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Mapping of Spatial Distribution of Above Ground Biomass Carbon in Natural Forests of Central Western Ghats using Spectral Modelling

T. S. Hareesh and C. Nagarajaiah
Department of Forestry and Environmental Sciences, College of Agriculture, UAS, GKVK, Bengaluru - 560 065
E-mail: tshareesh@gmail.com

Abstract

Remote sensing and GIS approach combined with field data was adopted for estimation of above ground biomass (AGB) and carbon (C) pool of a forest areas of Kodagu district in central Western Ghats of Karnataka. In the present study, tree biomass was estimated by non-destructive methods, by laying 120 quadrats across the three forest types of Kodagu. Biomass was estimated by using species specific volume equations and specific gravity. Carbon stock was estimated as per IPCC guidelines. Based on field measured biomass and carbon, geo-spatial modelling was done by using NDVI values of high resolution SENTINEL 2 satellite image and best fit regression equation was used to develop biomass and carbon distribution map of entire forest area of the district. AGB ranged from 175.14 Mg ha^{-1} to 233.40 Mg ha^{-1} among the different forest types while the carbon stock ranged from 82.32 Mg ha^{-1} to 109.70 Mg ha^{-1}. The geospatial model estimated the average total above ground biomass of 212.49 Mg ha^{-1} with an average carbon density of 99.86 Mg ha^{-1} among the different forest types of Kodagu. The present study revealed that RS and GIS technique can be used conveniently for quick and reliable estimates of above ground carbon stocks of natural forests.

Keywords: Above ground biomass, Carbon, Spectral modelling, GIS and Western ghats

Natural forests are the significant natural sinks of carbon which had the great sequestration potential. The world forest contains an estimated 350,000 Tg (1 Tera gram=10^{12} grams) of carbon, of which tropical forests accounts for 40 percent and thus play a significant role in the global carbon cycle. These forest areas will act as a source when they got disturbed or degraded and become sink when forests are regenerated (Pan *et al.,* 2013). Human-induced environmental changes have a significant impact on forest productivity and C storage, among them, deforestation is the main factor which alter the vegetation structure and habitat inturn responsible for releasing of large quantity of CO_2 stored in biomass. Nearly 13 per cent of the carbon emissions to the atmosphere is through deforestation between 2000 and 2010 (Friedlingstein *et al.,* 2010). CO_2 load in the atmosphere is increasing from the past few decades which is significantly contributing for global climate change. Forest biomass carbon (C) estimates are the very important inputs in understanding the global C cycle and are essential for evaluating the possibilities of future C sequestration potential, deriving appropriate management practices and also taking a proper policy decision. Furthermore, forest for carbon inventories are essential for successful implementation of REDD programmes and other mitigation policies (Saatchi *et al.,* 2011).

The vegetation carbon pools in India are estimated based on very coarse resolution data which has absence of primary data for the many regions of the country, hence most of the carbon inventories suffer with adequate accuracy. Due to the lack of reliable data on standing biomass and rates of forest degradation, the net carbon emission estimates for India are highly variable. Thus, the improved quantification of carbon pools and fluxes in forest ecosystems is important for understanding the contribution of forests to net carbon emissions and their potential for carbon sequestration.

Kodagu is one of the greenest landscapes in India and is part of the Western Ghats, with 81 per cent of the geographical area under tree cover of which about

43 per cent of the area under natural forests. The district harbours diverse ecosystems such as natural forests, sacred groves, coffee agroforests and forest plantations that contribute to the diversity of species representing 8 per cent of India's plant wealth (Pascal and Pelissier, 1996. This diverse landscape is undergoing transformations concerning biodiversity and canopy density due to the changed production system under the current liberalized market situation (Devagiri *et al.,* 2012). There is a gradual increase in area under coffee agroforests, rubber and other tree species plantations (CAFNET, 2011). An assessment of change in forest cover of Kodagu district during the last 20 years between 1977 and 1997 indicated a decline in forest cover from an area of 2566 km^2 to 1841 km^2 representing a reduction of 18 per cent of the total geographical area. A large part of it has been converted into coffee, teak and teak mixed with other tree species plantations. Land Use and Land Cover of 2011-12 reveals that only 1775.26 km^2 is forest area in the district.

