*Natural Resources Research* (© 2019)
https://doi.org/10.1007/s11053-019-09588-0

*Original Paper*

# Carbon Sequestration Potential of the Forest Ecosystems in the Western Ghats, a Global Biodiversity Hotspot

**T. V. Ramachandra[1,2,3,4] and Setturu Bharath[1]**

*Received 4 July 2019; accepted 4 November 2019*

Global warming with the burgeoning anthropogenic greenhouse gas (GHG) emissions (400 parts per million from 280 ppm $CO_2$ emissions of pre-industrial era) has altered climate, eroding the ecosystem productivity and sustenance of water, affecting the livelihood of people. The anthropogenic activities such as burning fossil fuel, power generation, agriculture, industry, polluting water bodies and urban activities are responsible for increasing GHG footprint of which 72% constitute $CO_2$. GHG footprint needs to be in balance with sequestration of carbon to sustain ecosystem functions. Forests are the major carbon sinks (about 45%) that aid in mitigating global warming. The current research focusses on the carbon budgeting through quantification of emissions and sinks in the forest ecosystems and changes in climatic conditions of Western Ghats. This would help in evolving appropriate mitigation strategies toward sustainable management of forests and mitigate impacts of global warming. The land-use land-cover (LULC) dynamics are the prime driver of climate change due to the loss of carbon sequestration potential as well as emissions. The Western Ghats are one among 36 global biodiversity hotspots and forests in this region sequester atmospheric carbon, which aid in moderating the global climate and sustaining water to ensure water and food security in the peninsular India. Assessment of LULC dynamics using temporal remote sensing data shows the decline of evergreen forest by 5% with an increase in agriculture, plantations and built-up area. The interior or intact forests have declined by 10%, and they are now confined to protected areas. The simulation of likely changes indicates that the region will have only 10% evergreen cover and 17% agriculture, 40% plantations and 5% built-up. Quantification of carbon reveals that the WG forest ecosystem holds 1.23 MGg (million gigagrams or Gt) in vegetation and soils. The annual incremental carbon is about 37,507.3 Gg, (or 37.5 million tons, Mt) and the highest in the forests of Karnataka part of WG. Simulation of the likely changes in carbon content indicates the loss of 0.23 MGg (2018–2031) carbon sequestration potential under business as usual scenario. The conservation scenario depicts an increase in carbon sequestration potential of WG forests with the protection. Sequestered carbon in WG is about INR 100 billion ($1.4 billion) at carbon trading of INR 2142 ($30) per tonne. Large-scale land-cover changes leading to deforestation has contributed to an increase in mean temperature by 0.5°C and decline in rainy days, which necessitates evolving prudent landscape management strategies involving all stakeholders for conservation of ecologically fragile WG. This will enhance the ability of

[1]Energy and Wetland Research Group, CES TE 15, Environmental Information System, Centre for Ecological Sciences [CES], Indian Institute of Science, New Bioscience Building, Third Floor, E-Wing, [Near D-Gate], Bangalore 560012, India.
[2]Centre for Sustainable Technologies (ASTRA), Bangalore, India.
[3]Centre for Infrastructure, Sustainable Transportation and Urban Planning [CiSTUP], Indian Institute of Science, Bangalore, Karnataka 560 012, India.
[4]To whom correspondence should be addressed; e-mail: tvr@iisc.ac.in, envis.ces@iisc.ac.in

forests to sequester atmospheric carbon and climate moderation, with the sustenance of ecosystem goods and services.

**KEY WORDS:** Carbon sequestration, Western Ghats, Land-use dynamics, Modeling, Climate change.

## INTRODUCTION

Forests ecosystems play a vital role in sequestering carbon from the atmosphere, which helps in mitigating carbon footprint and aid in moderating the global warming and consequent changes in the climate. Atmospheric carbon gets stored in the above- and below-ground biomass, dead organic matter and soil organic matter. Mismanagement of forests leading to deforestation and enhanced emissions during the post-industrial revolution have increased carbon dioxide concentration in the atmosphere to 400 ppm from 270 ppm (pre-industrial era). Forest ecosystems aid in capturing 45% of terrestrial carbon and are responsible for ~ 50% net ecosystem production (McGarvey et al. 2015). Forests and soil play a vital role in the carbon cycle, evident from sequestration of about 30% of annual global anthropogenic $CO_2$ emissions (2 petagrams (Pg) of carbon per year) from the atmosphere (Lal 2005; Achat et al. 2015) and hence are aptly regarded as moderators of climate (Bellassen and Luyssaert 2014). Quantification of carbon sequestered by forests across the globe was estimated as 861 ± 66 Pg C (Pan et al. 2011), with 383 ± 30 Pg C (44%) in soil (to 1-m depth), 363 ± 28 Pg C (42%) in live biomass (above and below-ground), 73 ± 6 Pg C (8%) in deadwood, and 43 ± 3 Pg C (5%) in litter, respectively. Soil carbon is the major pool of carbon terrestrial ecosystem, with major ecosystem services of advancing nutritional security, quality of water, improving biodiversity, and strengthening elemental recycling. The retention of carbon in soil depends on land-use, anthropogenic pressure, disturbance regimes and climate. The native and intact forests enhance mean residence time of carbon sinks with minimal re-emission (Lal et al. 2015). The land-use land-cover (LULC) changes in forest ecosystem have been altering forest structure with the increase in forest fragmentations (loss of contiguity), biodiversity loss, alteration in biogeochemical cycles and hydrological processes (Bharath et al. 2013; Vinay et al. 2013; Ramachandra et al. 2016; Armenteras et al. 2019; Ramachandra and Bharath 2019). Deforestation due to LULC changes is the prime causal parameters of global warming and increase in earth's ambient temperature due to carbon emissions and loss of ecosystem ability to sequester carbon.

Large-scale land-cover changes leading to deforestation with land degradation contribute to 20–25% of anthropogenic carbon emissions (Pachauri and Reisinger 2007) with the regional impacts on climate patterns altering the hydrological regime. The immediate effect of deforestation is the increase in carbon load in the atmosphere, and cumulative impacts are global warming, changes in the climate and ecosystem degradation. The loss of forest cover has modified local rainfall regime due to the changes in thermodynamic and mesoscale circulation processes (Lawrence and Vandecar 2015), with consequences of extreme weather conditions. Large and intact forest areas are responsible for transforming sensible heat to latent heat through the leaves; leaf area and forest canopy thereby an increase in dynamics of wind and increases precipitation events. Lower evapotranspiration with deforestation across the region has consequences of delay in the onset of the rainy season and decline in the number of rainy days with higher dry conditions (Debortoli et al. 2017). The delay in onset rainfall is positively correlated with forest cover change and extended length of the dry season (Funatsu et al. 2012). It will influence the adaptive capacity of populations and cause a shift in their diversity. Additionally, persistent drier conditions in a region can aggravate the probability of tropical evergreen forest to transform dry forest and savannah (Malhi et al. 2009). Plant metabolic activity and respiration are intensified with higher temperatures resulting in vegetation die-off due to unavailability of water. Unfavorable conditions with loss of moisture releases the soil carbon escape to the atmosphere. The biophysical variations due to deforestation has significantly altered the microclimate conditions with rapidly increasing air and land surface temperature (Alkama and Cescatti 2016; Ramachandra et al. 2018). Higher temperature changes induce higher annual water demand resulting in the loss of canopy, microflora, microclimate alteration as well as higher incidences of forest fire.

Availability of the spatial data acquired at regular intervals through spaceborne sensors (remote sensing data) helps in analyzing LULC dynamics, deforestation, forest cover status and quantification of carbon stock. This helps in framing appropriate policies for sustainable management of forests and mitigation of degradation. Traditionally, forest inventories were based on ground data, which is time and labor intensive. Integration of geo-informatics with temporal remote sensing data and ground inventory data help in the cost-effective estimation of surface characteristics such as total biomass across various biomes (Gallaun et al. 2010; Rodríguez-Veiga et al. 2019). Realizing the impacts of global warming with escalating greenhouse gas emissions, due to accelerated deforestation process necessitated measures toward adaptation and mitigation of effects of climate changes. In this regard, Kyoto Protocol was the first global initiative proposed at third Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 to curb deforestation and promote forest conservation (Humphreys 2008). Reduced Emissions of Deforestation (RED) has emerged as an initiative for conservation in 2005 at 11th COP meeting to support developing countries. REDD + materialized at the 18th COP proposed to offer incentives for the conservation and enhancement of the forest carbon stock and the sustainable management of forests in 2012. It has been playing a significant role in forest conservation and helps in addressing challenges, supporting direct/indirect costs involved in forest management (Ghazoul et al. 2010). REDD + adaptation is a form of Payments for Ecosystem Services (PES) and, while providing economic benefits to the local communities, has improved natural resource management in developing countries (Agrawal et al. 2011). This necessitates a comprehensive understanding of the carbon stock and the dynamic drivers of LULC change, to devise effective policy measures to mitigate global deforestation.

The current study investigates landscape dynamics with climate trends and carbon sequestration potential in the ecologically fragile Western Ghats (WG). The investigation involved:

(i) analyses of land-use dynamics (using temporal remote sensing data), assessment of fragmentation of forests, modeling and visualization of land-use dynamics in the WG;
(ii) evaluation of rainfall and climate dynamics associated with deforestation;
(iii) quantification of carbon sequestration potential and productivity of forests; and
(iv) formulation of appropriate management strategies to arrest deforestation and ecological security of forests.

## MATERIALS AND METHODS

### Study Area

The WG is one among 36 global biodiversity hotspots (https://www.conservation.org/) and 8 hottest hotspots of biodiversity (https://www.iucn.org/) with the exceptional endemic flora and fauna. The region is endowed with 4600 species of flowering plants (38% endemics), 330 butterflies (11% endemics), 156 reptiles (62% endemics), 508 birds (4% endemics), 120 mammals (12% endemics), 289 fishes (41% endemics) and 135 amphibians (75% endemics). It covers an area of approximately 160,000 sq. km and extends from 8° N to 21° N latitudes and 73° E to 77° E longitudes. It is considered as a water tower of India due to numerous streams originates and draining millions of hectares. The rivers of WG sustain water ensuring water and food security of 245 + million people in the peninsular Indian states. WG has 261 persons per square kilometer located in six states under such as Kerala, Tamil Nadu, Karnataka, Goa, Maharashtra, Gujrat and Dadra and Nagar Haveli (Union Territory). The region has tropical evergreen forests, moist deciduous forests, scrub jungles, sholas, savannas, including the high rainfall savannas, of which 10% of the forest area is under protection legally. The region has 261 persons per square kilometer density of population. Areca nut, coconut, coffee, tea, rubber, spices, paddy, sugarcane, cereals and cotton are major agriculture and horticulture products grown across the regions. The prime forests are being transformed to other land-uses from past 4 decades due to commercial establishments, hydroelectric projects, industries and monoculture plantations (Fig. 1).

