Anonymous Referee #3

The paper provides evidence that the vegetation optical depth VOD derived from passive microwave satellite data at L-band frequency has strong correlation with the above-ground biomass and can be used to monitor vegetation status. The paper is well-written and the methodology and results are sound and at the same intriguing, suggesting VOD as a potential satellite derived parameter to explore in future studies. I recommend the paper for publication but I have few suggestions and recommendations that may help improve the interpretation of the results before final publication of the paper.

We thank the reviewer for his/her encouraging comments

1. The paper does not provide a strong motivation of what VOD can be used for. Vegetation aboveground biomass is one of the most important global ecosystem variable for carbon cycle and climate mitigation. However, the strong correlation of VOD with biomass does not necessarily mean VOD from passive microwave at approximately 0.5-degree resolution is useful for biomass estimation or monitoring. VOD can be used to monitor vegetation water content at regional scales given its coarse resolution and frequent observation. I would like to suggest that although the authors correlate the result with biomass, they emphasize the use of VOD for monitoring vegetation water content. Biomass and water content are similar in magnitude with biomass being more static and water content more dynamic.

Examples of the use of VOD for vegetation, in general, and AGB monitoring, in particular, are given in the introduction (page 2 lines 17-23). We do think that VOD, in particular L-VOD is useful to monitor the temporal evolution of AGB at a lower spatial resolution but with a higher temporal resolution than other types of observations at least until the launch of the ESA Biomass mission, whose goal is to produce a global biomass map twice per year. Liu et al. 2015 have provided a very good example on how L-VOD can be used to study the evolution of global carbon stocks. We do think that all this pieces of information are already in the manuscript since the abstract and the introduction.

Regarding the use of VOD to monitor the VWC, the reviewer is right. Everything depends on the temporal scale of the study. The current manuscript being devoted mainly to AGB, long times periods were used. Studying the evolution of VWC requires to use much shorter time scales and it is an on-going work for a dedicated study. We agree that this was not fully explicit in the manuscript. In addition, a few important references were lacking:

Konings, A. G. & Gentine, P. Global variations in ecosystem-scale isohydricity Global change biology, Wiley Online Library, 2017, 23, 891-905

Li, Y.; Guan, K.; Gentine, P.; Konings, A. G.; Meinzer, F. C.; Kimball, J. S.; Xu, X.; Anderegg, W. R.; McDowell, N. G.; Martinez-Vilalta, J. & others Estimating Global Ecosystem Isohydry/Anisohydry Using

Active and Passive Microwave Satellite Data Journal of Geophysical Research: Biogeosciences, Wiley Online Library, 2017

Therefore, we will change the text of the introduction and we will include the following sentences:

VOD has also been used to study the VWC and variations in ecosystem-scale isohydricity (Konings and Gentine, 2017; Li et al., 2017).

