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Retrieval of forest biomass for tropical deciduous mixed forest using ALOS PALSAR mosaic imagery and field plot data

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ABSTRACT

Tropical forest is an important ecosystem rich in biodiversity and structural complexity with high woody biomass content. Longer wavelength radar data at L-band sensor provides improved forest biomass (AGB) information due to its higher penetration level and sensitivity to canopy structure. The study presents a regression based woody biomass estimation for tropical deciduous mixed forest dominated by Shorea robusta using ALOS PALSAR mosaic (HH, HV) and field data at the lower Himalayan belt of Northern India. For the purpose of understanding the scattering mechanisms at L-band from this forest type, Michigan Microwave Canopy Scattering model (MIMICS-I) was parameterized with field data to simulate backscatter across polarization and incidence range. Regression analysis between field measured forest biomass and L-band backscatter data from PALSAR mosaic show retrieval of woody biomass up to 100 Mg ha^{-1} with error between 92 and 94 Mg ha^{-1} and coefficient of determination (r^2) between 0.53 and 0.55 for HH and HH + HV polarized channel at 0.25 ha resolution. This positive relationship could be due to strong volume scattering from ground/trunk interaction at HH-polarized while in combination with direct canopy scattering for HV-polarization at ALOS specific incidence angles as predicted by MIMICS-I model. This study has found that L-band SAR data from currently ALOS-1/-2 and upcoming joint NASA-ISRO SAR (NISAR) are suitable for mapping forest biomass ≤100 Mg ha^{-1} at 25 m resolution in far incidence range in dense deciduous mixed forest of Northern India.

1. Introduction

Forest ecosystems are the most widely distributed vegetation ecosystems covering approximately 30% of the land surface (FAO, 2015). These have received special attention since long due to their main driver for terrestrial carbon sink (~80% of global plant biomass) (Bonan, 2008) and regulating the climate system in varying time and space (Waring and Running, 2007). However, magnitude of the global terrestrial carbon (C) pool and related fluxes against the atmosphere are still poorly known where maximum C are stored as living biomass in the tropical forest (Pan et al., 2011). This is partly due to the uncertainty of the forest aboveground biomass (AGB) which is much greater in the tropics (Phillips and Lewis, 2014).

The relationship between productivity (AGB) and biodiversity has generated long interest in ecology about the processes regulating local diversity (Tilman et al., 1996). A positive relationship is commonly reported between productivity and diversity, and this relationship can be affected by community composition, resource levels (e.g., fertilizer) and disturbance (Adler et al., 2011; Mittelbach et al., 2001; Rosenzweig and Abramsky, 1993). In some cases, highly productive sites are known to be resource rich and species poor (Adler et al., 2011) and often lead to declines in the species richness relationships at high productivity.

Generally, forest AGB can be estimated through three available methods: model-based simulations (Landsberg and Waring, 1997), measurements from ground inventories (Malhi et al., 2002), and retrievals from satellite datasets (Saatchi et al., 2011a). Model-based simulation methods usually provide forest AGB estimations from local to global scales based on model inputs (e.g., radiation, climate surfaces and elevation) instead of the actual forest AGB distribution (Lu, 2006). Traditional forest inventory methods (e.g., direct harvest methods and indirect allometric modeling methods) which involve sample plot measurements can provide reliable information on biomass at local or regional scales (Chave et al., 2015). This approach of biomass measurement has been regarded as highly accurate; however, it involves high uncertainty primarily due to the use of allometric models from sample which are indirect measurements, when upscaled to plot or landscape scale (Chen et al., 2015). Furthermore, with the limited inventory plots in tropical forest, mapping of forest biomass has been

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carried out using interpolation techniques (Malhi et al., 2006).

Due to the nature of the sampling with low temporal repeat frequency and a small number of inventory plots, satellite data are often being combined with field measurements (Saatchi et al., 2011a). For example, satellite-based estimations have been shown to be similar to predictions derived from field estimates when averaging at large scales e.g., stand, landscape or even continental scale (Saatchi et al., 2011b) despite having differences with inventory biomass particularly in regions with few sampling sites. Compared with the model and forest inventory approaches, remote-sensing techniques significantly improve the efficiency of forest AGB mapping in areas that are difficult to access (Lu, 2006) with improved spatial and temporal coverage.

2. L-band radar based forest AGB estimation

Remote sensing signal received from forest canopy interactions behaves differently at optical and microwave wavelengths (Disney et al., 2006). For instance, signal scattering is predominantly controlled by the spectral reflectance, absorptance and transmittance properties of all green leaf material in the optical domain (i.e. wavelength ~0.4–0.7 µm for visible, up to ~1.4 µm in the NIR) due to biochemical and positional orientation of green materials. In the microwave domain (wavelength 0.1–50 cm), signal scattering is controlled by the size of canopy components (trunk, branches, leaves, needles), soil roughness and their dielectric constants (water content) to the incident wavelength, polarisation and incidence angles (Liang et al., 2005; Ulaby et al., 1990).

Active remote sensing based side-looking Synthetic Aperture Radar (SAR) data is extensively used in assessing forest biomass due to cloud insensitive and partly backscatter sensitivity to structural component (trunks, branches, leaves and needles) that forms the complex forest canopy (Woodhouse et al., 2012; Clark and Kellner, 2012). Wall-to-wall pan-tropical forest AGB derived from an integration of optical, radar and field measurements are available (Saatchi et al., 2011a; Baccini et al., 2012).

