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Discussions

Interactive comment on "Tropical montane forests are a larger than expected global carbon store" *by* D. V. Spracklen and R. Righelato

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We thank the editor for the opportunity to respond to reviewer comments and for taking the time to consider a revised manuscript. We also thank Gergory Asner for his time and for comments on our manuscript.

We respond to these comments in detail below. To guide the review process, reviewer comments are in italics, our responses are in normal text and additions to the manuscript are marked in red. We believe that our manuscript has been improved by this process and we hope that it may be acceptable for publication.

General Comments

This paper presents an interesting synthesis of aboveground biomass (AGB) estimates

in tropical montane forests (TMF). The analysis focuses in two main areas: (i) AGB stocks in TMF associated with tropical mountains in different parts of the world; and (ii) adjusted estimates of AGB based on topographic slope correction. The authors find that AGB stocks are often high in TMF, and not necessarily any lower than the lowlands, and that correction for slope angle results in much higher AGB stocks than would be otherwise estimated using terrain-based (plot) estimates alone. I think this paper will have lasting value, especially if a few issues can be addressed to make the results and interpretation clearer, as described below.

Specific Comments

(1) The premise and introduction to the paper make clear why this issue is interesting and of potential importance to a variety of biogeosciences-related applications. However, the methods and results sections of the paper are more difficult to follow, mainly because of the organization and perhaps a bit of missing content from other datasets. In the methods, it would be much more clear if the authors could adjust the content of section 2.2 to describe the process of calculating the topographic adjustment and projections. As it stands now, this section lists remotely sensed data used, but it does not provide a clear procedure for how the analyses were performed so that others can adjust their data in the future. This seems very important since the authors are (rightly) pushing the need for topographic adjustment of plot- and remotely sensed- AGB estimation. The results-discussion is where more organization would really yield a clearer analysis that can be used and cited by others. Mixing the results and discussion creates a challenge for the reader to understand what is fact and what is commentary. The authors should therefore try to create a very organized presentation in this section. I strongly recommend that the section be broken up into the following two simple sub-sections: (3.1) Plot inventory results and statistics; (3.2) Effects of slope on AGB estimates. A concluding paragraph similar to the current one can close the section. I think this would be very helpful and would yield more use of the paper by others in the future.

We introduce sub-sections as suggested. We have added a new sub-section (Topographic adjustment to account for slope) and included details of how we adjust for slope (Section 2.3):

"In the forest plot studies (Section 2.1), AGB was typically reported per unit area of the Earth's surface although some studies reported AGB per unit planimetric area. For the latter studies, we used information on slope angle reported by the study to convert AGB to a surface area basis. Remote sensed data (Section 2.2) reports planimetric area.

In both forest plot and remote sensed studies we converted planimetric area (P) to Earth's surface area (S) using: S=P cos(theta) where theta is the angle of the slope. For the remote sensed data we calculated slope angle from the variability in elevation of the data (Section 2.2). "

We have also added a separate conclusions section:

We synthesised data of above-ground biomass (AGB) in tropical montane forests (TMF) (elevation $>$ 1000 m) from forest plot inventory studies located in undisturbed forest. We found that mean biomass storage in TMF was 271 t per hectare of land-surface (n=94), significantly less than in lowland tropical forests. The AGB stored by TMF exhibited substantial variability, with the variability not significantly different from that observed in lowland tropical forests. Widely measured topographical (elevation and slope angle) and climatological (annual mean temperature, annual mean rainfall) parameters only explain a modest fraction of the variability in AGB in TMF (r^2 typically $<$ 0.2). Other environmental parameters are therefore likely to be more important in determing AGB and future studies should endeavour to measure a wider suite of environmental parameters.

Our analysis, based on forest plot measurements, is consistent with airborne imaging spectroscopy and lidar studies quantifying changes in forest structure at a spatial scale of 25 ha along a 3000 m elevation gradient in the Peruvian Andes (Asner et al.,

2014). Such airborne observations promise to be a powerful method to further our understanding of forest structure and AGB along elevation gradients (e.g., Asner et al., 2012; 2014), with errors from this technique of similar magnitude to those from forest plot studies (Mascaro et al., 2011).

