Tropical Ecology **54**(2): 149-165, 2013 ISSN 0564-3295

www.tropecol.com

Assessment of above ground biomass and carbon pool in different vegetation types of south western part of Karnataka, India using spectral modeling

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Abstract: Remote sensing and GIS based approach was used for estimation of above ground biomass (AGB) and carbon pool at regional scale in south western part of Karnataka. Present study integrates field measured biomass with spectral responses of different bands and indices of MODIS 250 m spatial resolution. Based on relative forest area within the MODIS pixel, area weighted biomass was estimated for each site using ground measured plot (0.4 ha) biomass. Field measured AGB ranged between 7.25 to 287.047 t-dry wt ha^{-1} across different vegetation types in the region. The best fit regression equation ($Y = 0.053e^{9.382x}$) was obtained between area weighted AGB (Y) and NDVI of December month (x) with R^2 value of 0.8074. This equation was further used for spectral modeling to estimate the AGB and vegetation carbon pool and to prepare a map to understand the geospatial distribution in the region. Total AGB on dry weight basis was estimated at 6.43 Mt (mean biomass density of 70 t ha^{-1}) and carbon stock of 3 Mt (mean carbon density of 33 t ha^{-1}) in the entire region. The present study revealed that remote sensing technique combined with field sampling provides quick and reliable estimates of above ground biomass and carbon pool and such approach could be used more conveniently for carbon inventories at the State and National level.

Resumen: Se utilizó un enfoque de percepción remota y de SIG para estimar la biomasa aérea (AGB, siglas en inglés) y el almacén de carbono a escala regional en el suroeste de Karnataka. El estudio integra la biomasa medida en el campo con las respuestas espectrales de las diferentes bandas e índices de MODIS con una resolución espacial de 250 m. Con base en el área forestal relativa dentro de cada píxel MODIS, se estimó la biomasa ponderada por el área para cada sitio usando la biomasa medida en parcelas en el campo (0.4 ha). La AGB medida en campo varió entre 7.25 y 287.047 t de peso seco ha^{-1} entre los diferentes tipos de vegetación en la región. La ecuación de regresión de mejor ajuste ($Y = 0.053e^{9.382X}$) se obtuvo entre la AGB ponderada por área (Y) y el NDVI de diciembre (x), con una R^2 de 0.8074. Esta ecuación se usó además en la modelación espectral para estimar la AGB y el almacén de carbono en la vegetación, y para elaborar un mapa que permitiera entender la distribución geoespacial en la región. La AGB total estimada, calculada sobre una base de peso seco, es de 6.43 Mt (densidad promedio de biomasa de 70 t ha^{-1}) y que el almacén de carbono es de 3 Mt (densidad promedio de carbono de 33 t ha^{-1}) en toda la región. El estudio reveló que la percepción remota, en combinación con muestreos de campo, proporciona estimaciones rápidas y confiables de la biomasa aérea y el almacén de carbono, y que este enfoque puede ser conveniente para realizar inventarios de carbono en los niveles estatal y nacional.

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Resumo: A abordagem com recurso à detecção remota e GIS foi utilizada para a estimativa da biomassa aérea (AGB) e o reservatório de carbono à escala regional no sul da parte ocidental de Karnataka. Este estudo integra a medida de campo da biomassa com as respostas espectrais de diferentes bandas e os índices de resolução espacial 250 m do MODIS. Com base na área florestal relativa dentro do pixel MODIS, a biomassa aérea ponderada foi estimada para cada estação usando as medidas de biomassa em parcelas de 0,4 ha. As medidas de campo da biomassa AGB variaram entre 7,25-287,047 t-peso seco ha^{-1} para diferentes tipos de vegetação na região. A equação de regressão mais ajustada ($Y = 0.053e^{9.382x}$) foi obtida entre a AGB (Y) ponderada por área e NDVI do mês de Dezembro (x) sendo o valor do R^2 de 0,8074. Esta equação foi seguidamente utilizado na modelação espectral para a estima da AGB e do reservatório de carbono na vegetação e na preparação de um mapa para entender a sua distribuição geoespacial na região. A AGB total, na base do peso seco, foi estimada em 6,43 milhões de toneladas (densidade média da biomassa de 70 t ha^{-1}) e o estoque de carbono em 3 milhões de toneladas (densidade média de carbono de 33 t ha^{-1}) em toda a região. O presente estudo revelou que a técnica de detecção remota, combinada com amostragem de campo, fornece estimativas rápidas e fiáveis de biomassa aérea e reservatório de carbono e que tal abordagem poderá ser usada de forma mais conveniente para inventário dos estoques de carbono a nível estadual e nacional.

Key words: Above ground biomass, biomass, carbon pool, MODIS, NDVI, remote sensing, spectral modeling, tropical forest, vegetation type.

Introduction

Biomass assessment is important for national development planning as well as for scientific studies of ecosystem productivity, carbon budgets, etc. (Pande *et al.* 2010; Parresol 1999; Zheng *et al.* 2004; Zianis & Mencuccini 2004). Biomass analysis is an important element in the carbon cycle especially, carbon sequestration. Recently biomass is being increasingly used to help quantify pools and fluxes of green house gases (GHG) from terrestrial biosphere associated with land use and land cover changes (Cairns *et al.* 2003). The importance of terrestrial vegetation and soil as significant sinks of atmospheric CO_2 and its other derivatives is highlighted under Kyoto Protocol (Wani *et al.* 2010). Vegetation especially, forest ecosystems store carbon in the biomass through photosynthetic process, thereby sequestering carbon dioxide that would otherwise be present in the atmosphere. Undisturbed forest ecosystems are generally highly productive and accumulate more biomass and carbon per unit area compared to other land use systems like agriculture. It is estimated that the carbon stored globally in the forest biomass amounts to 2,40,439 Mt with an average carbon density of 71.5 t ha^{-1}. A recent estimate indicates that tropical forests account for 247 Gt vegetation carbon, of which 193 Gt is stored above ground (Saatchi *et al.* 2011). Many researchers have estimated biomass and C stocks present in India's forests. Hingane (1991) estimated total phytomass carbon pool and carbon density of India's forests at 2,587 Tg C and 49.2 Mg C ha^{-1}, respectively, based on ecological studies and mean phytomass density for each forest type. The carbon present as total carbon pool and density in phytomass of India's forests for the year 1880, with total forest area of 102.68 million ha, was estimated at 7,940 Tg C and 77.3 Mg C ha^{-1}, respectively. The approach was based on historical records, ecological data and population based forest biomass inventory (Flint & Richards 1994). Ravindranath *et al.* (1997) estimated the standing biomass (both above and below ground) in India to be 8,375 Mt for the year 1986, of which the carbon storage was reported to be 4,178 Mt. The total carbon stored in forests of India including soil was estimated at 9,578 Mt. Dadhwal *et al.* (1998) using FAO inventory for ecological zones estimated the carbon pool at 3117 Tg C and carbon density at 60.2 Mg C ha^{-1}. However, these estimates exhibit large temporal and spatial variation in biomass and C stocks. Hence, developing appropriate biomass estimation methods for accurate and consistent reporting of forest carbon inventories is important.