and

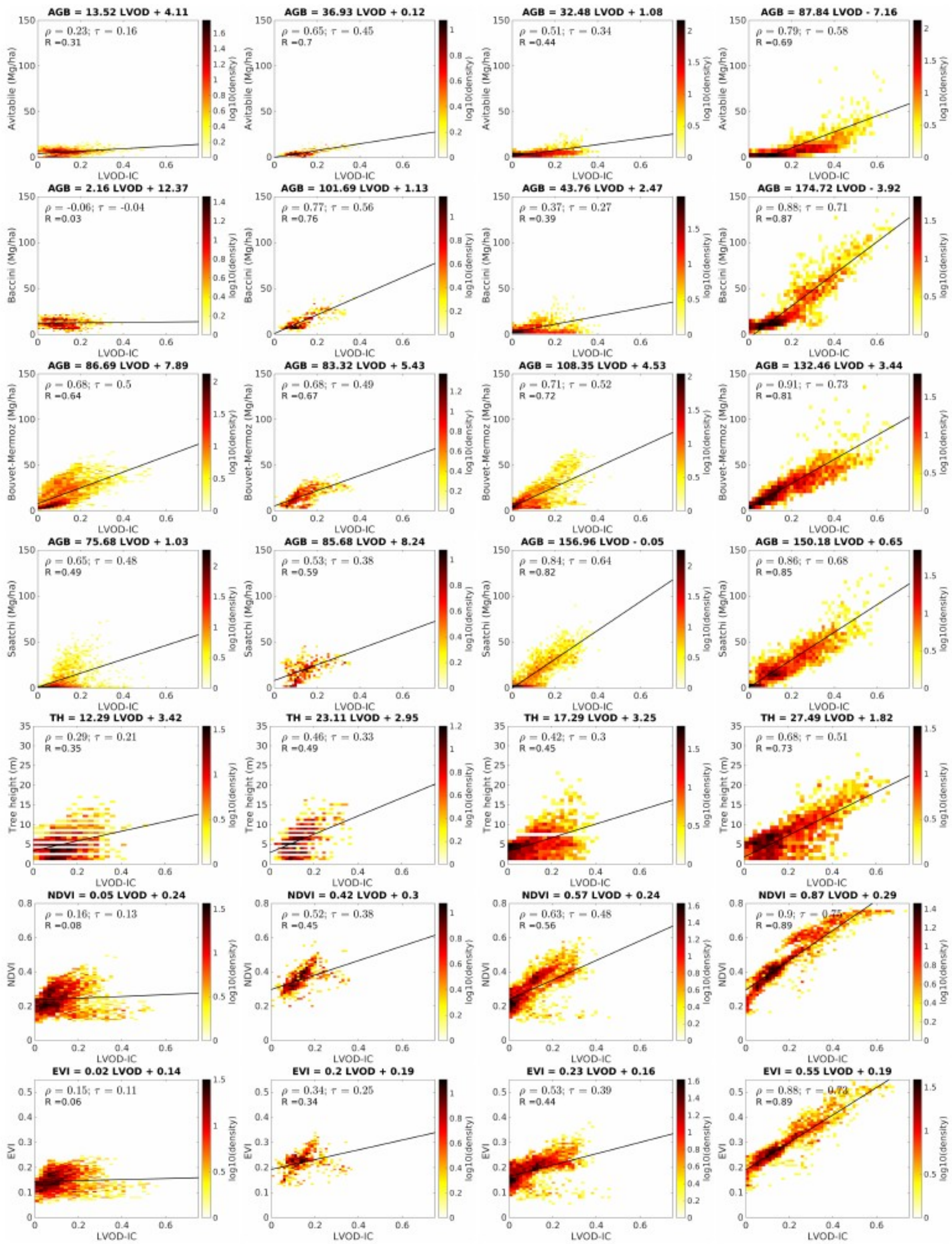
Since this study is mainly devoted to AGB, long time averages (typically annual) will be used. Studying the evolution of VWC would require to use much shorter time scales.

2. The method says: "The main evaluation strategy used in this study is to spatially compare L-VOD to the evaluation data set." Although the pixel values are extracted from all the data sets to compare. However, this is not a spatial analysis because the spatial information almost disappears in the correlation studies. Unless a specific spatial correlation model was used to capture the pattern. Some of the vegetation classes are separated that can help with spatial variation of the data sets but again this is only a simple correlation study and does not include spatial analysis of data sets.

We agree. "Spatially" can be misleading. It will be removed.

3. Figure 2. The density scatter plots with multiple parameters show that there is a strong relationship between VOD and all the parameters. Some of the most interesting ones are the optical data and precipitation showing a strong saturation with respect to VOD suggesting that VOD can be used as a complementary measurement to look at the vegetation. Wavelength is probably the most powerful aspect of the VOD measurements compared to optical data. If VOD correlated with EVI and NDVI over the entire range, then the interpretation of VOD could've been more difficult. I recommend the authors discuss this in the paper.

Following different reviewers comments, Fig. S6 will be moved to the main text and it will include all the land cover classes without grouping some of them (which requires making two figures instead of one, see Figures below). In addition, the new version will include EVI and NDVI.



gure 4. SMOS IC L-VOD relationships to the AGB and tree heigh evaluation datasets for different land cover classes: From left to right: Open shrublands. *(ii)* Croplands, *(iii)* Grasslands, and *(iv)* Cropland/natural vegetation mosaics. See Table S2 for more details on these ıd cover classes.

