

Estimation of Above Ground Biomass Using Texture Metrics Derived from IRS Cartosat-1 Panchromatic Data in Evergreen Forests of Western Ghats, India

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Abstract Assessment of above ground forest biomass (AGB) is essential in carbon modelling studies to provide mitigation strategies as demonstrated by reducing emissions from deforestation and forest degradation. Several researchers have demonstrated the use of remote sensing data in spatial AGB estimation, in terms of spectral and radar backscatter based approaches at a landscape scale with several known limitations. However, these methods lacked the predictive ability at high biomass ranges due to saturation. The current study addresses the problem of saturation at high biomass ranges using canopy textural metric from high resolution optical data. Fourier transform based textural ordination (FOTO) technique, which involves deriving radial spectrum information via 2D fast Fourier transform and ordination through principal component analysis was used for characterizing the textural properties of forest canopies. In the current study, plot level estimated AGB from 15 (1 ha) plots was used to relate with texture derived information from very high resolution datasets (viz., IKONOS and Cartosat-1). In addition to the estimation of high biomass ranges, one of the prime objective of the current study is to understand the effects of spatial resolution on deriving textural-AGB relationship from 2.5 m IRS Cartosat data (Cartosat-A, viewing angle = -5°) to that of IKONOS imagery with near nadir view. Further, since texture is impacted by several illumination geometry issues, the effect of viewing geometry on

the relationship was evaluated using Cartosat-F (Viewing angle = 26°) imagery. The results show that the FOTO method using stereo Cartosat (A and F) images at 2.5 m resolution are able to perform well in characterizing high AGB values since the texture-biomass relationship is only subjected to 18 % relative error to that of 15 % in case of IKONOS and could aid in reduction of uncertainty in AGB estimation at a large landscape levels.

Keywords Above ground biomass · Canopy texture · Fourier transform · IRS Cartosat · Western Ghats

Introduction

Forests play a critical role in global carbon cycle as carbon sinks of the terrestrial ecosystem. Tropical forests store over 40 % of the terrestrial carbon (Dixon et al. 1994), majorly as above ground biomass (hereafter referred as AGB or biomass). Quantification of forest spatial biomass is essential in understanding carbon cycle, and climate change studies (Beer et al. 2010) as well as for assessing the forest productivity and sustainability for better management. It also provides an estimate of carbon dioxide emissions into the atmosphere due to deforestation or burning (DeFries et al. 2002; Baccini et al. 2012) and monitoring carbon stocks (Tuominen et al. 2010). Therefore, accurate estimation of AGB is essential to assess the impacts of carbon losses due to deforestation and degradation on global and regional levels (Houghton 2005; Van der Werf et al. 2009).

The most accurate way of estimating biomass is using extensive field measurements, especially using destructive sampling (Gibbs et al. 2007; De Boer 2008). However, field measurements are often strenuous, expensive, time

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consuming and destructive (which may not be practical for all forest types due to various environmental regulations). Therefore, remote sensing is used as a tool for upscaling small scale field measurements to large areas (Lu 2006; Couteron et al. 2012).

Satellite remote sensing (both optical and microwave) provides useful information about structure and phenology but are usually limited by low spatial resolutions. Several studies have shown that these signals saturate at intermediate biomass levels (around 250 t ha^{-1}) (Madugundu et al. 2008; Nizalapur et al. 2010; Devagiri et al. 2013; Thumaty et al. 2015). Further the obtained relations are on a pixel basis, and does not use any information from neighboring pixels (texture) (Barbier et al. 2010). This limits the extension of these relations to areas with high biomass range (around $500\text{--}600 \text{ t ha}^{-1}$), especially over Western Ghats, India (Rai and Proctor 1986; Swamy et al. 2010). Airborne remote sensing data (e.g., Lidar and stereo-pair images) have shown their potential in estimation of biomass but are quite expensive to acquire and are limited to small areas (Véga et al. 2015).

