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Document Authorship

	NAME	FUNCTION	ORGANISATION	SIGNATURE	DATE
PREPARED	M. Santoro	Project scientist	Gamma Remote Sensing		
PREPARED	O. Cartus	Project scientist	Gamma Remote Sensing		
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
VERIFIED	R.Lucas	Project Manager	Aberystwyth University		
VERIFIED	H. Kay	Project Coordinator	Aberystwyth University		
VERIFIED	S. Quegan	Science Leader	Sheffield University		
APPROVED					

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ORGANISATION	NAME	QUANTITY
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2.0	2020-04-06	Adapted the ADP to year 2 algorithm. Added the strategy to map AGB changes	
3.0	2021-06-16	Adapted the ADP to year 3 algorithm. Added aspects to be developed in future studies	

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SYMBOLS AND ACRONYMS

ADP	Algorithm Development Plan
AGB	Above Ground Biomass
ATBD	Algorithm Theoretical Basis Document
BCEF	Biomass Conversion & Expansion Factor
CCI	Climate Change Initiative
CCI-Biomass	Climate Change Initiative – Biomass
CD	Canopy Density
DARD	Data Access Requirements Document
E3UB	End to End ECV Uncertainty Budget
ECV	Essential Climate Variables
EO	Earth Observation
ESA	European Space Agency
FAO	Food and Agriculture Organization
GCOS	Global Climate Observing System
GEDI	Global Ecosystem Dynamics Investigation
GSV	Growing Stock Volume
ICESat GLAS	Ice, Cloud, and land Elevation Satellite Geoscience Laser Altimeter System
PSD	Product Specification Document
PVASR	Product Validation and Algorithm Selection Report
PVP	Product Validation Plan
SAR	Synthetic Aperture Radar
SMOS	Soil Moisture & Ocean Salinity
SRTM	Shuttle Radar Topography Mission
URD	User Requirement Document
WCM	Water Cloud Model

Table 1-1: Reference Documents

ID	TITLE	ISSUE	DATE
RD-1	Users Requirements Document		
RD-2	Product Specification Document		
RD-3	Data Access Requirements Document		
RD-4	Product Validation and Algorithm Selection		
RD-5	Algorithm Theoretical Basis Document		
RD-6	End to End ECV Uncertainty Budget		
RD-7	Product Validation Plan		
RD-8	Algorithm Theoretical Basis Document of GlobBiomass project		

1. Introduction

Above-ground biomass (AGB, units: Mg ha^{-1}) is defined by the Global Carbon Observing System (GCOS) as one of 54 Essential Climate Variables (ECV). For climate science communities, AGB is a pivotal variable of the Earth System, as it impacts the surface energy budget, the land surface water balance, the atmospheric concentration of greenhouse gases and a range of ecosystem services. The GCOS requirement is for AGB to be provided wall-to-wall over the entire globe for all major woody biomes at 500 m to 1 km spatial resolution with a relative error of less than 20% where AGB exceeds 50 Mg ha^{-1} and a fixed error of 10 Mg ha^{-1} where the AGB is below that limit.

One of the objectives of the CCI Biomass project is to generate global maps of AGB using a variety of Earth Observation (EO) datasets and state-of-the-art models for three epochs (2010, 2017 and 2018) and assess biomass changes relative to the 1-year difference and to an almost 10-years difference. The maps should be thematically consistent with data layers similar to the AGB datasets that are produced in the framework of the CCI Programme (e.g., Fire, Land Cover, Snow etc.).

