Remote Sensing of Environment 194 (2017) 77–88

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Area-based vs tree-centric approaches to mapping forest carbon in Southeast Asian forests from airborne laser scanning data

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ARTICLE INFO

Article history:
Received 24 September 2016
Received in revised form 24 January 2017
Accepted 17 March 2017
Available online xxxx

Keywords:
Allometry
Aboveground carbon density
Biomass estimation
Image analysis
LiDAR
Object recognition
Power-law
Tree delineation
Tropical forests

ABSTRACT

Tropical forests are a key component of the global carbon cycle, and mapping their carbon density is essential for understanding human influences on climate and for ecosystem-service-based payments for forest protection. Discrete-return airborne laser scanning (ALS) is increasingly recognised as a high-quality technology for mapping tropical forest carbon, because it generates 3D point clouds of forest structure from which aboveground carbon density (ACD) can be estimated. Area-based models are state of the art when it comes to estimating ACD from ALS data, but discard tree-level information contained within the ALS point cloud. This paper compares area-based and tree-centric models for estimating ACD in lowland old-growth forests in Sabah, Malaysia. These forests are challenging to map because of their immense height. We compare the performance of (a) an area-based model developed by Asner and Mascaro (2014), and used primarily in the neotropics hitherto, with (b) a tree-centric approach that uses a new algorithm (*itcSegment*) to locate trees within the ALS canopy height model, measures their heights and crown widths, and calculates biomass from these dimensions. We find that Asner and Mascaro's model needed regional calibration, reflecting the distinctive structure of Southeast Asian forests. We also discover that forest basal area is closely related to canopy gap fraction measured by ALS, and use this finding to refine Asner and Mascaro's model. Finally, we show that our tree-centric approach is less accurate at estimating ACD than the best-performing area-based model (RMSE 18% vs 13%). Tree-centric modelling is appealing because it is based on summing the biomass of individual trees, but until algorithms can detect understory trees reliably and estimate biomass from crown dimensions precisely, areas-based modelling will remain the method of choice.

1. Introduction

Forests are an important component of the global carbon cycle, and their future management is key to international efforts to abate climate change. During the 1990s, about 89,000 km^2 of tropical forests were lost to agriculture each year, and a further 24,000 km^2 were degraded (Nabuurs et al., 2007). Estimates of deforestation rates vary, but somewhere in the region of 230 million hectares of forest were lost per year between 2000 and 2012 (Hansen et al., 2013). Furthermore, some 30% of tropical forests were degraded by logging and/or fire during that period (Asner et al., 2009). These changes resulted in significant releases of greenhouse gases (GHGs) to the atmosphere, constituting approximately 10% of global emissions (Baccini et al., 2012) and emphasising the significance of forests in the terrestrial carbon cycle (Pan et al., 2011). Forest conservation and restoration are increasingly recognised as critical for mitigating climate change (Agrawal et al., 2011). The climate change agreement brokered at COP21 in Paris, and signed by over 200 nations, may be significant in this respect. It is now recognised that, as well as harbouring biodiversity and supporting a billion livelihoods, tropical forests are essential for climate change abatement. Even if nations de-carbonise their energy supply chains within agreed schedules, we are unlikely to avoid 2 °C global warming

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http://dx.doi.org/10.1016/j.rse.2017.03.017

unless 500 million ha of degraded tropical forests are protected, and land unsuitable for agriculture is afforested (Houghton et al., 2015). Forest protection can offset emissions over the next 40 years, buying time for humanity to reduce its dependency on fossil fuels (Houghton et al., 2015).

Accurate monitoring of forest extent and carbon density is essential for these renewed efforts to protect forests, because this information is the basis of programmes to reduce emissions from deforestation and forest degradation and industrial zero-net-emissions programmes, and airborne laser scanning (ALS) is widely recognised as an essential component of these projects. Regional ALS maps of carbon density are all currently generated using “area-based” approaches (Næsset, 2002). These approaches, applied in over 70 publications (Zolkos et al., 2013), relate live-wood aboveground carbon density (ACD) estimates obtained from field plots to simple summary statistics, such as mean canopy height, derived from the ALS point cloud through statistical models (Fig. 1). These approaches for mapping structural attributes of complex multi-layered forests, as outlined by Drake et al. (2002, 2003), have since been applied to carbon mapping in several tropical regions (Englhart et al., 2011; Englhart et al., 2013; Asner et al., 2012, 2013; Vincent et al., 2012; Jubanski et al., 2013; Laurin et al., 2014; Réjou-Méchain et al., 2015). However, a well-recognised problem is that many different ALS structural metrics can be used to construct the multiple regression equations, and so these models are idiosyncratic by virtue of their local fine-tuning and cannot be applied more widely than the region in which they were calibrated. An alternative approach, advocated by Asner and Mascaro (2014), uses a simple power-law function of mean top-of-canopy height (TCH) to predict carbon density within tropical landscapes. This generalised approach has obvious advantages when it comes to mapping carbon across the tropics. Yet this power-law model hinges on the assumption that (i) forest basal area and TCH are closely related and (ii) that average (i.e., 1-ha resolution) between-plot variation in basal area-weighted wood density is low at regional scales (Asner and Mascaro, 2014; Vincent et al., 2014; Duncanson et al., 2015). Currently, however, we do not have a clear understanding of situations in which these assumptions are supported.

