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Interactive comment on "Detecting tropical forest biomass dynamics from repeated airborne Lidar measurements" *by* V. Meyer et al.

V. Meyer et al.

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Dear Reviewer,

We are grateful for your review comments and recommendations. We have incorporated most of your suggestions and comments in our revised manuscript and we think the paper has improved significantly. Enclosed please find our responses to the review comments.

1) The lidar data are key to this whole study, particularly the ability to compare the LVIS and DRL datasets collected a decade apart. In this case, making sure these two datasets are estimating the same things, as far as possible, and quantifying differences that arise for reasons other than actual changes in height between the two dates, is key

to robust, useful results. The authors make little or no mention of these impacts, the differences between the two surveys, and their possible effects. All detail of the lidar acquisitions is in the supplementary information & the descriptions are also incomplete. For example, what altitude were the LVIS data collected at? What scan angles were the DRL collected at? What were the instrument characteristics of the DRL in terms of the threshold for pulse collection (if known)?

Answer : We have added several sections discussing the characteristics of the sensors and their potential impacts on the results. The two surveys have characteristics that affect the data differently. A table showing the differences between the two surveys has been added to the supplement. Differences in footprint size and density of points have to be taken into account when extracting and analyzing the data. In order to have a fairer comparison between the two datasets, the DRL data was first aggregated at 20m resolution to calculate the relative height metrics at 1ha (as suggested by the reviewer). Some areas are not covered by any LVIS shots, which makes it hard to compare the two surveys in these areas. At the 0.04ha scale, 180 subplots are not covered by any LVIS shots, out of 1250. These subplots were not included in the 0.04ha scale analysis. Geolocation errors are small (less than 1m for LVIS, and 0.1m for DRL) but they are hard to quantify. They are considered negligible at the 1ha scale. However, they can be a major source of error at smaller spatial scales, especially at 0.04ha. We discussed potential sources errors for each sensor and at each scale of analysis. We also included a footprint-by-footprint analysis driven by the LVIS shot size of about 20 m. For your information, LVIS was flown at 1000m and DRL scan angle was within $\pm$ 17°.

2) As an example, the geo-location accuracy of the two lidar datasets and the ground measurements, will probably be a major source of error, particularly if it is more than a few m (which is very likely) & particularly for any analysis at that order of scale. And what is the quantitative (not qualitative) impact of this?

Answer : Geo-location accuracy of the Lidar datasets is less than 1m (0.1m for DRL), as

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reported by recent literature. The impact of geo-location error on AGB estimations from the ground data has been calculated and discussed in a new section under uncertainty analysis. However, there is no information about the location of the crown of the trees. A tree located at the edge of a subplot will most likely have a part of its crown in adjacent subplots. These errors are negligible at a 1ha scale, but they dominate at 20m (see Figure S3).

3) This suggests that all the analysis here at much less than 0.5-1 ha would be dominated simply by this aspect, so is there any point in doing it any finer?

Answer : The analysis is done at different scales in order to show the forest dynamics at different scales within the 50ha plot. We believe that this is an important part of our analysis and find it less discussed in the literature. In most small footprint lidar studies special scale of the analysis is ignored and data collected over plots ranging from 0.04 to 1.0 ha are mixed in one lidar model. Given the interest in spatial scales, it is true that the Lidar analysis at 0.04 ha scale is dominated by geo-location errors and crown location errors. Moreover, most of LVIS footprints, which are around 20m, include data from adjacent plots, which brings more errors in the analysis. However, we show in our analysis that DRL does not give better results than LVIS at the 0.04ha, which we did not know before. We removed the 0.25ha and 0.04ha analysis of AGB change, since we are showing that AGB estimation is not accurate at these scales. The AGB change analysis is now only presented at 1ha scale. At the same time, ground estimation of biomass using allometric data at 20 m resolution can have large errors due to the small number of trees. Allometry, being a regression model, provides accurate estimation of biomass when the number of trees in the plot is large, hence at large plot size (Chave et al., 2004). Therefore, a combination of large errors of ground estimated biomass and geolocation and potential other remote sensing errors make the analysis at 20 m resolution difficult and subject to large uncertainty.

4) The authors say: “In contrast, the DRL sensor provides an accurate estimate of ground elevation and vegetation height.” – how accurate and how do you know?

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Answer : In BCI, the ground surface was verified using 36 ground surveyed points on flat, hard, well-defined surfaces free of obstacles that could occlude GPS signal. Mean vertical error of the terrain is -0.069m (RMS=0.076m, std=0.032m). Similar studies have reported horizontal and vertical errors of 0.106m for DRL (Evans and Hudak, 2007).

5) The LVIS correction also depends very much on the accuracy of co-location as the DRL- derived DEM is used to correct the LVIS data. As a result, errors in this will propagate through to all AGB estimates.

Answer : Since the horizontal accuracy of LVIS is <1m and DRL horizontal accuracy is 0.1m, geo-location error is not an issue when using the DRL-derived DEM to correct the LVIS data. Moreover, we use a 20m radius circular shot representing the LVIS footprint and take the average of the DRL DEM within the LVIS shot, which makes the geo-location error even less important.