Very high spatial resolution (VHR) data, i.e. a spatial resolution of about $<1 \text{ m}$, are now widely available from various satellites (viz., Ikonos, Quickbird, Spot5 and Cartosat). Due to the level of information on a VHR data, geometrical/textural characteristics could be taken into account rather than just considering the individual pixels. Several attempts have been made to characterize the textural properties of VHR data over forest canopies, on basis of spatial autocorrelation methods such as variography (Bruniquel-Pinel and Gastellu-Etchegorry 1998), lacunarity analysis (Frazer et al. 2005) and 2D-power spectral analysis (Fourier transform) (Couteron et al. 2005, 2006). Principal component analysis (PCA) is used to reduce the dimensionality of the resulting information to compare with forest parameters (e.g. biomass, DBH etc.) (Couteron et al. 2005; Proisy et al. 2007).

Fourier Textural Ordination (FOTO; Couteron 2002) uses the textural properties of the remotely sensed VHR data using power spectrum constructed from Fourier transform to identify fineness and coarseness gradients across the image and relate to AGB. Proisy et al. (2007), have demonstrated the use of FOTO method in mangroves, French Guiana for AGB estimation using IKONOS imagery. Recent study shows the potential of FOTO method in resolving high AGB values of different forest types in oil palm-tropical forest in Sabah, Malaysian Borneo using SPOT imagery (Singh et al. 2014). Ploton et al. (2012), has implemented FOTO method in Western Ghats of India using both IKONOS and Google Earth imagery. As the part of the study 15 (1 ha) plots were used to relate the textural information obtained from VHR data to biomass. However, the study did not infer on the relation with the change of

satellite view angle geometry, which is a key parameter that affects texture information due to differences in canopy shadowing (Barbier et al. 2010).

In this regard, the present study would focus on understanding the effect of satellite view geometry by using IRS Cartosat-1 data and also evaluate the potential of high resolution Cartosat-1 imagery (2.5 m) to resolve the texture information with respect AGB and compare the results with the VHR data of IKONOS (1 m) based estimated AGB in Western Ghats of India. Indian Remote sensing Satellite (IRS) Cartosat-1 acquires images at a spatial resolution of 2.5 m covering a swath of 30 km. The two cameras are mounted for near simultaneous imaging of the same area from two different angles (Aft camera has 5° viewing angle and Fore camera has 26° viewing angle; NRSA 2006). By envisaging the effect of viewing angle difference on the obtained textural-biomass relationship, it would define the possible inclusion of stereo derived information for reducing uncertainty in biomass predictions for the future studies.

