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Tree height and tropical forest biomass estimation

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Abstract

Tropical forests account for approximately half of above-ground carbon stored in global vegetation. However, uncertainties in tropical forest carbon stocks remain high because it is costly and laborious to quantify standing carbon stocks. Carbon stocks of tropical forests are determined using allometric relations between tree stem diameter and height and biomass. Previous work has shown that the inclusion of height in biomass allometries, compared to the sole use of diameter, significantly improves biomass estimation accuracy. Here, we evaluate the effect of height measurement error on biomass estimation and we evaluate the accuracy of recently published diameter : height allometries at four sites within the Brazilian Amazon. As no destructive sample of biomass was available at these sites, reference biomass values were based on allometries. We found that the precision of individual tree height measurements ranged from 3 to 20 % of total height. This imprecision resulted in a 5–6 % uncertainty in biomass when scaled to 1 ha transects. Individual height measurement may be replaced with existing regional and global height allometries. However, we recommend caution when applying these relations. At Tapajós National Forest in the Brazilian state of Pará, using the pantropical and regional allometric relations for height resulted in site biomass 26 % to 31 % less than reference values. At the other three study sites, the pan-tropical equation resulted in errors of less than 2 %, and the regional allometry produced errors of less than 12 %. As an alternative to measuring all tree heights or to using regional and pantropical relations, we recommend measuring height for a well distributed sample of about 100 trees per site. Following this methodology, 95 % confidence intervals of transect biomass were constrained to within 4.5 % on average when compared to reference values.

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1 Introduction

Tropical forests are an important component of global carbon stocks. They contribute an estimated 428 Pg (1 Pg = 10^{15} g) of carbon globally, divided approximately evenly between vegetation and soils (Watson, 2000). This total is approximately one fifth of the global carbon stock, and the vegetation component is one half of the above ground carbon stored in vegetation of all biomes. However, there is a great deal of uncertainty in these numbers (Watson, 2000). While some of this uncertainty is due to the unknown amount of deforestation and degradation in tropical forests, another large component is due to the uncertainties involved in estimating standing biomass in the field (Houghton, 2005). This uncertainty is compounded when a limited area sampled is used to predict biomass over large tracts of forest.

Because of their high carbon density, tropical forests are increasingly viewed as an avenue for mitigation of climate change. In an effort to reduce deforestation and degradation by creating monetary value for the carbon in forests, the United Nations has developed REDD (Reducing Emissions from Degradation and Deforestation) (Gibbs et al., 2007). However, to implement this framework it is first necessary to quantify carbon stocks.

In an effort to create global biomass maps that can serve as REDD baseline carbon stock estimates, moderate and coarse resolution optical and microwave data from satellites has been combined with lidar remote sensing by ICESat to extrapolate field measured biomass over the global extent of tropical forest (Saatchi et al., 2011; Baccini et al., 2012). Recognizing the importance of biomass estimation the European Space Agency is scheduled to launch the BIOMASS radar satellite mission in 2020 in an effort to create three dimensional maps of the world's forests (Le Toan et al., 2011). NASA missions (such as the completed ICESat and the upcoming ICESat II lidar missions) have secondary goals of estimating forest biomass (Lefsky et al., 2007; Nelson, 2010; Saatchi et al., 2011). However, neither existing nor planned remote sensing data sets directly measure biomass; they all rely on field data for calibration.

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In most applications, estimation of tropical forest biomass is ultimately linked to the estimation of biomass of individual trees (although see Clark and Kellner, 2012 who suggests an alternative approach). Individual tree biomass estimates depend upon allometric equations that are developed using a finite number of individuals from a limited region or a broader combination of sites (Chambers et al., 2001, and others). By necessity, these allometries are often applied beyond the region(s) for which they were developed, and often beyond the range of diameters sampled as well (Chave et al., 2003). Unfortunately, allometric equations do not transfer without error across all sites. For example, Vieira et al. (2008) applied allometric equations developed at sites in the central Amazon and Puerto Rico to Atlantic Forest trees and compared them with an allometry specific to the Brazilian Atlantic Forest. Equations developed at Puerto Rico and the central Amazon deviated by more than 36% and 68% respectively from the Atlantic forest values. Recently, broader analyses have been conducted that create regional and global allometric relations based on data from multiple sites (Chave et al., 2005; Feldpausch et al., 2012). These allometries are based on significantly larger sample sizes, and are assumed to be more robust for regions without site-specific equations. The Chave (2005) allometry uses stem diameter and wood density, and optionally total tree height. Feldpausch et al. (2011) have developed global and regional equations to relate height to diameter for sites where height measurements are lacking.

Studies in temperate and tropical regions have shown the advantages of species-specific biomass and volume allometries (Basuki et al., 2009; Litton and Kauffman, 2008). Given the variation in tree form and growth properties, species specific allometries are desirable. However, the species diversity present in tropical forests makes this prohibitively costly for most sites. For example, a study conducted near Manaus showed 280–285 species per hectare for three hectares sampled for trees greater than 10 cm diameter (De Oliveira and Mori, 1999). Sites in the Brazilian Amazon typically have upwards of 100 tree species per hectare (Campbell et al., 1986), most of which do not have species specific allometries.

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The inclusion of height in allometric equations greatly improves the accuracy of individual tree biomass estimation (Chave et al., 2005; Feldpausch et al., 2012; Lima et al., 2012; Maia Araújo et al., 1999; Vieira et al., 2008). Chave reported (Chave et al., 2005) that the inclusion of height for stand level estimates of biomass reduced error from 19.5% to 12.8%, across all forms of tropical forests and across continents. At Brazilian sites specifically, the root mean squared error of individual tree biomass was reduced from 16% to 6%.

The accuracy of biomass estimation for individual trees and subsequently for plot scale biomass fundamentally depends on the accuracy of tree height measurements. Tree heights can be difficult to measure under the best conditions (Rennie, 1979; Williams et al., 1994). Height measurements are dependent on forest conditions, observer experience, and the equipment used. Tropical forests typically include significant obstacles for traditional field-based estimates of tree heights, including dense under-story vegetation, tall canopies, and closed-canopy conditions that limit the line of sight. Tree height measurements in tropical forests are both labor intensive and have potentially large errors. Although researchers agree that height is a valuable addition when estimating biomass, the degree of acceptable error has been debated. Williams and Schreuder (2000) found that a height error of up to 40% was acceptable in temperate forests before the use of a diameter-only equation provided a better biomass estimate. Molto and colleagues (2012) showed that a height error of 2–5% can significantly influence estimates of above ground biomass for a tropical forest in French Guiana. We evaluate how tree height accuracy affects biomass estimation accuracy for moist tropical forests in Brazil by responding to a number of questions.

