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Interactive comment on "Tree height integrated into pan-tropical forest biomass estimates" *by* T. R. Feldpausch et al.

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Response to Reviewer 2: "Tree height integrated into pan-tropical forest biomass estimates" by T. R. Feldpausch et al.

The paper addresses one of the key questions about the use of tree height in improving the biomass allometry. This paper is definitely an excellent contribution to improving the biomass estimation in tropical forests. The presentation of the methodology and the results are sound and accurate. However, the paper suffers from some general and to a large extent unrelated and sometimes erroneous statements in the discussion section. The discussion section is long and includes many subsections covering a variety of topics, and in most cases longer than the methodology and results sections. The authors try to comment on everything from remote sensing methods, carbon, REDD, climate, global emissions, sources, sinks, etc. I recommend the paper for publication after major revisions and reduction of the discussion section. Revisions are mainly editorial and do not suggestion any revisions of the analysis or the results. General Comment: The authors present a negative view of the remote sensing results in the discussion section. They have several claims that are not correct: 1. “Transforming variation in tropics-wide biomass estimate due to H into reliable. . . “ is not a correct statement. The authors should not forget that the resent enthusiasm in biomass estimation at spatially refined scales and inclusion of height predominantly originated in the remote sensing community when forest height measurements from space became available. Height could not and cannot be measured accurately in the field and if it was not because of Lidar and to some extend radar technology, height would've been ignored completely in field inventory data. Most of the fild data, including Rainfor data never included height estimation in earlier years. In recent years, several algorithms have been developed to relate forest height metrics (various estimates of height such as maximum, mean canopy height, etc.) to biomass. There will never be one algorithm to fit all. However, with few models in place, we have the general form that can work for tropical forests. I think the remote sensing approaches related to height and biomass is definitely more developed than field approaches and allometry.

Response: We would like to thank the reviewer for the overall positive assessment of our work, for the many useful suggestions to focus the manuscript and convey our main points in the results and discussion, and help in improving the manuscript.

We disagree with the reviewer's comment that “height could not and cannot be measured accurately in the field.” as it is, simply stated, not correct. Ground-based height measurements are well established and follow international protocols (e.g. Chave et al. 2005, “Measuring Tree Height for Tropical Forest Trees” http://www.edb.ups-tlse.fr/equipe1/chave/tree-height-protocol.pdf); and, a recent comparison of ground-based methods found that ground-based trigonometric methods resulted in no bias (non-laser method), or resulted in a small underestimate of actual tree height (ground

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laser-based methods) compared to heights measured from an observational tower (M. Larjavaara and H. Muller-Landau, in prep). A second study reported a Pearson correlation of r2 = 0.977 for trigonometry versus laser rangefinder estimates of height (Marshall et al. 2012). Our ground-based height estimates based on similar methodologies are therefore robust and provide an important step in determining how H:D allometry varies for individual trees among regions, and how those differences affect the error in biomass estimates and the actual biomass estimate. As the reviewer points out, one algorithm will never fit all. It is therefore also important to note that, for the interested researcher, the large ∼40,000 tree H:D database of Feldpausch et al. 2011 provides an unprecedented opportunity to develop regional Lorey's height relationships to relate to co-located GLAS footprints, rather than relying on pantropical relationships, and so improve the fidelity of remote-sensing estimates of forest biomass.

2. The authors claim that in Saatchi et al., 2011, "this study estimates biomass based on equations that were developed using height data collected from temperate forests from North America and tropical forests rather than exclusively from tropical forests." This statement is not correct. Saatchi et al. 2011. They used individual lidar waveform data from ICE- SAT GLAS sensor (not Lefsky 2010 height map), then computed Lorey's height using the form of the equation given by Lefsky 2010 for broadleaf forests, but calibrated the relation with only the data in tropical data (coefficients of the equations are different). The supplementary material of the PNAS paper states this: "The model was calibrated with three study areas with ground estimates of height in the Amazon basin, located in the municipalities of Santarem, Para State; Manaus, Amazonas State; and Canarana, Mato Grosso State, all in Brazil." Even though the form of the model is the same for the broadleaf forests shown in Lefsky 2010, the coefficients are different. In addition, Saatchi et al. 2011-used Lorey's height to biomass relationship developed strictly from tropical data (Figure 1; shows equations from 493 plot data). In fact, the slightly lower estimate of biomass in tropical America from Saatchi et al 2011 can be partially attributed to the use of height for biomass estimation.

Response: Our understanding, on reading the Saatchi et al. 2011 paper and the supplemental information in Baccini et al. 2012 (the latter referring to methods used in Saatchi et al. 2011), was that the models were based on data from temperate regions, not just the model form. We thank the reviewer for pointing out this error in our understanding and we have amended our text appropriately. The indisputable point remains, however, that Feldpausch et al 2011 and Banin et al. 2012 have shown H:D allometry to vary significantly by region and continent, and accounting for this richly sampled variation will improve remotely-sensed estimates of biomass, rather than basing spaceborne estimates on Lorey's height calibrated from only three sites in Amazonia.

