A GIS-based study on the estimation of fixed atmospheric CO$_2$ in tropical tree biomass from Neyyar Wildlife Sanctuary, South India

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ABSTRACT

This study aims to estimate the fixed CO$_2$ in tree biomass in the Neyyar Wildlife Sanctuary in Western Ghats, India. The methodology consists of a GIS-based estimation of atmospheric CO$_2$ based on the Food and Agriculture Organization (FAO) estimation method. Prior to further analyses such as satellite image classification processes, radiometric and geometric corrections were conducted to remove unwanted artefacts, such as additive effects due to atmospheric scattering, using a set of preprocessing or clean-up routines. Tree vegetation categories – dense evergreen, evergreen, dense semi-evergreen, semi-evergreen, and moist deciduous – were identified. Tree formations were also categorized based on their elevation: high elevation, medium elevation, and low elevation. Findings showed that fixed CO$_2$ per unit area (1 ha) ranged from 356.98 t for high elevation dense evergreen to 205.24 t for low elevation semi-evergreen vegetation. Different elevation ranges in those tree formations also displayed distinct differences in the fixed CO$_2$ per unit area. For dense evergreen formation, fixed CO$_2$ was highest at high elevation, lowest at medium elevation. Evergreen and dense semi-evergreen showed higher values at low elevations compared to those at medium elevations. In semi-evergreen and moist deciduous, medium elevation trees showed higher values than those at low elevations.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report stated that ‘anthropogenic greenhouse gas emissions have increased since the pre-industrial era driven largely by economic and population growth’ (IPCC 2014, 44). Among the renowned greenhouse gases (GHG) listed by IPCC (2006), which include carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF$_6$), nitrogen trifluoride (NF$_3$), trifluoromethyl sulphur pentfluoride (SF$_5$CF$_3$), and halogenated ethers, concentrations of GHGs, such as carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O), are reported to have shown large increases since 1750 (IPCC 2014). These gases enhance the retention of heat by allowing shortwave radiation (light) to pass through but act as a barrier to longwave radiation (heat). Over the last three decades, GHG emissions have increased by an average of 1.6% per year, with CO$_2$ emissions from the use of fossil fuels growing at a rate of 1.9% per year, and these emission trends are expected to continue in the absence of additional policy actions (IPCC 2014, 2006; Land et al. 2019). The increased emission rate and decreased naturally available mechanisms to reduce atmospheric CO$_2$ are the two paths for a higher concentration of atmospheric CO$_2$. According to Cole et al. (1997), land-use change (predominantly in the tropics) and agricultural activity account for about one-third of the warming effect globally from increased GHG concentrations alone, not counting the enormous waste generated by agro-industry and magnifying the solid waste disposal issues faced by many countries (Jawaduddin et al. 2019; Sadh, Duhan, and Duhan 2018).

Adaptation and mitigation are two unavoidable options for sustainable development at the global and regional levels, resisting the dangerous effects of global warming. Huesemann (2006) explained some options to mitigate global warming by reducing the CO$_2$ concentration in the atmosphere by improving energy efficiency, reducing carbon intensity, limiting population growth, limiting economic growth, and sequestering more carbon. Carbon sequestration in terrestrial ecosystems (soil and biota) is based on the natural process of photosynthesis, and humification of biosolids applied to the soil (Lal 2009). In tree vegetation, the rate of sequestration can be increased through the increase in the extent of vegetation and their...
conservation. As trees grow and their biomass increases, they absorb CO$_2$ from the atmosphere and store it in plant tissue (Matthews et al. 2000). Some of this carbon is emitted back into the atmosphere, but the remainder is left in living and dead plant parts, above and below ground, which make up the organic carbon reservoir (Trumper et al. 2009). The carbon pool from the global forest has been estimated as 359 PgC [PgC = $10^{15}$ gC] (IPCC 2000).

