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Biogeosciences Discussions

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Interactive Comment

Interactive comment on "Characterizing Leaf Area Index (LAI) and Vertical Foliage Profile (VFP) over the United States" *by* H. Tang et al.

H. Tang et al.

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We thank the two referees for their insight and very helpful comments. Below are our detailed responses to their concerns respectively:

Referee 1

General Comments:

A) Section 2.2. Leaf-off season is indeed from November to March, but for maximum foliage, it would be recommended to use May to September shots only. Can you provide a short evaluation of shots chosen in leaf flushing and senescence

periods? This factor may be responsible for your negative LAI bias.

The referee is correct about the bias introduced by seasonality, and a simple average of GLAS LAI over different months supports this hypothesis: 3.02 for May, 3.14 for June, 2.93 for October and 2.22 for November. However, we did not exclude the leaf flushing/senescence periods because we tried to maximize the usage of GLAS shots. The GLAS/ICESat mission was not operated year round but deployed for three 33-day campaigns per year due to defects in laser design which required it to maximize its operations for ice sheets (Schutz et al., 2005). The starting dates of each campaign were around mid-February, mid-May and early-October. The sampling bias caused by not using the October data, given how few shots we would have otherwise, far outweighed the small potential bias of using these data for continental scale mapping.

B) Section 2.2. An equation defining the gap profile derived from the lidar waveform, and/or the choice of variables, e.g. the clumping factor if used and the g function. Just a little more information about this would be useful.

We thank the referee for this helpful comment. We have now included all relevant equations in the supplement for easy reference, while also referring readers to the original equations and variables in Tang et al. 2014a and 2014b.

C) Section 3.2 paragraph 2. Figure 3 and Figure 6 should be in sync. Do not present 5 m intervals if your final qualitative product is in 10m intervals. Either also present the 10 m intervals or only present 10m.

We understand this point and debated whether to show them at the same intervals before submission. We decided it was more informative to show different intervals for the following reasons. Figure 3 shows that the accuracy of vertical foliage profile (VFP) varies at different height layers with lowest value in the understory (0 - 5 m). This result is very important because there is a large uncertainty of GLAS VFP at fine vertical resolutions (5 m or smaller) and therefore the product may not be reliable close to the ground. Secondly, the comparisons between Figure 1 and Figure 3 suggest that

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the accuracy of VFP is also dependent on the length of the integration interval, and a longer interval will lead to a higher accuracy (see Discussion P13686L26 - P13687L5). So the take home message is that the product is better used at 10 m intervals vs. 5 m, but this is really only evident if we actually show the 5 m intervals. When we then produce the continental map we naturally want the maps to be as accurate as possible a depiction of reality, and this is best achieved by going to 10 m intervals. So the two figures are serving different purposes and we still feel that it is probably better to keep them as they are.

D) I agree that showing the LAI for the WWF regions is significant, and an important result. What would also be useful would be to present LAIs for large gridded areas over the contiguous US, e.g. 1-3 degrees depending on the density of the GLAS pulses. This may also tie in well with the comparisons to elevation, forest cover, and precipitation. In fact, these could be presented alongside.

Thank you for the suggestion. We have calculated 1 degree maps and now present these in the Supplement (shown below).

Specific Comments

1) P. 13681 Lin 10. 3x3 what?

3×3 Landsat window

2) Figure 2 3. Put the RMSE and R2 and bias on these figures or on the caption.

Thank you. All three have been put on the figures.

3) Figure 2 caption: 'Each VFP point represents an integrated value of foliage density at 5m height interval.' Change this to '. . . at each 5m height interval' or '. . .for all 5m height intervals'.

Thank you. We have changed this to '. . . at each 5m height interval'

4) Figure 910. Not sure why the boxplots are of different sizes. This is cosmetic,

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but some would prefer the same sizes.

The standard visualization for data distributions using box plots is that their length corresponds the quartile values, the whiskers give the extremes of the range, and the widths are proportional to the actual number of observations. We would prefer to keep this standard.

5) Section 3.3: By Forest Ratios do you mean canopy cover defined by some passive satellite? This is not clear. Do you use land class products under the footprint to define forested pixels vs non forested?

