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Mapping tropical forest carbon: Calibrating plot estimates to a simple LiDAR metric

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A B S T R A C T

Mapping aboveground carbon density (ACD) in tropical forests can enhance large-scale ecological studies and support CO_2 emissions monitoring. Light Detection and Ranging (LiDAR) has proven useful for estimating carbon density patterns outside of field plot inventory networks. However, the accuracy and generality of calibrations between LiDAR-assisted ACD predictions ($EACD_{LiDAR}$) and estimated ACD based on field inventory techniques ($EACD_{field}$) must be increased in order to make tropical forest carbon mapping more widely available. Using a network of 804 field inventory plots distributed across a wide range of tropical vegetation types, climates and successional states, we present a general conceptual and technical approach for linking tropical forest $EACD_{field}$ to LiDAR top-of-canopy height (TCH) using regional-scale inputs of basal area and wood density. With this approach, we show that $EACD_{LiDAR}$ and $EACD_{field}$ reach nearly 90% agreement at 1-ha resolution for a wide array of tropical vegetation types. We also show that Lorey's Height – a common metric used to calibrate LiDAR measurements to biomass – is severely flawed in open canopy forests that are common to the tropics. Our proposed approach can advance the use of airborne and space-based LiDAR measurements for estimation of tropical forest carbon stocks.

1. Introduction

Over the past decade, estimation of tropical forest carbon stocks has evolved from an activity based largely on field inventories (e.g., Malhi et al., 2006), to an effort assisted by airborne and spaceborne remote sensing (Asner et al., 2010; Baccini et al., 2012; Drake et al., 2002; Lefsky et al., 2002; Saatchi et al., 2011). As the more recent approach, remote sensing-based carbon estimates are usually compared to field inventory-based assessments. However, as noted by Clark and Kellner (2012), virtually all field-based carbon assessments also represent estimates. Inventory data (i.e., tree diameters, heights, wood densities) are passed into allometric models (e.g., Chave et al., 2005), previously developed by harvesting and weighing trees to determine their biomass (of which ~48% is carbon in tropical forests; Martin & Thomas, 2011), and the summation of each tree's carbon stock estimate within a plot is derived as the field-estimated aboveground carbon density ($EACD_{field}$, units of $Mg\,C\,ha^{-1}$). Uncertainty can be estimated as well (Chave et al., 2004), but true measurement of ACD will ultimately require whole-plot harvests of forest biomass, which are extremely labor intensive and thus rarely carried out (Colgan, Asner, & Swemmer, 2013). In the interim, tree allometry will continue to underlie $EACD_{field}$ because allometry is one of the most conserved properties in nature (e.g., Niklas, 2006), and remote-sensing approaches that can accurately predict $EACD_{field}$ will be critical to carbon stock mapping and monitoring.

LiDAR (light detection and ranging) has become a commonly used technology in the effort to remotely predict $EACD_{field}$ in many forest types (e.g., Ene et al., 2012; Gobakken et al., 2012; McRoberts, Næsset, & Gobakken, 2013). Unlike passive optical techniques, LiDAR uses emitted laser pulses to derive metrics of forest structure in three dimensions (e.g., Omasa, Qiu, Watanuki, Yoshimi, & Akiyama, 2003). Whereas $EACD_{field}$ assessments have applied tree allometry from the bottom-up to all trees encountered in a plot, most LiDAR-based efforts apply allometric equations at the whole plot or stand level. This approach is not strictly allometry, which refers to scaling at the organism level, but instead it can be thought of as *plot-aggregate allometry*. Plot-aggregate allometry posits that if forest structure and biomass organization follow consistent scaling patterns, simple plot-level variables could capture as much information about $EACD_{field}$ as full field inventories. Several tropical studies have used LiDAR metrics, such as canopy profile height, to form plot-aggregate allometries to predict $EACD_{field}$ (e.g., Asner et al., 2010; Drake et al., 2002; Lefsky et al., 2002). Other tropical studies have utilized a 'daisy-chain' of plot-aggregate allometries, for example, by linking LiDAR metrics to the plot variable Lorey's height – the basal area-weighted average height of all trees – and subsequently linking Lorey's height to $EACD_{field}$ (Harris et al., 2012; Saatchi et al., 2011). However, the trade-offs between direct calibration of LiDAR metrics to $EACD_{field}$ versus daisy-chain type approaches have not been communicated in the literature.