In forest vegetation, trees are long-lived plants that develop a huge biomass, thereby capturing large amounts of CO$_2$ over a growth cycle of many decades, especially in tropical forests (Daba and Soromessa 2019), unlike annual plants that die and decompose yearly. An old-growth forest acts as a reservoir, holding large volumes of carbon (Sedjo 2001). Understanding forest biomass carbon pools is important for sustainable development and conservation of forests, quantifying the contribution of national and regional forests to the net CO$_2$ release to the atmosphere as well as in implementing mitigation strategies for carbon sequestration (Chhabra, Palria, and Dadhwal 2002). While some studies report the estimation of carbon stocks at the present time and also in the future in other forest types such as temperate forests (for example, Yu et al. 2013), the available data on carbon sequestration, i.e. net woody biomass accumulation in trees for long-term storage in tropical forests, are extremely limited and incomplete in India (Baishya, Barik, and Upadhaya 2009). Regional factors differ from average climate predictions, which highlight the need for regional studies (Romero et al. 2011).

Western Ghats is considered one of the most highly populated hot spot regions of the world. Population pressure and reduced availability of land area have led to tremendous land-use changes and depletion of forest. An analysis of a 40,000 km$^2$ area, covering three Western Ghats states (Karnataka, Kerala, and Tamil Nadu), showed a forest cover loss of 25.6% from 1973 to 1995 (Jha, Dutt, and Bawa 2000). Ramesh, Menon, and Bawa (1997) estimated that between 1920 and 1960, 0.07% of the forest area of the Agasthyamala region (southern part of Western Ghats) was lost annually. Between 1960 and 1990, the loss rose to 0.33%. Thus, a large area of forest biomass is lost, thereby significantly affecting atmospheric CO$_2$ by the emission of previously sequestered carbon to the atmosphere. Though a significant change in land cover and biomass production in tropical ecosystems such as Western Ghats (Ravindranath et al. 2006) is predicted as a corollary of climate change, no serious attempt has been made to understand the importance of this forest in controlling climate change. Therefore, this manuscript is especially essential in its contribution to highlighting the role of tropical forest in sequestering atmospheric CO$_2$. The aim of this study is to estimate the fixed CO$_2$ in the biomass present in the tree vegetation of Neyyar Wildlife Sanctuary.

2. Materials and methods

2.1. Study area

Neyyar Wildlife Sanctuary is one of the oldest protected areas of Western Ghats. Western Ghats, a ‘biodiversity hotspot’ in the world, is a chain of mountains spread over an area of about 54,000 km$^2$, unique in terms of its endemic flora and fauna, as well as the biological affinities it shares with forests in southeast Asia (Figure 1). The southern region of Western Ghats is one of the richest abodes of tropical moist forests in the country, where the Neyyar Wildlife Sanctuary resides with an area of 128 km$^2$. Geographically, this sanctuary is located between 8° 29’ 30” and 8° 37’ 30” North latitude and 77° 8’ 20” and 77° 17’ 05” East longitude. The climate is moderately hot and humid, and the high hills are cooler and drier compared to the foothills and valleys. The maximum mean daily temperature in the hottest month of March is about 35°C, and the mean daily minimum in the coldest month of January is about 16°C. The mean annual rainfall is about 3000 mm.
2.2. Remote sensing data processing

2.2.1. Radiometric and geometric corrections

Radiometric correction was performed to remove unwanted artefacts, such as additive effects due to atmospheric scattering, through a set of preprocessing or clean-up routines. First-order corrections were performed by dark-pixel subtraction technique. This technique assumes that there is a high probability of at least a few pixels within an image, which should be in black colour, i.e., with zero reflectance. However, because of atmospheric scattering, the image system records a non-zero digital number (DN) value at the supposedly dark-shadowed pixel location. This represents the DN value that must be subtracted from the particular spectral band to remove the first-order scattering component (Joshi et al., 2002; Roy and Joshi, 2001). For geometric correction, ground control points from the Survey of India Toposheets (1:50000) and Global Positioning System (GPS) were used. The Universal Transverse Mercator (UTM) projection was used for the analyses.