Materials and Methods

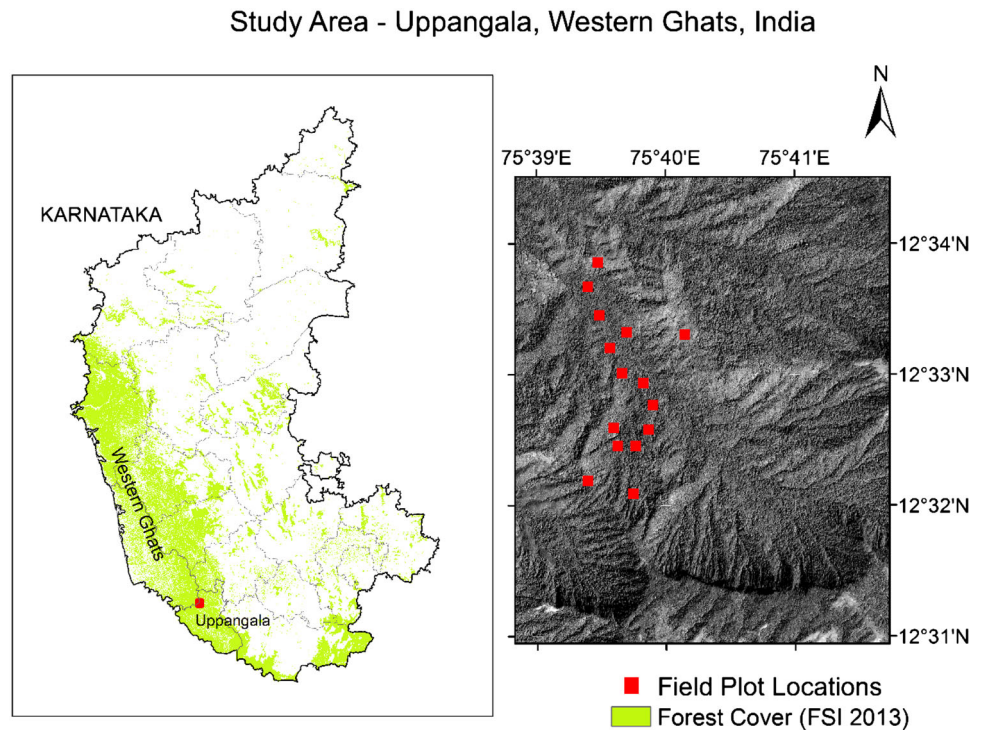
Study Area

Large permanent plots (1 ha) are setup in area of about 30 km^2 surrounding Uppangala ($12^\circ 32' 15'' \text{ N}$, $75^\circ 39' 46'' \text{ E}$), located near Pushpagiri wildlife sanctuary in the Western Ghats of India (Pascal and Pelissier 1996; Pélissier et al. 2011). The study site (Fig. 1) shows extreme topography with elevation ranging between 200 and 1000 m above sea level. Due to the inaccessibility in the study area, this is regarded as one of the last well preserved wet evergreen forests of the Western Ghats (Pascal 1988). As part of reserve forest, no logging has been carried out in recent past and thus current forest structure is almost natural, but the gradient of forest degradation levels can also be seen in the study area caused due to a fire disturbance in the past (Pelissier et al. 1998).

Field Data Collection and AGB Estimation

A total of fifteen (15) 1-ha plots were laid during two field campaigns in 2009 and 2010, to cover different canopy cover gradients observed in the satellite image, since texture would relate canopy cover. Further, plots were placed in accessible zones possessing a homogeneous canopy texture to reduce uncertainties due to plot geolocation. Each plot was $100 \times 100 \text{ m}$ corrected for slope angle and geo-tagged using Trimble Juno SB GPS device (Trimble; California, USA). For each plot, field measurements of diameter at breast height (DBH, diameter at 1.3 m above

Fig. 1 Study site showing location of fifteen (15) 1-ha field plots in Uppangala, Western Ghats, India



the ground or above the buttresses if any) were obtained for all the trees with $DBH > 10$ cm (Ploton et al. 2012). DBH is measured using standard measuring tape.

AGB was estimated using the regional allometric model constructed from Rai (1981) dataset obtained by destructive sampling. A log transformed power model was used to relate tree AGB and tree DBH ($R^2 = 0.998$; residual standard error = 0.274; intercept = 0).

$$\ln(AGB) = 1.998 \ln(DBH)$$

This model was selected as it outperformed the other model proposed by Rai and Proctor (1986) using the same dataset ($R^2 = 0.92$) and also global model by Chave et al. (2005) ($R^2 = 0.957$). The detailed model description and evaluation is described in Ploton et al. (2012).

Satellite Data

IRS Cartosat-1 is a dedicated stereo platform with two camera assemblies known as Fore camera (Carto-F) and the Aft Camera (Carto-A). The Fore camera is tilted at 26° while the Aft camera is tilted by -5° with respect to nadir in along track direction. The two images (Carto-A and Carto-F) acquired are single band panchromatic images with wavelength of $0.5\text{--}0.85 \mu\text{m}$ at a spatial resolution of 2.5 m.

For the current study, the stereo-pair during Jan 2012 was obtained (sun azimuth = 145, sun elevation = 50). Both images were ortho-corrected and precisely registered