- How precise are ground-based tree height measurements using a hand-held clinometer and metric tape?
- How accurate are ground-based tree height measurements using the clinometer approach?

- What is the affect of tree-level uncertainty in height on the estimation of plot biomass?
- Are global and/or regional height-diameter relations adequate for accurate biomass estimation?
- 5 – How can field work be optimized to achieve acceptable accuracy in plot level biomass while limiting the number of tree height measurements used?

2 Methods

2.1 Site descriptions

10 Data from four sites of contrasting forest structure distributed across the Brazilian Amazon were used to answer the questions posed above (Table 1). Climate data for all sites was extracted from the WorldClim 2.5 min resolution database (Hijmans et al., 2005) in order to remain consistent with climate data requirements for regional allometries proposed by Feldpausch et al. (2011). The precipitation variability was defined as the standard deviation of monthly precipitation divided by the mean. Dry season length
15 was defined as the number of months with less than 100 mm of precipitation.

Forest structural characteristics derived from field data are presented in Table 1. Basal area, maximum diameter measured and mean canopy height all vary among sites. The mean canopy height was calculated from field data as Lorey's height (basal area weighted mean height). Where possible, field estimates of mean canopy height
20 were compared with the mean height of the outer canopy surface (i.e. canopy height model (CHM)) based on airborne lidar data.

2.1.1 Reserva Adolpho Ducke

Reserva Adolpho Ducke (59° 57' W 2° 57' S) is a 10 000 ha forest preserve managed by the National Institute for Amazon Research (INPA) north of Manaus, Brazil. It is

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dominated by rolling terrain (30–120 m a.s.l.) cut by small streams and covered by upland terra firme forest with a large number of palms present, especially in seasonally flooded valleys. The soils vary with topography with oxisols similar to those of Tapajos National Forest (see below) present on the upland plateaus, ultisols on the slopes and spodosols in the valleys (Chauvel et al., 1987). These soils are acidic and low in nutrients. Mean annual temperature is 27 °C, and precipitation averages 2208 mm with a short dry season (1–3 months) during July–September (Table 1).

2.1.2 Tapajos National Forest

The Tapajós National Forest (54° 58′ W, 2° 51′ S) is a 550 000 ha reserve situated south of Santarém, Brazil between the Tapajós River and the Cuiabá-Santarém Highway (BR-163). The reserve is dominated by upland forests on a nutrient-poor, clay oxisol plateau (Silver et al., 2000). The mean annual temperature and precipitation at Tapajos are 25 °C and 1909 mm, respectively. The dry season generally lasts five months, from July–December (Vieira et al., 2004). Two field sites were installed within the Tapajós National Forest referred to by their entrance points along the BR-163 highway; an undisturbed forest site (km 67) and a selectively-harvested site (km 83).

2.1.3 Fazenda Tanguro

Fazenda Tanguro (52° 23′ W 13° 4′ S) is a private land holding of approximately 80 000 ha within the municipality of Querência, Mato Grosso. Located near the forest–cerrado transition, Fazenda Tanguro is classified as transitional forest characterized by comparatively low biomass and tree species diversity. Soils are oxisols throughout this generally flat region, with slopes less than 2 degrees (Balch et al., 2008). It has a mean temperature of 25 °C, annual precipitation of approximately 1740 mm and a 5–6 month dry season lasting from May to September (Balch et al., 2010). Though the annual temperature and dry season length are similar to that of Tapajos, the variability in precipitation is much higher at Tanguro.

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under 50° to minimize error within the trigonometric calculation. A tape-measure was used to measure the distance from the observer to the measurement point. In the case of measurements on sloped ground, the slope of the tape-measure was also measured and the distance corrected. Heights were calculated trigonometrically. All height measurements were taken by a single observer. Crown radius was measured in four cardinal directions with respect to the trunk. Notes were taken on the availability of light to the tree crown (full direct, partial direct, full indirect light) and the crown's position within the canopy (emergent, canopy or sub-canopy). Emergent trees were defined as those standing above the surrounding tree's canopies, not those taller than the dominant canopy height. While multiple life forms (including vines and palms) and standing dead were included in the field sampling, only the 817 living trees were analyzed.

2.2.2 Tapajos National Forest

A total of twelve 500 m transects were installed; six within the old-growth portion (km 67) of Tapajós National Forest in June 2009, and another six in a selectively-logged portion (km 83) of Tapajós National Forest in January 2010. The sampling method and measurements at the Tapajós site were the same as at Reserva Ducke (see Sect. 2.2.1). A total of 1813 living trees were sampled at Tapajos, with a resulting average nominal plot size of 0.85 ha.

Geolocation of individual stems at the Tapajós site differed from the methods at Reserva Ducke. Stems were mapped with respect to the transect, and geo-located using differential GNSS (Trimble GeoXH 6000) in combination with data collected using hand-held GPS units (Garmin 76csx). Differential GNSS was used to collect a point at the start of each transect and hand-held GPS measurements taken at 50 m increments. Hand-held GPS points were used to determine the orientation of the transect. At two transects a greater density of differential GNSS was available (approximately six points spaced every 100 m along the transect) and transect and tree positions were compared to the single dGNSS point in combination with hand-held GPS data. Tran-

sect positions varied up to 19.2 m and individual trees had a horizontal RMS error of 5.7 m.

During the survey of Tapajos km 67 a random subset of 20 % of trees (174 individuals) were remeasured within a week of the initial survey. Diameter at breast height, commercial height, top of canopy height and light characteristics were all remeasured to assess the repeatability of field measurements.

2.2.3 Fazenda Tanguro

Eighteen 0.37 ha circular plots were installed in 2005, designed for correlation with satellite-based lidar footprints (ICESat-GLAS). Further sampling design information is available in (Lefsky et al., 2005). Total height, commercial height and longest crown dimension of all trees greater than 35 cm diameter were measured. Trees with 10 cm to 35 cm diameter were measured in a sub-plot of 0.075 ha with a random subset of 20 % selected to measure canopy characteristics. Both total and commercial height were measured using a clinometer and tape measure.

2.2.4 Fazenda Cauaxí

Fourteen 1 ha plots (500 m × 20 m transects) were surveyed at Fazenda Cauaxí in 2000 for trees greater than 20 cm diameter, totaling 2271 individuals (Asner et al., 2002, 2012). Additional crown measurements were taken for a subset of 300 stems. These crown measurements included top of canopy height, commercial height and crown width along the estimated longest axis. See Asner et al. (2002) for the complete methodology. Tree heights were estimated using a handheld laser range finder (Impulse-200LR, Laser Technology Inc., Englewood, CO), that measures distance using laser ranging and estimates height using a clinometer incorporated into the instrument.

