CCI

BIOMASS

PRODUCT USER GUIDE

YEAR 1

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	NAME	FUNCTION	ORGANISATION	SIGNATURE	DATE
PREPARED	M. Santoro	WP6 Lead	GAMMA RS		
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
PREPARED					
VERIFIED	S. Quegan	Science Leader	Sheffield University		
APPROVED					

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ORGANISATION	NAME	QUANTITY
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SYMBOLS AND ACRONYMS

AGB	Above Ground Biomass
ALOS	Advanced Land Observing Satellite
ATBD	Algorithm Theoretical Basis Document
BCEF	Biomass Expansion and Conversion Factor
BGB	Below-ground biomass
CCI	Climate Change Initiative
CF	Climate and Forecast
CMUG	Climate Modellers User Group
CRDP	Climate Research Data Package
DEM	Digital Elevation Model
DUE	Date User Element
E3UB	End-to-end Uncertainty Budget
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
FAO	Food and Agriculture Organization
FBD	Fine Beam Dual-
FTP	File Transfer Protocol
GCOS	Global Carbon Observing System
GEDI	Global Ecosystem Dynamics Investigation
GSV	Growing stock volume
JAXA	Japan Aerospace Exploration Agency
NFI	National Forest Inventory
NISAR	NASA-ISRO Synthetic Aperture Radar
PALSAR	Phased Array-type L-band Synthetic Aperture Radar
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
SAR	Synthetic Aperture Radar
UN-REDD	United Nations Reducing Emissions from Deforestation and Forest Degradation
URD	User Requirement Document
WB	Wide Beam
WGS	World Geodetic System

Table 1: Reference Documents

ID	Title	Issue	Date
RD-1	Climate Research Data Package	1.0	2019-08-07
RD-2	Users Requirements Document	1.0	2018-11-15
RD-3	Algorithm Theoretical Basis Document	1.0	2019-02-25
RD-4	End-to-End ECV Uncertainty Budget	1.0	2019-02-28
RD-5	Product Validation and Algorithm Selection	1.0	2019-04-04
RD-6	Product Validation & Intercomparison Report	1.0	2019-08-31

1. Introduction

1.1. Context

The aim of the Climate Change Initiative (CCI) Programme is to advance scientific understanding of the climate system and climate change by producing long-term datasets that meet climate data quality conditions (IPCC, 2003) and that can be readily linked to climate models. A basic input to this process is the series of reports by the Global Carbon Observing System (GCOS) that set out a continually reviewed set of Essential Climate Variables (ECVs) and a process to implement the acquisition of these ECVs. The primary motivation for including biomass as an ECV is that above-ground biomass (AGB) is crucial in order to understand both the source and sink terms in the global carbon cycle (which is fundamentally what drives climate change by controlling the carbon dioxide in the atmosphere). The source term comes from carbon emissions when biomass is lost due to fire and land use change; the sink term arises because growing forests extract CO_2 from the atmosphere and tie it up in long-lasting wood and soil stores.

Although satellite data limitations are such that biomass products from space cannot provide the 30-year climate quality datasets sought by the climate community, the CCI BIOMASS project is a start in this direction since spaceborne data records exist and their usefulness to derive spatially explicit estimates of AGB has been demonstrated. In addition, the coming years will see a wealth of mission targeting biomass as one of the primary objectives. As such, this project sets out not only to produce the best possible validated maps of biomass suitable for climate modelling with existing data, but also ensures that biomass estimation methods being developed are sustainable to include new and additional data streams towards progressively more accurate biomass products.

1.2. Purpose of document

The Product User Guide (PUG) provides a description of the data products generated and disseminated by the CCI BIOMASS project as part of the Climate Research Data Package (CRDP) [RD-1]. The data products are here presented in terms of a brief summary of the algorithms used, their thematic content and technical specifications (data format, file names and metadata).

This PUG describes the data products obtained at the end of the first year of the CCI BIOMASS project.

1.3. Contents

The document consists of the following sections:

Section 2 provides an overview of the CCI BIOMASS project;
Sections 3 and 4 describe the data products obtained at the end of the reporting year (Year 1 in this case) and provided as part of the CRDP of the current year.
Section 5 provides details on data access and data policy

Appendices include additional information on the datasets with the intention to act as reference guides for the interpretation of the AGB map and the map data format.

2. CCI Biomass Project

2.1. AGB and Earth Observation

According to the Food and Agriculture Organization (FAO), above-ground biomass (AGB) is defined as the amount of living biomass (organic matter) stored in vegetation above the soil including stem, stump, branches, bark, seeds and foliage, expressed as dry weight. This is opposed to below-ground biomass (BGB) that refers to the amount of biomass stored in vegetation below the soil. AGB is sometimes differentiated between woody and non-woody vegetation. AGB stored in woody vegetation requires a definition of the minimum size of trees that constitute woody vegetation. Non-woody vegetation instead consists of trees smaller than a given tree size threshold, shrubs, and all other non-herbaceous live vegetation.

In this context, AGB is here referred to in terms of density (i.e., the amount of living biomass per unit area). Accordingly, AGB is expressed in units of mass of dry matter per unit ground area (i.e., Megagrams per hectare; Mg/ha^{-1}).

By definition, AGB can be measured only with destructive sampling. Such a procedure is not viable when the aim is to quantify the overall biomass pool on Earth. Therefore, alternative methods based on models come into play. Allometries derived from felled sample trees (i.e., equations linking various structural parameters of a tree to biomass), favour non-destructive sampling. Yet, they require on ground surveys, which can be costly, are logistically non-trivial and are time demanding. To overcome some of these issues, terrestrial, airborne and spaceborne remote sensing techniques have been developed in recent years to provide an alternative or a complement to local surveys. Accordingly, models relating the observables to measurements collected on the ground have been developed. An advantage of using airborne and spaceborne remote sensing as a tool to estimate AGB is the possibility to cover large areas at reduced costs when compared to on-ground surveys. However, a map of AGB obtained from any remote sensing observation is an estimate of the true biomass on the ground and relies heavily on the type of models implemented to convert measurements of the observables to AGB.

The remote sensing community operates in this context towards the generation of so-called "wall-to-wall" datasets that span a wide geographical region, a specific biome or the entire globe. The CCI Programme recognized the maturity of Earth Observations (EO) to provide global and repeated measurements of land surfaces and the significant boost in recent years aiming at the generation of global data records of AGB estimates from space. With this, the CCI Programme allocated the ECV AGB to its own CCI+ project, having the primary objective of generating climate-relevant time records of biomass estimates that fulfil requirements set by GCOS. Key to this is the integration of multiple EO data sources, local surveys and an inter-disciplinary team that includes remote sensing experts, ecologists, statisticians and climate modellers.

2.2. Users' requirements

The CCI BIOMASS project was built on the requirements set by GCOS in terms of spatial detail, temporal resolution and thematic accuracy of AGB datasets. The requirement is for wall-to-wall maps of AGB to be provided wall-to-wall over the entire globe for all major woody biomes, with a spatial resolution between 500 m and 1 km (based on satellite observations of 100-200 m), 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.