Thank you for pointing this out. The Forest Ratio uses a MODIS land cover map to derive the number of GLAS shots that are classified as being over forest or non-forest (and the ratio gives this percentage). We have added a reference to its definition in Section 3.3 and Figure 9 (p13684 line 22): Each GLAS footprint was classified as either forest or non-forest with an overlay of MODIS land cover map, and the Forest Ratio was defined as the percentage of footprints classified as forests in total GLAS shots within each elevation group..

6) Are all your boxplots in Fig 9 10 equivalent to your ecoregions, or some predefined grid size?

The boxplots are not related to ecoregion. In each plot, the boxes represent a range of the value being associated with LAI (precipitation or elevation) to illustrate the relationship of LAI to these variables. The relationships are much easier to see when binned into classes.

7) P. 13686 line2. Pedantic. . .but perhaps don't use 'reasonable'.

Thank you. We changed the word 'reasonable' to 'acceptable'

8) P. 13687. Are GLAS LAIs derived from the raw waveform or the modelled 6 Gaussians?

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GLAS LAI were derived from the raw waveform. The modeled Gaussians were internal variables used in the algorithm. More details can be found in Tang et al. 2014a.

Referee 2

GENERAL COMMENTS

My main concern is about the presentation of the GLAS LAI over US (Figure 5). This figure does not help much about our understanding of the LAI distribution but may even lead to misunderstandings, because of the overly simple statistics at the ecoregion level. I would suggest the authors to draw dotted maps or gridded maps in 65 m resolution, that may give readers a better concept of the GLAS LAI. Grassland and crop types may be avoided, as they are not discussed in the text and may have been severely underestimated. Likewise, I doubt the value of the LAI statistics in Table 1. The standard deviations are rather high, many times larger than the mean LAI values, because of the huge diversity over an ecoregion.

While we understand the reviewer's concern about mapping at the ecoregion level, it is impossible to map at the suggested scale because ICESAT is a transecting mission. It does not provide wall-to-wall coverage, but rather only provides along track samples spaced about 100 m apart but with cross-track distances as large as 30 km. Therefore, the only way to provide a continuous map of LAI intervals is by mapping the samples into strata. In our case, we chose ecoregions as those strata for reasons explained in our response to reviewer 1. Once this concept is understood (that we have samples and are mapping into strata), there should be no misunderstanding as to what the maps represent. We stress furthermore that these are the first maps to show the vertical distribution of LAI, not just total LAI, on a continental basis and thus represent a substantive contribution.

In terms of the variability of LAI given in Table 1, the statistics are correct. Again, the mapping into strata explains why the standard deviations are large, but they are

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certainly not "many times larger than the mean LAI values" as the referee asserts. Table 1 gives 40 pairs of mean-s.d. values (10 ecoregions * 1 Total LAI * 3 LAI layers). None of the total LAI values (column 1 in Table 1) have a s.d. that exceeds the mean, and indeed the C.V. is about 50

A fine validation of the GLAS LAI over the conterminous US may only be realized through comparison with existing Landsat and MODIS LAI. My understanding is that the Landsat LAI was generated over California only (Ganguly et al. 2012). Please provide the proper reference for the Landsat LAI over the US, which was used in the comparison with the GLAS LAI (Figure 4). I would like to know the quality of the Landsat LAI maps over US. I strongly encourage the authors to further compare GLAS LAI with MODIS LAI, as was done in their earlier study (Tang et al. 2014). This won't be much effort based on what has been done by the authors. Moreover, please note the differences between the Landsat and MODIS estimated LAIs and the lidar derived Plant Area Index (PAI), even though they may be numerically similar (Tang et al. 2014).

Validation of GLAS LAI: We have presented a coherent series of papers that has addressed the issue of validation in the Tang et al. publications that go from physical theory to ground-based validations to airborne lidar validations that are then linked to GLAS, to Landsat and to MODIS. Our experience is that the scale of MODIS is too coarse to serve as a validation for GLAS, and there are generally too few ICESAT samples within a MODIS pixel to make this comparison very illuminating (and Tang et al, 2014a show that the data sets have low correlation). In contrast, Landsat is much more appropriate because the spatial scales match, but as we have shown in the earlier Tang et al. work and again here, Landsat LAI saturates, not just against ICESAT, but against airborne lidar data. Therefore, really the question should be turned on its head: it is the GLAS data that can be used to validate the Landsat data, again given the progression of research we have presented over the three papers.