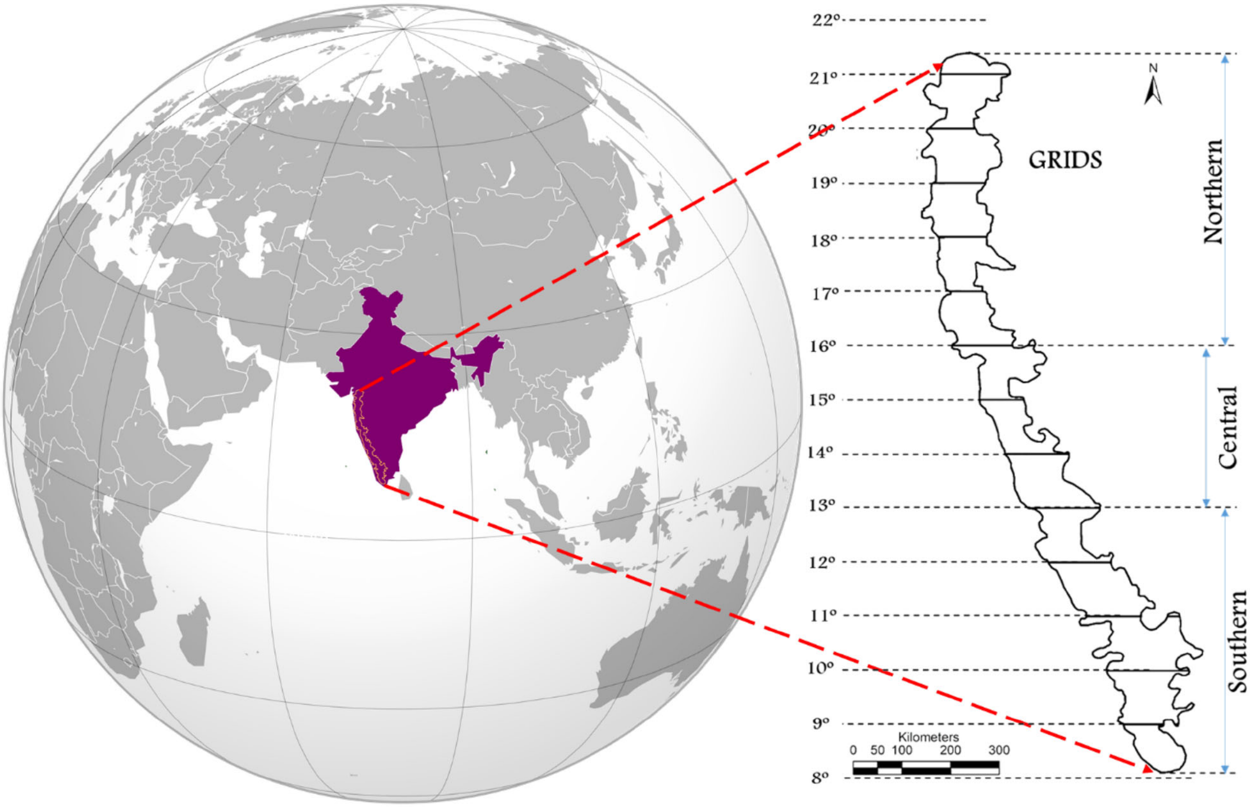

**Figure 1.** Study Area—Western Ghats, India.

## Methodology

The approach followed to quantify carbon sequestration potential of WG and climate variation, as portrayed in Fig. 2, included (i) spatial analyses of land-use dynamics and modeling, (ii) assessment of carbon sequestration potential of forests ecosystems in WG, and (iii) assessment of climate variability with land-use dynamics.

### *Quantification and Modeling of Land-use Changes*

The land-use analysis is performed by using the Landsat 8 Operational Land Imager (OLI-30 m resolution) 2018 data integrated with field estimations and decadal land-use (1985, 1995, 2005–100 m resolution) available from International Geosphere-Biosphere Programme (IGBP). The collateral data included the vegetation maps developed by French institute Puducherry, topographic maps (the Survey of India) and virtual earth data (Google Earth, Bhuvan). GPS- and AGPS-based field surveys were done in order to supplement land-use analysis and geometric correction. The process of classification involves the following. Firstly, creation of false color composite (FCC) using three bands of Landsat data, which helped in identifying the heterogeneous regions and the selection of training sites. Secondly, collection of attribute data from the field for the training polygons and virtual data (Google Earth, Bhuvan). Thirdly, land-use classification information derivation from RS data through Gaussian maximum likelihood algorithm using training data. Finally, accuracy assessment through computation of error matrix (confusion matrix) and kappa statistics. The Gaussian maximum likelihood classifier (GMLC) is proved to be an efficient supervised classification technique for deriving 8 different land-use categories from RS data (Vinay et al. 2013; Bharath et al. 2014; Ramachandra et al. 2016; Ramachandra and Bharath 2018) using free and open source GRASS GIS (Geographical Analysis Support System—http://wgbis.ces.iisc.ernet.in/grass/). The training data (60%) collected have been used for classification, while the

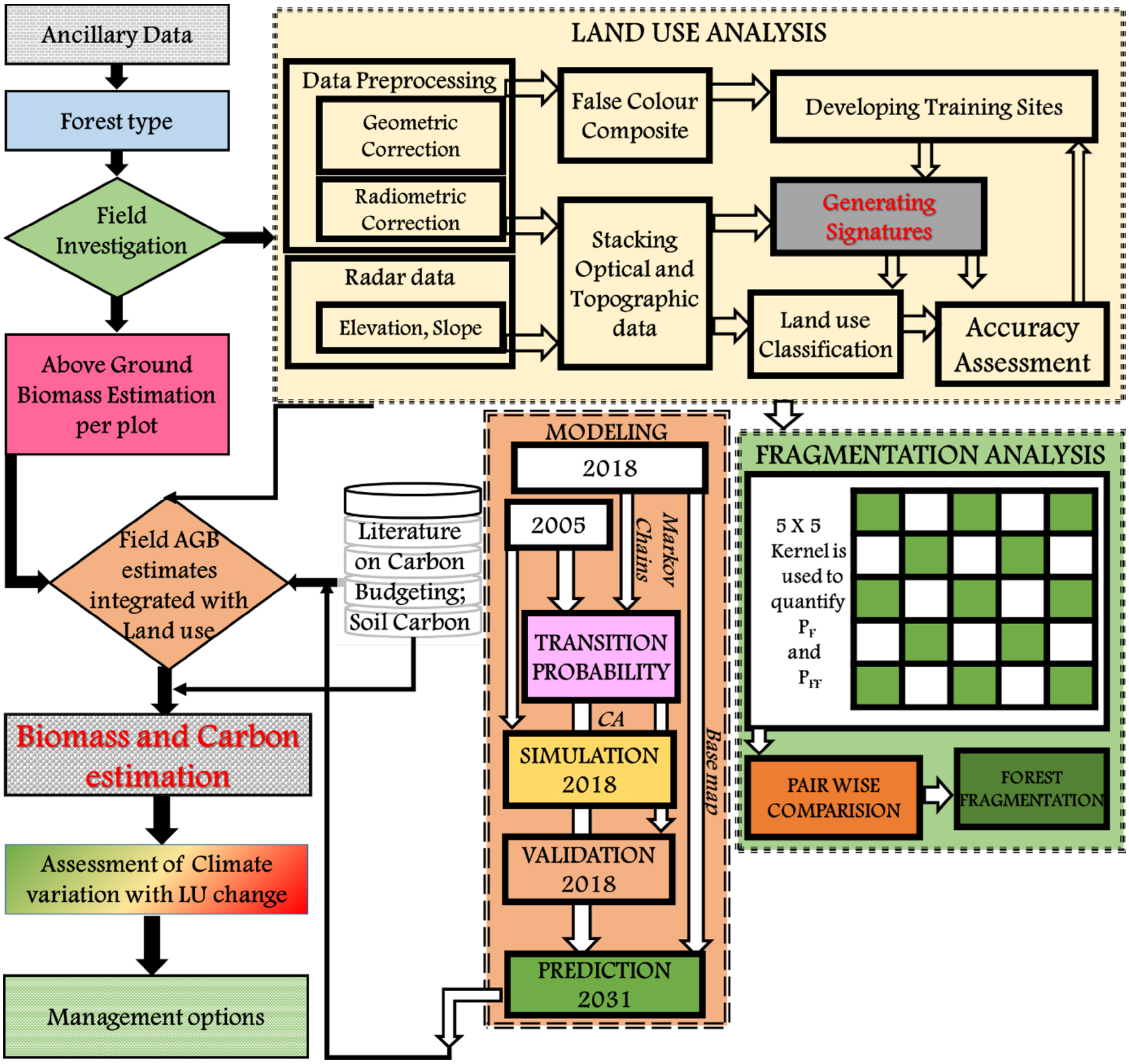

**Figure 2.** Method used for the analysis.

balance for accuracy assessment and validation (Lillesand et al. 2014). The forest fragmentation has been analyzed using two prime indicators such as $P_f$ and $P_{ff}$ (cardinal direction) (Riitters et al. 2002; Ramachandra et al. 2016). These were computed as per Eqs. (1) and (2), respectively, through a moving window of 5 × 5 pixels in order to maintain a fair representation of the proportion as given that the results of the model are scale dependent and threshold dependent (Riitters et al. 2000, 2002; Kuèas et al. 2011). Water bodies or river courses are considered non-fragmenting features and constitute natural corridors in a forested landscape, while anthropogenic landscape elements (such as buildings, roads, agricultural field, and barren land) are drivers of forest fragmentation.

$$P_f = \frac{\text{Proportion of number of forest pixels}}{\text{Total number of non - water pixels in window}} \tag{1}$$

$$P_{ff} = \frac{\text{Proportion of number of forest pixel pairs}}{\text{Total number of adjacent pairs of at least one forest pixel}} \tag{2}$$

The constrained Cellular Automata and Markov chain (CA-Markov) has been used for the simulation of likely land-use (2031). The CA-Markov modeling technique has been widely used and efficient technique for land-use simulation across the globe due to its simplicity and predictive power (Fu et al. 2018). CA-Markov uses the spatial arrangement, states, neighborhood, rules of transition, temporal scale of cells for enhanced simulation (Arsanjani et al. 2013). Water bodies or river courses and protected areas are considered as constraints of land-use change. The transition probability and area metrics were generated and used for the simulation as outlined in Bharath et al. (2014).

