CCI

BIOMASS

Algorithm Development Plan

Version 2.0

Document ref:	CCI_BIOMASS_ADP_V2
Deliverable ref:	D2.4-ADP
Version:	2.0
Creation date:	2020-04-06
Last modified	2020-04-06

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					
PREPARED					
PREPARED					
VERIFIED	S. Quegan	Science Leader	Sheffield University		
APPROVED					

Document Distribution

ORGANISATION	NAME	QUANTITY
ESA	Frank Seifert	

Document History

VERSION	DATE	DESCRIPTION	APPROVED
0.1	2020-03-05	First draft version	
1.0	2020-04-06	Finalised version	

Document Change Record (from Year 1 to Year 2)

VERSION	DATE	DESCRIPTION	APPROVED
1.0	2020-04-06	Adapted the ADP to year 2 algorithm. Added the strategy to map AGB changes	

Table of Contents

LIST OF FIGURES

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 dataset 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 2 of the CCI Biomass project to generate the three global datasets of AGB. 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.

This document builds on the ATBD and E3UB documents of Year 2 to identify major elements that require development in Year 3 of the CCI Biomass project in order to overcome errors in the estimates of AGB produced in Years 1 and 2. In addition, we consider the review of the CCI BIOMASS data product of 2017 and Year 1 algorithm reported in the Product Validation and Algorithm Selection Report (PVASR) [RD-4] and the Product Validation Plan (PVP) [RD-7]. This Algorithm Development Plan (ADP) will guide the developments needed to improve the three global AGB datasets. As for the ATBD and the E3UB documents, the ADP 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 2.

Section 2 reviews the CCI Biomass CORE algorithm implemented in years 1 and 2. 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. An initial set of thoughts on how to address AGB changes is described in Section 5.

2. CCI Biomass CORE algorithm

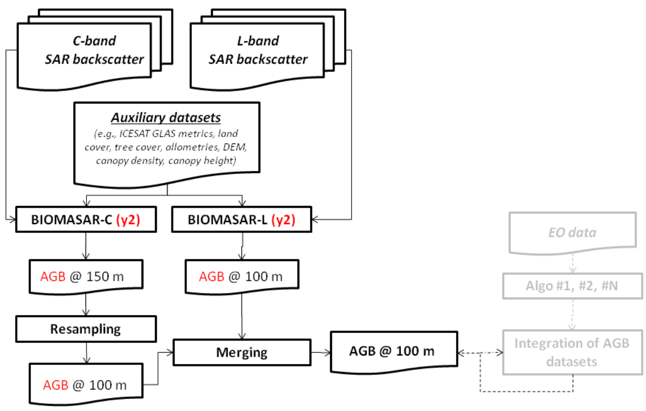

Figure 2-1 shows the flowchart of the CORE biomass estimation procedure implemented in Year 1 and Year 2 of the CCI Biomass project to generate global datasets of AGB estimates for the epochs 2017, 2018 and 2010 [RD-5].

