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Discussions

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Interactive comment on "Tree height and tropical forest biomass estimation" *by* M. O. Hunter et al.

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We are encouraged by the reviews and appreciate the comments. We note that both reviewers accept our major conclusions and neither reviewer has questioned the validity of our methods or the quality of our results. We have quoted from the reviews and provided our replies below (each reply begins with >). Modified tables and figures are included at the end of our response.

Interactive comment on "Tree height and tropical forest biomass estimation" by M. O. Hunter et al. Anonymous Referee #1 Received and published: 10 September 2013

The study is one of several recent papers that attempts to determine how important height estimation is in the estimation of tropical forest biomass. Several similar papers have appeared in the journal, although in general these data are difficult to collect and the authors have focused on a critical issue currently debated in the tropical forest

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carbon community (i.e., contrast recent papers by Saatchi et al., Baccini et al., Chave et al., Asner et al. on this point). However, a number of major issues deserve added attention.

The methods of the study are extremely unclear, and this makes the results very difficult to interpret. I recommend that the authors make a simple declaration, in a single table, of all the site information; whether or not the site was used for biomass sampling and / or tree height sampling; what type of biomass sampling was applied; what type of height sampling was applied; etc. From a simple read of the methods it is not at all clear which sites were used for which type of sampling and which sites were used to test which hypotheses. The reliance on site names should be minimized and at minimum it should be standardized. The table should be separate from any computational analyses, which likely belong in a second table. For instance, the authors say that they used Lorey's height to determine mean canopy height (Page 10496, lines 18-22), yet they present LiDAR mean canopy height for some regions but not others. Lorey's height, LiDAR MCH, BA, and biomass estimates should be on a separate table and it should be made very clear which sites have LiDAR data and which do not.

>Some of the sites studied here are important for tropical forest research (Keller, et al. 2004), and many readers will be familiar with the names. However, we accept the suggestion and site names were standardized. The usage of TNF is replaced with Tapajos k67, Tapajos k83 or Tapajos sites in all cases. We also removed usages of Ducke to consistently refer to this site as Reserva Ducke. Additionally, we accepted the suggestion of limiting Table 1 to present site climatic parameters and locations only. A new table has been added that presents computational analysis, both structural information on each site and basic information from the lidar data collections including the date of all collections. To minimize confusion regarding the differences between Tapajos km 67 and Tapajos km 83, these two sites are counted as separate sites because they are not pseudo-replicates. We include separate columns for each site in both the revised Table 2 (what was Table 1) and the new Table 3. Additionally,

the reviewer suggests clarifying what data sets are applied to each question. This suggestion was accepted, and this information is now included at the beginning of the methods section 2.1, and in a new Table 1. All new and revised tables are included at the end of this response. "Data from five sites in four regions of contrasting forest structure distributed across the Brazilian Amazon were used to answer the questions posed above. The precision of ground-based tree height measurements was evaluated by comparing repeat measurements of height at one of the field sites, Tapajos km 67. The accuracy of height measurements was evaluated by comparing field and lidar data at the Tapajos sites and at Reserva Ducke. The resulting estimates of accuracy were applied at Tapajos sites and at Reserva Ducke to answer the third question, and the remaining questions were addressed using field data from all sites."

The number of sites (four) is touted, but only two have LiDAR data. The authors need to justify why this low number of sites with both field data and LiDAR make this study convincing.

>We believe the data presented is sufficient to assess the questions posed. There are in fact five sites studied within four areas of the Brazilian Amazon. Two sites are within the Tapajos National Forest, Tapajos km 67 and Tapajos km 83. The former site is undisturbed and the latter site was selectively logged and therefore is a true replicate. Three of these five sites have lidar data. Furthermore, lidar data is only used to answer one of the five questions posed, whether height measurements are accurate. The lidar data covers areas with tall, dense canopies and topographic variability. Given that these conditions should maximize error in both lidar and field data, we believe this data is sufficient to draw conclusions on accuracy of height measurements. With regard to the field data, the five sites are spread over a fair amount of the Amazon biomass and climate regime, as shown in Table 1. With exception to the comparison with the Feldpausch model conclusions are consistent across all sites, suggesting that our results are not site dependent. With regards to the Feldpausch model, additional sites would strengthen our ability to draw conclusions on the general validity of these

models. Future studies will further elaborate the broad applicability of our results.