We demonstrated that AGB storage in tropical forests declines moderately with both increasing elevation and slope angle. Despite this, our analysis confirms that TMF store considerable biomass both at high elevations (up to 3600 m) and on steep slopes (slope angles up to 40). On such steep slopes the land-surface area is substantially greater than the planimetric area, meaning that estimation of regional biomass storage in montane forests needs to account for slope.

We used remote sensed datasets of forest cover and elevation to show that 75% of the planimetric global area of TMF are on steep slopes (slope angles greater than 27). We used the remote sensed datasets to demonstrate that this prevalence of steep slopes results in the global land-surface area of TMF (1.22 million km^2) being 40 % greater than the planimetric (horizontal) area that is the usual basis for reporting global land surface areas and remotely sensed data.

(2) The results shown in figure 2 are core to the outcome of the paper. The fact that lowland AGB varies as widely as TMF AGB is important, and it has been observed in other studies as well. In previous studies, we have found that AGB varies widely in the lowlands based on soils, hydrology, and floristic compositional variation. As we ascend into the mountains, variability in AGB decreases while average AGB declines slightly (or often not at all until very high altitudes are reached – e.g. > 3000 m a.s.l.). It would be helpful if the authors could describe this in more detail so that this result stands out more. As it is written now, this important result is barely noticeable in the paper. A supporting set of results focusing on tropical forest structural change with elevation was recently reported in Biogeosciences Discussions. See:

Asner, G. P., Anderson, C., Martin, R. E., Knapp, D. E., Tupayachi, R., Kennedy- Bow-

doin, T., Sinca, F., and Malhi, Y.: Landscape-scale changes in forest structure and functional traits along an Andes-to-Amazon elevation gradient, Biogeosciences Discuss., 10, 15415-15454, 10.5194/bgd-10-15415-2013, 2013.

This is a good point and we were remiss not to compare variability in TMF and lowland forests. We add a short analysis on variability including a reference to the suggested paper:

"In our dataset we find substantial variability of AGB across forest plots in both lowland forests (n=229, standard deviation σ =113 t ha-1; coefficient of variation (CV) = 0.31) and TMF (σ =144 t ha-1, CV=0.53). Previous studies have suggested that variability in AGB decreases at higher elevations (Asner et al., 2012; 2014). In our dataset, we find that variability in upper montane forests (elevation $\geq$ 2000 m, n=33, σ =106 t ha-1, CV=0.45) is less (F-test, P=0.015) than in lower montane forests (1000 < elevation < 2000 m, n=61, σ =158 t ha-1, CV=0.54). However, when we restrict our analysis to studies that include tree height in the allometric equation used to calculate AGB, we find there is no significant difference (P>0.1) in variability between upper-montane forests (n=17, σ =106 t ha-1, CV=0.52) and lower-montane forests (n=50, σ =102 t ha-1, CV=0.40). We also find that the variability of AGB in upper montane forests is not significantly different from lowland forests (F-test, P > 0.1), with consistent results independent of choice of allometric equation."

We also add the following to the conclusions (section 4): "Our analysis, based on forest plot measurements, is consistent with airborne imaging spectroscopy and lidar studies quantifying changes in forest structure at a spatial scale of 25 ha along a 3000 m elevation gradient in the Peruvian Andes (Asner et al., 2014)."

(3) In addition, the patterns shown for changing AGB with elevation and slope (figures 2b, 2c) have been observed in studies that have tightly calibrated plot inventory to airborne lidar. Airborne lidar produces AGB estimates that have been proven to be within 10

Asner, G., Clark, J., Mascaro, J., Vaudry, R., Chadwick, K. D., Vieilledent, G., Rasamoelina, M., Balaji, A., Kennedy-Bowdoin, T., Maatoug, L., Colgan, M., and Knapp, D.: Human and environmental controls over aboveground carbon storage in Madagascar, Carbon Balance and Management, 7, 2, 2012.

See Figure 4 of that paper for example. Repeatedly, we see two things in high resolution AGB mapping studies: (1) Average AGB stock decrease slightly, but often not statistically so. (2) Variance in AGB declines with increasing elevation. In other words, the AGB becomes more homogeneous at higher elevations. We have found this in the Colombian and Peruvian Andes, the Hawaiian Islands and elsewhere. It is important to the story being told here since average stock may/may not change, yet evenness seems to consistently increase with elevation.

