t + \beta 1_t \, AnnualPrecipitation_t + \beta 2_t \, AnnualMeanTemperature_t + e_t$$

$$Ecodist_t = \beta 0_t + \beta 1_t \, AnnualPrecipitation_t + \beta 2_t \, AnnualMeanTemperature_t + e_t$$

Unlike traditional linear regression, in this model the regression parameters, the intercept $\beta 0_t$ and the regression slopes $\beta 1_t$ and $\beta 2_t$ change with time. The annual rainfall, and the annual mean temperature were used as the explanatory variables in the DLM.

We evaluated the trends in the time-varying intercept and slope obtained from the DLM analysis. The linear trend of time-varying intercept values from DLM indicate the direction and magnitude of the monotonic change in the phenological variables over time. Similarly, the linear trend of the time-varying slope values from DLM indicate the monotonic change in sensitivity of the phenological variables to temperature and precipitation. We used the non-parametric Sen's slope estimator to assess monotonic changes in the intercept and slope values from DLM results. Additionally, we conducted a segmented regression on the time-varying intercept values. The segmented regression analysis was conducted to find a single breakpoint to identify the year in which there was a notable change in the direction of the temporal trends in phenology and to examine the distribution of slope before and after the breakpoint. The distribution of the slopes before and after the breakpoint was compared using the analysis of variance and *post-hoc* Tukey's test. (refer to Annexure II for details on the analytical methods)

The time-varying slope of the interaction between the phenology variables and climate variables was examined for forest types/land uses along the elevation gradient. The NBR was classified into four altitudinal zones: < 450 m, 450 m–900 m, 900 m–1500 m, > 1500 m. The median values of the time-varying slopes was calculated for different land uses and examined how the median time-varying relationship varied over different altitudinal zones.

To derive an overall understanding about the influence of temperature and precipitation in determining phenology over the NBR, the trends in time-varying intercept and slope values were evaluated for altitudinal bins of 200 m. The Sen's slope values calculated for the time-varying intercept and slope results from the DLMs were binned into 200 m elevation intervals and their mean slope was calculated. All the mean Sen's slope were analyzed on the increasing gradient of altitude at the regional level.

## Results

The vegetation growth ($F_{7, 40405} = 1846$, $p < 0.001$; Fig. 1a) and the growth period ($F_{7, 40405} = 651$, $p < 0.001$; Fig. 1b) varied significantly among different land use land cover types. The growth period, expressed as number of days, does not vary much between evergreen (183.34 ± 11.95; mean ± sd), moist deciduous (183.95 ± 16.21), and dry deciduous (181.50 ± 27.33) forest areas. However, comparatively, dry deciduous (263.97 ± 67.55) followed by moist deciduous (222.23 ±46.38) showed higher vegetation growth when compared to evergreen forests (205.45 ± 40.22).

The DLM models improved our ablity to detect significant trends by 54.8%, 52.8% and 22.3% in vegetation growth, growth period, and eco-climatic distances respectively, when compared to performing trend analysis on the raw datasets. The time-varying intercept results for the growth period from the dynamic linear model showed nearly an equal percentage of area in the NBR experiencing monotonic decrease (32.79 ± 4.38%), increase (35.66 ± 4.27%), and no change (31.54 ± 2.02%) (Table 1; Fig. 2). However, similar analysis for the vegetation growth showed that a higher percentage of area was experiencing an increase (44.5 ± 8.9%) (decrease: 26.44 ± 9.12%, and no change: 28.86 ± 1.84%; Table 1). Among the natural habitats, grasslands (41%) showed comparatively higher percent area with increase in the growth period (Table 1). Savanna (58%), and dry deciduous forests (46%) showed higher percentage of area with increase in vegetation growth. The trends in the eco-climatic distance suggested that more areas within the NBR were greening (29.44%) compared to browning (17.48%). Natural vegetation types, dry-deciduous forests (34%), and moist-deciduous forests (32%) showed more vegetation greening trends in the NBR, while savannas experienced more browning (36%) (Table 1).

Majority of the area in all land use land cover types experienced increasing sensitivity of the growth period to temperature. However, drier regions represented by dry deciduous forests (40.89%) and savanna (48.49%) showed higher percentage area under increasing sensitivity to temperature (Table 2). Forest plantations (44.84%) and grasslands (40.92%) also showed increasing sensitivity to temperature. These results were similar for sensitivity of vegetation growth to temperature with dry deciduous (44.23%), savanna (42.77%), and forest plantation (40.93%) showing increasing sensitivity to temperature (Table 2). With respect to sensitivity of the growth period to precipitation, moist deciduous (47.54%), dry deciduous (42.69%), grassland (42.47%), and orchard (43.13%) showed increasing sensitivity (Table 2). In contrast, for sensitivity of vegetation growth to precipitation, across land use land cover types (with the exception of grasslands), approximately equal areas experienced increase, decrease, and no change trends with precipitation. In grasslands, the majority of the area (44.58%) showed a decline in sensitivity to precipitation (Table 2). The results from the analysis of the eco-climatic distance suggested that larger percentage of areas had a positive relationship with temperature across all land use and land cover types, while drier vegetation types (dry deciduous forests: 47.43%, savanna: 75.74%, and forest plantations: 53.45%) showed higher response to precipitation (Table 2). Similarly, a larger percentage of high altitude grasslands was positively influenced by rainfall (Table 2).

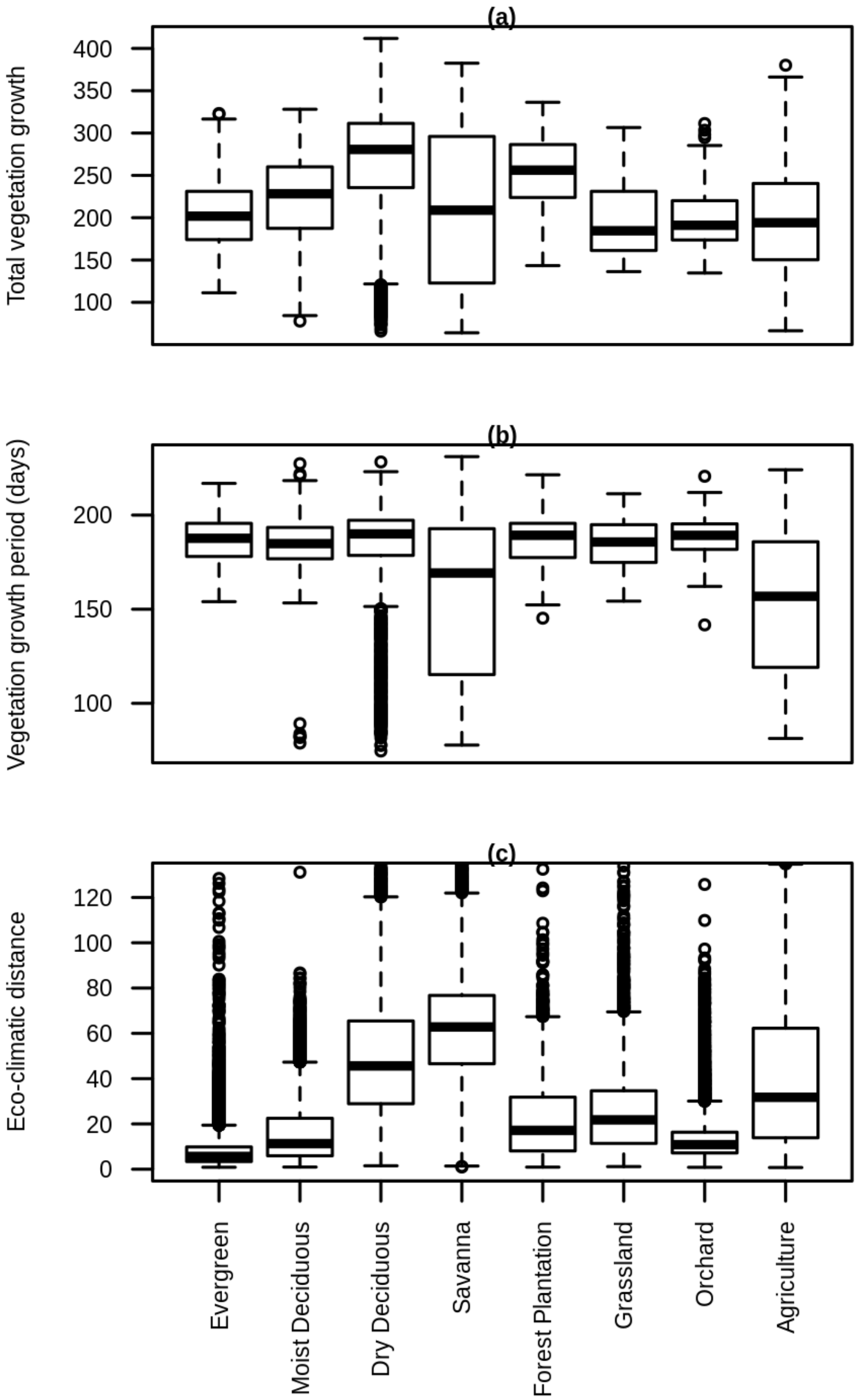


*Figure 1: Spatial variation in the long-term means (2001-2018) of the phenology variables over different land uses in the Nilgiri Biosphere Reserve: a) Variation in vegetation growth over different land uses; dry deciduous followed by moist deciduous showed comparatively higher vegetation growth compared to evergreen forests; b) The growth period does not vary much across different land cover/land uses except for the savanna, which shows a lower median values; c) Eco-climatic distance increases with increased dryness of the vegetation.*

*Table 1: Percentage area in different land use which have experienced an increase or decrease in the phenology variables between 2000-2019: The trend in time-varying intercepts of growth period (2001-2018) showed nearly an equal percentage of area experiencing a monotonic decrease or increase in the Nilgiri Biosphere Reserve across land use/land cover classes except for grasslands and forest plantations (mainly Acacia and Eucalyptus), which showed relatively higher percentage of area with increased growth period. Analysis of vegetation growth intercept trends (2001-2018) showed that areas with drier vegetation represented by savanna and dry deciduous forests showed comparatively higher percent area with increase in vegetation growth. Forest plantations, which mainly includes teak, acacia and eucalyptus, and grasslands, mainly distributed in higher elevations, also showed higher percentage of area with increase in vegetation growth. Trends in eco-climatic distance (2000-2019) suggested that deciduous forests (moist and dry) and high-altitude grasslands had more area showing vegetation greening trends, while savanna and scrub experienced more browning.*

| | **Growth Period** | | **Vegetation Growth** | | **Eco-distance** | |
|---|---|---|---|---|---|---|
| **Land use** | ***%Decrease*** | ***%Increase*** | ***%Decrease*** | ***%Increase*** | ***%Browning*** | ***%Greening*** |
| Evergreen | 31.78 | 36.79 | 31.81 | 38.08 | 20.45 | 20.75 |
| Moist Deciduous | 37.29 | 34.03 | 34.07 | 35.07 | 11.53 | 31.49 |
| Dry Deciduous | 37.48 | 30.10 | 24.05 | 45.66 | 14.82 | 33.70 |
| Savanna | 33.45 | 31.36 | 12.95 | 57.75 | 36.28 | 17.31 |
| Forest Plantation | 26.42 | 40.93 | 14.95 | 57.33 | 18.12 | 26.62 |
| Grassland | 27.54 | 40.53 | 25.10 | 46.14 | 14.55 | 30.91 |
| Orchard | 37.26 | 32.42 | 39.34 | 35.58 | 10.71 | 36.21 |
| Agriculture | 31.13 | 39.17 | 29.30 | 41.14 | 15.69 | 33.14 |

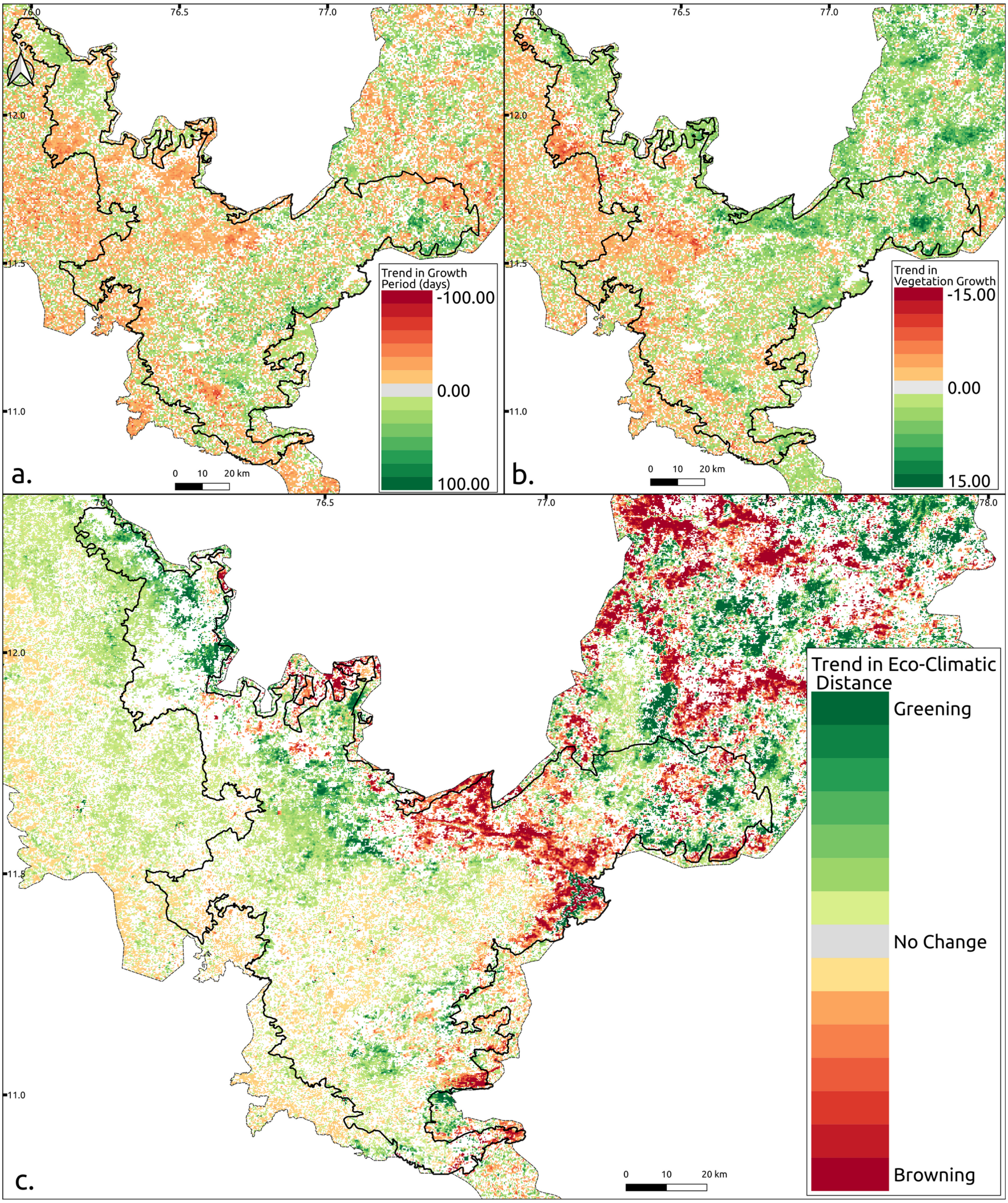


*Figure 2: The estimated trends in the time-varying intercept values of the phenological (2001-18) variables and eco-climatic distance for the time period 2000-19: a) Temporal change in the growth period. An equal percentage of area in the Nilgiri Biosphere Reserve (NBR) expereinced a monotonic decrease (32.33%) and increase (31.77%) in the NBR; b) Temporal change in vegetation growth. A higher percentage of area experienced an increase (44.5%) in vegteation growth; c) Temporal trend in eco-climatic distance; more areas showed vegetation greening (29.44%) than browning (17.48%) in the NBR.*

*Table 2: Percentage area in different land use where the phenological variables, vegetation growth period and vegetation growth, and eco-climatic distance have expereinced an increase or decrease in sensitivity/response to temperature and precipitation. Growth period: The majority of the area in all landuses experienced increased sensitivity to temperature. Drier regions represented by dry deciduous forests and savanna, along with forest plantations and grasslands, showed higher percentage area under increased sensitivity to temperature. Moist deciduous, dry deciduous forests and grasslands showed increased sensitivity of the growth period to rainfall. Vegetation growth: Dry deciduous, savanna, and forest plantation showed increased sensitivity. All land uses, with the exception of grasslands, had approximately equal area that experienced an increasing or decreasing trend with precipitation. In grasslands, a majority of the area showed a decline in sensitivity to precipitation. Eco-climatic distance: Grasslands which are mainly distributed in high altitudes showed an increased response to temperature. Dry deciduous, savanna, and forest plantations showed higher response to precipitation.*

| | **Growth period** | | | | **Vegetation growth** | | | | **Eco-climatic distance** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Temperature** | | **Precipitation** | | **Temperature** | | **Precipitation** | | **Temperature** | | **Precipitation** | |
| **Land use** | **-ve** | **+ve** | **-ve** | **+ve** | **-ve** | **+ve** | **-ve** | **+ve** | **-ve** | **+ve** | **-ve** | **+ve** |
| Evergreen | 32.26 | 37.5 | 31.94 | 37.51 | 34.04 | 37.46 | 33.31 | 37.03 | 19.52 | 19.35 | 29.87 | 31.01 |
| Moist Deciduous | 32.87 | 37.84 | 22.42 | 47.54 | 31.38 | 37.88 | 30.43 | 37.12 | 15.03 | 38.21 | 34.70 | 20.53 |
| Dry Deciduous | 29.19 | 40.89 | 23.57 | 42.69 | 25.98 | 44.23 | 27.24 | 36.3 | 23.09 | 30.71 | 19.77 | 47.43 |
| Savanna | 21.96 | 48.49 | 30.42 | 31.79 | 24.27 | 42.77 | 36.3 | 23.4 | 28.40 | 36.22 | 6.79 | 75.74 |
| Forest Plantation | 29.61 | 44.84 | 30.33 | 34.98 | 33.09 | 40.93 | 30.62 | 36.14 | 16.72 | 28.34 | 27.06 | 38.68 |
| Grassland | 30.87 | 40.92 | 27.70 | 42.47 | 35.76 | 36.47 | 44.58 | 27.43 | 10.15 | 31.89 | 30.95 | 41.81 |
| Orchard | 34.96 | 37.36 | 28.4 | 43.13 | 40.22 | 32.58 | 35.13 | 36.05 | 11.60 | 38.69 | 39.08 | 28.82 |
| Agriculture | 28.49 | 43.96 | 35.22 | 34.19 | 32.82 | 38.55 | 34.86 | 33.43 | 25.05 | 31.61 | 26.20 | 43.72 |

The segmented regression analysis showed that the breakpoint predominantly occurred during the time period 2009–2014 for the growth period, 2008–2014 for vegetation growth and eco-distance (Figs. 3a,4a,&5a). Tukey's honest significant difference test for comparing the distribution of time-varying intercept slopes before and after breakpoint showed p-values of 0.81, 0.34, and 0.23 for the growth period, vegetation growth, and eco-climatic distance, respectively (Figs. 3b,4b,&5b). These results suggested that there was no significant directional change in all three phenological variables in the NBR. Growth period and vegetation growth showed increased variability in the slopes in the post break period. Whereas, eco-climatic distance showed a significant decline in variability in the post break period.

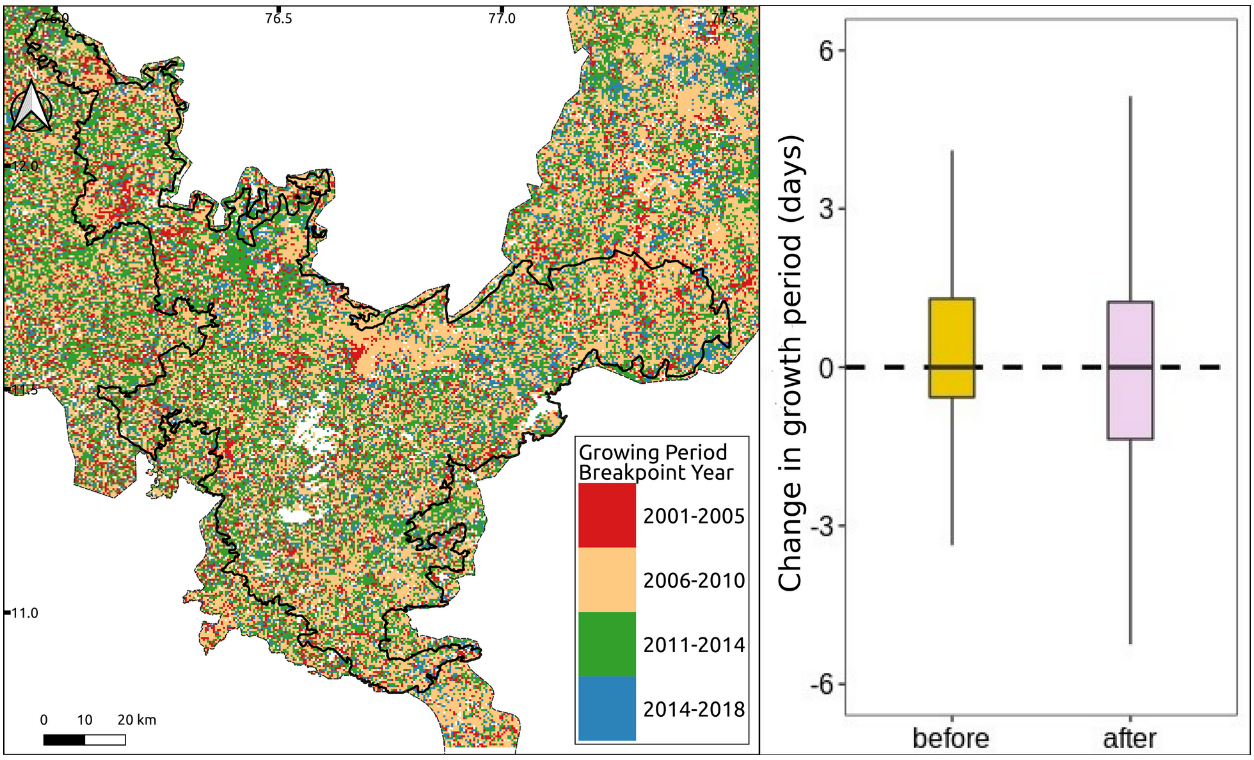

*Figure 3: Segmented regression analysis on the time-varying intercept values of the growth period during 2001–2018. a) Distribution of the breakpoint year in the Nilgiri Biosphere Reserve suggests that the breakpoints predominantly occurred between 2009 and 2015; b) Distribution of slope values showed no significant increase or decrease in vegetation period before and after the breakpoint.*