In the current "table 2" the authors present site names that are not compatible with Table 1. Are these TNF sites psuedoreplicates or subplots? This is unclear from both the text and the table captions. Please revise as recommended above.

>Site names in table 2 should be "Tapajos km 83", "Tapajos km 67", and "Reserva Ducke". The two sites within Tapajos National Forest are physically distant from one another (approx. 15 km) and one is old growth forest while the other has been selectively logged. The site description of Tapajos National Forest has been corrected to read,

"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 (Tapajos km 67) and a selectively-harvested site (Tapajos km 83)."

None of the Figure captions or Table captions are clear. What, exactly, is being shown in Figure 1?

>The figure 1 caption has been edited to read,

"Figure 1. The canopy height model is shown for a region of Tapajos km 67, with darker shades of grey corresponding to lower canopy heights. Field data collected along a transect within this area include four measurements of crown radius and position. This field data was used to draw crown ellipses for emergent stems that are overlaid on the canopy height model."

Figure 4 is highly confusing at looks like it contains an error of some kind. If I look at the "Pan-Tropical" Feldpausch model (the green line), I see that it is drawn differently in each panel. This makes no sense. Why doesn't the model appear consistently in all four panels?

>The pan-tropical and regional models of Feldpausch et al. (2011) take into account local climatic and structural parameters (including mean annual temperature, precipi-

tation variability, dry season length and basal area). The figure caption was edited to read,

"Figure 4. Comparison of allometric scaling relationships. Regional and Pan-tropical allometries from Feldpausch et al. (2011) that include site-specific climatic and structural parameters (reported in Table 2 and Table 3 respectively) and a site-specific allometry (Field) based on height and diameter measurements at all sites: Reserva Ducke, Tapajos, Tanguro and Cauaxí."

The text is not concise. Paragraph one of the discussion is an example. Overall, manuscript length could be shorted by 25%.

>We have rewritten the paper to respond to reviewers comments, aiming to be both clear and concise in our presentation. Often, we found that to respond to reviewer comments it was necessary to add detail to the manuscript (see for example the next comment below). We are perplexed by the selection of the example where we concisely restate the general questions in only 67 words. The revised paper is well within the length limits normally observed for Biogeosciences and although we did endeavor to remove excess words and to keep the text as short as possible while retaining clarity, we did not find it possible to shorten by 25% as proposed by the reviewer.

The paragraph beginning on Page 10511 lines 24 is an exception that should be expanded. Over and over tropical forest studies recommend height measurements that will improve upon biomass estimates from diameter alone – yet the current authors say little about why this is the case except that D:H relationships vary. This was well known to Chave, yet they still provided a diameter-only model. It seems that the authors are arguing that such models are obsolete in the tropics yet they never become clear on this point. Based on their results, it would seem that diameter-only models are totally unreliable.

>This paragraph was expanded to include additional information on potential reasons for the variability in diameter-height allometries. In our conclusions we recommend that

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diameter and height allometric equations be used wherever possible, and specifically suggest field methodology that reduces variability in biomass allometries through the measurement of a limited number of heights.

"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 (Figure 6). All four areas studied here are moist tropical forests within the Brazilian Amazon but their diameter:height allometries vary significantly. Some of this variability in diameter-height allometries is believed to be due to climatic variability (Feldpausch et al., 2011). Other research has shown that the use of species-specific allometries improves precision of biomass estimates (Basuki et al., 2009). However, the high species richness and lack of species specific allometries makes the use of species-specific allometries in the Amazon infeasible. Tree architecture and variable species assemblages are also important drivers of variability in generalized diameter-height allometries. As shown by Jansen et al. (2008) trees also respond to their immediate environments, causing additional variability in diameter to height allometry. In some cases, the use of diameter-only allometries cause large errors in the estimation of biomass. Vieira et al. (2008) used two diameter-only allometries to estimate biomass in the Brazilian Atlantic forest (Chave et al., 2005 and Chambers et al., 2001) and found overestimates of biomass by 52% and 68% respectively."

Minor issues:

Page 10493, lines 27-28: Very few field studies "measure" biomass by harvesting and weighing; field studies typically rely on allometric equations to link field measurements of diameter, height, etc. to biomass stocks – this is not fundamentally different from remote sensing studies (see extensive discussion in Asner et al. 2013 Carbon Balance and Management).