Algorithms to estimate AGB from Earth Observation (EO) data are described in the Algorithm Theoretical Basis Document (ATBD) [RD-5] whereas the End-to-End Uncertainty Budget (E3UB) document [RD-6] describes the accuracy associated with the estimates of AGB. The ATBD and the E3UB documents are live documents, updated once yearly to provide a thorough description of the algorithms implemented to generate the AGB and, in the future, AGB change maps. The current version of the ATBD and the E3UB documents describe the CORE algorithm used in Year 3 of the CCI Biomass project to generate the three global datasets of AGB and related AGB change maps. The CORE algorithm developed in Year 1 was based on the GlobBiomass global retrieval algorithm [RD-8] (see http://globbiomass.org/products/global-mapping/). In Year 2 the CORE algorithm was advanced by expanding on concepts presented in the first version of this document. Namely, (i) the retrieval models expressed the SAR backscatter as a function of forest height and canopy density, (ii) allometries between canopy density, forest height and AGB were implemented in the retrieval models (iii) the model training accounted for the effect of local topography on the relationship between SAR backscatter and biomass. These advances were possible thanks to an in-depth analysis of the ICESat GLAS observations of canopy density and height, and the increasing number of publications that focus on the relationship between LiDAR height metrics and AGB. As a consequence, the CORE retrieval algorithm used in year 2 provides estimates of AGB instead of GSV so that a Biomass Conversion and Expansion Factors (BCEF) layer becomes unnecessary.

In year 3, the CORE algorithm was consolidated with the addition of recent LiDAR observations by the GEDI and the ICESat-2 missions. Also, the CORE algorithm implemented measures to avoid unnatural fluctuations of the AGB estimates. These measures, however, could not fully compensate for artefacts because of the different EO data available in 2010, 2017 and 2018. To quantify biases in each of the three maps, a model-based framework relying on the plot database available to CCI Biomass was implemented and coarse resolution maps of AGB bias (0.1°) were generated. The bias layers are supposed to build confidence on the reliability of the map rather than to represent a correction factor to be applied to the AGB estimates, not least because of the much poorer pixel spacing (10,000 ha vs. 1 ha). The AGB change maps derived from the year 3 dataset were based on AGB differencing rather than signal differencing because of the multi-sensorial approach pursued in this project. Given that AGB changes were assessed on maps of different quality and only for three epochs, the approach developed so far has to be seen as preliminary. Some ideas to pursue in future activities are presented in this document. Such ideas involve both the estimation of AGB and the estimation of AGB in time to track changes, as it is likely that a multi-sensorial approach to estimating AGB is superior to the use of one set of observations from which AGB dynamics can be derived directly.

This document builds on the ATBD and E3UB documents of Year 3 to identify major elements that require development in future endeavours of the CCI Biomass project. In addition, we consider the review of the CCI BIOMASS data products of Year 2 reported in the Product Validation and Algorithm Selection Report (PVASR) [RD-4] and the Product Validation Plan (PVP) [RD-7]. As for the ATBD and the E3UB documents, this Algorithm Development Plan relies on the Users Requirements Document (URD) [RD-1], the Product Specifications Document (PSD) [RD-2] and the Data Access Requirements Document (DARD) [RD-3] of Year 3.

Section 2 reviews the CCI Biomass CORE algorithm implemented in year 3. Section 3 elaborates on the known major weaknesses of the CORE algorithm based on the initial assessment of AGB retrieval reported in the ATBD. The PVP and the analyses reported in the PVASR provide further information on these weaknesses. Section 4 lists potential solutions to the issues identified in Section 3. Advancing the estimation of AGB change based on the experiences gathered with three AGB data products foreseen by the CCI Biomass project is the topic of Section 5.

2. CCI Biomass CORE algorithm

Error! Reference source not found. shows the flowchart of the CORE biomass estimation procedure implemented in Year 3 of the CCI Biomass project to generate global datasets of AGB estimates for the epochs 2010, 2017 and 2018 [RD-5]. Text in red visualizes modifications introduced from year 1 to year 2. The shaded part of the flowchart represents potential improvements following the implementation of additional retrieval techniques. [RD-5].

With the CORE algorithm, two independent estimates of AGB are obtained from the same BIOMASAR algorithms but implementing a different modelling framework. The SAR backscatter is related to canopy density and height with the same type of Water Cloud Model used in year 1. Allometric equations based on LiDAR data are used to relate these variables. A second set of allometries linking height and AGB is then used to express the SAR backscatter directly as a function of AGB. Linear weighting is applied to generate a final map of AGB. With this implementation of the CORE algorithm we make explicit use of laser observations in the retrieval and follow a promising line of research aiming at relating LiDAR-based canopy height metrics to AGB. Also, we embarked on a characterization of how topography affects the retrieval by using experimental relationships between topographic index (incidence angle) and backscatter rather than developing models that would have probably failed due to the subtle difference in backscatter as landscape and topography change. Finally, the estimation of the model parameters does not rely on self-calibration alone but implements a blend of self-calibration and least squares regression, which was found to yield more precise estimates. A quantitative assessment of the results achieved with the CORE algorithm is presented in the Product Validation Report.