Landsat LAI Validation: We have added a reference for the U.S. Landsat LAI product as "In Prep". While the data set is finished it is not yet published. That accuracy of the Landsat data set is in part given by the results we show here in our comparison of GLAS LAI to Landsat. It is again obvious that Landsat saturates, as has been shown in our previous research.

LAI vs. PAI: We would like to argue that the LAI derived from Landsat or MODIS is actually plant area index (PAI) too, because non-foliage elements can contribute to their reflected radiometric signal (Garrigues et al. 2008) in a similar mechanism to that of the lidar sensor. Because the lidar observation is in the near-IR, it is not nearly as sensitive to branches as leaves. Nevertheless, its contribution is generally of secondary importance, and we have discussed this issue in Tang et al. (2014a).

I'm not in favor of the environmental studies in Section 3.3. It would be more interesting to look into the seasonal LAI and VFP variations since the multi-year data are available.

The GLAS/ICESat mission was not operated across full year round but deployed for three 33-day campaigns per year due to deficits in laser design (Schutz et al., 2005). The starting dates of each campaign were around mid-February, mid-May and early-October, and the ground tracks did not repeat each year. As a result, it is impossible to do an effective seasonal study. The environmental analyses per se showed interesting results, and therefore we favor their inclusion.

DETAILED COMMENTS

contiguous United States -> conterminous United States. The latter is more used in authoritative publications.

Both terms mean the same thing (the lower 48 states) and each are widely used. We have added a definition of CONUS to clarify the ambiguity in P13676L6.

P13677L24. Saturation is also an issue for lidar LAI estimations. Likewise, I disagree with the statement in P13687L17 "the non-saturation advantage of lidar

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data against passive remote sensing in observing high LAI forests".

Our comparison results between airborne LVIS and destructively-sampled field data in the La Selva Biological Station have demonstrated that lidar-derived LAI did not saturate even when the LAI exceeding 10 m2/m2. We are also testing our results over other dense forests and do not see any saturation trend towards high LAI yet. Under the vast majority of real forests, it is highly unlikely that lidar will saturate, provided there is enough laser energy to get a return signal from the ground, but this is an entirely different issue. We are not clear why the referee disagrees with the statement. Everywhere we have looked, Landsat saturates and lidar does not. For this paper, all we can do is reference our previous work, and provide the results of the experiment presented. Our conclusions for the work presented in this paper are well-supported by the results.

P13679L3. Full name for CONUS The full name has been added.

Section 2.2. P13680L4-9. Please briefly introduce the methods here, rather than referring to other papers.

We thank the referee for this helpful comment. We have added a supplement to describe necessary details of the methods, since our primary focus here is the large-scale comparison and validation of GLAS LAI and VFP data set.

Section 2.3 How good are the LVIS retrievals compared to field measurements? Please mark the four LVIS field sites in Fig. 5. Please put all resultant R2, bias, and RMSE in the figures. Only introduce them in the text when necessary.

LVIS LAI have shown excellent agreement with field measurements from destructively sampled data, hemispherical photos, LAI-2000 and terrestrial scanning lidar across different landscapes (Tang et al., 2012 and 2014a; Zhao et al., 2011 and 2012). The r2 varies from 0.63 to 0.85, and the error varies from 0.52 to 1.36. All four LVIS sites have been marked in Figure 5 now. We have added those statistical results in Figures

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1 - 4 while we prefer to also repeat these within the text.

P13685L7-10. The Pearsno's correlation was not shown. Why this is relevant anyway?

All Pearson's correlation coefficients are listed in the text specified. The analyses are relevant towards developing an understanding of how LAI may be correlated with environmental variables and how strong these are.

P13686L11. Slope may be a factor. How's the topography of the four validation sites?

Slope is indeed a very important factor on the derived LAI and VFP product as we have discussed in this paper and previous publications (Tang et al. 2014a and 2014b). Only Sierra Nevada forests have very rugged topography with slopes exceeding 30°, and our previous work suggests that best agreement can only be achieved with slopes less than 20°.