6) The authors note that ". . .it is difficult to quantify the improvements made by these corrections at the plot level on AGB estimations because there are only a few outliers in this part of the island." But this is key to the subsequent results as the authors are interested in the absolute differences between the two. As a result they cannot at present quantify errors arising from uncertainty in the two lidar datasets.

Answer : Details about the cross-calibration and the improvements made by these corrections both at the plot level and at the island level were added to the Supplemental Material (See Section (2) LVIS Calibration). Improvements made by the corrections are now quantified. Although the cross-calibration does not improve the relationships between LVIS and DRL intermediate metrics (RH25, RH50, RH75), it does improve RH100LVIS relationship to RH100DRL and to ground estimated AGB. At the footprint level, correlation between RH100LVIS and RH100DRL (extracted from the 20m diameter circles representing each LVIS shot) went from $R2 = 0.65$ to $R2 = 0.73$ over the whole island. At the subplot level, the relationship between RH100LVIS and

RH100DRL is now closer to a one-to-one relationship, with an intercept of -1.68 and a coefficient of 1.02, versus an intercept of 4.46 and a coefficient of 0.88 without correction (1ha subplots). As for the relationship between LVIS metrics and ground estimated AGB, correlation between RH100LVIS and AGB2000 went from R2=0.48 without correction to R2 = 0.56 with correction. We also quantified the differences between LVIS and DRL intermediate height metrics, due to their different footprint size and the way these metrics were calculated for each sensor. LVIS intermediate height metrics are systematically lower than DRL's. RH25DRL >RH25LVIS by 9m $\pm$2.8m), RH50DRL >RH50LVIS by 6.9m $\pm$1.8m), RH75DRL >RH75LVIS by 5.1m $\pm$1.3m). Quantifying these differences help us justify why we could not estimate AGB change from change in Lidar height metrics.

7) Another issue is the use of the height metrics and regression models derived from them. This is key in going from lidar to biomass, but again, all this information and analysis of this is in the supplementary information, not the main paper. This is the heart of the method to estimate biomass (and hence biomass change) from lidar, so again is absolutely critical to the results and conclusion, but is rather hidden away. The assumptions made here, and their robustness and generality (or otherwise) must be analysed critically and in full in the main paper. If this is at the expense of the discussion of the resulting biomass change values, then those could go in the supplementary information – after all, those results are essentially the demonstration of the method, and so are only useful in the light of the method's accuracy.

Answer : We added information about the regression models in the main paper. However, we think details should remain in the supplementary material because we want the main paper to focus on AGB estimations more than on how the metrics were produced. We also think that by focusing on the results and their ecological interpretations, we meet the requirements of the journal of Biogeosciences much better.

8) A key question here is: are the differences in biomass between the dates is due to differences in the observation methods and metrics derived from the lidar data, or

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genuine changes? In order to answer this question (and as noted above), the methods ought to be made as similar as possible in order to determine these potentially rather small changes against a background large variation in height. However, rather than provide a common metric/framework the authors find empirical best fits between lidar height and AGB, and this is different for the different lidar datasets (eqns 1 and 2 from the main paper). Not only are different numbers of parameters used (5 for LVIS, 4 for DRL) but the form appears to be different (quadratic for LVIS, linear for DRL). There is no justification given for these different forms, and the decision is based purely on RMSE of fit.

Answer : Regression models have been modified. We are now using a power law model, in which each metric has its own power associated. This model is more appropriate to fit the data than the square of a linear function of height metrics that was previously used to fit AGB. Moreover, we are now using the same metrics for LVIS and DRL (RH25, RH50, RH75, MCH and RH100). We tested the models with different number of metrics and we found that using all metrics was the best way to estimate AGB, given that the metrics that contribute the most to the model are different for LVIS and DRL. Using less metrics would mean that we would have to use different metrics for LVIS and DRL models, which would not be consistent with our goal to use similar methods for both datasets. We have also added models based on the use of mean canopy height (MCH) as a single height metric widely used in lidar literature. The use of MCH has the advantage of having almost exactly the same coefficients for both LVIS and DRL, which makes the estimations more comparable. We are showing the results of both approaches in the main paper. Figure 2 shows the relationship between MCH and AGB.

9) But the form of the required relationship is known (eqns ES1 and ES2) and so why is this not used to inform the regression model form (which makes sense in eqn2 but not eqn1)? This immediately means that i) the models are different for the two different dates; and ii) the results are entirely dependent on the particular local calibration, and

for each date.

Answer : Equations ES1 and ES2 estimate AGB from DBH (Diameter at Breast Height) and wood density at the tree level. Our regression model to estimate biomass from Lidar data is performed at the subplot level and does not involve DBH or wood density. It would not make sense to use the same form of relationship as in ES1 and ES2. Instead, we estimate AGB using height metrics from our Lidar datasets. However, (i) now we have similar frameworks for both dates, and (ii) the results are dependant on the local calibration, for each date. It means that the accuracy of the results depends greatly on the accuracy of the ground data that is used as the calibration for the lidar data.

10) The authors note: “Consequently, we used DRL and LVIS metrics independently in the determination of regression models for AGB estimations.” – one way around this would be to generate a pseudo-LVIS dataset from the DRL by aggregation at the same scale, and comparing at that level (this is done at 1m scale, rather than 20m scale). This would seem a fairer comparison in many ways.