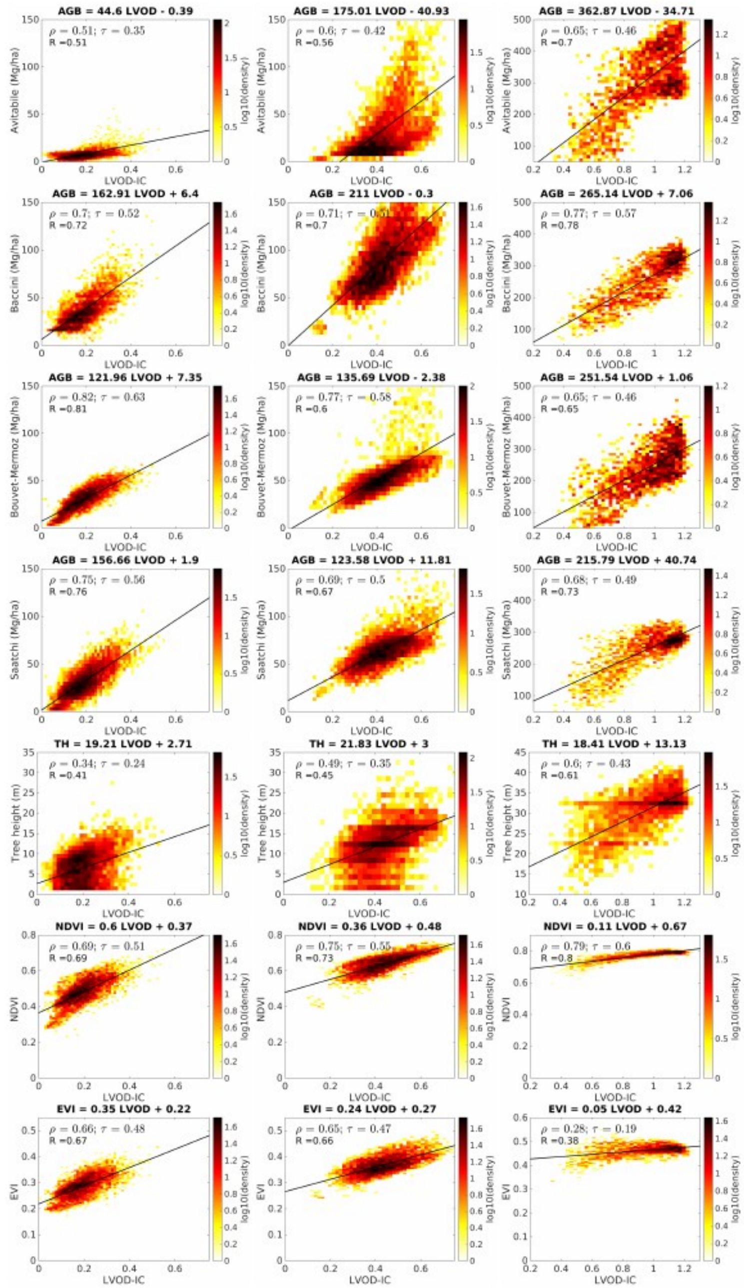


Figure 5. SMOS IC L-VOD relationships to the AGB and tree heigh evaluation datasets for different land cover classes: From left to right: *(i)* Savannah *(iii)* Woody savannah and *(iv)* Evergreen broadleaf. See Table S2 for more details on these land cover classes.

The complementary of L-VOD with respect to NDVI and EVI is clear as both saturates strongly. In addition, it is interesting to remark that there are no significant differences in between NDVI and EVI, even if EVI is supposed to be more sensitive than NDVI to high AGB.

Lines 2-3 of page 10, dealing the slopes of the NDVI versus AGB relationships will be rephrased as follows:

Regarding the L-VOD and NDVI/EVI relationships in different biomes, in contrast to AGB, the slope of the relationship decreases from low vegetation types to savannahs and dense forest as the optical/infrared indices saturates. It is noteworthy that no significant difference is seen on the behavior of EVI and NDVI for high L-VOD values.

With respect to precipitation. Panels c and d of figure 3 will be now a single Figure. The rest of the panels will be removed as they will be redundant with those of the new figures showed above. Here showing only two groups of biomes is pertinent as we want, as the reviewer says, to show the possible link of precipitation as one of the drivers of the vegetation properties. Thus, we show that there are basically two regimes. In the first one, as precipitation increases the amount of vegetation as traced by AGB maps, VOD or NDVI/EVI increases. In contrast, there is threshold of ~1500 mm/year over which AGB, VOD and NDVI are decoupled from the amount of the annual precipitations.

