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Spatial distribution of forest biomass carbon (Above and below ground) in Indian forests

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A B S T R A C T

Forest carbon (C) estimates are the key inputs to the understanding of the global C cycle. We report the estimates of forest carbon pool and its spatial distribution in the Indian forests for the years 1994 and 2010 at 5 km grid level. This study improves upon earlier spatial estimates of Indian forest biomass carbon by using data from a robustly designed National Forest Inventory (NFI). The realized sampling intensity has addressed the large heterogeneity of the Indian forest types and allowed the computation of 5 km grid level forest C, yielding a realistic estimate of forest biomass C in Indian forests. Forest cover density maps were intersected with 5 km mesh and estimates of forest area, forest carbon density for each Agro-ecological sub region and forest carbon pools were linked to the 5 km grid coverage of India. National forest carbon estimates for the years 1994 and 2010 are 3911.78 and 4368.03 TgC respectively, and these estimates showed a net increase of 456.25 TgC in 16 years. Uncertainty of the estimates has been addressed spatially. Mean forest carbon density increased from 61.14 Mg ha^{-1} in 1994 to 64.08 Mg ha^{-1} in 2010. C densities for dense and open forest in 1994 estimated as 77.08 and 38.47 Mg ha^{-1} with total C pools of 2895.28 TgC and 1016.50 TgC which has increased to 80.24 Mg ha^{-1} and 41.69 Mg ha^{-1} with total C pools of 3176.48 TgC and 1191.55 TgC in 2010. This study provides the first 5 km level C analysis for Indian forests. Spatial distribution of C shows large differences in C density over Indian forests indicating that estimates of the spatial distribution of C are even more important than the total C pool estimates of the country.

1. Introduction

The increasing carbon dioxide (CO_2) loading in the atmosphere has become one of the major global environmental issues in recent years because increasing atmospheric CO_2 causes climate change (Stocker et al., 2013). Forests contain about 80% of global terrestrial above-ground carbon stocks in their vegetation and soils, and also exchange large quantities of carbon with the atmosphere through photosynthesis and respiration playing an important role in the global carbon (C) cycle (Noble et al., 2000). Estimations of forest biomass and its change are important for assessing historical and present anthropogenic C releases from forests and also in evaluating the possibilities of future potential C sequestration (Ciais et al., 2013; Tan et al., 2007). Forested areas can behave as a source of atmospheric carbon when they get disturbed by human or natural causes, and an atmospheric carbon sink during the re-growth after disturbance, and hence they can be managed to alter the magnitude and direction of their C fluxes (Brown et al., 1996). Forest carbon inventories at national level and state/regional level are essential for developing countries, as well-authenticated estimates of forest carbon stocks are necessary for successful implementation of mitigating policies to take advantage of the REDD programme (Saatchi et al., 2011).

Pan et al. (2013) has estimated the global forest C pool as 363 PgC, based on global aggregation of forest inventories and field observations. Analysis of forest C cycle indicates large spatial differences in C pools, fluxes and net C releases due to land use changes, environmental and anthropogenic factors (Chhabra and Dadhwal, 2004; Achard et al., 2004; Houghton, 2008). Improved understanding of forest C pools is important for the sustainable development and conservation of forests, formulating strategies for carbon sequestration, and accurate estimation of contribution of land use changes to C emission in India (Chhabra et al., 2002a).

Abbreviations: GS, growing stock; Mg ha^{-1}, million gram per hectare; Mha, million hectare; TgC, tera gram carbon; WD, wood density; BEF, biomass expansion factor

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This study presents the spatial forest carbon stock estimates at 5 km grid for the years 1994 and 2010. This study indicates that Indian forests are sequestering carbon, and carbon stored in Indian forest has increased over the study period.

1.1. Carbon (C) estimation of Indian forests –earlier studies

India ranks fifth in the world in carbon dioxide emissions (Sathayea and Reddy, 2013). Among the tropical Asian countries, India has a high potential C content in forest vegetation. India along with Indonesia and Myanmar accounts for about 70% of total carbon pools in tropical Asian forests (Brown et al., 1993; FAO, 2010). Several studies have been published on the Indian forest carbon pool (Chhabra et al., 2002a,b; Kishwan et al., 2009; Haripriya, 2000) and also on emission from deforestation and land use changes (Chhabra and Dadhwal, 2004; Kaul et al., 2009). Growing stock from forest inventories is the primary input for C estimates. Based on the various approaches, the current estimates of Indian forest C pools are in the range of 2000–4400 tera gram carbon (TgC) (Chhabra et al., 2002a,b). The estimated Indian forest carbon densities for the recent periods (past 2 decades) range from 50 to 65 Mg ha^{-1} (Kishwan et al., 2009; Lal and Singh, 2000).

Using C densities based on ecological studies and remote sensing (RS), aggregated country level forest C pool was estimated as 4179 TgC for 1986 (Ravindranath et al., 1997), 3321.7 TgC and 3117 TgC for 1980 and 1990, respectively (Dadhwal et al., 1998). Using field inventory of growing stock and standard biomass expansion and conversion factors, forest C pool was estimated as 3978 TgC and 4071 TgC for 1982 and 1991, respectively (Dadhwal and Shah, 1997), and 4341.8 TgC for 1993 (Chhabra et al., 2002b).