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2.3 Airborne lidar data

Airborne lidar was collected over Tapajos National Forest and Reserva Ducke between 7 June and 3 July 2008 by Esteio, Ltda. (Curitiba, Parana, Brazil) using a Leica ALS-50 discrete-return lidar system capable of capturing four returns per outgoing pulse.

Flights were conducted between 700–900 m a.g.l., resulting in a footprint diameter of 15–20 cm. The instrument was operated with a two sided scan angle of 30 degrees. Minimum pulse densities of 10 pulses m^{-2} were specified at TNF km 67 and Reserva Ducke and 3 pulses m^{-2} at TNF km 83. With up to 4 returns for every shot and flight line overlaps, mean return densities of 46.7 points m^{-2} for high density sites and 12.1 points m^{-2} for low density sites were observed. Position errors were tested using overlapping data from multiple flight lines. Features identifiable in both scenes, such as the crown edges of emergent trees were used to estimate offset. Mean differences did not exceed 70 cm vertical and 40 cm horizontal. This is an extremely conservative estimate of point accuracy as it includes both the geolocation error and error due to the likelihood of repeat sampling of the exact same point within the tree crown.

The lidar point cloud was summarized to create a Digital Terrain Model (DTM) and Canopy Height Model (CHM). The DTM was created by first separating ground returns following the algorithm of Zhang et al. (2003). Delauney triangulation was used to create a triangular irregular network (TIN) of ground hits, and the TIN was then used to interpolate DTM elevations on a raster grid of 1 m spatial resolution. Additionally, the TIN was used to interpolate the elevation of every feature return in every grid cell, and feature heights were calculated as the difference from this elevation (Cook et al., 2013). The CHM was created by selecting the greatest height of all non-ground return points within a given 1 m grid cell (minimum of 3 returns per grid cell).

2.4 Lidar estimation of tree heights

Georeferenced crown locations were used to estimate tree heights from the lidar data at the Tapajós and Ducke sites. For each crown, an ellipse of crown inclusion was

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created based on four crown radii measured in the field in combination with the geo-referenced trunk position (Fig. 1). The 99th percentile height of the lidar data within each crown ellipse was defined as the lidar estimated maximum tree height.

2.5 Statistical analysis and simulation

To analyze the effect of the uncertainty in tree height on biomass estimates, a Monte Carlo analysis was conducted. Stems with multiple measurements at Tapajos ($n = 174$) were split into four diameter classes with an equal number of stems: 5–7.3 cm, 7.4–13.7 cm, 13.8–33.4 cm, and greater than 33.5 cm. The standard deviation of the differences between initial and repeat height measurements was calculated for each class.

Returning to the full data set, a series of random numbers with a mean of zero, and a standard deviation matching that of the height difference within each diameter class was calculated. A random number from this distribution was added to each field height measurement and the Chave Model I (Chave et al., 2005) moist forest allometry was then used to re-calculate biomass for each stem, using a site average wood density of 0.64. The simulation was conducted 1000 times, and the resulting transect level biomass was reported.

To assess the necessity of time consuming height measurements at individual sites, site-specific diameter to height allometric relationships were compared with the best regional and pan-tropical allometries published by Feldpausch et al. (2011). These allometries include environmental and structural parameters that are site-dependent. Site-specific allometries were fit to a log-log formulation following Feldpausch et al. (2011) using all field measurements of height. Individual stems were weighted evenly within each of four diameter classes, determined by the range of diameters sampled at a given site. The diameter classes were defined in reference to the range of the minimum to 99.9th percentile diameter measured, are proportional to the distribution of biomass, and are presented as fractional ranges: 0–0.22, 0.22–0.35, 0.35–0.51, 0.51–1.0. Although these four diameter classes are weighted equally, the first three ranges are divided in half to further distribute the sample.

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At sites where heights were measured for all trees, reference values for site and transect level biomass were calculated using field measured height. At Tanguro and Cauaxí reference values for biomass were calculated by applying the site-specific diameter:height allometries. To determine the approximate sample size of tree height necessary to estimate biomass within 5% of the value calculated based on all trees, bootstrap resampling was applied. For a given sample size, the entire data set was subset 1000 times (sampling without replacement within each subset) and allometries were fit to each subset. The weighting scheme applied for the site specific fit was also applied to sample stems by diameter class. To determine the given allometry's accuracy in terms of biomass prediction, field data was regrouped to compare approximately 1 ha sized plots in all cases.

3 Results

3.1 Precision of ground-based height measurements

Remeasurement of 174 stems from the Tapajos 2009 field survey showed no significant difference from zero between the first and second measurements (t test $p = 0.38$). The overall mean difference in height (first measurement minus second measurement) was 1.1 m, with a standard deviation of 4.7 m. There was a slight tendency toward lower remeasured heights (i.e. positive residuals) both overall and by diameter class (Fig. 2). Offsets were an average of 16.57% of the mean height measured (median of 11.9%). Dividing the remeasured heights into four equally-sized diameter classes, the standard deviation increases by a factor of eight from 1.09 m to 8.17 m.

3.2 Accuracy of field measurements of height compared to lidar

The comparison of lidar height to field height measurements was limited to emergent stems in order to be visible in the lidar canopy height model (Fig. 3). Emergent stems were considered to be any tree whose canopy is above its immediate neighbors. The

height difference between emergent crowns measured in the field versus the height estimated using lidar was 1.4 m (lidar – field height).

The mean residual of lidar minus field height was -1.2m at Reserva Ducke (standard deviation of 6.4 m) and -1.8m at Tapajós (standard deviation of 7.8 m), suggesting a slight but non-significant bias towards overestimation of height in the field or toward underestimation of height using lidar. A slight increasing trend was found when the residual of lidar minus field height was compared with lidar height. The increase in residuals is consistent with the observation that heights are increasingly difficult to measure above the dominant forest canopy (34 m at Tapajos and 25 m at Reserva Ducke). However, the uncertainty of field measurements is larger than the mean residual in all cases.

3.3 Effect of height error on plot level biomass

At Tapajos the 95 % confidence interval of transect-level biomass due to variability in field estimated heights ranged from 13–22 Mg ha^{-1} with transect biomass estimates ranging from 147 to 398 Mg ha^{-1} (Table 2). The mean biomass is lower and more variable at TNF km 83 (288 Mg ha^{-1}) as compared with the old-growth site TNF km 67 (325 Mg ha^{-1}). Typically, transects with higher biomass show a larger 95 % confidence interval and smaller error in terms of percent biomass, although this is dependent on the size distribution of individual trees. The 95 % confidence interval as a percentage of biomass ranged from 5.2 % to 8.7 % with a mean of 6.3 %.