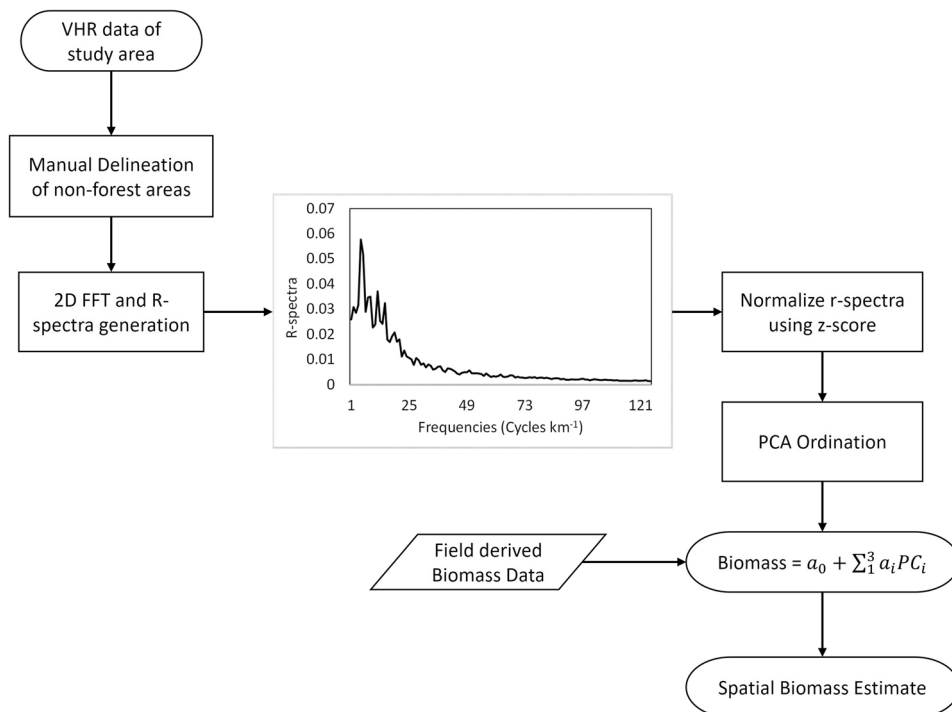
($\sim 1\text{--}2$ pixel) with the reference IKONOS imagery to avoid any geo-location issues. IKONOS imagery (satellite azimuth = 148; sun elevation = 49), was used to verify and compare the obtained relationships with Cartosat (Ploton et al. 2012). No atmospheric corrections were performed in any of the images.

Fourier Based Textural Ordination (FOTO) Method

The fundamental idea of FOTO method is that different spatial frequencies relate well to the canopy grain size. This method has been used to analyze vegetation canopy information from VHR satellite data and the information has been used to predict AGB in different forest types with moderate to high biomass ranges (Proisy et al. 2007; Ploton et al. 2012).

FOTO method uses multivariate ordination of Fourier spectra to classify canopy images into different texture gradients based on canopy grain (Couteron et al. 2005). It is a two-step process. (1) Converting spatial information into frequency domain using 2D FFT and computation of radial spectra (r-spectra) and (2) ordination of r-spectra using PCA. R-spectra, is obtained by conversion of 2D FFT information to polar form, which explains the level of spatial variation in each spatial frequency and is expressed in the units of cycles km^{-1} (Barbier et al. 2010). The methodology in the current study has been adapted from Proisy et al. (2007) and is represented by Fig. 2.

Fig. 2 Flow chart of methodology. (Adapted from Proisy et al. 2007)



The satellite image of the study area was first divided into 125×125 m contiguous unit windows (i.e. at least five times of the largest crown diameter ~ 25 m in Uppangala). Also, this allowed to overrule the GPS positional error (<5 m) and also the orientation of the plots. On each square unit window, 2D FFT was applied and r-spectra was generated. The generated r-spectra was then standardized using z-score normalization over all windows over the entire image.

Principal component analysis was performed on the standardized r-spectra. PC axes ordinate the image windows along the coarse–fine texture gradients and also provides information about the dominant periodicity of particular texture gradient in the image, that agrees with the visual appraisal (Couteron et al. 2005). The first three PC axes (explaining ~ 90 % of the r-spectra variation) are used as texture indices. These texture indices are related to 15 plots with measured AGB using a multivariate linear regression.

Results

FOTO Analysis Using Carto-A and IKONOS

The estimated AGB values from the 15 large (1 ha) plots covered a significant range of biomass varying from a minimum of 124 t ha^{-1} to a maximum of 684 t ha^{-1} with an average of 435 t ha^{-1} . In comparison, previous studies

by Rai and Proctor (1986) and Swamy et al. (2010) have reported an AGB range of 420–649 and 416–553 t ha^{-1} respectively in tropical forests of Western Ghats, Karnataka.