Globally India stands third in position w.r.t. CO_2 emission (2467 million metric tonnes, amounts to 6.81 per cent of total global emission) during 2017 through the various activities. According to Global Forest Resource Assessment-2015, the total forest carbon stock of Indian forests is 6754 million tonnes which include above ground, below ground, dead organic matter and soil, whereas, carbon stock in living forest biomass is around 2647 million tonnes (37 t ha^{-1}; FAO, 2015). FSI (2017) had reported that the carbon stock of 7083 million tonnes from Indian forests, which had increased by 39 million tonnes from the previous assessment. According to FSI (2017), report total carbon stock of forests of Karnataka is approximately 475.08 million tonnes (126.52 t ha^{-1}; 1741.978 million tonnes of CO_2 equivalent) which is 6.71 per cent of total forest carbon of the country.

However, some of these estimates are based on field and other secondary data which show large variations. However, developing suitable methodologies which gives reliable estimates of biomass and carbon of different spatial scale is very important. Field based measurements are accurate but time consuming and involves high cost. Advanced tools like remote sensing and GIS combined with field based inventories offers ample opportunities for such estimations. Vegetation indices such as NDVI, EVI, LAVI etc., are the best indicators which are positively correlated and have been used successfully for accurate biomass and carbon mapping at local and regional scales (Devagiri *et al.,* 2013 and Rajashekar *et al.,* 2018).

The present study aims to estimate the above-ground biomass and carbon stock in different forests of Kodagu using high resolution satellite data combined with field measurements.

Material and Methods

Study Area

The present study was carried out in Kodagu district of Karnataka aimed at developing spatially explicit estimates of forest biomass and carbon pool of Kodagu forests in central Western Ghats region (70°25' 6 76°14' E and 12° 15' - 12°45' N) using field inventory based biomass estimation combined with satellite data. Kodagu covers an area of 4106 km^2 of which about 43.28 per cent (1775.26 km^2) is under natural forest and tree plantations. Evergreen, moist deciduous and dry deciduous forests are predominant types along with teak and rubber plantations. The rest of the district is occupied by shade-grown coffee plantations which complement the forested landscapes. The elevation in the district range from 300 to 1300 m above MSL with an average rainfall ranging from 1500 to 3500 mm and most of which is received during monsoon season (June to September). A maximum temperature of 32° C is experienced during April and a minimum temperature of 15° C during January. The main soil types are lateritic to red loamy with a rock composed of peninsular gneiss, gneissic granites and gneiss.

Data Collection and Sampling Design

Three forest types, namely evergreen forest (EGF), moist deciduous forest (MDF) and dry deciduous forests (DDF) were sampled in the Kodagu district, and their locations are shown in the Fig.1. These forests were selectively logged until the 1980s, and later commercial timber harvest was banned due to the enacting Forest Conservation Act, 1980 and designated these forests as "reserve forests" (Kushalappa and

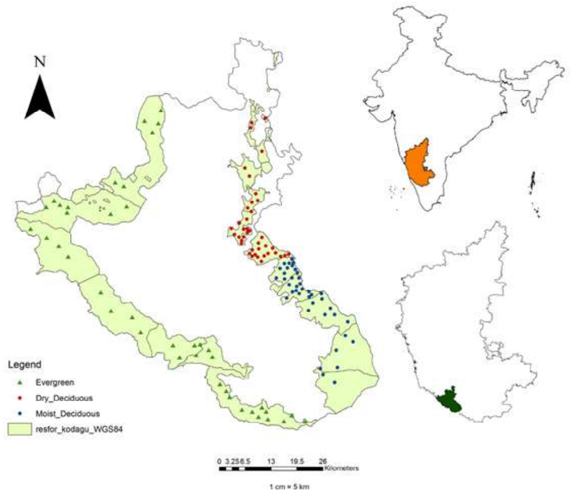

Fig. 1 : Map showing the location of sample plots laid in different forests of Kodagu

Kushalappa 1998). However, these forests continued to experience some kind of anthropogenic and biotic pressures such as fuelwood collection, a collection of fodder for livestock, grazing, illegal felling of trees, wildfires, *etc*. Some of the secondary forests were clear felled and planted with teak and other fast-growing tree species. In the 19th century, most of the privately owned forests in this area were converted to coffee plantations by retaining many original trees of evergreen and moist deciduous forests as shade trees for coffee.

A non-destructive nested sampling approach was adopted for collection of data on trees, herbs and shrubs (Fig.2). In each forest type, forty sample plots of 20 m × 20 m size were laid randomly, and all the woody plants were identified at species level using field keys of Pascal and Ramesh (1987). The unidentified specimens were later got identified at College of Forestry, Ponnampet with the help of taxonomist. Height and girth at breast height (GBH) of the trees above 30 cm GBH were measured using Blume Leiss Hypsometer and measuring tape. Within the quadrat, two 5 x 5 m nested quadrats were laid at opposite corners to collect data on the shrubs and five 1 x 1m nested quadrats were laid at four corners and one at the middle of the quadrats for recording the data on herbs (Fig.2).