Although repeat field measurements were not available for Reserva Ducke, the height error estimated at Tapajos was applied to estimate variability due to the lack of precision of field measurements. The 95 % confidence interval of transect biomass ranged from 17 to 21 Mg ha^{-1} with biomass estimates ranging from 306 to 431 Mg ha^{-1} . Based on these calculations the lack of precision in height measurements results in a 95 % confidence interval of 5.0 % to 5.7 % of biomass.

To test the effect of the potential bias towards over-estimating field height, the mean residual was subtracted from trees within 10 m of the mean canopy height and above.

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This shrank the height of canopy and emergent trees by 1.82 m at Tapajos and 1.23 meters at Reserva Ducke resulting in an average decrease of 4.1 % of transect level biomass at Reserva Ducke and an average decrease of 3.5 % at Tapajós.

3.4 Height prediction via allometry

5 The variability in the diameter and height ranges between sites was large, with maximum heights varying between 39 and 66 m, and maximum diameters ranging from 70 to 213 cm. This variability is indicative of some of the variation in site specific diameter to height allometries. Two of the sites are within the eastern-central Amazon region: Tapajós and Reserva Ducke; whereas the Cauaxí and Tanguro sites are within the
10 Brazilian Shield according to the classification of Feldpausch et al. (2011).

Pan-tropical and regional allometries resulted in substantial differences in estimated heights and biomass at both the individual tree and transect scales (Fig. 4). At all sites, heights calculated using generalized allometries were compared with site-specific allometries based on all field measured heights. At Tapajos the pan-tropical and regional allometries estimated tree heights as 27 % and 33 % less than reference values, with
15 percentages calculated by evenly weighting across all diameter classes. Pan-tropical and regional allometries performed better at Reserva Ducke. There, the height estimate based on the pan-tropical equation was 1 % higher than the reference value whereas the regional equation resulted in height estimates 12 % lower.

20 At Tanguro and Cauaxí, both sites within the Brazilian shield, the generalized allometries performed well. At Tanguro, the pan-tropical equation fit the site extremely well, with an average height 0.3 % higher than the reference. The regional equation also performed relatively well at this site, averaging 4 % greater than the reference. At Cauaxí, the regional and pan-tropical equations also performed well, with heights 1 %
25 higher than the reference using the regional equation and 1 % lower when using the pan-tropical allometry.

Applying these height allometries to the estimation of biomass the regional Feldpausch allometry was 33 % lower than the reference biomass at Tapajos and 12 %

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lower at Reserva Ducke. The same allometry resulted in higher estimates of biomass at Tanguro (by 4%) and at Cauaxí (by 1%). The pan-tropical allometry resulted in lower estimates of biomass at Tapajós (by 26%), Reserva Ducke (by 1%) and Cauaxí (by 2%). This allometry yielded biomass estimates 1% above the reference value at Tanguro.

3.5 Optimization of height measurement for biomass prediction

Local measurements of height:diameter relationships may be important to improve biomass estimates in tropical forests. Sample sizes of 40, 60, 80 and 100 trees were tested for each of the four sites, with trees weighted equally within unequally sized diameter classes. A subset of 40 trees resulted in 95% confidence intervals of transect-level biomass of 7–10%. Increasing the sample to 100 trees decreased this variability to between 4 and 6% at all sites. As expected, as the sampled number of trees increased, the allometry became increasingly consistent with that found for all stems (Fig. 5). Likewise, the variance in biomass estimates due to the differences in allometry converged.

4 Discussion

We aimed to evaluate how precisely and how accurately we could measure tree height on the ground. We then evaluated how the uncertainty in tree height measurements translated into uncertainty in biomass estimates. Because height is important for biomass estimation, we evaluated the accuracy of global or regional allometries. That evaluation suggests caution when employing those relations. We evaluated a labor-efficient alternative as we discuss below.

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4.1 Height measurement precision

The variability in the field measured tree heights was significantly greater for trees above the mean canopy height (Fig. 2). We note that the imprecision of height measurements causes a small error (5 % to 9 %, mean of 6 %) in transect level biomass but that the majority of sources of this error have a consistent positive bias.

Most sources of height measurement error are pronounced for large trees. We recognize five sources of uncertainty that contribute to the precision of field height measurements. Issues in the field measurement of height are: offset between measured distance and crown top position, tree top occlusion, ground slope, obstacles for distance measurements, and clinometer operator error.

Offsets between the distance measured and the true horizontal distance to the crown can cause an unbiased error in height measurement. It is equally likely that distances are overestimated as underestimated. In obvious cases, such as where the trunk was sloped, or the canopy was offset from the trunk location, we attempted to correct the distance measurement in the field. Offsets are most pronounced for the largest trees with large crowns. For these trees the tallest point (measured for total height) are not necessarily centered within the crown area (Andersen et al., 2006).

As the distance between the observer and the tree increases, visibility is reduced by surrounding vegetation resulting in tree top occlusion. This effect was most pronounced for large crowned trees with relatively flat crowns. For the ground-based observer, the flat-topped canopies of some broad leaf trees were indistinguishable from a more rounded shape, even at large distances without obstructions. The observer made assumptions about crown shape to approximate the total tree height. This error was reduced by increasing the distance from the tree and diminishing the extent that the view of the tallest crown point would be occluded by the crown itself.

Ground slope, if not properly accounted for, will cause a systematic overestimation of the distance between the observer and the stem measured. This overestimation of distance will result in an overestimate of height. This was only an issue for sites

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that were measured using a clinometer (Tapajós, Reserva Ducke, Tanguro). The laser range finder automatically corrects for slope when calculating horizontal distance. Of the three sites measured with a clinometer, only Reserva Ducke had notable slopes and for this site, the slope of the measurement tape was measured and the distance corrected.

The distance measurement is also affected by obstacles. When pulling a measuring tape through the forest it is necessary to weave through understory vegetation and other trees. This will create a small bias towards over-estimating distance. Given that the individual making measurements must have a line of site with the trunk base, or a ground position directly beneath the canopy maximum, this line of site can also be used to pass the measuring tape. The measuring tape is always pulled taught and leveled before any reading is made to minimize the potential for overestimating distance.

Because of the perceived difficulty of measuring distance properly, many researchers prefer to use laser range finders or hypsometers (RAINFOR, 2009; Chave et al., 2005 – CTFS). However, it is worthwhile to point out that replacement of the tape and clinometer with a laser range finder does not preclude two major sources of error, offset between measured distance and crown top position and tree top occlusion. Identifying the correct tree top position is the most difficult part of the measurement and the more sophisticated instrumentation does nothing to improve this situation. In addition, the laser range finder adds a source of error. Specifically, the presence of dense understory vegetation may lead to underestimation of the distance between the observer and the tree of interest because of intervening obstacles inadvertently hit by the laser beam (i.e. leaves, branches). This uncertainty led to our preference for direct measurement using a tape measure at the more recently studied sites.