Answer : This approach was tested by aggregating the 20m DRL metrics to 100m. There was still no relationship between ground estimated AGB change (AGB2010-AGB2000) and change in the height metrics (RH25DRL-RH25LVIS,etc). However, we used this new dataset in our 1ha regression model, in order to be more consistent with the LVIS dataset. Moreover, we are now comparing top canopy elevations (canopy height over the ellipsoid) (RH100E), which are not affected by ground finding errors and are comparable at the footprint level (Figure 1 and Figure 4). We used a 20m circular footprint to extract the DRL data for each LVIS shot within the 50ha plot using the nearest neighbor approach. Although this analysis does not translate to AGB estimation, it gives valuable information in terms of canopy change. We are showing that RH100E DRL is lower than RH100E LVIS by about 1m over the entire 50 ha plot, suggesting a significant average height change.

11) In section 4.1 the authors note the issues of uncertainty in choice of metric, but then do not present any quantitative analysis. As a result they are not able to propagate sources of uncertainty through from the height change estimates to the resulting biomass change estimates, despite their claims to do so (see abstract and p1962).

Answer : We included a section on the sources of uncertainty and quantified them both for the ground and remote sensing data analysis. Due to lack of detailed information about the errors associated with the ground data, we could not perform a rigorous error propagation model to estimate the uncertainty of biomass change at various scales. However, by making some assumptions based on published results in the literature and quantifying errors associated with our lidar and ground data, we were able to elaborate on the sources of uncertainty and the range of errors present in the data analysis.

12) Figure S2 "In all cases, the correlations among the height metrics are strong" – yet in all cases but 1 $r2<0.6$ and in 7 out of 9 <0.5. So what do you mean by strong? FigS2 is critical to the results but again is in the supplementary info and needs more detailed analysis.

Answer : We consider that metrics are correlated and quantified the correlations among the height metrics and within our multivariate regression model. We decided to leave Figure S2 in the supplementary material, but we are analyzing it in more details and discussing some of the results in the manuscript. Our analysis is based on standard statistical analysis, and we express our results based on the coefficient of determination (R-squared) and provide the R-squared in our analysis for all standard significance levels ($p< 0.01$).

13) Re comparison with Mascaro et al 2011 - present study is locally calibrated and uses many params so is this "realistic" (p1972). What does this mean?

Answer : By realistic, we mean that we only used data from BCI. We changed the sentence in the paper. Moreover, we have added the MCH as a single metric to estimate forest biomass with the intension of making our approach comparable to published

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method in Mascaro et al. 2011.

14) “analysis and used these errors when analyzing the Lidar estimation of biomass and biomass change” – so what are these errors? I presumed the SDs quoted in the main text were due to variation within the dataset not errors propagating from the biomass regression. Is this not the case?

Answer : We included detailed information about the source and magnitude of most important errors in the data analysis. We kept the SD values for showing how changes above SD levels can be detected by the two lidar sensors. We have included the overall range of errors associated with the biomass change and show that these errors are about the same level as the SD. The uncertainty levels for detecting biomass changes are discussed in section 5.

Technical comments

Are changes significant at each scale?

Answer : The change analysis has been removed for the 0.25 and 0.04ha scales, as it did not show any significant results.

P1966 line 27 - is this statsig? Answer : We are using the standard deviation of Lidar-derived AGB change as our significance threshold. It is particularly robust when ground estimation and Lidar estimation of AGB change have opposite direction above this threshold. With the added uncertainty analysis, we show how the significant threshold level based on the SD level is comparable to the potential error level.

P1967 line 17 - don’t use amplitude you mean range or variance Answer : Amplitude has been replaced.

Table 1 6dp?? Answer : We are now showing 2dp

Higuchi 1994 missing Answer : reference added

Fig S4 RMSE not RSME. Answer : RSME was replaced by RMSE

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And why not just remove all erroneous trees from the census rather than replacing them with mean measurements? They are wrong so leave them out.

Answer : These trees are erroneous but they still contribute to the AGB of the plot, since they are not dead. Taking them out would erroneously make AGB drop in the subplots. Instead, we replace the erroneous DBH values by values that correspond to the growth rate corresponding to the DBH class that the tree was part of during the previous census. This method has been used by Chave et al. PLoS Biol (2008) to calculate the biomass change. The method is an innovative and at the same time the only way to estimate biomass and biomass change in permanent plots. However, the approach can definitely introduce errors in the biomass estimation. The errors associated with the estimation cannot be quantified readily. We predict the errors from ground estimation of biomass from multiple census inventory can be large enough to make the change detection difficult at the small plot scale.

p1974: uncertainty in detecting small changes of biomass . . . is minimized in the BCI dataset "because of intensive effort in the field". What does this mean?

Answer : We agree that this sentence is not very clear. It has been removed from the main text. It has been replaced by : "BCI is known to have ground campaigns of very good quality".

When analysing in terms of forest age - why not see if the analysis detects these differently, independent of a priori stratification? As it is this is imposed on analysis so if hypothesis is changes in these different age stands look different to lidar then analysis ought to show this maybe?

Answer : The numbers given in the paper are indeed extracted from a priori stratification. A paragraph showing where the areas that significantly lost or gained AGB has been added to the paper. We are showing that in both models (using 5RH and MCH only), areas that lost the most AGB are located in old growth forest, whereas areas that gained the most AGB are located in secondary forest. A detailed analysis is presented

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in the main paper.