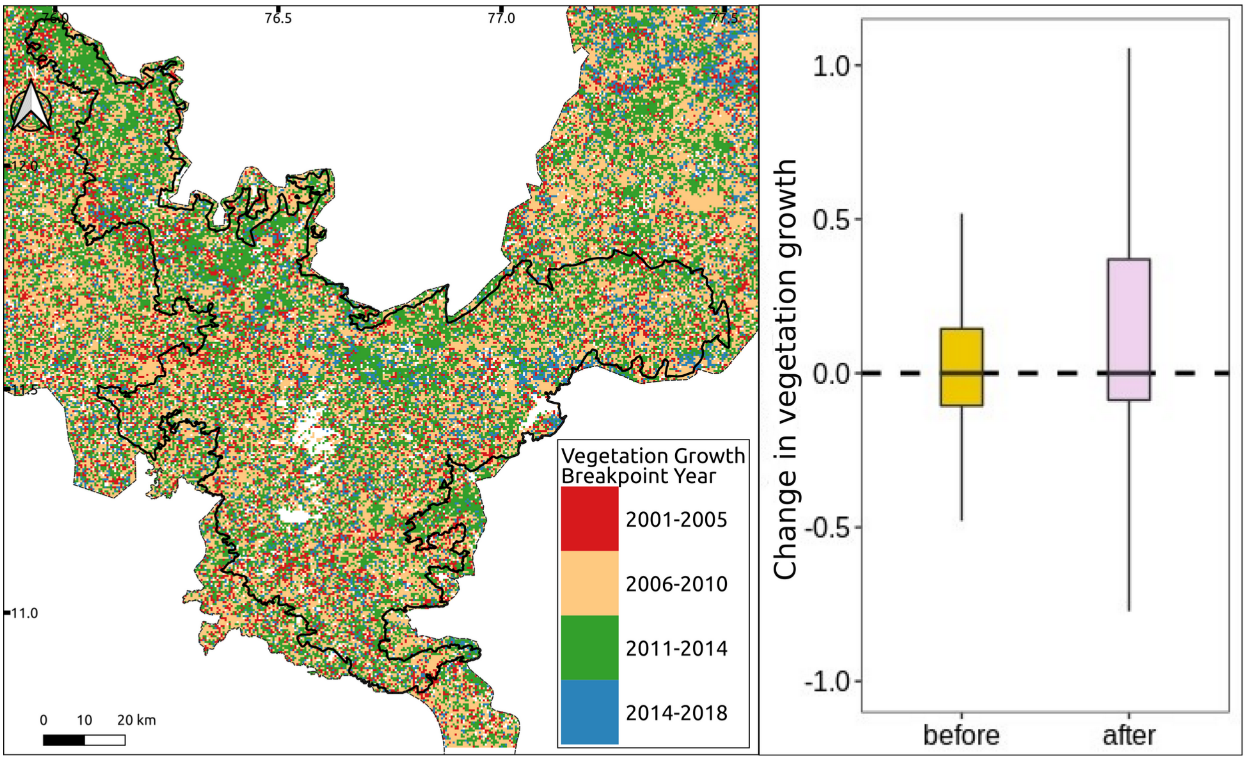


*Figure 4: Segmented regression analysis on the time-varying intercept values of vegetation growth during 2001–2018. a) Distribution of the breakpoint year in the NBR suggests that the breakpoints predominantly occurred between 2008 and 2014; b) Distribution of slope values showed no significant increase or decrease in vegetation growth before and after the breakpoint.*

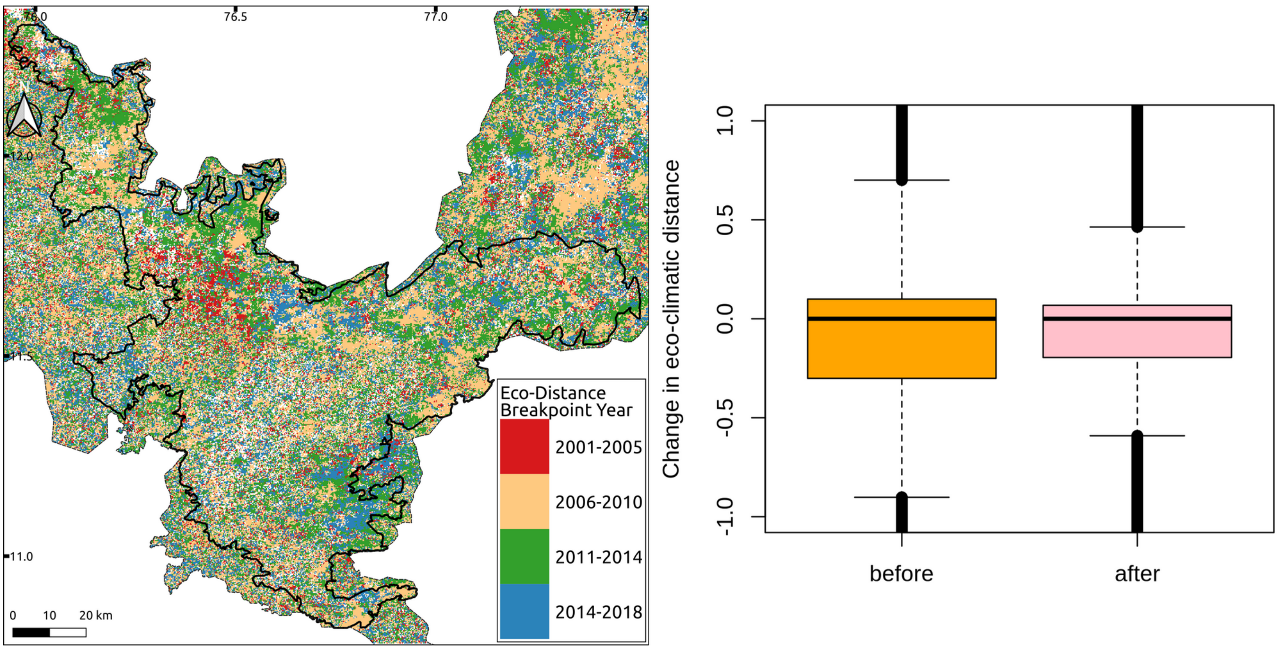


*Figure 5: Segmented regression analysis on the time-varying intercept values of eco-climatic distance during 2000–2019. a) Distribution of the breakpoint year in the NBR, suggests a high concentration of breakpoint years between 2008 and 2014; b) Distribution of slope values showed no significant increase or decrease in vegetation growth before and after the breakpoint.*

Sensitivity and the direction of influence of precipitation over the growth period varied in different land uses and altitudinal zones (Fig. 6a). The evergreen forests at high altitudes (> 1500 m) did not show any significant relationship with precipitation, which was indicated by the median slope values of the growth period and precipitation close to zero. Evergreen forests in the altitudinal range of 900 m–1500 m showed an increasing positive relationship. In contrast, evergreen forests in the the altitude range of 450 m–900 m showed a declining negative sensitivity over the past two decades. The growth period–precipitation relationship for moist-deciduous forests showed a declining negative trend for the altitude zone < 1500 m, but for higher altitudes it showed an increasing positive trend. The dry deciduous forests that are predominantly distributed in the mid-altitude zones showed a positive sensitivity in the response of the growth period to rainfall and it has been increasing since 2010. Similarly, the growth period in the savanna also showed an increasing positive relationship with rainfall across all elevation zones, except in the lower elevation zone where its influence has been declining in recent years. Forest plantations at higher altitudes showed no significant relationship between the growth period and precipitation and for lower and mid-altitude ranges, it showed a declining negative relationship. Grasslands showed considerable inter-annual variations and an increase in positive sensitivity to precipitation in recent years across all elevation zones. Orchards, which are mainly distributed in the altitude zones higher than 900 m, show an increasing positive sensitivity from 2008. Across all elevation zones the influence of rainfall on the growth period remained stable in the agricultural landscape.

The influence of temperature on the growth period was positive in the lower elevation range and negative in the high altitude zones across all land use and land cover types (Fig. 6b). The lowland (< 450 m elevation) dry deciduous forests showed a shift from negative sensitivity to positive sensitivity to temperature over the time period.

The vegetation growth showed high variation in the direction and magnitude of sensitivity to precipitation for different land uses and altitudinal zones (Fig. 7a). Evergreen forests in the high and mid-elevation ranges showed a shift in sensitivity from negative to positive with an increasing trend in sensitivity to precipitation in the recent years. The moist deciduous forests in the altitude zone of 450 m–900 m showed an increasing positive sensitivity after 2008. Dry deciduous forests in the altitude zone of 450 m–900 m and 900 m–1500 m showed positive sensitivity, which sharply increased post 2011. Savanna showed a highly variable but positive sensitivity whereas grasslands showed a consistent declining positive sensitivity to precipitation. Orchards in the higher elevation zone showed an increase in positive sensitivity post 2010. Agriculture did not show any trend in the vegetation growth–rainfall relationship across all the elevation zones.

Vegetation growth showed a growing positive trend with temperature in majority of the land uses except for grasslands and orchards (Fig. 7b). Evergreen forests in the high-altitude zone showed a shift from negative to positive sensitivity over the last two decades. Moist deciduous forests showed an increasing positive sensitivity, except in the higher elevation zone. Lower elevation savanna regions showed increasing positive sensitivity with temperature. Orchards expereinced an increasing negative sensitivity in the high altitude zone (> 1500 m) whereas it showed highly variable sensitivity in the 900 m–1500 m altitude zone. Agriculture in the low altitude zone showed a consistent negative sensitivity, whereas, in the altitude zone of 450 m–900 m an increasing positive sensitivity with temperature was seen.

The influence of rainfall on eco-climatic distances remained stable across all elevation and land use land cover types except for moist deciduous forests in the lower and mid elevation zones, which has witnessed a consistent decline across the NBR. Eco-climatic distance showed no directional trend in it’s response to temperature across all land use land cover types. However, the influence of temperature was higher than that of rainfall, especially in dry deciduous forests, savannas, and grasslands (Fig. 8).

Vegetation period showed increasing sensitivity to precipitation for the altitude range of 400 m–1200 m (Fig. 9a). However, with respect to temperature, vegetation period showed high positive sensitivity at low altitudes (< 600 m) (Fig. 9b). For vegetation growth, higher altitudes showed a declining sensitivity to precipitation (Fig. 10a). With respect to temperature, vegetation growth showed high positive sensitivity for mid-altitude range of 600 m–1000 m and relatively low negative sensitivity in 1500 m–2000 m (Fig. 10b). Eco-climatic distance showed a positive response to rainfall across all altitudes with an increase in response in a narrow altitudinal range of 400 m – 800 m (Fig. 11a). Eco-climatic distance did not show any directional positive or negative influence of temperature over altitude (Fig. 11b).

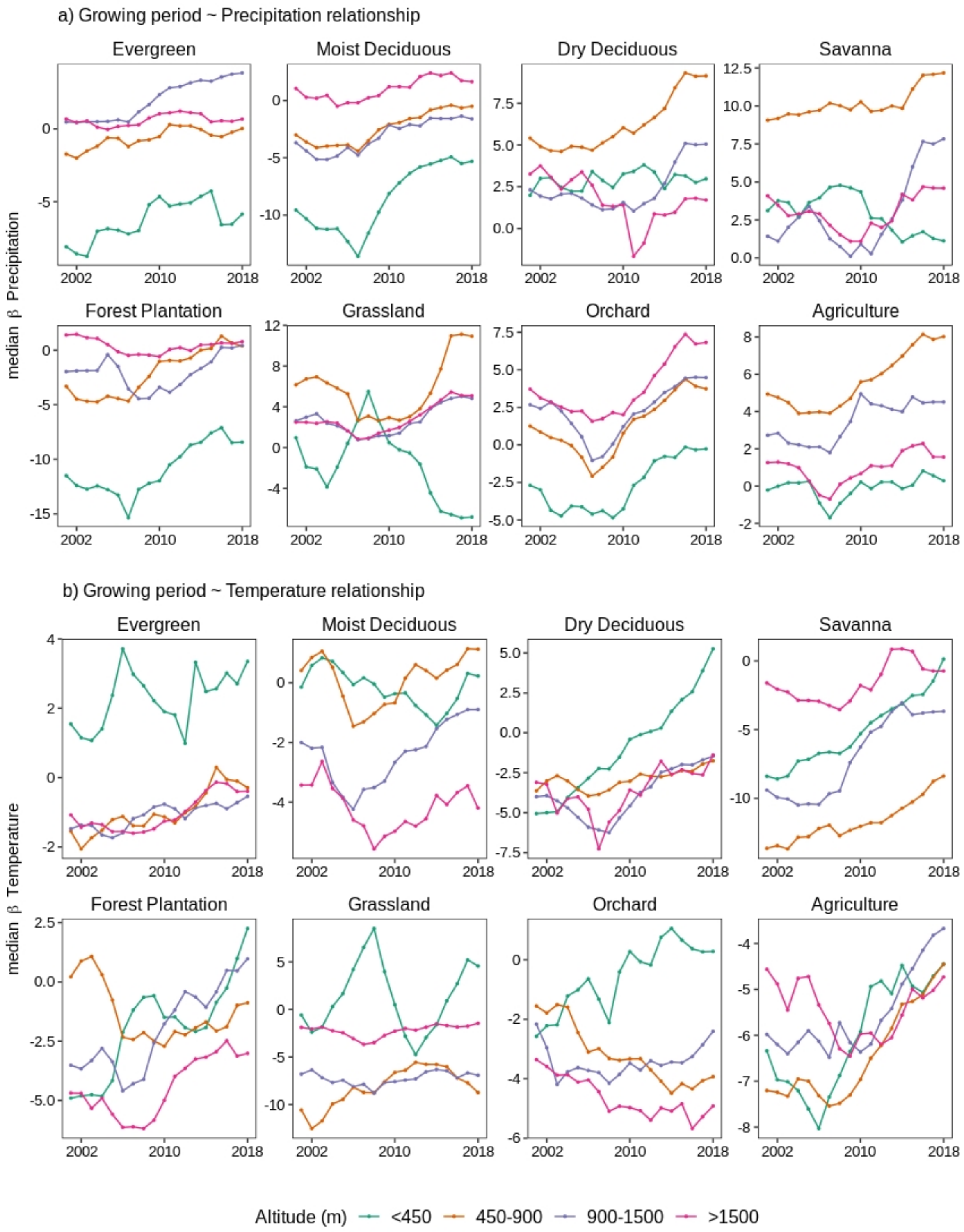


*Figure 6: Altitudinal variation in the time-varying relationship between the growth period and climatic variables over different land uses. Slope values indicate direction and magnitude of the sensitivity of the growth period and climatic variables. a) Annual median slope values of vegetation period–precipitation over four altitudinal zones. Sensitivity and the direction of influence of precipitation over the growth period varied in different land uses and altitudinal zones. 6b) Annual mean slope values of vegetation period–temperature over four altitudinal zones. Sensitivity and the direction of influence of temperature over the growth period varied in different land uses and altitudinal zones.*

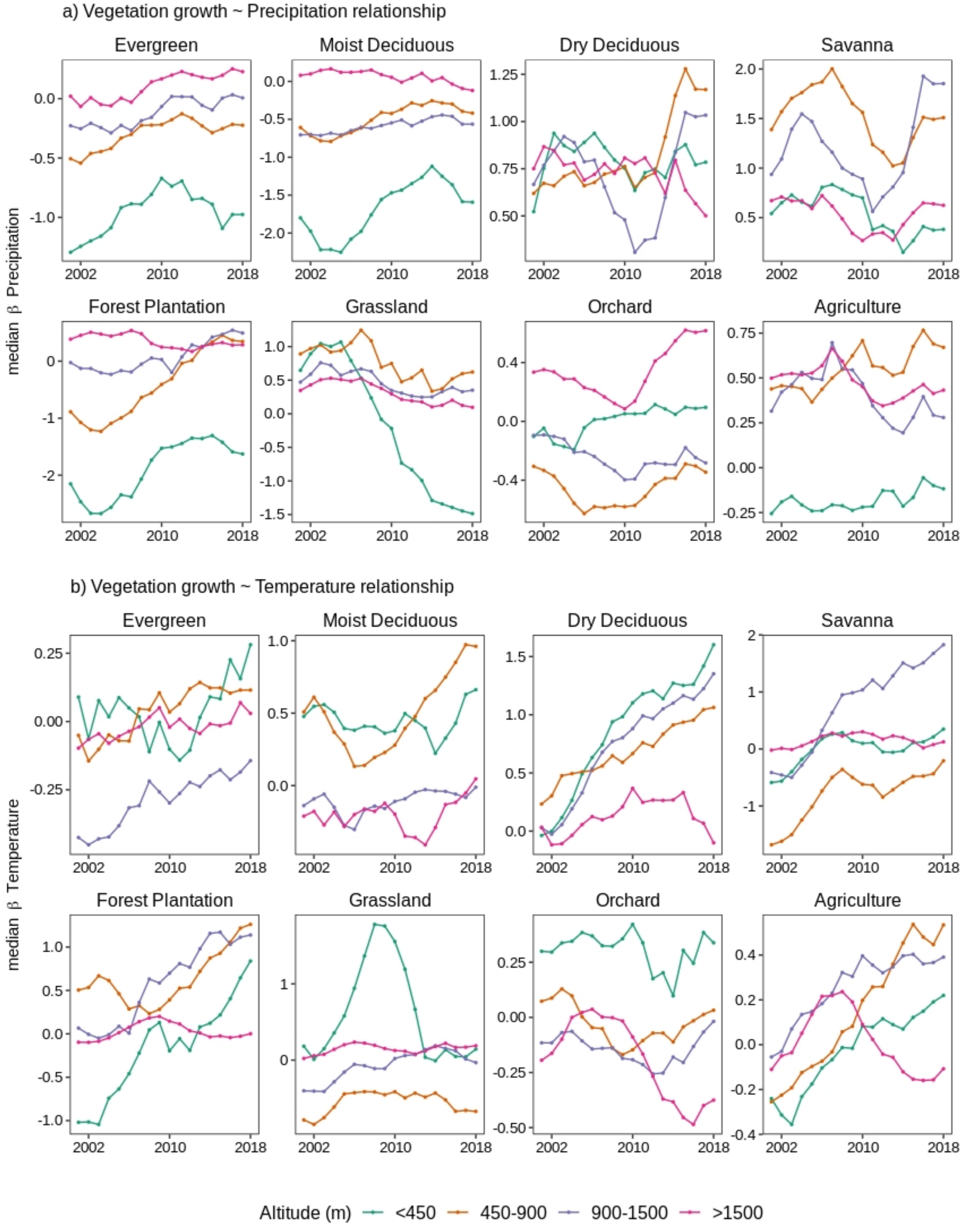


*Figure 7: Altitudinal variation in the time-varying relationship between vegetation growth and climatic variables over different land uses. Slope values indicate direction and magnitude of the sensitivity of the growth period and climatic variables. a) Annual mean slope values of vegetation growth–precipitation over four altitudinal zones. The vegetation growth showed high variation in the direction and magnitude of sensitivity to precipitation for different land uses and altitudinal zones. b) Annual mean slope values of vegetation growth–temperature over four altitudinal zones. Vegetation growth showed a growing positive trend with temperature in majority of the landuses except.*

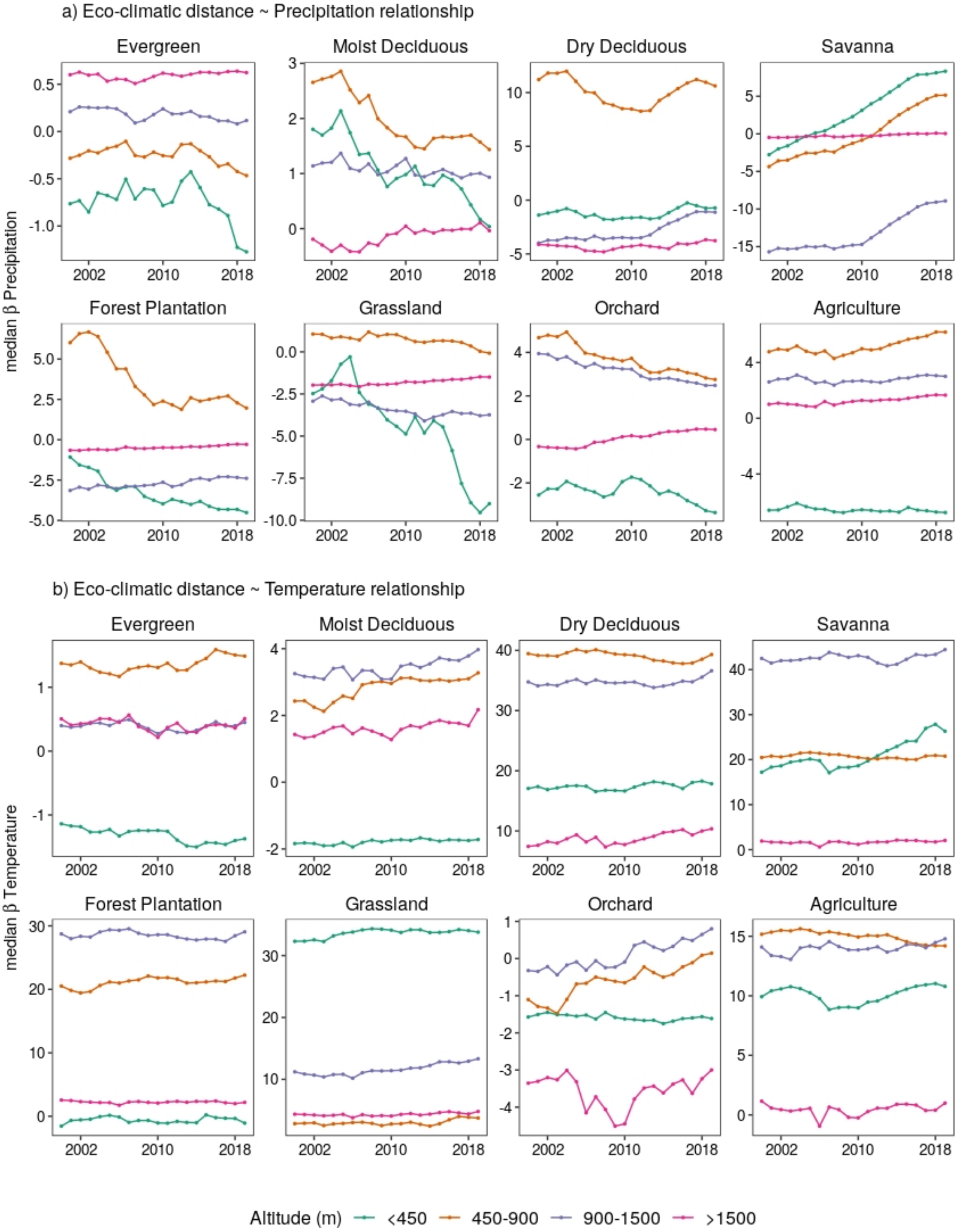


*Figure 8: Altitudinal variation in the time-varying relationship between eco-climatic distance and climatic variables over different land uses. Slope values indicate direction and magnitude of the sensitivity of eco-climatic distance and climatic variables. a) Annual mean slope values of eco-climatic distance–precipitation over four altitudinal zones. Savanna showed increasing trend in response to temperature. b) Annual mean slope values of eco-climatic distance–temperature over four altitudinal zones. A high variation in magnitude and direction of response was observed across altitudinal gradient and land use types.*

