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Integrating Airborne LiDAR and Terrestrial Laser Scanner forest parameters for accurate above-ground biomass/carbon estimation in Ayer Hitam tropical forest, Malaysia

Muluken N. Bazezew[a,*], Yousif A. Hussin[b], E.H. Kloosterman[b]

[a] Department of Natural Resources, College of Agriculture and Natural Resources, Dilla University, P.O. Box 419, SNNPE, Dilla, Ethiopia
[b] Department of Natural Resources, Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, 7500 AE Enschede, The Netherlands

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ABSTRACT

Parameters of individual trees can be measured from LiDAR data provided that the laser points are dense enough to distinguish tree crowns. Retrieving tree parameters for above-ground biomass (AGB) valuation of the complex biophysical tropical forests using LiDAR technology is a major undertaking, and yet needs vital effort. Integration of Airborne LiDAR Scanner (ALS) and Terrestrial Laser Scanner (TLS) data for estimation of tree AGB at a single-tree level has been investigated in part of the tropical forest of Malaysia. According to the complete tree-crown detection potential of ALS and TLS, the forest canopy was cross-sectioned into upper and lower canopy layers. In a first step, multiresolution segmentation of the ALS canopy height model (CHM) was deployed to delineate upper canopy tree crowns. Results showed a 73% segmentation accuracy and permissible to detect 57% of field-measured trees. Two-way tree height validations were executed, viz. ALS-based upper and TLS-based lower canopy tree heights. The root mean square error (RMSE) for upper canopy trees height was 3.24 m (20.18%), and the bias was −1.20 m (−7.45%). For lower canopy trees height, RMSE of 1.45 m (14.77%) and bias of 0.42 m (4.29%) were obtained. In a second step, diameter at breast height (DBH) of individual tree stems detected from TLS data was measured. The RMSE obtained was 1.30 cm (6.52%), which was as nearly accurate as manually measured-DBH. In a third step, ALS-detected trees were co-registered and linked with the corresponding tree stems detected by TLS for DBH use. Lastly, an empirical regression model was developed for AGB estimated from a field-based method using an independent variable derived from ALS and TLS data. The result suggests that traditional field-methods underestimate AGB or carbon with the bias −0.289 (−3.53%) Mg, according for approximately 11%. Conversely, integrative use of ALS and TLS can enhance the capability of estimating more accurately AGB or carbon stock of the tropical forests.

1. Introduction

The concern about global climate change has highlighted the need to find efficient and more accurate ways of estimate forest carbon at national, continental and global scale. Estimating biomass is essential for improved understanding of the carbon cycle because forest ecosystems serve as main reservoirs of terrestrial carbon (Garcia et al., 2010). Reliable auditing of forest biomass or carbon stock changes over time has an environmental and economic gain when a country is involved in the context of climate change issues of the United Nations Framework Convention on Climate Change (UNFCCC). Quantification of forest carbon sequestration offers a comprehensive understanding of the biogeochemical processes such as the vegetation responses towards atmospheric carbon emissions from anthropogenic activities (Houghton, 2005). A number of forest above-ground biomass (AGB) or carbon stock estimating methods are currently being implemented. A review by Lu (2006) showed that the use of traditional field-based, geographic information systems, and earth observation data are common approaches.

In the complex biophysical environment of the tropical forests, practical experiences have shown that measuring carbon stock is difficult and often rife with uncertainties. Such uncertainties have derived from tree parameters retrieval, fundamentally associated with height and diameter at breast height (DBH) estimates (Larjavaara and Muller-Landau, 2013). Principally, individual tree height measurements using traditional field-based methods are associated with high uncertainties due to structural nature of tropical forests which makes it difficult to see treetops. A growing need for spatially-explicit mapping and more

* Corresponding author.
E-mail addresses: mulukenn@du.edu.et (M.N. Bazezew), y.a.hussin@utwente.nl (Y.A. Hussin), e.h.kloosterman@utwente.nl (E.H. Kloosterman).

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accurate estimating of forest carbon is currently being partly compensated by the recent advanced earth observation technologies. Particularly, Light Detection and Ranging (LiDAR) technologies such as Airborne LiDAR or Airborne Laser Scanner (ALS) and Terrestrial Laser Scanner (TLS) are capable of directly measuring basic vegetation inventory parameters with a high accuracy. The use of these laser technologies is becoming a primary choice for remotely sensed forest AGB as compared to optical remote sensors that have saturation problem in spectral responses to dense canopies with high biomass. Several studies have confirmed that ALS and TLS offer highly accurate basic tree parameters, such as height, DBH, crown area and individual tree position through target scanning with laser pulses (e.g. Hyyppa et al., 2012; Ramirez et al., 2013; Ferraz et al., 2016).

In recent years, the use of ALS technology to measure biophysical structures of the forest has been rapidly growing. The method is based on ALS range measurements from aircraft and the accurate orientation of the measurements between a sensor position and the reflecting object using differential global positioning system (GPS) and an inertial measurement unit (IMU) where the position of x, y and z is defined. ALS measures the vertical structure of forests by determining the distance between the sensor and a target through the use of time measurements between the emitted pulses from the sensor and the time of reflected light from the target. The resulting georeferenced point cloud data allows for computation of a digital terrain model (DTM), digital surface model (DSM) and canopy height model (CHM) or normalized DSM (nDSM). This technique makes it possible to automatically define individual tree crowns. Using the CHM, individual tree crown delineations can be done by region growing segmentation (Carleer et al., 2005), spatial wavelet analysis (Falkowski et al., 2006), segmentation of voxels or clustering into three-dimensions (Reitberger et al., 2009; Gupta et al., 2010), or by fitting cone-shaped objects through Hough transform (Leeuwen et al., 2010). A single tree analysis utilizing ALS data can offer a highly accurate tree height, and can also develop statistical models to estimate other variables such as DBH and stem volumes. For instance, Andersen et al. (2006) have indicated that tree height accuracy of 0.02 ± 0.73 m can be achieved from ALS data, while Yamamoto et al. (2011) and Kronseder et al. (2012) have also confirmed that ALS technology can assess tree height more accurately and efficiently than the field-methods.