>This topic has been treated in great depth by Clark and Kellner (2012) who empha-size the fundamental problem that biomass estimates are evaluated without actual measurement of biomass in the field. This sentence was changed to clarify that field measurements are used in combination with allometries to calibrate remote sensing estimates of carbon stocks, and is included below,

"However, neither existing nor planned remote sensing data sets directly measure biomass; they all rely on field data in combination with allometric estimations for cali-bration (see further discussion in Clark and Kellner, 2012)."

Page 10494, line 18: Feldpausch et al. 2012 made the 2011 study obsolete, replacing flawed power-law height models with more appropriate asymptotic models (i.e., weibull functions).

>Initially we used the 2011 allometries because they were designed to estimate height as opposed to biomass and that could be directly compared with our own data. As a result of direct discussions with Dr. Feldpausch regarding an earlier draft of this manuscript, we ran comparisons with the 2012 equations and results did not change significantly. Additionally, we attempted to fit Weibull curves to the site specific data and found that in more than one case, the fit would not converge. This is especially problematic when trying to minimize the size of the data set necessary.

Page 10495, lines 17-19: It is not clear what is meant by this statement. If biomass is estimated from diameter alone, how could height measurements influence the corre-sponding output from allometric models that use diameter alone?

>This paper specifically compared a height and diameter based allometry to one using diameter alone. The sentence in question was changed to clarify this,

"Williams and Schreuder (2000) compared a diameter-only allometry to a diameter and height allometry and 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."

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Page 10499, line 11: the number of living trees has already been mentioned.

>The second reference to the number of stems will be removed.

Page 10503, line 23 – Page 10504, line 2: this information should be moved to the methods section.

>We moved the majority of this paragraph to section 2.4, within the methods. However, the last statement regarding the mean difference between the lidar and field measurement of height of emergent stems was left in the results.

Figure 3: consider coloring the points by site and adding additional detail to the figure caption.

>We accept this suggestion and have changed the figure and caption description accordingly. They are included at the bottom of this response.

Interactive comment on "Tree height and tropical forest biomass estimation" by M. O. Hunter et al. Anonymous Referee #2 Received and published: 11 September 2013

This research provides valuable insight into the uncertainties inherent in the height relationship with biomass and allometric estimation in terrestrial forests; including field measurement precision, field measurement accuracy, sample quality, and generalization uncertainty in allometric relations. This work maintains its focus on relevance to field estimation and allometric models, while offering a breadth of discussion on both implications of uncertainty into estimation at scale and makes recommendations on in-field techniques.

This review identified no technical or procedural inconsistency or anything that indicated poor methodology.

The language and presentation of the work was generally good and clear, however there are instances where the language is awkward or hard to interpret. It is also recommended that terminology be re-evaluated, for instance there were instances where

the word "offset" was being used to describe differences which was confusing (this is just an example). But overall the language and presentation was good/acceptable.

Specific Comments: Intro:Line 27: this may not be implicitly asserted in your text, but it is literally impossible to measure anything directly from space, it is all proxy and model from radiation.

>With regard to biomass, we agree with the reviewer and specifically use "estimate" as opposed to "measure" in these cases.

2.1 line 12: It is not immediately clear to the reader why climate information is relevant, is it just anecdotal, or will this influence things like generalized allometric relationships that are used in this study? Please give a short note on why you are telling us this.

>Feldpausch et al. (2011) found that environmental and structural parameters significantly improved diameter-height allometries. The regional and pan-tropical allometries that are analyzed in this paper include these parameters. This is now addressed in section 2.5.

2.3 line 8: "returns for every shot", the term "shot", is this synonymous with pulse? Or are you indicating a set of pulses? Please clarify what a shot is.

>Shot is synonymous with pulse, the line has been changed to read, "returns per outgoing pulse" to clarify.

2.3 line 13: "use to estimate offset", it is unclear what you mean by "offset". Is this measurement differences, error, ...?

>This refers to the position error of the lidar collection, and has been changed to "position error".

2.3 line 20-23: You cover the uncertainty of the canopy top lidar estimates. However you do not really cover the uncertainty in your estimate of modeling the forest ground floor. It appears that the point density of ground hits is low, and that a TIN model is

used to interpolate in between these hits. Please give some indication of the ground hit point density, and your confidence in the ability to estimate the depth to ground. It was mentioned that the topography of these sites with one exception was relatively flat, if this is the argument please comment on that.