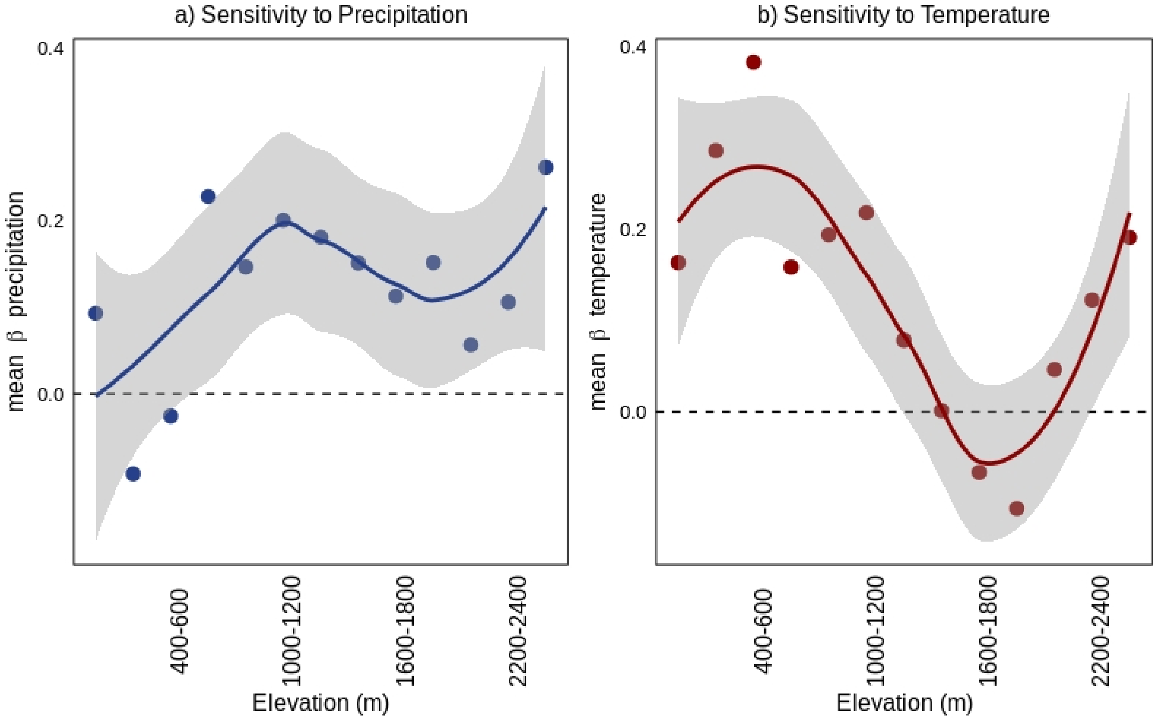


*Figure 9: Variation in the temporal trends in the time-varying slope values representing the growth period–climatic variables relationship along elevation gradient. a) Increasing sensitivity to precipitation at high and mid-altitude regions. b) Increasing sensitivity in low and high altitudes but, declining sensitivity to temperature in the altitude zone of 1600 m–2000 m.*

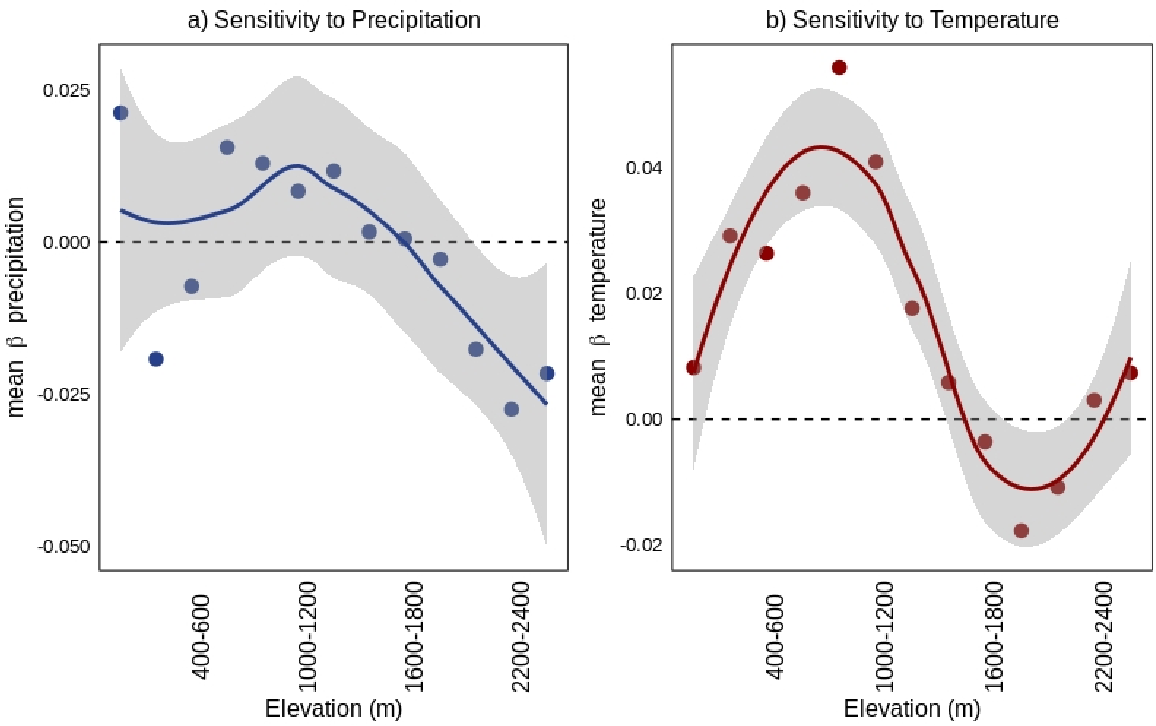


*Figure 10: Variation in temporal trends in the time-varying slope values representing vegetation growth–climatic variables relationship along elevation gradient. a) Increasing sensitivity at mid-altitude regions and declining sensitivity at high altitude regions to precipitation. b) Increasing sensitivity at mid-altitudes to temperature*

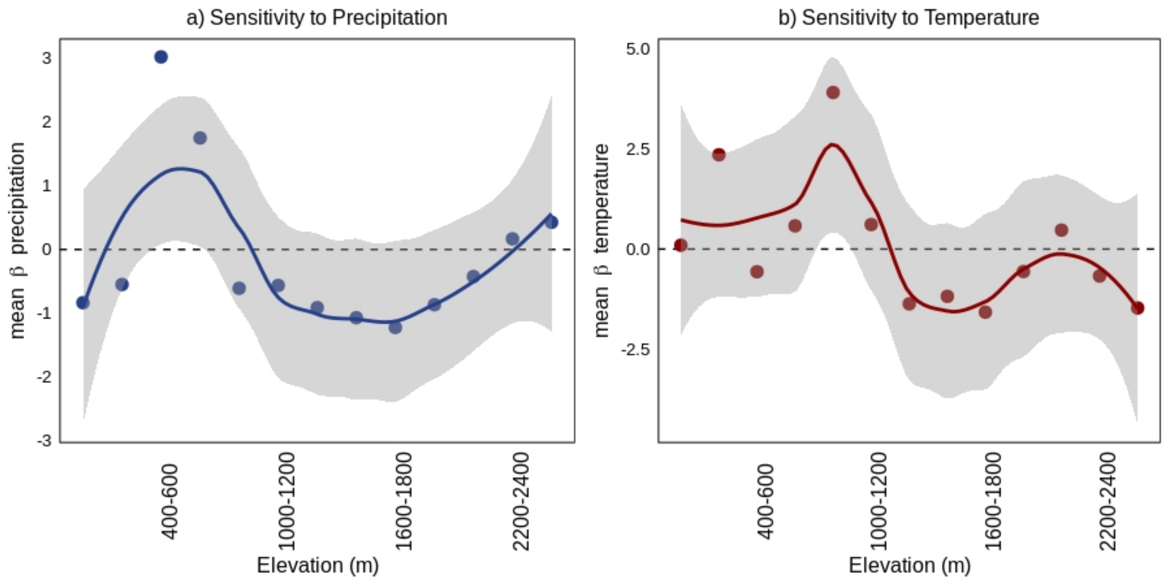


*Figure 11: Variation in the temporal trends in the eco-climatic distance–climatic anomalies relationship along an elevation gradient. Eco-climatic distance does not show any directional influence to either precipitation or temperature anomalies over altitude. a) A positive response to rainfall was observed across all altitudes with an increasing sensitivity in a narrow altitudinal range of 400 m – 800 m. b) Temperature does not have a directional positive or negative influence over elevation.*

## Discussion

The key results from our analysis of phenological variables in response to long term fluctuations of rainfall and temperature shows that there was no considerable difference in the percentage of areas witnessing increase or decrease in the length of the growth period across all land use land cover types, except grasslands which showed the highest percentage of area with an increase (Table 1). The percentage area within the NBR that witnessed an increase in the vegetation growth was higher than areas undergoing decline across all LULC. The temporal trends in the eco-climatic distance showed relatively higher percentage of area with vegetation greening than browning. However, savannas witnessed the highest percentage of area that were browning. (Table 1).

Rainfall has a positive influence on the growth period, except in the wetter forests where it was negative or close to zero. This influence was found to increase in recent times and was higher than the influence of temperature across all LULC categories and across the elevational zones (Fig. 6). Temperature had a negative influence on the growth period across all vegetation and elevation zones, except in the lower elevation dry deciduous forests with the influence becoming positive in recent years. Rainfall and temperature have a similar magnitude in their influence on vegetation growth, the influence of rainfall increased in areas above the altitude of 900 m (Fig. 7). Whereas, the influence of temperature on the vegetation growth increased at lower elevations and at the 900–1500 m zone (Fig. 7). The influence of rainfall on eco-climatic distances remained stable across all elevation and land use land cover types except for moist deciduous forests in the lower and mid elevation zones, which had witnessed a consistent decline in sensitivity. Eco-climatic distance showed no directional trend in it’s response to temperature across all land use land cover types. However, the influence of temperature was positive and higher than that of rainfall, especially in the dry deciduous forests, savanna, and grasslands. We discuss these results with respect to historical climatic trends which have shown a decline in annual rainfall total and increase in annual temperatures and the possible scenarios with future climatic shifts.

In the NBR precipitation had a growing positive effect whereas temperature had a declining negative influence on the length of the growth period. The length of the growth period is determined by events of leaf flushing and rapid leaf turnover which are dependent on the water availability and hydraulic traits of the plants (Asner et al., 2004). In tropical forests, the leaf flushing events coincide with dry season peaks, thus temperature and precipitation both play an important role (van Schaik et al., 1993). With increase in temperature, the timing of leaf fall would be early and consequent buildup of leaves to reach maturity would be delayed. In the temperate regions, warming delays the onset of autumn senescence. Whereas, in the tropical regions, such thermal constraints due to extremely low temperatures are absent. Thus temperature increase in the future is expected to decrease the growth period and vegetation growth (Workie & Debella, 2018). Precipitation is expected to induce the opposite effect of temperature, as increase in precipitation would lead to increase in soil moisture, leading to decrease in dry season; thus aiding either delayed leaf fall or rapid deployment of new leaves (Huete et al., 2006). Thus, precipitation is expected to increase the vegetation period and growth. However, the future climate regime increased variability in rainfall could lead to a reduction in the summer rainfall negating the positive influence that rainfall has on vegetation growth and length of the growth period.

The trends reported here were similar to the phenology trends observed in the South East Asian tropical region, where the extension of the growth period was attributed to the increase in the rainfall period (Suepa et al., 2016). In Africa, the timing and duration of rainfall mainly determined the timing of onset of greening and dormancy in different vegetation types (Zhang et al., 2005). Global phenology studies have shown that phenological phases like the onset of greening and dormancy are associated with temperature and latitude, with an average increase of 2 days/degree latitude and 5 days/°C (Zhang et al., 2004, 2002). However, these trends are specific to higher latitudes and for the tropical regions, it depends on precipitation, but the strength of this relationship is spatially variable (Zhang et al., 2005). For example, the tropical regions of South China do not show any significant relationship with precipitation (Cui et al., 2018) whereas large areas of

Malaysia, Myanmar, Thailand, Laos, and Vietnam showed positive correlation with precipitation (Suepa et al., 2016). These results show that phenological patterns depend on biome and land cover type.

The greening trends that has been observed in the NBR is similar to other global studies, which are based on analysis of trends in satellite based leaf area indices (Cortés et al., 2021). The net greening observed in this study is also consistent with previous global assessments (Jong et al., 2012). Relationship between eco-climatic distance and rainfall has weakened or was negative across LULC classes and elevation zones. The lack of a positive rainfall-sensitivity can be attributed to the long term rainfall induced moisture stress. This is in contrast to temperate regions where vegetation greenness was found to be influenced by temperature-induced moisture stress (Krishnaswamy et al., 2009). In the NBR, the eco-climatic distance–temperature relationship remained positive and stable across most LULC classes and elevation zones, except for wetter forest types at lower elevations (< 450m), indicating that these forest types might also be influenced by temperature-induced moisture stress.

Overall, the phenology of the NBR has shown elevation related sensitivity to climatic variables. However, the net changes of phenological variables in the NBR appear to be stable as approximately equal percentage of area experienced decrease, no change, and increase in the growth period, vegetation growth, and eco-climatic distances. There has been a general lacuna of understanding of phenological changes in the tropical regions compared to temperate regions due to paucity of long-term field observations (Chen et al., 2017; Park & Schwartz, 2015). This study tries to fill this knowledge gap by analyzing the long-term vegetation records using satellite vegetation indices. In the context of climate change, where temperature is expected to increase with increasing variation in rainfall, our study results show that historical trend in the relationship between phenology and climate variables in wetter forests is largely driven by precipitation induced moisture stress, while in drier forest types, it shows a positive and mildly increasing response to both temperature and precipitation. The physiological response of plants to water and temperature stress might help them to adapt to changing climatic stresses (Huete et al., 2006; Jones et al., 2014; McDowell et al., 2008; van Schaik et al., 1993; Vicente-Serrano et al., 2013). However, extreme moisture constraints might prevent such adaptations. Understanding this would require long term monitoring and experimental studies, both in the wetter and drier vegetation types, especially as historical trends suggests differences in phenological response and in the strength and direction of the relationship with temperature and rainfall.

## References

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Tank, A. M. G. K., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Kumar, K. R., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D. B., Burn, J., Aguilar, E., Brunet, M., … Vazquez-Aguirre, J. L. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, *111*(D5). https://doi.org/10.1029/2005JD006290

Asner, G. P., Nepstad, D., Cardinot, G., & Ray, D. (2004). Drought stress and carbon uptake in an Amazon forest measured with spaceborne imaging spectroscopy. *Proceedings of the National Academy of Sciences*, *101*(16), 6039–6044. https://doi.org/10.1073/pnas.0400168101

Barr, A. G., Black, T. A., Hogg, E. H., Kljun, N., Morgenstern, K., & Nesic, Z. (2004). Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. *Agricultural and Forest Meteorology*, *126*(3), 237–255. https://doi.org/10.1016/j.agrformet.2004.06.011

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*, 222–235. https://doi.org/10.1016/j.agrformet.2017.01.002

Cleland, E. E., Chuine, I., Menzel, A., Mooney, H. A., & Schwartz, M. D. (2007). Shifting plant phenology in response to global change. *Trends in Ecology & Evolution*, *22*(7), 357–365. https://doi.org/10.1016/j.tree.2007.04.003

Condit, R., Hubbell, S. P., & Foster, R. B. (1996). Assessing the response of plant functional types to climatic change in tropical forests. *Journal of Vegetation Science*, *7*(3), 405–416.

Cortés, J., Mahecha, M. D., Reichstein, M., Myneni, R. B., Chen, C., & Brenning, A. (2021). Where Are Global Vegetation Greening and Browning Trends Significant? *Geophysical Research Letters*, *48*(6), e2020GL091496. https://doi.org/10.1029/2020GL091496

Cui, L., Shi, J., & Ma, Y. (2018). Temporal and spatial variations of the thermal growing season in China during 1961–2015. *Meteorological Applications*, *25*(1), 56–65. https://doi.org/10.1002/met.1669

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, *2*, 1–21. https://doi.org/10.1038/sdata.2015.66

Gao, M., Piao, S., Chen, A., Yang, H., Liu, Q., Fu, Y. H., & Janssens, I. A. (2019). Divergent changes in the elevational gradient of vegetation activities over the last 30 years. *Nature Communications*, *10*(1), 2970. https://doi.org/10.1038/s41467-019-11035-w

Herrick, J. D., & Thomas, R. B. (2003). Leaf senescence and late-season net photosynthesis of sun and shade leaves of overstory sweetgum (Liquidambar styraciflua) grown in elevated and ambient carbon dioxide concentrations. *Tree Physiology*, *23*(2), 109–118. https://doi.org/10.1093/treephys/23.2.109

Huete, A. R., Didan, K., Shimabukuro, Y. E., Ratana, P., Saleska, S. R., Hutyra, L. R., Yang, W., Nemani, R. R., & Myneni, R. (2006). Amazon rainforests green-up with sunlight in dry season. *Geophysical Research Letters*, *33*(6), L06405. https://doi.org/10.1029/2005GL025583

Hulme, M., Barrow, E. M., Arnell, N. W., Harrison, P. A., Johns, T. C., & Downing, T. E. (1999). Relative impacts of human-induced climate change and natural climate variability. *Nature*, *397*(6721), 688–691. https://doi.org/10.1038/17789

Jones, M. O., Kimball, J. S., & Nemani, R. R. (2014). Asynchronous Amazon forest canopy phenology indicates adaptation to both water and light availability. *Environmental Research Letters*, *9*(12), 124021. https://doi.org/10.1088/1748-9326/9/12/124021

Jong, R. de, Verbesselt, J., Schaepman, M. E., & Bruin, S. de. (2012). Trend changes in global greening and browning: Contribution of short-term trends to longer-term change. *Global Change Biology*, *18*(2), 642–655. https://doi.org/10.1111/j.1365-2486.2011.02578.x

Krishnaswamy, J., Bawa, K. S., Ganeshaiah, K. N., & Kiran, M. C. (2009). Quantifying and mapping biodiversity and ecosystem services: Utility of a multi-season NDVI based Mahalanobis distance surrogate. *Remote Sensing of Environment*, *113*(4), 857–867. https://doi.org/10.1016/j.rse.2008.12.011

Krishnaswamy, J., John, R., & Joseph, S. (2014). Consistent response of vegetation dynamics to recent climate change in tropical mountain regions. *Global Change Biology*, *20*(1), 203–215. https://doi.org/10.1111/gcb.12362

Lichtenthaler, H. K., & Babani, F. (2004). Light Adaptation and Senescence of the Photosynthetic Apparatus. Changes in Pigment Composition, Chlorophyll Fluorescence Parameters and Photosynthetic Activity. In G. C. Papageorgiou & Govindjee (Eds.), *Chlorophyll a Fluorescence: A Signature of Photosynthesis* (pp. 713–736). Springer Netherlands. https://doi.org/10.1007/978-1-4020-3218-9_28

Linderholm, H. W. (2006). Growing season changes in the last century. *Agricultural and Forest Meteorology*, *137*(1), 1–14. https://doi.org/10.1016/j.agrformet.2006.03.006

McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D. G., & Yepez, E. A. (2008). Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? *New Phytologist*, *178*(4), 719–739. https://doi.org/10.1111/j.1469-8137.2008.02436.x

Menzel, A., & Fabian, P. (1999). Growing season extended in Europe. *Nature*, *397*(6721), 659–659.

Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F. M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., … Zust, A. (2006). European phenological response to climate change matches the warming pattern. *Global Change Biology*, *12*(10), 1969–1976. https://doi.org/10.1111/j.1365-2486.2006.01193.x

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G., & Nemani, R. R. (1997). Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, *386*(6626), 698–702. https://doi.org/10.1038/386698a0

Norby, R. J., Hartz-Rubin, J. S., & Verbrugge, M. J. (2003). Phenological responses in maple to experimental atmospheric warming and CO2 enrichment. *Global Change Biology*, *9*(12), 1792–1801. https://doi.org/10.1111/j.1365-2486.2003.00714.x

Nord, E. A., & Lynch, J. P. (2009). Plant phenology: A critical controller of soil resource acquisition. *Journal of Experimental Botany*, *60*(7), 1927–1937. https://doi.org/10.1093/jxb/erp018

Park, I. W., & Schwartz, M. D. (2015). Long-term herbarium records reveal temperature-dependent changes in flowering phenology in the southeastern USA. *International Journal of Biometeorology*, *59*(3), 347–355. https://doi.org/10.1007/s00484-014-0846-0

Peñuelas, J., Rutishauser, T., & Filella, I. (2009). Phenology Feedbacks on Climate Change. *Science*, *324*(5929), 887–888. https://doi.org/10.1126/science.1173004

Reich, P. B. (1995). Phenology of tropical forests: Patterns, causes, and consequences. *Canadian Journal of Botany*, *73*(2), 164–174. https://doi.org/10.1139/b95-020

Richardson, A. D., Andy Black, T., Ciais, P., Delbart, N., Friedl, M. A., Gobron, N., Hollinger, D. Y., Kutsch, W. L., Longdoz, B., Luyssaert, S., Migliavacca, M., Montagnani, L., William Munger, J., Moors, E., Piao, S., Rebmann, C., Reichstein, M., Saigusa, N., Tomelleri, E., … Varlagin, A. (2010). Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1555), 3227–3246. https://doi.org/10.1098/rstb.2010.0102

Steltzer, H., & Post, E. (2009). Seasons and Life Cycles. *Science*, *324*(5929), 886–887. https://doi.org/10.1126/science.1171542

Suepa, T., Qi, J., Lawawirojwong, S., & Messina, J. P. (2016). Understanding spatio-temporal variation of vegetation phenology and rainfall seasonality in the monsoon Southeast Asia. *Environmental Research*, *147*, 621–629.

Trujillo, E., Molotch, N. P., Goulden, M. L., Kelly, A. E., & Bales, R. C. (2012). Elevation-dependent influence of snow accumulation on forest greening. *Nature Geoscience*, *5*(10), 705–709. https://doi.org/10.1038/ngeo1571

van Schaik, C. P., Terborgh, J. W., & Wright, S. J. (1993). The Phenology of Tropical Forests: Adaptive Significance and Consequences for Primary Consumers. *Annual Review of Ecology and Systematics*, *24*(1), 353–377. https://doi.org/10.1146/annurev.es.24.110193.002033

Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., & Sanchez-Lorenzo, A. (2013). Response of vegetation to drought time-scales across global land biomes. *Proceedings of the National Academy of Sciences*, *110*(1), 52–57. https://doi.org/10.1073/pnas.1207068110

White, M. A., Thornton, P. E., & Running, S. W. (1997). A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles*, *11*(2), 217–234. https://doi.org/10.1029/97GB00330

Workie, T. G., & Debella, H. J. (2018). Climate change and its effects on vegetation phenology across ecoregions of Ethiopia. *Global Ecology and Conservation*, *13*, e00366. https://doi.org/10.1016/j.gecco.2017.e00366

Zhang, X., Friedl, M. A., Schaaf, C. B., & Strahler, A. H. (2004). Climate controls on vegetation phenological patterns in northern mid-and high latitudes inferred from MODIS data. *Global Change Biology*, *10*(7), 1133–1145.

