Int J Appl Earth Obs Geoinformation 65 (2018) 105–113

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Research Paper

Influence of micro-topography and crown characteristics on tree height estimations in tropical forests based on LiDAR canopy height models

Cici Alexander[a,b,*], Amanda H. Korstjens[a], Ross A. Hill[a]

[a] Department of Life and Environmental Sciences, Bournemouth University, Talbot Campus, Poole, Dorset, BH12 5BB, United Kingdom
[b] Aarhus Institute of Advanced Studies (AIAS), Aarhus University, DK-8000 Aarhus C, Denmark

ARTICLE INFO

Keywords:
Airborne laser scanning
Tree delineation
ITC
Forestry
REDD

ABSTRACT

Tree or canopy height is an important attribute for carbon stock estimation, forest management and habitat quality assessment. Airborne Laser Scanning (ALS) based on Light Detection and Ranging (LiDAR) has advantages over other remote sensing techniques for describing the structure of forests. However, sloped terrain can be challenging for accurate estimation of tree locations and heights based on a Canopy Height Model (CHM) generated from ALS data; a CHM is a height-normalised Digital Surface Model (DSM) obtained by subtracting a Digital Terrain Model (DTM) from a DSM. On sloped terrain, points at the same elevation on a tree crown appear to increase in height in the downhill direction, based on the ground elevations at these points. A point will be incorrectly identified as the treetop by individual tree crown (ITC) recognition algorithms if its height is greater than that of the actual treetop in the CHM, which will be recorded as the tree height. In this study, the influence of terrain slope and crown characteristics on the detection of treetops and estimation of tree heights is assessed using ALS data in a tropical forest with complex terrain (i.e. micro-topography) and tree crown characteristics.

Locations and heights of 11,442 trees based on a DSM are compared with those based on a CHM. The horizontal (D_H) and vertical displacements (D_V) increase with terrain slope ($r = 0.47$ and $r = 0.54$ respectively, $p < 0.001$). The overestimations in tree height are up to 16.6 m on slopes greater than 50° in our study area in Sumatra. The errors in locations (D_H) and tree heights (D_V) are modelled for trees with conical and spherical tree crowns. For a spherical tree crown, D_H can be modelled as R sin θ, and D_V as R (sec θ – 1). In this study, a model is developed for an idealised conical tree crown, $D_V = R (\tan\theta - \tan\psi)$, where R is the crown radius, and θ and ψ are terrain and crown angles respectively. It is shown that errors occur only when terrain angle exceeds the crown angle, with the horizontal displacement equal to the crown radius. Errors in location are seen to be greater for spherical than conical trees on slopes where crown angles of conical trees are less than the terrain angle. The results are especially relevant for biomass and carbon stock estimations in tropical forests where there are trees with large crown radii on slopes.

1. Introduction

Tropical rainforests play an important role in regulating the Earth's climate by being a large sink for carbon dioxide (Corlett, 2016; Thomas and Baltzer, 2001). An accurate estimation of carbon components within a forest is a first step in the recent United Nations initiative for Reducing carbon Emissions from Deforestation and forest Degradation (REDD). However, limited knowledge about the quantity and spatial distribution of biomass at the landscape level has led to considerable uncertainties in the estimation of carbon stocks (Mascaro et al., 2011). Canopy height is an important component of biomass/carbon stock estimates in forests (Hudak et al., 2012).

Tropical forests also support a large proportion of the Earth's plant and animal species, many of which are endangered by increasing deforestation and forest degradation leading to fragmentation of habitats (Thomas and Baltzer, 2001). Field-based surveys of habitats are difficult for tropical forests in terms of access, and the species diversity is extremely high while the existing knowledge of taxonomy is relatively poor (Salovaara et al., 2005). Remote sensing can be an efficient source of information for mapping these forests, and to identify habitats for more detailed field surveys (Moran et al., 1994; Salovaara et al., 2005).

Large trees account for most of the biomass in tropical forests, serve as a focal point for biological activity and create large gaps at death, altering the forest structure dynamics in addition to releasing the sequestered carbon (Chambers et al., 2007; Ferraz et al., 2016). Presence of tall trees would be a useful input for modelling species distributions

* Corresponding author at: Aarhus Institute of Advanced Studies (AIAS), Aarhus University, Høegh-Guldbergs Gade 6B, DK-8000 Aarhus C, Denmark.
E-mail address: cici.alexander@gmail.com (C. Alexander).

http://dx.doi.org/10.1016/j.jag.2017.10.009
Received 30 August 2017; Received in revised form 28 October 2017; Accepted 30 October 2017
Available online 05 November 2017

and assessing the quality of habitat for many species including birds and arboreal primates (Lesak et al., 2011). For example, emergent trees are the preferred resting and sleeping places for endangered primates such as siamangs, gibbons and langurs (Nijman and Geissman, 2008). Canopy or tree heights are therefore also important for understanding the habitat preferences of species and for devising conservation strategies for species threatened by the destruction and degradation of their habitats.

Light Detection and Ranging (LiDAR) has significantly contributed to the remote sensing of forests in the last two decades (Dubayah and Drake, 2000; Lim et al., 2003). This is mainly due to the capability of LiDAR to collect data in the form of x, y and z locations of points (often referred to as a point cloud), even from the ground below forest canopy. Airborne Laser Scanning (ALS), using a LiDAR sensor from an airborne platform, has been extensively used for deriving structural attributes of forest canopies. ALS provides information about the three-dimensional structure of forests, which provides an additional perspective of the habitat needs and requirements of species compared to two-dimensional satellite imagery (Bergen et al., 2009; Coops et al., 2016). Canopy height is an important attribute which can be used to derive other forest structural characteristics such as stand volume, basal area and above-ground biomass (AGB).