Textural information was captured using FOTO method for these 15 plots using both IKONOS and CARTOSAT (A and F) images. Radial spectra was computed for the squared windows of 125 m size centered at these plot locations. The r-spectra captured wide range of information pertaining to canopy gradient ranging from low to high biomass ranges in these plots. Figure 3, depicts the different r-spectra obtained from the measured plots for different biomass range using Carto-A images. It was observed that for higher biomass plot (Plot H = 632 t ha^{-1}), dominant frequencies at $15 \text{ cycles km}^{-1}$ [i.e. wavelength (λ) = 66.7 m] corresponding to the large contiguous crowns. It was also observed that there was a secondary dominant frequency at $30 \text{ cycles km}^{-1}$ ($\lambda = 33.33 \text{ m}$) corresponding to the secondary crowns. For the medium biomass plot (Plot U = 365 t ha^{-1}), dominant frequencies existed at $15 \text{ cycles km}^{-1}$ as in accordance with plot H but with relatively less dominance in the radial spectra (Fig. 3). This is due to less number of large crowns in plot U compared to plot H. In case of lower biomass plot (Plot J = 160 t ha^{-1}), it was evident that the impact of larger crowns was considerably small, and is represented by wide range of dominant spatial frequencies up to $55 \text{ cycles km}^{-1}$ ($\lambda = 18.18 \text{ m}$) suggesting smaller canopy sizes.

Fig. 3 Radial spectra derived for different canopy texture gradients (Coarse to Fine) for different plots of varying biomass (Plot ID's H, U and J)

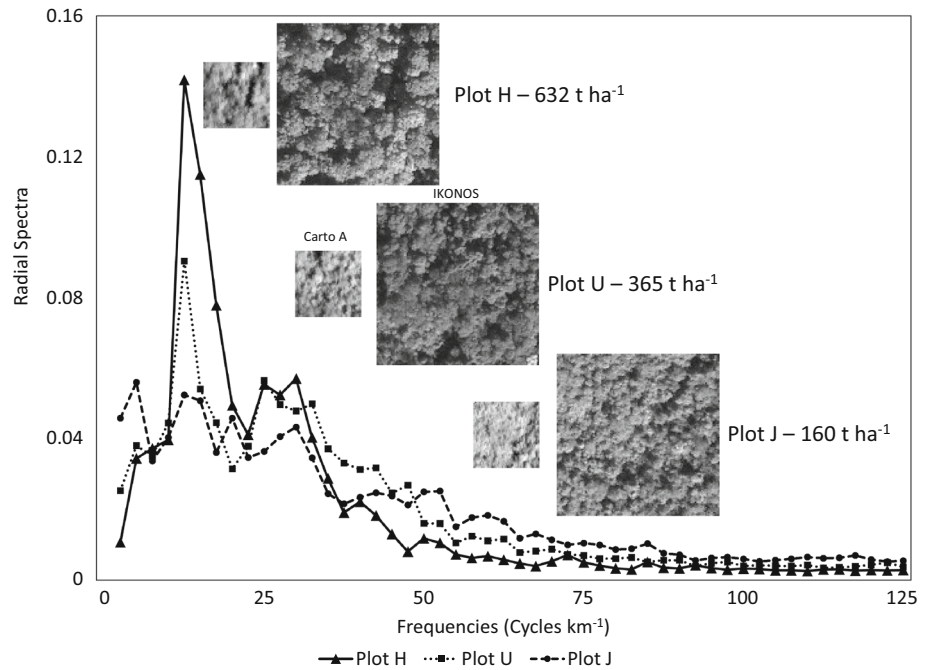
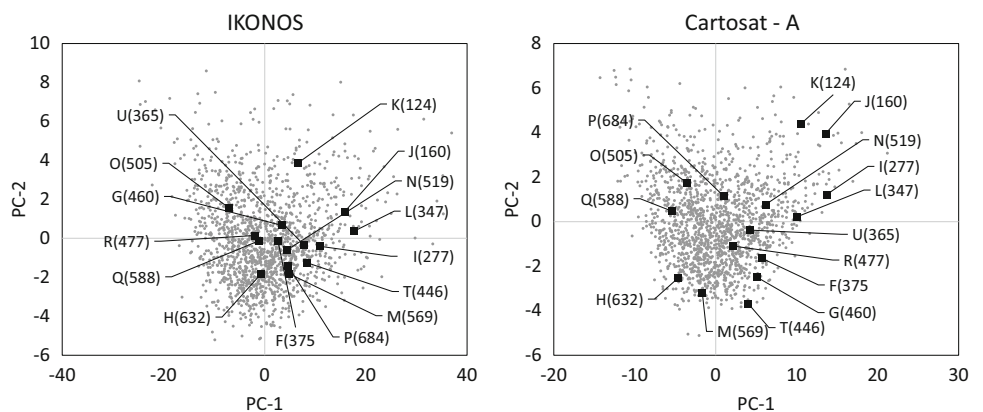