Further to that, the AGB data products delivered by the CCI BIOMASS project need to take into account indications, requirements and wishes by potential users of such data products. These were reported in the User Requirement Document (URD) [RD-2] of the CCI BIOMASS project, which was compiled at the beginning of the project as a result of the first CCI BIOMASS User Workshop (September 2018) and a Climate Modellers User Group (CMUG) meeting (October 2018). The URD includes input from climate and carbon modelling, ecology, geography, resource assessment, climate policy and other user families. Ultimately, the user requirements were found to cover the needs of two different communities: the modelling community and the policy community.

Table 2 summarizes the requirements reported in the URD. Requirements were divided into minimum and desired. Although these two communities agree on many of the major desirable properties of the products (text in bold), the requirements on spatial resolution are not compatible with each other (text in italic). The climate and carbon modelling community, which are the primary focus for CCI BIOMASS, prioritize unbiased estimates of AGB while being more relaxed on the spatial resolution given the coarse grid-cell structure of climate models. The community centred on the United Nations (UN) Reducing Emissions from Deforestation and Forest Degradation (REDD+) Programme appears to have its top priority on single countries and requires resolutions of 1 ha or better. Notwithstanding the sensitivity of certain EO data to "biomass" and the capability of retrieval models to infer biomass from observations, the requirements in Table 2 imply that the project should deliver data products at the highest possible resolution when compared to what is available in terms of EO data and provided aggregates at coarser spatial resolution. These ultimately have the benefit of increased accuracy and precision with respect to individual pixels at the highest spatial resolution.

Table 2: Requirements for an AGB data product formulated by the modelling and the policy communities as reported in the CCI BIOMASS URD. Requirements in bold are common to the two communities. Requirements in italic are community-specific (M for the modelling community, P for the policy community).

	Threshold (minimum) Requirements	Target (desired) Requirements
Product	**Map of aboveground biomass with associated precision.** This should be unbiased but if this cannot be achieved with current sensors, information on likely bias should be provided (M)	Map of aboveground biomass (and belowground biomass) with associated precision *and information on possible bias (M)* Map of biomass change with associated precision *and information on possible bias (M)*
Spatial Coverage	Global	**Global** with targeted/calibrated products for specific countries or other areas of interest (P)
Spatial	1 km x 1 km (M) At least 100x100 m / 1 ha resolution	100 m resolution is desirable, and 30 m resolution data could be used (M)

Resolution	(P)	0,25-1 ha - resolution might vary depending on forest and ecosystem type, and country needs (P)
Temporal Extent	One time coverage for most recent period	2000-now
Temporal Resolution	Every 5 – 10 years (M) One time (P)	1 year (annual maps)
Reference System	Lat-Long (WGS-84) and equal-area projections	Lat-Long (M) Provided in country-specific reference grids (P)
Accuracy	Accuracy should be higher than existing maps. Continental-scale uncertainty estimation.	Data should unbiased and with high precision for target estimation regions (i.e. countries) (P)
Delivery Mode	FTP for global products Web Service for regional products	FTP or Web Service and combined with training materials on how to use the data and within country capacity development (P)
Data Format	NetCDF for global products (M) GeoTIFF - for regional products (M)	NetCDF for global products (M) GeoTIFF - for regional products (M other country preferred formats (P)
Other Requirements	Fully documented, transparent and standardised mapping methods Robust and standardised global validation scheme with protocol Metadata available Free and open access Full reporting of validation results and implications for possible product bias and precision (M)	Fully documented, transparent and standardised mapping methods Metadata available, Robust calibration and validation using available national data sources (i.e. NFI data) Access to underlying data in an accessible processing system *to produce their "own" data (P)* Free and open access Consistency with forest area change data Full reporting of validation results and implications for possible product bias and precision (P) Clear and transparent reporting of regional accuracy / uncertainty (P)

		Consistent spatial-temporal coverage (P)

Further interpreting the table of requirements, the data products by CCI BIOMASS described in this PUG fulfil all threshold requirements. Details are provided in Sections 3, 4 and 5, as well as in the Appendices. For the mapping methodology, it is referred to the Algorithm Theoretical Basis Document (ATBD) [RD-3] and the End-to-End ECV Uncertainty Budget (E3UB) [RD-4] documents.

2.3.Project outputs

The CCI BIOMASS project expands biomass mapping methodologies developed in the GlobBiomass project funded by ESA within the Data User Element (DUE). The GlobBiomass project (http://globbiomass.org) generated a global map of AGB with a spatial resolution of 100 m using multiple remote sensing observations from around the year 2010. CCI BIOMASS aims to a) generate annual global estimates of AGB for two current epochs (2017-2018 and 2018-2019), b) refine the 2010 data product derived in the GlobBiomass project, c) quantify AGB changes between epochs and d) prototype estimation of AGB in the mid 1990s.

At the end of Year 1, a global map of AGB for the year 2017 and associated accuracy has been generated. The dataset is presented in Section 3.

3.AGB Maps

3.1.Product descriptions

The CCI BIOMASS project delivers spatially explicit estimates of AGB and related accuracies (standard errors) in the form of two separate map products. The AGB data product consists of global datasets with estimates of above ground biomass (unit: tons ha^{-1} i.e., Mg ha^{-1}). In this context, AGB is defined as the mass, expressed as oven-dry weight of the woody parts (stem, bark, branches and twigs) of all living trees excluding stump and roots. The AGB standard error data product is a separate data layer providing per-pixel accuracy of the AGB estimates, expressed in Mg ha^{-1}.

For Year 1, the data products provided by the CCI BIOMASS project consist of an AGB and AGB standard error map based on EO data acquired in 2017. The spatial resolution of the map products is 100 m.

Figure 3-1Figure 3-1 and 3-2 show the CCI BIOMASS AGB dataset of 2017 in Mg ha^{-1} and the corresponding map of standard errors. To enhance image contrast, the AGB map in Figure 3-1 has been clipped between 0 and 350 Mg ha^{-1}. The AGB standard error map (Figure 3-2), expressed in the form of a relative error with respect to the AGB, has been clipped between 0% and 100%. For display reasons, AGB and AGB standard errors are shown for pixels labelled as forest according to the CCI Land Cover dataset of 2015 (version 2.07).

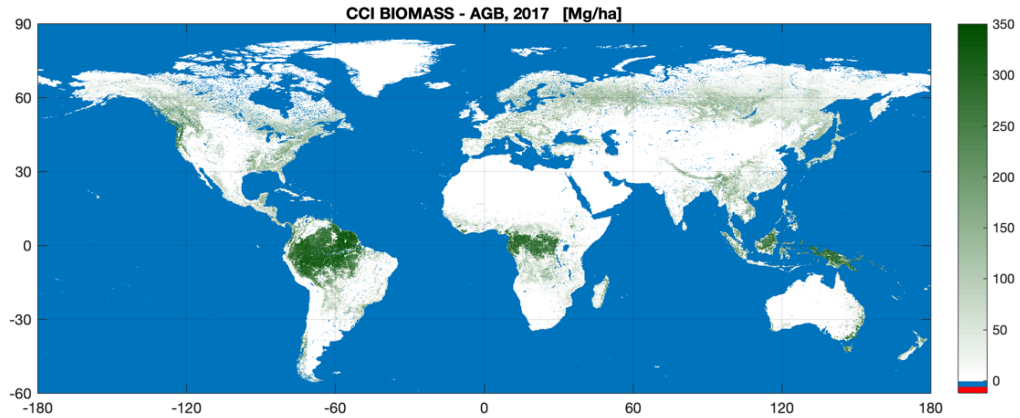

Figure 3-1: Global AGB estimates for the year 2017. Spatial resolution: 100 m.