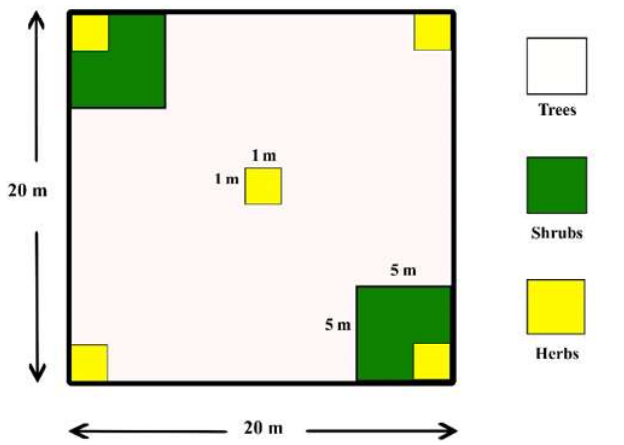

Fig. 2 : Diagram showing nested sampling design (20 m ×20m for trees; 5m × 5m for shrubs and 1m × 1m for herb)

Data Analysis and Software's used

From the collected data, species richness (SR) was estimated by counting individuals of different tree species per unit area and plotting species-area accumulation curves as suggested by Chazdon *et al.,* (2009). Species diversity (Shannon-Wiener Diversity Index-*H'*) and Simpson's index of dominance (D) was calculated as per Magurran (1988) given below. Vegetation structure was characterized by GBH classes, Importance Value Index (IVI) (sum of relative density, relative frequency and relative dominance) for each species among plots was computed (Curtis and McIntosh, 1950).

Shannon-Wiener Diversity Index-*H'*

$$H' = -\sum_{i=1}^{s}\left[\left(\frac{ni}{N}\right)\ln\left(\frac{ni}{N}\right)\right]$$

Where,

ni - Number of individuals of the species

N - Total number of all the individuals

ln - natural logarithm

Simpson's index of Dominance (D)

$$D = \sum (P_i)^2$$

Pi = the proportion of the important value of the ith species

Where,

Pi = ni / N

ni - Number of individuals of the species

N - Total number of all the individuals

Estimation of Above Ground Biomass (AGB)

For estimating the AGB, the strata considered were trees, shrubs and herbs. Tree biomass was estimated non-destructively by calculating the stem volume and multiplying with wood density (Chave *et al.,* 2005; Vashum and Jayakumar 2012; Devagiri *et al.,* 2013 and 2019). While biomass for shrubs and herbs was estimated by destructive method. The data collected on tree parameters such as GBH and height were used for volume estimations using species specific volume equations published by Forest Survey of India (FSI, 2006). The regional volume equation, $V = 0.16948-1.85075D+10.63682D^2H$ was used for estimating the volume of tree species for which species specific equations were not available (FSI, 2006). Tree biomass was estimated by multiplying volume with wood density values of particular species obtained by Forest Research Institute (FRI, 1996). All shrubs and herbs occurring in sample plot of 5m × 5m and 1m × 1m respectively, were harvested and oven-dried to estimate the dry weight. Biomass estimated for different strata were summed to calculate total AGB and expressed in Mg dry wt. ha^{-1}. Carbon stock was estimated by multiplying estimated dry biomass weight with 0.47 as suggested by IPCC (2007).

AGB (Mg) = Volume x Species specific gravity

Carbon content (Mg C) = 0.47 x Biomass (Mg)

Quantification of CO_2 = the quantum of carbon is converted into the quantum of carbon dioxide by using the following equation.

$$\text{Quantum of } CO_2 = \frac{\text{Quantum of carbon x 44}}{12}$$

Where,

44 is the molecular weight of CO_2

12 is the atomic weight of the carbon

Spectral Modelling and Up-Scaling of Biomass and Carbon

Spectral modelling was done for up-scaling of plot observation into regional scale. Regression model were developed between biomass and Normalized Difference Vegetation Index (NDVI) of the satellite image. For modelling of biomass and carbon, Sentinel 2 image was used. Out of the four models such as linear, logarithmic, exponential and power function relating biomass and NDVI value, linear model was selected on the basis of R^2. From the best fit model, the regression equation was developed for above ground biomass and carbon.