Several experimental and modelling studies have shown that SAR backscatter at longer L-band (~21 cm) wavelength is sensitive to forest characteristics, thus allowing the estimation of forest AGB (e.g. Ulaby et al., 1990; Liang et al., 2005; Mitchard et al., 2011; Saatchi et al., 2011b). Ulaby et al. (1990) identified seven components of radar backscatter of tree canopies, considering direct and diffuse scattering from ground and canopy components, as well as their interactions, depending on the microwave wavelength, incidence angles and polarizations (HH, VV, HV or VH, with H and V representing the horizontal and vertical transmit/receive polarization, respectively). The range of signal sensitivity to forest structure also depends on the canopy type (open to dense; homogeneity to complex) (Woodhouse et al., 2012), moisture content (Lucas et al., 2010) at spatial variability (Saatchi et al., 2011b). In all forest types, microwaves emitted at L-band are more sensitive to forest AGB due to deeper penetration and more interaction with the woody branches, trunks and ground surface than the twig and leaf contribution negligibly (Saatchi et al., 2011b). This has been largely related with the cross-polarized channels (HV), which have comparatively lower returns but generally increase asymptotically to the amount of woody biomass.

The first L-band observations at global scale were provided by the Japanese Earth Resources Satellite (JERS-1) SAR (1992–1998) at HH-polarization, while fully polarimetric (HH, HV) observations by the Advanced Land Observing Satellite/Phased Array L-band Synthetic Aperture Radar (ALOS-1/PALSAR-1: since 2006 and ALOS-2/PALSAR-2: since May 2014) sensors. PALSAR data were used to estimate AGB of forest plots from tropic forests in Africa, Asia and Australia (Table 1). It is also well-known that radar backscatter can saturate at low biomass levels; that is, above this biomass level a further increase of biomass causes no further increase of the backscattering intensity. Lower frequencies such as L-band is preferable as saturation emerges at higher biomass levels (Carreiras et al., 2012; Michelakis et al., 2015; Mitchard et al., 2009).

Amongst the different radar wavelengths, studies focusing on L-band data for forest structure and biomass characterization are extensively investigated due to long-term data availability from JERS-1, ALOS-1 and current ALOS-2 and positive correlation against field measured AGB. Several studies suggests that nonlinear regression is an appropriate method to fit the relationship between forest AGB and PALSAR backscatter coefficients with varying results (Englhart et al., 2011; Carreiras et al., 2012; Mitchard et al., 2011; Morel et al., 2011; Saatchi et al., 2011b). Sensitivities of forest biomass levels at L-band frequency have also been reported from different forest types, e.g. coniferous (Les Landes and Duke) and broadleaved evergreen (Hawaii) achieving around 40 Mg ha^{-1} and 100 Mg ha^{-1} saturation levels respectively (Imhoff, 1995). The saturation level using PALSAR Fine Beam HV polarization has been found to range between 88 and 150 Mg ha^{-1} (Morel et al., 2011), reaching up to more than 250 Mg ha^{-1} (Lucas et al., 2010), 400 Mg ha^{-1} (Englhart et al., 2011; Morel et al., 2011) and even 900 Mg ha^{-1} (Mitchard et al., 2009) (Table 1).

The L-band PALSAR mosaic data has been widely used for biomass retrieval at large −scale areas in different ecosystem: low biomass woody savanna of Cameroon (Mermoz et al., 2014), dense forest of Cameroon and Central African Republic (Mermoz et al., 2015), mangroves in Malaysia (Hamdan et al., 2014) and temperate mixed forests of Northeastern China (Ma et al., 2017). For instance, in the dense forest of Cameroon and Central African Republic having the forest biomass reaching up to 550 Mg ha^{-1} have found a saturation of signal attenuation up to 150 Mg ha^{-1} with HV polarization due to loss of signal in the higher biomass levels (Mermoz et al., 2015). Hamdan et al. (2014) have reported a saturation level of PALSAR mosaic HV-backscatter up to 100 Mg ha^{-1} biomass where high errors are associated when the AGB exceeded beyond 150 Mg ha^{-1} in the Matang Mangroves, Malaysia. In the temperate region of Northeastern China, PALSAR mosaic HV backscatter has shown sensitivity to forest biomass better for needleleaf (~160 Mg ha^{-1}) followed by mixed (~130 Mg ha^{-1}) and broadleaf (~100 Mg ha^{-1}) forests (Ma et al., 2017).

The sensitivity of L-band backscatter to forest structure, species richness and biophysical parameters of mixed deciduous forest of Western Himalayan region (India) having high woody biomass density has not been fully investigated. The main objective of this study was to estimate forest structure in particular forest biomass and validate forest AGB from L-band backscatter data from PALSAR mosaic 2007 acquisitions using field plot data at stand level. These L-band radar biomass maps were investigated using the Landsat and Lidar derived biomass map at 30 m resolution following the Baccini et al. (2012) methodology. The Michigan Canopy Scattering (MIMICS-I) radiative transfer model (Ulaby et al., 1990) was used to understand the radiative scattering processes at L-band in matured forest canopies with high biomass density.

3. Data and methods

3.1. Study area

Dudhwa National Park (DNP) (28° 18′- 28° 42′N, 80° 28′- 80° 57′E) is in the foothill plain of western Himalayan belt of Uttar Pradesh, India bordering Nepal (Fig. 1). Total park area is about 684 km^2. *Shorea robusta* forest dominate the landscape (as climax species) followed by semi-evergreen forest, moist deciduous forest, *Terminalia tomentosa* forest, *Acacia catechu-Dalbergia sissoo* forest and *Syzigium cumini* forest (Champion and Seth, 1968). The dominant understorey species in *S. robusta* forests include *Murraya koenigii*, *Tiliacora acuminata*, *Clerodendrum viscosum* and *Ichnocarpus frutescens*. Several stands of *Tectona-grandis*, *Eucalyptus hybrid*, *Dalbergiasissoo*, *Acacia catechu* and *Lagerstroemia parviflora* plantations are also found. For relating forest structure and AGB to L-band backscatter, the DNP was chosen based on