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In a previous study, we found that relationships between simple plot-aggregate allometries and airborne LiDAR metrics are not consistent across tropical ecosystems (Asner et al., 2012). To address the additional variation, we devised a general approach to plot-aggregate allometry and LiDAR calibration in tropical forests. We argued that because tree-level carbon stocks depend on diameter, wood density and height (Chave et al., 2005), $EACD_{field}$ should similarly depend on basal area (the cross sectional area of all stems), basal-area-weighted wood density, and canopy height. However, our previous airborne LiDAR calibrations to plot-aggregate allometry for tropical forests were based on a particular 3-D metric termed Mean Canopy Profile Height, or MCH (sensu Lefsky et al., 2002). The MCH metric approximates the vertical centroid of all canopies within a plot, which in turn, is a proxy for the distance stretching from the ground to the top of the main stem of the trees. While this approach yielded consistent relationships with $EACD_{field}$ when using a single LiDAR sensor (e.g., Asner, Hughes, Varga, Knapp, & Kennedy-Bowdoin, 2009; Asner et al., 2010, 2011, 2012; Mascaro et al., 2011), we recently found that different LiDAR sensors produce inconsistent MCH values based on instrument specifications. In particular, laser beam divergence and power, and the sensitivity of the LiDAR receiver, causes differences among LiDAR measurements of the vertical distribution of the canopy tissues, upon which the MCH and similar metrics are calculated (see also Næsset, 2009). This issue affects all LiDAR metrics that are sensitive to the vertical profile of the vegetation, such as RH50, RH80, and many others (Ni-Meister et al., 2010). Fortunately however, our tests also indicate that top-of-canopy height (TCH) – the distance from ground to the topmost point on the canopy – is a much more consistent index among different modern LiDAR sensors, thereby offering a way to circumvent the highly variable, sensor-specific performance of vertical profile metrics. However, the generality of TCH-based approach to plot-aggregate carbon stock estimation has not been broadly examined for tropical vegetation.

Another recent development is that LiDAR-based estimates of tropical forest ACD ($EACD_{LiDAR}$) approach $EACD_{field}$ when field plots reach one hectare in size (Asner et al., 2010; Mascaro, Detto, Asner, & Muller-Landau, 2011; Zolkos, Goetz, & Dubayah, 2013). Several factors contribute to this: (1) errors caused by spatial misalignment of plots and LiDAR data are diminished with larger plots (Asner et al., 2009), (2) integrating measurements over larger plots provides a more representative average (Zolkos et al., 2013), and (3) disagreement in protocol between LiDAR and field observations – namely the effects of bisecting tree crowns in LiDAR data versus calling a tree "in" or "out" of the plot in field data – decreases to a manageable level (Mascaro, Detto, Asner, & Muller-Landau, 2011). Although such patterns may be consistent in sign across tropical vegetation types, the magnitude of the plot-size effect on error – and particularly the improvements detected at 1 ha in size – reflect not plot size *per se*, but the size of the plot relative to the average crown size, which provides the bulk of the LiDAR return signal (e.g., contrast with boreal forest, where crowns are much smaller; Naesset et al., 2011). Because 1-ha plots entail a very large amount of labor to measure for biomass inventory (indeed, they are the upper limit in the size of most tropical forest inventory plots; Malhi et al., 2006), they represent a costly and labor-intensive trade-off with the number of plots that must be used for validation. This issue is central to determining the generality of LiDAR-based approaches for tropical forest carbon mapping, and thus additional research that might reduce the need for exhaustive plot-based calibration is warranted.