2.2.2. Image classification

Indian Remote Sensing (IRS) P6 LISS 4 satellite images (January and February 2007) with 5.8-m spatial resolution and software, such as ArcGIS 9.3 and ERDAS IMAGINE 8.3, were used for this study. Standard false-colour composite (FCC) imagery was generated by combining bands 3, 2, and 1. A digital image classification technique was performed for forest-type classification from satellite images. In the FCC image, forests appear in dark-red to light-red tone. The richness of the red indicates the vigour of the leaves and their sizes. Patches of light red tones represent degraded formations. The light greenish to white tones indicate barren lands. Water bodies are indicated in blue and black tones. Shuttle Radar Thematic Map (SRTM) was used for elevation-wise classification.

Since the ground-truth information was available, supervised classification with a maximum likelihood classifier algorithm was preferred in the present study. Supervised classification proceeds with the analyst 'supervising' the pixel categorization process by specifying, to the computer algorithm, numerical descriptors of the various cover types present in a scene (Roy, Dutt, and Joshi, 2002). Forest input training sites were used to characterize tree vegetation into dense evergreen, evergreen, dense semi-evergreen, semi-evergreen, and moist deciduous. Since the forest physiognomy varied with altitude, the elevations generated from the satellite images of the study area were categorized as low elevation, medium elevation, and higher elevation. The interval of each elevation class was adapted from Pascal, Ramesh, and De Franceschi (2004) as the following: lower elevation was <800 m, medium elevation was 800–1450 m, and higher elevation was >1450 m. All formations of tree vegetation from the classified image were checked in the field by taking GPS points from the corresponding forest regions. As per the identified errors, necessary corrections were done, and the forest type maps were finalized.

2.3. Biomass carbon

A non-destructive method was used to estimate the tree biomass in the natural forest, excluding plantations in this study. A plot sampling technique adapted from Ramachandran et al. (2007) was used in pre-determined regions from classified maps. The 20 m × 20 m plots were laid, and the girth at breast height (GBH) measurement (in cm) of all trees was collected from the different forest types. The GBH measurement was taken at 130 cm above the soil surface for normal trees and 130 cm above from the buttress region for buttressed trees. The above-ground biomass (AGB) of each tree was calculated using the allometric equation prepared for tropical trees (Brown, 1997),

\[ \text{AGB} = e^{(-2.134 + 2.530 \times \log(\text{DBH}))} \]

where AGB is Above-Ground Biomass; DBH is the diameter at breast height (in cm).

The below-ground biomass (BGB) was estimated from the AGB, using a standard conversion ratio of 0.26 (IPCC, 2006). The amount of carbon present in the biomass carbon was estimated by multiplying the biomass value by 0.5 and calculating the equivalent CO₂ for the available biomass carbon. The overall methodology flowchart used in the study is shown in Figure 2.

3. Results

Estimation of fixed atmospheric CO₂ in tree biomass from Neyyar Wildlife Sanctuary was carried out by a course of action that embraces the identification and area estimation of different forest types, biomass carbon, and equivalent CO₂ per unit area from each forest type. Finally, the extrapolation of carbon and equivalent CO₂ present per unit area to the total area of each forest type was performed.

Tree vegetation occupies 5693.32 ha of Neyyar Wildlife Sanctuary. In this unevenly covered area, each forest type is represented with 57.69% (3300.38 ha) of dense semi-evergreen, 20.93% (1191.79 ha) of moist deciduous, 11.40% (649.06 ha) of dense evergreen, 5.58% (318.20 ha) of semi-evergreen, and 4.108% (233.89 ha) of evergreen. Dense evergreen was represented in all three elevation classes, whereas
evergreen, dense semi-evergreen, semi-evergreen, and moist deciduous were confined to medium elevation level. The area-wise distribution of each forest type varied from lower to higher elevation (Figures 3-7, and Table 1).

