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Synergistic use of Landsat 8 OLI image and airborne LiDAR data for above-ground biomass estimation in tropical lowland rainforests

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ABSTRACT

Developing a robust and cost-effective method for accurately estimating tropical forest's carbon pool over large area is a fundamental requirement for the implementation of Reducing Emissions from Deforestation and forest Degradation (REDD+). This study aims at examining the independent and combined use of airborne LiDAR and Landsat 8 Operational Land Imager (OLI) data to accurately estimate the above-ground biomass (AGB) of primary tropical rainforests in Sabah, Malaysia. Thirty field plots were established in three types of lowland rainforests: alluvial, sandstone hill and heath forests that represent a wide range of AGB density and stand structure. We derived the height percentile and laser penetration variables from the airborne LiDAR and calculated the vegetation indices, tasseled cap transformation values, and the texture measures from Landsat 8 OLI data. We found that there are moderate correlations between the AGB and laser penetration variables from airborne LiDAR data ($r = -0.411$ to -0.790). For Landsat 8 OLI data, the 6 vegetation indices and the 46 texture measures also significantly correlated with the AGB ($r = 0.366$–0.519). Stepwise multiple regression analysis was performed to establish the estimation models for independent and combined use of airborne LiDAR and Landsat 8 OLI data. The results showed that the model based on a combination of the two remote sensing data achieved the highest accuracy ($R^2_{adj} = 0.81$, RMSE = 17.36%) whereas the models using Landsat 8 OLI data airborne LiDAR data independently obtained the moderate accuracy ($R^2_{adj} = 0.52$, RMSE = 24.22% and $R^2_{adj} = 0.63$, RMSE = 25.25%, respectively). Our study indicated that texture measures from Landsat 8 OLI data provided useful information for AGB estimation and synergistic use of Landsat 8 OLI and airborne LiDAR data could improve the AGB estimation of primary tropical rainforest.

1. Introduction

Tropical rainforests are among the largest terrestrial carbon reservoirs, as well as supporting some of the highest levels of biodiversity (Brown and Lugo, 1982; Huston and Marland, 2003; Saatchi et al., 2011). Conserving these biodiversity and carbon-rich habitats through reduction of deforestation and forest degradation is seen as an effective mitigation measure to combat climate change and conserve biodiversity (Imai et al., 2014). Under the United Nations Framework Convention on Climate Change (UNFCCC), there are ongoing negotiations to develop a mechanism to reduce emissions from deforestation and forest degradation, through conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+). Developing a robust and cost-effective method for accurately estimating carbon pool in tropical rainforests over large area is a fundamental requirement for the implementation of REDD + . Estimating above-ground biomass (AGB) is critical to quantify carbon stocks in the tropics since AGB of trees in tropical forests account for a significant part of the total carbon pool (Houghton et al., 2001).

AGB estimation in tropical forest involves field measurements which are time-consuming, costly and labor intensive. AGB estimation using remote sensing with field measurements is a cost-effective approach recommended for REDD+ (Stern, 2007). To date, spaceborne optical and radar data as well as airborne Light Detection and Ranging (LiDAR)

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data have been employed and analyzed to develop AGB estimation models in different types of forests at various scales (Gibbs et al., 2007, Koch, 2010). Several studies have demonstrated useful relationships between backscatters from spaceborne Synthetic Aperture Radar (SAR) data and AGB in tropical forests (Englhart et al., 2011, Morel et al., 2011, Saatchi et al., 2011), but it has been shown that the signal saturates at the high forest AGB, depending on wavelength (Balzter et al., 2007, Englhart et al., 2011, Mitchard et al., 2011). On the other hand, spaceborne optical data, especially Landsat data is probably the most frequently used medium spatial-resolution data in AGB estimation at local and regional scales (Sader et al., 1989, Roy and Ravan, 1996, Nelson et al., 2000, Foody et al., 2003, Phua and Saito, 2003, Lu, 2005, Kelsey and Neff, 2014, Karlson et al., 2015). The advantages of medium resolution satellite data are the acquisition cost, revisiting frequency and the broad spatial coverage. However, a critical limitation of AGB estimation from Landsat data and other medium-to-coarse spatial resolution multispectral images is that the estimation is heavily affected by the spectral saturation in high biomass forests (Dube et al., 2014; Ingram et al., 2005; Lu, 2006; Mutanga et al., 2012; Mutanga and Skidmore, 2004; Nichol and Sarker, 2011). Therefore, vegetation-index based approaches have achieved only limited success in tropical and subtropical regions where the forests have high AGB, associated with complex structure and dense canopy, as well as high species diversity (Foody et al., 2001; Lu, 2005; Nelson et al., 2000).