>The manuscript has been edited to include the average number of ground returns per area (m2). The problem of modeling the forest floor is being addressed currently by another member of our research group. Veronika Leitold has a manuscript in preparation using data from the same instrument and similar operational conditions. This data shows that with the level of return density in our data, the error in DTMs is negligible even in complex terrain. Briefly, Veronika Leitold and colleagues worked in the Brazilian Atlantic forest using data from the same instrument with return density on average of about 20 returns m-2. They worked on terrain with slopes up to 30 degrees, and collected 35 points with differential GNSS. Using the 30 best dGNSS points (sigma < 1m) a mean difference of 7.4 cm was found between the lidar DTM and the dGNSS points (V Leitold et al., in preparation). The following sentence is added to section 2.3.

"The density of ground returns was 0.44 per m2 at Tapajos km 67, 0.19 at Tapajos km 83 and 0.83 per m2 at Reserva Ducke. Using a similarly high density of data collection and the same methods for constructing a DTM (1 m grid), a mean error of less than 10 cm was achieved (V. Leitold, personal communication)."

2.5 line 5-7: Is there any temporal difference in your repeat sampling in the Tapajos? If the time difference is significant you have to factor in the possibility of growth increments. If sampling was done in relatively close temporal proximity, please note that.

>Temporal differences of about one year are present at both Tapajos sites and Reserva Ducke. We have added the dates of collection to Table 2. We tested the potential effect of this temporal offset by comparing heights measured in the field with a one year inter-sample period. Although the means have a -0.6 m height loss over this period, there is no significant difference (t-test p=0.73). This potential issue is now addressed in the

methods and results sections.

2.5 line 13: Regarding the random number generation. What was the distribution you selected random numbers from, the reader may assume uniform as a default, is this the correct assumption?

>A normal distribution was used, and this sentence was clarified as follows,

"Returning to the full data set, a series of random numbers normally distributed with a mean of zero, and a standard deviation matching that of the height difference within each diameter class was calculated."

2.5 line 24: This sentence is pretty awkward, please make it more concise and easier for the reader to interpret. (awk will indicate other instances)

>The sentence has been modified in the hopes of improving clarity,

"The range of diameters used to determine the four diameter classes spans from the minimum to the 99th percentile of diameters measured. In order to divide the diameters into bins, the full range is further divided into fractional sub-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 sub-ranges are divided in half to further distribute the sample."

3.1 line 19: Awk, also, please be clear or definitive about what "offset" means.

>This sentence is edited as follows,

"The difference between first and second measurements were an average of 16.57% of the mean height measured (median of 11.9%)."

3.1 line 21: I may have interpreted your explanation wrong, but it is statistically unlikely that standard deviations of sub-samples will increase, when taken from the whole population. A spread in mean values should decrease the average distance between the means and their respective sample points. This was either confusing and surprising, could you please check/explain/clarify this result?

>The standard deviation reported is specific to individual size classes. As the size class increases, the standard deviation of height also increases in relative terms as well as absolute terms. This suggests that we measure tall trees less precisely than short trees in the field. The manuscript text was modified to clarify this result as follows,

"Dividing the remeasured heights into four diameter classes with an equal number of samples, the standard deviation of height differences within individual size classes increases by a factor of eight from 1.09 m to 8.17 m. This represents an increase in relative terms as well as absolute terms and suggests that field measurements of tall trees are less precise than short trees."

3.2 line 27: Should this be -1.4m?

>Yes, this has been changed to 1.4 m.

3.2 line 8: (awk)

>Edited to read as follows,

"Height residuals (lidar minus field height) show a slight positive trend when regressed against lidar height. This 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."

3.4 line 13: "were compared with heights modeled via site-specific ..." or something similar

>This sentence was changed as suggested.

3.4 line 15: "reference values", I assume this means the field measurements, but explicitly stating this will be easier for the reader

>The reference values are in fact the values modeled using the allometry based on field height. It should be noted that the values in the text below are different from the original

text. This is due to a correction sent personally by Dr. Ted Feldpausch, who pointed out that the basal area of the undisturbed forest should be used for both Tapajos sites. This resulted in a small change to final values, but no change in the conclusions. This comment was accepted, and the text was revised as follows,

"At Tapajos the pan-tropical and regional allometries estimated tree heights as 22% and 27% less than the field height based model, with percentages calculated by evenly weighting across all diameter classes."

3.5 line 6-7: The first sentence does a weak job at motivating your analysis and discussion of the sample size.