Table 2 shows the estimated total biomass (above-ground + below-ground) per unit area (1 ha), varying from 410.48 to 713.95 t·ha⁻¹ in different forest types of the Neyyar Wildlife Sanctuary. Dense evergreen forest at high elevation showed the highest value (713.95 t·ha⁻¹), whereas the least amount (410.48 t·ha⁻¹) was estimated for semi-evergreen at low elevation. Medium and low elevation dense evergreen (628.34 and 641.98 t·ha⁻¹) and low elevation evergreen (603.39 t·ha⁻¹) showed values higher than 60 t·ha⁻¹, after the highest value in high elevation dense evergreen. Remaining formations such as medium elevation evergreen,

Table 1. Total biomass, biomass carbon, and fixed CO2 of total area.

| Tree formation | Area (ha) | Total B (t) | Total BC (t) | Fixed CO₂ (t) | Fixed CO₂ (%) |
|----------------|-----------|-------------|--------------|---------------|---------------|
| HE-TEG         | 36.28     | 25.9        | 12.95        | 47.49         | 0.88          |
| ME-TEG         | 530.44    | 333.3       | 166.65       | 611.05        | 11.26         |
| ME-EG          | 186.99    | 109.76      | 54.88        | 201.23        | 3.71          |
| ME-TSE         | 322.63    | 173.78      | 86.89        | 318.6         | 5.87          |
| ME-SE          | 73.14     | 35.78       | 17.89        | 65.6          | 1.21          |
| ME-MD          | 78.24     | 36          | 18           | 66.01         | 1.22          |
| LE-TEG         | 82.34     | 52.86       | 26.43        | 96.91         | 1.79          |
| LE-EY          | 46.9      | 28.3        | 14.15        | 51.89         | 0.96          |
| LE-TSE         | 2977.75   | 1587.08     | 793.54       | 2909.64       | 53.64         |
| LE-SE          | 245.06    | 150.59      | 50.3         | 184.42        | 3.40          |
| LE-MD          | 1113.55   | 475.58      | 237.79       | 871.89        | 16.07         |
| **Total**      | 5693.32   | 2958.93     | 1479.47      | 5424.73       | 100.00        |

A – biomass, BC – biomass carbon.

Table 2. Biomass and biomass carbon in different tree formations.

| Tree formation | Biomass (t ha⁻¹) | Biomass carbon (t ha⁻¹) | AG | BG | Total |
|----------------|------------------|-------------------------|----|----|-------|
|                |                  |                         | AG |    |       |
| HE-DEG         | 566.63           | 147.32                  | 713.95 | 283.31 | 73.66 | 356.98 |
| ME-DEG         | 498.68           | 129.66                  | 628.34 | 249.34 | 64.83 | 314.17 |
| ME-EG          | 465.86           | 121.12                  | 586.98 | 232.93 | 60.56 | 293.49 |
| ME-DSE         | 427.49           | 111.15                  | 538.63 | 213.74 | 55.57 | 269.32 |
| ME-SE          | 388.31           | 100.96                  | 489.27 | 194.15 | 50.48 | 244.63 |
| ME-MD          | 365.23           | 94.96                   | 460.19 | 182.61 | 47.48 | 230.09 |
| LE-DEG         | 509.51           | 132.47                  | 641.98 | 254.76 | 66.24 | 320.99 |
| LE-EY          | 478.88           | 124.51                  | 603.39 | 239.44 | 62.25 | 301.69 |
| LE-DSE         | 432.00           | 109.98                  | 532.98 | 211.50 | 54.99 | 266.49 |
| LE-SE          | 325.78           | 84.70                   | 410.48 | 162.89 | 42.35 | 205.24 |
| LE-MD          | 291.43           | 135.65                  | 427.09 | 145.72 | 67.83 | 213.54 |

HE – high elevation, ME – medium elevation, LE – low elevation, DEG – dense evergreen, EG – evergreen, DSE – dense semi-evergreen, SE – semi-evergreen, MD – moist deciduous.
medium and high elevation of dense semi-evergreen and moist deciduous exhibited 586.98, 538.63, 532.97, 489.26, 460.18, and 427.08 t·ha\(^{-1}\) respectively.