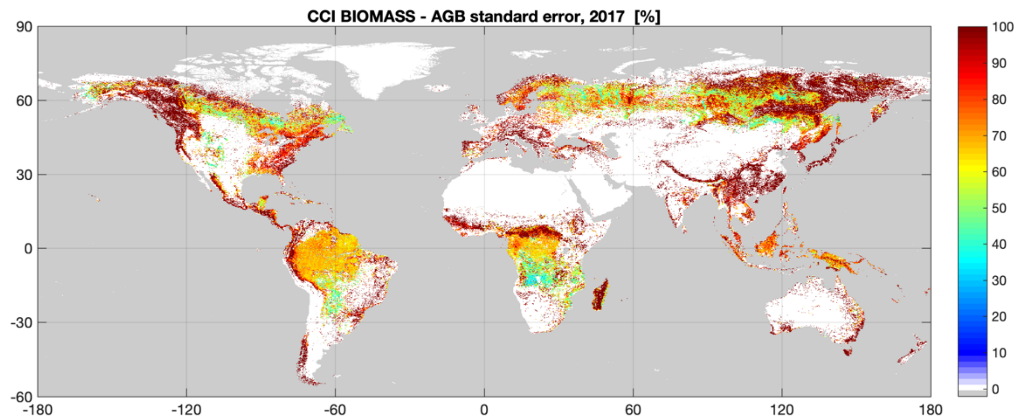

Figure 3-2: Standard error of global AGB estimates for the year 2017. Spatial resolution: 100 m.

Figure 3-3 shows two subset examples from the AGB maps, with each covering an area of approximately 50 × 50 km^2, with these highlighting the spatial details contained in the AGB dataset. As reference, each AGB map can be compared with the corresponding image from Google Earth. The panels on the left hand side of Figure 3-3 show a forested region south of the Angara River in Central Siberia, which is affected by intensive logging activities. Forests are dominated by boreal coniferous species and the AGB can be as high as ~200 Mg ha^{-1} . Clear-cuts are clearly visible in the Google Earth image (yellow rectangles) and appear in the AGB map as white (i.e., with a value close to 0 Mg ha^{-1}). The panels on the right-hand side of Figure 3-3 show detail within the Amazonian forest along the Trans-Amazonian Highway, which connects the cities of Uruará and Altamira. While the forest north of the highway has been extensively logged and the area is likely to be replaced by agriculture, forests south of the highway remain intact.

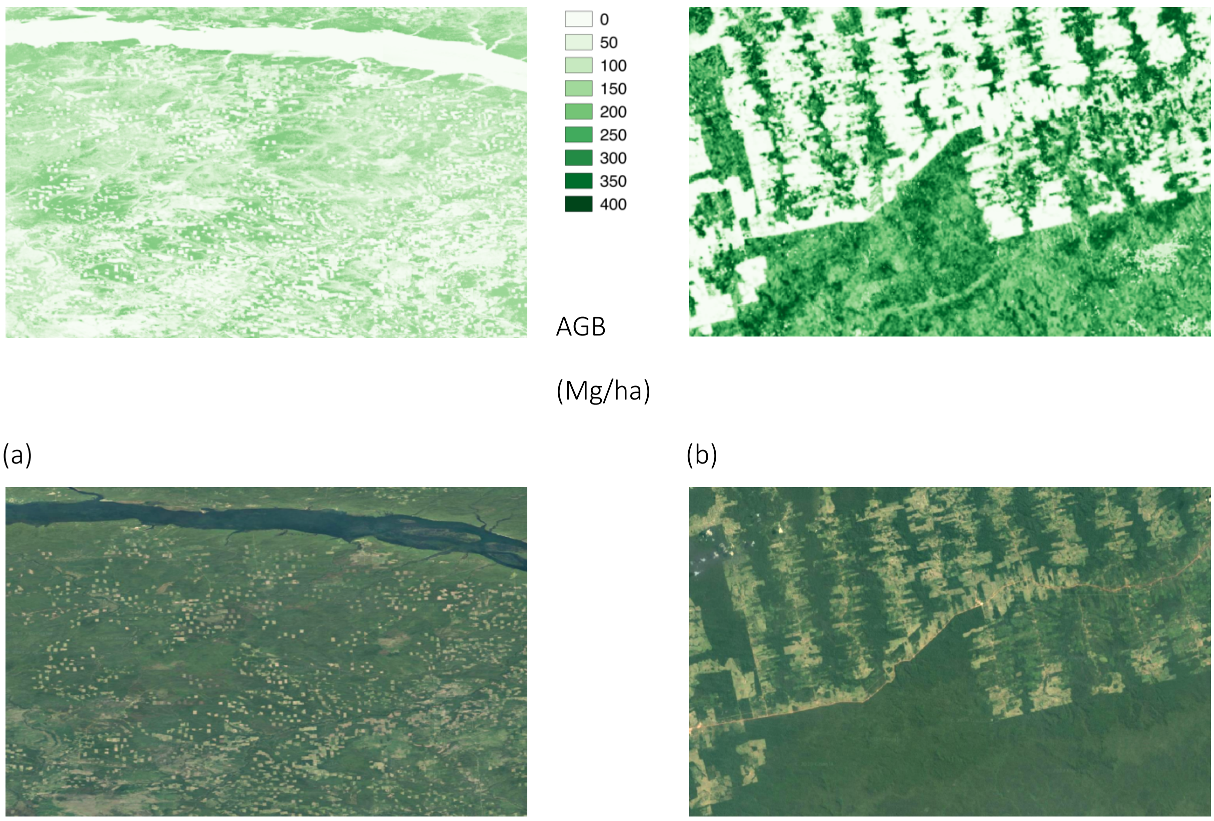

Figure 3-3: Detailed views of the AGB map for the region of Bratsk, Central Siberia, (a) and along the Trans-Amazonian Highway, between the cities of Uruará and Altamira, Brazil (b). Panels (c) and (d) are optical imagery from Google Earth and serve as reference for each of the AGB maps.

3.1.1. Processing chain

Since AGB is a quantity inferred from measurements of structural parameters of a forest, retrieval from remote sensing data needs to explore and exploit a large range of diverse observations. The diversity of data sources is reinforced by the limited sensitivity of currently available spaceborne remote sensing observations to forest structural parameters.