Additional changes to the paper :

LVIS correction has been enhanced by adding the difference of ground elevation at the shot level. It was previously done by taking the average ground difference of the 20m resolution DEMs of LVIS and DRL.

A figure showing big trees (DBH > 70cm) in 2000 and 2010 in the 50ha plot has been added to the paper (Figure 10), in order to show the dynamics of this DBH class. Although the number of trees in this DBH class is similar at both dates,we show that there has been a big turn over during that period. A figure showing ground-estimated AGB change between 2000 and 2010 has also been added to the paper (Figure 3), replacing the histograms of ground AGB, that are now presented in the supplementary material.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/10/C2124/2013/bgd-10-C2124-2013-supplement.pdf

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Interactive comment on Biogeosciences Discuss., 10, 1957, 2013.

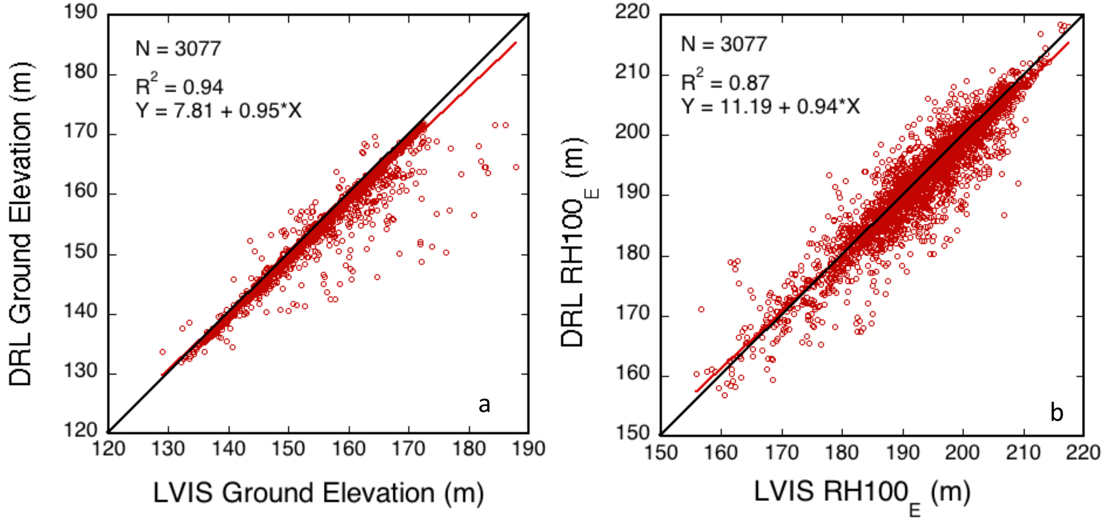

Fig. 1. Relationship between LVIS ground elevation and DRL ground elevation, and between LVIS top canopy elevation and DRL top canopy elevation.

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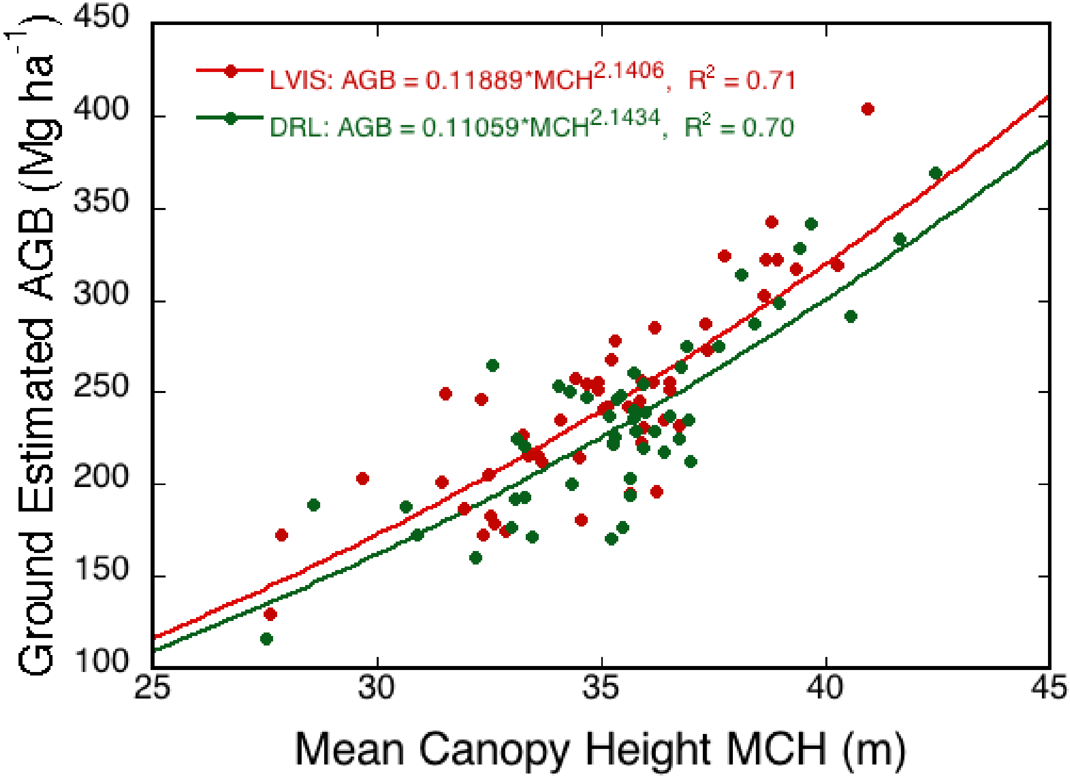

Fig. 2. Relationship between ground estimated AGB and MCH from LVIS and DRL, at 1ha.