3. Caveats of the CORE algorithm

The above brief summary of the CCI Biomass CORE algorithm highlights the major elements of the retrieval approach. This may not be the best possible algorithm but rather is a global approach constrained by the available EO data and ground observations. The CCI Biomass CORE algorithms rely on a number of assumptions that appear viable when comparing large-scale averages of estimated AGB with corresponding values based on inventory information [RD-5] and [RD-7]. Nevertheless, these assumptions, which were made in order to allow the CORE algorithm to perform globally, also introduce systematic errors into the retrieved biomass, which may become apparent when focusing on particular areas [RD-4], [RD-5] and [RD-7]. In the ATBD, we provided a list of potential areas of improvement of the CORE algorithm. These are reported below and then expanded in the next Section with a proposed development of the CORE algorithm.

- The retrieval of biomass implemented in year 1 was found to be rather conservative because it missed the extreme values of AGB. One of the reasons was that the retrieval models did not explicitly involve height information. In year 2, we have exploited height information in the form of allometries, with interesting preliminary results. The allometries were based on ICESat GLAS metrics, which did not provide a uniform sampling of all land masses on Earth and required us to be rather generic in the way the allometries could describe the relationship between canopy density, height and AGB. With the denser coverage of GEDI and ICESat-2, the allometry between canopy density and tree height was further characterized in year 3. The impact of the allometries on the AGB maps was substantial, reducing the overestimation in the low AGB range and the underestimation in the high AGB range. Both GEDI and ICESat-2 data products are still under development, which suggested moderate usage in year 3. Interaction with the data production teams and progressive ingestion of new data releases should improve the allometries and, thereof, auxiliary datasets used by the retrieval algorithms (e.g., the maximum AGB).

- The retrieval of biomass is based on some simplifying assumptions that cause the retrieval models to be too general to capture the spatial variability of the relationship between the radar observations and vegetation properties. Vegetation structural information as developed in the Data Access Requirement Document [RD-3] should provide the backbone for a more targeted estimation of model parameters. Unfortunately, most EO-based datasets that could complement a retrieval do not have a full error characterization so that the impact of a direct implementation in our retrieval schemes may not be controllable.

- Regarding alternative approaches to retrieving AGB from the set of observations currently available from spaceborne sensors, we have not identified ground-breaking approaches that may improve our retrievals while fulfilling at the same time the requirements in terms of spatial resolution and temporal coverage of CCI biomass maps.

- A wide range of observations is, in our opinion, fundamental to avoid systematic biases caused by the fact that no remote sensing observation is a direct measure of biomass. One line of research that has been developing quickly in recent years is inversion of coarse-resolution observations from spaceborne microwave radiometers and scatterometers to AGB. Although such observations do not match the requirement on spatial resolution of the CCI biomass maps, data from radiometer and scatterometer missions cover several decades and have been demonstrated to allow characterization of biomass dynamics. As such, experiences gathered at coarse resolution may serve as guidelines in the process of establishing rules to ensure that the dynamics of AGB obtained from less frequent high-resolution EO data are well captured.

- Moving from a GSV-centric to an AGB-centric retrieval implies that the BCEF is no longer a crucial variable in the process of biomass estimation. Nevertheless, only once global maps of AGB with both CORE methods are compared will it be possible to understand whether efforts should be dedicated to characterizing wood density and expansion factors beyond the results obtained in the GlobBiomass project.

- Finally, regardless of the procedures here developed to estimate biomass, the accuracy of the retrieval strongly depends on the quality of the EO data used as predictors. We have identified a number of systematic issues in the SAR data that prevent us obtaining the highest possible quality AGB results. It is believed that having the possibility to pre-process the EO data would allow such quality to be attained. Hence continual interaction with data providers is needed.