Requirements on global coverage during the epoch 2017-2018, open access to the data and certain sensitivities of the observations to forest structural parameters restricted the extensive pool of remote sensing observations for that epoch to images acquired by Synthetic Aperture Radar (SAR) C-band Sentinel-1 and L-band Advanced Land Observing Satellite (ALOS-2) Phased Array L-band SAR (PALSAR-2).

The Sentinel-1 dataset consisted of images of the SAR backscatter acquired during 2017 over land between 75°N and 60°S. Sentinel-1 is a mission of the European Commission Copernicus initiative and consists of two units (1A and 1B) operating according to a predefined observation strategy that targets understanding and management of major environmental and societal challenges. The images were terrain geocoded, speckle filtered and corrected for slope-induced distortions. As a trade-off between processing speed, preservation of features and fulfilling the requirements on spatial resolution of an AGB product (see Section 2), each Sentinel-1 image was processed from the original 20 m to a pixel size of 150 m.

The ALOS-2 PALSAR-2 dataset consisted of terrain geocoded mosaics of the SAR backscatter acquired in Fine Beam Dual- polarization (FBD) and Wide Beam (WB) modes. All mosaics were produced by the Japan Aerospace Exploration Agency (JAXA) (Shimada and Ohtaki, 2010; Shimada et al., 2014). While the FBD mosaics are publicly available, the WB mosaics are only available to members of the research community forming the Kyoto and Carbon (K&C) Initiative, which is lead and coordinated by JAXA's Earth Observation Research Center (EORC). In particular, the K&C datasets are unique because they are tailored to support data needs raised by international environmental Conventions, Carbon Cycle Science, Climate Change and Conservation of the environment. The FBD mosaic consisted of a single global dataset of the SAR backscatter per year. The WB mosaics covered the tropics only and were produced on a repeat-pass cycle basis (i.e., every 46 days). While the WB mosaics were provided with a pixel spacing of 100 m, the FBD mosaics had a pixel spacing of 25 m. To be consistent with the hectare-scale at which the Sentinel-1 and the WB mosaics were processed, the FBD mosaics were averaged to 100 m.

The overall quality of the SAR data was high and considered to be sufficient for generating a global dataset of AGB at the hectare scale. Nonetheless, the ALOS-2 PALSAR-2 mosaics were characterized by imperfect geolocation, banding and seams [RD-3]. Co-registration between datasets and balancing were used to reduce such systematic errors, but these could not be removed entirely. The impact on the estimates of AGB is discussed in Section 3.4.

The estimation of AGB is illustrated by the flowchart in Figure 3-4. At first, two algorithms (both sharing the same theoretical basis) were applied to the Sentinel-1 and the ALOS-2 PALSAR-2 datasets separately. With each algorithm, referred to as BIOMASAR, a global map of growing stock volume (GSV) was obtained. GSV refers to the volume of all living trees per unit area and is measured in m^3 ha^{-1}. The estimation of GSV instead of AGB was undertaken on the assumption that the SAR backscatter is affected by the structural properties of a forest in terms of size, density and canopy arrangement. The BIOMASAR algorithm inverts a semi-empirical model relating the forest backscatter to the GSV by means of three parameters that are unknown *a priori*. These parameters correspond to specific backscatter components (ground, canopy) and backscattering properties of the forest. In order to estimate them, auxiliary datasets describing canopy density, microwave transmissivity, maximum biomass etc. are used. A detailed description of these data layers is available in the ATBD of the CCI BIOMASS project [RD-3]. The two maps of GSV obtained from the Sentinel-1 and the ALOS-2 PALSAR-2 data are finally merged with a set of weighting rules (see ATBD) in order to reduce systematic estimation errors in one or the other map. In a nutshell, the weighting uniquely allows BIOMASAR-L GSV estimation in regions of high GSV where there is a lower sensitivity of C-band backscatter to biomass, namely in mature and dense forest. The GSV of younger and regrowing forest is often an average of the two values estimated by BIOMASAR-C and -L. In Appendix C, we illustrate the GSV maps by BIOMASAR-C (Figure B1) and BIOMASAR-L (Figure B2), as well as the map with weights applied in the merging process (Figure B3). Prior to merging, the BIOMASAR-C dataset of GSV was resampled from 150 m to 100 m so as to be compatible with the pixel spacing of the BIOMASAR-L dataset.

AGB is estimated from GSV with a biomass conversion and expansion factor (BCEF) that takes into account the wood density to convert volume to mass (conversion) and the proportion of stem biomass to total biomass (expansion). Here, we used the BCEF dataset developed in the GlobBiomass project following approaches to extend on ground estimates of wood density and stem-to-total biomass expansion factors to obtain a global raster dataset. The map of BCEF is illustrated in Appendix B.

The shaded part in Figure 3-4 indicates that the estimation framework foresees the integration of additional AGB datasets. This aspect will become relevant in the nearest future with a multitude of global AGB datasets planned be released as part of mission objectives (GEDI, NISAR, BIOMASS) or as part of currently ongoing activities of quantifying biomass.

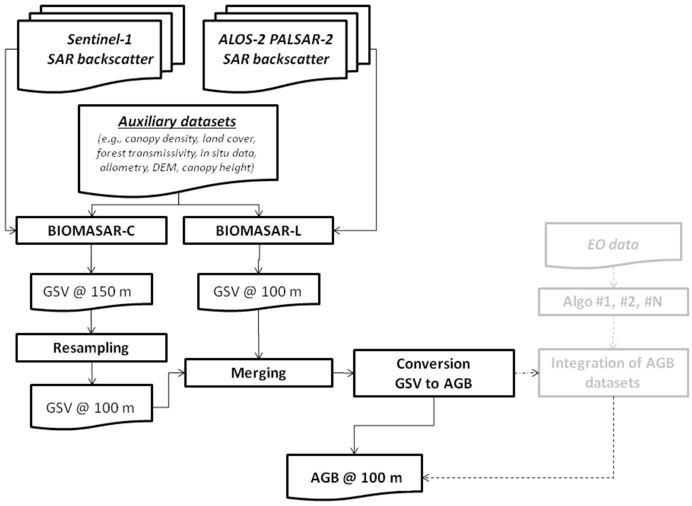

Figure 3-4: Functional dependencies of datasets and approaches forming the CCI Biomass global biomass retrieval algorithm in year 1. The shaded part of the flowchart represents potential improvements following the implementation of additional retrieval techniques.

The AGB map is accompanied by a per-pixel estimate of its accuracy, defined as the standard error of the AGB estimate. The standard error is computed by propagating individual accuracy of (i) the SAR measurement, (ii) the modelling framework behind the BIOMASAR algorithms, (iii) the merging procedure and (iv) the BCEF. Full characterization of the standard errors is provided in the E3UB report [RD-4].

3.1.2. Specifications of data products

Spatial coverage: global

Validity of estimates: Estimates have been generated for each point on Earth for which the remote sensing data were available. Urban areas according to the Copernicus Global Land service land cover dataset of 2015 (Buchhorn et al., 2019), available at https://land.copernicus.eu/global/products/lc, have been re-mapped to 0 Mg/ha.