Fig. 4 Principal component cloud distribution using IKONOS and Cartosat windows (each point describe the texture score in PC1 and PC2 in 125 × 125 m window) positioned along with field plots (Plot ID's are described using alphabets along with biomass values in t ha⁻¹ in brackets)



Non-forest areas were visually masked and radial spectra was computed on each 125 m window on IKONOS and Carto-A images. The r-spectra for all these windows were then standardized and PCA ordination is performed. The first two PC components were used to interpret unit windows in terms of canopy gradient ranging from coarse to fine texture (Fig. 4). The cloud of unit windows in both IKONOS and Carto-A suggested a similar response in respect to the positions of the plots (Fig. 4). The first two prominent axes explained a significant variation of about 45 and 55 % in the data matrix in case of IKONOS and Carto-A respectively.

Figure 4 also suggested that the position of plots on the PCA cloud were separated well in case of Carto-A image than IKONOS image. These principal axes in turn correlated with the stand level parameters. PC1 acts as the

strong predictor variable to explain the variations in stand structure (Couteron et al. 2005). In the current study, when related to plot level biomass PC1 has explained about 36 % of the variation using IKONOS image, but a significant 70 % of the variation using Carto-A image.

The biomass models were estimated using the first three PC components relating to the plot level AGB values using a multi-variate linear regression. The regression analysis suggest that field measured and FOTO derived AGB values are strongly correlated with both IKONOS ($R^2 = 0.82$; $p < 0.001$) Carto-A ($R^2 = 0.76$; $p < 0.001$) images (Fig. 5). This result show that the FOTO derived texture information from Carto-A is capturing the similar canopy gradient in accordance with IKONOS imagery.

Further, the RMSE computed for predicted and field measured biomass using IKONOS and Carto-A imagery

Fig. 5 Predicted versus observed AGB estimation using IKONOS and Carto-A images for 15 1-ha plots

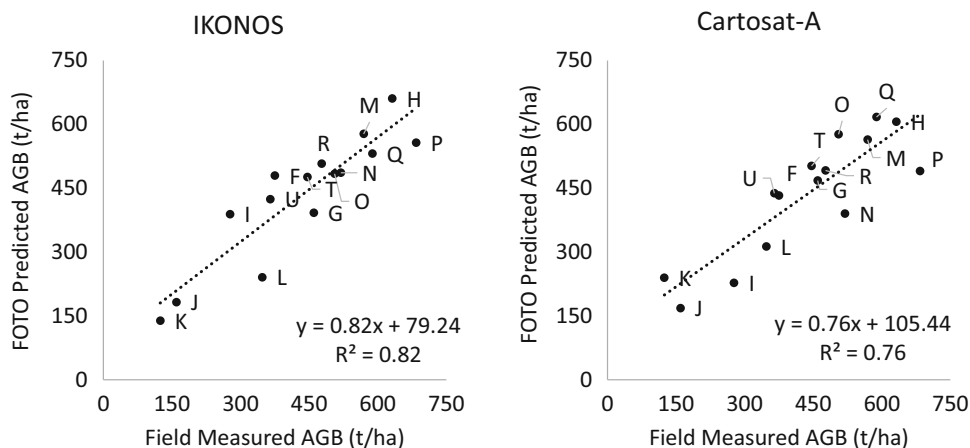


Table 1 Multi-variate linear regression statistics of texture-AGB relationship using IKONOS and Cartosat images

Sensor	Biomass = (a) * PC1 + (b) * PC2 + (c) * PC3 + d	R ² ; RMSE; <i>p</i> value
IKONOS (1 m)	a = -13.35; b = -3.11; c = -73.24; d = 506.05	0.82; 67.03 t ha ⁻¹ ; <i>p</i> < 0.001
Cartosat-A (2.5 m)	a = -20.16; b = -9.71; c = -13.92; d = 521.96	0.76; 77.32 t ha ⁻¹ ; <i>p</i> < 0.001
Cartosat-F (2.5 m)	a = -16.71; b = -17.36; c = -26.26; d = 518.77	0.76; 77.28 t ha ⁻¹ ; <i>p</i> < 0.001