### *Carbon Sequestration Potential of Forests and their Future Status*

The carbon sequestration potential of forest ecosystems was assessed based on (i) published literature based on the standard biomass experiments and (ii) field-based measurements collected across the forests of WG of Karnataka using transect-based quadrat sampling techniques (Fig. 3). The field estimations were done across the varied forest types, which cover ~ 300 transects in Uttara Kannada, Shimoga, Chikmagalur, Kodagu, Dakshina Kannada and Udupi districts. The WG is divided into $5' \times 5'$ grids (2300) for biomass and carbon estimation. The biomass was estimated using GBH (girth at breast height) for the trees > 30 cm. The transect data and standard literature data were used for the quantification.

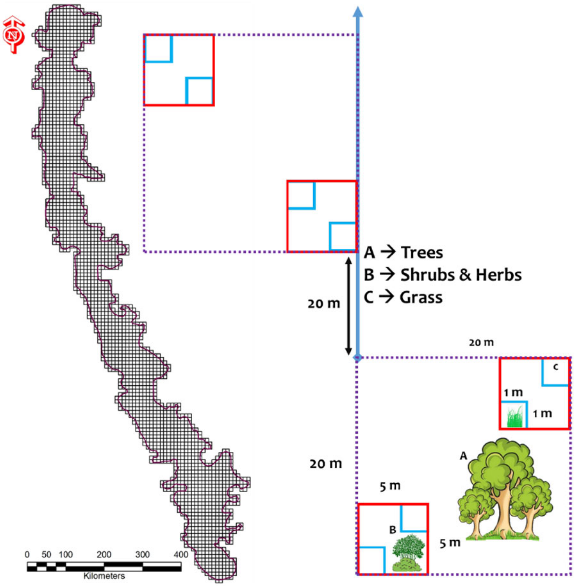

**Figure 3.** Transect cum quadrat method.

The Western Ghats consists of three diverse agro-climatic zones, namely (i) coastal, (ii) Sahyadri interior and (iii) Plains. Probable relationship between basal area (BA) and forest cover and extent of interior forest given in Eq. (3) is based on the field data (standing biomass) coupled with land-use data (land-use—forests and interior forest/contiguous forests from the fragmentation analyses). The multivariate statistical analysis was done for estimating the relationship between a dependent (standing biomass) and independent variables (BA, forest cover, percentage of interior forests-computed from land-use analysis). The standing biomass and carbon stock in each grid of Western Ghats region were quantified as per Eq. (3).

$$\text{Standing biomass} = \mathrm{F}\{\text{basal area, interior forest,forest cover}\} \tag{3}$$

Statistically significant equations based on the BA with land-use and interior forest were obtained and given in Eqs. (4), (5) and (6), respectively, for coastal, Sahyadri and plains. Validation of BA based on Eqs. (2) to (4) was done with the known BA (collected through field sampling) in the respective grids. Later, BA (Table 2) for all grids in the coast, Sahyadri interior and plains were computed considering forest land-use and interior forests (in the respective grids) using Eqs. (4), (5) and (6).

Coastal regions:

$$\mathrm{BA} = \{30.1 + (0.0414 \times (\text{forest land use}) + 0.053 \times (\text{interior forest}))\}; \quad \mathrm{n} = 50, \mathrm{SE} = 6.2 \tag{4}$$

Sahyadri interior regions:

$$\mathrm{BA} = \{39.1 + (-0.099 \times (\text{forest land use}) + 0.091 \times (\text{interior forest}))\}; \quad \mathrm{n} = 55, \mathrm{SE} = 6.3 \tag{5}$$

Plain regions:

$$\mathrm{BA} = \{34.8 + (-0.186 \times (\text{forest land use}) + 0.12 \times (\text{interior forest}))\}; \quad \mathrm{n} = 11, \mathrm{SE} = 5.5 \tag{6}$$

where n is a number of transects and SE refers to standard error. Comparisons of predicted BA (as per Eqs. (2), (3) and (4) for different agro-climatic regions) and BA quantified from the field showed a reasonable agreement with the coefficient of determination (R) of 0.878 and standard error of 11.73. Parameters such as annual increment of biomass (standing biomass) and carbon were evaluated based on field measurement and the review of literatures based on forest types as listed in Table 1. Carbon storage in forests is estimated by taking 50% of the biomass as carbon. The carbon is stored in the soil as soil organic matter (SOM) in both organic and inorganic forms. Soil carbon is calculated based on the field estimations in top 30 cm soil for different forests and extrapolated for all grids as per Table 2. Sequestered carbon and annual increment of carbon have been computed considering various land-use types as per Table 3.

### *Assessment of Climate Variability and Trend with Land-Use Changes*

Daily rainfall and temperature data (of 0.50º resolution) for the period 1901 and 2017 were collated from Princeton University Database (Princeton data—THRG 2019), NCAR climate data guide (NCAR 2019), Indian Meteorological Department (IMD 2018) and Local climate data (Karnataka State Natural Resource Disaster Monitoring Centre (KSNDMC 2018)). Princeton data and NCAR data were validated at latitude levels by comparison with the surface measurements of IMD and local climate data. The mean and variance were computed and compared, which illustrates the global data are comparable to surface measurements (with deviation ≤ 4.3%) These climatic data at latitude level were further analyzed for variability and trend. Climate (rainfall and temperature) data were compared with land-use changes to understand the role of land-use in the regional climate variability.

**Table 1.** Above-ground biomass for various forest types *Source*: Rai and Proctor (1986), Ramachandra et al. (2000a, b), Chandran et al. (2010), Ramachandra et al. (2010), Rao et al. (2013), Ramachandra et al. (2014), Ramachandra and Bharath (2019)

| Forest type | Standing biomass (t/ha) |
|---|---|
| Dense evergreen to semi-evergreen | 485.67–833.22 |
| Low evergreen | 226.55 |
| Dense deciduous | 258.12 |
| Degraded deciduous | 129.92 |
| Savanna woodlands | 74.25–90 |
| Thorn degraded | 40 |
| Littoral and swamp | 213.8 |

## RESULTS

### Land-Use Dynamics and Modeling

The spatiotemporal land-use analyses presented in Fig. 4 highlight the loss of forest cover due to anthropogenic pressure. The region had 16.21% evergreen forest cover in 1985, which is reduced to 11.3% in 2018. The region has 17.92%, 37.53%, 4.88% under plantations, agriculture, mining and built-up, respectively (Fig. 5). The increase in monoculture plantations such as Acacia, Eucalyptus, Teak, Rubber, developmental projects and agriculture expansions are the major drivers of land-use changes. The region has lost 12% of interior (contiguous) forest cover during 1985 to 2018 with an increase in non-forest cover (11%). The interior forests (25% in 2018) are confined to major protected areas; edge forests are becoming more prominent due to sustained anthropogenic pressure (Fig. 6). The Goa has experienced loss of large tracts of interior forest cover due to the indiscriminate rampant mining activities. The simulated land-use (of 2018) was compared with the actual land-use (of 2018), which shows a consistent result evident from higher accuracies (92.6%) and overall kappa ($K_{(overall)}$: 0.91, $K_{(histo)}$: 0.95, $K_{(location)}$: 0.95). The projected land-use of 2031 highlights likely loss of evergreen forest with increases in agriculture cover (39%) and built-up area (5%). The large-scale changes of agriculture and built-up cover are noticed as per Fig. 7, in the eastern Kerala, Tamil Nadu and Maharashtra states of WG. The evergreen forest will cover only 10% of the WG, which would threaten the sustenance of water and other natural resources, affecting the food security and livelihood of people in the peninsular India.

### Quantification of Carbon Sequestration

The carbon sequestration potential of WG has been quantified as discussed earlier in the method section, by using field data as well as the information from published literatures. The current study confirms that the forests of WG are incredible reservoirs of biomass and carbon stock, which highlights the decisive role of forests in lowering atmospheric carbon (emitted due to anthropogenic activities) and mitigating global warming. The above-ground biomass in WG is about 1.62 MGg (million gigagrams or tera metric tons or Tt) with the sequestered carbon of 0.81 MGg per year, respectively, which are reflected spatially across WG in Fig. 8a and b, respectively. The southern and central WG regions endowed with the rich native forests have biomass > 1200 Gg/ha and carbon 600 Gg/ha. The soils are rich in carbon (0.42 MGg) especially southern and central WG, evident from Fig. 8c. The total carbon captured by WG forests, above-ground biomass and soil, is 1.23 MGg (Fig. 8d). The annual incremental biomass of 62,869.11Gg (Fig. 9a) with the carbon capture of 31,434.55 Gg (Fig. 9b) shows the higher carbon sequestration potential in southern WG. Similar trend is noticed in the incremental carbon captured by soil 15,120 Gg as shown in Fig. 9c, d, and relatively higher carbon content increment per year is noticed in Karnataka and central Kerala parts of WG. The productivity of biomass (17,442.01 Gg) given in Fig. 10a–d reveals higher values for the states of Karnataka, Kerala and Tamil Nadu portions of WG (Fig. 10a–d). The total incremental carbon excluding carbon loss through productivity is accounted to be 37,507.3 Gg. The likely changes in carbon sequestration potential in the WG were estimated considering simulated land-use with (a) conservation scenario and (b) business-as-usual scenario. The business-as-usual scenario (with the current trend of decline of forest cover due to land-use changes) depicts the above-ground biomass of 1.3 MGg with stored carbon of 0.65 MGg and soil carbon of 0.34 MGg. The total carbon captured by WG forests in 2031 shown in Fig. 11a will be about 1.0 MGg from both above-ground biomass and soil. The large tracts of forest cover are likely to retreat due to land-use changes with increases in the agriculture and built-up area, which will erode the carbon sequestration potential of forests by 0.23 MGg (2018–2031) as illustrated in Fig. 11b. The conservation scenario depicts an increase in carbon sequestration potential of WG forests with the protection. The total carbon sequestered would be 1.5 MGg by 2031 as shown in Fig. 11c due to higher protection with minimal disturbances.