Terrestrial Laser Scanner (TLS) is an active remote sensing technique that can offer highly accurate three-dimensional (3D) point cloud data consisting of distance measurements of the transmitted laser pulses from the scanner to the surrounding surface, and analyse the returned energy as a function of time. The raw of scan dataset contains a huge number of laser points, and it is essential for accurate recognition of objects in order to estimate forest characteristics. Sample plots can be measured in a single or multiple-scanning mode. Single-scanning mode offers the lower capability for 3D reconstruction of individual tree trunks, due to occlusions. Multiple-scanning mode results highly detailed reconstruction of individual tree trunks, which requires coregistration of the scanning positions into one reference point. The common ways to estimate tree height, stem diameters and positions from TLS data is using either the Hough transform or manual detection (Hopkinson et al., 2004), cylindrical fitting (Bienert et al., 2006) or to fit a circle along tree stems using least square regression (Henning and Radtke, 2006). The applications of TLS point cloud data has been studied in the following forest applications: accuracy of forest parameters measurement (e.g. Loudermilk et al., 2009; Moskal and Zheng, 2012), tree location accuracy (e.g. Liang et al., 2012; Kankare et al., 2013), reconstruction of a tree stem and biomass estimation (e.g. Kaasalainen et al., 2014). In general, these studies have confirmed that TLS allows for highly accurate measurements of important tree characteristics such as DBH, height, and location.

Determination of AGB requires accurate delineation and measurement of individual tree stems and heights. These measurements are time-consuming, especially in multiple-canopied tropical forests. Accurate field-based measurements can only be achieved through destructive methods. ALS and TLS-based technique form 3D point cloud data for the individual tree in which accurate statistical and geometrical characteristics can be computed. However, these techniques encounter limitations regarding the capacity of treetop and stem detection related to the size of LiDAR footprint, the density of the laser return points, the scan angle, and the complexity nature of the forests. The ALS instrument fails to recognize significant features of the lower canopy trees as the laser points obscured by the upper canopy tree crowns. The studies of Clark et al. (2004) and Hilker et al. (2010) have confirmed that ALS provides accurate treetops detection and crown projection area (CPA) under a wide range of canopy conditions. Similarly, TLS data can be used for highly accurate tree stem and lower canopy tree height measurements up to the angle of view of the sensor where blocking of the laser point with tree crowns is minimal. Henning and Radtke (2006) prove that TLS offers DBH measurements with an error not exceeding 1 cm, and height accuracy of < 2 cm from a height of trees up to 13 m. Autonomous use of TLS in a tropical forest gives high uncertainties of higher tree height measurements in a multiple-canopies structure where large trees and interlocking branches make it difficult for the instrument to view treetops.

Subsequently, in the circumstance of the complex biophysical structure of the tropical rainforests, integrative use of ALS and TLS provides a possibility of detecting trees under different canopy condition for more accurate tree parameter measurements. ALS and TLS have been combined to estimate canopy structure of the forest at a plot level (Hilker et al., 2010). In the present study, ALS and TLS are integrated at a tree level. One of the few studies where ALS and TLS are integrated at a tree level is Lindberg et al. (2012) who found that about one-third of trees detected from TLS could possibly link to ALS-detected trees. Integrative use of ALS and TLS data requires co-registration of the data sources. Trees identified from ALS data were then connected to TLS-detected tree stems for DBH use. To link trees detected from ALS and TLS data with the corresponding trees in the field, tree position, tree-labeling and stem attributes measured in the field are required since GPS positions of trees measured under canopy layers are less accurate.

The main objective of this study is to develop an approach for more accurate estimation of AGB and carbon stock through integrating ALS and TLS-derived forest parameters in Ayer Hitam tropical rainforest of Malaysia. Specifically, among the objectives presented from this processing-chain: (1) evaluation of ALS-CHM region growing segmentation for treetops delineation, (2) comparison of the accuracy of a single tree level manual field-based height when trained with ALS and TLS-measurements of the corresponding canopy trees, (3) validation of DBH derived from TLS data against manual measurements, and (4) comparison of AGB and carbon stock estimated from remotely sensed (ALS + TLS) data and traditional field-based methods.

2. Materials and methods

2.1. Study area

The study was carried out in the Ayer Hitam tropical rainforest reserve located in Selangor State, Petaling District of Malaysia (3°0′0″ to 3°2′0″ latitude and 101°38′0″ to 101°40′0″ longitude) (Fig. 1). Elevation within the study area ranges from 15 to 233 m a.s.l. The annual average temperature ranges from 23 to 32°C. The area has high rainfall distribution throughout the year with an annual average precipitation of 1, 765 mm, and mostly higher precipitation occurs from October to February. The area is also characterized by relatively high average monthly humidity ranging from 94 to 97%. The forest was selectively logged frequently from 1936 to 1965, and at present, it covers 1248 ha. It is the only natural lowland forest left in Putrajaya area and is leased by the University of Putra Malaysia (UPM) since 1990 to be used for education and research purpose in the field of forestry. The vegetation throughout the study site is dominated by Dipterocarpaceae, which