>This sentence was modified to make a stronger case motivating the analysis,

"We ask whether local measurements of height:diameter relationships are important to improve biomass estimates in tropical forests and if so, how much effort must be put into local estimation."

3.5 line 9: "weighted equally", this is unclear what this means. Do you mean that samples attempted to balance or have equal selections from the various size classes?

>This refers to the fact that an equal number of trees were selected from each of the four diameter classes previously defined in section 2.5. The text in question was edited to clarify this point as follows,

"For each sample, an equal number of trees were chosen from each of four diameter classes (defined in section 2.5)."

3.5 line 11: why is there a range 7-10%, is this the cross site range? Please clarify

>This is across sites, but the 95% confidence interval reported is for transect biomass. At a given site, this interval is relatively constant. Between sites, the confidence interval varies.

4.1 line 3: The plot shows variability in the differences between re-sampled individuals

no, the text does not specify what exactly is varying. Please be a little more concise about what exactly is varying.

>This sentence referenced a figure that was removed from the manuscript, and the reference to the figure was therefore removed.

4.1 line 5: "but the majority of the source", please elaborate and clarify, little awkward, what sources and what positive bias?

>This was an attempt at foreshadowing. We removed the second part to improve clarity.

4.1 line 11: offsets -> differences

>Accepted.

4.1 line 14: this usage of "offsets" make sense, please treat this as a non-comment! 4.1 line 16: this usage of offset... this is a physical offset between the horizontal position of the crown top and the trunk base, in this context you are indicating there measurement uncertainty attributed to this offset, which is a source of error or uncertainty. My point is to just have a consistent strategy and clear delivery of these concepts.

>We see your point with regards to our indiscriminate use of the word "offset". In all but cases where "offset " means a difference between two physical locations, we have changed the wording to clarify our specific meaning.

4.1 line 29 (after break 10507, talking about Rennie 1979): "bias low" consider changing to "underestimation bias", and for subsequent usages: "overestimation bias" and "underestimation bias"

>Comment accepted. The text now reads as follows,

"Rennie (1979) showed that measurements made with clinometers were generally precise, but showed a slight underestimation bias for the tallest trees measured. However, when conducting a similar experiment Williams (Williams et al., 1994) showed a slight

underestimation bias for small trees (less than 10 m) and an overestimation bias for tall trees (greater than 20 m). This overestimation bias was more pronounced for conifers than for all species, though the 95% confidence interval contained zero in all cases."

4.2 line 15: "The uncertainty in the precision", unsure what this means. Please clarify.

>This should be the precision. It is the standard deviation of trees within 10 m below the canopy height at Tapajos. The text was changed.

4.3 line 28: "applying the diameter only Chave and Chambers" (awk)

>Accepted. The text now reads as follows,

"Vieira et al. (2008) used two diameter-only allometries to estimate biomass in the Brazilian Atlantic forest (Chave et al., 2005 and Chambers et al., 2001) and found overestimates of biomass by 52% and 68% respectively."

4.3 line 8: "reference case" using this terminology is not inaccurate, but it is easier for the reader to explicitly state what reference case is (field estimates).

>This was not changed as the 'reference case' is not the same thing for all sites. For Reserva Ducke and Tapajos, where all trees were measured, the reference case is biomass calculated using all tree heights (Table 3, column 1). At Tanguro and Cauaxi, where only a subset of tree heights were measured, the reference case is calculated using the modeled height (Table 3, column 2). However, to improve clarity, the reference case was emboldened in the table.

Interactive comment on Biogeosciences Discuss., 10, 10491, 2013.

Site / Data Available	Reserva Ducke		Tapajós km 67		Tapajos km 83		Tanguro	Cauaxí
	Field	Lidar	Field	Lidar	Field	Lidar	Field	Field
Q1. Precision of ground-based height measurements			X					
Q2. Accuracy of ground-based height measurements	X	X	X	X	X	X		
Q3. Affect of height uncertainty on biomass prediction	X	X	X	X	X	X		
Q4. Use of global / regional diameter-height allometries	X	X	X	X	X	X	X	X
Q5. Optimization of field data collection	X	X	X	X	X	X	X	X

Fig. 1. Table 1. Data used to address each of the five questions posed by this research. Lidar data was available for three of the five sites.

