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Assessing the influence of return density on estimation of lidar-based aboveground biomass in tropical peat swamp forests of Kalimantan, Indonesia

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A B S T R A C T

The airborne lidar system (ALS) provides a means to efficiently monitor the status of remote tropical forests and continues to be the subject of intense evaluation. However, the cost of ALS acquisition can vary significantly depending on the acquisition parameters, particularly the return density (i.e., spatial resolution) of the lidar point cloud. This study assessed the effect of lidar return density on the accuracy of lidar metrics and regression models for estimating aboveground biomass (AGB) and basal area (BA) in tropical peat swamp forests (PSF) in Kalimantan, Indonesia. A large dataset of ALS covering an area of 123,000 ha was used in this study. This study found that cumulative return proportion (CRP) variables represent a better accumulation of AGB over tree heights than height-related variables. The CRP variables in power models explained 80.9% and 90.9% of the BA and AGB variations, respectively. Further, it was found that low-density (and low-cost) lidar should be considered as a feasible option for assessing AGB and BA in vast areas of flat, lowland PSF. The performance of the models generated using reduced return densities as low as 1/9 returns per m^2 also yielded strong agreement with the original high-density data. The use model-based statistical inferences enabled relatively precise estimates of the mean AGB at the landscape scale to be obtained with a fairly low-density of 1/4 returns per m^2, with less than 10% standard error (SE). Further, even when very low-density lidar data was used (i.e., 1/49 returns per m^2) the bias of the mean AGB estimates were still less than 10% with a SE of approximately 15%. This study also investigated the influence of different DTM resolutions for normalizing the elevation during the generation of forest-related lidar metrics using various return densities point cloud. We found that the high-resolution digital terrain model (DTM) had little effect on the accuracy of lidar metrics calculation in PSF. The accuracy of low-density lidar metrics in PSF was more influenced by the density of aboveground returns, rather than the last return. This is due to the flat topography of the study area. The results of this study will be valuable for future economical and feasible assessments of forest metrics over large areas of tropical peat swamp ecosystems.

1. Introduction

Peat swamp forests (PSF) have been recognised as important forest ecosystems due to their large capacity for terrestrial carbon storage (Page et al., 2011). However, an enormous amount of carbon is emitted when PSF are cleared, degraded or converted to agricultural land (Miettinen et al., 2012). High emissions also result from peat decomposition (Hergoualc'h and Verchot, 2014; Hooijer et al., 2006) and peat land fires (Page et al., 2002). Page et al. (2002) estimated that approximately 0.9 gigatons of carbon was emitted from peat fires in 1997. The figure was far greater than Indonesia's annual emissions from deforestation and forest degradation from 2000 to 2012 (MoEF, 2015). In recent decades, PSF in South East Asia have contributed the largest portion of global greenhouse gas (GHG) emissions from the land use, land use change and forestry (LULUCF) sector (Murdiyarso et al., 2010). The majority of such emissions come from peat soil oxidation due to fires; however, the loss of aboveground primary vegetation plays a crucial role in increasing the likelihood of the occurrence of fires (Siegert et al., 2001). Despite their critical role in climate change mitigation,

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estimates of emission factors from PSF in Indonesia remain scarce and are far from accurate (MoEF, 2015).

Due to a combination of factors, including limited studies at the landscape scale, reliance on low-resolution remotely-sensed data and the absence of locally-developed tree biomass models, global-scale aboveground biomass (AGB) estimates for tropical forests have generally had high levels of uncertainty (Houghton et al., 2012). A review of previous studies showed high levels of variability in the AGB estimates within Indonesian PSF mainly due to limited sample sizes (MoEF, 2015). Establishing plots within PSF of Indonesia is logistically difficult and labour intensive; thus, field studies are expensive and spatially limited. Consequently, there has been strong interest in the use of remote sensing to decrease the costs and increase the efficiency of forest assessments and monitoring in Indonesian PSF.

Tools such as radar and high-resolution optical satellite imagery have been used to support forest inventory in PSF; however, the results of previous studies, particularly, in terms of predictive power, were not favourable (Englhart et al., 2011; Hirata et al., 2014; Schlund et al., 2015). For example, the coefficients of determination (R^2) (a statistical measure of the strength of the regression relationship between remote sensing metrics and AGB measurements) have been found to range from 0.5 to 0.65. Conversely, studies using airborne lidar system (ALS) yielded significantly more precise estimates of AGB in PSF with R^2 values of lidar derived metrics and AGB that range from 0.77 to 0.88 (Englhart et al., 2013; Jubanski et al., 2012).

However, compared to satellite-based remote sensing technologies, the costs associated with ALS acquisitions are relatively high; for example, at a small scale, the overall cost of ALS can approach that of ground measurements for a forest stand assessment (Hummel et al., 2011). Given that the largest component of the costs of a lidar acquisition is aeroplane flight time, it is more economical to acquire lidar by having an aircraft fly higher and faster; however, all other things being equal, this results in a lidar point cloud that has a lower return density (and thus poorer spatial resolution). Flying at a higher altitude not only affects reduced return density and intensity, but also increases footprint size. Footprint size may affect the accuracy of individual tree measurements (Andersen et al., 2006); however, it has an insignificant effect on area-based forest metrics assessments (Goodwin et al., 2006; Næsset, 2004).