Zhang, X., Friedl, M. A., Schaaf, C. B., Strahler, A. H., Hodges, J. C., & Gao, F. (2002). Using MODIS data to study the relation between climatic spatial variability and vegetation phenology in northern high latitudes. *IEEE International Geoscience and Remote Sensing Symposium*, *2*, 1149–1151.

Zhang, X., Friedl, M. A., Schaaf, C. B., Strahler, A. H., & Liu, Z. (2005). Monitoring the response of vegetation phenology to precipitation in Africa by coupling MODIS and TRMM instruments. *Journal of Geophysical Research: Atmospheres*, *110*(D12).

# Impacts of climate variability on hydrological services

Rajat Ramakant Nayak*, Srinivas Vaidyanathan* and Jagdish Krishnaswamy#

## Highlights

- Rainfall that is converted to surface flows and groundwater has increased at a rate of nearly 1% per decade between 2001–2020 in the Nilgiri Biosphere Reserve.
- While there is an overall increase in water available as surface flows and groundwater, there has been a decline from 2016 onwards.
- In large parts of the Nilgiri Biosphere Reserve, blue water was more sensitive to rainfall than to temperature trends.
- At higher elevations, temperature had a negative influence, while rainfall had negligible influence on blue water.

## Abstract

Climate change has a direct impact on hydrological cycles. In many parts of the world, a decrease in water quantity has been evident over the years. Similarly, an increased water discharge resulting in large floods have also been observed in many parts of the world. The Western Ghats, a global biodiversity hotspot, has witnessed both a shortage in drinking water and stream-flow during the dry season, and devastating floods during the monsoon. However, there are no long-term studies available from India that establishes a relationship between fresh water availability and climate variations. To understand the impacts of temperature and rainfall on hydrological services, in this study, we analysed the trends in blue water availability in the Nilgiri Biosphere Reserve (NBR) as a function of time-varying temperature and rainfall between the periods 2001 and 2019-2020. Blue water refers to the amount of water available as surface flows and groundwater and which is available for irrigation, domestic purposes, power generation, and is important for maintaining ecological processes. Large parts (55.32%) of the NBR did not show any trends in blue water. We observed significant monotonic declines in the blue water in nearly 6.75% of the area in the NBR, while a significant increase was observed in 37.93% of the area. Among the different vegetation types considered, agricultural landscape showed maximum increase (51% of the area) in blue water. Among the natural land covers, savanna and scrub showed a maximum increase in blue-water

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(49.5%) followed by forest plantations (45.3%) and high-altitude grasslands (40.5%). Blue-water trends in deciduous forests were found to be more sensitive to change in temperature and showed an increasing response to temperature, while in evergreen forests trends were sensitive to rainfall patterns and showed an increasing response to rainfall. In high elevations blue-water trends were more sensitive to temperature trends and showed a negative response to temperature. Segmented regression of median trend values indicates an increase in blue-water upto 2015 – 2016 and a decrease thereafter. As blue-water – rainfall and temperature slopes show positive cofficient in recent time, the recent declining trend suggest the role of other climatic and anthropogenic factors in influencing blue water trends. An understanding of climate variability and hydrological trends, and spatial distribution of trends could help in developing better regional water resilience models to climate change.

## Introduction

Natural ecosystems provide a large number of provisional and regulatory services (Brauman et al., 2007; Daily, 1997; Daily et al., 2009; Mooney et al., 1997). One such important group of services is hydrological services, which refer to a range of regulatory and provisioning services including evapotranspiration, discharge as stream flows, soil moisture retention, mitigation of water damage, and recharge of ground water (Brauman, 2015; Brauman et al., 2007). These water services are inarguably the most important services and an alteration in these services could have a direct influence on human well-being (Alcamo et al., 2003; Millennium Ecosystem Assessment, 2005). Recent research has found that climate change has drastically altered some of these hydrological processes and services globally. There are evidences of an increase as well as a decrease in water quantity globally, which have been attributed to climate change (Abedin et al., 2019; Brown et al., 2019; Milly et al., 2002, 2005; Tabari, 2020). For example, in many parts of India, a significant increase in extreme rainfall and flood risks have been documented (Guhathakurta et al., 2011), while a decrease in stream-flow and rainfall has been observed in parts of the Western Ghats in India (Mudbhatkal et al., 2017). Similarly, there has been an increase in flood events in North China (Zhou et al., 2013). In Australia, declines in stream-flows have been observed in sub-humid and semi-arid landscapes as a result of increased water use by plants under elevated concentrations of $CO_2$ (Ukkola et al., 2015). An increase in temperature along with elevated $CO_2$ concentrations could increase transpiration losses in plants and evaporation losses from surface, resulting in a decrease in total available water on the surface and in soil (Falkenmark & Rockström, 2010; Leakey et al., 2009; Ukkola et al., 2015). On the other hand, an increase in rainfall could act in the opposite direction resulting in an increase in overall water availability on the surface and in the soil (Brauman et al., 2007). Understanding the influence of climate variability on these services and identifying areas undergoing rapid changes is essential to develop effective watershed management plans and adapting to changing climate for the future well-being of humans.

The Western Ghats is one of the global hotspots of biodiversity (Mittermeier et al., 2004; Myers et al., 2000). This long chain of mountains is known for its tropical forests and receives one of the highest rainfalls in the world. It forms the headwaters of six major river basins which are the lifeline of a large part of the human population in South India (WRIS 2020, https://indiawris.gov.in/wris/#/). In recent times, there has been an increase in the number of reports on scarcity of drinking water (Iqbal, 2019; Nair, 2017) and reduced stream flows (Mudbhatkal et al., 2017) from several parts of the Western Ghats. Recent estimates suggest that the region "will have 81 million people with insufficient water by 2050" (McDonald et al., 2011). On the other hand, from many other parts of the Western Ghats, there have been reports of increase in flood events (Menon, 2019; Safi, 2018) and increased stream flows (Mudbhatkal et al., 2017). However, there are no long-term landscape level studies available from India that establishes a relationship between climate variations and water supply. Anecdotal evidences as well as analysis of long-term climate trends suggest a slight change in rainfall and temperature patterns throughout the Western Ghats (Krishnaswamy et al., 2015; Ramachandra & Bharath, 2020). In view of these uncertainties, a long term trend analysis of climate variables and water services could help in understanding our regional ecosystems better. In order to develop climate change resilience such an understanding and a study exploring these patterns is essential.

The Western Ghats, much like many other parts of India, are poorly gauged and field measurements of hydro-meteorological parameters are sparse. Under these circumstances the only way to understand the influence of changing climate on hydrological services is to use remotely sensed products. In this study, we analyse the trends in two important climatic parameters, rainfall and temperature, and trends in water supply using blue water as a proxy between the periods 2001 and 2019-2020. Blue water refers to the amount of water available as surface flows and groundwater and which is available for irrigation, domestic purposes, power generation, and is important for maintaining ecological processes. We undertook this study in the Nilgiri Biosphere Reserve (NBR), the first biosphere reserve in India, established in 1986. The NBR is spread across three Indian states covering an area > 5000 $km^2$ and has diverse vegetation types ranging from savanna woodlands to deciduous forests to evergreen forests and high-altitude grasslands. The NBR also forms an important catchment area for several perennial rivers including the Kaveri and Bhavani, on which large human populations living downstream are dependent on. There are many uncertainties with respect to rainfall trends among global and regional future climate projection models, for example, some global models suggest an increase in rainfall in the Western Ghats (Milly et al., 2002), while some predict overall decrease in rainfall in the Western Ghats (Varghese et al., 2020). Similarly, both increases and decreases in evapotranspiration have been reported at the global scale (Gedney et al., 2006; Piao et al., 2007). Our study provides a historical trend in blue water and its response to climatic variabilities which could be used in taking informed decisions under future climate change scenarios at a regional scale. Understanding the spatio-temporal trends could help in identifying areas undergoing rapid changes, which should be managed to build water resilience locally under the ongoing climate change scenario.

## Methods

We derived an annual blue water estimate by using remotely sensed eight-day composite net evapotranspiration data and the daily rainfall dataset for the Western Ghats from 2001 to 2019-2020. In this study we followed the definition of a water year to define an annual dataset, which begins on June 1$^{st}$ and ends on May 31$^{st}$. We analysed trends in blue water over this period and the influence of rainfall and temperature on these trends using dynamic linear models.

### *Deriving Blue water*

The overall framework to derive blue water is the water balance equation, which is defined as follows,

$$P = ET + R + D + \Delta S \qquad (1)$$

where, P is precipitation, ET is evapotranspiration, R is surface runoff or stream-flow, D is ground water discharge, and ΔS is change in soil-water storage. This can be simplified to,

$$P = ET + Q + \Delta S \qquad (2)$$

where, Q = R +D or the total runoff which includes surface, base flows, and inter-flow (Zhang et al., 2004).

Change in soil-water storage is assumed to be a constant over annual time periods, and thus the equation can be further simplified as,

$$P = ET + Q \qquad (3)$$

As per equation 3, if we can measure ET (or green water) and assume the term $\Delta S$ to be constant, we can determine the proportion of surface water, Q, which is blue water (Zhang et al., 2001). Thus the equation for blue water is

$$Q = P - ET \tag{4}$$

We used MODIS (Moderate Resolution Imaging Spectroradiometer) eight-day composite net evapotranspiration product (MOD16A2 version 6) (Running et al., 2017), available at a resolution of 500 m globally, to derive annual net evapotranspiration product for the Western Ghats. Steps involved with pre-processing of this product, removal of bad-pixels, and gap-filling details are provided in Annexure I of this report.

For rainfall data we used the daily Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) product (Funk et al., 2015) and aggregated it to the annual data and resampled to a 500 m resolution.

We derived blue water from these precipitation and ET products using equation 4. We compared the performance of the derived blue water product with stream-discharge data recorded at Muthankera ground station (Central Water Commission http://www.cwc.gov.in/) located upstream of the Kabini reservoir within the NBR boundary. The values obtained from satellite based derived products was less than the actual discharges measured at the ground stations. However, it followed a pattern similar to that recorded from the ground station data, thus validating our approach (Fig. 1). For better presentation of the data we have used a ratio of annual blue water to annual rainfall (Q/P) (henceforth referred as blue water) in the analysis.

***Analysis***

We used dynamic linear models (DLM) to analyse trends in blue water and the influence of climate variables—annual rainfall and mean annual temperature—on these trends, which we expected to vary with time. We used MODIS eight-day land surface temperature product (MOD11A2) to obtain the annual mean temperature layer (Refer Annexure I for preprocessing details of this product). The climatic variables were scaled and centred for the analysis.

As we have used scaled and centred values of covariates, the time-varying intercept from the DLM represents the changing baseline of blue water with reference to long term averages of annual rainfall and mean annual temperature. We further analysed monotonic increase or decrease in blue water trends in the Western Ghats using Sen’s slope (Sen, 1968). Time-varying slopes from the

DLM indicates the strength of the relationship between the response variable and the covariate. The trend analysis using Sen's slope on this relationship indicates the growing or declining influence of the covariates with respect to its long term influence on the response variable (Refer Annexure II for details on analytical methods).

We performed a segmented regression analysis on the time-varying intercept to detect breakpoints at which a drastic directional change in linear trend was observed (Refer Annexure II for details on analytical methods).

We expected these trends to vary with different vegetation types. Hence, we also analysed trends across different land cover types in the NBR. In addition, we looked at the influence of elevation on these observed trends. An analysis of the median intercepts and slopes from the DLM model and a segmented regression on these median values was used to summarise the observed trends in blue water and the evolving nature of the blue water–climate relationship across the NBR.

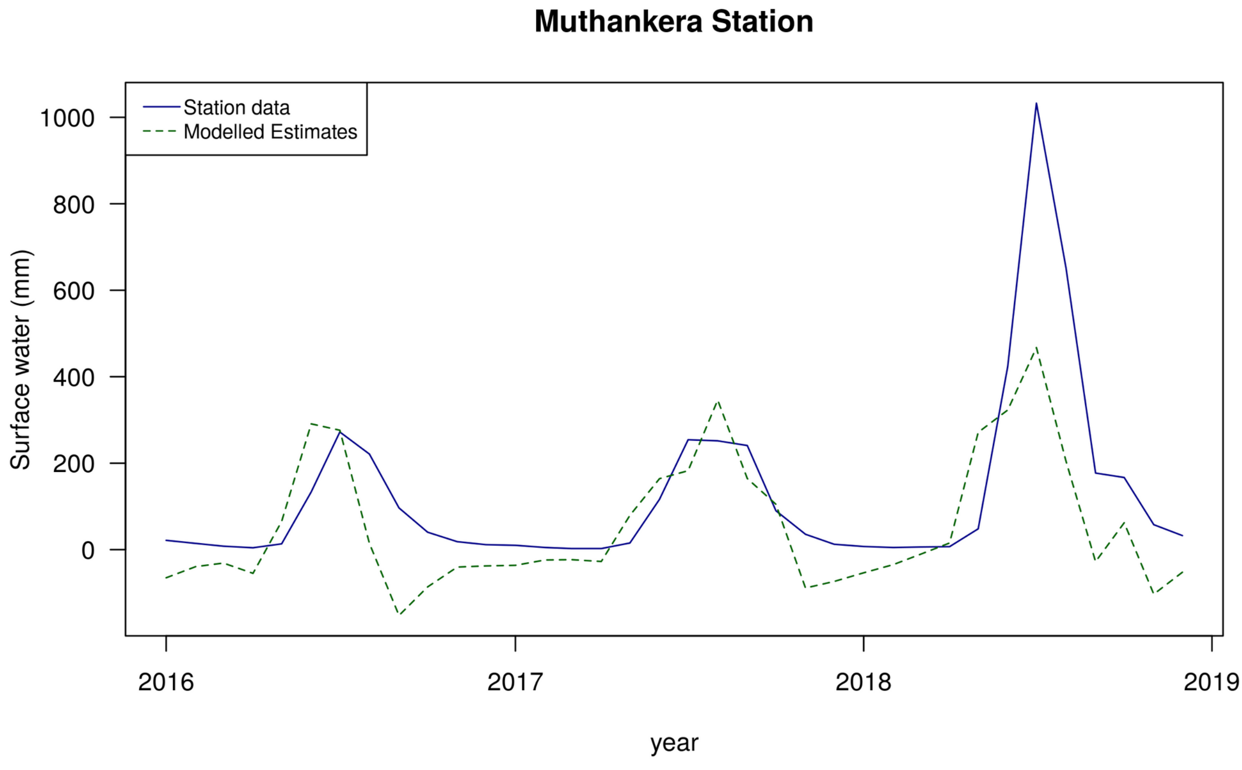


*Figure 1: We compared the performance of the derived blue water product with stream-discharge data recorded at the Muthankera ground station (Central Water Commission http://www.cwc.gov.in/) located upstream of the Kabini reservoir within the NBR boundary. We found our derived product to follow a pattern similar to that recorded from the ground station data.*

## Results

### *Trends in blue water*

The median annual blue water to rainfall ratio over the period 2001–2019 was 0.23 suggesting that nearly 23% of the annual rainfall was being converted into surface and ground water flows in the NBR. Among the different land cover types, evergreen and moist deciduous forests had the maximum blue water with a blue water to rainfall ratio of 0.27 each, followed by grasslands (0.22). Savanna and scrubs had the lowest ratio (0.17) followed by forest plantations (0.18), which mainly included *Acacia*, *Eucalyptus*, and teak.

Monotonic trend analysis using Sen's slope on blue water shows a significant change in trends in nearly 18.9% of the landscape. Whereas, the DLM approach, which accounts for the trends in climatic covariates, shows changes in blue water trends in nearly half of the NBR (44.7%).

The time-varying intercept from the DLM represents the changing baseline of blue water with reference to long term average of rainfall and temperature. A monotonic trend analysis of this intercept indicated that nearly 45% of the NBR has experienced a significant change in blue water trends over the last two decades. More areas experienced a significant increase in blue water (37.93%) compared to areas that experienced a significant decreasing trend (6.75%) (Fig. 2). The overall trend in DLM intercept values suggested that the blue water has increased at a rate of nearly 1% per decade between 2001 and 2020.

All land use land cover types showed higher percentage of area with an increase in blue water. Among different natural land use land cover types, area under savanna and scrub, showed maximum increase in blue water (49.51%), followed by areas dominated by forest plantations (45.29%) and grasslands (40.54%) (Table 1). Deciduous forests (moist and dry deciduous) had the lowest net increase in blue water in the landscape (Table 1).

A pixelwise segmented regression and breakpoint analysis on the DLM intercepts suggests a spatial clumping of breakpoint years in the landscape (Fig. 3). Breakpoints were observed as early as 2002, and up to 2018, with maximum breakpoints observed in 2016 (17%) (Fig. 4). Evergreen forests, mainly distributed in the south-western part of the landscape, showed three distinct peaks in breakpoints—the first peak occurring in 2007, second one in 2011, and the third peak occurring in 2016 (Fig. 4). Moist deciduous forests also showed a similar trend in the distribution of breakpoints. Orchards, which mainly composed of tea and coffee plantations showed maximum number of breakpoints in 2011 and in 2016 (Figs. 2&4). Whereas, dry deciduous forests and forest plantations, which are mainly distributed in the northern (Nagarhole, Waynad and Bandipur), central, and southern parts of the NBR showed maximum number of breakpoints in 2016. High altitude montane grasslands also showed maximum breakpoints in 2016. Although savanna/scrub forests, distributed in the central parts covering the Sathyamangalam and Bandipur Tiger Reserves, showed maximum number of breakpoints in 2016, nearly 31% of all breakpoints were observed between 2006 and 2008 (Figs. 2,3,&4). Distribution of regression slopes indicated that slopes prior to breakpoint were predominantly positive suggesting an increasing trend in blue water in the initial years in large parts of the landscape (Figs. 3 a & b). Slopes post-breakpoint are predominantly negative, suggesting a decreasing trend in blue water in the recent years in large parts of the landscape (Figs. 3a&b). This trend was consistent across all the land cover/land use types considered in the study.

*Table 1: Percentage of area under different land cover types showing significant increase or decrease in blue water to rainfall ratios in the NBR. Increase or decrease refers to significant monotonic trends obtained by running Sen's slope on blue water trends (DLM intercept). Savanna and agricultural areas show relatively higher increase in blue water over the years.*

| **Land use/Land cover** | **%Decrease** | **%Increase** | **%Net change** |
|---|---|---|---|
| Evergreen | 5.59 | 31.44 | +25.85 |
| Moist deciduous | 11.94 | 28.42 | +16.48 |
| Dry deciduous | 8.65 | 33.58 | +24.93 |
| Savanna/scrub | 3.75 | 49.51 | +45.75 |
| Grassland | 5.27 | 40.54 | +35.27 |
| Forest plantation | 3.99 | 45.29 | +41.30 |
| Orchards | 4.37 | 44.34 | +39.97 |
| Agriculture | 3.09 | 51.43 | +48.33 |

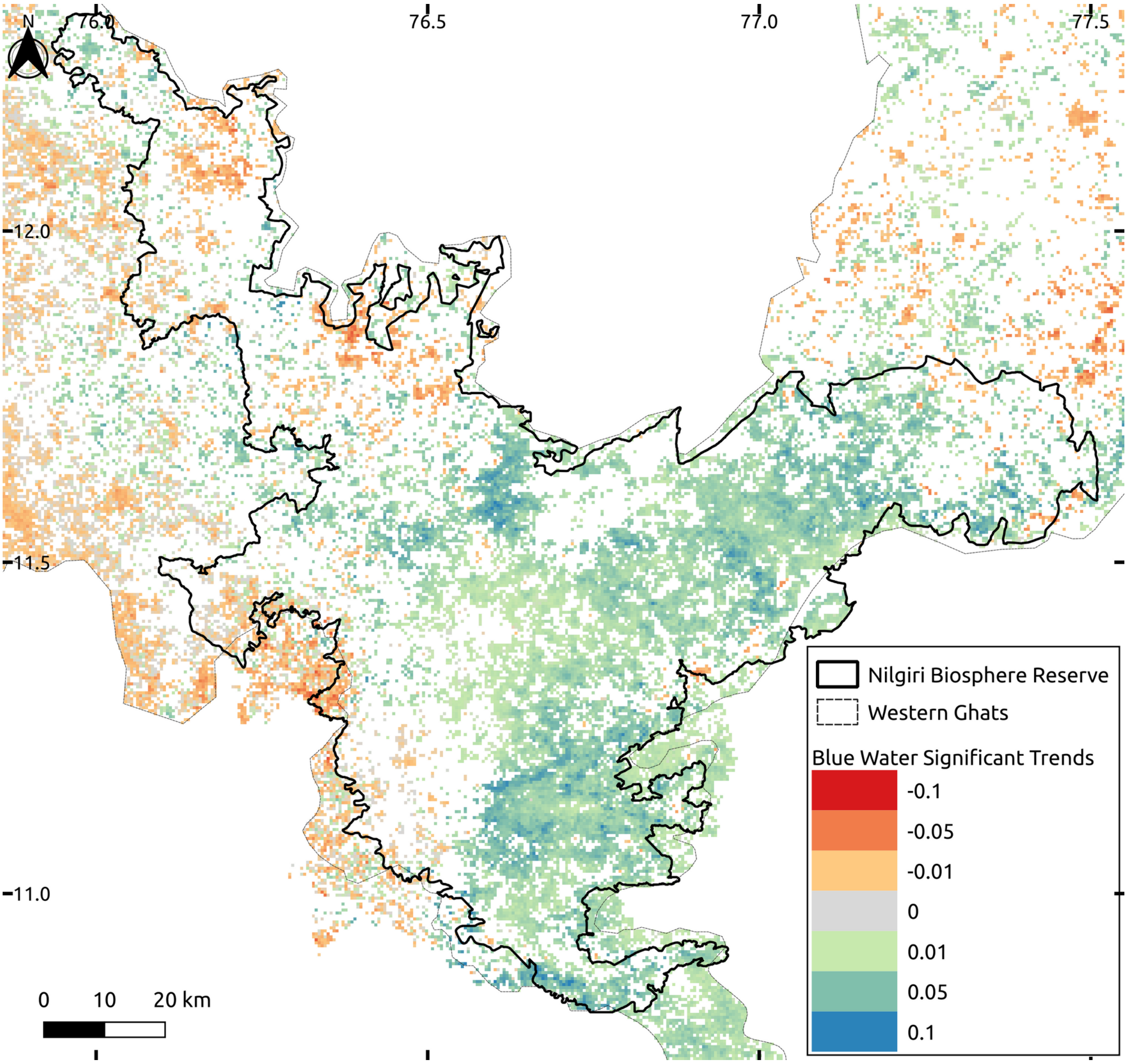


*Figure 2: Climate corrected trends in blue water to rainfall ratio across the Nilgiri Biosphere Reserve between 2001 and 2019 (water year starting from June 1 and ending on May 31). Monotonic trend analysis of blue water suggested an increase in water quantity in 38% of the area in the Nilgiris Biosphere Reserve, and a significant decline in 7% of the areas.*

### *Blue water-climate trends*

Our DLM analysis provided time-varying slopes which indicates the strength of the relationship between the blue water and the changing temperature and rainfall. Monotonic trend analysis of the blue water–temperature slopes suggested that, in nearly 54% of the area, temperature had a significant influence on blue water trends. Around 29% of the area in the NBR showed a significant increasing response of blue water to temperature, while 25% of the area showed a significant decreasing response to temperature (Fig. 5a).