Thanks for pointing us to these papers. They are very useful to help us put our analysis of forest plot based studies into context. We decide to restrict our analysis to synthesis of forest plot data. We have clarified this in our Methods. We agree that remote sensed studies of biomass storage are particularly useful. However, we feel that restricting our analysis on methodological grounds is suitable. Furthermore, much of the lidar data (especially that in Madagascar) may not meet our forest selection criteria: that is, to be primary, undisturbed forest. Our forest selection criteria was not well explained in our previous manuscript and we now describe this in more detail (see our response to comments from J. Homeier). We have added discussion on the remote sensed data throughout our paper (Introduction, Results and Discussion and Conclusions). Specifically, we added the following sentence to the introduction (section 1):

"However, airborne imaging spectroscopy and lidar has recently been applied to quantify changes in forest structure along elevational gradients (Asner et al., 2012; 2014), and is a promising technique to further our understanding of AGB in TMF."

We add a discussion of the airborne lidar data, since as you point out this is very helpful in confirming our analysis (Section 3.1.2):

“Our mean AGB in lower-montane forests agrees well with that reported by Asner et al. (2012), who used an aircraft-borne lidar over Madagascar to estimate AGB of 197 t ha-1 (assuming a factor 2 conversion between biomass and carbon) in lower montane forests (1000 < elevation < 2000 m). In upper-montane forests ($\geq$2000 m) our mean AGB was greater than the 82 t ha-1 reported by Asner et al. (2012) for Madagascar.”

We also add (Section 3.3):

“The prevalance of steeper slopes at higher elevations has been shown previously for forests in the Andes, where a transition between flat terrain and steep slopes occurs at around 900 m elevation (Asner et al., 2014).”

We have also added a short discussion on the change in variability with elevation (see above).

(4) Pages 18899-18900: These pages are densely written, to the point of detracting from the main points of the discussion. Also, there seems to be over-citation of some references and a lack of citation to others.

We have added subsections as suggested which helps break up the text. We have included citations of additional references as suggested.

Technical Corrections

Page 11897, lines 24-25: Since the difference it not statistically significant, the authors cannot state that Asian TMF is greater than Neotropical TMF. Please change this to state that there are simply not significant differences detectable based on the plot data synthesized in this study.

Changed as suggested: “We found no significant difference (Student’s t test, P>0.1) between mean AGB in Asian TMF (257 t ha-1, n=31) compared to Neotropical TMF (247 t ha-1, n=56).”

Page 18899, Line 24: It is not correct that species richness peaks in the 1000-1500 m

range in the Andes-Amazon. This is an artifact of plot estimates. The truth is that we really do not know, but mounting evidence suggests uniformly high plant diversity from lowlands to about 2800 m, then a steep decline right up against treeline in the Andes (Silman 2006).

Silman, M. R.: Plant species diversity in Amazonian forests, in: Tropical rain forest responses to climate change, edited by: Bush, M., and Flenly, J., Springer-Praxis, London, 2006.

Thanks for spotting this. We have removed any mention of a peak in species richness. We have changed to:

“Change in woody species richness, which often declines with increasing elevation, has potential implications for carbon storage (Girardin et al., 2014a).”

Figure 1: This figure is too small to reveal where the plots are located. Also, Hawaii seems to be missing. It would be good to enlarge the figure and to make the squares larger or somehow more prominent.

We have enlarged the figure to make it more readable. We do not include Hawaii in the map as this would greatly expand the lat/lon range that we would need to plot. To clarify, we add the following to the figure caption: “(sites in Hawaii are not shown here).”

We would prefer not to increase the size of the symbols marking the plots as this will hide the background elevation data. We think the larger size figure is readable and we will work with the editors to optimise figure size and readability.

Figure 5: Again, this figure is too small to take away much of an understanding of the ratio of land-surface to planimetric surface area. It would be good to enlarge the figure.

We have enlarged the figure.

Interactive comment on Biogeosciences Discuss., 10, 18893, 2013.