As with any measurement, operator error may occur. The largest differences in repeat height measurement may have been cases of mistaken identity (the crown of one tree was thought to be another). In a comparison of multiple height measurement techniques, Rennie (1979) showed that measurements made with clinometers were generally precise, but showed a slight bias low for the tallest trees measured. However,

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when conducting a similar experiment Williams (Williams et al., 1994) showed a slight bias low for small trees (less than 10 m) and a bias high for tall trees (greater than 20 m). This bias high was more pronounced for conifers than for all species, though the 95 % confidence interval contained zero in all cases.

5 Recently, researchers have proposed an alternative method of height estimation (“the sine method”) that does not require a horizontal distance measurement (Goodwin, 2004). This measurement uses a single distance and angle measurement to the highest point on the tree crown using a laser range finder or hypsometer, and a second measurement of distance and angle to the tree base. The vertical component of each measurement can be calculated by the equipment used and added to yield the total tree height. Larjavaara and Muller-Landau (2013) compared this technique to the traditional tangent method used here and showed that the tangent method resulted in large errors, but unbiased results, consistent with results presented here. The sine method, however, resulted in underestimation of height by an average of 20 %.

15 4.2 Height measurement accuracy

The errors that contribute to field height measurement precision likewise contributed to measurement accuracy. Errors due to slope and due to obstacles when measuring distance will result in overestimation of the horizontal distance and lead to overestimation of tree height. Errors associated with the difficulty in seeing the tree top may result in underestimation or overestimation of tree height. To assess the accuracy of height measurement, field measured heights were compared with lidar estimated heights for emergent stems. Errors that contribute to lidar height error are: overtopping of canopy stems, geolocation error, and lidar measurement error (Andersen et al., 2006; Popescu et al., 2002; Ørka et al., 2010).

25 Overtopping of canopies will result in a positive bias for lidar heights. This bias is due to the use of the Canopy Height Model (CHM) for extracting lidar heights. In our study, this model filtered for the tallest returns within a given 1 m grid cell. By filtering for the highest points, only trees whose canopies are not over-topped by surrounding crowns

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or by taller vegetation are correctly measured (see Fig. 1). This was taken into account when making comparison between lidar and field heights by only comparing emergent stems.

Error in lidar estimations of height are also expected due to error in crown position.

5 Tree canopy positions were referenced to the trunk position, which was referenced to the transect. Transects were geolocated using a combination of differential GNSS and navigational GPS measurements. Errors are present in each of these components that may cancel or compound each other to affect canopy position. These errors will have the largest impact on the smallest crowns. Emergent crowns tend to have large
10 canopies that extend beyond the extent of location error. Emergent crowns average 6.2 m radius while the stem RMS error in horizontal position was about 5.7 m. This, in combination with the lack of local over-topping vegetation results in more accurate lidar heights for the tallest and largest canopies (i.e. emergent trees) compared to smaller, lower canopies.

15 The expected vertical uncertainty of the lidar instrument is 15 cm. The uncertainty in the precision of field measurement was 3.8 m for trees within 10 m below the dominant canopy height, and greater than 8.2 m for trees above this height. Previous research has shown a consistent bias toward underestimation of height using lidar remote sensing in both broadleaf and coniferous trees. Gaveau and Hill (2003) showed an underestimation of 2.1 m for broadleaf trees, and Ronnholm (2004) showed an underestimation of 0.7–1.4 m somewhat dependent on tree species (Gaveau and Hill, 2003; Rönholm et al., 2004; Wang and Glenn, 2008). Clark et al. (2004) found similar results for a tropical forest in Costa Rica. Gaveau and Hill (2003) showed that this underestimation of height is likely due to penetration of the lidar signal into the upper section of
20 the canopy. However, this potential bias is small when compared to the uncertainty in field estimates of canopy tree height.

25 Our field heights were consistently higher than lidar heights for emergent trees. This is consistent with Williams (1994) results showing height measured with a clinometer to be biased about 1 m high on average for trees over 20 m, and in opposition to the

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results of Rennie (1979) showing a slight low bias. This result is also consistent with results showing underestimation of height based on lidar CHMs due to penetration of the outer canopy surface (Gaveau and Hill, 2003). Whether this difference is due to true overestimation of height in the field or due to lidar penetration is unclear. This 1–2 m potential bias represents a difference of less than 6 % of the mean height of emergent trees.

The accuracy and precision of lidar and field measured heights further affects our ability to measure changes in height over short time spans. Where lidar data is available it provides a more accurate source of height information for canopy and emergent stems. This improved accuracy and precision reduce the variability in height measurement. Given that height growth in gaps is greater than 1 m yr^{-1} (Fredericksen and Pariona, 2002), significant changes in height should be distinguishable over shorter time spans using lidar as compared to field data once trees exceed a maximum height accessible by extensible measuring poles (10 to 15 m).

4.3 Biomass precision

The effect of height imprecision on biomass is approximately 6 % and the effect of potential inaccuracy on biomass is smaller (4.1 % at Reserva Ducke and 3.5 % at Tapa-jos) despite the large uncertainty in the height of tall trees (8–10.5 m for trees greater than 34 m). The uncertainty in biomass on the plot basis is less than the uncertainty of height in the largest trees partly because the measurement errors cancel each other out. More importantly, the errors are greatest for the largest trees and most biomass was in medium-statured trees (canopy stratum) that had smaller relative error in height measurements.

Height has been repeatedly shown to improve biomass estimates as compared with diameter only in allometric relations for tropical forest trees (Chave et al., 2005; Feldpausch et al., 2012; Lima et al., 2012; Maia Araújo et al., 1999; Vieira et al., 2008). This result is obvious from inspection of height:diameter relations (Fig. 6). All four sites studied here are moist tropical forests within the Brazilian Amazon but their di-

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iameter : height allometries vary significantly. As Vieira (2008) showed for the Brazilian Atlantic Forest, applying the diameter only Chave and Chambers biomass allometries to a site within the short statured Brazilian Atlantic Forest resulted in overestimates of biomass by 52 % and 68 % respectively.

We compared a number of approaches to biomass estimation using both height and diameter information for the four sites in our study (Table 3). Applying diameter only equations to estimate biomass led to variation of between 4 % to 52 % from our reference case. The largest effect was found at Tanguro, which has the smaller stature of a transitional forest. Other sites generally showed differences of less than 10 %, though the Chambers (2001) allometry performed significantly worse at Cauaxí.