There are three main approaches to biomass assessment viz., field measurements, remote sensing (RS) and geographic information system (GIS) (Lu 2006). The field measurement is considered to be accurate but proves to be costly and time consuming (de Gier 2003). The modern tools like RS and GIS have provided new opportunities for quick and reliable assessments and for monitoring of above ground biomass and carbon pools. Until recently there were not many efforts in India and abroad to take full advantage of high resolution remote sensing data in assessing vegetation carbon pool. NOAA AVHRR, SPOT Vegetation, MODIS and ASTER satellite data have enormous potential in assessing terrestrial biomass and carbon pools. Vegetation indices, particularly NDVI, is a good indicator of leaf area index (LAI), which in turn is positively correlated to biomass and productivity (de Fries *et al.* 1995; Kale *et al.* 2001; Roy & Ravan 1996). NDVI coupled with energy conversion efficiency has been extensively used for biomass estimations. Brown *et al.* (1993) assessed carbon densities and pools in forests (144 Mg ha^{-1}) and forest soils (148 Mg ha^{-1}) of tropical Asia using geospatial technology. Dadhwal & Shah (1997) used state wise remote sensing based forest area, field inventory based growing stock and crown density based biomass expansion factor to derive phytomass carbon pool (4,017 Tg C) and phytomass carbon density (63.6 Mg C ha^{-1}) for India's forests. Using a similar approach, Chhabra *et al.* (2002) estimated the forest phytomass carbon pool of the entire country which ranged between 3871.2 to 3874.3 Tg C. Madugundu *et al.* (2008) estimated the above ground biomass in deciduous forests in Western Ghats of Karnataka using IRS P6 LISS-IV satellite data. In this study, remote sensing data based leaf area index (PLAI) image was generated using regression model based on NDVI and field measured LAI ($r^2 = 0.68$, $P \leq 0.05$). Further, they developed regression model between PLAI and field measured above ground biomass ($r^2 = 0.63$, $P \leq 0.05$) to generate the map depicting geospatial distribution of above ground biomass in the region. The present study, which is a part of the Vegetation Carbon Project (VCP) of India, aims to estimate the above ground biomass and carbon pools in different vegetation types of south western part of Karnataka using satellite data combined with field measurements. The other important objective was to develop spectral model to generate geospatial distribution of biomass and C stock in the region.

Materials and methods

Study area

The present study was carried out in south western part of the Karnataka state consisting of Kodagu, Hassan and Mysore districts. These districts are topographically not uniform and have West to East climatic gradients. The study area lies between 11° 50′ to 13° 08′ N latitude and 75° 35′ to 76° 24′ E longitude. The altitude ranges from 300 to 1750 m above MSL. The extent of forest cover in these districts is given in Table 1. Present study covered eight vegetation types namely, evergreen forest, moist deciduous forest, dry deciduous forest, teak plantation, *Acacia auriculiformis* plantation, rubber plantation, coffee plantation and mixed plantations distributed in three districts. Evergreen forest type in the study region mainly comprised *Hopea parviflora*, *Vateria indica*, *Palaquium ellipticum, Canarium strictum, Cinnamomum malabatrum, Artocarpus lakoocha, Knema attenuata, Dipterocarpus indicus*, etc. Moist deciduous forest in south western part of Karnataka is dominated by *Lagerstroemia parviflora, Terminalia crenulata, Terminalia paniculata, Terminalia bellerica, Gmelina arborea, Lannea coromandelica, Dalbergia latifolia, Pterocarpus marsupium,* etc. Dry deciduous forest in the region is dominated by *Anogiessus latifolia* and other associated species like *Diospyros melanoxylon*, *Terminalia crenulata, Emblica officinalis,* etc. Presence of native shade trees makes coffee plantations rich in floristic composition. Dominant tree species in coffee plantations include *Artocarpus heterophyllus*, *Syzygium cumini*, *Acrocarpus fraxinifolious, Grevillea robusta*, etc. Mixed plantations in Hassan district mainly consisted of *Cassia siamea* and *Pterocarpus marsupium*.

Methods

In the present study a new approach was adopted which used ground data as well as remote sensing data to get an accurate estimate of vegetation carbon pool in the region. From the above ground biomass data of the sample plots (see below), area weighted biomass was calculated for all the sites in order to take into account the variation in vegetation density. Area weighted biomass was correlated with satellite derived parameters. The best fit regression equation was used for spectral modeling of above ground biomass and carbon pool in the region. The detailed methodology is described below.

Table 1. Area under forest cover and different density classes in south western part of Karnataka.

District	Geographic area (km^2)	Forest cover (km^2)			Total (km^2)	Per cent of geographic area
		Very dense	Moderately dense	Open		
Kodagu	4102	246	2142	951	3339	81.4
Mysore	6854	04	648	417	1069	15.6
Hassan	6814	67	752	511	1330	19.52

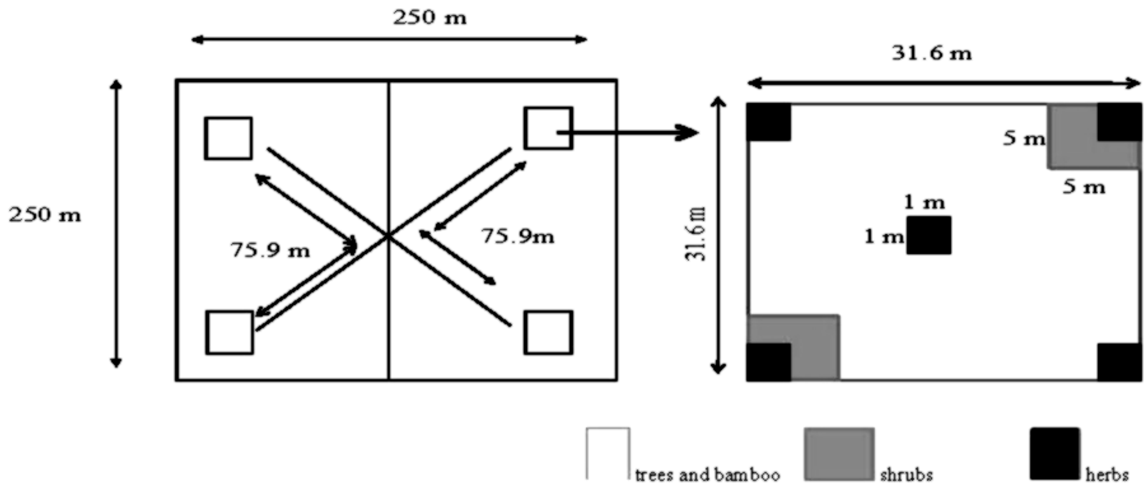

Fig. 1. Diagram showing the nested two stage sampling.

Sampling design

A non-destructive sampling approach was adopted to estimate the above ground tree and bamboo biomass and destructive sampling for herbs and shrubs in different vegetation types distributed in three districts. Satellite data was used for classification of various forest types and for identification of sites, the strata considered were forest type, forest density and Normalized Difference Vegetation Index (NDVI). NDVI was obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data. An attempt was made to select sample plots in all forest types and in all density classes. Nested two stage sampling approach was adopted to sample trees, herbs and shrubs (Fig. 1). One super plot of 250 m x 250 m size, which is equivalent to MODIS pixel size, was laid in each of the several sites. Four sample plots, each of 31.6 m x 31.6 m (0.1 ha) size, were laid in each super plot. Thus, the total sample size consisted of 15 super plots and 60 sample plots within super plots. Geographical details of study sites are presented in Table 2 and depicted in Fig. 2.