Reference system: Lat-long, WGS-84

Corner coordinates: top left corner of pixel

Pixel spacing: The AGB and AGB standard error estimates are provided with a pixel spacing of 0.0008888° (roughly corresponding to 100 m at the Equator).

Timeframe: year 2017

Data format: NetCDF

3.1.3. Format

- *Naming Convention*

The filename convention of the global AGB maps delivered by the CCI BIOMASS project is the following:

Filename = <id>-fv<version>.nc

where <id> = <project>-<level>-<var>-<code>-<spatres>-<epoch>

The dash "-" is the separator between name components. The filename convention obeys NetCDF Climate and Forecast (CF) conventions by using the postfix ".nc". The different name components are defined in Table 3.

Table 3: Elements of file name of the CCI BIOMASS AGB data product delivered by the CCI BIOMASS project.

Field	Signification	Value
project	Project acronym	ESACCI- BIOMASS (constant)
level	Processing level	L4 (constant)
var	Unit of the product	AGB (constant)
code	Product code identifier	MERGED (constant)
spatres	Spatial resolution	100 m (constant)
epoch	Year of the product	2017 (constant)
version	Incremental that follows the successive revisions of the CCI-BIOMASS processing lines	Version of product revision, preferably major.minor, optionally with processing centre [a-zA-Z0-9._]*

The file name of the global AGB map for year 2017 is:

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2017-fv1.0.nc

- *Processing Level*

Level 4 (i.e. "variables that are not directly measured by the instruments, but are derived from these measurements" according to CEOS, 2008)

- *Units*

Each pixel value corresponds to an AGB value measured in Megagrams per hectare (Mg/ha). Valid AGB values are between 0 and 10,000 Mg ha^{-1}.

- *Spatial Extent*

All terrestrial zones of the Earth between the parallels 90°N and 60°S.

- *Spatial Resolution*

100 m

- *Temporal resolution*

Annual

- *Product layers*

The AGB map is delivered with a layer of AGB standard error. Both are expressed in Mg ha^{-1}.

- *Projection*

The Coordinate Reference System (CRS) is a geographic Lat/Long coordinate system (EPSG: 4326) based on the World Geodetic System 84 (WGS84) reference ellipsoid. The projection specifications consist of semi-major axis (6378.14 km), semi-minor axis (6356.76 km) and inverse flattening parameter (298.26 m). The latitude and longitude coordinates are specified in decimal degrees. A complete description of the CRS is given as an ISO 19111 WKT representation (Table 3.2).

```
GEOGCS["GCS_WGS_1984",
    DATUM["D_WGS_1984",
        SPHEROID["WGS_1984",6378137.0,298.257223563]],
    PRIMEM["Greenwich",0.0],
    UNIT["Degree",0.0174532925199433],
AUTHORITY["EPSG",4326]]
```

Table 3.2. Description of the coordinate reference system defining the global AGB products.

- *Format*

The AGB maps are delivered in NetCDF-4 format. The NetCDF files specification follows CF conventions (ESA Climate Office, 2019).

- *Metadata*

The metadata for the AGB maps are provided as global attributes in the NetCDF file. It follows the CCI guidelines (ESA Climate Office, 2019).

- *Estimated size*

The size of the AGB dataset of 2017, including the standard error layer, in NetCDF format is 28 GB.

3.2. Qualitative assessment

The level of detail of the CCI BIOMASS map of AGB for the year 2017 has been already discussed in Section 3. As there is no data product of forest variables (canopy height, canopy density, AGB) contemporary to this map, it is not possible to assess the AGB map with a cross-comparison exercise with regards to a global dataset that was created independently from this one.

The CCI BIOMASS dataset of Year 1 provides a wall-to-wall portrait of AGB for the year 2017 and reproduces the major patterns of biomass distribution (Figure 3-1). The highest AGB (> 300 Mg ha^{-1}) is located in the wet tropics of South America, Africa and Southeast Asia, and in the temperate rainforest of the Pacific Northwest between Canada and the U.S., southern Australia and along the Andes between Chile and Argentina. The map in Figure 3-1 shows a clear gradient of biomass for decreasing latitude in the northern hemisphere, following the transition from boreal to temperate and tropical forest. In the southern hemisphere, AGB progressively decreases when transitioning from tropical wet to tropical dry forest and savannah vegetation. At the southernmost latitudes corresponding to temperate cool forests, a notable increase in AGB is observed.

The standard error of the AGB estimates in Figure 3-2 depends on the proportional contribution of C- and L-band estimates. For the wet tropics, where the estimate depends solely on L-band data, the standard error is about 60% of the estimated AGB. In the boreal zone, the effect of the weighting becomes quite evident. The standard error in regions where the AGB estimate is based primarily on L-band (Figure A3) is much smaller than in regions where the estimate is driven by the C-band result (e.g., Central and East Canada vs. Alaska and Yukon or western Russia vs. Siberia). The reason for the high standard error for the C-band based estimates of biomass is the weak sensitivity of the backscatter to AGB and the strong temporal correlation of the retrieval errors so that the multi-temporal combination of individual GSV estimates implemented in BIOMASAR only marginally reduces the uncertainty.

3.3.Validation

Validation refers to a comparison of the map value of AGB with an independent dataset of measurements that can be considered to act as reference for the AGB on the ground. Forest field inventory measurements with well-known and well-described reporting protocols represent the primary source for conducting a validation. Validation of the AGB map of 2017 is described in the Product Validation & Intercomparison Report (PVIR) [RD-6]. Validation confirmed the visual impression that the spatial distribution of AGB is well captured globally, especially when considering reference measurements covering an area comparable to the size of a pixel in the map (e.g., approximately 1 ha; Figure 3-5). The scatter of Figure 3-5 also highlights a number of limitations that are further described in Section 3.4.

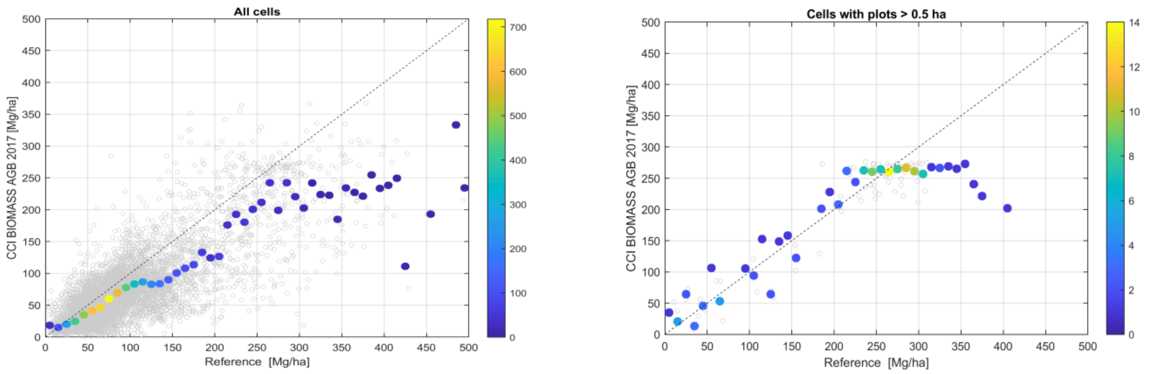

Figure 3-5: Scatter plot of average AGB from in situ data (x axis) and corresponding values from the AGB map (y axis) using an 0.1° (i.e., 10 km) grid. The scatter plot on the right hand side shows data points for grid cells associated with inventory plots larger than 0.5 ha in area. In each scatter plot, the coloured circles represent the average map value for the binned reference AGB (10 Mg/ha wide intervals). The colour represents the number of grid cells within a specific bin. The scatter plots are based on data provided by Wageningen University and used to compile the CCI BIOMASS PVIR [RD-6].