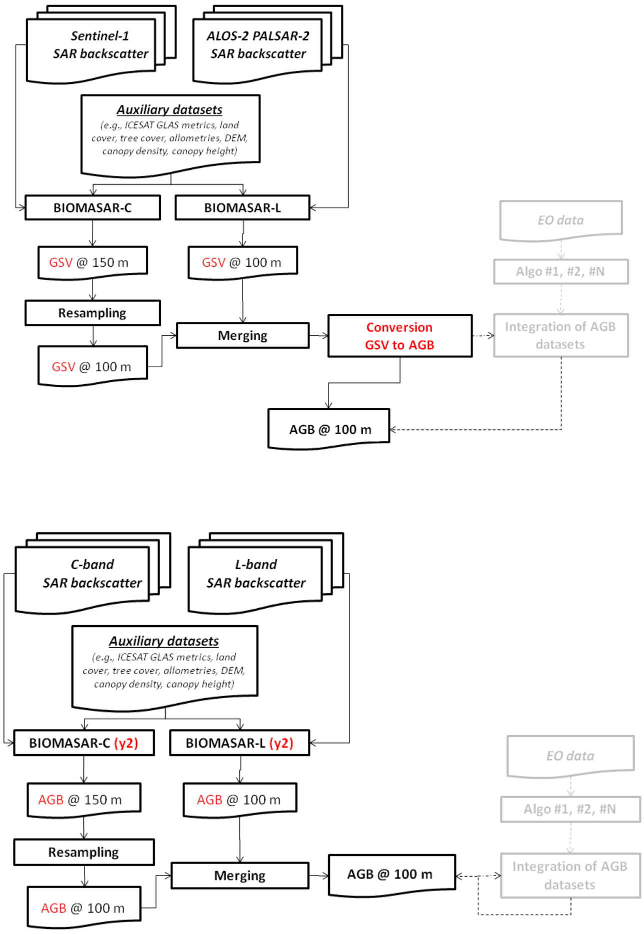

Figure 2-1: Functional dependencies of datasets and approaches forming the CCI Biomass CORE global biomass retrieval algorithm in year 2 (bottom) and year 1 (top). Text in red visualizes modifications introduced from year 1 to year 2. The shaded part of the flowchart represents potential improvements following the implementation of additional retrieval techniques. [RD-5].

With the year 1 CORE algorithm, two independent estimates of growing stock volume (GSV, unit: m^3/ha) are obtained from the BIOMASAR algorithm adapted to ingest C-band SAR backscatter data (BIOMASAR-C) and L-band SAR backscatter data (BIOMASAR-L). These estimates are combined using linear weighting to obtain a final estimate that should have higher precision than the original values. The C- and L-band datasets have different pixel spacing, so the GSV estimates from the BIOMASAR-C algorithm (with slightly lower resolution) are resampled to the geometry of the BIOMASAR-L estimates. Finally, GSV is converted to AGB using a Biomass Conversion and Expansion Factor (BCEF).

With the year 2 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. The same linear weighting is applied to generate a final map of AGB. With this new implementation of the CORE algorithm we make more 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. The combination of these advances seems to mitigate some systematic issues in the retrieval, namely the overestimation in the low biomass range and underestimation in the high biomass range. A quantitative assessment of the results achieved with the new version of the CORE algorithm will be presented in the next version of 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 y1 was found to be rather conservative because it missed the extreme values of AGB. One of the reasons was that the retrieval models were canopy-centric and 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 will be characterized globally. These recent spaceborne missions will also boost investigations on relating laser-based metrics and AGB, which should yield improved allometries, thus bolstering what at the moment is seen as a weak component of the retrieval algorithm.

- The retrieval of biomass is still based on simplifying assumptions that cause the retrieval models to be too general to capture the spatial variability of the relationship between observables 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 retrieve 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 guarantee the temporal consistency of AGB estimates in this project.

- 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.

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 ICESAT GLAS datasets of canopy height and canopy density to support modelling of backscatter as a function of biomass rather than as surrogate reference data for model training.

LiDAR senses vegetation structure and therefore is a primary candidate to estimate biomass. From a global point of view, however, the coverage until recently has been insufficient to achieve wall-to-wall estimates of AGB. The recent start of operations of two spaceborne LiDAR missions (GEDI on-board the International Space Station and ICESAT-2) potentially allows datasets similar to those obtained with airborne laser scanning systems to be obtained and these are likely to provide major support to estimation of biomass in the CORE algorithm.

The Global Ecosystem Dynamics Investigation (GEDI, https://gedi.umd.edu) instrument has operated since December 2018 and covers latitudes between 51.5°N and 51.5°S. GEDI is a full waveform LiDAR, specifically designed to observe vegetation. Sampling and spatial resolution are higher than ICESAT GLAS (1 km vs. 60 km cross-track, 60 m vs. 170 m along-track, 25 m vs. 70 m footprint diameter) so that a LiDAR-only biomass product (1 km spatial resolution) is an explicit target. GEDI data is available since January 2020. The GEDI L2B Canopy Cover and Vertical Profile Metrics Data Global Footprint Level (GEDI02-B) is particularly suited to support model calibration in the CORE algorithm because it provides the two input observables to the allometric equations that allow expressing the SAR backscatter as a function of AGB. The density of observations is such that virtually any 1 km^2 surface on the ground contains one or multiple observations, thus allowing for a finer description of how canopy density and canopy height vary in space. Unfortunately, the coverage of GEDI is limited to latitudes between 51.5°N and 51.5°S, thus not allowing any characterization of vertical and horizontal forest properties in the boreal zone.