Taking this into account, lines 13-17 of page 10 will be replaced by :

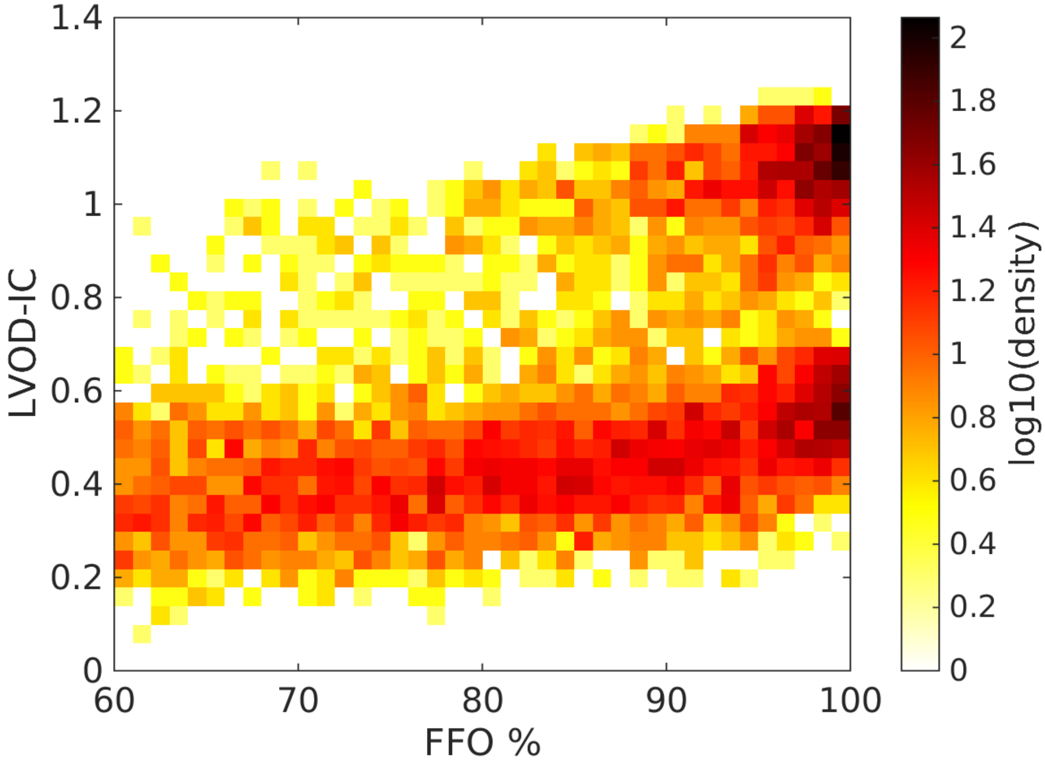
Regarding the relationship with respect to annual precipitation, Fig. 7 shows the precipitations and L-VOD scatter plots for two land cover groups: (i) grasslands, croplands, shrublands, savannahs and woody savannahs and (ii) ever-green broadleaf forest. For the first group, L-VOD increases with increasing annual precipitations until a value of ~ 0.7 for ~ 1500 mm. In this range of L-VOD all other vegetation tracers increase as well. For instance, Bouvet-Mermoz and Saatchi's AGB increase up to 85 Mg/h and ~ 100 Mg/h, respectively, and NDVI and DVI increase up to ~ 0.7 and ~ 0.45, respectively (Fig. 6). In contrast, over that threshold of ~ 1500 mm of annual precipitations, which occurs basically in the evergreen broadleaf forest, L-VOD and the other vegetation tracers are not linked to the amount of precipitation.