**Table 2.** Soil carbon storage in different forest types *Source*: Swamy (1992), Ravindranath et al. (1997), Ravindranath and Ostwald (2008), Ramachandra and Bharath (2019)

| Forest types | Mean soil carbon in top 30 cm (t/ha) |
|---|---|
| Tropical wet evergreen forest | 132.8 |
| Tropical semi-evergreen forest | 171.75 |
| Tropical moist deciduous forest | 57.14 |
| Littoral and swamp forest | 34.9 |
| Tropical dry deciduous forest | 58 |
| Tropical thorn forest | 44 |
| Tropical dry evergreen forest | 33 |

$CO_2$ emissions in India are about 3.1 MGg (2017), with the per capita $CO_2$ emissions of 2.56 metric tonnes (WRI 2014; Garg et al. 2017; Le Quéré et al. 2018). Carbon footprint is contributed by emissions from the energy sector (68%), agri-

**Table 3.** Biomass and sequestered carbon estimations based on forest types

| Index | Equation | Significance | Forest type |
|---|---|---|---|
| Biomass (t/ha) | (Forest cover) × 485.67<br>(Forest cover) × 258.12<br>(Forest cover) × 74.25 | Above-ground biomass content | Evergreen<br>Deciduous<br>Scrub |
| Carbon stored (t/ha) | (Estimated biomass) × 0.5 | Sequestered carbon content | All |
| Annual increment in biomass (t/ha) | (Forest cover) × 10.48<br>(Forest cover) × 13.82<br>(Forest cover) × 5.4 | Incremental growth in biomass (Ramachandra et al. 2000b; Pandey et al. 2011; Do et al. 2018) | Evergreen<br>Deciduous<br>Scrub |
| Annual increment in carbon (t/ha) | (Annual Increment in Biomass ) ×0.5 | Incremental growth in carbon storage | All |
| Net annual biomass productivity (t/ha) | (Forest cover) × 3.6<br>(Forest cover) × 3.9<br>(Forest cover) × 0.5 | Used to compute the annual availability of woody biomass in the region (Ramachandra et al. 2000b) | Evergreen<br>Deciduous<br>Scrub |
| Carbon sequestration of forest soil (t/ha) | (Forest cover) × 132.8<br>(Forest cover) × 58<br>(Forest cover) × 44 | Carbon stored in soil (Ravindranath et al. 1997) | Evergreen<br>Deciduous<br>Scrub |
| Annual increment of soil carbon | (Forest cover) × 2.5 | Annual increment in carbon stored in the soil | All |

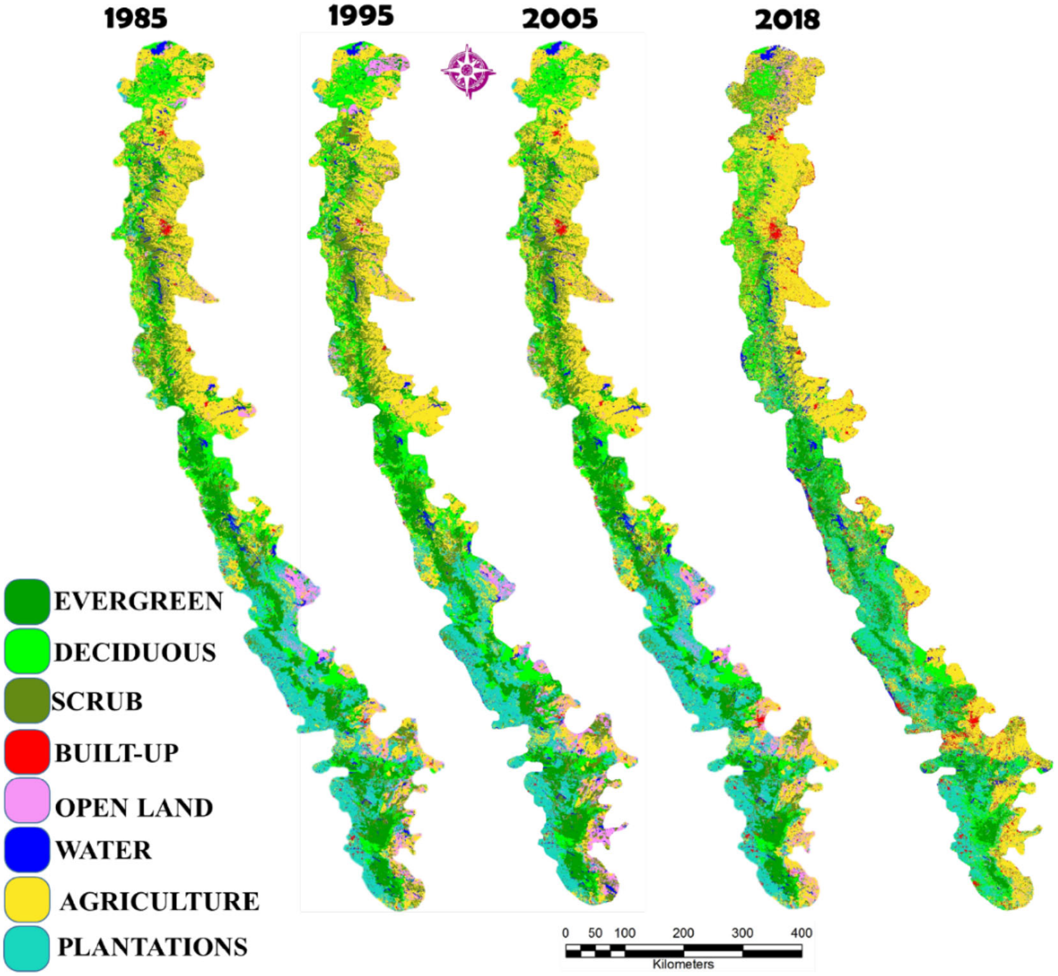

**Figure 4.** Land-use analyses of WG from 1985 to 2018.

culture (19.6%), industrial processes (6%), land-use change (3.8%) and forestry (1.9%), respectively. India, emitting 7% of total GHG emissions across the globe (336.6 MGg), is in the 4th place after major carbon emitters—China (27%), USA (15%) and European Union (10%). Carbon emission contributed by major metropolitan cities of India is about 1.3 MGg such as Delhi (38,633.20 Gg), Greater Mumbai (22,783.08 Gg), Chennai (22,090.55 Gg), Bengaluru (19,796.6 Gg), Kolkata (14,812.1 Gg) Hyderabad (13,734.59 Gg) and Ahmedabad (6580.4 Gg) from energy, transportation, industrial sector, agriculture, livestock management and waste sectors per year (Ramachandra et al. 2015). The current study illustrates the pivotal role of sequestering carbon by an ecologically fragile WG. The Western Ghats has the potential to sequester carbon emission of all southern Indian cities and 1.62% of the total $CO_2$ emissions from India. The total emissions from WG states accounted to be 352,922.3 Gg (Table 4), and forests of WG have the ability to sequester 11% of the emissions, which highlights vital carbon mitigation role and moderating climate. India has committed to reducing its the emissions by 33–35% by 2030 during the Paris Climate Change Agreement, which is challenging task considering the likely economic growth momentum to sustain 1.25 billion people consumptions (Garg et al. 2017). This necessitates immediate implementation of carbon capture (with afforestation of degraded landscapes with native species, regulations of LULC changes) and de-carbonization (through large-scale implementation of renewable and sustainable energy alternatives). These can be

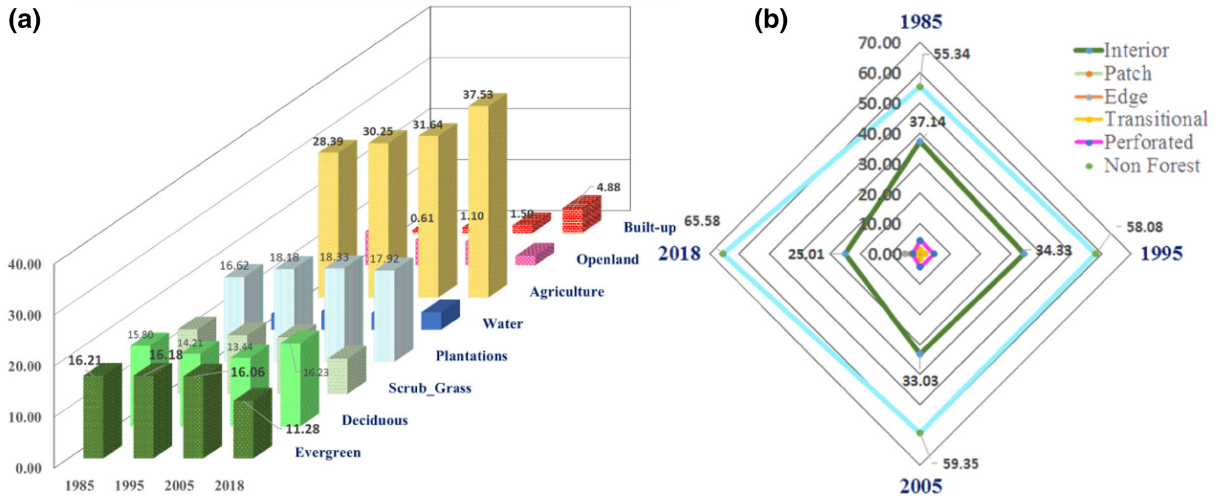

**Figure 5.** Spatiotemporal land-use and fragmentation details.

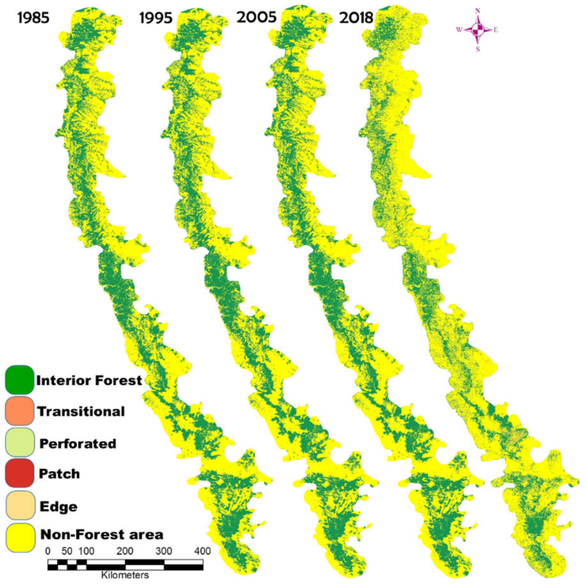

**Figure 6.** Forest fragmentation from 1985 to 2018.

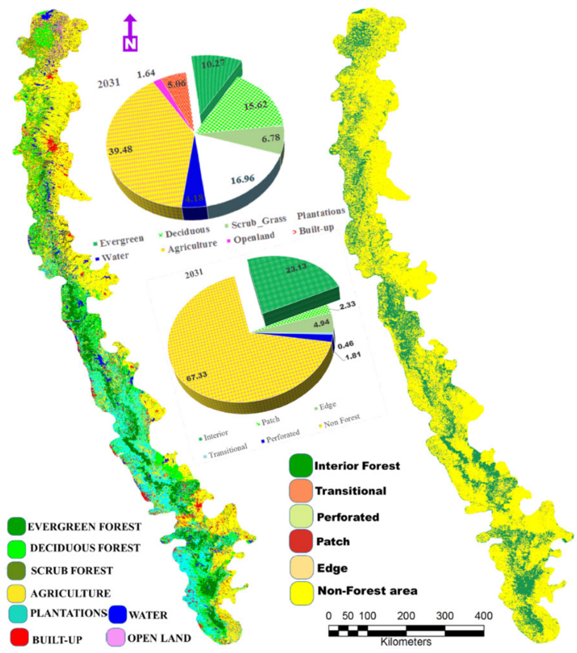

**Figure 7.** Likely land-use and fragmentation of WG for year 2031.

achieved through stringent norms toward (i) protection of ecologically fragile regions, (ii) dis-incentives for continued higher emissions based on 'polluter pays' principle, (iii) adoption of cluster-based decentralized developmental approaches and (iv) incentives for reduced emission. The carbon trading has demonstrated the potential in monetary values across the globe of Indian forests in capturing carbon (Atkinson and Gundimeda 2006; Guthrie and Kumareswaran 2009; Damandeep 2017). The monetary values of sequestered carbon vary from $10 to $1000 based on specific assumptions (Ricke et al. 2018). Based on this, the WG forests are worth INR 100 billion ($1.4 billion) at $30 per tonne. Carbon credit payments offers an effective means of increasing carbon sequestration and will proved to be a viable conservation approach via business plan.