One of the intrinsic limitations of the validation with inventory data is that the samples are an opportunistic collection of measurements having a purpose that is different than validating estimates of the same quantity with remote sensing techniques. For this reason, trends identified by the validation with inventory plots need to be understood before coming to conclusions. The same applies if the source of reference AGB measurements is a high-resolution map.

Nonetheless, before using the map for local-/regional- scale applications, users may want to evaluate the accuracy of the map in their respective area of interest. This could be achieved, for instance, with the aid of locally available in situ information on AGB. A frequent scenario may be that forest inventory data collected in the form of small diameter plots (e.g., 10-20m diameter) are used, despite the mismatch with respect to the spatial resolution of the CCI AGB map (100 x 100 m^2). In this context, it is important to understand that (i) this spatial mismatch poses limits on the possibility to quantify the local error, and more importantly, the bias of the CCI AGB map and (ii) comparisons of map and in situ AGB estimates need to be interpreted with caution.

With the aid of airborne laser scanner (ALS) derived AGB maps, we demonstrate below the limitations associated with assessing the precision and bias of a low(er) resolution AGB map (such as the CCI AGB map with 100x100 m^2 resolution) using a sparse network of plot-level inventory data where plots cover only a small fraction of the corresponding pixel in the AGB map. Specifically, we demonstrate that the error associated with comparing AGB estimates in the 1 hectare map with AGB information collected in small(er) plots reveals not only in form of an underestimation of the map precision, but also in a false representation of the bias of the AGB estimates. We here focus on this sampling-related error and do not consider additional error sources such as geolocational and measurement errors in the in-situ data or the allometric equations used to estimate from above-ground biomass at plot level.

The AGB maps considered here were produced from ALS data acquired over two forest sites, in Remningstorp, Sweden, and Lope, Gabon (i.e., with these representing a boreal and a tropical forest situation respectively). Both ALS datasets were acquired in the frame of the airborne ESA BIOSAR (Ulander et al., 2011) and AfriSAR (Hajnsek et al., 2017) campaigns to provide detailed information on the forests vertical structure and to produce high-resolution AGB maps. The maps with a spatial resolution of 20 m (Figure 3-6) cover an area of 22 km^2 (Remningstorp) and 52 km^2 (Lope), respectively. For further information on how the maps were produced, the reader is referred to the references cited above.

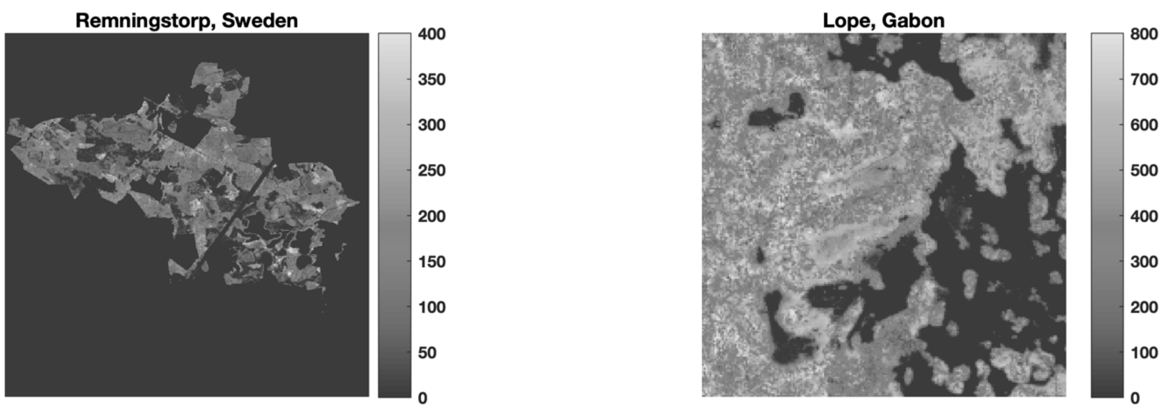

Figure 3-6: AGB maps with a resolution of 20 m × 20 m derived from ALS data acquired over the test sites Remningstorp, Sweden, and Lope, Gabon.

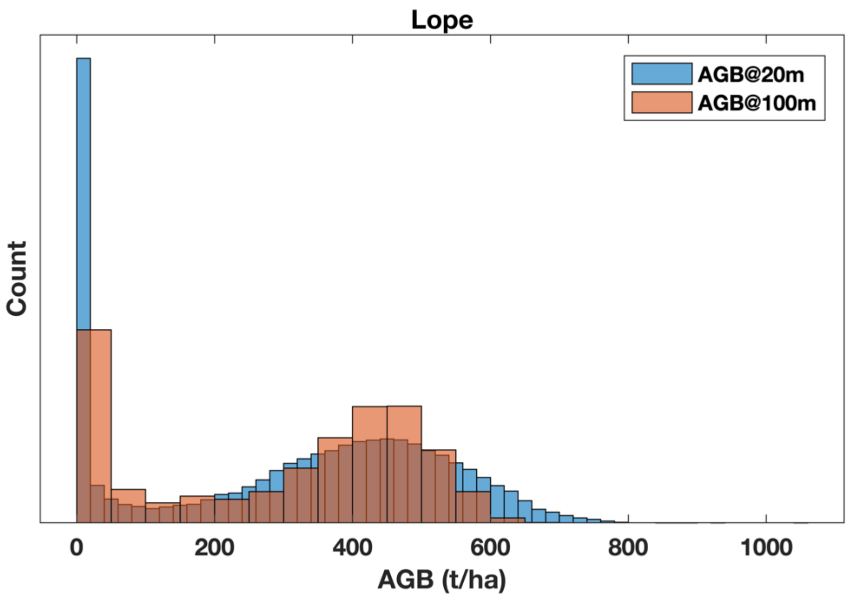

Figure 3-7: Histograms of AGB in Lope at 20 m × 20 m and 100 m × 100 m pixel size.