The ALS point cloud is initially classified into ground and non-ground; this process, known as ground filtering, is still an active area of research, especially in complex terrain and forests (Maguya et al., 2014; Yang et al., 2016). A Digital Terrain Model (DTM) is generated from the ground points (Axelsson, 2000; Kraus and Pfeifer, 1998; Sithole and Vosselman, 2004), and the highest points, or the 95th percentile to avoid outliers (Kane et al., 2010), within grid cells are typically used to generate a Digital Surface Model (DSM). A Canopy Height Model (CHM), which represents the height of canopy above the ground, can then be derived by subtracting the DTM from the DSM.

Delineation of individual trees from ALS data is a topic which has received considerable attention from researchers in forestry. The first step in most algorithms for delineating tree crowns based on a CHM is the detection of treetops based on local maxima within predefined windows (kernels). The grid cells belonging to a tree crown are then delineated or "grown" from adjacent cells with lower height or elevation values, often using a watershed algorithm. The algorithm terminates when there are no more cells adjacent to, and lower than, the detected cells (Chen et al., 2006; Popescu and Wynne, 2004).

Dense forests on complex terrain, especially on steep slopes, are considered to be challenging both for the generation of accurate DTMs and for the height estimation of forest stands and individual trees. Fewer points from the ground may be collected from below dense forests, reducing the accuracy of the generated DTM since local variations in micro-topography, such as peaks and pits, may not be detected. The ground below points of a tree crown on sloping terrain, in the downslope direction, are lower than the ground below the tree top, causing an upward shift in the height percentiles of forest stands with increasing slope (Breidenbach et al., 2008; Khosravipour et al., 2015).

ALS is increasingly being used to characterise tropical forests and quantify above-ground biomass, where approaches are based either on the characteristics of individual tree crowns or grid-based models (Asner and Mascaro, 2014; Asner et al., 2012; Ferraz et al., 2016; Vaglio Laurin et al., 2016). The influence of slope and crown characteristics on the estimation of tree locations and heights in tropical forests on complex terrain has not yet been analysed or modelled. Since carbon stock estimations are based on canopy and individual tree heights to a large extent (Ioki et al., 2014), it is important to assess the influence of slope on height estimations from ALS data.

It has been noted that height-normalisation of a DSM or the point cloud, based on a DTM, could introduce errors in the case of sloping terrain (Vega et al., 2014), and the estimation of tree locations before normalisation may be a better alternative. However, there has been only one attempt to quantify the influence of terrain slope on the estimation of tree locations and heights. Tree heights were shown to be overestimated by up to 1.8 m for Scots pine (*Pinus sylvestris*) trees for terrain slopes above 30°, while there was no influence of slope on height estimates of conical mountain pine (*Pinus uncinata*) trees, in an analysis of 395 trees belonging to the two species (Khosravipour et al., 2015). However, the crown radii of Scots pines did not have a correlation with errors in height estimation, as would have been expected from a theoretical model.

The aim of this study is to assess the influence of slope and crown characteristics on the detection of treetops and estimation of tree heights using ALS data in a tropical forest with complex terrain and tree crown characteristics. The first objective is to estimate the differences in the locations and heights of trees using a DSM and a CHM generated from ALS data; the CHM-based method is more widely used and implemented in software packages (Chen, 2007; Chen et al., 2006; Kini and Popescu, 2004; McGaughey, 2015). The second objective is to assess the effect of slope on the horizontal and vertical displacements in the detected treetops using the two methods. The third objective is to model the differences in estimated tree height based on terrain slope and tree crown characteristics, using crown slope in addition to crown radius, thereby extending the model developed by Khosravipour et al. (2015). This could provide a method to model errors in above-ground biomass and carbon stock estimations based on terrain and tree crown characteristics.

2. Materials and methods

2.1. Study area and dataset

The study area is in Batang Toru (1° 49′N, 99° 5′E), in the Indonesian province of North Sumatra, and covers an area of approximately 14.7 km^2. The Batang Toru forests are home to a number of unique plant and animal species including the critically endangered Sumatran orang-utans (*Pongo abelii*), Malayan tapirs (*Tapirus indicus*) and Sumatran tigers (*Panthera tigris sumatrae*).

ALS data were collected between 23rd March and 4th April 2015, using a Leica ALS-70 HP LiDAR system from a fixed wing aircraft for an area of 162 km^2. The flying height was between 900 m and 1350 m above ground level, and the scan half angle was 22.5°. This generated an ALS point cloud with an average density of 12 returns m^{-2} (Alexander et al., 2017). The returns were classified into ground and non-ground using an algorithm based on adaptive Triangulated Irregular Network (TIN) filtering implemented in Terrasolid software, and divided into 240 (1 km × 1 km) tiles for both the ground returns and non-ground returns (Axelsson, 2000; McElhanney, 2015). Sixteen tiles from this dataset were used for this study.

2.2. Generation of terrain, surface and canopy height models

A DTM with a grid cell size of 1 m was generated using the mean elevation of all ground returns within each cell in FUSION v3.60 (McGaughey, 2015). The cells that did not contain any returns were filled by interpolation. The slope of each grid cell in the DTM was calculated in ArcGIS™ 10.1 based on the maximum rate of change in value from that cell to its eight neighbours.

The ground and non-ground returns were merged in FUSION. A DSM at a grid cell size of 1 m was generated from these points using the *CanopyModel* function, which assigns the highest elevation within each grid cell to that cell. A CHM which represents the height of each cell above the ground was generated by subtracting the DTM from the DSM.

2.3. Detection of treetops

Most algorithms for identifying treetops using ALS data locate the local maxima within windows of variable sizes (Popescu and Wynne, 2004; Popescu et al., 2002). The window sizes are determined by