The total tree vegetation of Neyyar Wildlife Sanctuary contains 1479.47 k t (1 k t = 1000 t) of biomass carbon (Figure 8). Its allocation in each forest types is illustrated in Tables 1 and 2. Since the amount of biomass carbon is calculated as 50% of the total biomass, its variation per unit area with different tree formations is directly proportional to the variation of the biomass. Of the 1479.47 k t of biomass carbon, 59.51% (880.43 k t) is estimated to come from the dense semi-evergreen types, with a large portion (793.54 k t) at low elevation and the remaining (86.89 k t) at medium elevation. The moist deciduous type accounts for 17.29% of the total biomass carbon (with 237.79 k t at low elevation and 18 k t at medium elevation). Dense evergreen holds 13.93% of the total biomass carbon, and it is allocated at high, medium, and low elevations as 12.95, 166.65, and 26.43 k t, respectively. Evergreen shares 4.67% (14.15 k t at low and 54.88 k t at medium elevation) of the total biomass, and semi-evergreen shares the smallest part, 4.61% (50.30 k t at low and 17.89 at medium elevations).

Tree vegetation fixed carbon in the form of biomass was converted to equivalent CO\(_2\) reduced from the atmosphere (Figure 4 and Table 1). The amount of fixed CO\(_2\) per unit area for all tree formation types ranged between 1505.09 and 2617.82 t·ha\(^{-1}\) (Figure 9). The rate of fixed CO\(_2\) was gradually reduced in the way of dense evergreen (DEG) > evergreen (EG) > dense semi-evergreen (DSEG) > semi-evergreen (SEG) > moist deciduous (MD). The highest rate of fixed CO\(_2\) in the dense evergreen type occurs at high elevation, and dense evergreen and evergreen showed greater values at low elevation (2353.94 t·ha\(^{-1}\) and 2212.42 t·ha\(^{-1}\) respectively) than at medium elevation (2033.92 t·ha\(^{-1}\) and 2152.27 t·ha\(^{-1}\), respectively). The difference between low and medium elevation of dense evergreen was 50.02 t·ha\(^{-1}\), and for evergreen, it was 60.14 t·ha\(^{-1}\). The CO\(_2\) fixed rate in the medium elevation type (1974.98 t·ha\(^{-1}\)) of dense semi-evergreen was 20.73 t·ha\(^{-1}\) greater than the low elevation formation (1954.25 t·ha\(^{-1}\)). Remaining formations – semi-evergreen and moist deciduous – showed fixed rates of CO\(_2\) in low elevation types to be less than medium elevation types, with differences of 288.88 t·ha\(^{-1}\) and 121.38 t·ha\(^{-1}\), respectively.

All types of tree vegetation altogether showed fixed CO\(_2\) of 424.72 k t in the Neyyar Wildlife sanctuary, with a range between 51.89 and 2909.64 k t, as illustrated in Figure 4. Dense semi-evergreen formations accounted for most of the fixed atmospheric CO\(_2\) (318.60 k t at medium elevation and 2909.64 k t at high elevation), whereas the least amount corresponded to the semi-evergreen formations (65.60 k t at medium elevation and 184.42 k t at low elevation). The amount of CO\(_2\) fixed by the remaining tree vegetation types lies within the above range. The sequence of fixed CO\(_2\) for all formations of Neyyar Wildlife Sanctuary is dense semi-evergreen > moist deciduous > dense evergreen > evergreen. This sequence shows CO\(_2\) fixing efficiency is found to be more pronounced in undisrupted formations like evergreen and dense evergreen than remaining formations. Distribution of moist deciduous and semi-evergreen formations is found in areas close to human settlements, thus more subject to human interventions, whereas concentrations of dense evergreen and evergreen formations distribution are far from human settlements.