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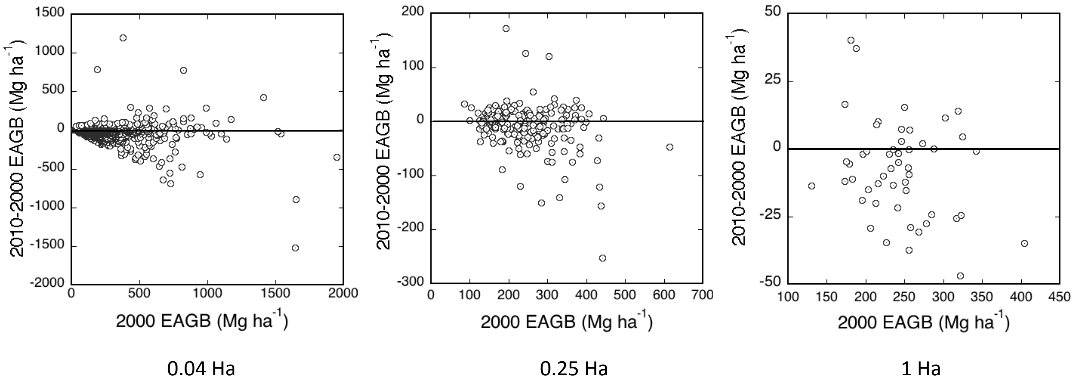

Fig. 3. Ground AGB change between 2000 and 2010 at 0.04ha (left), 0.25ha (center) ad 1ha (right).

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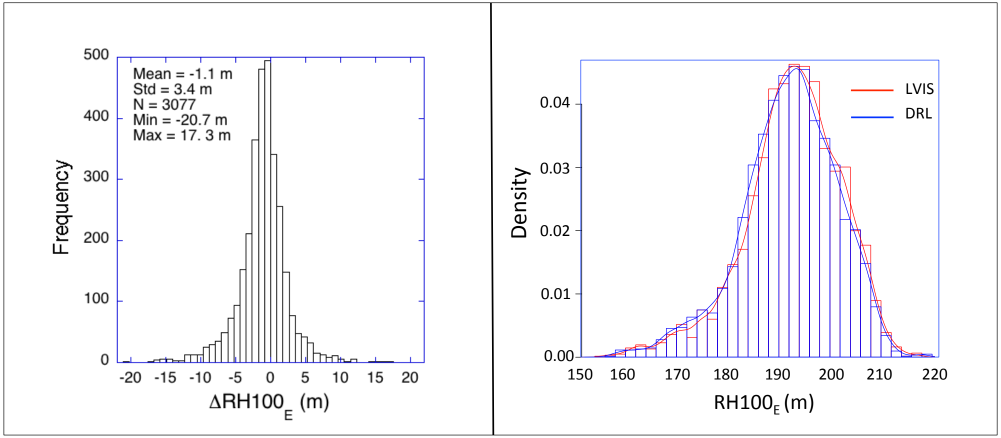

Fig. 4. Distribution of RH100E change between 1998 (LVIS) and 2009 (DRL) (a), and distribution of RH100E for each date (b).

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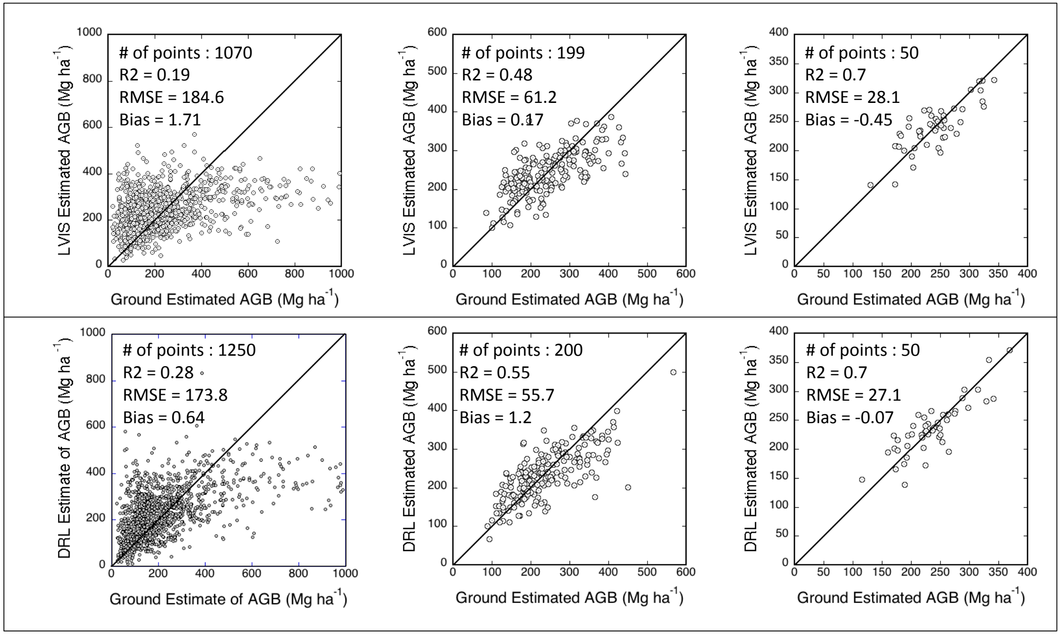

Fig. 5. Relationship between Ground estimated AGB and Lidar estimated AGB (top : LVIS, bottom : DRL), using five height metrics in the regression model.