Specific comments 1. Introduction: Biomass cannot be estimated by passive remote sensing (landsat). Drake, Stienenger, and Mitchard did not use Landsat to estimate biomass. It is better to change the statement and mention radar and lidar, both active sensors and use references such as Saatchi et al., 2011; Mitchard et al., 2011; Drake et al., 2002; Asner et al., 2009.

Response: Reworded as requested.

2. Introduction: line 25: The statement: "Nevertheless, these all require plot-based. . .." needs to be changed. I am not sure why the authors say this. Almost any technique needs to be calibrated and validated. Even the ground measurement of biomass (harvesting) or estimation (allometry) should go through calibration and vali- dation. Furthermore, the statement says at the end " and have large uncertainty." This is again a wrong statement what has large uncertainty? High-resolution Lidar data calibrated with the ground measurements can have less uncertainty over landscapes than limited samples of ground plots estimating landscape scale biomass. I suggest, the authors be careful about use of these terms. Unfortunately, field researchers have assumed what they estimate from ground over highly selective areas are not uncertain or biased. In fact, most of the recent results show that field data from research plots (using preferred locations) is extremely inadequate to understand distribution of biomass in tropics. Most of the field plots are located in selectively large biomass forests. A rea-

sonable field estimation approach requires systematic sampling of the forest and a true error propagation effort. S such field techniques are very common in Forestry practices in Northern Hemisphere.

Response: The sentence as written is correct in that it states that any remote sensing of biomass is impossible without ground-based measurements. Likewise space-borne estimates of tree height to infer stand-level biomass are meaningless without plot-based verifications. And our results show that those ground-based estimates of biomass are prone to greater error when excluding height. The reviewer would seem to be mixing questions of accuracy of point-based estimates of biomass (either remotely- or ground-based) with uncertainty associated extrapolation of those estimates to a greater area. This section, as written, could have been better constructed as it refers to estimation of biomass at a point, with the paragraph then going on to explain how extrapolation from those points to larger areas results in great uncertainty. We have modified the paragraph construction and contents to reflect these concerns, also including the Houghton et al. 2010 and Saatchi et al. 2007 references as requested below.

3. Please do not use Houghton et al 2001 as an example of biomass being uncertain. Since that publication, there have been several papers including new papers by Houghton in 2010, Saatchi et al., 2007; and others. Houghon et al. 2010 used very old data (44 plots), do not have a remote sensing estimate of biomass.

Response: We have included these updated references as requested.

4. “Accounting for H:D allometry may reduce uncertainty may reduce. . . from plots to pan-tropical scales.” I agree that it is important to include H in allometry. However, it is still not clear how the authors extend this to pan-tropics. First, H cannot be measured accurately in the field. Second, uncertainty in pan-tropic estimate of biomass may be related to sampling error than allometry. This has not been proven yet. It is in fact easy to argue that the largest uncertainty may be in sampling and measurement errors. Other errors such as wood density can contribute to the same degree as height

to biomass estimation over large regions.

Response: (i) as described above, we disagree that H cannot be measured accurately in the field and we really do wonder why the reviewer would think that; (ii) in scaling from plots to pan-tropical scales, the reviewer, taking a remote sensing viewpoint, depends on the same site-based ground-based biomass estimates that our scaling depends on. As we have previously noted, space-borne estimates of biomass are impossible without plot-based ground-based estimates of biomass. Space-borne methods then suffer the same potential sampling error that the reviewer describes. The goal, for both methods, is to reduce uncertainty in ground-based estimates of biomass prior to scaling and they are complimentary (as opposed to competing) approaches. We show that incorporating height into biomass estimates reduces uncertainty, thereby providing improved estimates of biomass for scaling (ground-based) or potentially improved estimates of biomass to calibrate space-borne estimates of biomass (which are ultimately scaled from discrete GLAS footprints to the landscape, often by using MODIS). We agree that wood density is more important than height in estimating biomass (Chave et al. 2005). There was previously some understanding of how variation in wood density affected biomass estimates (e.g. Baker et al. 2004); we now have a greater understanding of how variation in height also modifies estimates and by including this variation, uncertainty in reduced in scaling from plots to regions.

5. In the four–step process, the assumption of height estimation from diameter may also introduce large errors. In fact, in most studies, including papers by authors, it is obvious that estimation of the height of large trees from H:D allometry can contribute to the error. Height needs to be measured as accurately as possible for large trees. I suggest the authors discuss this point. H:D allometry has large errors for large diameter trees (either over estimating or under estimating depending on the relationship). This error can impact the biomass estimation because of the contribution of large trees.