In response to these potential issues with area-based approaches for estimating ACD from airborne laser scanning, there is current interest in developing individual-tree-based approaches to make greater use of the 3D information contained in ALS data (Fig. 1; Eysn et al., 2015; Ferraz, Saatchi, Mallet, and Meyer, 2016; Vauhkonen et al., 2012). Advances in sensor technology and computational power have generated a proliferation of approaches for detecting individual tree crowns within discrete-return ALS point clouds – including those working with the rasterized upper surface of the ALS point cloud (e.g. Hyyppa et al., 2001; Chen et al., 2006; Yu et al., 2011), and those exploiting the entire point cloud (Morsdorf et al., 2004; Reitberger et al., 2009; Duncanson et al., 2014; Ferraz et al., 2016). There are several advantages of individual-tree-based mapping compared to area-based approaches: (i) it has a strong fundamental basis because it is conceptually similar to allometric approaches used in field-based inventories; (ii) uncertainty in the estimation model is much less dependent on plot size, allowing calibration using individual trees and small plots (Dalponte and Coomes, 2016); (iii) narrow patches of forest with high conservation value, such as riparian strips, can be mapped; (iv) growth and death of individual trees can, in principle, be tracked and this information used to

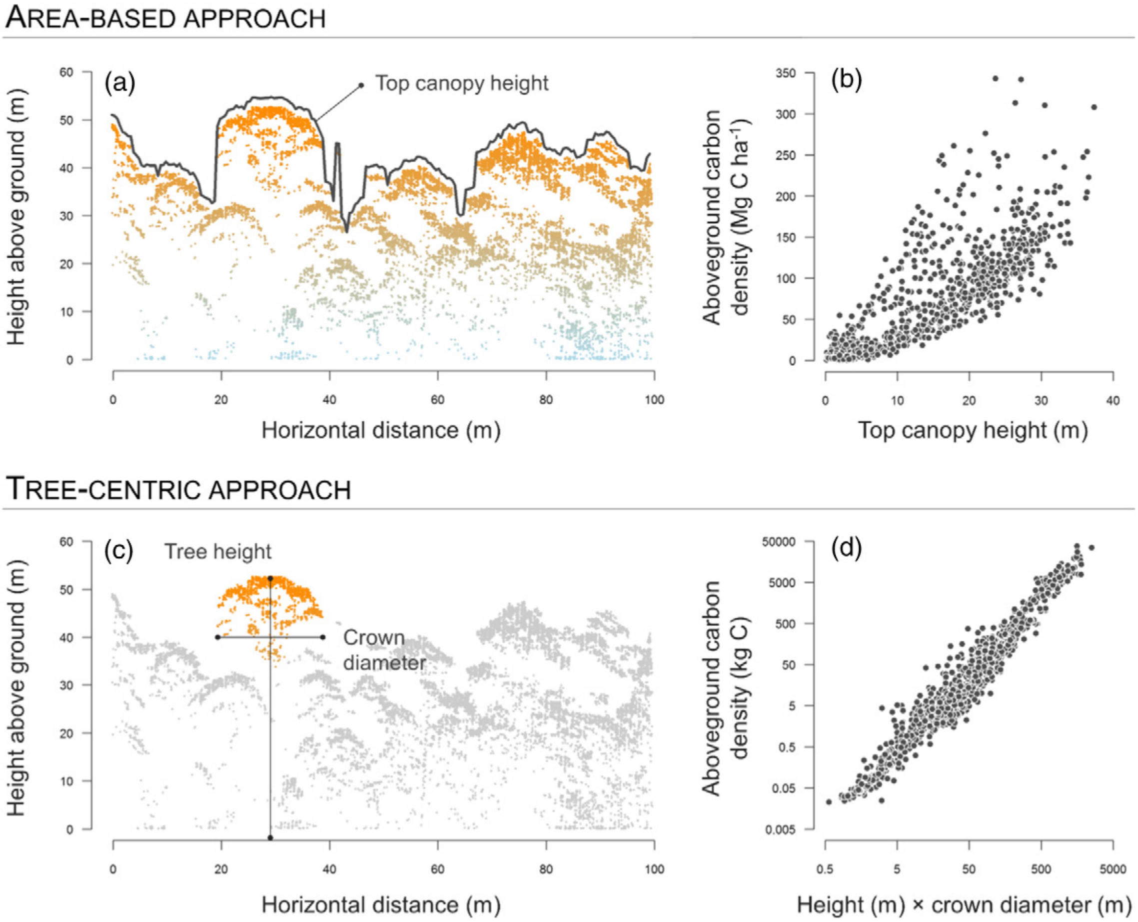

Fig. 1. Schematic diagram illustrating the key differences between area-based and tree-centric approaches used to estimate aboveground carbon density (ACD) from ALS data. Area-based approaches rely on summary statistics calculated from the ALS point cloud (e.g., top canopy height in a) to develop statistical relationships for estimating ACD (b). In contrast, tree-centric mapping aims to identify and measure the crown dimensions of individual trees within the ALS point cloud (c), and then use these to estimate their ACD (d). Data shown in panels (b) and (d) were taken from Asner and Mascaro (2014) and Jucker et al. (2016), respectively.