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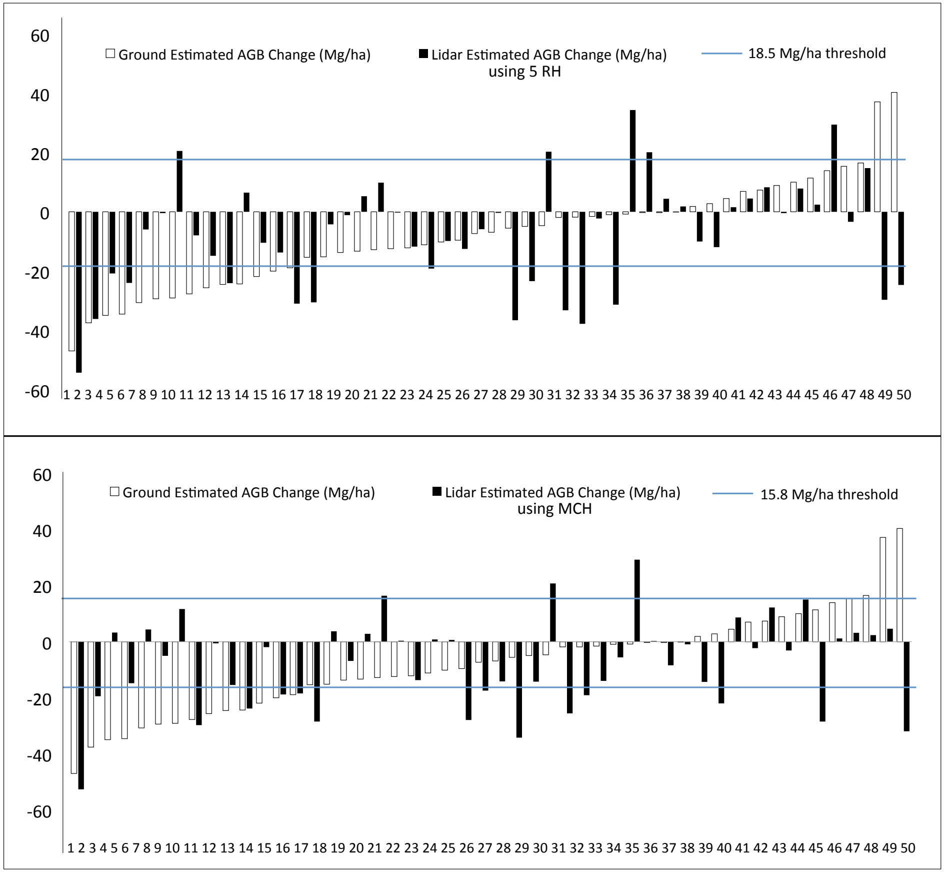

Fig. 6. Comparison of AGB change (Ground estimation vs. Lidar estimation) for every 1ha subplot using the 5RH approach (top) and the MCH approach (bottom).

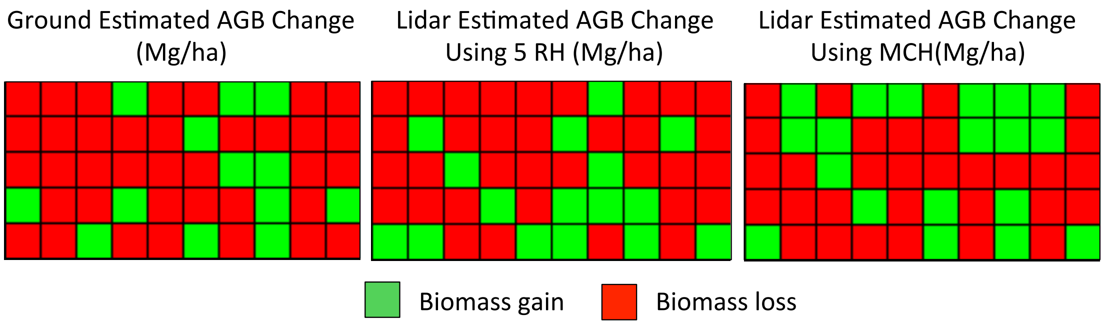

Fig. 7. AGB change (in Mg/ha) from Ground estimations (a) and from Lidar estimations (b and c) in the 50ha plot at 1ha spatial scale.