Response: (i) estimation error of height for the tallest emergent trees may actually be lower when using a laser with a filtering capacity for "last return" than for smaller diame-

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ter trees with crowns positioned in continuous canopy. At the very least it is impossible to overestimate height for emergent trees, so estimates are conservative; (ii) in predicting tree height from height models there is large uncertainty for the tallest trees; (iii) a main point of our study shows that biomass in most forests is concentrated in smaller to intermediate diameter classes, especially for South America. The Weibull model does the "best" job predicting height in this diameter range, and therefore when propagating error, reduces error relative to other height model forms (e.g. power functions) and relative to excluding height in biomass estimates. The large trees the reviewer refers to therefore probably contribute less than might otherwise be expected to the biomass estimation error. This is shown in the manuscript in Figure 4.

6. Referring to Figure 1 and the location of plots, I am afraid the plots cannot be used to extrapolate over the entire continents. The number of plots is relatively small, and they do not represent the landscape variations within each continent. The authors have better data over Amazonia but not in Africa and Asia. I suggest the paper focuses on showing the results on existing plots rather the continental scale extrapolations. 7. Section 3.3. I suggest removing this section. There is no real significance of these results because it is basically an algebraic extrapolation of results from few samples to global. These numbers do not mean anything and can be readily verified. As men- tioned above, the sampling is extremely biased and limited and cannot be used to discuss global carbon stock. Everyone reads the paper can easily guess that the implication of the results of the paper can potentially be large on the global scale. However, there is no reason to include these numbers. The community is getting more confused from groups from limited ground data trying to artificially create large scale science results. We should try to be careful about throwing these numbers out there without any justification. What if, having enough samples over the tropical forests suggest that the biomass may increase or decrease depending on the landscape (topography, geology, soil) variations, climate, and disturbance history and the ensemble effect is negligible.

Response: In response to (6) and (7): We note that our pantropical compilation of data from RAINFOR, AFriTRON and other networks represents the largest long-term set of permanent plot data available to date to represent biomass in tropical forests. These same data have been used in continental and pantropical estimates of biomass and carbon stocks (e.g. Phillips et al. 2009; Lewis et al. 2009). The reviewer appears to have missed the scale of our pantropical study and the source for most of the data which supports "benchmark maps" such as Saatchi et al. 2011, since the RAINFOR, AfriTRON and other networks which contribute to our study likewise provide the baseline data used for large-scale remote sensing studies. If our study suffers from "limited ground data artificially creating large scale science results," then Saatchi et al. 2011 and similar studies must also suffer the same shortcoming.

There is certainly large landscape variation within each continent, and we acknowledge that more plots may help to account for variation among forest types. Until additional plots are established, including plots in disturbed forest, our scaling represents an accepted method, albeit "first approximation" of biomass stocks and the order of downscaling estimates due to height integration. The reviewer points out that readers "can easily guess" that the implications of the results on the global carbon estimates would be large; it is important to put the results in perspective and not leave it to the reader to guess. As we clearly point out, future work may show the downscaling due to height to be less important. Until that time, our results represent our best current understanding of the scale.

8. Section 4.1.2. The authors do not mention the use of Lorey's height as a good height index that can correct for both small and large tree biomass estimation and work that can work on plot scales rather than tree level. One of the main problems with current allometric equations is their application on the tree level data. By developing new allometry that can be applied on the plot level, using parameters such as Lorey's height, basal area, regional wood density values. If the goal is to be able to estimate biomass relatively accurately over landscapes, plot level allometry may be the way forward. Even after bringing together many destructively sampled tree data sets, we

may still have large errors in estimating biomass. Plot level allometry can be readily integrated with future remote sensing data when height, basal area, and average wood density values may become available spatially and globally.

Response: The reviewer has taken the perspective of a remote sensing expert in reviewing this section. Such a perspective represents one of many ways that people quantify biomass in forests and examine change. For example, rather than having estimates of plot-level biomass or basal area to relate to remotely-sensed data, one may instead ask how the biomass of trees of a certain diameter class are changing over time. Such questions require tree-level estimates. The heading of this section is "Modelling tree destructive biomass data," and the focus is on estimating biomass of individual trees. Thus, although Lorey's height might be useful for remote sensing, it is a basal area weighted estimate of plot-level height and provides no information on individual tree biomass estimates, and thus can provide little information about how forests are changing over time.

We do not dispute that Lorey's height for biomass estimation is an important and valuable tool for plot-based remote sensing, and hope that our data will help contribute to future efforts to develop such models. But the focus here is on reducing error in tree-level estimates, which ultimately scale to plots and regions. A detailed discussion on the usefulness of Lorey's height for remote sensing is beyond the scope of the current manuscript.