P13687L18-19. Fig. 4a shows that GLAS underestimates for all LAI values. Please discuss.

We discussed this in P13687L15-26, and we think there are multiple factors contributing to this relative underestimation, including differences in land cover classification schemes, adjustment of clumping effect, and data acquisition strategy.

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Schutz, B.E., Zwally, H.J., Shuman, C.A., Hancock, D., DiMarzio, J.P. (2005). Overview of the ICESat Mission. Geophysical Research Letters, 32

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Dubayah, R. (2014a). Deriving and validating Leaf Area Index (LAI) at multiple spatial scales through lidar remote sensing: A case study in Sierra National Forest, CA. Remote Sensing of Environment, 143, 131-141

Tang, H., Dubayah, R., Brolly, M., Ganguly, S., Zhang, G. (2014b). Large-scale retrieval of leaf area index and vertical foliage profile from the spaceborne waveform lidar (GLAS/ICESat). Remote Sensing of Environment, 154, 8-18

Tang, H., Dubayah, R., Swatantran, A., Hofton, M., Sheldon, S., Clark, D.B., Blair, B. (2012). Retrieval of vertical LAI profiles over tropical rain forests using waveform lidar at La Selva, Costa Rica. Remote Sensing of Environment, 124, 242-250

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Zhao, F., Yang, X.Y., Schull, M.A., Roman-Colon, M.O., Yao, T., Wang, Z.S., Zhang, Q.L., Jupp, D.L.B., Lovell, J.L., Culvenor, D.S., Newnham, G.J., Richardson, A.D., Ni-Meister, W., Schaaf, C.L., Woodcock, C.E., Strahler, A.H. (2011). Measuring effective leaf area index, foliage profile, and stand height in New England forest stands using a full-waveform ground-based lidar. Remote Sensing of Environment, 115, 2954-2964

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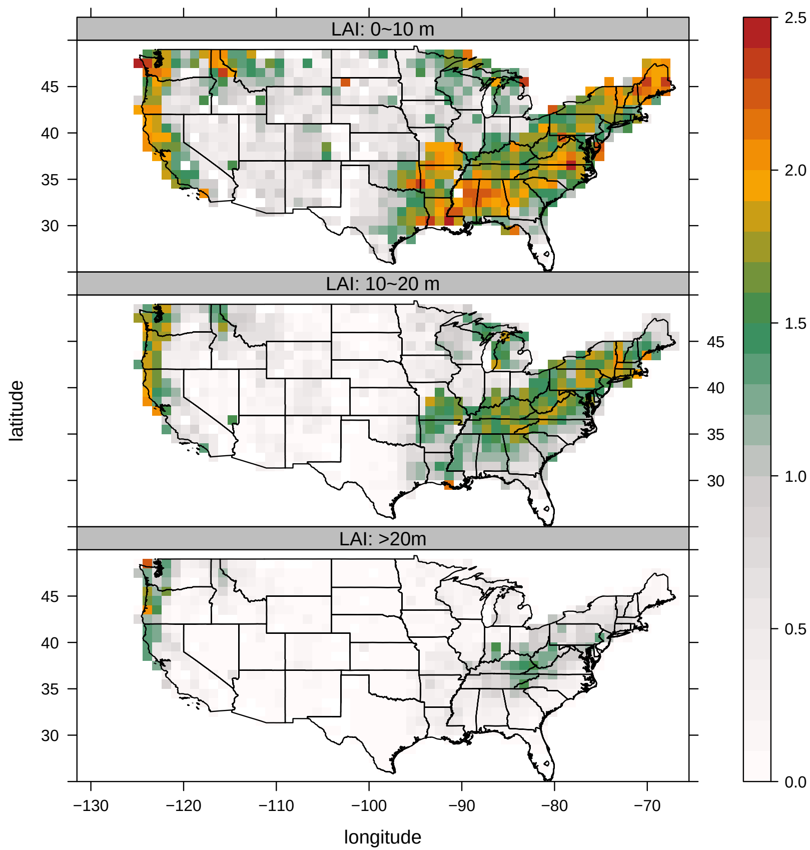

Fig. 1. LAI strata map aggregated at 1-degree grid cell over CONUS

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