The primary data consist of field data, size class distribution of species, IVI, biomass, carbon estimations were done in MS-EXCEL 2013. Species diversity indices, richness, Jaccard's index of similarity were computed using Bio Diversity Pro 2.0 software. For spectral modelling, remote sensing and GIS based work were done in ArcGIS 10.4.1.

RESULTS AND DISCUSSION

Vegetation Structure and Diversity

Results pertaining to species richness, diversity, tree density, basal area and similarity across the different forest types of Kodagu are presented in Table 1. Moist deciduous forests of Kodagu are represented by 42 species with a Shannon diversity of 2.99 and Simpson's index of 0.084. These forests are of moderately diverse and are dominated by Terminalia's. Dry deciduous forests possess a Shannon index of 2.85 and Simpson's index of 0.08 indicates that dry deciduous forests are also relatively rich in diversity and harbour 36 species. A total of 141 species were recorded from the study in the evergreen forest. Highest Shannon index (*H'*) of 4.55 and lower Simpson's index of 0.0148 was recorded from the evergreen forests. This inverse relationship indicates that evergreen forests of Kodagu had higher diversity in tree species and no single species was dominating in these forests. These results are comparable with earlier studies conducted in this region. Pascal and Pelissier (1996) reported a Shannon index of 3.6 to 4.3 at different altitudes of the Western Ghats. Swamy *et al.* (2010) reported a Shannon index of 2.0 to 3.7 and Simpson's index of 0.1 from different sites of evergreen forests of Kodagu region. In a similar study in Kodagu region, Devagiri *et al*., (2019) reported a Shannon index of 2.90 and Simpson's index of 0.08 for evergreen forests. Similarly, in the same study

TABLE 1
Vegetation structure, diversity and species composition of different forest types of central Western Ghats

Parameters	Forest Types		
	Dry Deciduous	Moist Deciduous	Evergreen
No. of species	36	42	141
Shannon-Weiner Diversity Index (*H'*)	2.85	2.99	4.55
Simpson's Index of Dominance (D)	0.0857	0.0841	0.0148
Tree Density (stems ha^{-1})	386.25	391.25	491.25
Basal Area (m^2 ha^{-1})	38.29	38.58	46.65
Jaccard's Similarity Index			
Dry Deciduous	-	66.559	15.6695
Moist Deciduous	-	-	18.272
Evergreen Forest	-	-	-

authors have reported a Shannon's and Simpson's index of 1.86 and 0.24 respectively, for the moist deciduous forests of Kodagu district.

Stand Density and Basal Area

Evergreen forests recorded highest tree density of 491 trees ha^{-1} with a basal area of 46.65 m^2 ha^{-1} (Table 1). Tree density and basal area recorded in our study fall within the range reported by other workers. Swamy *et al.,* 2010 reported a tree density in the range of 263 to 438 stems ha^{-1} in evergreen forests of Kodagu. Similarly, Devagiri *et al.,* 2013 reported tree density of 1142 stems ha^{-1} with a basal area of 14.55 m^2 ha^{-1} in evergreen forest of Kodagu. Pascal and Pelissier (1996) reported 257 to 644 trees ha^{-1} in various bioclimatic types of evergreen forests of Western Ghats. Moist deciduous forests contained 391.25 trees ha^{-1} with basal area of 38.58 m^2 ha^{-1}, whereas in dry deciduous forests relatively lesser stems (386.25 trees ha^{-1}) were recorded however, with almost same basal area (38.29 m^2 ha^{-1}) as that of moist deciduous forests. These results suggest that both moist and dry deciduous forests of this region are structurally more similar. Devagiri *et al.*, (2019) reported a stem density of 314 trees ha^{-1} with a basal area of 18.91 m^2 ha^{-1} in moist deciduous forests of Kodagu. Similarly, Salunkhe *et al.,* 2016 have reported a tree density between 14.8 to 59.3 ha^{-1} and a basal area between 0.15 to 8.37 m^2 ha^{-1} from the dry deciduous forests of Madhya Pradesh.