Estimation of plot biomass

The strata considered for the estimation of above ground biomass and carbon pool were trees, shrubs and herbs. Height and diameter at breast height (DBH) of all trees of $\geq$ 10 cm DBH in four sample plots within each super plot were measured using Blume Leiss Hypsometer (which is based on the trigonometric method) and digital tree caliper (Haglof, Sweden), respectively. The data thus collected were used for volume estimations using local volume equations published by Forest Survey of India (FSI 2006). We used local as well as regional volume equations depending on the availability for each species (see Appendix Table 1). Tree biomass was estimated by multiplying volume with specific gravity. Wood specific gravity data were obtained from Forest Research Institute (FRI 1996) (see Appendix Table 2). Methodology for biomass estimation of trees of $\leq$ 10 cm DBH was developed (Fig. 3) by relating the basal area and tree biomass in the plots. Biomass of *Bambusa bamboos* clumps (where ever present) in the sample plots was estimated using the biomass equation (Y= -3225.8 + 1730.4 DBH, $R^2 = 0.83$, $P \leq 0.001$, where, Y-Biomass (kg) clump^{-1},

Table 2. Geographical details of the sample plots selected for the present study.

Site ID	Vegetation type	District	Latitude (N)	Longitude(E)	Altitude (m) above MSL
1	Moist deciduous	Kodagu	12° 28′ 5.27″	75° 35′ 34.72″	300
2	Evergreen	Kodagu	12° 04′ 44.76″	75° 43′ 36.48″	247.8
3	Coffee plantation	Kodagu	12° 35′ 01.46″	75° 50′ 42.69″	1178
4	Rubber plantation	Kodagu	12° 26' 53.6"	75° 38' 14.6"	494.5
5	Teak plantation	Kodagu	12° 11' 54.34"	76° 00' 55.26"	883.5
6	Teak plantation	Kodagu	12° 11' 17.28"	76° 02' 15.59"	847.8
7	Dry deciduous	Mysore	11° 50' 30.65"	76° 24' 27.79"	793.6
8	Moist deciduous	Mysore	11° 53' 39.71"	76° 17' 39.27"	754.6
9	Moist deciduous	Mysore	12° 21' 27.24"	75° 59' 23.36"	945.6
10	Dry deciduous	Mysore	12° 27' 23.8"	76° 01' 45.4"	991.7
11	Acacia plantation	Mysore	12° 28' 10.81"	76° 02' 35.31"	964.1
12	Coffee plantation	Hassan	12° 56' 39.22"	75° 44' 31.72"	1047
13	Mixed plantation	Hassan	12° 43' 33.33"	76° 03' 42.29"	943.1
14	Dry deciduous	Hassan	13° 08' 56.0"	76° 04' 38.3"	1015
15	Coffee plantation	Hassan	13° 02' 16.2"	75° 47' 31.9"	1057

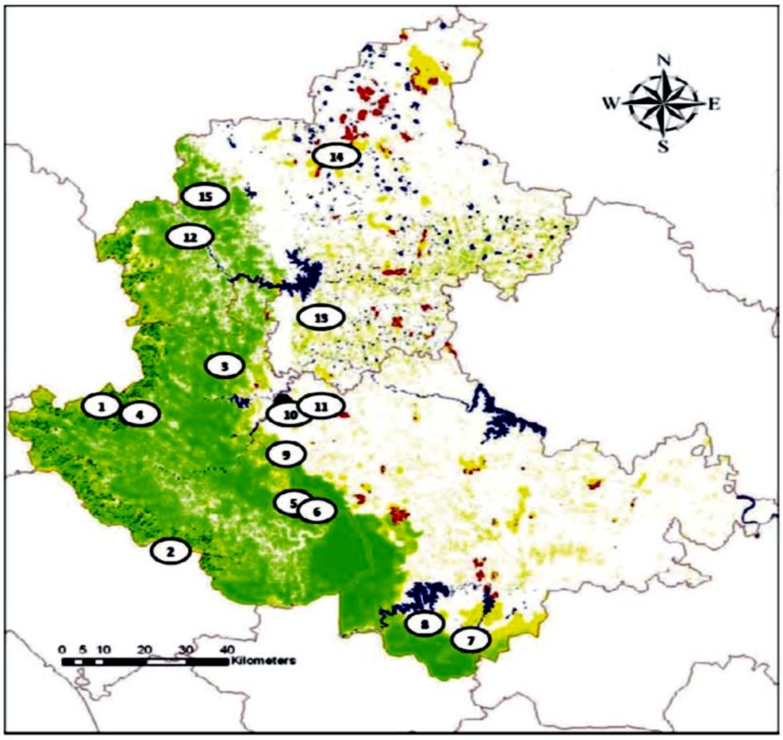

Fig. 2. Location of the sample plots selected for field sampling.

DBH-clump diameter at breast height) developed by Kumar *et al.* (2005). Biomass of herbs and shrubs was estimated using destructive method. Two quadrats each of 5 m x 5 m size for shrubs and two quadrats each of 1 m x 1 m size for herbs were laid in each sample plot. All shrubs and herbs occurring in the sample plot were harvested, oven dried and dry weight was estimated. Biomass obtained from four sample plots (each 0.1 ha) in different stratum was summed up to obtain total above ground biomass and expresses in t-dry wt ha^{-1}).

Estimation of area weighted biomass

In forest ecosystems, the site factors over a large area are seldom uniform and the consequent variation in fertility results in variation of growth. Crown density as well varies considerably as a result of both site factors and disturbances. Direct extrapolation of plot biomass to hectares under such situation may lead to erroneous results. In order to account for such variations, especially in crown density, the area weighted biomass was calculated. For this purpose, GPS points of the sample plots were overlaid on MODIS data having spatial resolution of 250 m and subsequently a vector layer was created in ARC VIEW 3.2a software by converting the pixel area of MODIS data within which the sample plots were occurring. Later the same vector layer was overlaid on forest density map (1 : 50000 scale) published by the Forest Survey of India (FSI). Visual interpretation within each vector-box for mapping of vegetation cover type, density and land use categories was carried out. Data collected during the field inventories were used appropriately. The relative area covered by each forest type and density was estimated in each pixel. Area weight of each land cover class occurring within the vector boundary was obtained by deriving the ratio between the area occupied by each class within the pixel and the total area of the MODIS pixel i.e. 250 m^2 or 6.25 ha. Area weighted biomass obtained for all the vegetation types belonging to different density classes occurring within the pixel boundary was summed up to get area weighted biomass of the respective pixel. This was done for each pixel in all the sample sites distributed in the study area. The classes such as water, settlement and agriculture/ barren land were given zero weight since the present study has focused on vegetation biomass assessment.