9. Section 4.13. This section is long and it is all speculations. I suggest the author reduce or delete the section. Most of the material in the second paragraph about "Harmattan Winds," "herbivore fauna," arrival of humans in south America 12000 yr ago (there is evidence of 40,000 years of human presence in Brazil.), are all anecdotal examples, and sometimes wrong, and are not relevant to the paper. There is no reason to spend some words (more than the description of the method and results) on these remotely related issues.

Response: Reduced as requested.

10. Section 4.1.4. Keep this section. It is short and relevant to the paper.

11. Section 4.1.5. You can add this to section 4.1.4 based on the relevance of forest structure on the regional allometry and variations of the biomass. The results on crown size distribution from Barbier et al. 2010 may not be as relevant. Central Amazonia with wetter climate appears to have smaller crown size and tree stature based on some more recent results from remote sensing and ground data.

Response: Merged as suggested.

12. Section 4.2. The remote sensing section can be reduced or deleted based on the earlier general comment. The only relevant implications of the paper for remote sensing are: 1. Remote sensing provides height and this height can be integrated in the allometry (perhaps more on the plot level than tree level). 2. Height included allometry may be more relevant to remote sensing estimation of biomass. In fact, most remote sensing data using height and tropical field data for calibration to estimate biomass show similar results as the paper. Lower biomass in South America and higher in Africa and Asia. In general, the comments about remote sensing techniques and papers including Baccini et al. is not valid and fair. These comments are only relevant when the authors are writing a remote sensing paper. Otherwise, it clearly sounds like passing a judgement without any in depth analysis or understanding the work presented in the papers.

Response: We have revised this section with regard to the methods of Saatchi et al. 2011, as described above. We have also removed the reference to Baccini et al. Nevertheless, our results do have implications for remote sensing, and we have revised the section to focus on the two main points the reviewer highlights.

13. One key issue about estimating biomass is also scale of analysis. Eventually allometry should be applied on the tree level data collected within a plot. The size of

the plot is extremely important in estimating biomass and the errors associated with it. In general, the difference between allometry equations reduces (not disappear) when applied on larger plots (> =1ha) relative to small plots. Studies that use small plots (< 0.2 or 0.25 ha) often have large errors in estimating biomass regardless of including or excluding tree height. The effect of tree height may also be less or more important when the plot size increases. The authors use large plots in their analysis. However, not all field measurements globally are in sufficiently large plots.

Response: As the reviewer correctly points out, plot size has been shown to be important in biomass estimates and with plots <∼0.25 ha having large bias (and random error). But the average plot size in our study is ∼1 ha, as the reviewer also points out. We advise in the manuscript, as the reviewer also suggests, that the eventual goal would be to have height measurements for each permanent plot to account for variation among forests.

14. Section 4.3. This section on sink and source is also a typical algebraic extrapolation that provides numbers without any verification. In fact, we find changes in sink and source values depending on the use of allometry with or without height regardless of any drought impact. A careful analysis is required to separate the effect of height, allometry, and sampling in understanding the source and sink effects on the pan-tropical scale carbon. Who knows which one has the largest effect and in what direction unless such an experiment is developed and implemented. In general, all of these points and potential implications can be lumped together in a small paragraph in the discussion section.

Response: The effect of allometry has been tested for its effect on estimates of the sink (Lewis et al. 2009); allometry does modify the magnitude of the sink, but the sink is still significant with or without height included in biomass estimates. Biomass stocks, sinks and sources have been scaled in exactly the same way (e.g. Lewis et al. 2009, Phillips et al. 2009) that have we scaled our current results, although with different biomass models (e.g. Baker et al. 2004 for Amazonia; Chave et al. 2005 for Africa and

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pantropical estimates). This short section has the goal of indicating the potential effect of height integration on these stocks and fluxes and remains pertinent.

15. Section 4.4. Another discussion section that can be easily deleted without any damage to the paper. Comparison with global emissions from IPCC is really a stretch of the findings of the paper. 16. Section 4.5. Another section that can be deleted without impacting the paper. No need to have a large section on this.

Response: We believe it is it is important to place our finding within the context of current policy, and include this section. Specifically, it is important to note that this discussion material is exactly of interest to those readers beyond those few who are dealing directly with allometric equations. We have, however, reinforced some of the caveats about uncertainties associated with the global numbers, in line with the second reviewer's request as we agree – as originally written, they could have been open to misinterpretation

17. Reduce the conclusion by focusing on the findings of the paper. There is no need to bring in 21 century estimate of tropical forest area and its errors in the conclusion.

Response: We have removed the reference to 21 century estimates in the conclusion and focussed our conclusion on the main findings and the "future considerations."

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