4. Discussions
4.1. Forest types

Different formations of tree vegetation, namely dense evergreen, evergreen, dense semi-evergreen, semi-evergreen, and moist deciduous were identified in the present study. Dense evergreen was present in the three elevation classes in this study. Pascal, Ramesh, and De Franceschi (2004) identified, by the presence of common species combinations, two types of evergreen formations at low elevations (Dipterocarpus indicus – Kingiodendron

![Figure 4. Evergreen forest type in different elevations.](image-url)
pinnatum – Strombosia ceylanica and Dipterocarpus indicus – Dipterocarpus boudilloni – Strombosia ceylanica) and medium elevation (Cullenia exarillata – Mesua ferrea – Palaquium ellipticum – Gluta travancorica and Cullenia exarillata – Mesua ferrea – Palaquium ellipticum) in the forest map of south India. In a revised survey of the forest types of India, Champion and Seth (1968) identified two types of wet evergreen forest in southern Western Ghats, i.e. west coast tropical evergreen forest (1A/C4) and southern hilltop tropical evergreen forest (1A/C3). Pascal, Ramesh, and De Franceschi (2004) identified the low elevation evergreen type, and Champion and Seth (1968) identified the west coast tropical evergreen forest type, representing the low elevation formations of dense evergreen and evergreen in the present study. The medium elevation type of Pascal, Ramesh, and De Franceschi (2004) represents the respective formation of the present study. Champion and Seth (1968) identified the southern hilltop tropical evergreen forest, representing the medium elevation formations of dense evergreen, evergreen, and high elevation dense evergreen of the present study. Pascal, Ramesh, and De Franceschi (2004) identified Bhesa indica – Gomphandra coriacea – Litsea spp. with common species composition, representing the high elevation dense evergreen forest formation of the present study.
At medium and low elevations, dense semi-evergreen and semi-evergreen formations were identified in this study. The same types were commonly grouped under the same type, west coast semi-evergreen forest by Champion and Seth (1968). Pascal (1988) explained that semi-evergreen forest formations could fall in between the evergreen and moist deciduous classifications. In the present study, the moist deciduous type was mainly found at medium elevations and was much less abundant at low elevation regions. According to the illustration of the Western Ghats forest (Pascal 1988), moist deciduous formation occurred in between the formations of semi-evergreen and tree savanna, and the tree savanna was considered as degraded formation, which took place at low elevation regions, which were most affected by anthropogenic influences. Many authors (Bor 1947; Gupta and Shankararayanan 1962) have agreed the tree savanna was of anthropogenic origin, and it was clear in the present study that most of the degraded formations were in human-approachable areas. These early studies illustrated the allocation trends of semi-evergreen and moist deciduous, which were apparent in the present study.