Spectral modeling and up-scaling of biomass and carbon

Spectral modeling was done for up-scaling of plot observations into regional scale. Regression models were developed for biomass as a function of satellite derived parameters viz., red and infrared reflectance and NDVI. For modeling of biomass and carbon, MODIS surface reflectance image was used. The spectral modeling was done using multi-season images (February, May, October and December, 2009) for establishment of regression between area weighted biomass and satellite derived parameters. Four models such as linear, logarithmic, exponential and power function relating biomass to the data from different bands (Red, Infrared and NDVI) were calculated. The best fit model was selected on the basis of R^2. The best fit model thus obtained was used to model biomass and carbon for the entire area. Regression model developed for above ground biomass was used for spectral modeling of carbon in the region. Carbon content was taken as 47 per cent of the above ground biomass as followed in the National Carbon Project (Dadhwal *et al.* 2009). The overall methodology adopted for the present study has been depicted in Fig. 4.

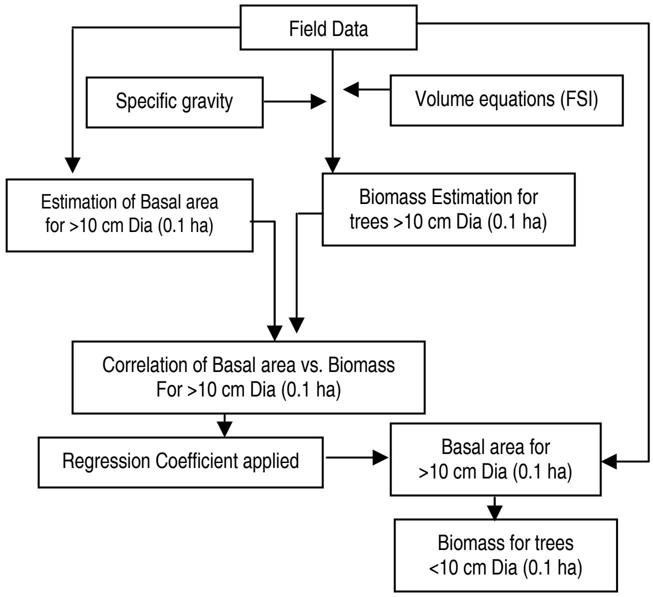

Fig. 3. Methodology for biomass estimation of trees with ≤ 10 cm DBH.

Data analysis and software's used

Primary and ancillary data were used in the present study. Primary data include field data collected during the year 2009 and MODIS NDVI of different months namely, February, May, October, and December, 2009. Ancillary data include species specific volume equations and species specific wood densities. Data base created during the study were organized and analyzed in MS-Excel, 2007. For spectral modeling, remote sensing and GIS based softwares (ERDAS IMAGINE 8.6 and ARC VIEW 3.2a) were used.

Results and discussion

Vegetation structure: Stand density and basal area

Across different vegetation types, tree density and basal cover varied considerably (Table 3). A total

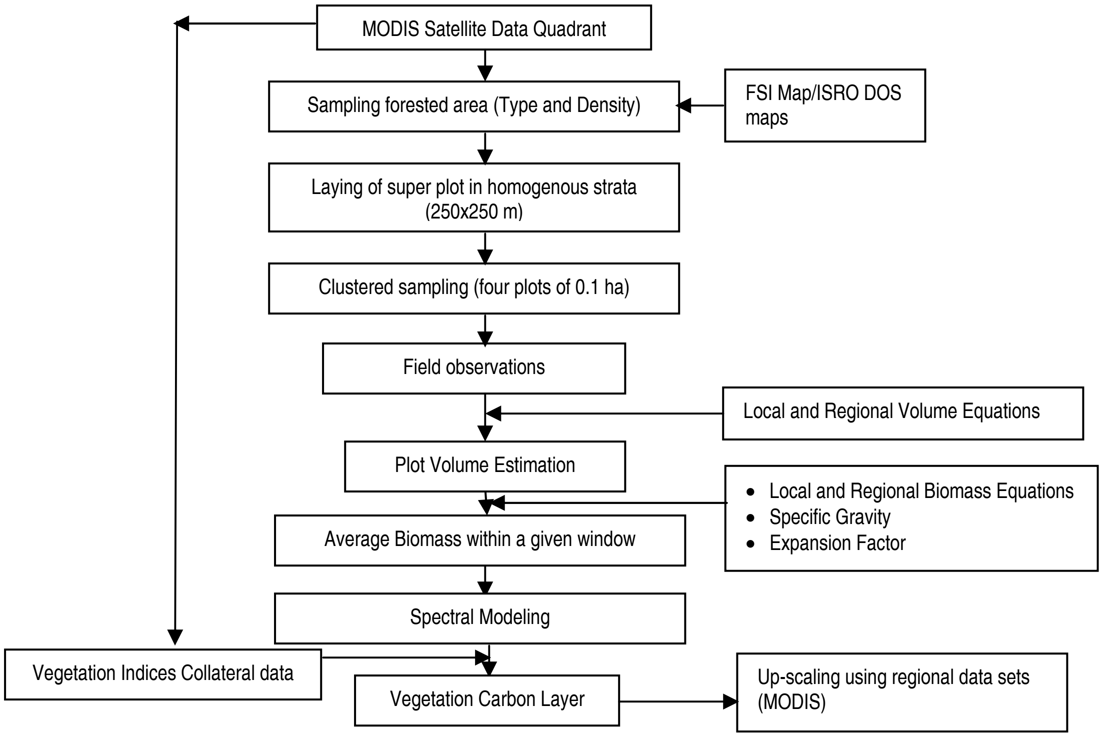

Fig. 4. Paradigm of the study.

Table 3. Tree density and above ground biomass in different vegetation types based on sample plots (0.4 ha) measurements.

Site	District	Vegetation type	Tree density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Above ground biomass (t ha^{-1})			
					Tree layer	Shrub layer	Herb layer	Total
1	Kodagu	Moist deciduous	265	18.40	88.9	0.59	0.14	89.63
2	Kodagu	Evergreen	1142	47.55	286.1	0.88	0.07	287.05
3	Kodagu	Coffee plantation	252	15.60	75.8	6.10	--	81.90
4	Kodagu	Rubber plantation	245	9.58	87.7	0.10	--	87.80
5	Kodagu	Teak plantation	207	26.40	128.4	1.46	0.02	129.88
6	Kodagu	Teak plantation	205	21.83	97.8	0.83	0.04	98.66
7	Mysore	Dry deciduous	225	5.61	17.5	2.96	0.02	20.48
8	Mysore	Moist deciduous	72	12.30	59.5	1.95	0.41	61.86
9	Mysore	Moist deciduous	97	16.10	141.2	1.50	0.43	143.17
10	Mysore	Dry deciduous	362	1.50	9.2	4.76	0.04	14.00
11	Mysore	Acacia plantation	502	3.90	46.0	0.64	0.15	46.79
12	Hassan	Coffee plantation	245	25.90	112.4	10.83	--	123.23
13	Hassan	Mixed plantation	18	1.48	4.8	2.36	0.09	7.25
14	Hassan	Dry deciduous	17	0.52	2.2	5.47	0.02	7.69
15	Hassan	Coffee plantation	156	28.92	116.6	10.45	--	127.05