Species Composition and Assemblages

It was observed based on β - diversity that 66.56 per cent similarity in terms of species composition exists between moist and dry deciduous forest types. Among the top ten species listed based on IVI between these two forest types, only four species differed (*viz., Tectona grandis, Grewia teliea folia, Gmelina arborea* and *Cassia siamea*). The common species shared between these forests includes *Anogeissus latifolia, Dalbergia latifolia, Lagerstroemia lanceolate, Lannea coromandalica, Pterocarpus marsupium, Terminalia bellarica, Terminalia paniculata* and *Terminalia tomentosa* (Table 2). We recorded 18.27 per cent similarity interms of species composition between moist deciduous and evergreen forest types of the district. *Lagerstroemia lanceolate* is the only species found common among the evergreen and moist deciduous forest types. Similarly, dry deciduous and evergreen forest types shared only 15.67 per cent of tree species

TABLE 2
Top ten dominant species in different forest types based on relative IVI

Species	Dry Deciduous	Moist Deciduous	Evergreen
Anogeissus latifolia	35.49 (2)	19.12 (3)	-
Artocarpus hirsutus	-	-	7.87 (3)
Canarium strictum	-	-	5.91 (9)
Cassia siamea	08.01 (9)	-	-
Dalbergia latifolia	22.02 (6)	16.23 (4)	-
Dimocarpus longan	-	-	7.81 (4)
Elaeocarpus tuberculatus	-	-	16.40 (1)

Species	Dry Deciduous	Moist Deciduous	Evergreen
Gmelina arborea	08.90 (7)	-	-
Grewia telieafolia	-	12.70 (9)	-
Lagerstroemia lanceolate	35.28 (3)	29.96 (2)	7.00 (7)
Lannea coromandalica	07.57 (10)	13.22 (8)	-
Litsea floribunda	-	-	7.13 (6)
Lophopetalum wightianum	-	-	6.33 (8)
Mangifera indica	-	-	5.54 (10)
Olea diocca	-	-	8.06 (2)
Pterocarpus marsupium	23.50 (5)	14.79 (6)	-
Syzygium cumini	-	-	7.58 (5)
Tectona grandis	-	14.13 (7)	-
Terminalia bellarica	30.24 (4)	11.20 (10)	-
Terminalia paniculata	08.25 (8)	16.19 (5)	-
Terminalia tomentosa	43.80 (1)	55.30 (1)	-

Values in bracket indicates the ranking based on IVI in their forest types

The population structure of all the three forests is depicted in Fig. 3. Most of the trees in dry deciduous forest belongs to 60-90 cm and 90-120 cm girth classes, and found lesser number of individuals in 30-60 cm girth class, which indicates that growing stock in these forests are abnormally distributed which is evident from abnormal reverse-J shaped girth class distribution. Similar pattern was observed in moist deciduous forests, where the majority of individuals belongs to 60-90 cm girth class and no trees were found in > 240 cm girth class. The evergreen forests showed a good representation of trees in all girth class with increasing number of trees in 30-60 cm, 60-90 cm and 90-120 cm girth classes, respectively. When compared to the other two forest types, the evergreen forest showed reverse-J shaped pattern which is commonly observed in climax forests of other forested regions, of Western Ghats.

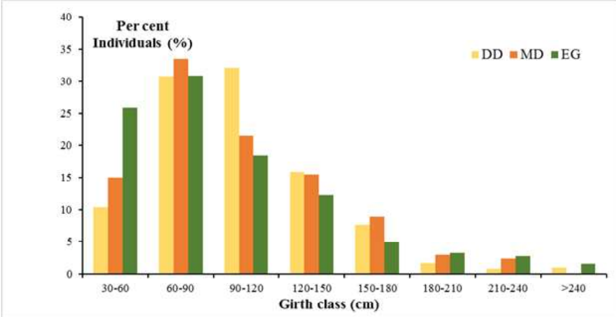

Fig. 3 : Girth class distribution of trees in different forest types

Above Ground Biomass and Carbon Stock: Based on Field Measurements

Results pertaining to above ground biomass (AGB) and carbon stock estimated in different forest types based on the field measurements are presented in Table 3. Across the various forest types, the AGB ranged from 175.14 Mg ha^{-1} in dry deciduous forest to 233.40 Mg ha^{-1} in evergreen forest. The moist deciduous forests contained AGB of 190.57 Mg ha^{-1}. In dry deciduous forest type, higher biomass was contributed by the 60-90 cm and 90-120 cm girth class individuals. While in moist deciduous forest type, higher biomass was contributed by 60-90 cm and 90-120 cm and 120-150 cm girth class individuals. Whereas, in the evergreen forest, higher biomass was contributed by 30-60 cm, 60-90 cm and 90-120 cm girth class individuals. These estimates are within the range reported for different forests of India by other workers [420-649 Mg ha^{-1} by Swamy *et al.* (2010) and Devagiri *et al.* (2013)] reported AGB of 397 to 527 Mg ha^{-1} and 287.05 Mg ha^{-1} respectively in evergreen forests of Kodagu. The estimates could be compared to global estimates of 30-273 Mg ha^{-1} and 213 - 1173 Mg ha^{-1} for tropical dry and wet forests, respectively. Since estimation of carbon was done by considering 47 per cent of total biomass, sequestration potential of carbon from these forests depends upon the type of forests, age and size classes of trees. The evergreen forest contained higher carbon (109.70 Mg ha^{-1}) followed by moist deciduous forest (89.57 Mg ha^{-1}) and dry deciduous forest (82.32 Mg ha^{-1}). Pande (2005) reported that disturbed tropical dry deciduous teak forests of Satpura plateau in Madhya Pradesh contained biomass of 28.1 - 85.3 t ha^{-1}. Salunkhe *et al.* (2016) reported biomass