Site	Reserva Ducke	Tapajós km 67	Tapajos km 83	Tanguro	Cauaxí
Location	59°57'W 2°57'S	54°57'W 2°51'S	54°58'W 3°01'S	52°23'W 13°04'S	48°17'W 3°45'S
Mean Annual Temperature (C)	27	25	25	25	27
Average Precipitation (mm)	2208	1909	1909	1740	2200
Precipitation Variability (%)	33	45	45	79	85
Dry Season Length (months)	1	5	5	5	6

Fig. 2. Table 2. Site locations and climatic characteristics.

Site	Reserva Ducke	Tapajós km 67	Tapajos km 83	Tanguro	Cauaxí
Number of trees measured (N)	817	913	852	844	2171
Tree heights measured (N_{ht})	817	913	852	308	306
Area sampled (ha)*	3	5.1	5.1	6.66	14
Basal Area ($m^2 ha^{-1}$) of trees ≥10 cm diameter	28.7	31	17.6	17.1	35.2
Diameter range measured (cm)	5 - 128	5 - 213	5 - 186	10 - 70	20 - 192
Lorey's height (m)	30	38	38	19	39
Date of field data collection	10/2009	06/2009	01/2010	11/2005	07/2000
Area of lidar data collected (ha)	1200	400	768	NA	NA
Mean CHM height (m)	25	34	34	NA	NA
Date of lidar data collection	06/2008	06/2008	06/2008	NA	NA

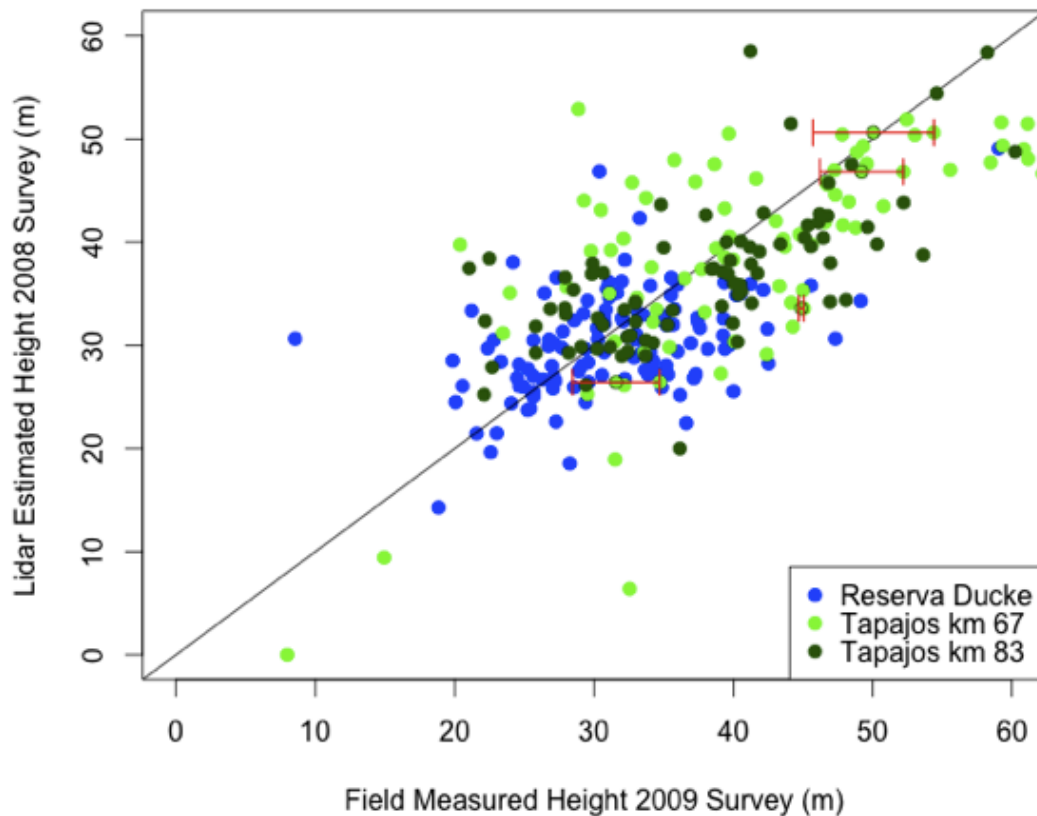**Fig. 3.** Table 3. Details of field and lidar data collections. Lorey's height is the basal area weighted mean canopy height.

Fig. 4. Figure 3. Comparison of field measured height to that estimated using the lidar Canopy Height Model (CHM) for stems with emergent crowns at Reserva Ducke, Tapajos km 67 and Tapajos km 83.