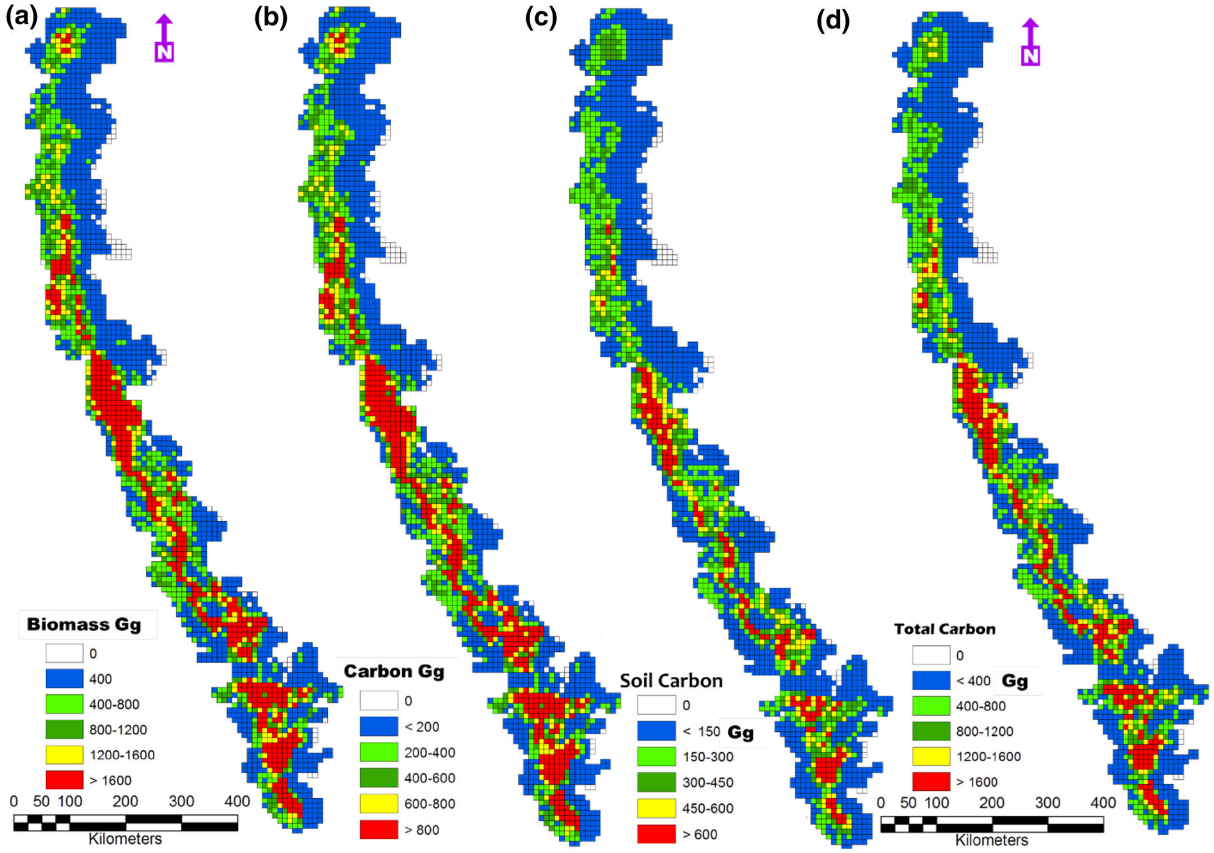

**Figure 8.** Above-ground biomass (standing biomass), carbon, soil carbon content and total carbon stock of WG.

The push of carbon credit payments, with streamlining through stakeholder's active participations, would dramatically reduce the abuse of forests. This would also encourage farmers to grow trees and converting the land to its next best use.

## Climate Trend with Land-Use Relationship

Global databases (NCAR and Princeton University) were validated through comparison with the surface measurements of ground-based monitoring stations in the regional climate datasets (IMD, KSNDMC), which shows 90% similarities. Spatial variability of precipitation, rainy days and temperature are presented in Fig. 12, which illustrates that central and northern WG have annual average temperatures less than 25.5°C, while at the southern WG show temperatures of 25.5°C to over 26.5°C. Rainfall analysis shows that the central WG receives rainfall of over 2500 mm and tends to decline to less than 1500 mm from south WG to the northern WG. Spatial distribution of rainy days illustrates that southern WG has significantly higher rainy days receiving precipitation for more than 180 days, compared to the northern parts.

Long-term trend analysis of climatic variable is depicted in Fig. 13. The southern Kerala (latitudes of 8°–9°) shows an increase in temperature from 0.5°C to greater than 1°C during the past 100 years, while the rainfall has declined by 250 mm and the decline of rainy days by 2 to 4 days. Latitude 10–12 shows that the temperatures have increased between 0.25° and 0.5°C in a century, while rainfall has declined between 100 and 250 mm and decline in rainy days by 2 days. The analysis indicated that the regions in the southern WG of Kerala and part of Karnataka (8–13°) have witnessed large-scale climate changes. The central WG portions (Karnataka) shows a very meager change in temperature, i.e., less than 0.05°C increase, while the rainfall shows increasing trends close to 100 mm and increase in rainy days up to 2 days. The

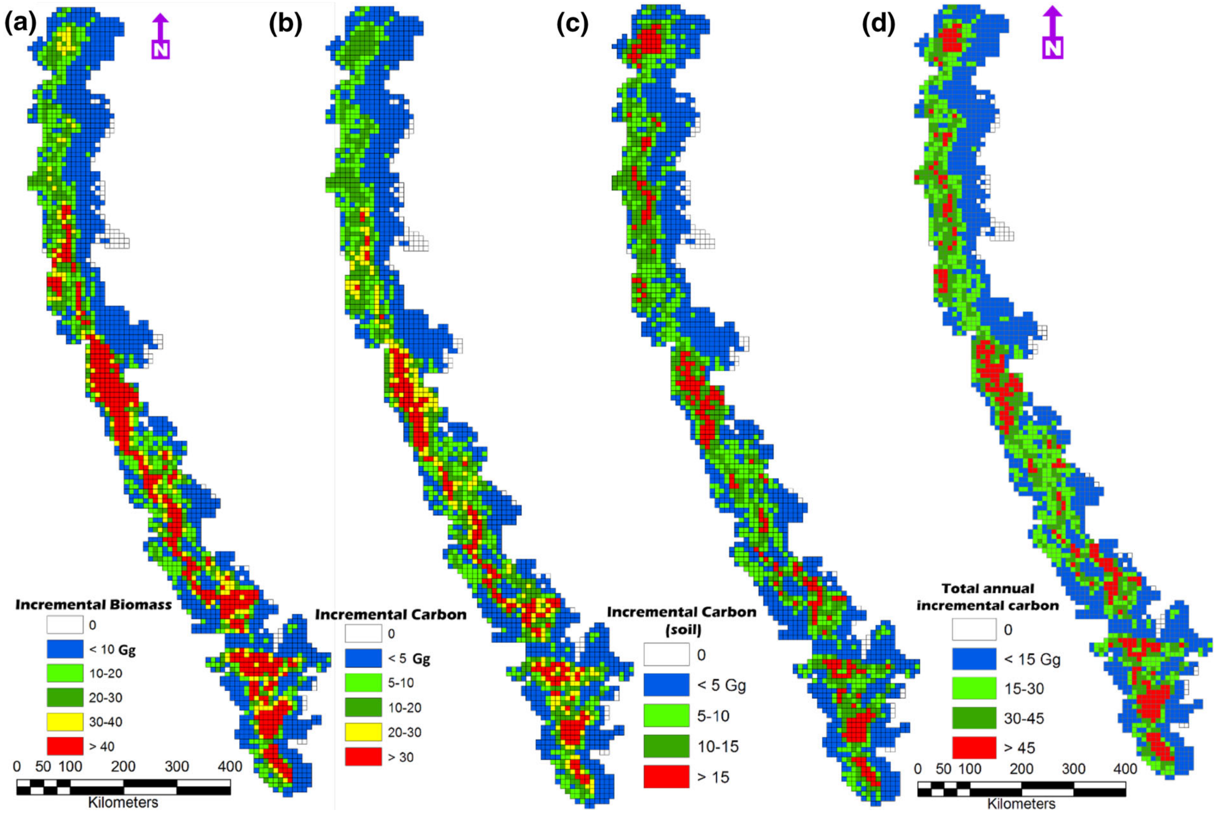

**Figure 9.** Incremental carbon of WG from above-ground biomass, below-ground biomass.

northern portion of the WG latitudes (16–21°) shows an increasing temperature of 0.5°C, 4 days increase in the number of rainy days and the increase in rainfall between 100 mm and just over 250 mm. These analyses demonstrate that land-use has played a major role in moderating microclimatic conditions in WG over a temporal scale. The reduction in rainfall and an increase in climate can affect carbon stock in the region. The fixed major soil carbon can release to the atmosphere due to land-use change and increase in temperature. The instances of vegetation die-off can occur with microclimate alterations, which further contribute to the increase in the carbon content of the atmosphere. Forests are also known as water towers and are responsible for capturing water from the atmosphere through rainfall and also aid in condensation, influencing land surface properties such as evapotranspiration, temperature and humidity (Bonan 2008; Syktus and McAlpine 2016). Reduction in the natural forests has reduced the surface roughness and aerodynamics, due to which the rain bearing clouds move along the winds causing rainfall in the windward direction. This could be observed with increasing rainfall and rainy days to the Northern WG and decreasing rainfall and rainy days in the southern WG.