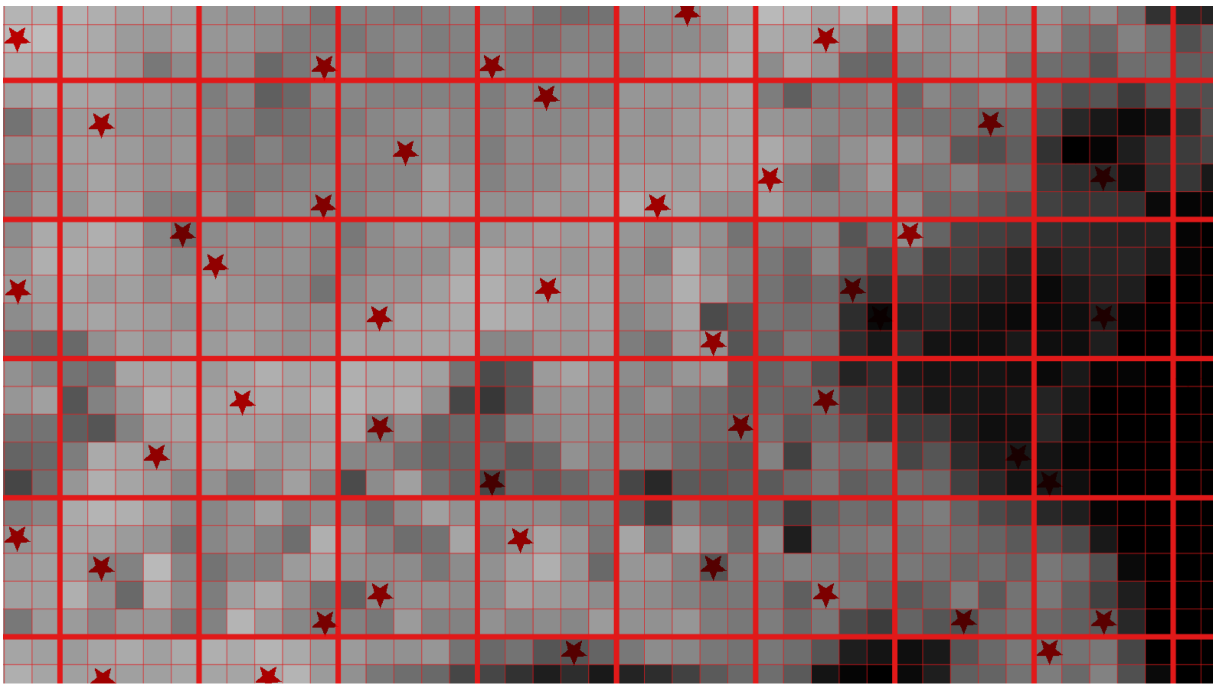

Figure 3-8: 20 m × 20 m^2 pixel grid (small red squares) of an ALS derived AGB map nested into a 100 ×100 m^2 pixel grid (larger red squares) representing the global AGB map at 100m spatial resolution. The 20 m pixels labelled with a star are used to simulate 20 m plot level AGB information, that is then used for evaluating the error of the 100 m AGB map.

The ALS AGB maps are used for simulating a scenario in which hectare-scale AGB estimates from EO data are validated using sub-hectare scale reference information. This is achieved by first aggregating the ALS derived maps from a 20 x 20 m^2 to a 100 x 100 m^2 pixel size. The histograms of AGB at 20 and

100 m scale are illustrated in Figure 3-7 for Lope. The aggregation from 20 to 100 m implies differences in the range of AGB values that are observed, in particular with respect to the maximum AGB. At 20 m scale, the maximum AGB is in the range of 800 Mg ha^{-1}; at 100 m scale the AGB estimates rarely exceed 600 Mg ha^{-1}. Subsequently, any of the 20 m pixels that are located within a 100 m pixel is treated as if it were a plot to be used to evaluate the error of the 100 m map. When randomly selecting a 20 m pixel in the area of each 100m pixel (Figure 3-8) and producing scatterplots in which the AGB in the 100 m map is plotted as function of the selected 20 m sub-pixel, we see (in the example in Figure 3-9 for Lope) that the agreement is weak with RMS errors, being of the order of 100 Mg ha^{-1} (30% of the mean AGB). The scatterplot in Figure 3-9 furthermore indicates deviations from the 1:1 line, with these being dependent on the AGB level. That this deviation is systematic and not limited to a given test site becomes clear when repeating the comparison of AGB estimates at 100 m x 100 m scale with random sub-pixel samples at 20 x 20 m^2 scale (100 times) and when plotting the 100 m AGB as function of 20 m AGB in the form of curves that reflect the mean trend (average 100m AGB in 20 Mg ha^{-1} intervals of the corresponding 20 m AGB) (Figure 3-10). Despite the fact that the 100 m maps simply represent the aggregated (averaged) version of the 20 m map, the comparison (falsely) suggests the 100 m map is biased in that low AGB ranges seem to be overestimated and high AGB ranges underestimated.

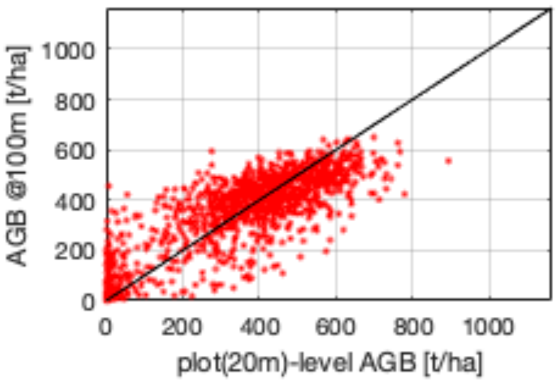

Figure 3-9: AGB estimates at 100 m × 100 m scale vs. sub-pixel random samples of AGB at 20 m × 20 m scale.

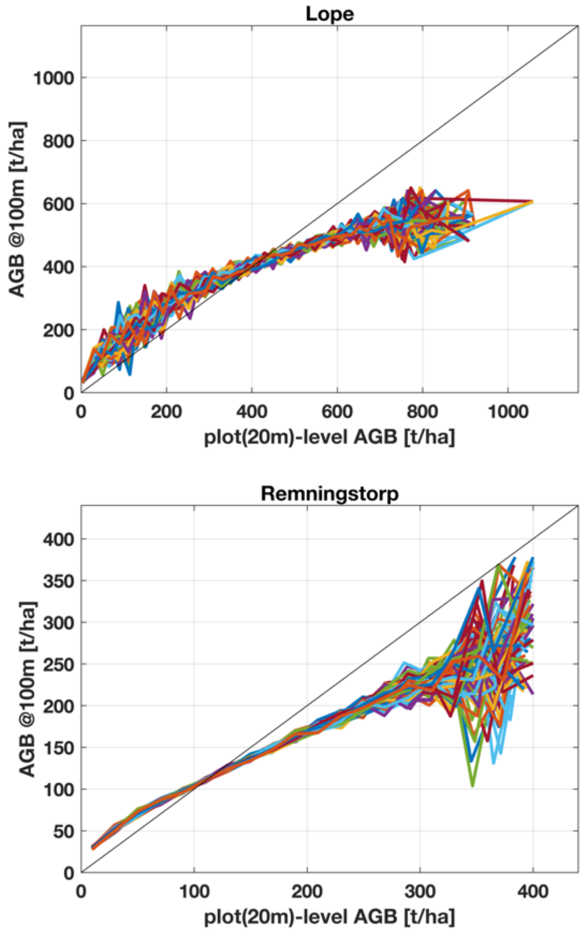

Figure 3-10: 100 m AGB plotted vs. sub-pixel samples of AGB at 20 m scale in Lope and Remningstorp.