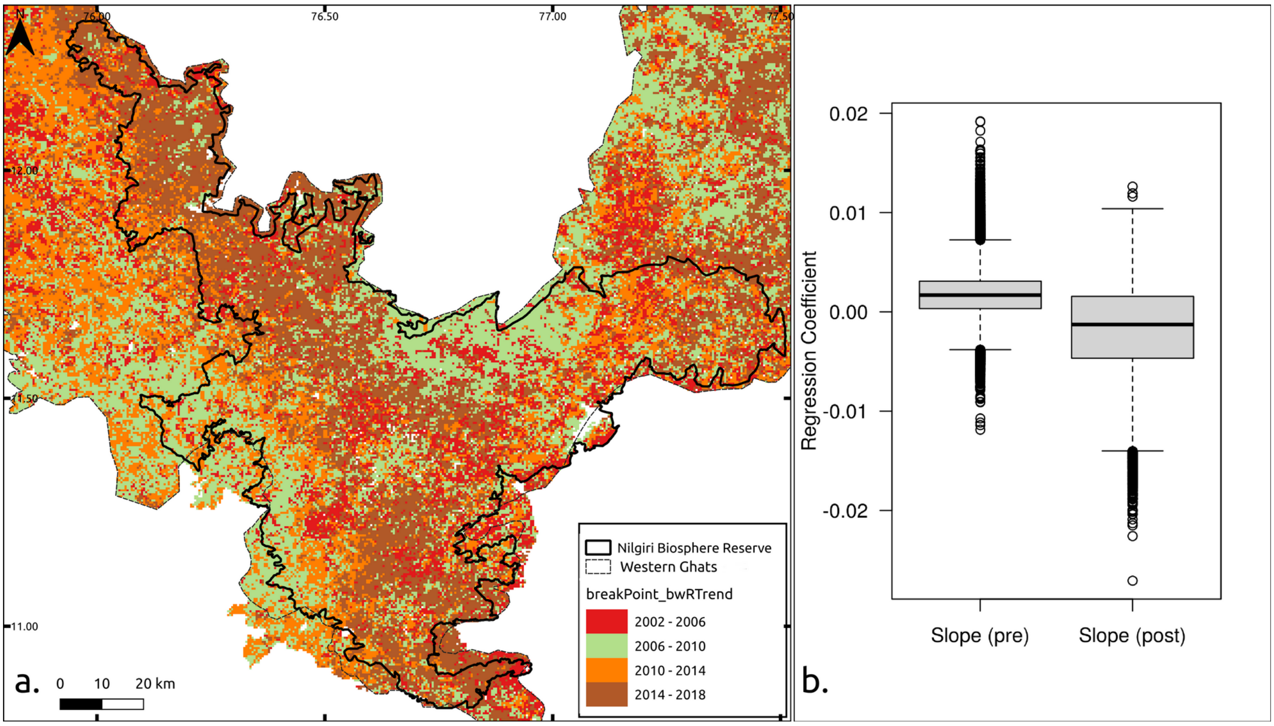


*Figure 3: a) Spatial distribution of breakpoint years (significant) in the Nilgiri Biosphere Reserve shows some amount of spatial clumping of breakpoint years with maximum breakpoints observed in 2016 (17%); (b). Blue water trends were predominantly positive before the breakpoint (positive slopes), while trends were negative post-breakpoint (right panel).*

Rainfall influence on blue water was more prominent in the landscape with more than 66% of the area showing a response of blue water to rainfall variabilities. We found a significant decline in the influence of rainfall on blue water in 41.70% of the NBR landscape, while a significant increase in this influence was observed in 24.87% of the landscape (Fig. 5b). There was a clear east to west gradient in blue water–rainfall coefficient—positive response in the western parts and a negative response in the eastern parts of the NBR was observed.

Among the natural land cover types considered, drier vegetation types, including the savanna/scrub and dry deciduous forests, showed an increase in blue water response to temperature while all other land use land cover types showed a decrease in blue water response to temperature. Savanna and scrub had the maximum area (37.6%) with a net increase in blue water as a response to temperature trends (Table 2). Grasslands had the maximum decreasing response in blue water to temperature (Table 2). Evergreen (35.7%) and moist deciduous forests (10.16%) showed maximum net increase in blue water –rainfall trends while dry deciduous and savanna had higher area showing a negative response in blue water to rainfall (Table 2).

***Blue water–elevation relationship***

Blue water trends were mostly positive across the elevation gradient, and slightly lower median values were recorded at low elevations < 250 m, and at elevations > 2000 m (Fig. 6a). Response of blue water to temperature showed much variation along the elevation gradient. The median of blue water–temperature coefficient was largely positive at elevations < 1000 m, while it was negative at elevations > 1000 m (Fig. 6b). Rainfall had a positive influence on blue water at elevation < 250 m, and for elevations > 250 m, blue water–rainfall coefficient was largely negative (Fig. 6c).

***Blue water and other factors***

An analysis of the residuals of the DLM model suggested that less than 2% of the area in the NBR showed a significant increase (1.6%) or decrease (0.1%) in blue water due to factors other than rainfall and temperature, such as land use land cover changes, and other anthropogenic pressures.

*Table 2: Percentage of area under different land cover types showing significant increase or decrease in response of blue water to temperature and rainfall in the NBR. Increase or decrease refers to significant monotonic trends obtained from running Sen's slope on blue water–climtic variable coefficients.*

| | **Temperature** | | **Rainfall** | |
|---|---|---|---|---|
| **Land use/Land cover** | **%Decrease** | **%Increase** | **%Decrease** | **%Increase** |
| Evergreen | 30.62 | 4.33 | 19.67 | 55.38 |
| Moist deciduous | 25.80 | 16.06 | 18.26 | 28.42 |
| Dry deciduous | 20.62 | 35.68 | 44.77 | 33.58 |
| Savanna/scrub | 16.71 | 54.31 | 59.50 | 49.51 |
| Grassland | 38.18 | 12.13 | 46.36 | 40.54 |
| Forest plantation | 40.18 | 4.06 | 39.07 | 45.29 |
| Orchards | 41.93 | 6.53 | 42.73 | 44.34 |
| Agriculture | 32.93 | 30.73 | 53.79 | 51.43 |

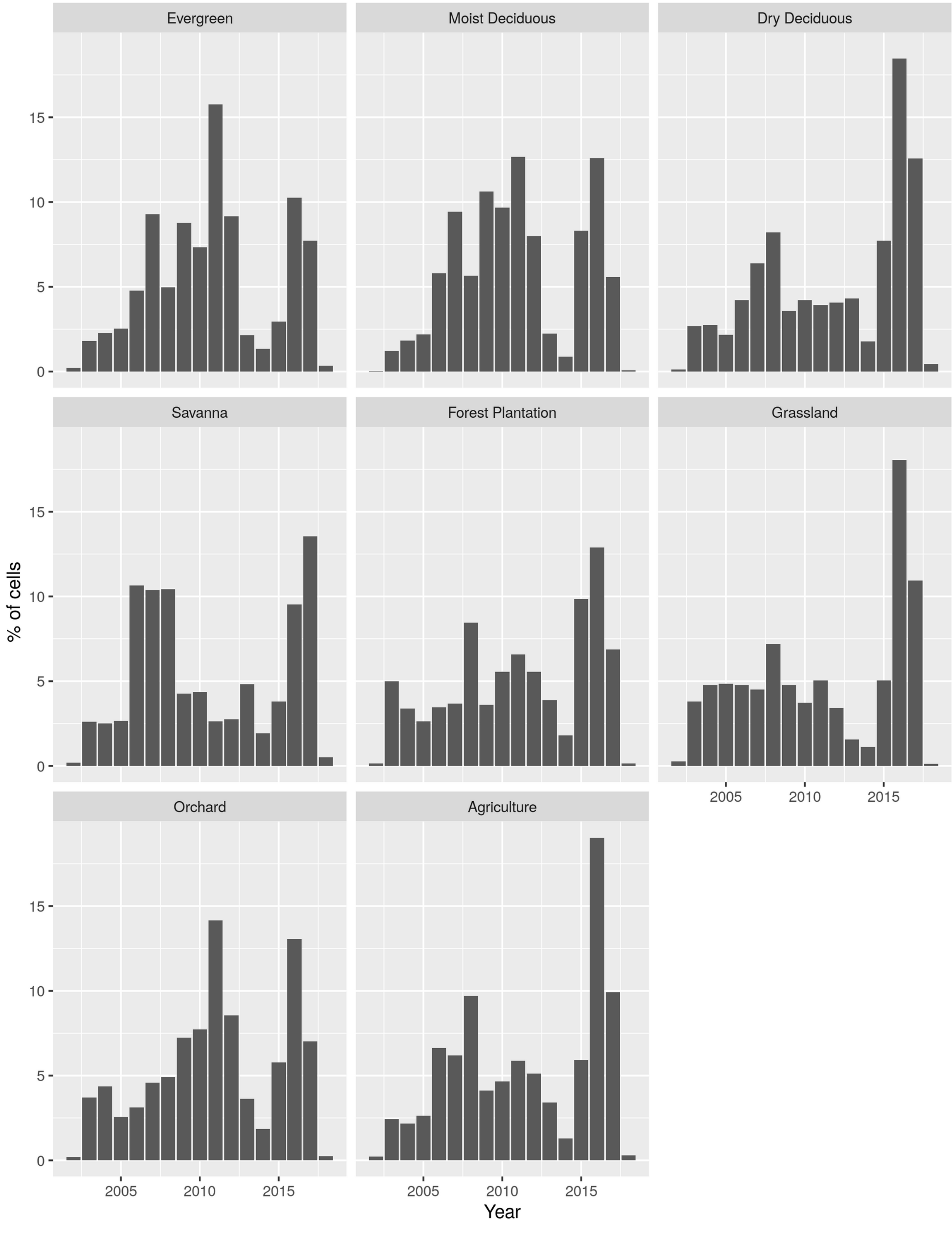


*Figure 4: In the evergreen and moist deciduous forests, the majority of the breakpoints in pixel-wise blue water trend was observed between 2007 and 2011 and in 2016, while in the dry-deciduous forests and grasslands, the majority of the breakpoints occurred between 2016 and 2017. In the savanna, more than 30% of the breakpoints occurred between 2006 and 2008.*

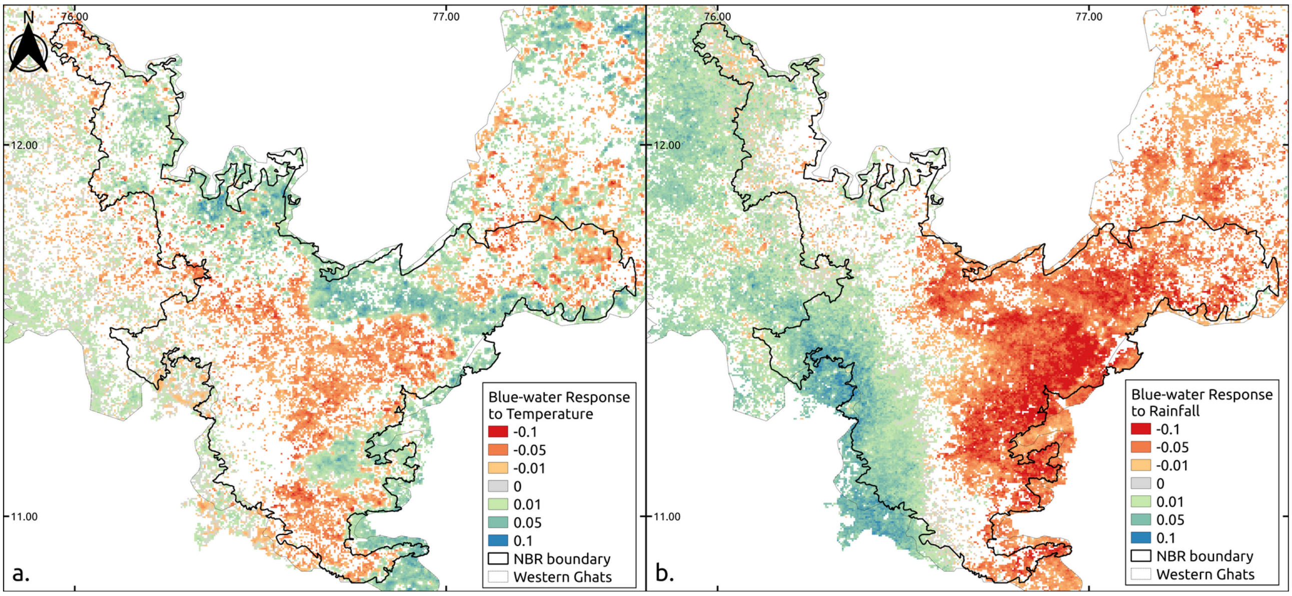


*Figure 5: Response of blue water to climatic variables across the Nilgiri Biosphere Reserve (NBR) between 2001 and 2019 (water year starting from June 1 and ending on May 31). a) Monotonic trend analysis of the response of blue water to temperature suggested an increase in this response in 29% of the area in the NBR, and a significant decline in 25% of the area; b) A significant increase in blue water response to rainfall was observed in 25% of the area in NBR, while a declining trend was observed in 42% of the area.*

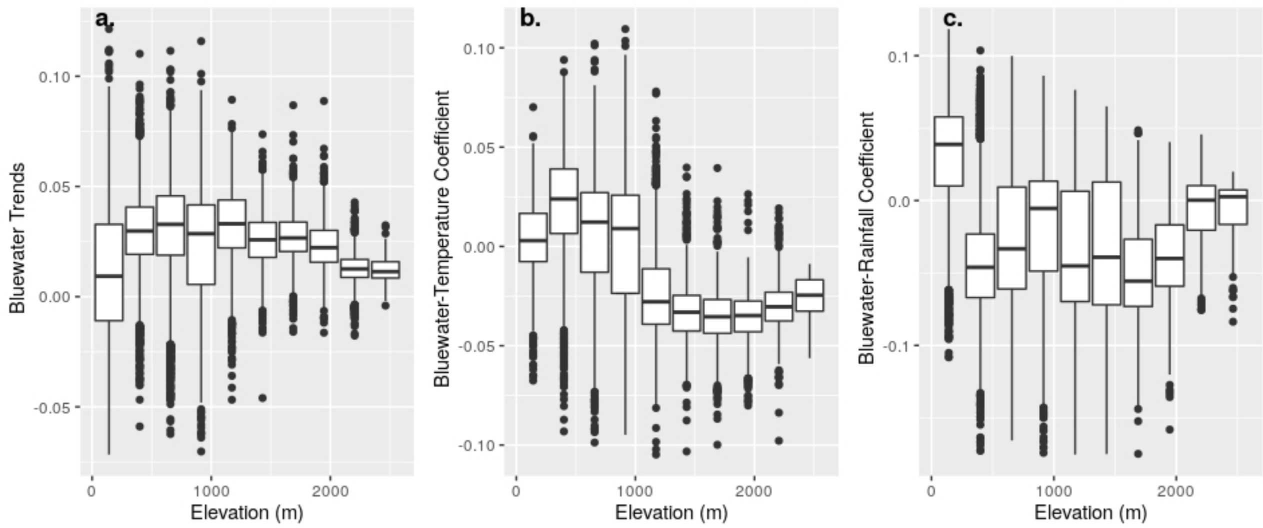


*Figure 6: Blue water and climatic trends along elevation gradient in the Nilgiri Biosphere Reserve. a) Blue water trends were mostly positive across the elevation gradient, and slightly lower median values were recorded between 0 m and 250 m, and > 2000 m elevations; b) The median blue water–temperature coefficient was positive in the 0 m–1000 m elevation range, while a negative response in blue water to temperature was observed at elevations > 1000 m; c) Rainfall had a positive influence on blue water at elevations 0 m–250 m, and for elevations > 250 m, blue water–rainfall coefficient was largely negative.*

An overall trend in the median blue water values (intercept) across the NBR suggests an increase in blue water over the time period. However, a segmented regression analysis on the median trend suggests a breakpoint at 2016-2017, after which a decrease in blue water was observed in the landscape (Fig. 7a). This pattern was consistent across all vegetation types. The observed increasing and decreasing trends in regression slopes before and after the breakpoint were significant as the lower and upper bounds of the 95% confidence-interval did not overlap with zero. We found that the blue water–rainfall and the blue water–temperature slope coefficients were positive in the recent years (Figs. 7b&c). This suggests that the recent declining trend in blue water may be associated with trends in other climatic and anthropogenic factors in the NBR. A comparison of the median blue water–climatic variable trends revealed that the influence of rainfall on blue water in each year was greater than that of temperature, both in terms of area impacted and the relative strengths (Figs. 7b&c).

## Discussion

Hydrological services are inarguably the most important services and alterations in these could have a direct impact on human well-being (Alcamo et al., 2003; Millennium Ecosystem Assessment, 2005). Water quantity is an important attribute of hydrological services, and in this study, we have looked at the trends in blue water, which represents the total water available on the surface and as groundwater that could be used for irrigation, domestic purposes, industries, and power generation. Our results indicate that blue water trends have changed drastically across the NBR in the past two decades. These changed trends are directly linked to changing trends in temperature and rainfall.

Monotonic trend analyses suggest an increase in blue water in majority of the areas in the NBR. This increasing trend in blue water was more prominent in the drier vegetation types (savanna/scrub and deciduous forests). An increase in runoff has been observed in many parts of the world and this has been attributed to elevated $CO_2$ conditions and reduced evapotranspiration losses due to $CO_2$ induced stomatal closure (Gedney et al., 2006). While there is an overall increase in blue water over the last two decades, there has been a decline from 2016 onwards. This change in trend was observed early in drier landscapes (savanna and scrubs) and was more prominent in 2016. This decline in blue water is consistent across all vegetation types. Global studies have also found a decline in water quantity and this has been linked to increased water use by plants in elevated $CO_2$ conditions. We found that deciduous forests were more sensitive to temperature changes while evergreen forests were sensitive to changes in rainfall patterns. An analysis of the temperature and rainfall patterns in the NBR suggests that both these variables have changed significantly in this

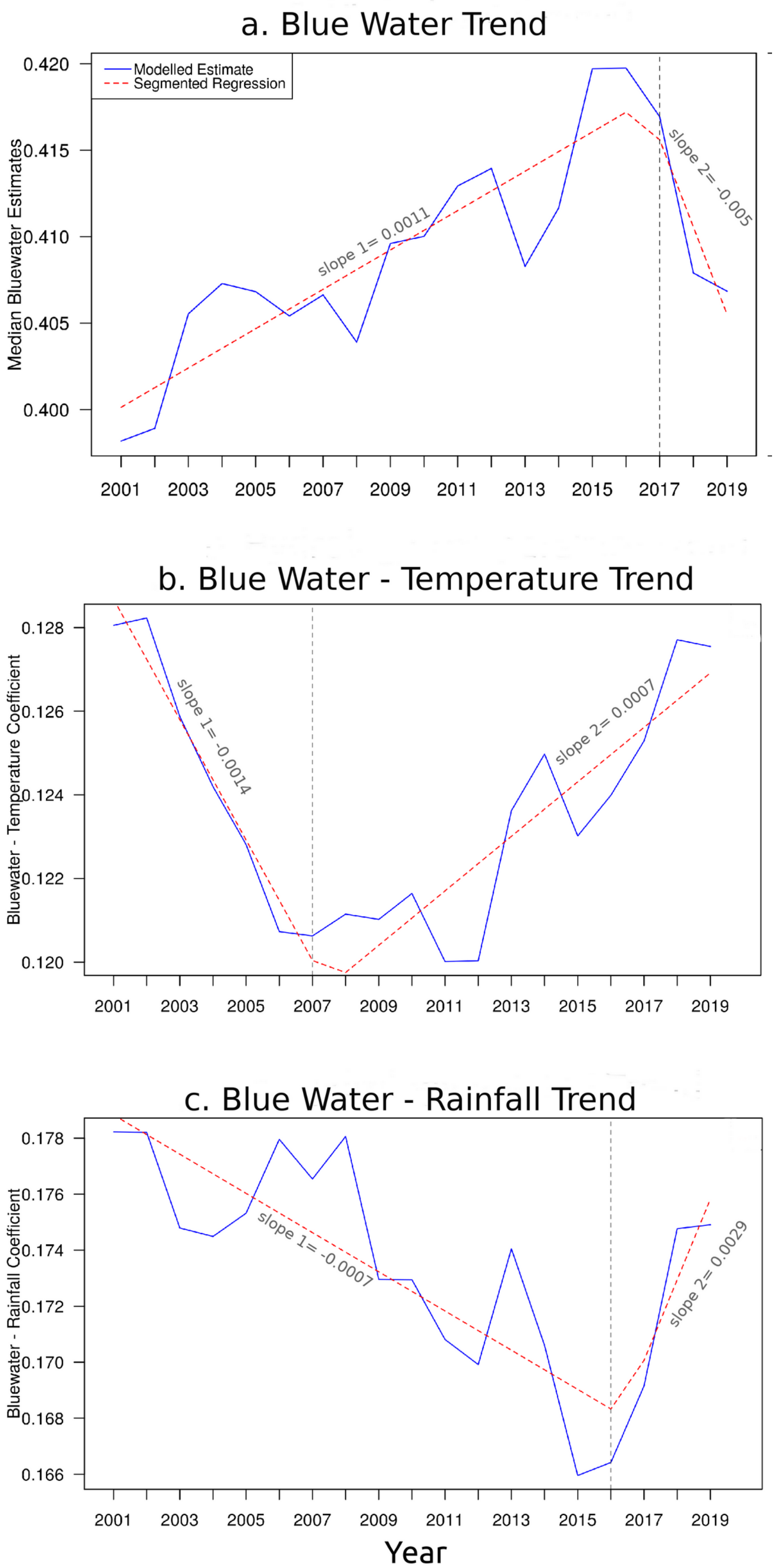


*Figure 7: a) Trends in the median intercept values showed an increase in blue water until 2015-2016, and then a decrease in blue water from 2016-2017; b) Blue water response to temperature was significantly low up to 2007 and this response increased after 2010; c) Blue water response to rainfall showed a decline until 2015-2016, and from 2016, an increasing trend in this response was observed in the NBR. Slope 1 = Trend from 2001 up to the breakpoint year; Slope 2 = Trend after the breakpoint year.*

landscape with temperature showing an increasing trend and rainfall showing variation in seasonal rains, with majority of the area showing a decline in rainfall (refer Fig. 2 on page 9). An increase in mean temperature and at the same time a decrease in rainfall could make the landscape (both wet and drier parts) more brown with more loss of water under future climate change scenarios.