TABLE 3

Above ground biomass (AGB) and carbon in different forest types based on field measurements (Mean ± SE)

Forest types	Above ground live biomass (Mg ha^{-1})				Carbon (Mg ha^{-1})	CO_2 e (Mg ha^{-1})
	Tree	Shrub	Herb	Total		
Dry Deciduous	173.44 ± 3.93	1.57 ± 0.17	0.130 ± 0.01	175.14 ± 4.53	82.32 ± 1.82	301.83 ± 6.66
Moist Deciduous	189.09 ± 6.84	1.28 ± 0.15	0.200 ± 0.01	190.57 ± 6.83	89.57 ± 3.21	328.42 ± 10.50
Evergreen	232.59 ± 12.90	0.72 ± 0.08	0.092 ± 0.01	233.40 ± 12.89	109.70 ± 6.06	402.23 ± 22.22

value of 54.9 Mg ha^{-1} in dry deciduous forests of Madhya Pradesh. Devagiri *et al.* (2013) had reported the carbon accumulation of 40.25 Mg ha^{-1} and 86.06 Mg ha^{-1} in moist deciduous and evergreen forests of Kodagu area, respectively.

Assessment of above Ground Biomass and Carbon stock: Remote sensing approach

In order to understand the relationship between satellite data based NDVI and biomass and in turn with carbon, regression analysis was carried out between NDVI vs. biomass (Fig. 4) and NDVI vs. carbon (Fig. 5). The results showed a strong relationship between NDVI and biomass and carbon with an R^2 value of 0.714. The NDVI map of Kodagu forests is shown in Fig. 6, which ranges from -0.350 to 0.882. In Madhya Pradesh, the R^2 value of 0.65 was obtained between NDVI and crop biomass density (Wani *et al.,* 2010). The regression models (eqn. 1 and eqn. 2) developed in the present study was used for spectral modelling of AGB and carbon.

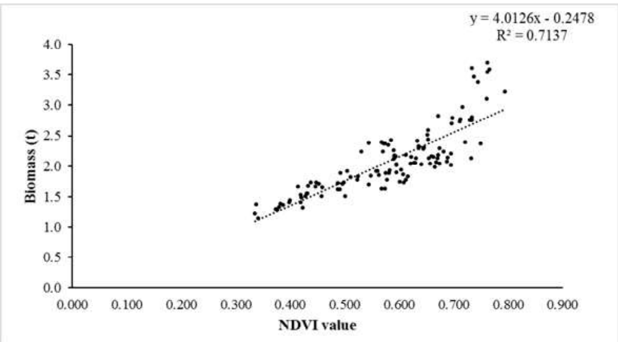

Fig. 4 : Relationship between satellite derived NDVI value and biomass (t)

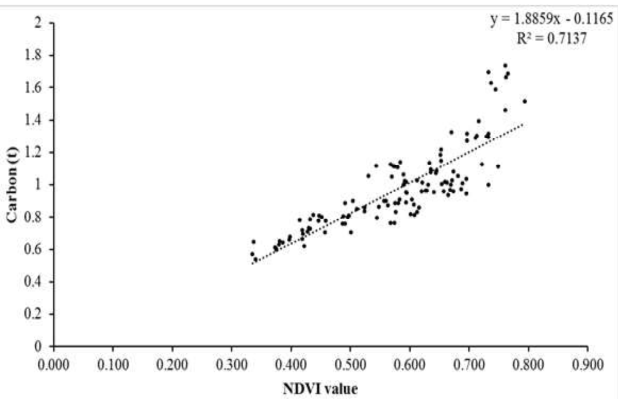

Fig. 5 : Relationship between satellite derived NDVI value and Carbon (t)