4. Proposed development of CORE algorithm

4.1. Use of LiDAR observations from ongoing missions

Observations that sense forest structure are of major benefit to estimation of biomass. Unfortunately, the majority of EO data available globally is in the form of energy reflected to the sensor, so that biomass can only be inferred with parametric or non-parametric approaches (Santoro and Cartus, 2018). SAR interferometry and laser scanning instead generate observations that contain information on the vertical and the horizontal distribution of vegetation, thus providing a more direct measure of parameters involved in the computation of biomass (canopy height, density of canopy).

The TanDEM-X and SRTM missions were conceived to acquire interferometric datasets that would allow the generation of surface elevation models (Farr et al., 2007; Krieger et al., 2007). Over forested terrain, an estimate of vegetation height can be inferred from the surface elevation assuming that the terrain elevation is known. To obtain the true vegetation height, an additional step that compensates the InSAR-based height of the vegetation for the penetration of microwaves into the canopy is required (Walker et al., 2007). Although high resolution and accurate (surface) elevation models based on interferometric data exist, there is no global dataset of terrain elevation, which hinders the use of interferometry for a "direct" measure of the vegetation vertical structure. It will not be until the BIOMASS mission is flying that estimates of ground elevation may be possible (Quegan et al., 2019), although the coverage will not be global (Carreiras et al., 2017) and at a coarser spatial resolution than the CCI BIOMASS products (Quegan et al., 2019). To the best of our knowledge, there is no spaceborne mission planned that can allow for a global estimate of terrain elevation.

Laser instruments also measure the elevation of the Earth surface and, in the case of vegetation, return a profile of reflection intensity along the vertical direction. The GLAS instrument on-board the ICESat satellite operated between 2003 and 2009 and recorded millions of waveforms along its orbital path. Unlike interferometric datasets, the signal recorded by a laser instrument contains also a ground return, so that an external dataset of terrain elevation is not required to estimate the height of vegetation. Waveform information in the GLA14 product was processed globally in the GlobBiomass project [RD-8] from which canopy density and several height percentiles were computed. A GLAS footprint has an approximately 70 m diameter and footprints were acquired sequentially along an orbit; however, the distance between orbits was around 60 km, leading to a sparse sampling of the Earth's vegetation. For this reason, it is preferred to use the GLAS datasets of canopy height and canopy density to derive allometries in support of the retrieval model relating SAR backscatter and AGB rather than as surrogate reference data for model training.

Since 2018, the GEDI and ICESat-2 laser systems have been providing observations with a much denser coverage of the Earth's landmasses compared to ICESat GLAS. In this respect, we have tested the contribution of data from these recent missions to the allometries. In spite of the much denser coverage, our retrieval approach still does not foresee estimation of AGB based solely on the LiDAR observations as this is already taken care of, for example by the GEDI team. Our understanding is also that retrieval of AGB should combine multiple observations from spaceborne SAR, optical and laser observations and exploit the information content on biomass in each set of observations.

The data providers warn about the use of some of their measurements (Neuenschwander and Pitts, 2019; Dubayah et al., 2020) in early data versions. With the advancement of processing routines by the data providers, the accuracy of the laser measurements will improve. Another reason for following closely the development of data products by the GEDI and ICESat-2 teams is their interest in releasing global datasets of forest variables, including AGB.

4.2. Characterizing the AGB - LiDAR height allometry

In the CORE algorithm developed since Year 2, we have introduced the allometry linking AGB with top-of-canopy height in the Water Cloud Model. The characterization of this power-law function was based on the ICESat GLAS top-of-canopy height measurements (RH100) and the GlobBiomass AGB dataset. Although the trend between AGB and RH100 was on average similar to results based on measurements at local scale, it was recognized that there is substantial work to be undertaken to: (i) reduce uncertainties and (ii) improve the spatial characterization of the model parameters. Studies at local sites allow determination of precise allometries, but these allometries may not be generalizable to larger areas. Remote sensing maps, on the contrary, allow us to obtain a region-wide perspective on how height and AGB are related but these relationships may be locally inaccurate. The availability of dense sets of LiDAR observations of RH100 (and in general, different height metrics) from GEDI and ICESat-2 allowed a more detailed characterization of AGB-to-height allometry, which however suffered from the early versioning of the data, implying that some height ranges may present some deficiencies. While the accuracy of the ICESat-2 and GEDI dataset will improve, there is a necessity to understand how well we are able to characterize the allometry spatially. Here, we identify local allometries, such as those developed in the context of CCI Biomass from airborne laser dataset and plot inventory data [RD-5] as a diagnostic tool for the map-based allometry. However, it is clear that in regions poorly covered by LiDAR observations, it will still be impossible to quantify the reliability of the map-based allometry.