of 1142 stems ha^{-1} (≥10 cm DBH) with basal area of 47.55 m^2 ha^{-1} was recorded in evergreen forest of Kodagu district. These values compare with tree density (1087 stems ha^{-1}) and basal area (52.60 m^2 ha^{-1}) reported by Swamy *et al.* (2000) for humid evergreen forest in Tamil Nadu. However, the density was higher than the range 257- 664 stems ha^{-1} and the basal area higher than the range 29 - 42 m^2 ha^{-1} reported by Swamy *et al.* (2010) for tropical evergreen forests of Western Ghats region in Karnataka. Tree density and basal area in moist deciduous forest (MDF) ranged between 72 to 265 stems ha^{-1} and between 12.3 to 18.4 m^2 ha^{-1}, respectively. These values are lower than the tree density (535 stems ha^{-1}) and basal area (26.57 m^2 ha^{-1}) reported by Verghese & Menon (1998) for MDF of Agastyamalai region in Kerala. MDF in Hassan district was of small stature as compared to the MDF in Mysore district. The dry deciduous forest (DDF) of this region varied widely in tree density and basal area (17 to 362 stems ha^{-1} and 0.52 to 5.61 m^2 ha^{-1}, respectively). However, these values are lower than those reported for the DDF of Bhadra Wildlife Sanctuary in Karnataka (density 890 stems ha^{-1}, > 10 cm DBH, and basal area 18.09 m^2 ha^{-1}) by Krishnamurthy *et al.* (2010). Tree density and basal area in DDF of Mysore district were respectively, 15 - 20 times and 10 times higher than those of Hassan district. Coffee plantations recorded 156 - 252 stems ha^{-1} with basal area of 15.6 - 28 m^2 ha^{-1} and teak plantations recorded 205 - 207 stems ha^{-1} with basal area of 21.8 - 26.40 m^2 ha^{-1}. These values are consistent with results reported by Devakumar *et al.* (2007) for coffee plantations, and Subramanian *et al.* (2009) for teak plantations.

Above ground biomass: Based on field measurements

Field measured above ground biomass (AGB) ranged between 7.25 to 287.05 t ha^{-1} across different vegetation types in the region (Table 3). As expected, the maximum biomass (287.05 t ha^{-1}) was recorded for the evergreen forest of Kodagu district and the minimum (7.25 t ha^{-1}) for the mixed plantation of Hassan district. The AGB in the moist deciduous forest ranged between 61.86 to 143.17 t ha^{-1} and in the dry deciduous from 7.69 to 20.48 t ha^{-1} across the districts. Coffee plantations in this region, which comprise considerable amount of native tree species, recorded AGB in the range of 81.9 to 127.05 t ha^{-1}. Among different kinds of plantations, teak recorded AGB ranging from 98.66 to 129.88 t ha^{-1}, rubber recorded 87.8 t ha^{-1} and *Acacia auriculiformis* recorded 46.79 t ha^{-1}. These estimates are within the range reported for the AGB estimates for certain other Indian forests (42 - 78 t ha^{-1}, Singh & Singh 1991 and 420 - 649 t ha^{-1}, Rai & Proctor 1986). The present estimates compare with the global estimates of 30 - 273 t ha^{-1} and 213 - 1173 t ha^{-1} for tropical dry and wet forests, respectively (Murphy & Lugo 1986).

The tree layer contributed most (2.2 - 286.1 t ha^{-1}) to the total AGB among different vegetation types followed by shrub (0.10 - 10.83 t ha^{-1}) and herb layer (0.02 - 0.43 t ha^{-1}). The contribution of the tree layer was in the order: evergreen forest > moist deciduous forest > teak plantation > coffee plantation > rubber plantation > *Acacia* plantation > dry deciduous forest > mixed plantation. The tree layer biomass values obtained in the present study are frequently lower as compared to the values 397 - 527 t ha^{-1} reported by Swamy *et al.* (2010) for evergreen forest, 46.7 t ha^{-1} reported by Singh & Singh (1991) for dry deciduous forest. However, for coffee and other plantations the present biomass values are consistent with the biomass estimates reported by Devakumar *et al.* (2007) for coffee plantations, and Subramanian *et al.* (2009) for teak plantations.

The shrub biomass was high (6.1 - 10.83 t ha^{-1}) in the coffee plantation mainly because of the biomass contributed by coffee plants. When compared to dry (2.96 - 5.47 t ha^{-1}) and moist (1.95 - 0.59 t ha^{-1}) deciduous forest, the shrub biomass in evergreen forest was comparatively low (0.88 t ha^{-1}). Mixed and teak plantations recorded shrub biomass of 2.36 t ha^{-1} and 1.46 t ha^{-1}, respectively. The herb biomass ranged from 0.02 to 0.43 t ha^{-1} across the vegetation types with maximum being recorded in moist deciduous forest. Evergreen forest contained 0.06 t ha^{-1} herb biomass while in the dry deciduous forest it ranged from 0.02 to 0.04 t ha^{-1}. Shrub and herb biomass values in the present study are consistent with the values reported by Roy & Ravan (1996), however, lower than the values reported by Singh & Singh (1991).

Above ground biomass: A remote sensing approach

The NDVI values varied across the vegetation types ranging from 0.46 to 0.86 (Table 4). Perusal of these results indicates that there is a relationship between NDVI and forest type and in turn with biomass. Higher NDVI values were recorded for the evergreen type where the area weighted biomass was also maximum. The lower NDVI values in dry deciduous types coincided with relatively low biomass. In order to understand this relationship, regression analysis was carried out between NDVI and the area weighted biomass obtained across the vegetation types. The results indicated a significant exponential relationship between satellite data and field observations (Fig. 5). Wani *et al.* (2010) used SPOT-VGT maximum NDVI to estimate the crop biomass carbon density in Madhya Pradesh and obtained a R^2 value of 0.65. Dadhwal & Shah (1997) and Thenkabail *et al.* (2000) have also reported similar relationship

Table 4. Comparison of NDVI with area weighted above ground biomass.

Site ID	District	Vegetation type	December NDVI	Area weighted AGB (t ha^{-1})
1	Kodagu	Moist deciduous	0.815	85.64 (40.25)†
2	Kodagu	Evergreen	0.818	176.73 (83.06)
3	Kodagu	Coffee plantation	0.860	99.37 (46.70)
4	Kodagu	Rubber plantation	0.731	63.46 (29.83)
5	Kodagu	Teak plantation	0.725	118.19 (55.55)
6	Kodagu	Teak plantation	0.739	118.19 (55.55)
7	Mysore	Dry deciduous	0.636	13.75 (6.46)
8	Mysore	Moist deciduous	0.760	92.62(43.53)
9	Mysore	Moist deciduous	0.739	51.54 (24.22)
10	Mysore	Dry deciduous	0.597	20.38 (9.58)
11	Mysore	Acacia plantation	0.549	7.62 (3.58)
12	Hassan	Coffee plantation	0.824	91.65 (43.07)
13	Hassan	Mixed plantation	0.460	4.82 (2.27)
14	Hassan	Dry deciduous	0.615	5.19 (2.44)
15	Hassan	Coffee plantation	0.843	101.58 (47.74)

†Values within parenthesis indicate C-t ha^{-1}.