4.4 Height allometries

We evaluated the overall accuracy of the Feldpausch (2011) regional and pan-tropical height allometries based on only four sites. In three cases the relations worked well but based on the substantial differences at one of the four sites we advise caution when applying generic diameter : height allometries. A sensitivity analysis conducted for Tapajos shows the inaccuracy in the diameter to height allometry is caused by variation in climatic variables, most importantly, dry season length. Applying the climatic variables specific to Manaus (which has a significantly shorter dry season) curiously yielded a better fit to the Tapajos data. This suggests that the inclusion of climatic parameters may not be universally advantageous.

The potential for inaccuracy of regional and pan-tropical allometries suggests that site-specific allometries are preferable for accurate estimates of biomass. When formulating site-specific allometries it is necessary to take into account the distribution of biomass at the site. The sampling scheme described in the methods section weighs diameter classes by their proportional biomass. The weighting scheme presented was applicable to all sites despite the variability in diameter ranges. Site-specific allometries estimate biomass within 2 % at Reserva Ducke and Tapajós compared to our reference case where all tree heights were measured.

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4.5 Height allometric optimization

Given the potential for error using regional diameter : height allometries and the importance of height in estimating biomass it is advantageous to have site specific diameter : height allometries. Because height measurements are time consuming, it is important to minimize the number of height measurements necessary to define an allometry to within a target uncertainty. Sample sizes tested were limited by the small number of trees in the largest diameter classes. While allometries fit to Tapajós data were well constrained at the largest diameter sizes, allometries fit to data from Reserva Ducke were not. However, the variability in predicted height for the largest diameter stems made little difference in the predicted biomass at the transect scale due to the extremely small number of individuals in the largest classes. The RAINFOR network has recommended a stratified sample for measuring heights (RAINFOR, 2009) with height measurements for a total of 40 trees divided equally between four diameter classes: 10–20 cm, 20–30 cm, 30–50 cm, and > 50 cm. This smaller sample size would result in a 95 % confidence intervals of transect level biomass approximately twice that of the 100 tree sample suggested here (see Fig. 5).

5 Conclusions

We found that the precision of height measurements of individual trees ranged from 3 to 20 % of total height, leading to a mean error of 16 % in the estimate of individual tree biomass. When scaled to the plot level, this lack of precision of height measurements led to 5–6 % uncertainty in overall plot biomass. Ground based measurements of height exceeded airborne lidar measurements of height by an average of 1.4 m. Whether this is due to overestimation of field height or underestimation by lidar, or a combination of these factors is unclear. If this represents a positive bias in field height, then overall plot-level biomass based on field measurements would be biased 4 % high.

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The use of pan-tropical and regional height-diameter relationships led to large biases for individual site biomass when compared to local field height measurements (Fig. 4): +31 % and 12 % at Tapajós and Reserva Ducke respectively using the Feldpausch regional allometry. The pan-tropical allometry performed better at Reserva Ducke (−1 %), but maintained a large bias at Tapajós (−21 %). For other sites, the regional and pan-tropical allometries were within 4 % of field-based height : diameter relationships. We recommend caution when employing regional and global relations and suggest that field work can be optimized by measuring the height of approximately 100 individuals to build a site specific height–diameter allometry. This approach reduced the potential uncertainty in the biomass of 1 ha plots due to the diameter : height allometry to an average of 4.5 % for all sites studied (Fig. 5).

Regional and global biomass estimates (e.g. Asner et al., 2011; Baccini et al., 2012; Saatchi et al., 2011) that use remote sensing and statistical algorithms for scaling ultimately depend upon the measurements of individual trees. Tree biomass estimates rely on field height measurements or estimates based on diameter–height allometries. Based on our work at sites in the Brazilian Amazon it is unclear whether heights of trees above mean canopy height were biased or merely imprecise. The majority of sources of field height error tend toward overestimation of height, whereas lidar has been shown to underestimate height. This apparent bias in field height results in an overestimate of biomass by about 4 %. This bias is small considering all of the uncertainties involved in field biomass estimates and it is drawn from a limited set of measurements. However, given the availability of airborne lidar height estimates at an increasing number of tropical field sites, we recommend further investigation of this potential bias because of the important role of tropical forests in the global carbon cycle.

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Table 1. Climatic and structural characteristics of field sites.

Site	Ducke	Tapajós	Tanguro	Cauaxí
Mean Annual Temperature (°C)	27	25	25	27
Average Precipitation (mm)	2208	1909	1740	2200
Precipitation Variability (%)	33	45	79	85
Dry Season Length (months)	1	5	5	6
Basal Area (m ² ha ⁻¹) of trees ≥ 10cm diameter	28.7	23.5	17.1	35.2
Diameter Range Measured (cm)	5–128	5–213	10–70	20–192
Mean Canopy Height (m) (Mean Lidar CHM Height)	30 (25)	38 (34)	19	39

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Table 2. Transect live biomass and 95 % confidence interval due to height uncertainty based on 1000 repetitions.

Site	Transect	Biomass (Mg ha ⁻¹)	95 % Confidence Interval
TNF Km 83	1	344	20
	2	310	18
	3	350	21
	4	314	17
	5	263	17
	6	146	13
TNF Km 67	1	267	18
	2	365	22
	3	318	22
	4	267	17
	5	339	21
	6	398	21
Res. Ducke	1	361	19
	2	306	17
	3	336	19
	4	431	21
	5	373	20

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Table 3. Above ground biomass estimate based on various allometries found for the four field sites detailed here. The biomass allometries applied are: the Chave (2005) Model I allometry including wood density, diameter and field measured tree height (“Reference”), the Chave Model I (2005) allometry with site-specific model of diameter : height (“Modeled Ht”), the Chave (2005) Model II equation without a height term (“Chave – D”), the Chambers (2001) allometry based purely on diameter, the Chave (2005) Model I allometry including height modeled using Feldpausch (2011) regional equation (“Regional”), and the Chave (2005) Model I allometry including height modeled using Feldpausch (2011) pan-tropical height allometry (“Pan-Tropic”). Percent difference from Reference value is shown for Reserva Ducke and Tapajós, and from the Modeled Height for Tanguro and Cauaxí.