In the recent years, there have been increasing reports on acute shortage of drinking water during summer months from these parts of the Western Ghats and new areas are being added to this list of drought affected areas every year (Iqbal, 2019; Nair, 2017). The long-term monotonic trend analysis on intercept values and yearly median intercept values indicate an increasing trend in blue water in the landscape. However, this increasing trend is reversed from 2015-2016 and there is a decreasing trend in blue water in the recent years. This suggests the dynamic nature of blue water trends in the NBR landscape, which needs to be studied at regional and seasonal scales. Blue water trends are largely influenced by trends in temperature and rainfall. Rainfall has a positive and a relatively higher influence than temperature on blue water trends. Any decline in future rainfall or increase in variability will reduce the blue water availability in the NBR and in the larger Western Ghats region. Global climate change models have predicted an increase in rainfall variability in the Western Ghats (Milly et al., 2002). However, regional models suggest an increase in rainfall in the northern parts of the Western Ghats and a decrease in the southern Western Ghats including the NBR (Varghese et al., 2020). Our study indicates a decline in the rainfall quantity received during the South West Monsoon, and an increase in temperature (refer pages 1 – 24). As there are inconsistencies between global and regional climate change predictions, especially rainfall patterns, there is an immediate need to develop fine scale regional models to predict the influence of climate change on ecosystem processes and on services they provide. With increasing temperature and erratic rainfall events, a decline in blue water is evident in the coming years and we might encounter more cases of water shortage in the NBR. Recent estimates also suggest that the Western Ghats region “will have 81 million people with insufficient water by 2050” (McDonald et al., 2011).

Our study provides a historical trend in blue water and its response to climate variations which could be used to make informed decisions and developing climate prediction models for the Western Ghats. This is important for developing water resilience and management plans to meet the needs of the people in the Western Ghats. Although, in the present study, the increasing temperature is not a major factor in influencing blue water trends when compared to rainfall in the larger NBR landscape, the results of vegetation respose to climatic variables suggest that the grasslands, which are mainly distributed at high altitudes in the NBR, are showing greater reduction in blue water as a response to temperature (Table 2). Study of the phenological trends (refer pages 43 – 70) suggest greening of high altitude grasslands, which could be associated with encroachment of montane grasslands by woody shrubs due to increased temperature (Joshi et al., 2018). Increase in tree cover in high altitude grasslands under warming conditions could result in increased evapotranspiration losses and reduced blue water flows in the future. Study from the mountainous catchments in the Nilgiris supports this argument as a decline in stream-flows was observed in areas dominated by invasive wattle trees as a result of increased evapotranspiration losses (Bhalla et al., 2015; Kumaran et al., 2016).

In addition to climatic factors, a loss of forest cover and changes in land use practices have been shown to contribute to changing water cycles (Bonell et al., 2010; Krishnaswamy et al., 2012; Nayak et al., 2020; Piao et al., 2007; Sinha et al., 2020). Historically, large parts of the NBR have remained stable with respect to hydrological services and climatic variation. However, this could change in the future due to climate change and anthropogenic factors. The NBR has undergone a drastic change in land use and land cover, with majority of the area showing an increase in tree cover (refer pages 93 – 108). Change in climatic variables in combination with changes in land cover and land use could further affect hydrological services in an irreparable way. As blue water–rainfall and blue water–temperature slopes show positive relationship in recent time, the recent declining trend in the blue water suggests a possible role of other regional climatic and anthropogenic factors in influencing blue water trends in the NBR. As shown in this study, an increase in rainfall could increase the total blue water availability, while an increase in temperature could reduce total available water by increasing transpiration losses in plants and evaporation losses from the surface (Falkenmark & Rockström, 2010; Leakey et al., 2009; Ukkola et al., 2015). In the NBR landscape, we have witnessed an increase in blue water over the years. This increasing trend may not be very desirable in mountainous parts as it can have negative consequences, such as floods and landslides. Our results provide spatial information on changes occurring in the Western Ghats. The areas that show a decline in blue water are the areas that will be facing water-shortage and drought in the future, whereas areas with increased blue water conditions, such as the drier belts in the western parts of the NBR, are likely to face flood conditions and changes in community structure and composition. These are the areas that should be prioritised while developing regional climate resilience and management plans. A similar study could be adopted to identify priority areas across the Western Ghats and India, and can form a basis on which policies related to water consumption and use, and water resilience plans to changing climate conditions could be developed.

## References


Abedin, A., Collins, A. E., Habiba, U., & Shaw, R. (2019). Climate change, water scarcity, and health adaptation in southwestern coastal bangladesh. *International Journal of Disaster Risk Science*, *10*(1), 28–42. https://doi.org/10.1007/s13753-018-0211-8

Alcamo, J., Ash, N. J., Butler, C. D., Callicott, J. B., Capistrano, D., Carpenter, S. R., Castilla, J., Chambers, R., Chopra, K., Cropper, A., & others. (2003). *Ecosystems and human well-being: A framework for assessment*. World Resources Institute. Island Press, Washington.

Bhalla, R. S., Kumaran, K., Vaidyanathan, S., Krishnaswamy, J., Chappell, N. A., & Jones, T. (2015, December). Estimating Evapotranspiration Demands of Different Land Covers. *American Geophysical Union Fall Meeting 2015*.

Bonell, M., Purandara, B. K., Venkatesh, B., Krishnaswamy, J., Acharya, H. A. K., Singh, U. V., Jayakumar, R., & Chappell, N. (2010). The impact of forest use and reforestation on soil hydraulic conductivity in the Western Ghats of India: Implications for surface and sub-surface hydrology. *Journal of Hydrology*, *391*(1), 47–62.

Brauman, K. A. (2015). Hydrologic ecosystem services: Linking ecohydrologic processes to human well-being in water research and watershed management. *WIREs Water*, *2*(4), 345–358. https://doi.org/10.1002/wat2.1081

Brauman, K. A., Daily, G. C., Duarte, T. K., & Mooney, H. A. (2007). The nature and value of ecosystem services: An overview highlighting hydrologic services. *Annual Review of Environmental Resources*, *32*, 67–98.

Brown, T. C., Mahat, V., & Ramirez, J. A. (2019). Adaptation to future water shortages in the united states caused by population growth and climate change. *Earth's Future*, *7*(3), 219–234. https://doi.org/10.1029/2018EF001091

Daily, G. C. (1997). *Nature's services* (Vol. 3). Island Press, Washington, DC.

Daily, G. C., Polasky, S., Goldstein, J., Kareiva, P. M., Mooney, H. A., Pejchar, L., Ricketts, T. H., Salzman, J., & Shallenberger, R. (2009). Ecosystem services in decision making: Time to deliver. *Frontiers in Ecology and the Environment*, *7*(1), 21–28.

Falkenmark, M., & Rockström, J. (2010). Building water resilience in the face of global change: From a blue-only to a green-blue water approach to land-water management. *Journal of*

*Water Resources Planning and Management*, *136*(6), 606–610. https://doi.org/10.1061/(asce)wr.1943-5452.0000118

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, *2*, 1–21. https://doi.org/10.1038/sdata.2015.66

Gedney, N., Cox, P. M., Betts, R. A., Boucher, O., Huntingford, C., & Stott, P. A. (2006). Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, *439*(7078), 835–838. https://doi.org/10.1038/nature04504

Guhathakurta, P., Sreejith, O., & Menon, P. A. (2011). Impact of climate change on extreme rainfall events and flood risk in India. *Journal of Earth System Science*, *120*(3), 359–373. https://doi.org/10.1007/s12040-011-0082-5

Iqbal, S. (2019). River river everywhere but not much to drink in wet Kerala. *Outlook*. https://magazine.outlookindia.com/story/india-news-river-river-everywhere-but-not-much-to-drink-in-wet-kerala/301575

Joshi, P. P., Murthy, I. K., Hegde, G. T., Sathyanarayan, V., Bhat, S., Patil, V., Esteves, T., & Ravindranath, N. H. (2018). Biophysical quantification of biodiversity and ecosystems services of forest ecosystems in the Western Ghats: A case study of Uttara Kannada District, India. *Journal of Forestry Research*, *29*(3), 735–748. https://doi.org/10.1007/s11676-017-0488-2

Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Lele, S., Kiran, M. C., Reddy, V., Badiger, S., & Rakesh, K. N. (2012). The rain–runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India. *Journal of Hydrology*, *472–473*(0), 216–237. https://doi.org/10.1016/j.jhydrol.2012.09.016

Krishnaswamy, J., Vaidyanathan, S., Rajagopalan, B., Bonell, M., Sankaran, M., Bhalla, R. S., & Badiger, S. (2015). Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. *Climate Dynamics*, *45*(1–2), 175–184. https://doi.org/10.1007/s00382-014-2288-0

Kumaran, K., Bhalla, R. S., & Deviprasad, K. V. (2016, August). Ecological and Anthropogenic Implications of Two Decades of Land Cover Changes in the Upper Nilgiris in The Context of Global Climate Change. *International Conference on Sustainable Forest Development in View of Climate Change*.

Leakey, A. D. B., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P., & Ort, D. R. (2009). Elevated CO2 effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE. *Journal of Experimental Botany*, *60*(10), 2859–2876. https://doi.org/10.1093/jxb/erp096

McDonald, R. I., Green, P., Balk, D., Fekete, B. M., Revenga, C., Todd, M., & Montgomery, M. (2011). Urban growth, climate change, and freshwater availability. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(15), 6312–6317. https://doi.org/10.1073/pnas.1011615108

Menon, A. (2019). Menon, A., 2019. Extreme rainfall devastates Kodagu yet again. [WWW Document]. *Mongabay*. https://india.mongabay.com/2019/08/extreme-rainfall-devastates-kodagu-yet-again/

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Island Press, Washington, DC.

Milly, P. C. D., Dunne, K. A., & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, *438*(7066), 347–350. https://doi.org/10.1038/nature04312

Milly, P. C. D., Wetherald, R. T., Dunne, K. A., & Delworth, T. L. (2002). Increasing risk of great floods in a changing climate. *Nature*, *415*(6871), 514–517. https://doi.org/10.1038/415514a

Mittermeier, R. A., Robles, G. P., Michael, H., John, P., Thomas, B., Mittermeier, C.G. Lamoreux, J. L., & Fonseca, G. (2004). *Hotspots Revisited: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions*. CEMEX.

Mooney, H. A., Ehrlich, P. R., & Daily, G. (1997). Ecosystem services: A fragmentary history. *Nature's Services: Societal Dependence on Natural Ecosystems*, 11–19.

Mudbhatkal, A., Raikar, R. V., Venkatesh, B., & Mahesha, A. (2017). Impacts of Climate Change on Varied River-Flow Regimes of Southern India. *Journal of Hydrologic Engineering*, *22*(9), 05017017. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001556

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858. https://doi.org/10.1038/35002501

Nair, N. (2017). Drought in the Western Ghats Part 4: In Kerala's Wayanad, acute water scarcity leading to man-animal conflict. *Firstpost*. https://www.firstpost.com/india/drought-in-the-western-ghats-part-4-in-keralas-wayanad-acute-water-scarcity-leading-to-man-animal-conflict-3437652.html

Nayak, R., Krishnaswamy, J., Vaidyanathan, S., Chappell, N., Kesavan, K., Ghatwai, P., & Bhalla, R. S. (2020). Exotic Plantations Increase Risks of Flooding in Mountainous Landscapes. *Earth and Space Science Open Archive*, 25. https://doi.org/10.1002/essoar.10503675.1

Piao, S., Friedlingstein, P., Ciais, P., De Noblet-Ducoudré, N., Labat, D., & Zaehle, S. (2007). Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(39), 15242–15247. https://doi.org/10.1073/pnas.0707213104

Ramachandra, T. V., & Bharath, S. (2020). Carbon Sequestration Potential of the Forest Ecosystems in the Western Ghats, a Global Biodiversity Hotspot. *Natural Resources Research*, *29*(4), 2753–2771. https://doi.org/10.1007/s11053-019-09588-0

Running, S., Mu, Q., Zhao, M., & Moreno, A. (2017). MODIS global terrestrial evapotranspiration (ET) product 500 m. *NASA EOSDIS Land Processes DAAC*, *1.5*, 34.

Safi, M. (2018). Kerala floods: Death toll rises to at least 324 as rescue effort continues. *The Guardian*. https://www.theguardian.com/world/2018/aug/17/kerala-floods-death-toll-rescue-effort-india

Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Sinha, R. K., Eldho, T. I., & Subimal, G. (2020). Assessing the impacts of historical and future land use and climate change on the streamflow and sediment yield of a tropical mountainous river basin in South India. *Environmental Monitoring and Assessment*, *192*(11). https://doi.org/10.1007/s10661-020-08623-5

Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, *10*(1), 1–10. https://doi.org/10.1038/s41598-020-70816-2

Ukkola, A. M., Prentice, I. C., Keenan, T. F., Dijk, A. I. J. M. V., Viney, N. R., Myneni, R. B., & Bi, J. (2015). *Reduced streamflow in water-stressed climates consistent with CO2 effects on vegetation*. *October*. https://doi.org/10.1038/NCLIMATE2831

Varghese, S. J., Surendran, S., Rajendran, K., & Kitoh, A. (2020). Future projections of Indian Summer Monsoon under multiple RCPs using a high resolution global climate model multiforcing ensemble simulations: Factors contributing to future ISMR changes due to global warming. *Climate Dynamics*, *54*(3–4), 1315–1328. https://doi.org/10.1007/s00382-019-05059-7

Zhang, L., Dawes, W. R., & Walker, G. R. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, *37*(3), 701–708. https://doi.org/10.1029/2000WR900325

Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H. S., Western, A. W., & Briggs, P. R. (2004). A rational function approach for estimating mean annual evapotranspiration. *Water Resources Research*, *40*(2), 1–14. https://doi.org/10.1029/2003WR002710

Zhou, T., Song, F., Lin, R., Chen, X., & Chen, X. (2013). The 2012 North China floods: Explaining an extreme rainfall event in the context of a long-term drying tendency. *Bull. Amer. Meteor. Soc*, *94*(9), S49–S51.

# Trends in land use land cover and the influence of non-climatic factors on ecosystem services in the Nilgiri Biosphere Reserve

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## Highlights

- The Nilgiri Biosphere Reserve was more stable in terms of tree cover trends with only around 18% of the landscape showing significant trends in tree cover.
- Drier landscapes like the savanna and scrub showed an increase in tree cover.
- Wetter areas, evergreen and moist deciduous forests, showed decrease in tree cover.
- Increasing trend in drier parts could be related to an increase in rainfall and invasion by woody plants.
- Increasing temperature could facilitate invasion of trees into high elevation grasslands.
- Non-climatic factors had greater influence on carbon sequestration compared to phenology and hydrological services.

## Abstract

Tropical landscapes have undergone drastic changes in land use and land cover (LULC) types across the globe over the last few decades. LULC change is known to impact biodiversity and a wide range of ecosystem services including hydrological and carbon services. The Nilgiri biosphere reserve (NBR), the first biosphere reserve in India, established in 1985, has undergone drastic changes in LULC over the last century. An understanding of changes in LULC in this landscape could help in identification of hotspots of forest loss and land use change. This information will be crucial for prioritizing areas for conservation. In this study, we analysed trends in LULC over NBR by using time-series of change in percentage tree cover over 20 years between 2000 and 2019. In addition, we also looked at trends in residuals of dynamic linear models (DLM) from the previous sections where we looked at the influence of the climatic variables, rainfall, and temperature, on ecosystem services—carbon sequestration, phenology, and hydrological services. The residuals of the DLM models provide information on the influence of non-climatic factors including LULC

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change on ecosystem services. Our study showed that only around 18.3% of the NBR landscape showed a significant trend in tree cover, with an increase in 11.6% of the area and a decrease in 6.7% of the landscape. A comparison of decadal trends suggested that increase in tree cover was more between 2000 to 2009 compared to 2010 to 2019. Most of the increase in tree cover was observed in the savanna/scrub forests (23.7%) and in agriculture land (23%) and orchards (14.9%). Vegetations with dense canopies, evergreen and moist deciduous forests, showed greater losses than gains in tree cover compared to all other land cover types considered in the study. Tree loss was less inside Protected Areas (PAs) than outside. Analysis of DLM residuals suggested that non-climatic factors had greater influence on carbon sequestration (annual net primary productivity) compared to phenology and hydrological services. A reduction in deforestation could be related to increased levels of protection in the landscape. Whereas, an increase in tree cover may indicate an increase in rainfall in the drier areas and an invasion of woody plants into the savanna and grassland systems. Increase in tree cover may also be a result of active afforestation programmes carried out by the Forest Department. Increased tree cover loss outside PAs is still a matter of concern and could be related to rampant deforestation for developmental projects, forest fire, and other anthropogenic activities. Our study provides information on such areas undergoing rapid tree loss which should be prioritized for conservation. LULC changes are known to affect ecosystem processes and services, and our study provides information on areas where a likely change in ecosystem services is expected and that needs to be considered in developing resilience to future climate change.

## Introduction

Tropical landscapes across the globe have undergone a drastic change in land use and land cover (LULC) types over the last few decades (Mayaux et al., 2005; Potapov et al., 2012; Prance, 2006; Roy et al., 2015; Tian et al., 2014). Studies in the Western Ghats of India, a global hotspot of biodiversity, suggest nearly 26% loss in the forest cover in 22 years between 1973 and 1995 (Jha et al., 2000). Similarly, nearly 16% loss in forest cover has been reported from the Eastern Ghats of India between 1920 and 2015 (Ramachandran et al., 2018). Global studies have found LULC change to impact biodiversity and a wide range of ecosystem services including hydrological and carbon services (DeFries et al., 1999; Lawler et al., 2014; Piao et al., 2007). Studies in the central Western Ghats suggest increased overland flows in degraded forests and forest plantations with reduced infiltration rates (Krishnaswamy et al., 2012). Studies simulating impact of ongoing deforestation rates on carbon content suggest a total loss of 0.23 MGg carbon sequestration between 2018 and 2031 (Ramachandra & Bharath, 2020). Hence, an understanding of changes in LULC in a landscape is important for developing management plans. Identification of hotspots of forest loss and land use change could provide crucial information in identifying priority areas for conservation. Such an understanding could also help in predicting future changes in LULC and ecosystem services under climate change scenarios.

The Nilgiri biosphere reserve (NBR), the first biosphere reserve established in India, in 1985, shows around 25% loss in total forest cover between 1920 and 2012 (Satish et al., 2014). This deforestation has been attributed mainly to conversion of natural grasslands and forests into commercial plantations and agriculture expansion (Joshi et al., 2018; Satish et al., 2014). In addition to this conversion, exotic species like lantana (*Lantana camara*), prosopis (*Prosopis juliflora*), wattle (*Acacia mearnsii* and *A. dealbata*), etc., have invaded natural forests and grasslands changing the vegetation composition. A study in the Nilgiris, a part of the NBR, has shown increased flood risks in catchments dominated by exotic plantations compared to natural vegetation types (Nayak et al., 2020). In this study, we analysed trend in LULC across the NBR to identify areas undergoing rapid deforestation. We used trends in percentage tree cover as a proxy for change in LULC. Identifying areas undergoing rapid deforestation as well as change in land use practices could be a key in monitoring ecosystem services and developing resilience to climate change at a regional level. We used a time series of tree cover data to assess change in land cover types in the NBR to determine changes between LULC categories rather than using hard classified vegetation maps, which needs a large number of good quality ground truth points.

In the previous sections, we observed the influence of rainfall and temperature on ecosystem services. We also found evidence for the influence of other non-climatic and anthropogenic factors such as fire, LULC change, etc., on these observed trends in ecosystem services. In certain cases, the influence of non-climatic factors on ecosystem services have been observed to be much more than the effect of rainfall and temperature (Ramachandra and Bharath 2020). In order to understand the influence of non-climatic factors on ecosystem services, we looked at the trends in residuals of the dynamic linear regression models (DLM) that we had generated in the previous sections.

## Methods

We used MODIS annual vegetation continuous field (VCF) percentage tree cover layer (MOD44Bv006) available at 250 m resolution to analyse trend in tree cover in the NBR over a period of 20 years from 2000 to 2019. For details on pre-processing, removal of bad-pixels, and gap-filling of this product refer Annexure I of this report. This product has been found promising for detecting and monitoring of deforestation and degradation (Amarnath et al., 2017; Gao et al., 2018; Morton et al., 2005). We analysed monotonic increase or decrease in tree cover trends using Sen's slope (Sen, 1968). We summarise these results in tree cover across different vegetation types and elevation ranges. We also looked at the efficiency of Protected Areas (PAs) in reducing forest deforestation and degradation by analysing trends between PAs and areas outside these PAs.

We ran a Sen's slope on the residuals obtained from the DLM models to detect montonic trends in residuals of carbon sequestration (annual net primary productivity; ANPP), vegetation greening and browning (phenology), and hydrological services (blue water). We then analysed significant trends in these residuals across different vegetation types. Residuals indicate the changes in ecosystem services due to anthropogenic and climatic factors that were not used as covariates in the analysis. A positive residual value suggests that the trends are above the fitted values while negative values suggest that the trends are below the fitted values. For more details on DLM models and analysis refer Annexure III.

## Results

A monotonic trend analysis of tree cover using Sen's slope indicated that the mean rate of change of tree cover was -0.42, suggesting a loss of tree cover at a rate of 0.01% per decade between 2000 and 2019 in the NBR landscape. However, there was a higher variability in this trend (SD ± 8.97). We found that only around 18% of the landscape exhibited a significant change in the percentage tree cover, and the areas showing a gain in tree cover were more than the areas with tree loss in the NBR. The landscape showed a total net increase in 4.95% of the landscape, with a significant decrease observed in 6.65% of the area, and a significant increase observed in 11.60% of the area (Fig. 1c). A comparison of tree cover trends on a decadal scale (2000–2009 and 2010–2019) suggested that, net area showing a significant increase (net increase: 2000–2009, 9.18%) in tree cover was reduced by nearly 5.5% in the second decade (net increase: 2010–2019, 3.7%) (Fig. 1a&b, Table 1a). Among all the pixels that showed a significant trend in tree cover, nearly 57% showed a gain in tree cover at a rate of 0–20% over the two decades from 2000 to 2019 (Fig. 2).

Savanna, which has low tree density, showed increase in area with total gain in tree cover between 2000 to 2019 (Table 1b). The maximum area gain in tree cover was observed between 2000 to 2009 (26.7%) compared to 2010 to 2019 (9.4%). This observed increase in tree cover might be related to invasion of *Prosopis* in some parts of the savanna landscape. There was a gain in tree cover in agricultural land and orchards, suggesting changed LULC practices across the landscape.