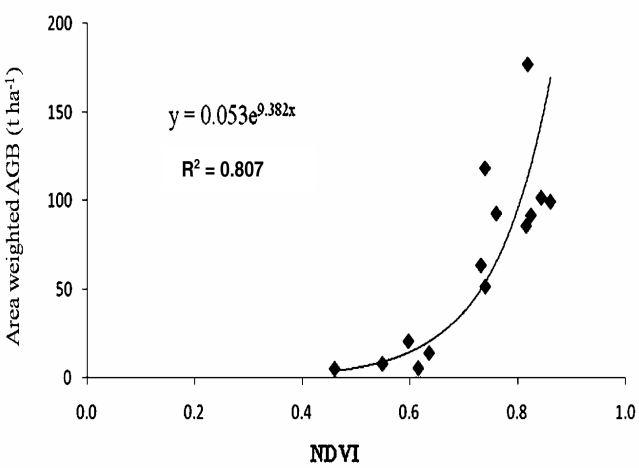

Fig. 5. Regression of area weighted above ground biomass on December NDVI.

between NDVI and the above ground biomass.

The best fit regression (exponential) model was obtained between area weighted above ground biomass and NDVI of December month with highest R^2 value of 0.8074 (Table 5). The R^2 varied between 0.021 - 0.712 and 0.365 - 0.803 for regressions between AGB and infra red and red reflectance, respectively. The regression equation given below was thus used for spectral modeling of the above ground biomass, and for carbon, the same equation was multiplied with the factor of 0.47.

$Y = 0.053e^{9.382x}$ ($R^2 = 0.8074$, $P \leq 0.05$)

where,

Y = above ground biomass (t ha^{-1});

x = December NDVI.

Table 5. Coefficient of determination (R^2)* of above ground biomass on NDVI.

Type of equation	February 2009	May 2009	October 2009	December 2009
Linear	0.4312	0.5848	0.6092	0.6484
Logarithmic	0.4592	0.582	0.5773	0.6309
Power	0.5322	0.7665	0.7311	0.8056
Exponential	0.4879	0.7479	0.7567	0.8074

(n = 60, *all the values are significant at $P \leq 0.05$).

This model estimated the total above ground biomass (TAGB) in three districts at 6.43 Mt dry wt. or 3 Mt C, of which vegetation in Kodagu, Hassan and Mysore districts contributed 70, 17 and 13 per cent of TAGB, respectively. Mean above ground biomass density in the region was estimated at 70 t-dry wt ha^{-1} (33 t-C ha^{-1}). Above ground biomass in Kodagu district ranged from 0.053 t ha^{-1} to 250 t ha^{-1} with a mean of 92 t ha^{-1} while, in Hassan district it ranged from 0.082 t ha^{-1} to 230 t ha^{-1} with a mean of 47 t ha^{-1} and in Mysore district it ranged from 0.0015 t ha^{-1} to 160 t ha^{-1} with a mean of 42 t ha^{-1}. Among three districts, Kodagu contained highest vegetation carbon pool (2.1 Mt) followed by Hassan (0.5 Mt) and Mysore (0.4 Mt) districts.

Regression analysis was carried out between biomass obtained through spectral modeling (predicted biomass) and estimates of area weighted biomass based on field measurements (Fig. 6). High R^2 (0.807) value indicates a significant positive relationship between predicted and area weighted biomass estimates suggesting that the remote sensing technique could be used confidently for quick and reliable estimates of biomass and carbon. The difference in biomass estimates between predicted and observed could be due to the differences in crown density and different phenological conditions of the trees or vegetation types existing in the study area. Remote sensing data are most sensitive to season, tree phenological characters and degree of crown closure (Dadhwal *et al.* 2009).

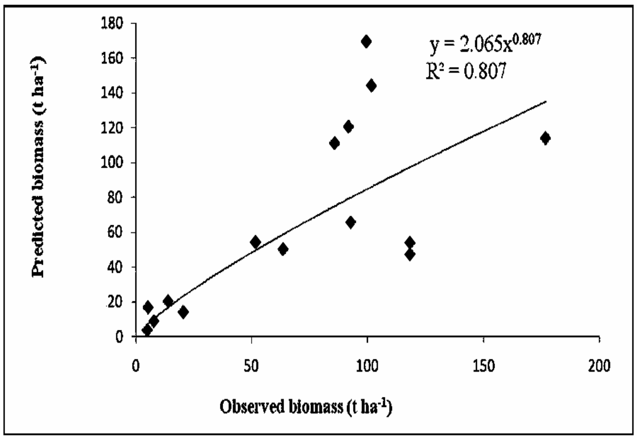

Fig. 6. Relationship between predicted biomass (based on spectral modeling) and area weighted AGB (based on field measurements).

Geospatial distribution of the above ground carbon in south western part of Karnataka is shown in Fig. 7. This map revealed the presence of maximum vegetation carbon pool in continuous forest belt along the western side of these districts. Kodagu district, which lies in the central part of the Western Ghats, contained highest vegetation carbon pool as compared to other two districts. The biomass and carbon pool was found to be highest in the western and south western parts of the district. It was estimated that above ground biomass in this part could be as high as 250 t ha^{-1} with a carbon density of 120 t ha^{-1}. Central and northern parts of the district are dominated by agricultural lands where the biomass and carbon stock was found to be comparatively low. The maximum above ground biomass in this part of the district was estimated at 45 t ha^{-1} with a carbon density of 21 t ha^{-1}.

In Mysore district, south and south western parts contribute the maximum biomass and carbon pool of the district. Bandipur national park and adjoining forests located in this region contribute significantly to the vegetation carbon pool of the district. The study reveals that biomass in this part was as high as 16 t ha^{-1} with a carbon density of 76 t ha^{-1}. The main forest types in this part are moist and dry deciduous types. North and north-eastern part of the district occurring under dry zone and mainly predominated by less dense, degraded and scrub forest types contained less biomass and carbon density (19 t ha^{-1} and 9 t ha^{-1}, respectively). In Hassan district, the above ground biomass was observed to be highest in Bisle Ghat region which lies in the west and south west part of the district and comprises mainly evergreen forests, coffee and cardamom plantations. Above ground biomass was estimated at 230 t ha^{-1} with a carbon density of 110 t ha^{-1} in this part of the district. Plains or maiden region in the north, south and eastern part of Hassan district has degraded forests. Main forests types in this region are open dry deciduous and scrub forests. Above ground biomass (24 t ha^{-1}) and carbon density (12 t ha^{-1}) in this part of the district were comparatively very low. These results could be compared with available biomass and carbon estimates of different forest types in India. Bhat *et al.* (2003) estimated the biomass accumulation in tropical rain forests of Uttar Kannada in the Western Ghats ranging from 92 to 268.49 t ha^{-1}. Chaturvedi *et al.* (2011) reported carbon density ranging from 15.6 to 151 t-C ha^{-1} in tropical dry forests of India. Srinath (2008) reported above ground biomass in the sacred groves of Kodagu district to the tune of 279.4 t ha^{-1}. According to Clark & Clark (2000), biomass accumulation in tropical forests ranged from 161 to 186 t ha^{-1} while FAO (2007) estimated the average carbon density in India at 35 t ha^{-1}.