4.3. Characterization of tree attenuation

Having fixed the functional dependencies between height and AGB on the one hand, and canopy density and height on the other, the WCM becomes invertible once the coefficients, σ^0_{gr} and σ^0_{veg}, and the two-way tree attenuation coefficient, α, have been estimated. A new approach for estimating the unknown WCM parameters is tested in which the three unknown parameters are estimated by fitting Equation 4-1 to observed relationships between backscatter and canopy density:

$$\sigma^0_{for} = (1-\eta)\sigma^0_{gr} + \eta\sigma^0_{gr}e^{-\alpha h(\eta)} + \eta\sigma^0_{veg}\left(1-e^{-\alpha h(\eta)}\right) \quad (4\text{-}1)$$

where the height term is expressed as a function of η by :

$$h = -\frac{\log(1-\eta)}{q} \quad (4\text{-}2)$$

Possible dependence of the parameters on the local incidence angle is dealt with by fitting separate models for different incidence angle intervals (Figure 4-2). Figure 4-3 illustrates the range of values for the two-way tree attenuation coefficient α obtained by fitting Equation 4-1 to observed relationships between ALOS-2 L-HV backscatter (year 2018 mosaic) and Landsat canopy density. The spatial distribution of the derived estimates reveals distinct regional differences. Low values for α, mostly less than 0.5 dB/m, are obtained primarily in boreal forest regions. In temperate and sub-tropical forests, the estimated values for α tend to exceed 1 dB/m. While the range of values obtained seems reasonable, in particular in the boreal zone, it remains unclear if the observed regional differences reflect actual differences in attenuation or rather properties/errors of the Landsat canopy density product. A sensitivity analysis was carried out to evaluate the effect of the attenuation coefficient on the multi-temporal AGB retrieval in different forest regions. A comparison of L-band radar-derived AGB estimates against LiDAR maps of AGB suggested that a fixed value of 0.5 dB/m for the attenuation coefficient, which has so far been assumed universally in the CORE algorithm, represents a reasonable choice for most forest types. Only in the wet tropics and sub-tropics, we find that the use of a fixed value for α of 0.5 dB/m was associated with underestimation of high AGB ranges and therefore opted in the Year 3 implementation of the CORE algorithm to use a fixed value for α of 1 dB/m in the latitude ranges between 23° S and 23° N. A direct use of the estimates for α obtained by fitting the model in Eq. 4.1 to observations of L-band backscatter as a function of Landsat canopy density did not improve the AGB mapping. Further improvements of the CORE algorithm with respect to a better characterization of differences in forest attenuation in the retrieval therefore remains subject to further investigations based, for instance, on a dense set of estimates of canopy density and height derived from GEDI or ICESAT-2.

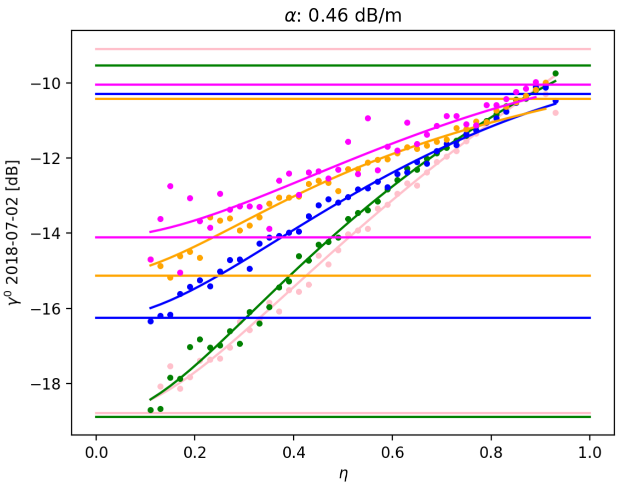

Figure 4-1: Observed and modelled relationship of L-HV backscatter as a function of Landsat canopy density. The model in Eq. 4-1 was fitted with variable transmissivity for different incidence angle ranges (pink: 20-30°, green: 30-40°, blue: 40-50°, orange: 50-60°). For each incidence angle range, the horizontal lines denote the level of the estimated σ^0_{gr} and σ^0_{veg}.