## DISCUSSION

Forests sequester atmospheric carbon and help in lowering GHG footprint apart from providing diverse goods and services to the humankind. The anthropogenic pressures resulting in large-scale LULC changes are altering the landscape structure which has affected ecological functions, namely hydrological regime, biogeochemical functioning and nutrient cycling. Implications of the implementation of unplanned developmental activities are evident from barren hill tops, decline in native biodiversity, spread of invasive species, alteration in hydrological regime (conversion of perennial streams and rivers to the seasonal one), increase in temperature, higher instance of flooding and droughts. The increase in greenhouse gas (GHG)

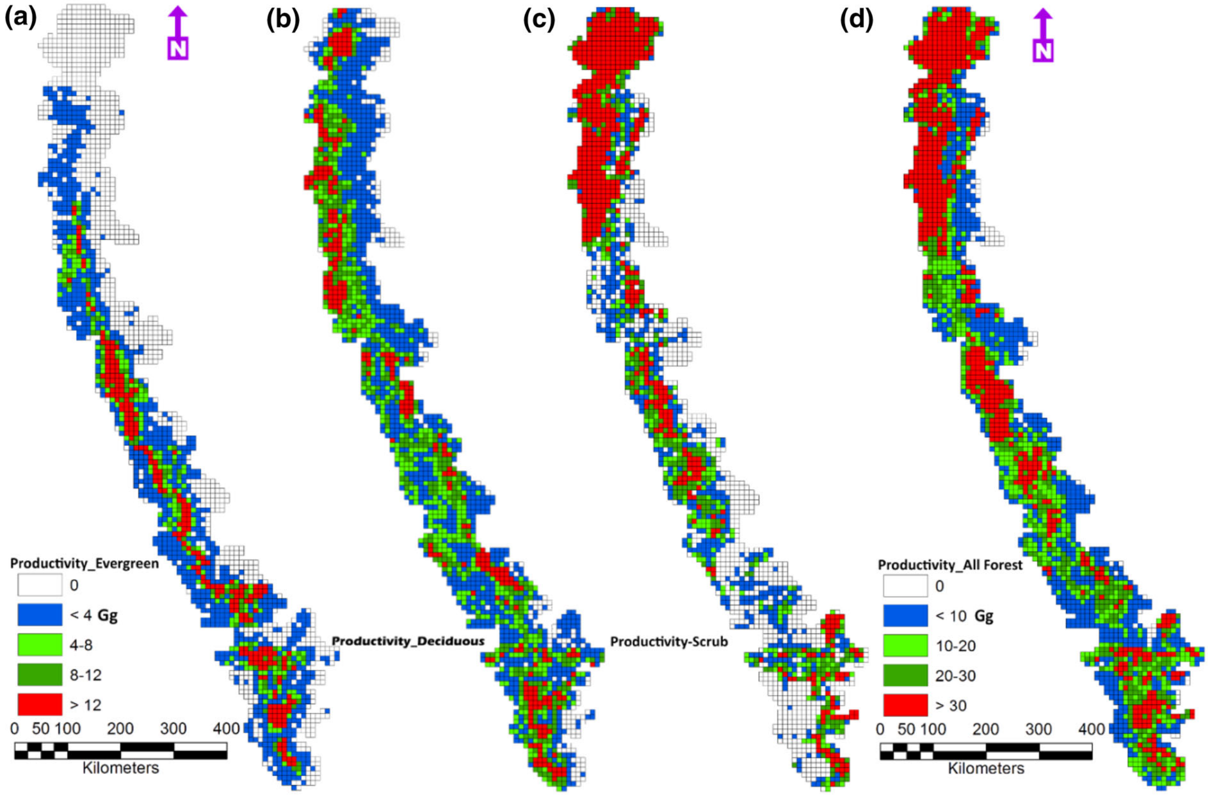

**Figure 10.** Productivity of forests across WG.

footprint due to deforestation with LULC changes has interrupted bidirectional interactions of surface vegetation cover, climate (Canziani and Gerardo 2012) and will further modify carbon budget (Schulp et al. 2008). Nogueira et al. (2015) assessed the carbon stock loss from deforestation in Brazil's 'Legal Amazonia' and 'Amazonia biome' regions (documented in 41 published studies, through field investigations in 2317 one-ha plots) and reported a gross reduction of 18.3% in Legal Amazonia (13.1 Pg C) and 16.7% in the Amazonia biome (11.2 Pg C). Emissions per unit area from forest clearing would lower the mean biomass of remaining vegetation due to various effects such as edges, disturbances and loss of microclimate. Deforestation will reduce the latent heat flux at a local scale that results in the increased warming, affecting the cloud formation process. The surface warming as a result of deforestation will increase drying of the boundary layer, could lead to reduced clouds, increase the drier period and, in turn, allow more downward solar radiation at the surface and hence warming (Bala et al. 2007).

LULC changes have directly modified the local climate, surface temperatures and rainfall regime in the WG, contributing to regional climate changes with water scarcity, increases in the vulnerability to fire and vegetation dieback. Few global studies demonstrated LULC changes and their interactions in climate and global terrestrial carbon cycle (Levy et al. 2004; Zaehle et al. 2007; Sitch et al. 2015; Zhu et al. 2018). Estimates of original biomass and likely changes in biomass are essential for estimating losses to forest degradation. In this context, the current endeavor estimates biomass and carbon stocks and attempts to present the likely changes through modeling and simulation. The modeling of likely changes with insights into agent's behavior helped in enhancing the accuracy, which will help in projecting d carbon sequestration (Zaehle et al. 2007; Schulp et al. 2008; Nogueira et al. 2018). Insights form the analyses of LULC simulated changes would help in evolving policies for prudent ecosystem management to mitigate carbon footprint by reducing the deforestation process at a regional scale.

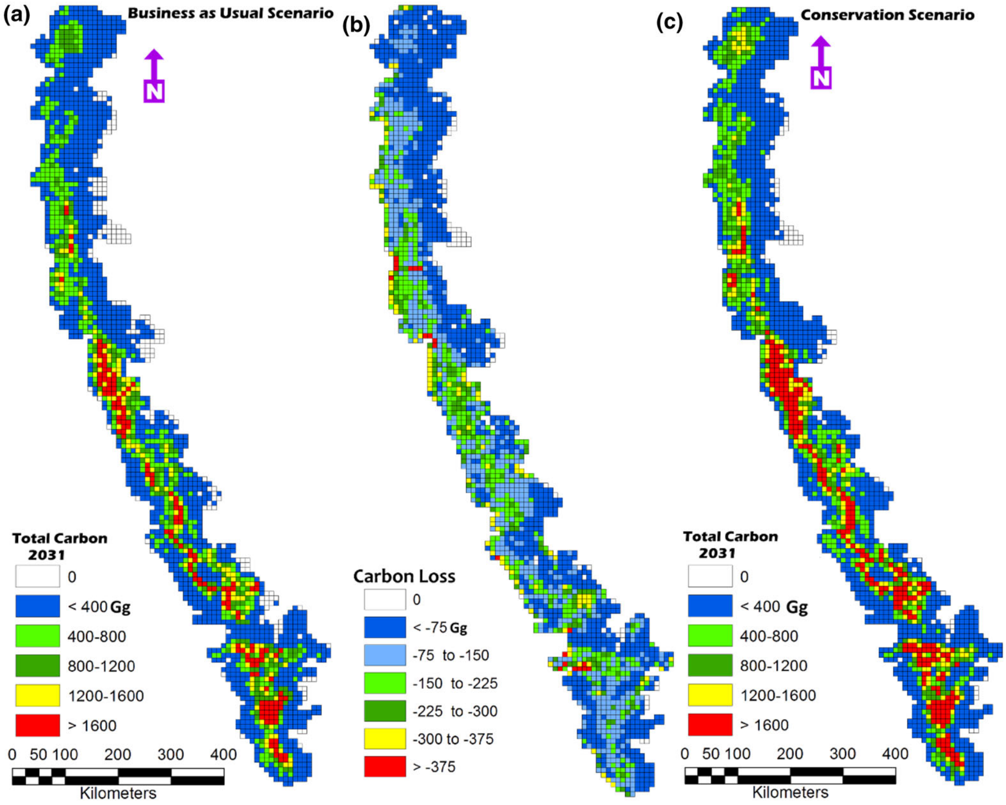

**Figure 11.** Simulated carbon stock across various scenarios.

**Table 4.** Carbon emission across the states of WG

| State/UT | Emission (Gg) per year | | | Total (Gg) | Carbon storage in WG (Gg) per year | % Removal |
|---|---|---|---|---|---|---|
| | $CH_4$ ($CO_2$ equivalent) | CO ($CO_2$ equivalent) | $CO_2$ | | | |
| Goa | 233 | 337 | 3881 | 4451 | 872 | 20 |
| Gujarat | 15,546 | 14,498 | 79,138 | 109,182 | 1947 | 2 |
| Karnataka | 15,662 | 15,239 | 54,337 | 85,237 | 10,401 | 12 |
| Kerala | 3167 | 6108 | 26,047 | 35,321 | 7617 | 22 |
| Maharashtra | 23,129 | 26,497 | 105,260 | 154,886 | 11,020 | 7 |
| Tamil Nadu | 15,761 | 19,190 | 71,107 | 106,058 | 5375 | 5 |
| Dadra and Nagar Haveli | 46 | 63 | 1458 | 1567 | 601 | 38 |
| Total emission (Gg) | | | | 496,703 | 37,833 | 8 |

## CONCLUSIONS

The assessment of land-use changes with carbon dynamics demonstrates the potential of ecologically fragile Western Ghats in mitigating global warming through carbon sequestration. Land-use analysis reveals the loss of evergreen forest cover from 16 to 11% (1985–2018) with the increase in anthropogenic