ICESAT-2 has operated since October 2018 (first official data release: spring 2019) and has global coverage. The sampling is slightly poorer than for GEDI (Figure 4-1), whereas the size of a footprint is slightly smaller (20 m diameter) (Neuenschwander and Pitts, 2019). Unlike GEDI, the ATLAS instrument on-board ICESAT-2 is a photon counting laser, meaning that the observations are not in the form of a waveform and are therefore not optimized for vegetation studies. Although the focus of the mission is on cryosphere, vegetation studies are one of the thematic targets of the mission. The ATL08 geophysical data product includes terrain and canopy heights from the ATLAS point clouds (Neuenschwander & Pitts, 2019). Unlike GEDI, the coverage of ICESAT-2 is global, thus allowing, in principle, characterization of the relationship between density and height in boreal forest and increasing the density of observations in regions covered by GEDI. It is however not clear whether ICESAT-2 observations can achieve an accuracy comparable to GEDI and, therefore, how the two sets of observations can be used jointly.

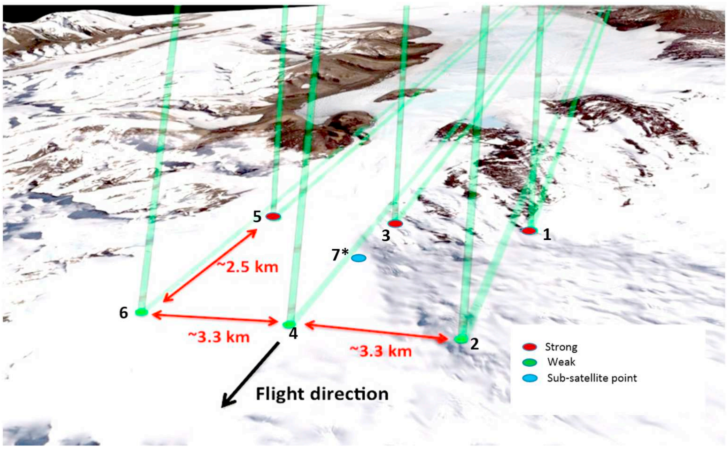

Figure 4-1: Observation geometry of the ATLAS laser instrument on-board the ICESAT-2 platform (taken from Neuenschwander and Pitts, 2019)

From the perspective of generating a global AGB data product, exploring the complementarity of data from both laser instruments is mandatory. However, this would involve a potentially huge amount of work to understand optimal trade-offs between datasets, filtering spurious observations, etc. GEDI and ICESAT-2 data are currently being downloaded, archived and reformatted to allow exploring of their quality and complementarity. Data analysis will follow in year 3 with the aim of understanding the contribution of the datasets to the characterization of allometries in the CORE algorithm. It is not foreseen to develop AGB retrieval algorithms 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.

4.2.Characterizing the AGB - LiDAR height allometry

In the CORE algorithm developed for 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. Our strategy in year 3 is to gather allometries developed at local sites and use them to benchmark allometries derived based on maps and spaceborne LiDAR observations. The availability of dense sets of LiDAR observations of RH100 (and in general, different height metrics) from GEDI and ICESAT-2 should allow more detailed characterization of AGB-to-height allometry, so that comparisons at the level of sites become possible. In other words, local allometries are seen as a diagnostic tool for the map-based allometry, even though 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 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 2010 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, as well as in parts of the wet tropics. 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. To investigate whether the attenuation coefficient can be estimated adaptively or it is appropriate to use a fixed value of 0.5 dB/m, as assumed in the CORE algorithm, requires LiDAR maps of AGB in different forest regions to act as a reference for assessing the sensitivity of the WCM to α.

