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Estimating above-ground biomass of tropical rainforest of different degradation levels in Northern Borneo using airborne LiDAR

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ABSTRACT

Deforestation and degradation of forests have severely depleted carbon storage in tropical countries, whose forests have the most carbon-rich ecosystems in the world. Estimating above-ground biomass (AGB) with high accuracy is critical to quantifying carbon stocks in the tropics. We propose a model to estimate AGB in the tropical montane forests of northern Borneo with different disturbance histories using airborne LiDAR data. The level of forest degradation was determined from species composition and field-observed AGB. Of 50 sample plots established in forests with various levels of degradation, we categorized 20 as highly degraded (AGB: 52.18–229.11 Mg/ha), 16 as moderately degraded (AGB: 136.00–382.59 Mg/ha), and 14 as old-growth forest (AGB: 280.31–622.79 Mg/ha). Height metrics and laser penetration rate (LP) at specific heights from the ground were derived from vertical point profiles of LiDAR data. After testing the performance of single variables, we used stepwise multiple regressions to select variables to include in the model for AGB estimation. The best model with a single variable used the mean height from the laser returns ($R^2 = 0.78$, RMSE = 65.54 Mg/ha). All LP variables were sensitive to AGB ($R^2 > 0.60$). The final model from stepwise analysis included the mean height of the canopy height model and LP at 7 m height (adjusted $R^2 = 0.81$, RMSE = 61.26 Mg/ha). The results confirm the suitability of LP variables for estimating AGB. We suggest that airborne LiDAR data can capture AGB variability at fine spatial scales, which correspond to deforestation and forest degradation caused by human activities and natural disturbances.

1. Introduction

Tropical forests in Southeast Asia have declined acutely over the past several decades (Achard, 2002; Stibig and Malingreau, 2003; Laurance, 2007). In particular, Borneo, long recognized as a biodiversity hotspot, has lost a third of its forest in less than 25 years (Rautner et al., 2005), with a deforestation rate between 2002 and 2005 of 1.7% per year (Langner et al., 2007). This has led to a severe decline in the carbon storage of Borneo's forests, which ranked among the highest carbon densities of tropical forests (Slik et al., 2010). The main causes of rapid loss and degradation of forests are human activities such as commercial logging, conversion to agricultural land, and forest fires, which are commonly attributed to shifting cultivation (Langner et al., 2007).

REDD+ (Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) is the framework for conserving and enhancing carbon stocks of forested areas in the tropics (UNFCCC, 2007). For REDD+ implementation, accurate estimation and monitoring of carbon stocks are required at the national and subnational scale. To establish robust and transparent monitoring systems, a combination of remote sensing and ground-based inventory approaches is recommended (UNFCCC, 2009). Above-ground biomass (AGB) of trees in tropical forests account for a significant part of the total carbon pool (Dixon et al., 1994; Houghton et al., 2001). Therefore, estimating AGB is critical to quantify carbon stocks in the tropics (Gibbs et al., 2007).

Estimating AGB from remote sensing data in tropical forests is challenging due to their complex forest structure, dense canopy,

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and cloud coverage (Gibbs et al., 2007; Olander et al., 2008). Satellite-mounted optical sensors have been widely used to estimate AGB (Asner et al., 2002; Anaya et al., 2009). However, optical sensors acquire information from the upper canopy and are unable to measure the three-dimensional structure, including canopy height and sub-canopy topography (Lu, 2006), which limits their use to quantify AGB in tropical forests as their canopy structures are complex. Remote radar sensors (e.g., ALOS/PARSAR) use microwave or radar signals to measure forest vertical structure (Gibbs et al., 2007) and can penetrate clouds. Radar sensors can be used for relatively young or homogeneous forests, but their accuracy and sensitivity decrease in old-growth forests (Lu, 2006).

Light detection and ranging (LiDAR) emits laser pulses and measures the return time to directly estimate the height and vertical structure of forests (Dubayah and Drake, 2000; Lefsky et al., 2002). LiDAR data can be acquired at high sampling density with excellent geometric accuracy (Reutebuch et al., 2005; Mallet and Bretar, 2009). Such advantages can reveal AGB variability at fine spatial scales. This is important because deforestation and forest degradation caused by human activities and natural disturbances often occur on small scales (Houghton, 2005). Thus, LiDAR can bridge the gap between satellite observations and field measurements (Asner, 2009).