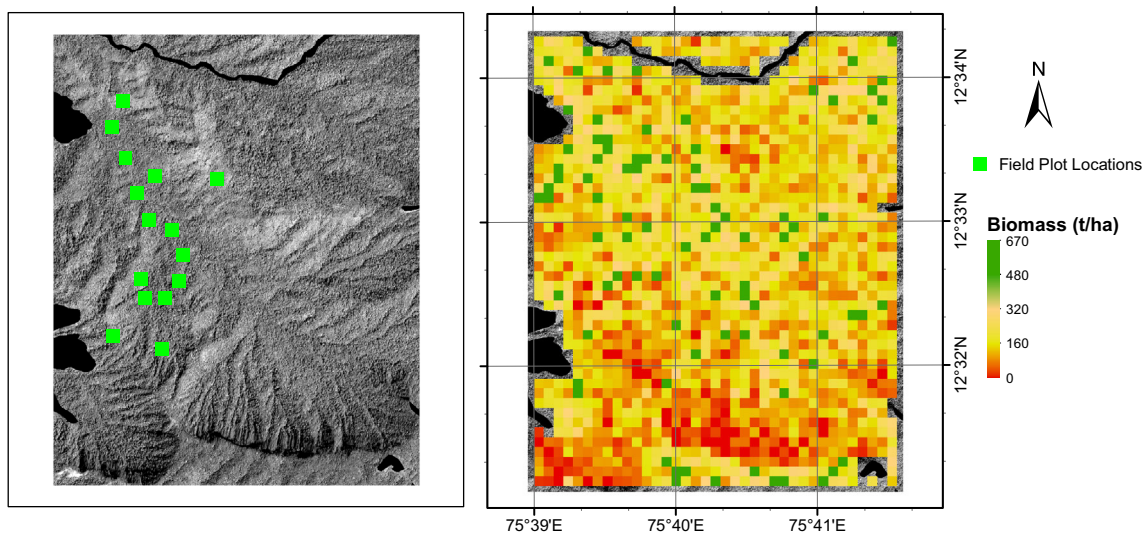


Fig. 6 Spatial biomass estimate of the study area using Carto-A image

were 67.03 and 77.32 t ha⁻¹ indicate that the spatial resolution of Carto-A (2.5 m) has least effected the derived textural-biomass relationship. The spatial biomass maps were generated using the estimated regression coefficients as mentioned in Table 1.

Figure 6 depicts the spatial biomass estimate generated using Carto-A imagery through regression estimation. The estimated total biomass was found to be 1.24 ± 0.18 Mt using Carto-A imagery, which was slightly above the estimated value of 1.21 ± 0.15 Mt using IKONOS imagery. A histogram was plotted with the spatial difference of biomass estimated using

Carto-A with respect to IKONOS reference (Fig. 7). It was found that the spatial error varied between -100 and +70 t ha⁻¹ indicating minimal bias between both estimates.

Effect of Viewing Angle (Carto-F)

Textural information was derived again using Carto-F as the input imagery to understand the effects of viewing angle geometry in a 26° tilted camera. The multi-variate regression between the field measured plots and the derived first 3 PC

components showed a similar R^2 of 0.76 ($p < 0.001$) in comparison with Carto-A result (Fig. 8). Further, the RMSE between field measured AGB and textured derived AGB was found to be 77.28 t ha^{-1} using Carto-F imagery, which was similar to that of Carto-A imagery.

In addition, it was observed that the point cloud distribution along the PC axes appeared to have shifted along quadrant-2 (Fig. 8). This was largely due to the increased shadowing due viewing angle variation which led to coarse texture compared to Carto-A imagery. However, the estimated biomass for the total extent using Carto-F was found to $1.23 \text{ Mt} \pm 0.18 \text{ Mt}$, which is nearly equal to the estimate using Carto-A Imagery. Thus, it could be inferred that the viewing angle has least influence on the derived texture-biomass relationship.

Discussions and Conclusion

The major challenges in estimation of AGB in tropical forests using remote sensing data has been the saturation of non-textural approaches at high biomass levels due to the

presence of complex canopy structure (Malhi and Román-Cuesta 2008; Mitchard et al. 2012). However, using FOTO method, the obtained textural-biomass relationship had avoided the issue of saturation at high biomass levels. Further, the computed RMSE using IKONOS image (67.03 t ha^{-1}) was about 15 % relative to the mean plot AGB, confirmed the potential of very high resolution optical data for AGB estimation. The computed RMSE using Cartosat images (both A and F), about 18 % relative to the mean, suggest that the sensor resolution of 2.5 m has least affected the derived textural-biomass relationship. The relationships were further studied to understand the effects of viewing geometry using Carto-F imagery. It was noted that the relationship was least hindered by the differences in viewing geometry with the evidences of similar R^2 and RMSE in case of both Carto-A and Carto-F imagery.