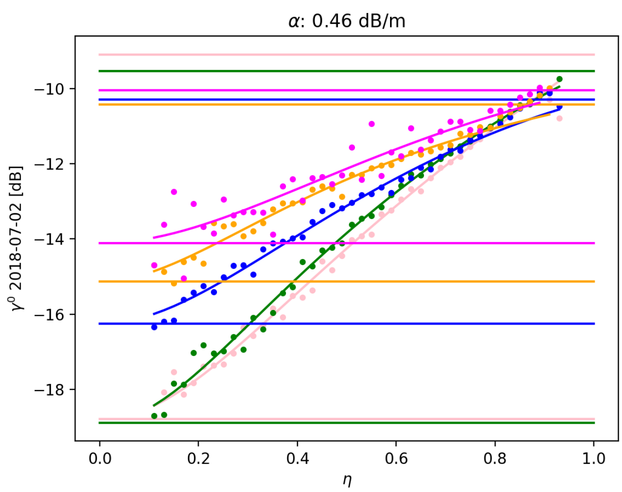

Figure 4-2: Observed and modelled relationship of L-HV backscatter as a function of Landsat canopy density. The model in Eq. 4-1 was fitted with fixed transmissivity for different incidence angle ranges (pink: 20-30°, green: 30-40°, blue: 40-50°, orange: 50-60°). For each incidence angle range, the horizontal lines denote the level of the estimated σ^0_{gr} and σ^0_{veg}.

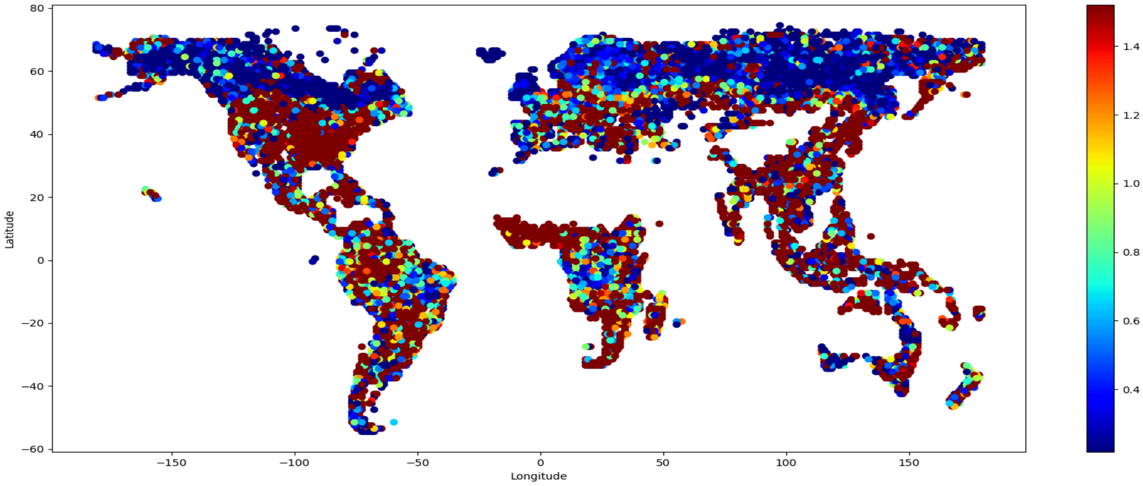

Figure 4-3: Estimates for the two-way tree attenuation coefficient α [dB/m] obtained by fitting Equation 4-1 to observed relationships between L-HV backscatter and Landsat canopy density.

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 have 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 Vegetation Optical Depth (VOD) observations

From the analyses reported in the PVASR [RD-4], it is clear that the AGB of high AGB forests needs be better estimated. L-band VOD observations from 25 km resolution SMOS data may help to address this issue, but it is unclear whether estimates at such coarse resolution can be transferred to the moderate resolution of the AGB maps to be generated in the CCI Biomass project.

5. Initial thoughts on how to assess AGB changes

During Year 3, AGB change maps will be generated for the 1-year time interval between 2017 and 2018, and for almost a decade between 2010 and 2017/2018. To estimate AGB changes one could either difference AGB maps or develop algorithms that related changes in signal to a change in AGB. A change in signal assumes that we have available the same type of EO data for each date. This is not the case in CCI BIOMASS, where we deliberately exploit global, repeated observations from multiple spaceborne missions because they are found to be of substantially higher predictive power than a single observation. In practice, AGB changes in the context of global mapping can only be achieved by differencing maps. The major caveats of such 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.

To illustrate the problems that may affect an estimate of AGB change, in Figure 5-1 we show the difference of the CCI BIOMASS AGB product (year 1) for 2017 and the GlobBiomass AGB product for 2010. The two datasets were generated with different remote sensing datasets but shared the same retrieval approach. This example is relevant because 2017 and 2010 are two epochs targeted by this project. In this version of the report, we do not discuss the impact of the precision of the estimates, which is about 40-50% at pixel level, on the results.