$Y=4.0126x-0.2478$ ($R^2 = 0.714$)……...Eqn. 1

Where,

Y= above ground biomass (Mg)

x= NDVI

$Y=1.8859x – 0.1165$ ($R^2 = 0.714$)….......…Eqn. 2

Where,

Y= Carbon (Mg)

x= NDVI value

These models estimated above ground biomass density of 212.49 Mg ha^{-1} and total forest area of Kodagu contained AGB of 37.72 Mt. Similarly, carbon density in these forest was estimated at 99.86 Mg ha^{-1} and the total forest of Kodagu holds a carbon stock of 17.73 Mt. Devagiri *et al.* (2013) reported above ground biomass density of 250 Mg ha^{-1} based on the spectral modeling using MODIS NDVI. Geospatial distribution of the above-ground biomass and carbon in forests of Kodagu is shown in Fig. 7 and Fig. 8, respectively. From the map, it is clear that western side of the Kodagu, which contain evergreen forest type possess higher above ground biomass carbon than the eastern side of the district which has mainly dry and moist deciduous forest types. The estimated highest AGB of 3.6 t pixel^{-1} with carbon of 1.74 t pixel^{-1} was observed in evergreen forest type and lowest of AGB

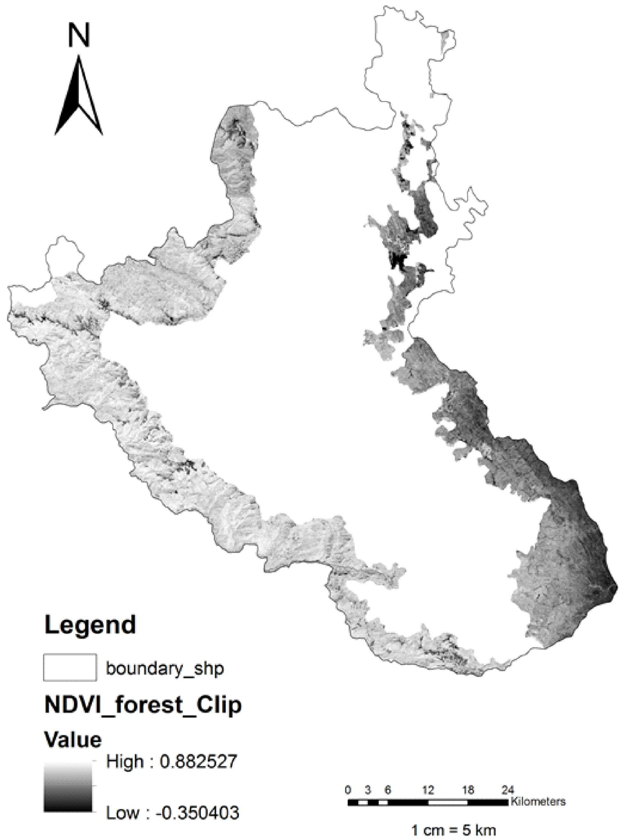

Fig. 6 : NDVI map of Kodagu forest area

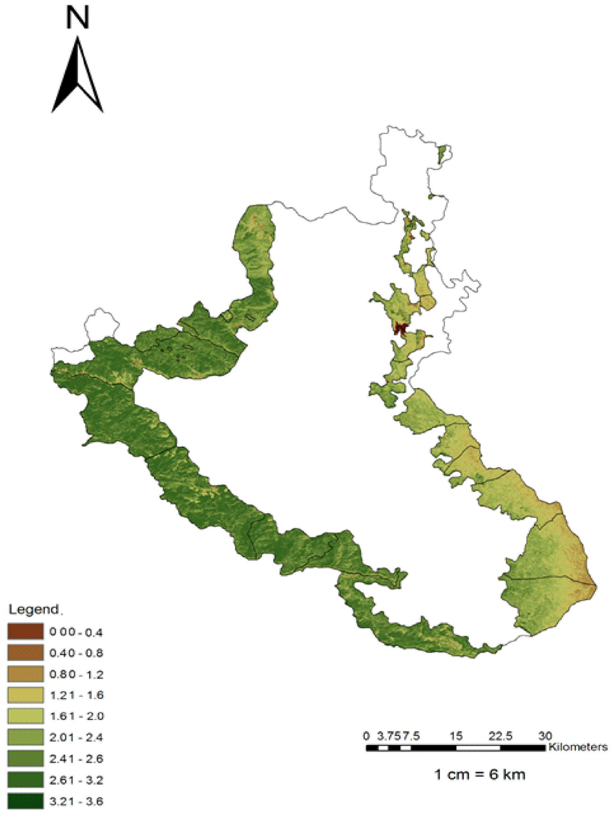

Fig. 7 : Spatial distribution of above ground biomass in forests of Kodagu (Mg/100 m^2)