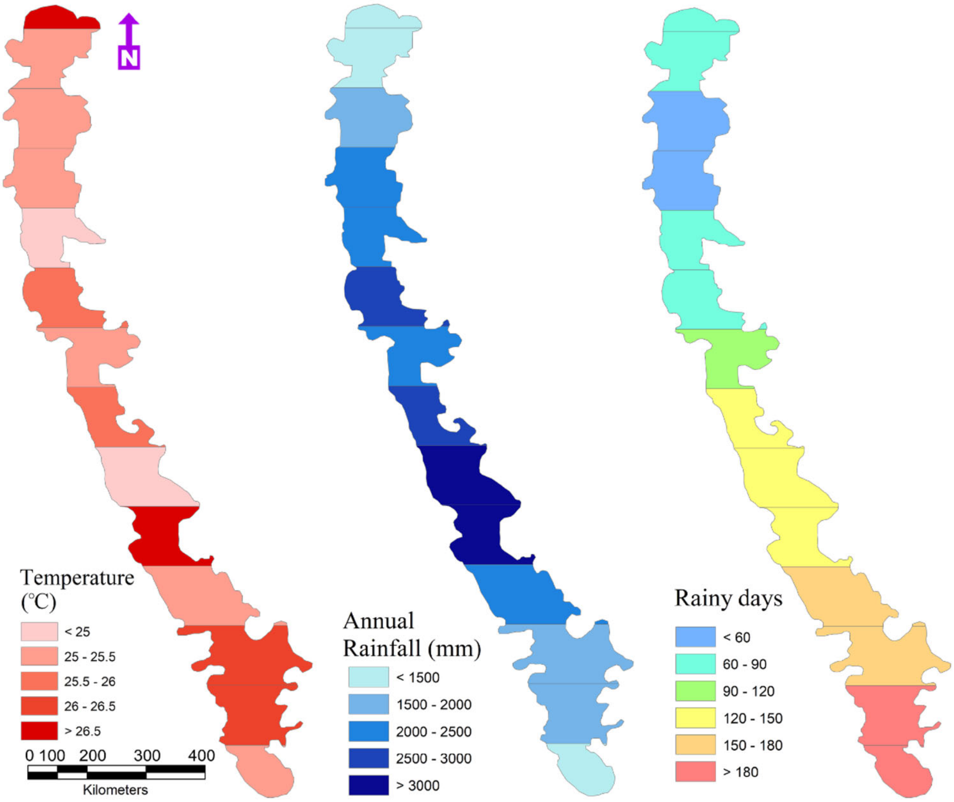

**Figure 12.** Spatial variations of climatic parameters.

pressure due to unplanned developmental activities. The simulation of likely changes depicts the region will have merely 10% evergreen cover (in protected areas) with agriculture (17%), plantations (40%) and built-up area (5%). The WG forests stores 1.23 MGg of carbon (both above-ground biomass and soil). The annual increment of 37,507.3 Gg highlights the role of forests in lowering carbon at the regional level. The temporal land-use and climate variable responses have revealed reduction in rainy days (4 days) in Kerala and Tamil Nadu parts of WG with the increase in Maharashtra. The regions in 8–12° latitude are experiencing an increase of 0.5–1°C mean temperature. The results indicate that the future trends of deforestation and associated carbon stock loss would induce higher instances of flooding and drought due to changes in the climate. This analysis demonstrates that land-uses (land-cover) in the Western Ghats landscape have played a decisive role in moderating microclimatic conditions over spatial and temporal scales.

Analyses of rainfall dynamics reveal a declining trend in southern Western Ghats, while an increasing trend in the northern Western Ghats. Across the agro-climatic zones at 1 degree latitude, Ghats and the transition zones in the south (Kerala, Tamil Nadu) show a decrease in rainfall ranging between 40 and 650 mm in the century with a decline of rainy days of 5–10 days. In contrast, the north (Maharashtra, Gujarat) showed increasing trends of rainfall ranging from 120 to 430 mm and rainy days by 3–6 days at Ghats and transition zones between Ghats and plains. Similar trend analyses of temperature show an increasing trend in temperatures all across the Western Ghats. Grid-wise analysis at one degree latitude reveals an increasing trend ranging

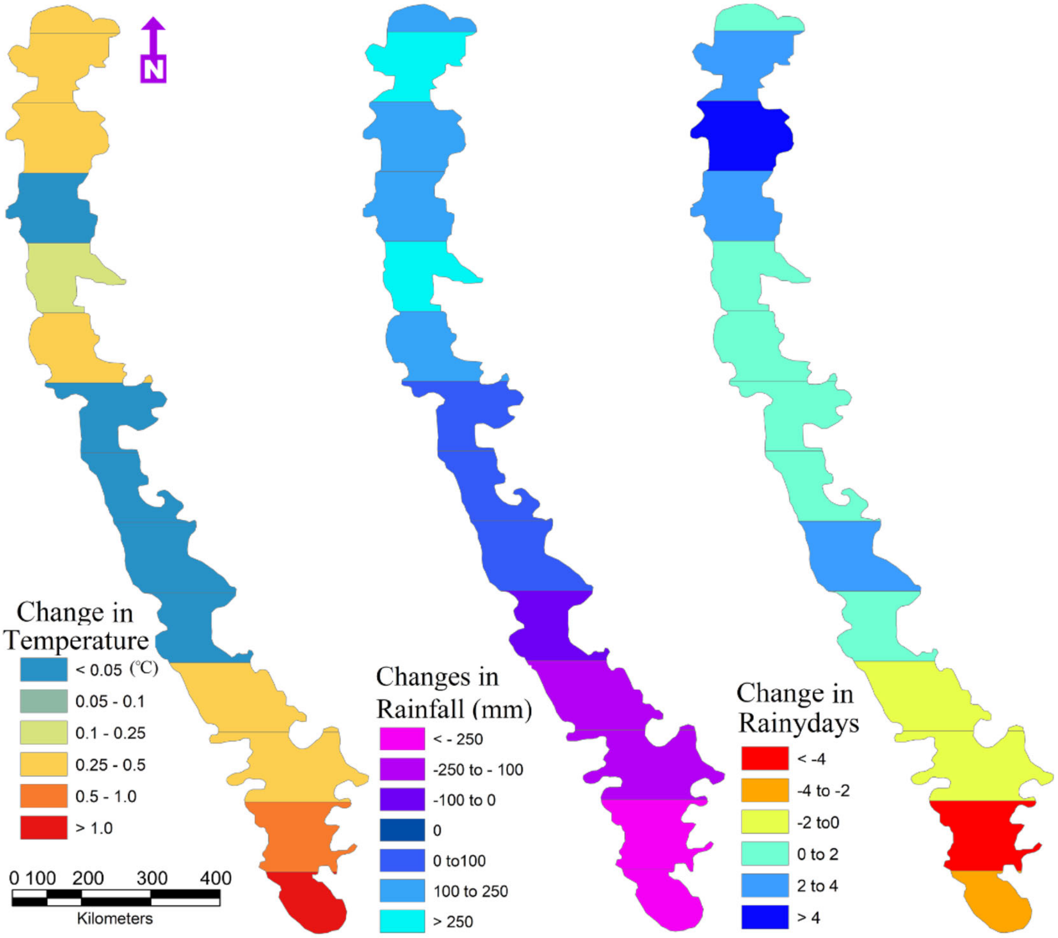

**Figure 13.** Spatiotemporal trend of climatic parameters.

between 0.31° and 1.1°C in the coast. Similar trends are observed in Ghats (0.1–1.0°C) and transition zones (0.1–0.8°C) with the highest changes in the south, followed by the north, while the central Western Ghats showed low variability in the last century.

The reduction in rainfall or rainy days and an increase in temperature (dryness) can affect carbon stock in the region. The farmers of peninsular India would face the threat of food security with erratic monsoon and lack of water. This necessitates immediate implementation of carbon capture (with afforestation of degraded landscapes with native species, regulations of LULC changes) and de-carbonization (through large-scale implementation of renewable and sustainable energy alternatives) through stringent norms toward (i) protection of ecologically fragile regions, (ii) dis-incentives for continued higher emissions based on 'polluter pays' principle and (iii) incentives for reduced emission. The WG has sequestered carbon worth INR 100 billion ($1.4 billion) at $30 per tonne of carbon. The analysis emphasizes the need for alternate development paradigm with the focus on conservation of ecologically fragile ecosystems considering the ecosystems' pivotal role in carbon capture, de-carbonization, moderating climate, sustaining water and supporting people's livelihood. Policy measures to mitigate global warming necessitates acceleration of de-carbonization measures including (i) stringent norms for carbon intensity in the industrial processes and transportation sectors, (ii) implementation of innovative carbon pricing in agreement with the internationally agreed comprehensive pricing mechanisms, (iii) shift from linear economy to circular economy through stringent regulations on recycling and reduction of wastes, energy and materials efficiency, (iv) arresting deforestation through stringent regulation on large-scale land-use changes in the ecologically fragile regions.

## ACKNOWLEDGMENTS

We are grateful to (i) ENVIS Division, the Ministry of Environment, Forests and Climate Change, Government of India (Grant: CES/TVR/DE007) and (ii) Indian Institute of Science (IISc/R1011) for the financial and infrastructure support. We acknowledge the support of Forest Department (Karnataka Forest Department), Government of Karnataka, for giving necessary permissions to undertake ecological research in central Western Ghats. We thank Vishnu Mukri and Srikanth Naik for the assistance during field data collection. We thank UNSD (United Nations Statistics Division) and MoSP (The Ministry of Statistics and Programme Implementation), Government of India for the data support.

## DATA AND ACCESSIBILITY

Data used in the analyses were compiled from the field. Data were analyzed and organized in the form of table, which are presented in the manuscript. The synthesized data are archived at http://wgbis.ces.iisc.ernet.in/energy/water/paper/researchpaper2.html#ce and at http://wgbis.ces.iisc.ernet.in/biodiversity/.

## REFERENCES

Achat, D. L., Fortin, M., Landmann, G., Ringeval, B., & Augusto, L. (2015). Forest soil carbon is threatened by intensive biomass harvesting. *Scientific reports, 5,* 15991. https://doi.org/10.1038/srep15991.

Agrawal, A., Nepstad, D., & Chhatre, A. (2011). Reducing emissions from deforestation and forest degradation. *Annual Review of Environment and Resources, 36,* 373–396.

Alkama, R., & Cescatti, A. (2016). Biophysical climate impacts of recent changes in global forest cover. *Science, 351*(6273), 600–604.

Armenteras, D., Murcia, U., González, T. M., Barón, O. J., & Arias, J. E. (2019). Scenarios of land use and land cover change for NW Amazonia: Impact on forest intactness. *Global Ecology and Conservation, 17,* e00567. https://doi.org/10.1016/j.gecco.2019.e00567.

Arsanjani, J. J., Helbich, M., Kainz, W., & Boloorani, A. D. (2013). Integration of logistic regression, Markov chain and cellular automata models to simulate urban expansion. *International Journal of Applied Earth Observation and Geoinformation, 21,* 265–275.

Atkinson, G., & Gundimeda, H. (2006). Accounting for India's forest wealth. *Ecological Economics, 59*(4), 462–476.

Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., et al. (2007). Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences, 104*(16), 6550–6555.

Bellassen, V., & Luyssaert, S. (2014). Carbon sequestration: Managing forests in uncertain times. *Nature News, 506*(7487), 153–155.

Bharath, S., Rajan, K.S., Ramachandra, T.V. (2013). Land surface temperature responses to land use land cover dynamics. Geoinfor Geostat: An Overview. https://doi.org/10.4172/2327-4581.1000112.

Bharath, S., Rajan, K. S., & Ramachandra, T. V. (2014). Status and future transition of rapid urbanizing landscape in central Western Ghats—CA based approach. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences, 2*(8), 69–75.

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science, 320*(5882), 1444–1449.

Canziani, P. O., & Gerardo, C. B. (2012). Climate impacts of deforestation/land-use changes in central South America in the PRECIS Regional Climate Model: Mean precipitation and temperature response to present and future deforestation scenarios. *The Scientific World Journal, 2012,* 1–20.