It could be inferred that the obtained textural-biomass relationship has been robust with relatively low RMSE values constituting different scenarios and would aid in reduction in uncertainty of AGB estimation. However, major uncertainty in AGB estimation in tropical forests is due to use of allometric equations which propagates along with the model error (Grainger 2010). On the other hand, in order to reduce uncertainty in AGB estimation, LIDAR has been used as an alternative technique to incorporate forest height information. Recently, one such study has been attempted at the same study site to relate LIDAR derived metrics to the field measured AGB using different models (Véga et al. 2015). It was reported that the relative error varied from 10.92 to 17.24 % and adjusted R^2 from 0.74 to 0.90.

In current study, the obtained relative errors are not significantly different from LIDAR derived estimations and thus showcase the vast potential of very high resolution optical data for large-scale biomass assessments considering the operational costs of an airborne LIDAR system.

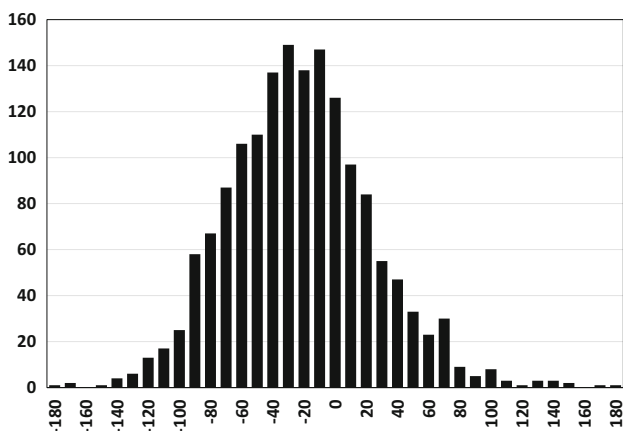
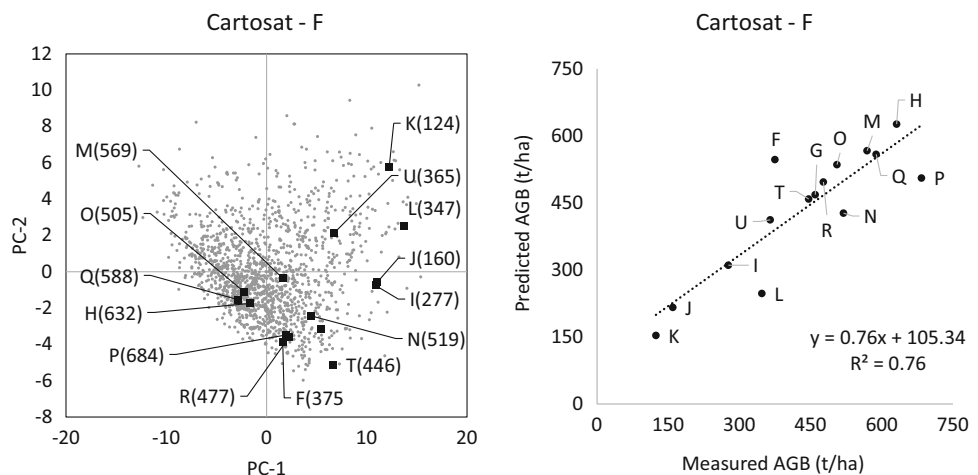


Fig. 7 Histogram showing the difference in predicted spatial AGB values using IKONOS and Carto-A images

Fig. 8 Principal component cloud distribution of Cartosat-F windows and AGB prediction using Carto-F Imagery



Further, extraction of relative tree height information using stereo optical data (Straub et al. 2013; Neigh et al. 2014), along with FOTO derived metrics would obtain a better relative error so as to reduce uncertainty in AGB estimation. Thus, satellite based VHR optical data along with field data would offer more cost effective management of forest cover by tracking ongoing evolution in forests and changes in related biomass.

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