Conclusions

Remote sensing, being an advanced technology, is quite useful for quick and reliable estimations of vegetation biomass and carbon over large areas. Furthermore, remote sensing is also useful for stratification of forests and in selection of proper sample plots for enumeration which is otherwise not possible through conventional methods. The predicted above ground biomass and carbon estimates obtained by spectral modeling were comparable with the observed values which signifies the soundness of this new technique. High R^2 value of 0.807 indicates a significant positive relationship between observed and predicted above ground biomass. The difference in the biomass estimates between the predicted and observed values was possibly due to the differences in the crown density and phenological conditions of the trees or vegetation types existing in the study area. Remote sensing data are most sensitive to season, tree phenological character and degree of crown closure. Above ground biomass and carbon map was prepared through spectral modeling in order to understand the geospatial distribution in the three districts. The present analysis also revealed the presence of highest above ground biomass carbon along the continuous forest belt in the western side of these districts occurring in the Western Ghats region.

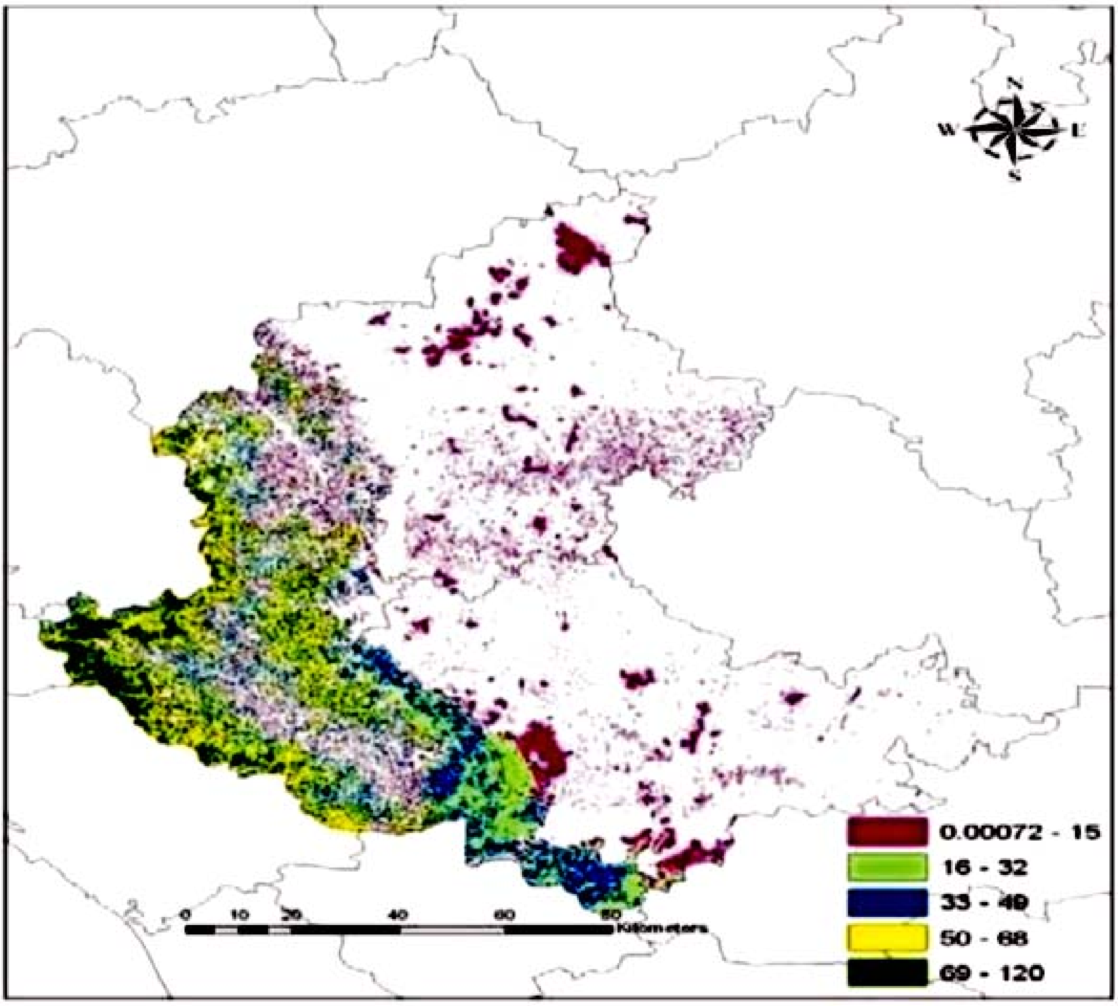

Fig. 7. Spatial distribution of vegetation carbon pool (t ha^{-1}) in south western part of Karnataka.

Acknowledgements

Authors thank Indian Space Research Organisation, Bangalore, for funding this project under Indian Geosphere Biosphere Programme. Our thanks are also due to the Head and faculty of Forestry and Ecology Division, IIRS, Dehradun, for data analysis and developing maps using RS and GIS software's. Thanks are also due to the Dean (Forestry), College of Forestry, Ponnampet, Kodagu, for encouraging the collaboration with IIRS, Dehradun. Authors are also grateful to the PCCF, Aranya Bhavan, KFD, Bangalore and Shri B. P. Ravi, Conservator of Forests, Mysore, for permission and support during field work in forest areas.

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(Received on 11.07.2011 and accepted after revisions, on 16.01.2012)

Appendix Table 1. List of volume and biomass equations used in the present study.

Sl. No.	Tree Species	Volume equations	Type of equation
1	*Acacia auriculiformis*	V/D^2= 0100961+4.03861D-56.387D^2 +362.638D^3-668D^4	L
2	*Acrocarpus fraxinifolious*	V/D^2= -0.0941/D^2=0.00097	L
3	*Adina cordifoilia*	V=0.296-2.829D+12.207D^2	L
4	*Albizzia* sp.	SQRT V=-0.07109+2.99732D	R
5	*Anogeissus latifolia*	V=-0.06868+1.56245D-2.9161D^2	L
6	*Aphnamixis polystachya*	V=-0.0263+0.40113D^2H	R
7	*Artocarpus hirsutus*	V=0.076-1.319D+11.370D^2	L
8	*Artocarpus lakoocha*	V=0.012951+0.000027D^2H *	R
9	*Bauhinia* sp.	V=-0.04262+6.09491D^2	L
10	*Bombax ceiba*	V/D^2H=0.002994/ D^2H+0.457283-0.00054 D^2	R
11	*Bridelia retusa*	V/D^2H=-0.003872/ D^2H+.383012	R
12	*Cassia fistula*	V=0.0066+0.287 D^2H	R
13	*Cassia siamea*	V=0.05159-0.53331D+3.46016D^2+4.60460D^3	L
14	*Cinnamomum malabatrum*	V=0.089-1.242D+9.732D^2	L
15	*Callophyllum elatum*	V=0.02492+0.43282D^2H	R
16	*Dalbergia latifolia*	V=0.018945-2.46215D+10.54462 D^2	L
17	*Diospyros melanoxylon*	V=0.024814-0.578532D+6.11017D^2	L
18	*Dipterocarpus indicus*	V=0.0303+0.4444D^2H	R
19	*Dysoxyllum malabaricum*	V=0.0795+0.457D^2H	R
20	*Emblica officinalis*	V=-0.406+3.540D-3.231 D^2	L
21	*Erythrina indica*	V=0.07803+1.70258D-9.1618D^2+33.91455D^3	L
22	*Eucalyptus territicornis*	V=0.02894-0.89284D+8.72416 D^2	L
23	*Ficus bengalensis*	SQRT V=0.03629+3.95389D-0.84421SQRT D	L
24	*Ficus* sp.	SQRT V=0.03629+3.95389D-0.84421 SQRT D	L
25	*Garuga pinnata*	V=0.034-0.901D+6.898D^2	L
26	*Gmelina arborea*	V=0.25058-3.55124D+16.41720D^2-8.32129D^3	L
27	*Grewia tiliaefolia*	V=-0.01611+4.90810 D^2	L
28	*Kingiodendron pinnatum*	V=-0.01855+0.44803D^2H	R
29	*Lagerstroemia lanceolata*	V=0.23839-2.48071D+10.14106D^2	L
30	*Macaranga peltata*	V=0.13333-2.18825D+13.12678 D^2	L
31	*Mallotus philippensis*	V=0.14749-2.87503D+19.61977 D^2-19.11630D^3	L
32	*Michelia champaca*	SQRTV=0.37142+5.64184D-2.27448SQRT D	L
33	*Myristica* sp.	V=0.79131-10.40359D+45.56029D^2-37.81912D^3	L
34	*Mitragyna parviflora*	V=0.048795-1.241364D+9.496613D^2	L
35	*Olea dioica*	V=-0.03001+5.755523D^2	L
36	*Palaquim ellipticum*	V=0.02245+0.047522D^2H	R
37	*Pterocarpus marsupium*	V=0.070-1.295D+9.429D^2	L
38	*Stereospermum* sp.	SQRT V=0.49746+5.98454D-2.84986 SQRT D	L
39	*Syzigium cumini*	V=0.0238+0.41681D^2H	R
40	*Tectona grandis*	V=-0.27773+3.10419D-6.12739 D^2+15.16993D^3	L
41	*Terminalia bellerica*	SQRTV V=-0.23519+2.672250D	L