4. The relationship between VOD and biomass from different products are interesting. The fact that L-band VOD does not show a clear saturation with biomass may be due to:

a. 1. At very coarse resolution (40-50 km), the variations of forest biomass on the landscape is dominated with the landscape heterogeneity. Larger heterogeneity (e.g. forest/non-forest mixture) will improve the relationship of VOD with biomass. This may mean that the VOD is also co-varying with the vegetation cover. In fact, the straighter relationship with Baccini data is the artifact of this effect. Baccini biomass is strongly correlated with MODIS VCF (vegetation continuous field) data and therefore causes a more linear relationship. Whereas other maps and including the vegetation height from Simard do not show this linear relationship. There is no reason for VOD and biomass to have a linear relationship. I recommend the authors discuss this point and may even include the MODIS VCF product as a layer similar to NDVI in the mix.

At *all* spatial resolutions the sensor output is a weighted average of the signal within the radiometer footprint or the CCD pixel and the instrument response. Since most of the time it is impossible to deconvolve the instrument response function and the function giving the 2D distribution of the signal, the physical parameters retrieved from the sensor output are “effective” values within that footprint or pixel. They are not independent of the 2D distribution … but two completely different 2D distributions can give the same sensor output.

The suggestion of using MODIS VCF is a valuable one, and we will certainly process that data for subsequent studies. For the present study, for simplicity, we have preferred to compute the forest fraction from ECOCLIMAP because it is provided with some SMOS products such as the L2 and L3 datasets as the “FFO” parameter. FFO is the fraction of forest within the SMOS footprint computed from the 1 km ECOCLIMAP dataset. The following figure shows the SMOS IC L-VOD as a function of the fraction of forest cover from 60% to 100 %. The distribution shows two structures. In a first structure, the VOD varies from 0.2 to ~0.7 for those FFO values, showing a very small sensitivity to the exact value of the fraction of forest (small slope) because VOD does not only depend on the fraction of forest but also on the type and the properties of the vegetation within that fraction (and on the low vegetation present outside the forested cover fraction). For instance, it is possible to have almost 0.6 of L-VOD with FFO of 60 % and values as “low” as 0.4 for FFO of 100 %. The second structure also illustrates this effect, it is the high L-VOD (>1) peak for FFO 90%-100%. This is the same peak seen in the scatterplots with respect AGB and that corresponds to the equatorial forest, for which the L-VOD is higher than for other types of forest with the same cover fraction.



We agree that there is no reason to have a linear VOD-AGB relationship and the new version of the figures clearly shows that analyzing the VOD-Baccini AGB per land cover class, the slopes change significantly. The reason that the global relationship looks close to linear is the high slope of the VOD-Baccini AGB relationship in woody Savannahs, which is close to that in evergreen broadleaf forest. With respect to the other three AGB datasets, the Baccini AGB dataset seems to overestimate AGB in woody savannahs with values of ~ 50 Mg/h for LVOD 0.2 to ~130 Mg/h for LVOD 0.6, while the regression lines for the other datasets show values lower than 100 Mg/h. However, unfortunately, the origin of this possible overestimation is not clear and getting further insight on the differences in between Saatchi, Baccini, Avitabile and Bouvet-Mermoz datasets is beyond the scope of the current study.

b. At coarse resolution, the global biomass values are much smaller on the average. Biomass at 1-ha can reach a very large number at some ecosystems. However, at 40 km as it is mixed with the heterogeneity the average is almost smaller. This is one more reason for better sensitivity to biomass. However, it would be interesting to focus on different range of biomass with VOD.

We refer to the answer to comment 4.a.1 regarding the sensitivity to biomass and heterogeneity.

Regarding the analysis for different ranges of biomass and VOD, we refer to the answer to comment 3 and to the discussion of the new figures that will replace Fig. S6. As now all biomes are treated independently, all different ranges of biomass and VOD are discussed independently.

c. Over Africa, all dense tropical forests are clustered around 300 Mg/ha of biomass on the graphs in figure 2. If the goal of the paper is sensitivity to biomass, it may not be a bad idea to separate areas of up to 150 Mg/ha that includes the first cluster from the second cluster and study it separately. The binary feature of biomass in Africa, from woodlands to dense humid tropical forests in area may introduce a false strong correlation with biomass that need to be discovered further. Figure 3 is supposed to show this effect. However, the authors mix this up with precipitation and NDVI and only show the result from Bouvet. It would be good to show this for all biomass maps so the variations of the relationships are discussed.

The referee is fully right, Figure 3 and Figure S6 were supposed to show that effect. Taking into account some comments from several reviewers, and as stated in the answers to comments 3 and 4.b, the former Fig. S6 will be moved to the main document and "expanded" into the two new figures shown above to deal with all biomes independently while former Fig. 3 will be dedicated only to precipitations.