of 1.15 t pixel^{-1} with carbon of 0.54 t pixel^{-1} was estimated from geospatial work in dry deciduous forest type. Rajashekar *et al.* (2018) estimated spatial distribution of above and below ground Indian forest biomass carbon as 252.04 Tg C by using LISS III data having spatial resolution of 23.5 m. Devagiri *et al.* (2016) had reported estimated spatial carbon distribution ranging from 21 Mg ha^{-1} to 120 Mg ha^{-1}in from Kodagu region. Carbon density in the tropical dry forests of India ranges from 15.6 to 151 Mg ha^{-1} (Chaturvedi *et al.* 2011). FAO (2007) estimated the average carbon density in India at 35 Mg ha^{-1}.

Results of the present study clearly indicates that evergreen forests of Kodagu are floristically rich as compared to moist and dry deciduous forest types. Highest tree density of 491.25 trees ha^{-1} with a basal area of 46.65 m^2 ha^{-1} was found in evergreen forests. Moist deciduous forests possess a tree density of 391.25 trees ha^{-1} and basal area of 38.58 m^2 ha^{-1}, whereas dry deciduous forests have the density of 386.25 trees ha^{-1} with a basal area of 38.29 m^2 ha^{-1}. Higher similarity was observed among the species between moist and dry deciduous forest types, but dry deciduous and evergreen forest types shared about 15.67 per cent of total species composition. *Lagerstroemia lanceolate* is the common species occurred in all three forest types of Kodagu. Only evergreen forest followed reverse-J shaped pattern which indicates normal distribution of the growing stock. Across the various forest types, the AGB ranged from 175.14 Mg ha^{-1} to 233.40 Mg ha^{-1}. Higher biomass was contributed by the 60-90 cm, 90-120 cm and 120-150 cm girth class individuals in all the forest types. The evergreen forest had more carbon content of 109.70 t ha^{-1} followed by moist deciduous forest (89.59 Mg ha^{-1}) and dry deciduous forest (82.31 Mg ha^{-1}). The geospatial model estimated the average total above ground biomass at 212.49 Mg ha^{-1} with a total AGB of 37.72 Mt in these forests. Similarly, the

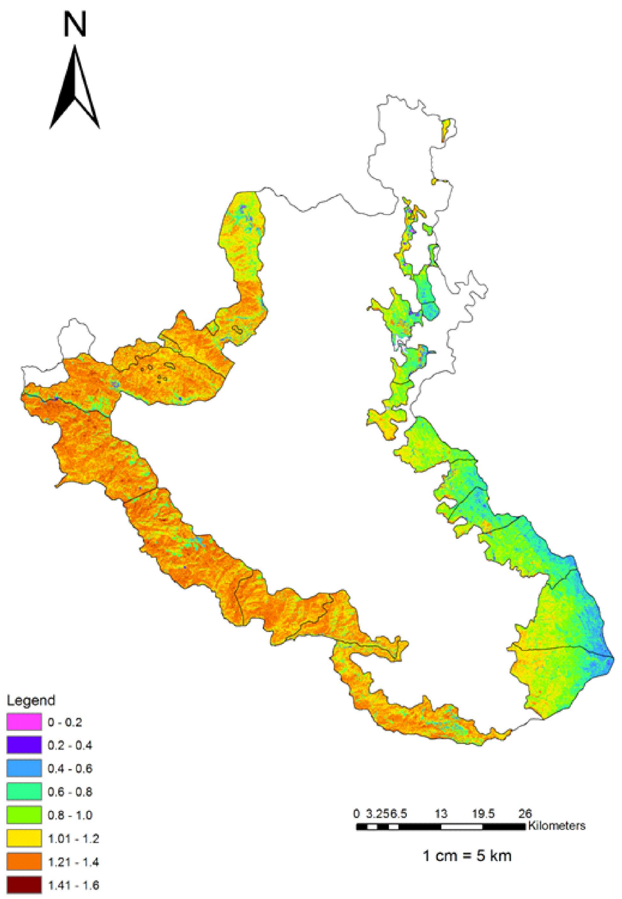

Fig. 8 : Spatial distribution of above ground carbon in forests of Kodagu (Mg/100 m^2)

average carbon content was estimated to 99.86 Mg ha $^{-1}$ with a total of 17.73 Mt carbon in the forests of Kodagu. The Spatial distribution of biomass and carbon is very important for sustainable management and conservation of natural forests. This study revealed that remote sensing technique combined with field observations provides quick and reliable estimates of above ground biomass carbon as well for long term monitoring of carbon dynamics at different spatio-temporal scale.

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