Contd...

Appendix Table 1. Continued.

Sl. No.	Tree Species	Volume equations	Type of equation
42	*Terminalia chebula*	$V=--0.05004-0.03440D+6.35715\ D^2$	L
43	*Terminalia crenulata*	$V=0.06517-0.21738D+3.96894D^2+4.63954D^3$	L
44	*Terminalia paniculata*	$V=0.13100-1.87132D+9.47861D^2$	L
45	*Tetrameles nudiflora*	$V=-0.50980+2.4116D+1.12639SQRT\ D$	L
46	*Vateria indica*	$V=-0.39452+2.7392D+6.03205D^2$	L
47	*Vitex* sp.	$V=-0.16386+2.23116D-7.00969D^2+22.13099D^3$	L
48	*Wrightia tinctoria*	$SQRT\ V=0.23229+4.41646D-1.55899SQRT\ D$	L
49	*Xylia xylocarpa*	$SQRT\ V=0.01631+2.20921D$	L
50	For other species		
	i) in Kodagu district	$V=0.16948-1.85075D+10.63682D^2H$	R
	ii) in Hassan and Mysore district	$V=0.058+4.598D^2H$	R
51	*Hevea brasiliensis*	Biomass (kg)=$0.0026G^{2.78}$	

V=volume (m^3), D= DBH (m), H= height (m), SQRT=square root, G=GBH (m), L=Local volume equation R=Regional volume equation.

Appendix Table 2. Wood specific gravity values used in the present study.

Sl. No.	Tree species	Wood specific gravity
1	*Acacia auriculiformis*	0.637
2	*Acacia chundra*	0.980
3	*Acacia mangium*	0.500
4	*Acacia nilotica*	0.670
5	*Acacia* sp.	0.670
6	*Acrocarpus fraxinifolious*	0.680
7	*Actinodaphne hookeri*	0.520
8	*Adina cordifoilia*	0.590
9	*Ailanthus* sp.	0.798
10	*Albizzia odoratissima*	0.760
11	*Albizzia* sp.	0.760
12	*Alstonia scholaris*	0.440
13	*Anogeissus latifolia*	0.780
14	*Aporusa lindliana*	0.620
15	*Artocarpus heterophyllus*	0.600
16	*Artocarpus hirsutus*	0.520
17	*Artocarpus integrifolia*	0.600
18	*Artocarpus lakoocha*	0.640
19	*Atlantia* sp.	0.798
20	*Bauhinia* sp.	0.700
21	*Bombax ceiba*	0.330
22	*Bridelia retusa*	0.500
23	*Butea monosperma*	0.560

Contd...

Appendix Table 2. Continued.

Sl. No.	Tree species	Wood specific gravity
24	*Calophyllum austroindicum*	0.530
25	*Calophyllum* spp.	0.530
26	*Carallia bracheata*	0.660
27	*Careya arborea*	0.800
28	*Cassia fistula*	0.710
29	*Cassia siamea*	0.860
30	*Cinnamomum malabatrum*	0.430
31	*Cinnamomum* sp.	0.430
32	*Citrus* sp.	0.780
33	*Cordia* sp.	0.530
34	*Dalbergia lanceolata*	0.640
35	*Dalbergia latifolia*	0.800
36	*Dalbergia* sp.	0.800
37	*Dillenia pentagyna*	0.530
38	*Diospyros* sp.	0.680
39	*Emblica officinalis*	0.800
40	*Erythrina indica*	0.320
41	*Eucalyptus territicornis*	0.640
42	*Ficus bengalensis*	0.590
43	*Ficus infectoria*	0.390
44	*Ficus mysorensis*	0.390
45	*Ficus recemosa*	0.390
46	*Ficus* sp.	0.390
47	*Garuga pinnata*	0.511
48	*Glyricidia sepium*	0.640
49	*Gmelina arborea*	0.560
50	*Grevillea robusta*	0.478
51	*Grewia tiliaefolia*	0.651
52	*Heavea brasiliensis*	0.490
53	*Holigarna arnotiana*	0.327
54	*Hopea parviflora*	0.790
55	*Knema attenuate*	0.530
56	*Lagerstroemia lanceolata*	0.579
57	*Lagerstroemia parviflora*	0.620
58	*Lannea coromandelica*	0.540
59	*Macaranga peltata*	0.290
60	*Mallotus philippensis*	0.640
61	*Mangifera indica*	0.680
62	*Michelia champaca*	0.590
63	*Myristica* sp.	0.530
64	*Mitragyna parviflora*	0.560
65	*Pongamia pinnata*	0.640

Contd...

Appendix Table 2. Continued.

Sl. No.	Tree species	Wood specific gravity
66	*Pterocarpus marsupium*	0.670
67	*Simaruba glauca*	0.480
68	*Spathodia campanulata*	0.220
69	*Stereospermum* sp.	0.600
70	*Syzygium cumini*	0.760
71	*Syzygium lanceolatum*	0.760
72	*Tectona grandis*	0.604
73	*Terminalia bellerica*	0.628
74	*Terminalia chebula*	0.880
75	*Terminalia crenulata*	0.760
76	*Terminalia paniculata*	0.720
77	*Tetrameles nudiflora*	0.300
78	*Trema orientalis*	0.310
79	*Vateria indica*	0.480
80	*Vitex* sp.	0.300
81	*Wrightia tinctoria*	0.800
82	*Xylia xylocarpa*	0.810