Site	Reference	Modeled Ht	Chave – D	Chambers	Regional	Pan-Tropic
Reserva Ducke	361	363 (+1%)	382 (+6%)	346 (–4%)	317 (–12%)	358 (–1%)
Tapajós	307	312 (+2%)	317 (+4%)	277 (–10%)	211 (–31%)	225 (–26%)
Tanguro	NA	121	170 (+40%)	184 (+52%)	126 (+4%)	122 (+1%)
Cauaxí	NA	328	360 (+10%)	261 (–21%)	331 (+1%)	322 (–2%)

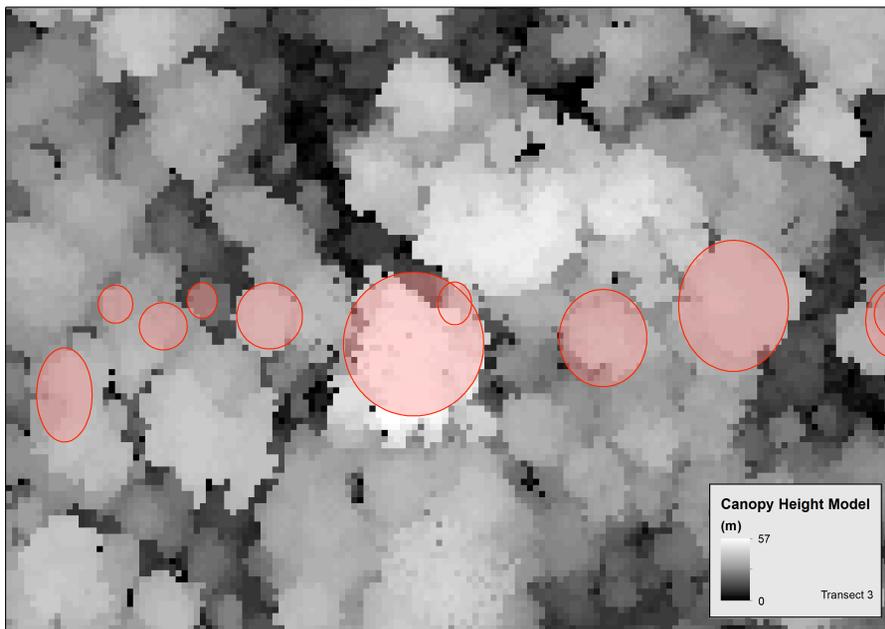


Fig. 1. Crown ellipses of emergent stems overlaid on the canopy height model.

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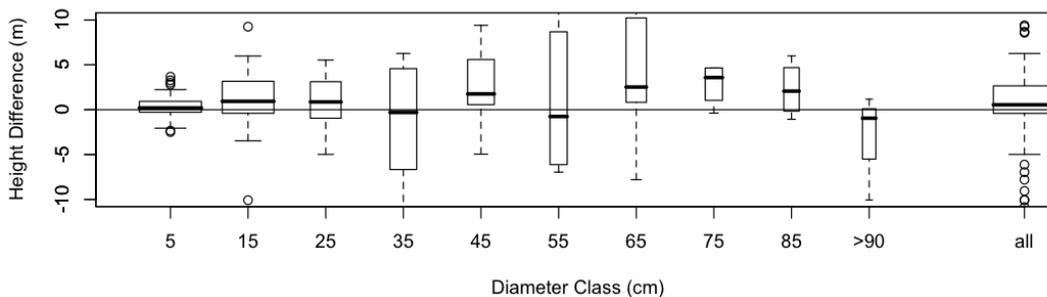


Fig. 2. Height measurements were repeated for 174 trees during a 2009 field campaign at the Tapajós National Forest. Box width is proportional to the square root of the sample size. The mean height difference for all re-measured trees is 1.1 m, with a standard deviation of 4.7 m.

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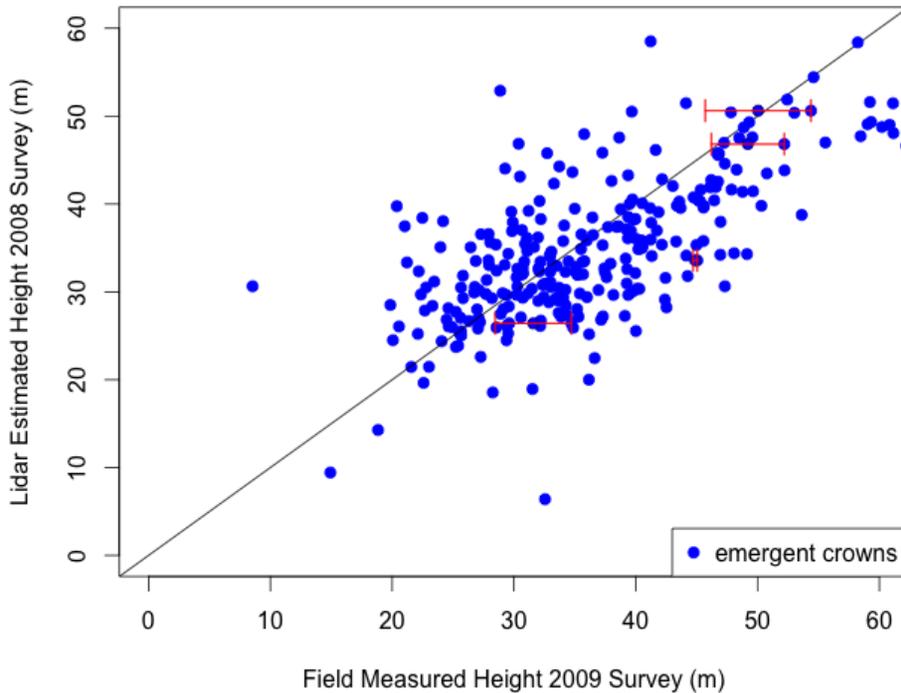


Fig. 3. Comparison of field measured height to that estimated using the Lidar Canopy Height Model (CHM) for stems with emergent crowns. RMSE of emergent crowns is 7.3m. Where multiple field heights were taken for emergent stems mean values are shown with error bar showing the range of repeated measurements.

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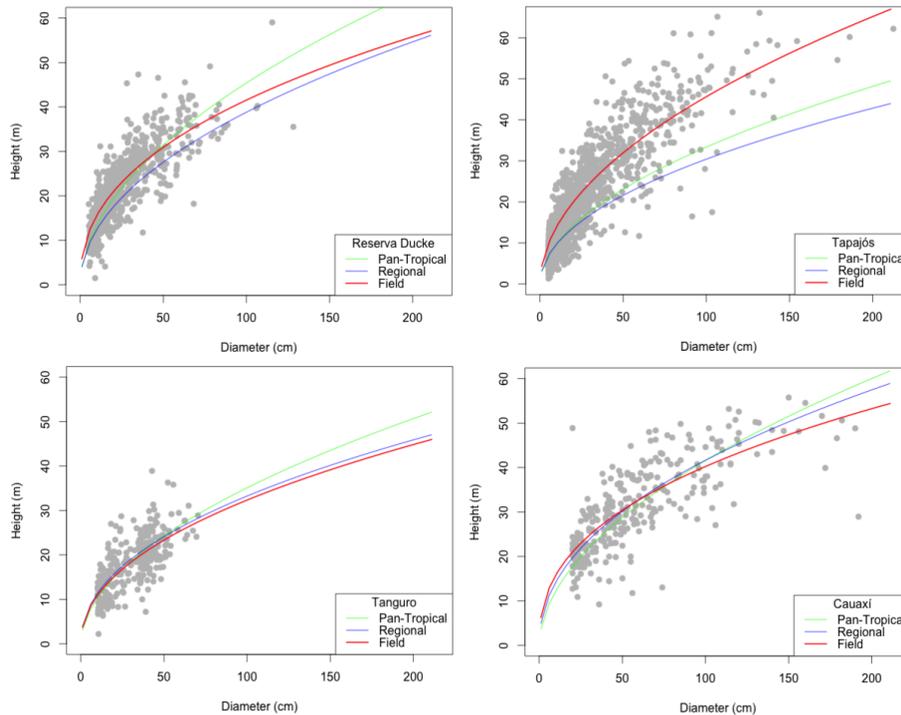