We are confident that the new version with these figures is clearer and it address the concern raised here by the referee. In the new figures, it is possible to see that L-VOD and AGB correlation exist within each land cover class and not only when all classes are shown together.

d. Although the paper is written for the biogeoscience community, it would be important for the authors to provide some explanation of why L-band data from passive measurements may have better relations with biomass compared to active measurements at the same frequency.

Currently we do not have any clear evidence showing that passive L-band data may have better relations with biomass than active L-band data. We do not think we suggest this in the manuscript. The main reason is that all AGB maps used come from active observations. Fully independent AGB estimations as for instance from in situ estimations of AGB would be needed to address that question by comparing to both active and passive L-band observations. But due to the coarse resolution of passive instruments this will be very challenging.

e. How different are the relationships between VOD and different biomass maps and how can the difference be interpreted?

The best correlations of AGB and L-VOD are found with (i) Bouvet-Mermoz for Shrublands and Savannahs (ii) Baccini for croplands and equatorial forest (iii) Saatchi for grasslands. Regarding natural vegetation and woody savannah the correlation values obtained with Saatchi and Baccini are very similar. One should note that correlation values obtained with Bouvet-Mermoz for woody savannah are degraded to the fact that for the highest values of AGB found in this class, at the SMOS resolution, the AGB estimation is a mix of Bouvet and Mermoz approaches. Therefore, all AGB datasets except that of Avitabile performs the best for a few land cover classes.

Interpreting where do this differences come from is not easy. Radar observations in low vegetation regions such as shrublands and grasslands are thought to be very sensitive to biomass variations, in spite of a significant sensitivity to soil moisture. The high correlation of the two AGB maps mainly based of radar data (Saatchi and Bouvet-Mermoz) with SMOS L-VOD in grasslands would confirm this fact, as the high correlation in shrublands for Bouvet-Mermoz.

The scatter plot found with Avitabile for woody-savannah resembles an overlay of the scatterplot obtained with Baccini and the scatter plot obtained with Saatchi. The low AGB vs L-VOD slopes obtained for low vegetation classes, significantly lower than those found with the original Saatchi and Baccini datasets, are rather difficult to understand. The strange behavior of Avitabile AGB probably comes from the fact that it is pure data driven method and that it is therefore very sensitive to the data used to train the method. In their training database, high AGB plots could be over-represented.

In addition as mentioned above, the distribution of Baccini AGB for woody savannah is significanly different to the other datasets, which much higher values.

These elements will be added to the results section when discussing the new figures that will replace Fig. 3 and S6.

f. In table 1, there are three metrics to show the relations between VOD and biomass and other parameters. However, only Baccini result is highlighted in the abstract. Why? The table does not necessarily support this. Furthermore, there is not physical reason that the scattering or emissivity has to be linearly related to biomass.

We understand the point by the reviewer that only Baccini is cited explicitly in the abstract and this could look strange. First, it a good style practice not to make citations in the abstract. In addition, the statement saying that the relationship of Baccini and L-VOD is linear was not correct. It as been removed from the abstract.

[…] four AGB data sets. The relationships between L-VOD and the AGB data sets were linear per land cover class, but with a changing slope depending on the class type, which makes a global non-linear relationship. In contrast, the relationship

*linking L-VOD to tree height ($R = 0.87$) was **close** to linear. For low vegetation classes [...]*

Actually, saying that the relationship with respect to Baccini is linear was motivated by the fact that it is closer to linear than those obtained with the other datasets. The degree of non-linearity of the L-VOD/AGB relationship clearly increases from Baccini to Saatchi and Bouvet-Mermoz (which are similar) and to Avitabile, which is strongly non-linear. Finally, we do not reckon that it is needed to give those details in the abstract and that it is better to say that the global relationship is non-linear in all the cases but basically linear per land cover class. The new version of Fig. S6 showing all the land cover classes shows clearly that the relationship of L-VOD and Baccini is not linear with slopes going from only 2.16-43 Mg/h for shrublands and grasslands to 100-170 for croplands and savannahs and to 220-260 for woody savannah and evergreen broadleaf forest.