Studies assessing the effect of return density on the accuracy of lidar derived forest metrics have mostly been conducted in temperate and boreal regions (Gobakken and Næsset, 2008; Jakubowski et al., 2013; Magnusson et al., 2007; Singh et al., 2015; Watt et al., 2014), but have been limited to tropical regions (Hansen et al., 2015). In mountainous regions, the use of low-density lidar should be avoided due to potentially large errors in the terrain model that can have deleterious effects on the accuracy of canopy height metrics (Leitold et al., 2015). However, it should be noted that other studies conducted in areas of complex topography have shown that highly accurate inventory estimates can be obtained using relatively low return densities (i.e., 1–2 returns per m^2 for biomass (Jakubowski et al., 2013) and 2–3 returns per m^2 for timber volume (Watt et al., 2014). Further, Ruiz et al. (2014) found that reducing return density to 1/4 returns per m^2 continued to provide good estimates of AGB in a steep terrain, suggesting that the size of field plots was crucial to the development of lidar metric models.

The majority of previous lidar studies have used direct canopy height metrics (Drake et al., 2003; Jubanski et al., 2012) and canopy height-related statistical metrics (d'Oliveira et al., 2012; Singh et al., 2015) to develop predictive models for forest inventory parameters. Such models have been shown to be more accurate in less-diverse temperate forests (Lefsky et al., 2005) than tropical forest regions (Andersen et al., 2014; Asner and Mascaro, 2014). A number of recent studies have explored the use of return proportion-related parameters (Ioki et al., 2014; Sheridan et al., 2014) and developed multivariate models that include the return proportion at 20–25 m height as an independent variable; however, the performance of these models was no better than that obtained using mean aboveground height parameters (Ioki et al., 2014). This type of model could be suitable for areas dominated by less disturbed forests, but is not suitable for areas characterised by a wide range of degraded conditions and succession levels.

The overall objective of this study was to demonstrate the ability of ALS in AGB estimation and mapping in large area of degraded tropical PSF in Central Kalimantan, Indonesia. The specific objectives of the study were to: identify the best AGB and basal area (BA) models using canopy height-related and return proportion parameters at various return density levels; assess the sensitivity of lidar metrics associated with reduced return densities; and estimate AGB levels for a large peat swamp area, using a model-based estimation/inferential framework. It appears that this study was the first to assess the effect of lidar return density on the estimation of AGB in tropical PSF.

2. Materials and methods

2.1. Study site

The study site was the former Kalimantan Forest Carbon Partnership (KFCP) project area, located in the Ex-Mega Rice Project (EMRP) in peat land of Central Kalimantan Indonesia (114° 23.5′–114° 40.3′ E; 1° 56.0′ to 2° 30.1′ S) (see Fig. 1). The KFCP boundary encompasses 123,608 ha of tropical PSF with a range of degradation levels. The topography of the area is very flat with elevations of 1–20 m above sea level and slope less than 0.1%. Peat dome fringes have their lowest elevations near riverbanks, but these elevations slowly increase as they approach the center of the dome.

From 2003 to 2010, the mean annual rainfall was 2900 mm (Ichsan et al., 2013) and the dry seasons (in which the monthly rainfall was less than 200 mm) were from June to September. From the 1970s to the 1990s, large concessionaires selectively logged the forest and small scale illegal logging continues today. Forests with a high variation of succession and high degradation levels dominated the northern part of the study site. The forests were dominated by non-dipterocarp species, including *Combretocarpus rotundatus, Campnosperma coriaceum, Tetractomia obovatum* and *Palaquium cochleariifolium.* The dominant tree species from dipterocarp family included *Shorea teysmaniana* and *Shorea balangeran*. Conversely, as a result of logging, land clearing and frequent fires, the southern part of the study site was covered by shrubs, ferns or grasslands (Graham et al., 2014) (see Fig. 2).

The tropical PSFs in Borneo occur in peat soil which developed from the accumulation of dead vegetation in a waterlogged environment since more than 30,000 years ago (Page et al., 2004). PSFs are considered to be the highest carbon stock ecosystem but lower in biodiversity and productivity, than the neighbouring lowland dipterocarp forests. The soil nutrient deficiency and acidity are increased toward the center of the dome, where the peat is deeper, providing a limiting factors for vegetation to grow. Thus, only low pole trees could grow in the peat dome center, commonly dominated by *Combretocarpus* sp and *Dacrydum* sp (Morley, 1981). In contrast, primary PSFs grow in the fringe of the dome harbour large emergent and commercial trees such as *Shorea spp* from dipterocarp family, *Agathis sp*, *Koompassia sp*, *Palaquium sp* and *Gonystylus bancanus* with maximum tree height between 40 and 45 m (Anderson, 1963; Page et al., 1999) (see Fig. 2).