Fig. 4. Comparison of allometric scaling relationships. Regional and Pan-tropical from Feldpausch et al. (2011) and site-specific allometry (Field) based on height and diameter measurements at four sites: Reserva Ducke, Tapajós, Tanguro and Cauaxí.

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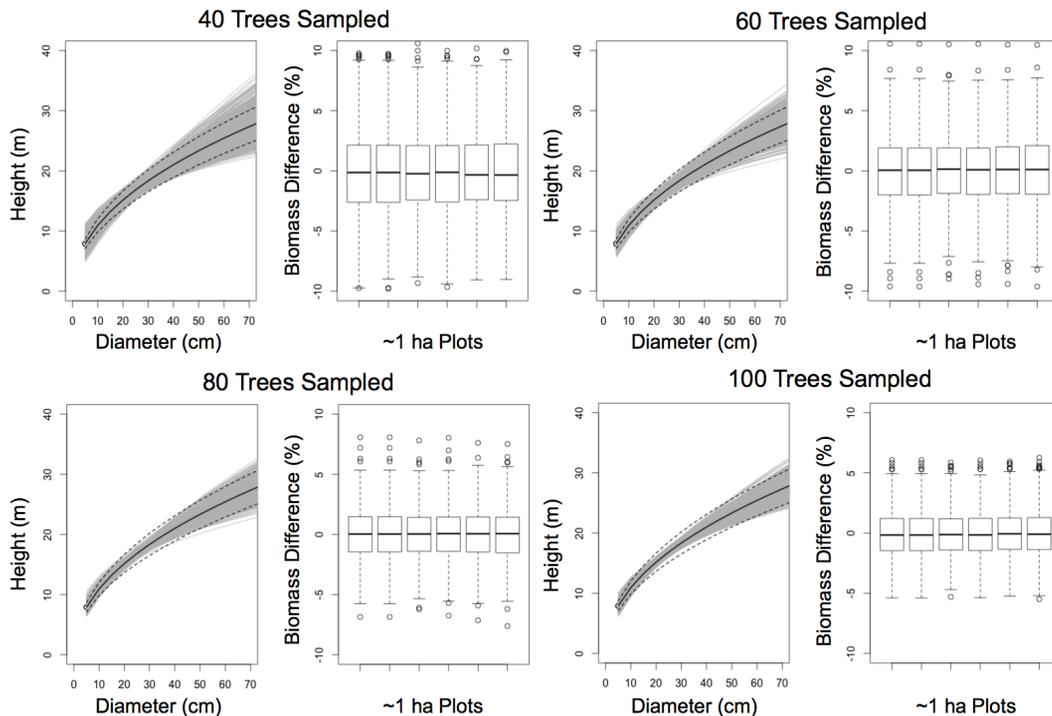


Fig. 5. Effect of sample size on the resulting diameter to height allometric equation for Tanguro. Dashed lines represent a range of 10% difference in height. The grey area represents the range of bootstrap estimates. Boxplots show the variability in six 1 ha transect biomass estimates due to differences in the predicted tree height based on sample sizes of 40, 60, 80 and 100 stems.

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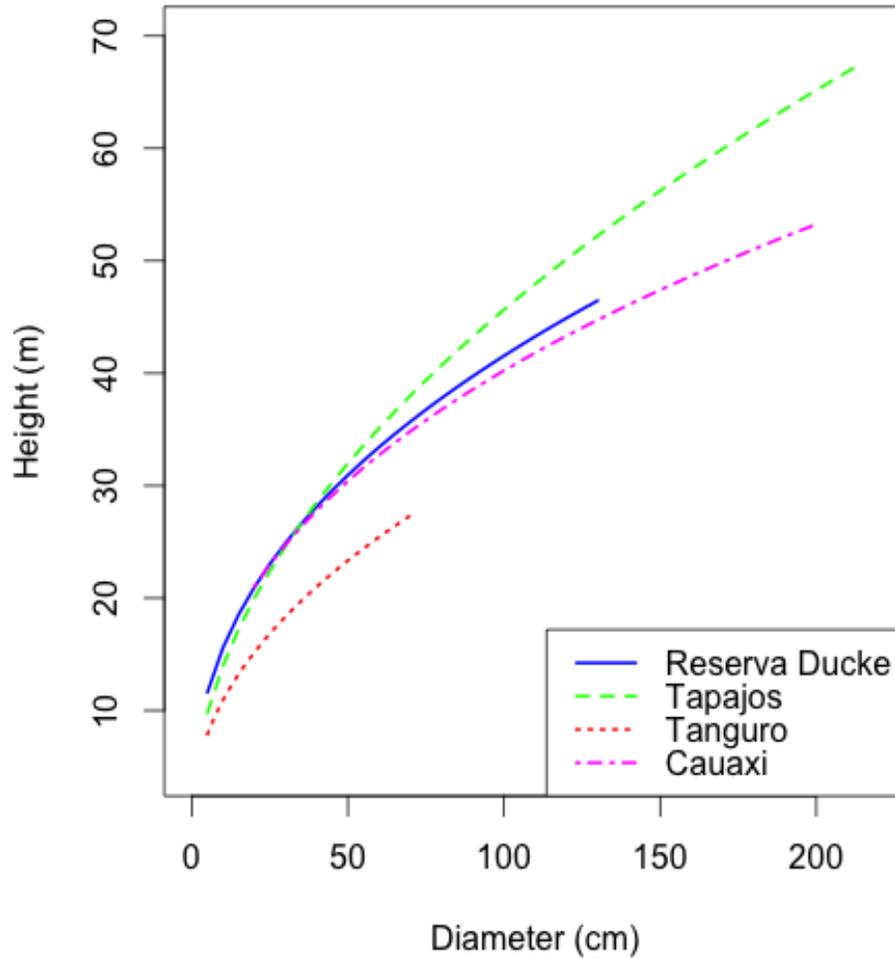


Fig. 6. Comparison of site-specific diameter : height allometries for the four study sites.

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