4.2. Biomass/ha

Since the Indian tropical forests, especially the Western Ghats, have a heterogeneous nature of topography, rainfall, temperature, evapotranspiration, soil, and water availability, a distinctive divergence in vegetation parameters was clear from place to place. Biomass studies in the tropical forests of India were rare, and available studies were conducted on a large area scale (Kaul, Mohren, and Dadhwal 2011; Gundimeda et al. 2007; Bhadwal and Singh 2002; Ravindranath, Somashekhar, and Gadgil 1997). A comparison of mean values of large areas with the small area of the present study was not appropriate. In this study, biomass ranged from 308.65 to 713.95 t·ha$^{-1}$ in different tree formations of the Neyyar Wildlife Sanctuary. From the tropical forest of French Guiana, Chave et al. (2008) reported that the above-ground biomass ranged from 356 to 398 t·ha$^{-1}$, corresponding to a range of 448.56–501.48 t·ha$^{-1}$ of total biomass. Zheng et al. (2006) and Zheng et al. (2008) reported a biomass range of 362.1 to 692.6 t·ha$^{-1}$ from the tropical forest of southwest China. From the tropical forest of Madagascar, Eckert (2012)
estimated the above-ground biomass varying from 323.30 to 1048.08 t·ha$^{-1}$ (its equivalent total biomass was 407.36–1320.58 t·ha$^{-1}$) in non-degraded forest and 217.16–572.22 t·ha$^{-1}$ (its equivalent total biomass was 273.62–721.0 t·ha$^{-1}$) in degraded forest. From the southern Western Ghats (Karnataka State of India), Rai and Proctor (1986) estimated the above-ground biomass to range from 420 to 649 t·ha$^{-1}$, equivalent to a range of 529.2–817.74 t·ha$^{-1}$ of total biomass. The biomass range in the present study was within the range of early reports of tropical forests in other regions and southern Western Ghats (for example, Rai and Proctor 1986).

Since the variations in biomass carbon and fixed CO$_2$ were directly proportional to the total biomass, comparative explanation between forest types is not relevant. The CO$_2$ molecule is the intermediate between the biomass and atmosphere in the carbon cycle. It enters the plant through the stomata, the small pores in leaves through which CO$_2$, water vapour, and other gases are exchanged with the atmosphere (Beedlow et al. 2004) in the photosynthetic process. Hence, plants produce the simple form of carbohydrate, glucose (C$_6$H$_{12}$O$_6$), composed of carbon, hydrogen, and oxygen. Some of the glucose is converted to cellulose in plant cells and eventually serves as one of the main structural compounds in wood, in the case of trees. About half the carbon absorbed through photosynthesis is later released by plants, as they use their own energy to grow. The rest is either stored in the plant as biomass, transferred to the soil where it may persist for a very long time in the form of organic matter, or transported through the food chain to support other forms of terrestrial life (Salwasser, 2006; Kumar et al. 2009). Tropical forests alone have a major impact on global carbon cycling, accounting for about a third of the overall terrestrial net primary production (Malhi and Grace 2000; Grace 2004; Del Grosso et al. 2008).

Although some researchers argue on the use of generalized allometric equations for tropical forests due to possible bias with the results, and instead using species and site-specific allometric equations (for example, Daba and Soromessa 2019), the current methodology is still preferred by several researchers due to the difficulties with using different equations for trees belonging to the same focused study site, which in turn may result in other possible bias with the interpretations, or limitations with regard to the surface area to cover.

5. Conclusion

Findings showed that the fixed CO$_2$ per unit area (1 ha) ranged from 356.98 t for high elevation dense evergreen to 205.24 t for low elevation semi-evergreen, among all tree formations. Different elevations in those tree formations also displayed distinct differences in fixed CO$_2$ per unit area. In dense evergreen formation, fixed CO$_2$ is highest at high elevation, lowest at medium elevation, and low elevation is positioned between the highest and lowest. Evergreen and dense semi-evergreen showed higher values for low elevation types than for medium elevation types. Meanwhile, in semi-evergreen and moist deciduous, medium elevation types showed higher values than low elevation types.

As per the present evaluation of tree vegetation of the Neyyar Wildlife Sanctuary, 424.72 k t of CO$_2$ was fixed. This type of study is essential in this region where less attempt has been made to understand the importance of its forest in controlling climate change. If this sanctuary was well conserved, the trees would, in turn, reduce atmospheric CO$_2$. Otherwise, the presently fixed CO$_2$ would be released to the atmosphere and, thereby, increase global warming and thereby magnify related impacts to the environment and to the society in general.

Disclosure statement

No potential conflict of interest was reported by the authors.

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