Grasslands showed both an increase and a decrease in the tree cover in similar proportions (decrease in 12.3% area, increase in 9.3% area), with greater decrease in the initial decade, 2000–2009, and a slight increase in tree cover area between 2010 and 2019. This suggests a possible encroachment of woody shrubs into the natural grasslands in some areas, and the death of trees in some parts (Table 1b). Vegetations with dense tree canopies, evergreen, and moist deciduous forests, showed greater areas with tree cover losses than areas with gains in tree cover compared to all other land cover types considered in the study area (Table 1b).

Tree cover loss was less inside the PAs (4.2%) compared to outside (8.7%). Similarly, increase in tree cover was less in the PAs (8.35%) than outside (14.26%). There are eight PAs within the NBR boundary—Nagarhole National Park, Bandipur National Park, Nugu Wildlife Sanctuary, Mudumalai National Park, Waynad Wildlife Sanctuary, Sathyamangalam Wildlife Sanctuary, Mukurthi National Park, and Silent Valley National Park. Among these PAs, Mukurthi National Park, which is predominantly a montane grassland PA, showed the greatest decline in tree cover (15.31%) followed by Waynad (12.37%) and Nagarhole (9.02%). Nugu (18.68%) and Sathyamangalam (12.95%) showed an increase in percent tree cover (Table 2).

Analysis of the residuals trend showed that, ANPP was greatly influenced by factors other than temperature and rainfall in the NBR (Fig. 3). Positive residuals were observed in less than 1% of the landscape and negative residuals were observed in 38.51% of the landscape. All land cover types showed an increase in area with negative residuals for ANPP, which suggests that other climatic (other than temperature and rainfall) and anthropogenic factors had a negative influence on ANPP trends. Forest plantations (-46%) and moist deciduous forests (-41%) showed the maximum decrease in ANPP, while grasslands showed a net decrease in 28% of the area (Table 3).

Analysis of the phenology residuals suggested that only around 5% of the landscape showed any change in phenology as a response to other climatic and anthropogenic factors (Fig. 3). We observed more vegetation greening (3% of the landscape) than browning (1.9%) in the NBR. Grasslands showed the maximum area with greening (3.3%) whereas evergreen forests showed slightly more areas with browning (3.10%) than areas with greening (2.97%) (Table 3).

Less than 2% of the landscape showed any change in blue water as a response to other climatic and anthropogenic factors in the landscape (decrease in 1% of the landscape, and increase in 0.6% of the landscape) (Fig. 3). Savanna showed the maximum area with net increase in blue water (0.5%), and forest plantation showed the maximum net decrease (-1.32%) in blue water in the landscape (Table 3).

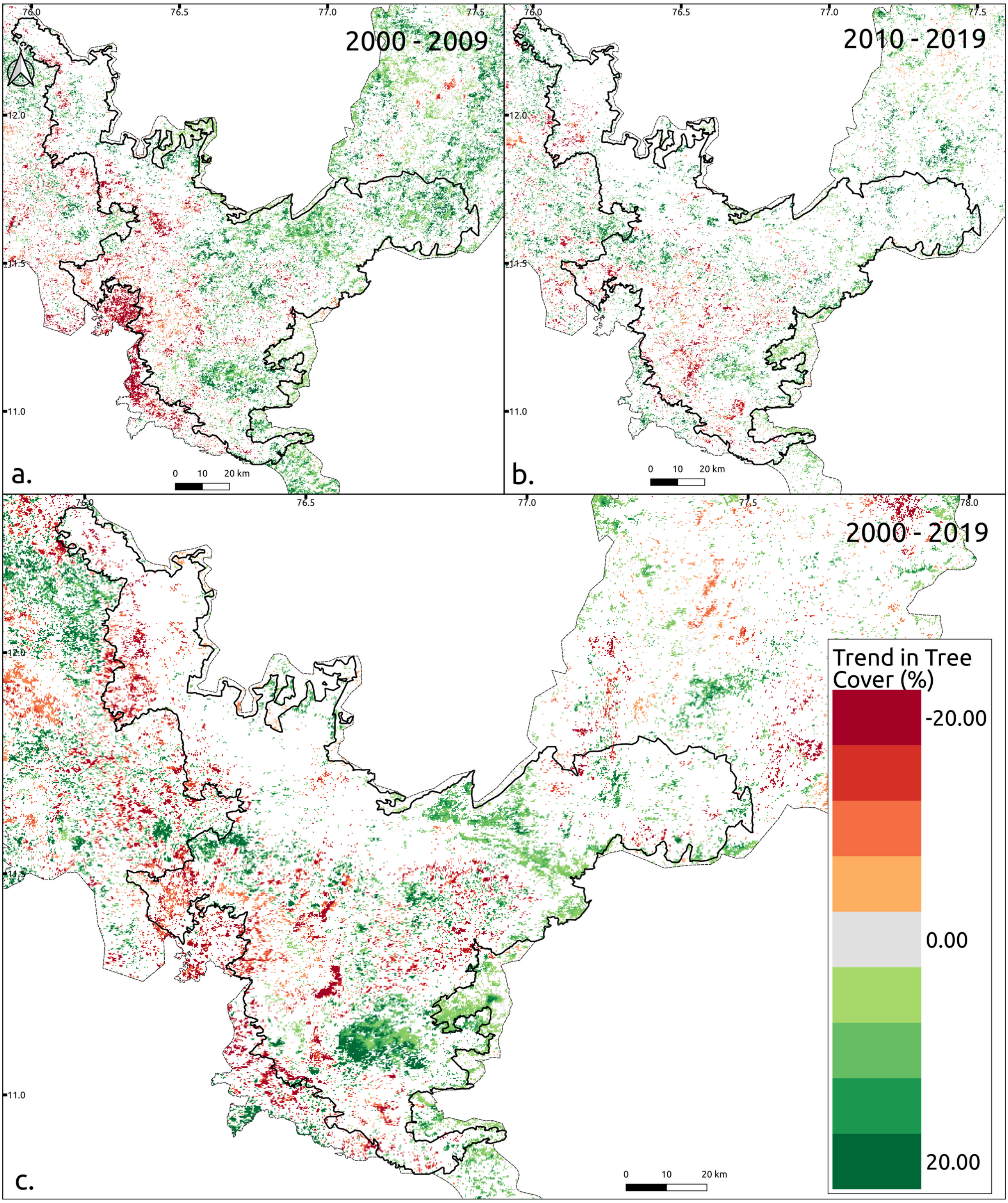



*Figure 1: a) Monotonic trend analysis of percentage tree cover between 2000 to 2009 suggests an increase in tree cover in 14% of the landscape and a decrease in 4.75% of the area in the Nilgiris. b) Tree cover trend between 2010 and 2019 shows an increase in 7% of the area and a decrease in 3.3% of area. c) An overall trend in tree cover from 2000 to 2019 suggests that there was a gain in tree cover in 11.6% of the area and a loss in 6.65% of the area in the Nilgiri Biosphere Reserve.*

*Table 1: a) A comparison of trend in tree cover suggested that the Nilgiri Biosphere Reserve landscape showed a total net increase in 4.95% of the landscape. A comparison of tree cover trends on a decadal scale suggested that, net area showing a significant increase in tree cover was reduced by nearly 5.5% in the second decade (2010–2019). b) A land use land cover wise trend analysis suggested that the savanna had the maximum increase in tree cover among all the vegetation types in the NBR.*

*a. Percentage area showing loss or gain in tree cover*

| **2000–2019** | | **2000–2009** | | **2010–2019** | |
|---|---|---|---|---|---|
| **%Decrease** | **%Increase** | **%Decrease** | **%Increase** | **%Decrease** | **%Increase** |
| 6.65 | 11.60 | 4.75 | 13.93 | 3.28 | 6.98 |

*b. Percentage of area under different land cover types showing significant loss or gain in tree cover in the NBR.*

| **Land use/Land cover** | **2000-2009** | | **2010-2019** | | **2000-2019** | |
|---|---|---|---|---|---|---|
| | **%Decrease** | **%Increase** | **%Decrease** | **%Increase** | **%Decrease** | **%Increase** |
| Evergreen | 7.20 | 7.74 | 10.72 | 3.20 | 12.30 | 5.89 |
| Moist-deciduous | 9.41 | 6.05 | 7.92 | 3.87 | 16.93 | 5.66 |
| Dry-deciduous | 3.94 | 12.36 | 1.18 | 5.88 | 3.86 | 6.88 |
| Savanna/scrub | 0.70 | 26.66 | 0.50 | 9.43 | 1.25 | 23.72 |
| Grassland | 6.62 | 14.83 | 4.76 | 6.52 | 11.98 | 9.86 |
| Forest plantation | 10.17 | 6.89 | 5.12 | 6.87 | 12.32 | 9.27 |
| Orchards | 6.95 | 7.13 | 4.26 | 11.14 | 10.71 | 14.87 |
| Agriculture | 2.55 | 23.72 | 2.09 | 11.09 | 4.07 | 23.03 |

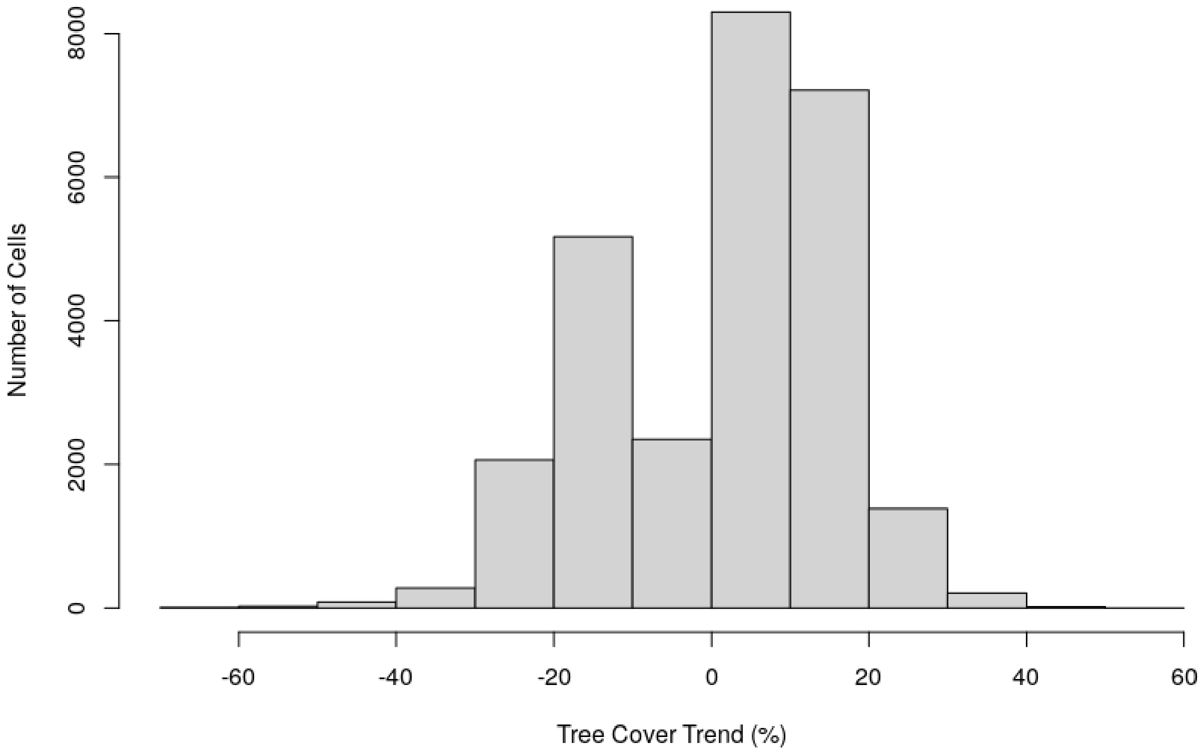



*Figure 2. Distribution of pixels with significant tree cover trend in the Nilgiri Biosphere Reserve: Among all the pixels that showed a significant trend in tree cover, nearly 57% showed a gain in tree cover at a rate of 0–20% over the two decades from 2000 to 2019.*

*Table 2: Percentage changes in tree cover inside the Protected Areas within the Nilgiri Biosphere Reserve. Among the protected areas within NBR, Mukurthi National Park showed the greatest decline in tree cover. Nugu and Sathyamangalam Wildlife Sanctuaries showed greater increases in percent tree cover.*

| Protected Area | %Decrease | %Increase | %Net change |
|---|---|---|---|
| Nagarhole | 9.02 | 0.60 | -8.42 |
| Bandipur | 1.11 | 7.68 | 6.57 |
| Nugu | 0.37 | 18.68 | 18.32 |
| Mudumalai | 2.03 | 2.76 | 0.73 |
| Waynad | 12.37 | 2.51 | -9.86 |
| Sathyamangalam | 1.89 | 14.91 | 13.03 |
| Mukurthi | 15.31 | 1.31 | -14.00 |
| Silent Valley | 3.91 | 11.61 | 7.70 |

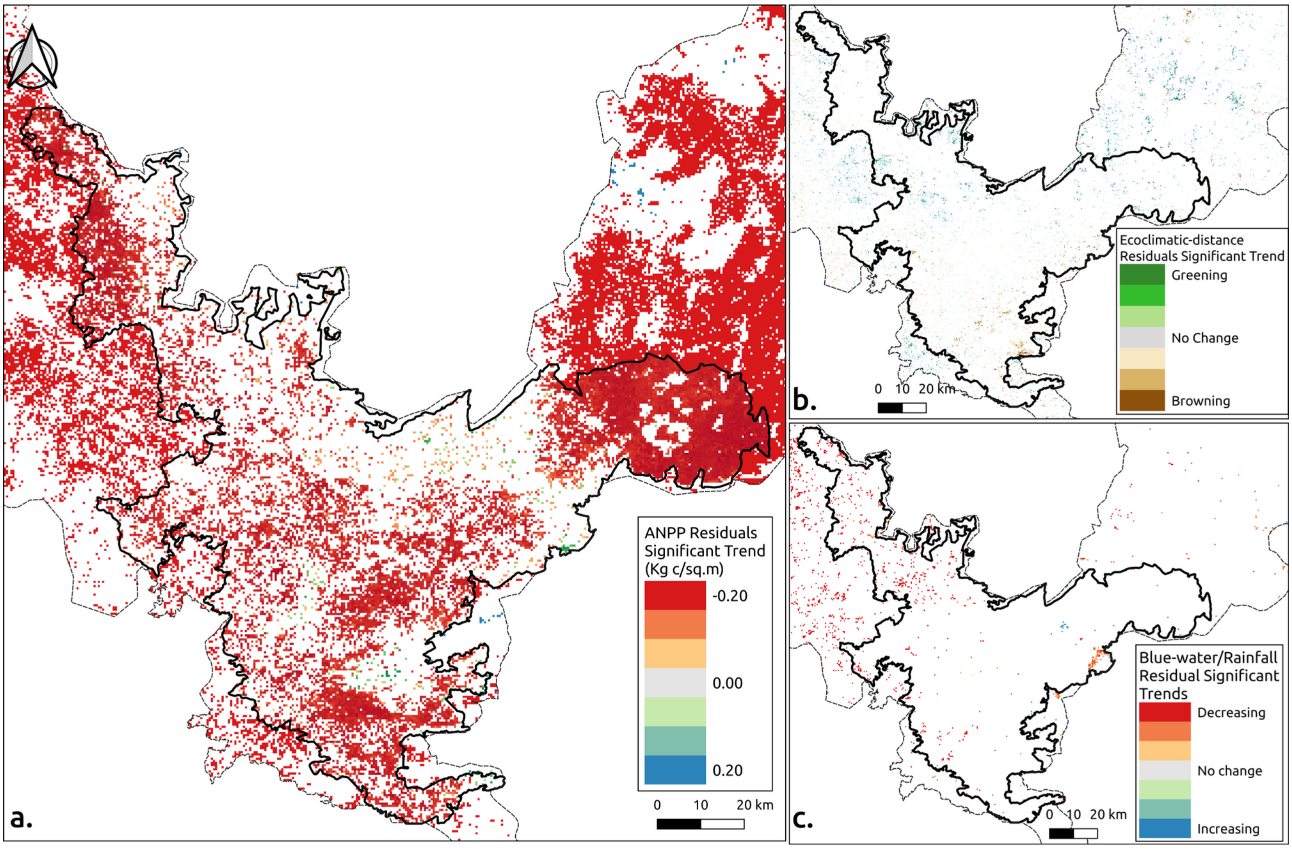



*Figure 3: Trends in residuals of DLM models suggests that the carbon services are predominantely affected by non-climatic variables (~40% area) (a), compared to phenology (~5% area) (b), and blue water (< 2% area) (c).*

## Discussion

Our results indicate that in majority of the area in the NBR there is an increase in tree cover over the years. However, most of this gain was observed in the savanna/scrub forests and in agricultural areas and orchards. An increased tree cover in agricultural areas may indicate changed cropping practices by farmers. Transition from cultivating food crops to commercial plantations has been observed in many parts of the Western Ghats (Jeromi, 2007; Joseph & Joseph, 2005; Sebastian et al., 2014). There is also an increased push towards agroforestry at a policy level (Sharma et al., 2017). The observed tree cover increase in agricultural lands may be related to these transitions. An increase in tree cover in the savannas/scrubs might be directly related to increased rainfall. Long-term trends in rainfall suggests an increase in rainfall received through the North East Monsoon in the NBR (Fig. 2 on page 9), and most of the savanna and dry forests are located in the eastern parts of the landscape that predominantly receives the North East Monsoon. This increase in tree cover could also be related to the spread of invasive tree species like *Prosopis juliflora* in these drier landscapes (Rajput et al., 2019; Sivakumar et al., 2018). Invasion of savanna systems by woody shrubs has been observed in the Western Ghats and in other parts of the world, and such increases in woody cover has been attributed to elevated $CO_2$ conditions, fire, rainfall, and management practices among other factors (Nayak et al., 2014; Ratajczak et al., 2012; Stevens et al., 2017). We also found an increase in tree cover in grasslands which are mostly distributed in higher altitudes in the NBR.

*Table 3: Percentage of area under different land cover types showing significant loss or gain in annual net primary productivity (ANPP), vegetation greening or browning (Phenology), and blue water in the Nilgiri Biosphere Reserve as a response to factors other than temperature and rainfall (other climatic and anthropogenic factors). Increase/greening or decrease/browning refers to significant monotonic trends obtained from running Sen's slope on ANPP, EVI based eco-climatic distance, and blue water layer.*

| **Land use/Land cover** | **ANPP** | | **Phenology** | | **Blue water** | |
|---|---|---|---|---|---|---|
| | **%Decrease** | **%Increase** | **%Browning** | **%Greening** | **%Decrease** | **%Increase** |
| Evergreen | 39.67 | 0.31 | 2.97 | 3.08 | 0.10 | 0.23 |
| Moist-deciduous | 41.31 | 0.35 | 3.18 | 2.06 | 0.63 | 0.56 |
| Dry-deciduous | 39.95 | 0.36 | 2.83 | 1.92 | 0.71 | 0.68 |
| Savanna/scrub | 33.13 | 1.75 | 2.31 | 1.08 | 0.25 | 0.81 |
| Grassland | 45.95 | 0.35 | 2.29 | 0.83 | 1.80 | 0.49 |
| Forest plantation | 29.71 | 1.37 | 3.27 | 1.18 | 0.20 | 0.26 |
| Orchards | 43.19 | 0.03 | 3.42 | 1.54 | 0.63 | 0.49 |
| Agriculture | 29.03 | 2.10 | 3.61 | 1.80 | 0.85 | 0.66 |

An increase in tree cover is observed in parts of grasslands. Historically, under the afforestation programme of state Forest Departments, trees have been planted in grasslands and shrublands throughout the Western Ghats (Joshi et al., 2018; Krishnan, 2015). In addition, many of the planted tree species have become invasive, colonising natural grasslands in the NBR(Joshi et al., 2018). The observed increase in tree cover in grasslands could be related to the spread of invasive woody species. Spread of woody shrubs into the high elevation grasslands is also facilitated by increasing temperatures (Joshi et al., 2020). Parts of grasslands also show a decrease in tree cover, and this might be due to the active efforts of the Forest Department in removing wattle (*Acacia spp.*) from natural grasslands following a judgement passed by the Madras High Court (WP (MD) no. 3633 of 2014).

Our results suggest greater decrease in tree cover in wetter forests (evergreen and moist deciduous forests) than the overall gain in tree cover in these forests. Results of trends in vegetation growth (refer to pages 43 - 70) also indicates relatively greater decrease compared to increase in vegetation growth in the moist deciduous and evergreen forests. Our analysis of the long term trends in rainfall suggest a decrease in rainfall received from the South West Monsoon in the NBR landscape (refer to pages 1 - 24). Most of the evergreen and moist deciduous forests in the NBR are distributed in the western parts, which mainly receive the South West Monsoon. Thus a reduction in rainfall could be a reason for reduced tree cover in these forests. Anecdotal evidences also suggest a die back of evergreen shola forests from several parts of the landscape, which could be associated with climate variations.

There is an increase in frequency and intensity of forest fires in the NBR, which could play a role in decreasing tree cover, especially in grasslands and evergreen forests (Kodandapani et al., 2004). Among the PAs within the NBR, Nagarhole and Mukurthi showed greater tree loss. Tree cover loss in Nagarhole could be related to multiple large fires that the landscape had witnessed in the recent years. Mukurthi is predominately a montane grassland system and it has been planted with exotic trees by the Forest Department. A die-back of wattle has been observed in large parts of Mukurthi (*pers. observation*). Also trees have been removed by the Forest Department in an effort to restore these natural grassland ecosystems. Among all PAs, Sathyamangalam showed greater gains in tree cover. Sathyamangalam is predominantly a savanna/scrub system. As mentioned before, an increase in rainfall received from the North East Monsoon and an increase in invasive tree species could be a reason for the observed tree cover increase in this PA.

Analysis of the influence of non-climatic factors on ecosystem services suggests that the influence of non-climatic factors is prominent on carbon sequestration (ANPP) compared to phenology and hydrological services. We found a decline in the ANPP across all land cover types. Factors such as forest fires, livestock grazing, logging, and LULC change are known to reduce ANPP globally (Irisarri et al., 2016; Kang et al., 2006; Ramachandra & Bharath, 2020; Wang et al., 2012). The lowest decrease in ANPP was observed in the savanna, which matches with the increased tree cover trends in the savanna and scrubs. Similarly, maximum decrease in the ANPP follows the declining tree cover trends observed in high altitude PAs like Mukurthi. The trends in residuals in other land cover types suggest that there might be other anthropogenic factors influencing these trends in the NBR.