Several studies have estimated spatial forest biomass using remote sensing approaches over different regions of India during past one decade (Jha et al., 2015; Thumaty et al., 2016; Devagiri et al., 2013). These studies used satellite derived parameters along with field inventory to develop spectral model for forest biomass estimation. Pargal et al. (2017) and Reddy et al. (2016) used texture metrics derived from high resolution remote sensing data to spatially map the forest above ground biomass. Véga et al. (2015) used airborne remote sensing data for above ground biomass estimation of complex tropical forest in India.

1.2. Forest C for Indian forests as part of global estimates

Table 1 presents the mean C densities and forest carbon stock for India based on the studies of global biomass estimation. All values include below and aboveground forest carbon. Houghton (1999); DeFries et al. (2002) distinguish forest types within region, whereas Brown (1997))/ Achard et al. (2004) distinguish only by region. The estimation procedure of Houghton (1991) is mostly based on compilation of harvest measurement from ecological studies.

Table 1
Average C densities and Carbon stock for India based on global estimates in million gram carbon per hectare (Mg ha^{-1}).

Forest type/regions Tropical Asia	Houghton (1999); DeFries et al. (2002)	Brown (1997); Achard et al. (2004)	Gibbs and brown (2007)	IPCC (2006)
Tropical forest C stock estimate using biomass average approach(Mg ha^{-1})				
All forests	–	151	–	–
Tropical equatorial forest	250	–	164	180/ 225*
Tropical seasonal forest	150	–	142	105/169
Tropical dry forest	–	–	120	78/96
National level forest biomass carbon estimates for Indian forest based on global studies (TgC)				
Indian Forests	8997	7333	8560	5085

* values here are for continental ad insular Southeast Asia, respectively.

The carbon values reported in Table 1 are mostly based on the global vegetation maps generated earlier (Whittaker and Likens, 1973; Olson et al., 1983) as well as from regional studies (Houghton et al., 1995), and include both above and below ground and ground cover Carbon. C estimates by Brown (1997) were based on forest inventory data converted to C stock using allometric models, and Achard et al. (2004) increased these values by 20% for root carbon stocks. Estimates by Gibbs et al. (2007) are based on method pioneered by Brown et al. (1993) using a rule base GIS analysis to spatially extrapolate forest field inventory data based on climate, soils, topography, population and land use information and produce a map of forest carbon stocks in the 1980 (Iverson et al., 1994; Brown and Gaston, 1995). Gibbs and Brown (2007) estimated carbon values for South East Asia by taking the average forest carbon stock for each biome from maps that represent actual forest carbon in 2000. IPCC (2006) default values for forest biomass, mostly based on Penman et al. (2003), are based on compilation of published studies. Biomass values presented in IPCC (2006) converted to carbon stock using IPCC default carbon conversion factor (carbon fraction of biomass = 0.47), and below ground carbon stock added using the ratio of belowground biomass to the aboveground biomass.

1.3. Spatial distribution of Indian forest

India is the seventh-largest country in the world, with a total area of 328.7 million hectare (Mha).The country is situated north of the equator between 8°4′ and 37°6′ north latitude and 68°7′ and 97°25′ east longitude. India's geographical area constitutes 2.4% of the world land area and about 1.7% of the global forests (FAO, 2010), while supporting 16% of the world's human population.

Using historical data, Richard and Flint (1994) estimated India's forest area in 1880 and 1980 as 102.68 and 64.6million ha, respectively. From 1981–83 onwards, the Forest Survey of India (FSI) has mapped and monitored India's forests on a biennial basis using satellite data (FSI, 1987). All lands, more than 1 ha in area, with a tree canopy density of more than 10 percent are considered as forest cover by FSI.

2. Materials and methods

The present study aims to develop specially explicit estimates of forest C pool at 5 km grid level (for 1994 and 2010) using field inventory based growing stock (GS) volume and remote sensing based forest area. The growing stock was estimated using species specific and regional volumetric equations (FSI, 1996). The growing stock was converted to carbon using wood density (WD), biomass expansion factor (BEF) and carbon correction factor.

2.1. Remote-sensing based forest area

Fourteen assessments of India's forest have been published by the Forest Survey of India (FSI 1987, 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2009, 2011, 2013, 2015). These reports provide data on forest area under three crown density classes, viz, very dense forest (D1) with more than 70% canopy density, moderately dense forest (D2) with canopy density between 40% and 70% and open forest (D3) with canopy density between 10% and 40% (FSI, 1995a). Canopy density is defined as the proportion of the forest floor covered by the vertical projection of the tree crowns (Jennings et al., 1999). For the purpose of this study, the area under very dense and moderately dense class were merged under dense category. Remote sensing based forest area under dense, and open forest were used for forest C estimation. Forest area under dense and open forest were obtained from forest canopy density maps developed by Forest Survey of India (FSI, 1995a, 2009) for the years 1994 and 2010 respectively.

In 1995 assessment of forest cover, Indian Remote Sensing Satellite product IRS–1 B LISS II with spatial resolution of 36.25 m were used.