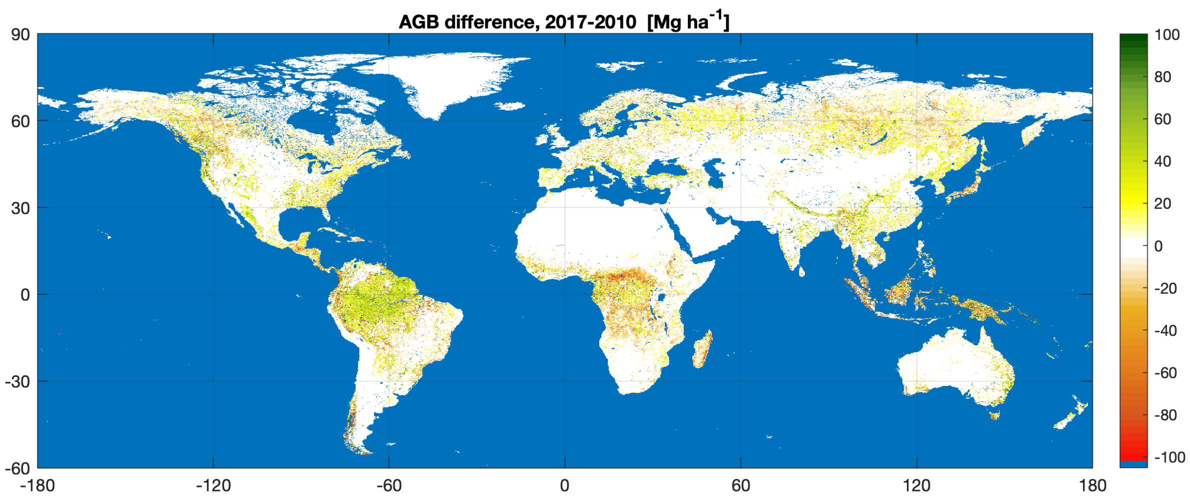

Figure 5-1: AGB difference between the CCI BIOMASS AGB data product of 2017 and the GlobBiomass data product of 2010

It is not the aim of this document to discuss spatial trends and whether the results obtained are realistic for two reasons.

1) Differencing is not an ideal approach because the two maps were obtained with different datasets, without consideration of an inter-annual comparison. For this reason any patterns appearing in this difference map are possibly caused by differences in the EO datasets rather than growth/mortality/degradation.

2) We are not aware of any publicly available datasets that were acquired in 2010 and 2017 and can act as a reference (from forest field inventory or from LiDAR observations).

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, initial 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].

6. Conclusions

The development of the CORE retrieval algorithm of the CCI Biomass project in Year 2 has implemented several aspects presented in the first version of this document. For the next version of the algorithms, we do not foresee substantial changes in how AGB is estimated but rather developments aimed at improving the accuracy of the retrieval. In particular, we expect a strong contribution from spaceborne LiDAR datasets.

The development of approaches that can quantify AGB changes is instead in its infancy. We have provided some initial thoughts related to strengths and weaknesses of possible approaches. These thoughts in turn affect further developments of the AGB retrieval algorithm.

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 or remote sensing. This will continue to be pursued in the upcoming activities.

7. References

Farr, T., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D. (2007). The Shuttle Radar Topography Mission. *Review of Geophysics,* 45 (RG2004), 1-33.

Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Werner, M., Younis, M. and Zink, M. (2007). TanDEM-X: a satellite formation for high-resolution SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing,* 45 (11), 3317-3341.

Neuenschwander, A. and Pitts, K. (2019). The ATL08 land and vegetation product for the ICESat-2 Mission. *Remote Sensing of Environment,* 221, 247-259.

Nilsson, M., Nordkvist, K., Jonzén, J., Lindgren, N., Axensten, P., Wallerman, J., Egberth, M., Larsson, S., Nilsson, L., Eriksson, J. and Olsson, H. (2017). A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the National Forest Inventory. *Remote Sensing of Environment,* 194, 447-454.

Santoro, M. and Cartus, O. (2018). Research pathways of forest above-ground biomass estimation based on SAR backscatter and interferometric SAR observations. *Remote Sensing,* 10 (4), 608, doi:10.3390/rs10040608.

Walker, W. S., Kellndorfer, J. M., LaPoint, E., Hoppus, M. and Westfall, J. (2007). An empirical InSAR-optical fusion approach to mapping vegetation canopy height. *Remote Sensing of Environment,* 109 (4), 482-499.