Several attempts at estimating AGB and other biophysical properties have beelinen made using LiDAR sensors in tropical regions. Drake et al. (2002a,b, 2003) successfully estimated AGB in Panama and Costa Rica with a large-footprint (25-m diameter), full-waveform LiDAR (laser vegetation imaging sensor). These studies show the usefulness of height metrics derived from the waveform. The most common type of LiDAR sensor, airborne small-footprint LiDAR, has wide commercial support (Wulder et al., 2012). Asner et al. (2012a) examined the effectiveness of the extracted mean canopy height to estimate AGB in Panama, Peru, Madagascar, and Hawaii. Kronseder et al. (2012) and Jubanski et al. (2013) tested the applicability of LiDAR derived metrics for the estimation of AGB in a lowland dipterocarp forest and a peat swamp forest in Central Kalimantan. They concluded that AGB in tropical regions could be estimated when height-related statistical variables were used. However, other variables from LiDAR returns have not been fully explored. In addition, most studies in tropical forests have been conducted on flat terrains, and few have estimated AGB on tropical mountains (Asner et al., 2012b).

The objective of this study is to assess the applicability of commercial small-footprint LiDAR for AGB estimation in mountainous rainforest in Sabah, Malaysian Borneo. The study site includes a wide range of forest degradation levels due to different human disturbance histories.

2. Materials and methods

The Modeling approach used in this study is area-based and we developed regression models relating the spatial distribution of LiDAR returns within a plot area. This area-based approach is considered to be appropriate when the vertical structure of the forest is complex (Reutebuch et al., 2005) and it has been applied in a wide range of forest types (e.g., Næsset, 1997, 2002; Magnussen and Boudewyn, 1998; Means et al., 2000; Popescu et al., 2004).

2.1. Study area

The study was conducted in the region of Ulu Padas, southwest Sabah, Malaysia, adjacent to the borders of Sarawak and East Kalimantan, Indonesia (4°23–27′N, 115°42–47′E; Fig. 1). The region lies in the transition zone of lowland and montane forests at around 1000–1800 m above sea level. The topography is characterized by generally steep and hilly terrain; most slopes are >20°, and only the lower hills around the floodplains are <15°. Total annual rainfall is estimated at 2000–3500 mm (Ministry of Tourism, Sabah, unpublished). The targeted area is state owned and is available for use as a common resource under native customary rights or applications for land title (McMorrow and Talip, 2001). Forest reserves are licensed to Sabah Forest Industries Sdn. Bhd. (SFI). We established two study sites: Site 1 (2 km × 8 km), close to the village of Long Mio, and predominantly state land; and Site 2 (5 km × 2.5 km), mostly SFI compartments. Since there was scarce information of land use on the state land, we interviewed villagers of Long Mio and Long Pasia on site. The villagers have used the land for shifting cultivation and occasional selective logging. Some areas were logged in 1993–1994 and 2005–2006 by local timber companies. The SFI concession area has been extensively logged since 1999 using a conventional logging technique. Both former logged-over areas and shifting cultivation areas are in the state of natural regeneration.

2.2. Field measurements

Field data was collected at both sites from October 2011 to October 2012. We established 50 square plots: 48 plots of 30 m × 30 m and 2 plots of 20 m × 20 m; the smaller plots were set up in degraded secondary stands with a tree height of <20 m. In each plot, we measured diameter at breast height (DBH) and tree height, and identified the species of all trees with DBH $\geqslant$ 10 cm. Voucher specimens collected from the trees that could not be identified *in situ* were identified by an expert taxonomist at the Herbarium, Forest Research Centre, Sabah Forestry Department, Sandakan. More than 300 species were found, including *Lithocarpus* spp. (Fagaceae), *Litsea* spp. (Lauraceae), and *Syzygium* spp. (Myrtaceae). The disturbed forests consist mainly of pioneer trees such as *Macaranga* spp. (Euphorbiaceae) and *Ficus* spp. (Moraceae). The location of all plots were determined by differential GPS (Global Positioning System), which collects GPS and GLONASS observations (Ashtech ProMark 100, Spectra Precision, Westminster, CO, USA, and Triumph-1, Javad GNSS, San Jose, CA, USA). The base station was established within Site 1 with a differential correction against a reference point registered by the Department of Survey and Mapping Malaysia in Kampong Long Pasia. Rover receivers were set up in each plot.

AGB was calculated with allometric equations developed by Yamakura et al. (1986) from a lowland forest in East Kalimantan, Indonesian Borneo. Dry weights per tree by stem (w_S), branch (w_B), and leaf (w_L) were determined and summed for each tree as:

$$w_S = 2.903 \times 10^{-2}(D^2H)^{0.9813}$$

$$w_B = 0.1192 w_S^{1.059}$$

$$w_L = 9.146 \times 10^{-2}(w_S + w_B)^{0.7266}$$

where D is DBH (cm) and H is tree height (m).

2.3. Determination of forest degradation level

Field data was collected in plots with different disturbance histories attributed to human activities. Tree community similarity, calculated by using species composition is a robust metric of the response of tree assemblage to anthropogenic disturbance (Imai et al., 2012; Ding et al., 2012). Therefore, to determine the forest degradation level of each plot, we performed permutational multivariate analysis of variance to test differences in tree community composition, using the "adonis" function in the "vegan" package (Oksanen et al., 2013) in R software, v. 3.0.1 (R Development