Here, we use a network of 804 tropical forest inventory plots to assess the ability of a very simple LiDAR metric – top of canopy height or TCH – to predict $EACD_{field}$ for a wide range of tropical vegetation types and ecological settings. We had three specific objectives: First, we assessed the effectiveness of calibrating LiDAR TCH to $EACD_{field}$ using both regionally- and generically-constrained estimates of plot-aggregate allometry. Second, we tested whether Lorey's Height can be used to enhance $EACD_{field}$ predictions as is often practiced in LiDAR-assisted carbon mapping studies. Finally, we examined the effect of plot size on LiDAR predictions of $EACD_{field}$, with specific attention to the use of fewer 1-ha validation plots to save time and reduce project cost.

2. Methods

2.1. Field plots

Greatly expanding on Asner, Mascaro, et al. (2012), our field plot network includes plots in 14 distinct tropical ecoregions, with more than a half million trees measured, and across an enormous range of forest types, floristic composition, disturbance regimes and successional states. The network presented here has been updated to 804 plots in Colombia, Hawaii, Madagascar, Panama and Peru (50 of which are reserved for validation; Table 1). The plots are positioned from sea level in the Pacific, to more than 3500 m altitude in the Andes, and across a wide range of climate conditions (mean annual precipitation range: 180–11,000 mm year^{-1}; mean annual temperature range: 6–27 °C). The types of vegetation included in the database range from dense, humid lowland forest to dry spiny woodlands, and from mature, closed canopy forests to open woodland-savanna physiognomies. A complete description of the plots can be found in the references provided in Table 1, and a plot-level listing of the data used for LiDAR-to-field calibration is provided in the Online Electronic Supplement 1.

$EACD_{field}$ was assessed for each plot following a consistent protocol detailed by Asner, Mascaro, et al. (2012). The minimum diameter class for all stems was standardized to 5 cm. In Peru and Colombia, stems 5–10 cm in size were estimated by a subplot one-eighth the area of the main plot. In Madagascar, a similar scheme was used for stems 5–10 cm and 10–20 cm in size (Asner, Clark, et al., 2012). Plot size and configuration differed across projects (Table 1), variables we consider in the *Uncertainty* section. However, tree-level allometries used to estimate biomass were consistent across all plots, and are based on the most local information first, followed by generalized equations from Chave et al. (2005). Tree height for field inventory data was measured for the three largest trees in each plot for all project areas, and for all trees in more recent projects, either using laser ranging hypsometers (Impulse 2000, Laser Technology, Durham NC), or clinometers. For remaining trees without a height measurement, height-diameter models were used to estimate individual tree height (sensu Chave et al., 2005). In all cases, we used height-diameter allometry at the species or regional level rather than defaulting to allometric equations that exclude a height parameter unless such equations were species-specific (thereby subsuming species-level diameter-to-height variation in the coefficients, discussed below). The inclusion of height in allometry has been found to be essential to preventing overestimation of $EACD_{field}$ in nearly all tropical regions (Feldpausch et al., 2012).

2.2. LiDAR data

The LiDAR data were collected using the Carnegie Airborne Observatory (CAO) Alpha (Asner et al., 2007) or AToMS (Asner et al., 2012) sensor packages, with data collection and analysis methods applied consistently across sites. Both the Alpha and AToMS scanning LiDAR sensors are full waveform, but the work presented here relied only on the discrete return data of up to four returns per pulse in order to make the results applicable to a much wider range of LiDARs currently in operation throughout the world. Over all field plots listed in Table 1, the CAO LiDARs were operated at 2000 m above ground level (a.g.l.) with a 30° field of view, pulse repetition frequency of 50 kHz, and a ground speed of ≤110 knots. Both LiDARs have a laser beam divergence set to 0.56 mrad (1/e), providing 1.12 m laser spot spacing from 2000 m a.g.l. However, 50% overlap between adjacent flight lines resulted in two laser