Chandran, M. D. S., Rao, G. R., Gururaja, K. V., & Ramachandra, T. V. (2010). Ecology of the swampy relic forests of Kathalekan from Central Western Ghats, India. *Bioremediation, Biodiversity and Bioavailability, 4*(1), 54–68.

Damandeep, S. (2017). *Putting a price on carbon: A handbook for indian companies*. New Delhi: TERI Press.

Debortoli, N. S., Dubreuil, V., Hirota, M., Filho, S. R., Lindoso, D. P., & Nabucet, J. (2017). Detecting deforestation impacts in Southern Amazonia rainfall using rain gauges. *International Journal of Climatology, 37*(6), 2889–2900.

Do, T. V., Trung, P. D., Yamamoto, M., Kozan, O., Thang, N. T., Thuyet, D. V., et al. (2018). Aboveground biomass increment and stand dynamics in tropical evergreen broadleaved forest. *Journal of Sustainable Forestry, 37*(1), 1–14.

Fu, X., Wang, X., & Yang, Y. J. (2018). Deriving suitability factors for CA-Markov land use simulation model based on local historical data. *Journal of Environmental Management, 206,* 10–19.

Funatsu, B. M., Dubreuil, V., Claud, C., Arvor, D., & Gan, M. A. (2012). Convective activity in Mato Grosso state (Brazil) from microwave satellite observations: Comparisons between AMSU and TRMM data sets. *Journal of Geophysical Research: Atmospheres*. https://doi.org/10.1029/2011JD017259.

Gallaun, H., Zanchi, G., Nabuurs, G. J., Hengeveld, G., Schardt, M., & Verkerk, P. J. (2010). EU-wide maps of growing stock and above-ground biomass in forests based on remote sensing and field measurements. *Forest Ecology and Management, 260*(3), 252–261.

Garg, A., Shukla, P. R., Kankal, B., & Mahapatra, D. (2017). CO2 emission in India: Trends and management at sectoral, sub-regional and plant levels. *Carbon Management, 8*(2), 111–123.

Ghazoul, J., Butler, R. A., Mateo-Vega, J., & Koh, L. P. (2010). REDD: A reckoning of environment and development implications. *Trends in Ecology & Evolution, 25*(7), 396–402.

Guthrie, G., & Kumareswaran, D. (2009). Carbon subsidies, taxes and optimal forest management. *Environmental & Resource Economics, 43*(2), 275–293.

Humphreys, D. (2008). The politics of Avoided Deforestation: Historical context and contemporary issues. *International Forestry Review, 10*(3), 433–442.

IMD. (2018). Indian Meterological Department, Hydrometerological Services, Minist. Earth Sci. Gov. India. http://www.imd.gov.in/pages/services_hydromet.php. Accessed 15 Mar 2019.

KSNDMC. (2018). Karnataka State Natural Disaster Monitoring Centre, Gov. Karnataka. http://dmc.kar.nic.in/default.asp. Accessed 13 Feb 2019.

Kuèas, A., Trakimas, G., Balèiauskas, L.I., & Vaitkus, G. (2011). Multi-scale analysis of forest fragmentation in Lithuania. *Baltic Forest, 17*(1), 128–135.

Lal, R. (2005). Forest soils and carbon sequestration. *Forest Ecology and Management, 220*(1–3), 242–258.

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability, 15,* 79–86.

Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change, 5*(1), 27–36.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., et al. (2018). Global carbon budget 2018. *Earth System Science Data*. https://doi.org/10.5194/essd-10-2141-2018.

Levy, P. E., Cannell, M. G. R., & Friend, A. D. (2004). Modelling the impact of future changes in climate, CO2 concentration and land use on natural ecosystems and the terrestrial carbon sink. *Global Environmental Change, 14*(1), 21–30.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2014). *Remote sensing and image interpretation*. New York: Wiley.

Malhi, Y., Aragão, L. E., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., et al. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences, 106*(49), 20610–20615.

McGarvey, J. C., Thompson, J. R., Epstein, H. E., & Shugart, H. H., Jr. (2015). Carbon storage in old-growth forests of the Mid-Atlantic: toward better understanding the eastern forest carbon sink. *Ecology, 96*(2), 311–317.

NCAR. (2019). Climate Data Guide. https://climatedataguide.ucar.edu/data-type/gridded-obs. Accessed 12 Jan 2019.

Nogueira, E. M., Yanai, A. M., de Vasconcelos, S. S., de Alencastro Graça, P. M. L., & Fearnside, P. M. (2018). Carbon stocks and losses to deforestation in protected areas in Brazilian Amazonia. *Regional Environmental Change, 18*(1), 261–270.

Nogueira, E. M., Yanai, A. M., Fonseca, F. O., & Fearnside, P. M. (2015). Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. *Global Change Biology, 21*(3), 1271–1292.

Pachauri, R. K., & Reisinger, A. (2007). *Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change,* Geneva, Switzerland: IPCC.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., et al. (2011). A large and persistent carbon sink in the world's forests. *Science, 333*(6045), 988–999.

Pandey, R., Rawat, G. S., & Kishwan, J. (2011). Changes in distribution of carbon in various forest types of india from 1995 to 2005 changements dans la distribution du carbone dans différents types de Forêts en Inde. *Silva Lusit, 19*(1), 41–54.

Rai, S. N., & Proctor, J. (1986). Ecological studies on four rainforests in Karnataka, India: I. Environment, structure, floristics and biomass. *The Journal of Ecology, 74*(2), 439–454.

Ramachandra, T. V., Aithal, B. H., & Sreejith, K. (2015). GHG footprint of major cities in India. *Renewable and Sustainable Energy Reviews, 44,* 473–495.

Ramachandra, T. V., & Bharath, S. (2018). Geoinformatics based valuation of forest landscape dynamics in central western Ghats. *India. J Remote Sensing & GIS, 7*(1), 227–236.

Ramachandra, T. V., & Bharath, S. (2019). Global warming mitigation through carbon sequestrations in the Central Western Ghats. *Remote Sensing in Earth Systems Sciences, 2*(1), 39–63.

Ramachandra, T. V., Bharath, S., & Chandran, M. D. S. (2016). Geospatial analysis of forest fragmentation in Uttara Kannada District. *India. Forest Ecosystems, 3*(1), 10–25.

Ramachandra, T. V., Bharath, S., & Gupta, N. (2018). Modelling landscape dynamics with LST in protected areas of Western Ghats, Karnataka. *Journal of Environmental Management, 206,* 1253–1262.

Ramachandra, T. V., Chandran, M. D. S., Harish, B. R., et al. (2010). *Biodiversity, ecology and socio economic aspects of gundia river basin in the context of proposed mega hydro electric power project, CES Technical Report 122*. Bengaluru: IISc.

Ramachandra, T. V., Hegde, G., Setturu, B., & Krishnadas, G. (2014). Bioenergy: A sustainable energy option for rural India. *Advances in Forestry Letters (AFL), 3*(1), 1–15.

Ramachandra, T. V., Joshi, N. V., & Subramanian, D. K. (2000a). Present and prospective role of bioenergy in regional energy system. *Renewable and Sustainable Energy Reviews, 4*(4), 375–430.

Ramachandra, T. V., Subramanian, D. K., Joshi, N. V., Gunaga, S. V., & Harikantra, R. B. (2000b). Domestic energy consumption patterns in Uttara Kannada district, Karnataka state. *India. Energy Conversion and Management, 41*(8), 775–831.

Rao, G. R., Krishnakumar, G., Dudani, S. N., Chandran, M. D. S., & Ramachandra, T. V. (2013). Vegetation changes along altitudinal gradients in human disturbed forests of Uttara Kannada. *Central Western Ghats. Journal of Biodiversity, 4*(2), 61–68.

Ravindranath, N. H., & Ostwald, M. (2008). *Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects* (Vol. 29). Springer Science & Business Media.

Ravindranath, N. H., Somashekhar, B. S., & Gadgil, M. (1997). Carbon flow in Indian forests. *Climatic Change, 35*(3), 297–320.

Ricke, K., Drouet, L., Caldeira, K., & Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change, 8*(10), 895–900.

Rodríguez-Veiga, P., Quegan, S., Carreiras, J., Persson, H. J., Fransson, J. E., Hoscilo, A., et al. (2019). Forest biomass retrieval approaches from earth observation in different biomes. *International Journal of Applied Earth Observation and Geoinformation, 77,* 53–68.

Riitters, K., Wickham, J., O'Neill, R., Jones, B., & Smith, E. (2000). Global-scale patterns of forest fragmentation. *Conservation ecology*. http://www.consecol.org/vol4/iss2/art3.

Riitters, K. H., Wickham, J. D., O'neill, R. V., Jones, K. B., Smith, E. R., Coulston, J. W., et al. (2002). Fragmentation of continental United States forests. *Ecosystems*, 5(8), 0815–0822. https://doi.org/10.1007/s10021-002-0209-2.

Schulp, C. J., Nabuurs, G. J., & Verburg, P. H. (2008). Future carbon sequestration in Europe—effects of land use change. *Agriculture, Ecosystems & Environment, 127*(3–4), 251–264.

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S. D., Murray-Tortarolo, G., Ahlström, A., et al. (2015). Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeosciences, 12*(3), 653–679.

Swamy, H. R. (1992). *Organic productivity, nutrient cycling and small watershed hydrology of natural forests and monoculture* *plantations in Chikmagalur District, Karnataka (No. CONF-9102202-)*. New York: Wiley.

Syktus, J. I., & McAlpine, C. A. (2016). More than carbon sequestration: Biophysical climate benefits of restored savanna woodlands. *Scientific Reports, 6,* 29194. https://doi.org/10.1038/srep29194.

THRG (2019). Terrestrial Hydrology Research Group, Global Meteorological Forcing Dataset for land surface modeling, Princeton University.

Vinay, S., Bharath, S., Bharath, H. A., & Ramachandra, T. V. (2013). Hydrologic model with landscape dynamics for drought monitoring. In *Proceeding of joint international workshop of ISPRS WG VIII/1 and WG IV/4 on geospatial data for disaster and risk reduction, Hyderabad, November* (pp. 21–22), India.

WRI. (2014). Climate analysis indicators tool: WRI's climate data explorer. World Resources Institute, Washington, DC.

Zaehle, S., Bondeau, A., Carter, T. R., Cramer, W., Erhard, M., Prentice, I. C., et al. (2007). Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990–2100. *Ecosystems, 10*(3), 380–401.

Zhu, Y., Wei, W., Li, H., Wang, B., Yang, X., & Liu, Y. (2018). Modelling the potential distribution and shifts of three varieties of *Stipa tianschanica* in the eastern Eurasian Steppe under multiple climate change scenarios. *Global ecology and conservation, 16,* e00501. https://doi.org/10.1016/j.gecco.2018.e00501.