Thanks for pointing this out. We agree that there is not physical reason that the scattering or emissivity has to be linearly related to biomass. And furthermore, emissivity is not linearly related to L-VOD either.

5. Figure 4 is a bit difficult to understand. The colors and what the legend provide cannot be easily deciphered. It seems one should the see the saturation of NDVI and a much linear relationship with VOD but I am not sure the figure explicitly shows this. I recommend either making the figure a bit simple or provide more information in the caption and change colors so the points are clear.

Definitely, this figure is not clear enough as the three referees were concerned about this point. Therefore, we have completely re-thought the best way to present this figure, which basically does not contain any new result and the goal is to illustrate the discussion by comparing L-VOD to results presented earlier and published results by Liu et al. 2015. Therefore, following reviewers comments, and to avoid misunderstandings the text on Sect. 4.4 discussing this figure will be moved to Sect. 5 “Discussion”. In addition, the new text will add more explanations on how the figure was done.

To make a clearer figure we decided to make a new one with two panels (see below).

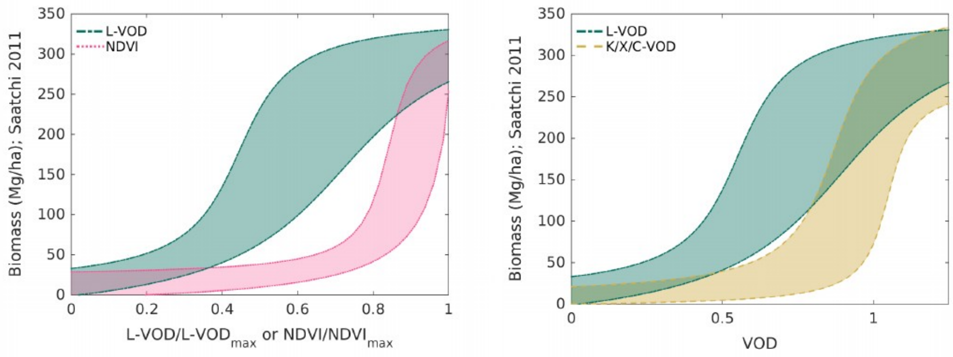


Figure 5. Left: Fits of the 5th and 95th percentile curves of the Saatchi et al. (2011) AGB with respect to SMOS-IC L-VOD (green) and NDVI (pink). To plot both distributions with the same scale, VOD and NDVI were normalized from 0 to 1 using their respective maxima (0.83 for NDVI and 1.24 for L-VOD). Right: Fits of the 5th and 95th percentile curves of the Saatchi et al. (2011) AGB with respect to SMOS-IC L-VOD (green) overlaid in the K/X/C-VOD versus Saatchi et al. (2011) AGB curves of Fig. S4 from Liu et al. (2015) (brown). No normalization is needed in this case as both VODs span a similar range of values.

In the right panel of the new figure, the L-VOD and K/X/C-VOD relationships to Saatchi AGB are shown without using any normalization as we realized that the normalization used to plot L-VOD, K/X/C-VOD and NDVI in the same plot could be misleading. The normalization is not needed to compare with other VOD, only for NDVI because their dynamic ranges are very different. The curves plotted here for the K/X/C-VOD are just those of Figure S4 from Liu et al. 2015, which were computed using Saatchi AGB and the same method that we used in the current study. Liu et al fitted their relationship using K/X/C-VOD data in the period 1998-2002 and Saatchi data acquired from 1995 to 2005 (page 6 of their supplementary information document). This will be reminded explicitly in the discussion section of a revised version of the manuscript. However, the non-linearity of the curve and the difference sensitivity to high AGB from different frequencies is driven by the high AGB values in the dense equatorial forest, which is not supposed to vary strongly in a few years time.

In the left panel L-VOD and NDVI relationships with respect to Saatchi AGB. In this case L-VOD and NDVI were normalized to 1 using their maximum values (1.24 and 0.83, respectively) to have both quantities with the same dynamic range in the same figure. We hope the figure is clearer now. The text will be updated accordingly

The curves for the other AGB datasets with respect to L-VOD are already shown in Fig S3. They will not add much information to this discussion and we tried to show them in the figure below but it becomes unreadable and even more difficult to understand.