Recent studies of AGB estimation suggest the usefulness of texture variables rather than spectral vegetation indices (Wijaya et al., 2010; Kelsey and Neff, 2014; Dube and Mutanga, 2015a). Several studies have used texture measures derived from high-resolution satellite data. These have shown that image textural measures have the potential to improve the characterization of different forest types (Eckert, 2012; Nichol and Sarker, 2011; Pandey et al., 2010; Pinto et al., 2012; Sarker and Nichol, 2011). Image texture variables could provide a promising opportunity for capturing forest structural attributes and may help improve AGB estimation in tropical forests by compensating for spectral saturation (Lu, 2005; Kelsey and Neff, 2014). Although there are several studies that have successfully used the texture variables of high-resolution satellite data to estimate AGB in tropical forests (Proisy et al., 2007; Ploton et al., 2012; Pargal et al., 2017), the relationship between the texture measures from medium spatial resolution sensors and AGB has not been studied fully, especially when compared to raw spectral band information and vegetation indices (Dube and Mutanga, 2015a). More recently, Landsat 8 Operational Land Imager (OLI) data became available and it is assumed to provide better opportunities for understanding the contribution of forest ecosystems to the carbon cycle (Dube and Mutanga, 2015b). Compared to Landsat 7 ETM+, the newly-launched Landsat 8 OLI sensor exhibits several design improvements, including narrower near infrared wavebands, higher signal-to-noise ratio, and enhanced radiometric sensitivity. Recent studies suggest that the image texture measures from Landsat 8 OLI data show good potential in estimating AGB in Sudano-Sahelian woodland (Karlson et al., 2015) and in African plantation forest (Dube and Mutanga, 2015a). The challenging task for texture extraction in AGB estimation is how to identify suitable texture parameters together with the optimal window size (Lu, 2005; Dube and Mutanga, 2015a).

Although spectral information and texture measures derived from satellite images can be useful in AGB estimation, it does not capture the vertical height information of forest canopy. Forest canopy height is the 3-dimensional determinant of AGB of a forest (Asner et al., 2012b). Forest canopy height can be derived from active remote sensing systems (Brown, 2002; Lu, 2006; Mitchard et al., 2009). Several attempts have been made to estimate forest canopy height using synthetic aperture radar (SAR) (Köhler and Huth, 2010; Saatchi et al., 2011). The bistatic TanDEM-Xmission acquires multiple globally consistent single-pass interferometric datasets to create global digital elevation model (Krieger et al., 2007). Recent studies have attempted to estimate forest canopy height from the interferometric coherence analysis of the TanDEM-X mission data. However, it is likely that the inherent limitation of penetration into dense forest canopy still remains and therefore saturation problems at higher AGB level are expected (Kugler et al., 2014). Although, Minh et al. (2016) had improved AGB estimates for tropical forests in French Guiana using an airborne tomographic SAR approach.

Airborne LiDAR is widely recognized as a remote sensing technology that is capable of acquiring very accurate data on forest canopy and terrain height. LiDAR has been used successfully to estimate forest AGB in various regions including in the tropics without saturation problems (e.g., Zhao et al., 2009; Drake et al., 2003; Asner et al., 2012b; Ioki et al., 2014; Phua et al., 2016; Coomes et al., 2017). Although airborne LiDAR data can provide highly accurate AGB estimation, it is possible that inclusion of an additional independent source of data that correlates with forest structure or other biophysical properties can further improve its ability to estimate AGB. Several studies have investigated the combined use of airborne LiDAR data and multispectral remotely sensed data for estimating AGB and other forest biophysical properties in boreal or temperate forests (Popescu et al., 2004, Hyde et al., 2006, Takahashi et al., 2010; Dalponte and Coomes, 2016). However, the performance of the integrated use of the airborne LiDAR and Landsat 8 OLI data for AGB estimation has yet to be examined in tropical forests. Considering the ability of the image texture measures from Landsat 5 and Landsat 7 images, synergistic use of airborne LiDAR and multispectral satellite data for estimating AGB deserves further attentions. This study aims to examine the independent and combined use of airborne LiDAR and the widely-available Landsat 8 OLI data to accurately estimate the AGB of tropical lowland rainforests in the Sepilok Forest Reserve (SFR), Sabah, Malaysia. SFR is a protection forest reserve that contains three distinctive types of lowland tropical forests: alluvial, sandstone hill and heath forests that represent a wide range of AGB density and stand structure (Nilus et al., 2011). Therefore, it provides an attractive opportunity to evaluate the performance of the derived variables from each remote sensing data across different types of tropical lowland rainforests.

2. Materials and methods

2.1. Study area

The study area, SFR, is located at Sandakan, Sabah (5°10′N, 117°56′E) (Fig. 1). SFR is a primary lowland tropical forest of 4294 ha in area under the protection of the Sabah Forestry Department. Sandakan receives an average annual rainfall of about 2400 mm throughout the year and has a mean annual temperature of 27.3 °C (Malaysia Meteorological Service Monthly Report, unpublished data).

The SFR consists of three different forest types: alluvial, sandstone hill and heath (Kerangas) forests (Fox, 1973). The alluvial forest is dominated by large dipterocarp trees: the most abundant species in this forest type include *Parashorea tomentella* and *Shorea johorensis*. For the sandstone hill forest, the most abundant tree species are *Shorea multiflora*, *Shorea beccariana* and *Dipterocarpus acutangulus*. The heath forest is dominated by *Tristaniopsis merguensis* (Nilus et al., 2011).

2.2. Field data collection

A total of 30 plots were established within SFR from May 2013 to May 2015. Plot size varied according to differences in tree height within the different forest types. We established 50 m × 50 m plots in the alluvial forest and 30 m × 30 m plots in the heath and sandstone hill forests. Within the plots, the diameter at breast height (DBH) and tree height were measured for all trees having a DBH greater than 10 cm. Crown diameter were recorded only for 10 alluvial, 3 heath, 3 sandstone hill forest plots. The plot coordinates were determined by post-processing of differential GNSS (DGNSS) data using Javad Triumph-1 (JAVAD GNSS, San Jose, CA, USA). Of the 30 plots, 12 plots were located within the alluvial forest, 9 plots in the sandstone hill