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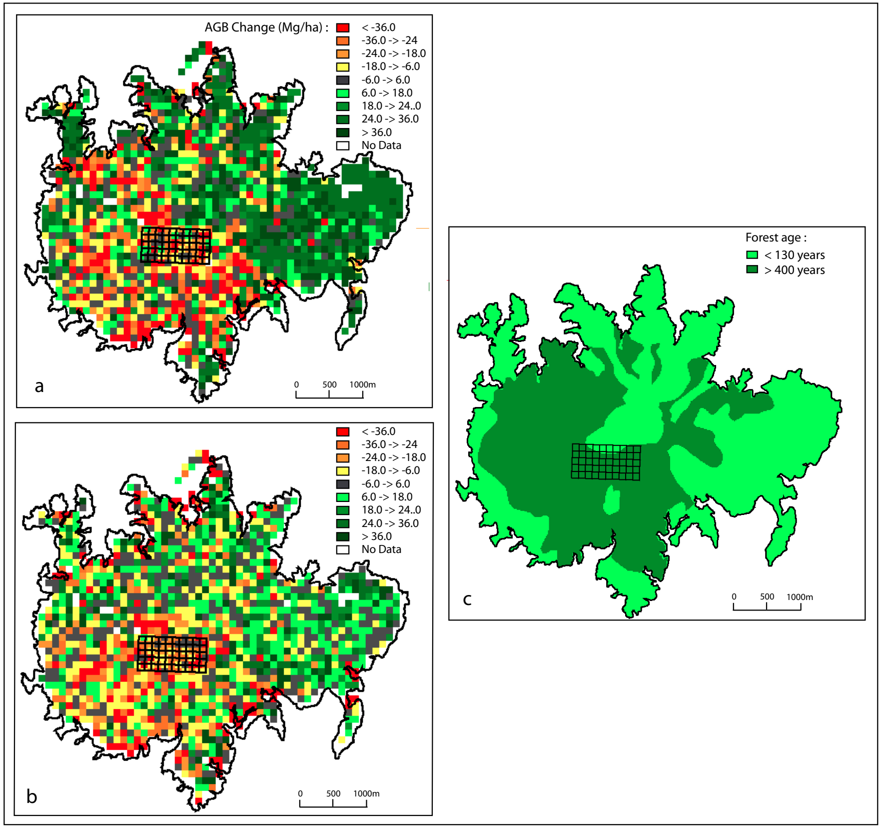

Fig. 8. AGB Change maps between 2000 and 2010 (a and b) and Forest Age map (c). The AGB change map from the 5RH approach (a) shows patterns of forest age more clearly than the AGB change map from the MCH appr

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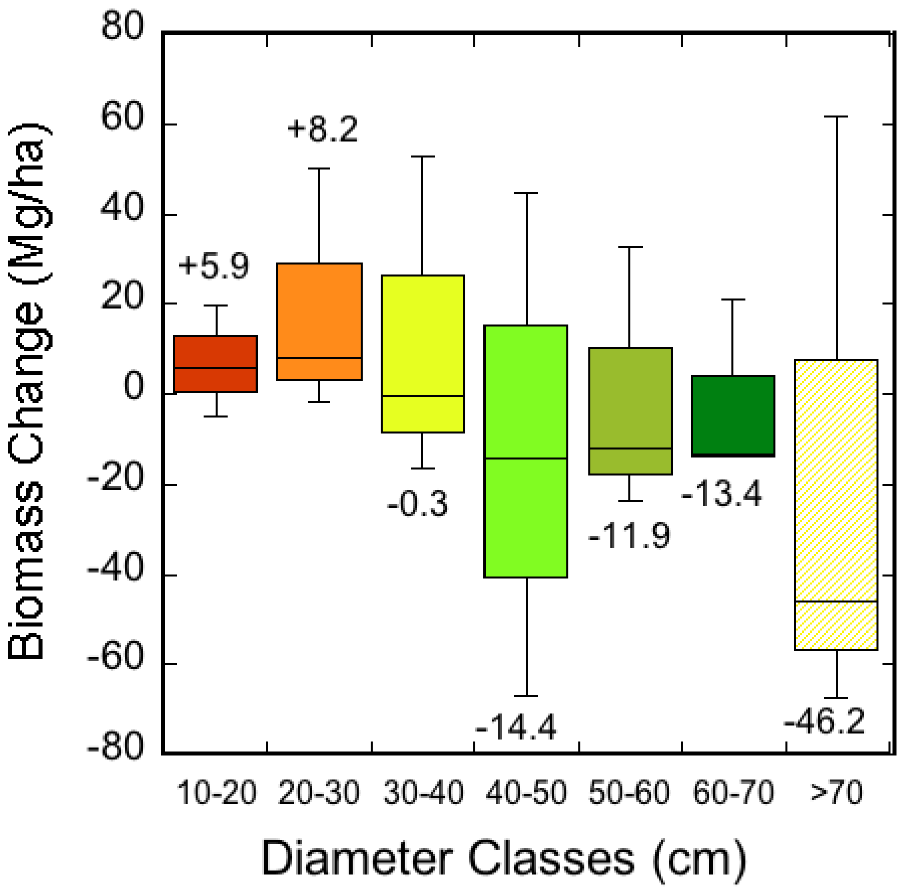

Fig. 9. DBH classes and AGB Change (20m spatial scale).