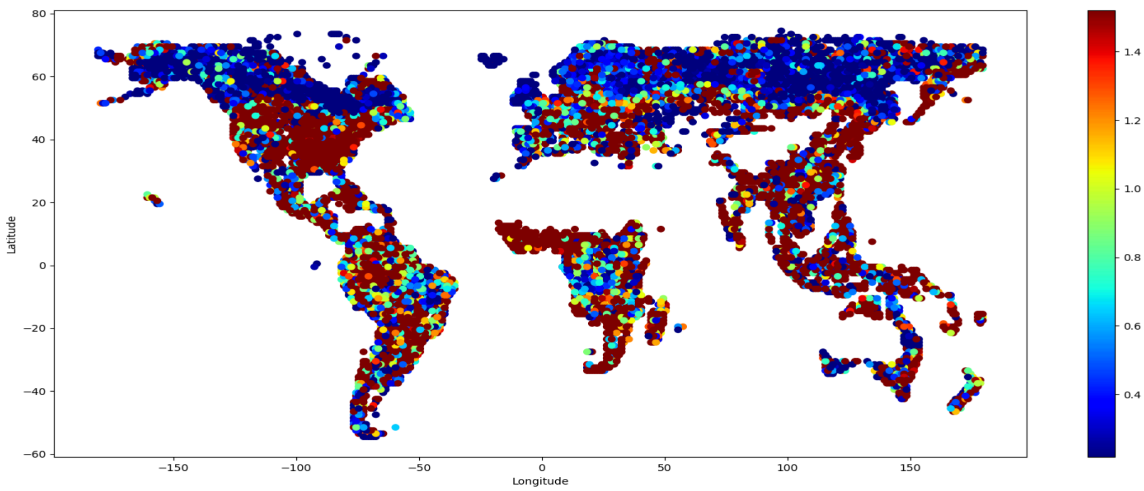

Figure 4-2: Estimates for the two-way tree attenuation coefficient α [dB/m] obtained by fitting Equation 4-1 to observed relationships between L-HV backscatter and Landsat canopy density.

4.4. Use of vegetation structural information

One of the limitations of the currently implemented BIOMASAR algorithms is the coarse representation of vegetation structure. In Year 1, some of the model parameters were estimated after stratifying the world by the FAO ecological zones. In Year 2, we introduced a finer stratification based on 883 ecoregions to characterize the relationship between canopy density and RH100 but still used ecological domains to characterize the relationship between RH100 and AGB. Vegetation structural information developed in the DARD [RD-3] should provide more targeted estimation of model parameters and allometries.

In the same vein, knowledge gathered by investigating the relationship between EO observables and AGB in specific forest classes should be exploited. When evaluating the GlobBiomass and the CCI Biomass map (Year 1) in mangrove forests, the specific scattering mechanisms occurring at C- and L-band were not correctly accounted for in the retrieval model. The AGB of mangroves was often underestimated because the absorption of microwaves in the canopy leads to low backscatter.

4.5. Use of coarse resolution EO data

From the analyses reported in the PVASR [RD-4], it is clear that the estimation of AGB of high AGB forests still needs to be improved. Observations from coarse resolution sensors operating at C- and L-band such as the L-VOD by SMOS have tremendous potential to improve AGB estimates. However, these datasets have a spatial resolution that ranges between 25 km and 50 km. It is unclear whether estimates at such coarse resolution can be transferred to 1 ha. In this respect, the experience of the soil moisture community concerning the re-scaling of coarse resolution soil moisture fields to high resolution maps could inform implementation of a similar strategy for estimating AGB.