Global studies on tropical forest deforestation suggest a steady rate of deforestation over the years (Broich et al., 2011; Curtis et al., 2018; Harris et al., 2017). Our study suggests a decrease in deforestation rate in the NBR, and loss in tree cover was less in the recent decade, 2010–2019 (-3.28%), compared to 2000–2009 (-4.75%). Similar reductions in tree loss have been reported in other parts of the Western Ghats in the recent decades (Kale et al., 2016). In the NBR, reduction in deforestation rates in the recent decades have been attributed to a high degree of protection (Satish et al., 2014). In support of this argument, we also observed a reduction in tree cover loss in PAs, which was two times less when compared to areas outside PAs. However, tree cover loss outside PAs is still a warning as it may indicate rampant deforestation due to developmental activities, forest fires, and other anthropogenic activities outside (Baskaran et al., 2012). Our study provides information on such areas undergoing rapid tree loss; these areas should be prioritized for conservation. We find some evidences of a relationship between change in LULC and some of the ecosystem services in different forest types. Although majority of the NBR shows an increase in tree cover, this could be related to invasion of grasslands and other natural systems by woody species. A decrease in forest cover while an increase in invasive trees and plantations could affect ecosystem processes and services in the NBR (Nayak et al., 2020). LULC simulation models under climate change scenarios in parts of the Western Ghats indicate an increase in mean streamflow and sediment yield with a decrease in forest cover and increase in plantation, agricultural, and urban areas (Sinha et al., 2020). In addition to LULC change, there are other anthropogenic factors influencing ecosystem services in the NBR. Our results provide information on areas where a likely change in ecosystem services is expected and which needs to be considered in developing resilience to future climate change.

## References


Amarnath, G., Babar, S., & Murthy, M. S. R. (2017). Evaluating MODIS-vegetation continuous field products to assess tree cover change and forest fragmentation in India–A multi-scale satellite remote sensing approach. *The Egyptian Journal of Remote Sensing and Space Science*, *20*(2), 157–168.

Baskaran, N., Anbarasan, U., & Agoramoorthy, G. (2012). India’s biodiversity hotspot under anthropogenic pressure: A case study of Nilgiri Biosphere Reserve. *Journal for Nature Conservation*, *20*(1), 56–61.

Broich, M., Hansen, M. C., Potapov, P., Adusei, B., Lindquist, E., & Stehman, S. V. (2011). Time-series analysis of multi-resolution optical imagery for quantifying forest cover loss in

Sumatra and Kalimantan, Indonesia. *International Journal of Applied Earth Observation and Geoinformation*, *13*(2), 277–291. https://doi.org/10.1016/j.jag.2010.11.004

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.

DeFries, R., Field, C., Fung, I., Collatz, G., & Bounoua, L. (1999). Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. *Global Biogeochemical Cycles*, *13*(3), 803–815.

Gao, Y., Ghilardi, A., Mas, J.-F., Quevedo, A., Paneque-Gálvez, J., & Skutsch, M. (2018). Assessing forest cover change in Mexico from annual MODIS VCF data (2000–2010). *International Journal of Remote Sensing*, *39*(22), 7901–7918.

Harris, N. L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Ansari, S., Lippmann, M., Bennett, L., Raad, M., Hansen, M., & others. (2017). Using spatial statistics to identify emerging hot spots of forest loss. *Environmental Research Letters*, *12*(2), 024012.

Irisarri, J. G. N., Derner, J. D., Porensky, L. M., Augustine, D. J., Reeves, J. L., & Mueller, K. E. (2016). Grazing intensity differentially regulates ANPP response to precipitation in North American semiarid grasslands. *Ecological Applications*, *26*(5), 1370–1380.

Jeromi, P. (2007). Farmers' indebtedness and suicides: Impact of agricultural trade liberalisation in Kerala. *Economic and Political Weekly*, 3241–3247.

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

Joseph, B., & Joseph, K. (2005). Commercial Agriculture in Kerala after the WTO. *South Asia Economic Journal*, *6*(1), 37–57.

Joshi, A. A., Ratnam, J., & Sankaran, M. (2020). Frost maintains forests and grasslands as alternate states in a montane tropical forest–grassland mosaic; but alien tree invasion and warming can disrupt this balance. *Journal of Ecology*, *108*(1), 122–132.

Joshi, A. A., Sankaran, M., & Ratnam, J. (2018). 'Foresting' the grassland: Historical management legacies in forest-grassland mosaics in southern India, and lessons for the conservation of tropical grassy biomes. *Biological Conservation*, *224*, 144–152.

Kale, M. P., Chavan, M., Pardeshi, S., Joshi, C., Verma, P. A., Roy, P., Srivastav, S., Srivastava, V., Jha, A., Chaudhari, S., & others. (2016). Land-use and land-cover change in Western Ghats of India. *Environmental Monitoring and Assessment*, *188*(7), 1–23.

Kang, S., Kimball, J. S., & Running, S. W. (2006). Simulating effects of fire disturbance and climate change on boreal forest productivity and evapotranspiration. *Science of the Total Environment*, *362*(1–3), 85–102.

Kodandapani, N., Cochrane, M. A., & Sukumar, R. (2004). Conservation Threat of Increasing Fire Frequencies in the Western Ghats, India. *Conservation Biology*, *18*(6), 1553–1561. https://doi.org/10.1111/j.1523-1739.2004.00433.x

Krishnan, S. (2015). Woody, Thorny, and Predatory Forests: Grassland Transformations in the Nilgiris, South India. *RCC Perspectives*, *3*, 39–44.

Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Lele, S., Kiran, M. C., Reddy, V., Badiger, S., & Rakesh, K. N. (2012). The rain–runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India. *Journal of Hydrology*, *472–473*(0), 216–237. https://doi.org/10.1016/j.jhydrol.2012.09.016

Lawler, J. J., Lewis, D. J., Nelson, E., Plantinga, A. J., Polasky, S., Withey, J. C., Helmers, D. P., Martinuzzi, S., Pennington, D., & Radeloff, V. C. (2014). Projected land-use change impacts on ecosystem services in the United States. *Proceedings of the National Academy of Sciences*, *111*(20), 7492–7497.

Mayaux, P., Holmgren, P., Achard, F., Eva, H., Stibig, H.-J., & Branthomme, A. (2005). Tropical forest cover change in the 1990s and options for future monitoring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1454), 373–384.

Morton, D. C., DeFries, R. S., Shimabukuro, Y. E., Anderson, L. O., Del Bon Espírito-Santo, F., Hansen, M., & Carroll, M. (2005). Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data. *Earth Interactions*, *9*(8), 1–22.

Nayak, R., Krishnaswamy, J., Vaidyanathan, S., Chappell, N., Kesavan, K., Ghatwai, P., & Bhalla, R. S. (2020). Exotic Plantations Increase Risks of Flooding in Mountainous Landscapes. *Earth and Space Science Open Archive*, 25. https://doi.org/10.1002/essoar.10503675.1

Nayak, R., Vaidyanathan, S., & Krishnaswamy, J. (2014). Fire and grazing modify grass community response to environmental determinants in savannas: {Implications} for sustainable use.

*Agriculture, Ecosystems & Environment*, *185*, 197–207. https://doi.org/10.1016/j.agee.2014.01.002

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D., & Zaehle, S. (2007). Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. *Proceedings of the National Academy of Sciences*, *104*(39), 15242–15247.

Potapov, P. V., Turubanova, S. A., Hansen, M. C., Adusei, B., Broich, M., Altstatt, A., Mane, L., & Justice, C. O. (2012). Quantifying forest cover loss in Democratic Republic of the Congo, 2000–2010, with Landsat ETM+ data. *Remote Sensing of Environment*, *122*, 106–116.

Prance, G. T. (2006). Tropical savannas and seasonally dry forests: An introduction. *Journal of Biogeography*, *33*(3), 385–386.

Rajput, N., Baranidharan, K., Vijayabhama, M., & Sawant, A. (2019). Ecological impact of Prosopis juliflora on the habitat conditions of blackbuck in Sathyamangalam tiger reserve, Tamil Nadu, India. *Journal of Entomology and Zoology Studies*, *7*(3), 610–615.

Ramachandra, T. V., & Bharath, S. (2020). Carbon Sequestration Potential of the Forest Ecosystems in the Western Ghats, a Global Biodiversity Hotspot. *Natural Resources Research*, *29*(4), 2753–2771. https://doi.org/10.1007/s11053-019-09588-0

Ramachandran, R. M., Roy, P. S., Chakravarthi, V., Sanjay, J., & Joshi, P. K. (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.

Ratajczak, Z., Nippert, J. B., & Collins, S. L. (2012). Woody encroachment decreases diversity across North American grasslands and savannas. *Ecology*, *93*(4), 697–703.

Roy, P. S., Roy, A., Joshi, P. K., Kale, M. P., Srivastava, V. K., Srivastava, S. K., Dwevidi, R. S., Joshi, C., Behera, M. D., Meiyappan, P., Sharma, Y., Jain, A. K., Singh, J. S., Palchowdhuri, Y., Ramachandran, R. M., Pinjarla, B., Chakravarthi, V., Babu, N., Gowsalya, M. S., … Kushwaha, D. (2015). Development of Decadal (1985–1995–2005) Land Use and Land Cover Database for India. *Remote Sensing*, *7*(3), 2401–2430. https://doi.org/10.3390/rs70302401

Satish, K., Saranya, K., Reddy, C. S., Krishna, P. H., Jha, C., & Rao, P. P. (2014). Geospatial assessment and monitoring of historical forest cover changes (1920–2012) in Nilgiri Biosphere Reserve, Western Ghats, India. *Environmental Monitoring and Assessment*, *186*(12), 8125–8140.

Sebastian, M. K., Azeez, P. A., Chaitra, S. J., & Arun, P. R. (2014). *Ecological and ethno-cultural examination of the rise and fall of rice culture in southern India with special reference to the Western Ghats* [Final Report]. Sálim Ali Centre for Ornithology and Natural History.

Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Sharma, P., Singh, M., Tiwari, P., & Verma, K. (2017). Agroforestry systems: Opportunities and challenges in India. *Journal of Pharmacognosy and Phytochemistry*, *1*(sp), 953–957.

Sinha, R. K., Eldho, T. I., & Subimal, G. (2020). Assessing the impacts of historical and future land use and climate change on the streamflow and sediment yield of a tropical mountainous river basin in South India. *Environmental Monitoring and Assessment*, *192*(11). https://doi.org/10.1007/s10661-020-08623-5

Sivakumar, K., Rawat, G. S., Badola, R., Adhikari, B. S., & Kamalakannan, B. (2018). *Study on ecological and socio-economic impact of invasive species, Prosopis juliflora and Lantana camara, and their removal from forest, common and fallow land of Tamil Nadu.* [Technical Report]. Wildlife Institute of India.

Stevens, N., Lehmann, C. E. R., Murphy, B. P., & Durigan, G. (2017). Savanna woody encroachment is widespread across three continents. *Global Change Biology*, *23*(1), 235–244. https://doi.org/10.1111/gcb.13409

Tian, H., Banger, K., Bo, T., & Dadhwal, V. K. (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.

Wang, S., Duan, J., Xu, G., Wang, Y., Zhang, Z., Rui, Y., Luo, C., Xu, B., Zhu, X., Chang, X., & others. (2012). Effects of warming and grazing on soil N availability, species composition, and ANPP in an alpine meadow. *Ecology*, *93*(11), 2365–2376.

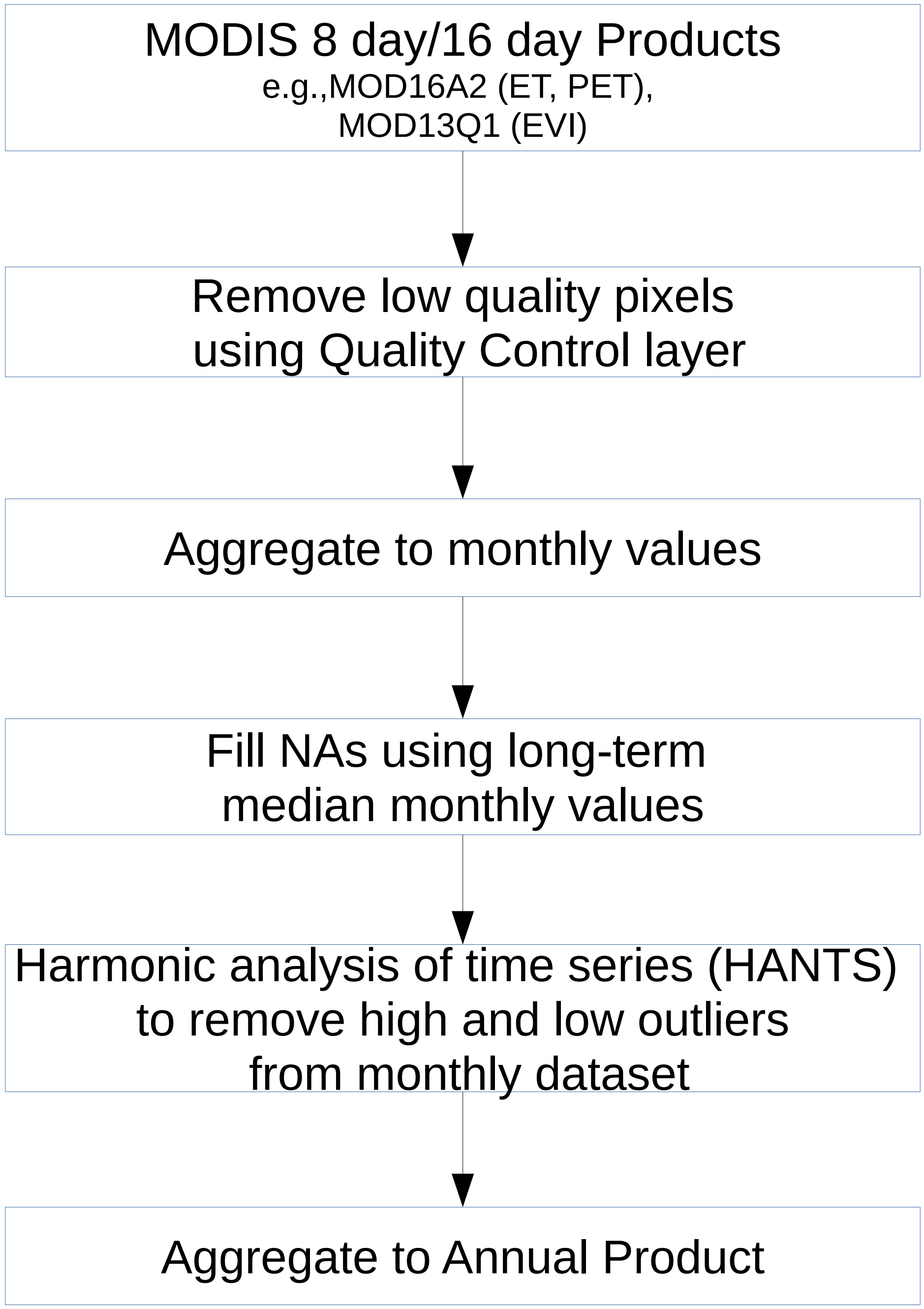
# ANNEXURE I

## List of products

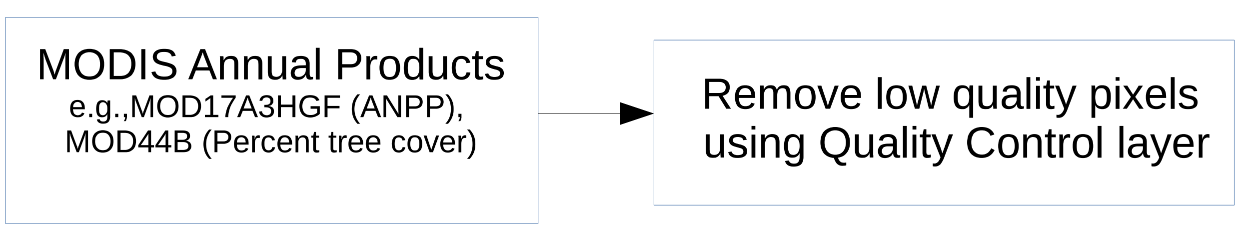
| Product | Description | Spatial Resolution | Time Period |
|---|---|---|---|
| NINO4 | Daily Average Sea Surface Temperature (SST) over 160°E to 150°W and 5°S to 5°N. An ENSO index based on the Extended Reconstructed SST dataset (ERSSTv3). http://iridl.ldeo.columbia.edu/. | | 1951-2015 |
| IOD | Daily difference in anomalies in SST between the western (50°E to 70°E and 10°S to 10°N) and eastern (90°E to 110°E and 10°S to 0°S) tropical Indian Ocean. This index is based on ERSSTv3 dataset. http://iridl.ldeo.columbia.edu/. | $0.25^0$ | 1951-2007 |
| APHRODITE | Daily rainfall totals. http://aphrodite.st.hirosaki-u.ac.jp/download/ | $0.25^0$ | 1951-2007 |
| APHRODITE | Daily mean temperature. http://aphrodite.st.hirosaki-u.ac.jp/download/ | $0.25^0$ | 1961-2015 |
| MOD17A3HGF | Annual Net Primary Productivity. https://lpdaac.usgs.gov/products/mod17a3hgfv006/ | 500 m | 2001-2019 |
| MOD16A2 | Eight day Total Potential Evapotranspiration (PET). https://lpdaac.usgs.gov/products/mod16a2v006/ | 500 m | 2001-2019 |
| MOD16A2 | Eight day Total Evapotranspiration (ET). https://lpdaac.usgs.gov/products/mod16a2v006/ | 500 m | 2001-2020 |
| CHIRPS | Daily rainfall totals. https://www.chc.ucsb.edu/data/chirps | $0.05^0$ | 2001-2020 |
| MCD12Q2 | Phenology variables: Spring green-up, maturity, autumn senescence, and dormancy. https://lpdaac.usgs.gov/products/mcd12q2v006/ | 500 m | 2001-2018 |
| MOD13Q1 | 16 days composite Enhanced Vegetation Index (EVI) layer https://lpdaac.usgs.gov/products/mod13q1v006/ | 250 | 2000-2020 |
| MOD11A2 | 8 days composite Land Surface Temperature (LST) layer https://lpdaac.usgs.gov/products/mod11a2v006/ | 1 km | 2000-2020 |
| MOD44B | Yearly percent tree cover layer https://lpdaac.usgs.gov/products/mod44bv006/ | 250 m | 2000-2019 |

**Pre-processing**

1.




2.



# ANNEXURE II

## Dynamic Linear Models

We fitted a series of Bayesian time-varying regression models (Petris et al., 2009) to various annual response variables (ANPP, bluewater, phenology, and rainfall) against scaled climatic variables (rainfall, temperature, water stress, and global teleconnections) to evaluate the historical trends in the response variables (Krishnaswamy et al., 2014, 2015). These models generate time-varying intercept and slopes which can be plotted against time and on which trends can be assessed. The general model structure used was:

$$\text{ResponseVariablet} = \beta 0t + \beta 1t\text{ClimateVariable1t} + \beta 2t\text{ClimateVariable2t} + et \qquad (1)$$

For example the ResponseVarirablet was annual blue-water and the explanatory variables were annual total rainfall and annual mean temperature.

$\beta 0t$ is the time varying intercept; $\beta 1t$, $\beta 2t$ are the regression slopes which change with time t; and et is the time-varying error.

A spatially explicit version of dynamic models was used to analyse relationships between the response variable and climatic variables for each grid cell. The model output contains time-varying intercepts and slopes for each covariate used in the analysis. The number of intercepts and slopes for each covariate used will be equal to the number of years in the time series. Finally, we estimated the Sen's slope, a robust measure of monotonic trend (Sen, 1968), for the original time-series of the response variable as well as the time-varying intercept and the regression slopes. P-values were estimated to map areas with significant ($p \leq 0.1$) monotonic trends. Trend analysis was carried out only if the time series had 65% or more data points in the time series.

The interpretation of the intercept in a static regression model is the estimated value of the response variable when the value of the covariate is zero. In the context of this study, this does not have any biophysical meaning as annual covariates might never reache zero (Eg., rainfall and temperature in the Western Ghats).

The covariates were scaled and centred to make the interpretation of the intercept more meaningful. When a scaled covariate is used in a regression model, the intercept is the estimated value of the response variable at the average value of the covariate. In scale and centred covariates, zero is the new average value of the covariate.

The interpretation is similar in a DLM with scaled and centred covariates, except that the intercept is time-varying. The time-varying intercept represents the changing baseline of the response variable with reference to long term average of the covariates. A trend analysis on the time series of intercepts will indicate the increase or decrease in the response variable due the covariate.

The time-varying slopes in the DLM provide information on the strength of the relationship between the response variable and the covariate, and how it evolves over time. Using scaled covariates helps in interpreting the time-varying slope as it represents perturbations above or below the long-term average. The trend analysis on this relationship indicates the growing or declining influence of the covariate with respect to its long-term influence on the response variable. The trend analysis on the residuals captures the changes in the response variable due to non-climatic factors (local climatic factors, LULC changes, fire, management, grazing, etc.).

## Break-point Analysis

A segmented regression analysis on the time-varying intercepts can detect break-points at which a drastic directional change in the trend occur. We performed one break-point (two segments) analysis on the intercept values obtained from the DLM. A significant break-point was identified when either of the two segmented slopes were significant, i.e., lower and upper bounds of 95% confidence interval of the slopes did not overlap zero. If both the slopes were insignificant, then the break-point year and the slope values were considered insignificant. The distribution of the slopes before and after the break-point was compared using analysis of variance and post-hoc Tukey's test.

The DLM analysis was conducted using the 'dlm' package, Sen slope was calculated using the 'zyp' package, and the segmented regression was conducted using the 'segmented' package in R. The land use and land cover types considered for the analysis were sourced from Roy et al., (2015) and it included evergreen, moist deciduous forests, dry deciduous forests, savanna and scrub, forest plantation, grassland, orchard, and agriculture.

## References


Krishnaswamy, J., John, R., & Joseph, S. (2014). Consistent response of vegetation dynamics to recent climate change in tropical mountain regions. Global Change Biology, 20(1), 203–215. https://doi.org/10.1111/gcb.12362

Krishnaswamy, J., Vaidyanathan, S., Rajagopalan, B., Bonell, M., Sankaran, M., Bhalla, R. S., & Badiger, S. (2015). Non-stationary and non-linear influence of ENSO and Indian Ocean Dipole on the variability of Indian monsoon rainfall and extreme rain events. Climate Dynamics, 45(1–2), 175–184. https://doi.org/10.1007/s00382-014-2288-0

Petris, G., Petrone, S., & Campagnoli, P. (2009). Dynamic linear models. In Dynamic Linear Models with R (pp. 31–84). Springer New York. http://link.springer.com/chapter/10.1007/b135794_2

Roy, P. S., Behera, M. D., Murthy, M. S. R., Roy, A., Singh, S., Kushwaha, S. P. S., Jha, C. S., Sudhakar, S., Joshi, P. K., Reddy, Ch. S., Gupta, S., Pujar, G., Dutt, C. B. S., Srivastava, V. K., Porwal, M. C., Tripathi, P., Singh, J. S., Chitale, V., Skidmore, A. K., … Ramachandran, R. M. (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

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall’s tau. Journal of the American Statistical Association, 63(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

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