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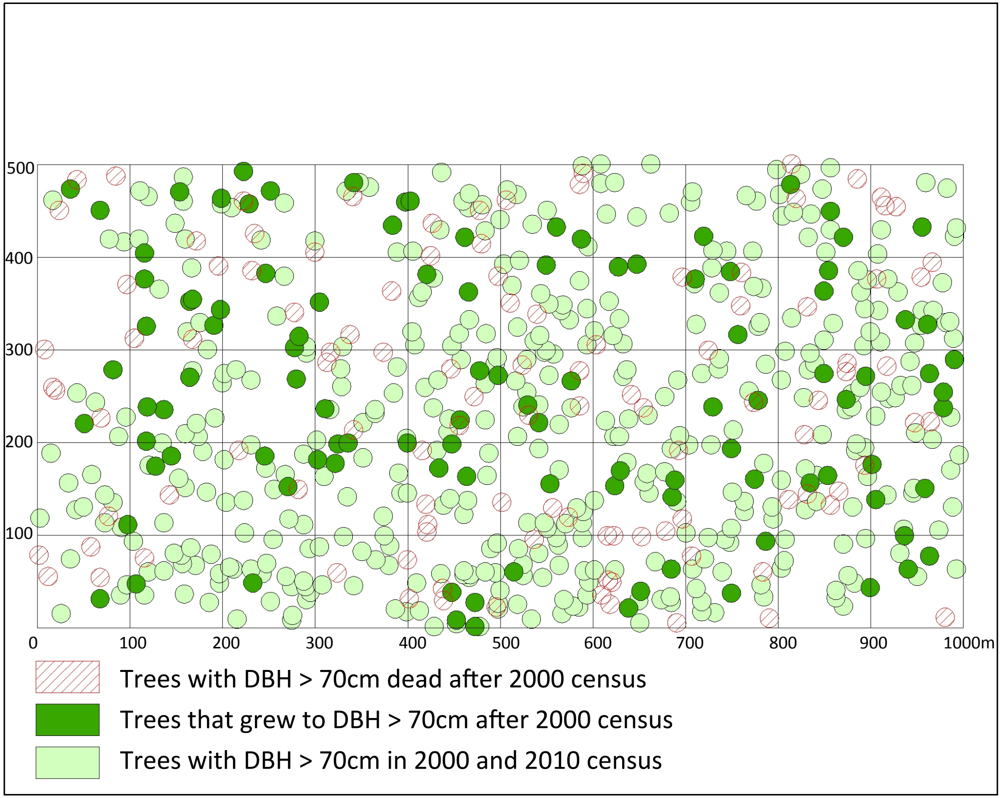

Fig. 10. Dynamics of big trees (DBH > 70cm) in the 50 Ha plot between 2000 and 2010.

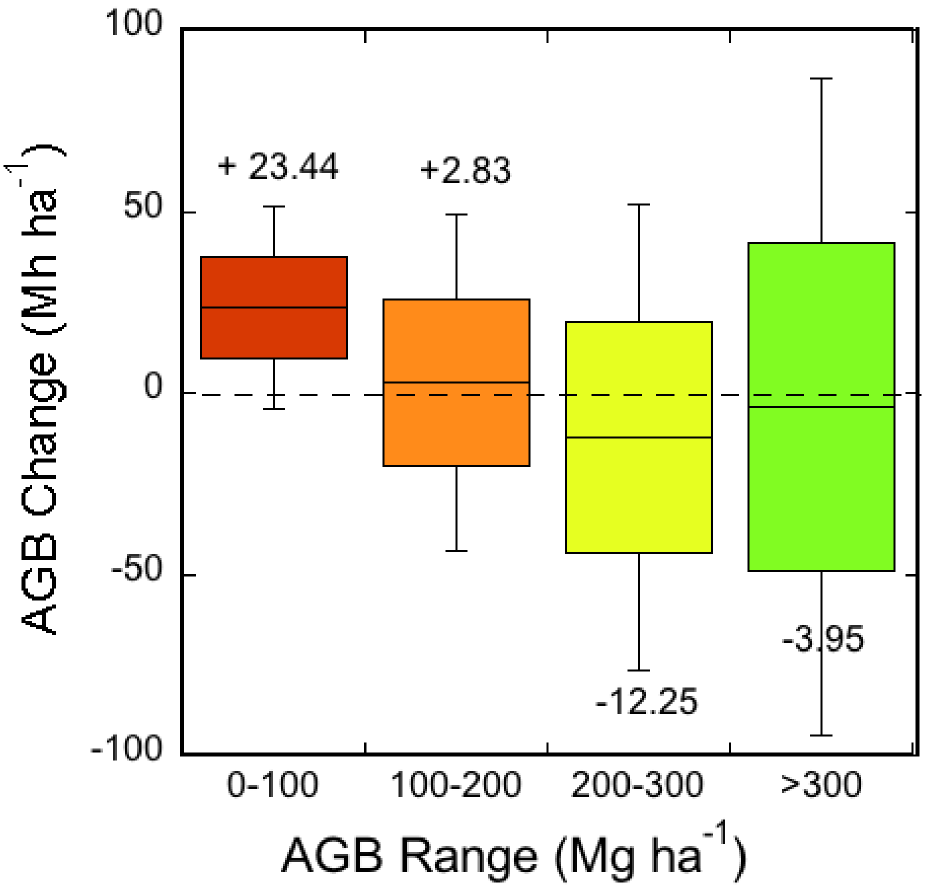

Fig. 11. Lidar-derived AGB range and AGB Change (20m spatial scale)

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