5. Advancing the estimation of AGB changes

Estimation of AGB changes between two epochs requires either two AGB maps that are subtracted from each other or an approach that relates changes in signal to a change in AGB. A change in signal assumes that the same type of EO data is available at each date. When this is not possible, the only alternative is to proceed by differencing AGB estimates.

In CCI BIOMASS, we exploit global, repeated observations from multiple spaceborne missions because they are found to be of substantially higher predictive power than a single type of observation. In practice, AGB changes in the context of global mapping can only be achieved by differencing maps. The major caveats of such an approach are (i) biases will propagate to the AGB change estimate and (ii) the variance of the estimated AGB change (i.e., the AGB difference) will be larger than the variance of each individual estimate. Both bias and precision issues were identified and discussed in the ATBD and the PVR, and both affect the quality of the AGB difference derived from CCI BIOMASS AGB data products in ways that need to be better characterised.

Despite its obvious problems, differencing maps is currently seen as the only viable method to assess AGB changes even if the sets of remote sensing observations used to estimate AGB differ between epochs. One way to potentially reduce uncertainties is to further develop the AGB retrieval algorithms so that they ensure temporal consistency of the estimates or correct AGB estimates by benchmarking the AGB trends with those obtained from time series of AGB estimates from other sensors (e.g., L-VOD, C-band scatterometers) under the assumption that such trends correspond to reality. These are, however, thoughts that need to be revisited by taking into account the specifications of the product in the Product Specification Document [RD-2]. Although the PSD currently does not specify requirements for a change product, this may need different specifications for pixel values and grid-cell histograms. However, the starting point is that the estimates of AGB change should be unbiased, which has different meanings for pixel values and grid-cell histograms. Also, methods to validate the product are currently undefined and would need to be addressed in future versions of the Product Validation Plan [RD-7].

In an attempt to mitigate the impact of biases on AGB change estimates, we have tested the correction of AGB estimates with a bias layer obtained with machine learning and a large number of covariates, including plot inventory AGB measurements. The preliminary results are not conclusive on the benefit of such correction but indicate that, if correctly modelled, a bias term can avoid unrealistic estimates of AGB change.

Since the bias correction term requires a dense network of in situ measurements, the spatial resolution is currently limited to 0.1°, which implies that it can currently support global studies on AGB dynamics at coarse resolution only. A denser network of observations would enable a finer characterization of biases.

6. Conclusions

The development of the CORE retrieval algorithm of the CCI Biomass project has implemented several aspects presented in the previous versions of this document. The current CORE algorithm has reached maturity in the sense that it can be applied to generate AGB maps for any year provided that the set of radar backscatter measurements are available. However, this does not imply that the AGB estimates are free from errors given that the retrieval relies on observations that only see a portion of the forest biomass and the inversion models involve a number of assumptions that tend to generalize the response of the radar backscatter to biomass.

We see two major developments that may further improve the accuracy of the retrieval, beyond the improvements already achieved in the first three years of the CCI Biomass project

- Stronger contribution by observations from novel spaceborne LiDAR missions.
- Integration of coarse resolution and high resolution EO datasets

The former should provide a more solid basis for the allometries implemented in the retrieval model. The latter should increase the reliability of the AGB estimates in time and improve the accuracy of the AGB estimates in forests with the highest AGB densities (> 300 Mg ha^{-1}).
Although not directly used in the retrieval algorithms, plot inventory measurements have a fundamental role in characterizing spatial errors in AGB estimates by modelling biases. The modelling of biases was prototyped and should enter a phase of stabilization.

The development of approaches that can quantify AGB changes is in its infancy. Since differencing maps appears to be the only viable solution in a scenario that involves a wide range of observations, AGB changes would be better characterized by working on a time series of AGB estimates rather than on maps scattered in time. Here, the integration of coarse resolution and high resolution EO datasets may help to stabilize AGB change estimates.

As a result of our analysis of possible pathways of research, it is clear that the estimation of AGB and AGB changes requires continual interaction with the AGB research community, including the fields of ecology, field inventory and remote sensing. This will continue to be pursued in the upcoming activities.

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