This false indication of bias may be compensated for by using more than one random sub-sample of 20 m AGB pixels per 100 m AGB pixel (Figure 3-11). Forest inventory data are generally not collected at such high spatial density. However, when for instance comparing AGB maps with reference AGB information derived from small-footprint LiDAR, such a strategy may be feasible.

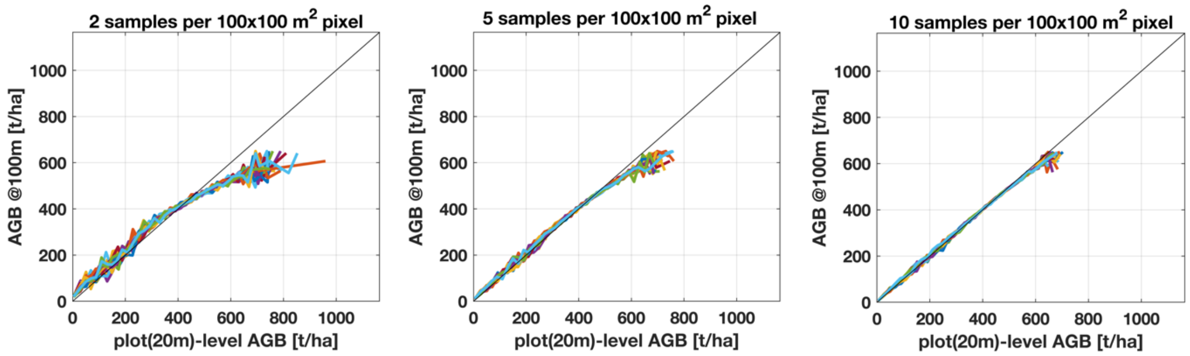

Figure 3-11: 100 m AGB plotted vs. sub-pixel samples of AGB at 20 m in Lope and Remningstorp when averaging for each 100 m AGB pixel more than one (two, five, ten) 20 m AGB pixels.

3.4. Limitations

The limitations of the CCI BIOMASS dataset of AGB for the year 2017 can be grouped into two major categories: signal-dependent and processing-dependent. The signal-dependent limitations relate to the fact that the EO data used to estimate AGB are only indirectly related to AGB and therefore several assumptions need to be made when attempting to obtain an estimate of AGB from the observations. This aspect is discussed under "local biases". The second type of limitation is a direct consequence of imperfections at the level of data processing (i.e., errors introduced in the remote sensing image by the data provider). These errors can be local and global. A description of errors affecting the remote sensing data is provided in the ATBD [RD-3]. The effect of local errors can be easily identified in the AGB dataset and is discussed under "seams" and "topography" separately. The impact of inaccurate geolocation on the AGB estimates is harder to demonstrate and is, therefore, not presented in this document.

As a result of our analysis, it is strongly discouraged to rely on the pixel-wise AGB values.

We also discourage the use of estimates over non-forested areas (including shrubland, grassland and cropland) because the estimation of AGB was based on models tailored to relate observations to woody vegetation, namely forests.

3.4.1. Local biases

An AGB estimate based on C- and L-band backscatter is prone to errors and large inaccuracies in regions where the backscatter has limited sensitivity to this vriable. This is typically the case in moderate to high biomass forest (i.e., for increasing AGB density) and when the environmental conditions alter the SAR backscatter so that the sensitivity to AGB is completely lost (e.g., under wet conditions). Specific environmental conditions can introduce an overall bias in the estimates of AGB. One way to overcome such issues is to retrieve AGB using multiple observations. In the CCI BIOMASS retrieval algorithms, multiple observations of C-band backscatter from Sentinel-1 and several mosaics of the L-band backscatter from ALOS-2 PALSAR-2 are used whenever possible, so as to reduce noise and errors. Still at the level of a single pixel, the error is not negligible. Even aggregates may be biased if the retrieval did not perform (e.g., insufficient number of observations, incorrect parameterization of algorithm). As shown by the dispersion of the data points in Figure 3-5, the CCI BIOMASS dataset shows both under- and over-estimation but these do not occur in a similar way at all locations. We give a brief summary of areas prone to errors and their explanation below

- Underestimation for AGB > 250 Mg ha^{-1}. In dense rainforest, the AGB here is based purely on L-band data (see Figure A3). The extremely weak sensitivity of the L-band backscatter to biomass and the conservative rules implemented in the BIOMASAR algorithm to estimate biomass partly explain this result [RD-3]. In addition, underestimation occurs in areas characterized by moderate to strong topography; this aspect is further discussed in the separate paragraph on topography. Although laser-based metrics should be more reliable to estimate AGB in dense forests than SAR backscatter, there was no spaceborne dataset that could support the estimation for the epoch of interest (2017-2018). Under the assumption that (i) laser measurements globally are becoming available (from the GEDI and ICESAT-2 missions) and (ii) allometries relating laser parameters to AGB will be improved, estimation in dense forests can be substantially improved by combining current EO datasets and laser observations. Linking laser observations with currently operating SARs may allow generation of unbiased and reliable AGB estimates for the epochs requested by the CCI BIOMASS project. In other regions with high AGB (e.g., central Europe, Pacific Northwest), underestimation occurs again as an effect of weak sensitivity of the backscatter to forest biophysical parameters in dense forests; the effect is exacerbated by strong topography and fragmented landscapes.
- Overestimation of AGB can occur in low biomass forest (around 50-100 Mg ha^{-1}). This is understood to be a result of the simplified modelling framework relating the forest backscatter to the GSV and the way the models are parameterized using auxiliary datasets [RD-3]. It is remarked that the BIOMASAR algorithms do not rely on in situ data for model training so that a series of assumptions needed to be created in order to have the models trained globally but still in an adaptive manner to local structural properties of the vegetation.

It is remarked that an assessment of whether AGB is over- or underestimated requires a correct usage of reference data as discussed in Section 3.3.

3.4.2. Seams

Seams are unnatural AGB variations that are related to the imagery. The origin of the seams in the CCI BIOMASS dataset was identified in the ALOS-2 PALSAR-2 mosaics, where images acquired on different dates and seasons were stitched together to obtain global coverage. Images acquired at different times may be characterized by strong radiometric differences. In the case where such images are stitched together, the feathering is sub-optimal and radiometric offsets are introduced between adjacent images. Although SAR pre-processing tried to reduce the impacts of such seams [RD-3] and the models used to retrieve AGB were made to be strongly spatially adaptive [RD-3], some of the seams remained at the end of the processing chain. In particular, these become visible in regions of weak sensitivity of the backscatter to AGB (e.g., in areas of dense tropical forest) and where AGB was based only on the L-band mosaics. Seams appearing in the form of a small radiometric offset (of the order of 0.1-0.2 dB) translates to a clear biomass offset > 10 Mg ha^{-1} and shows up as a clear anomaly (Figure 3-12).

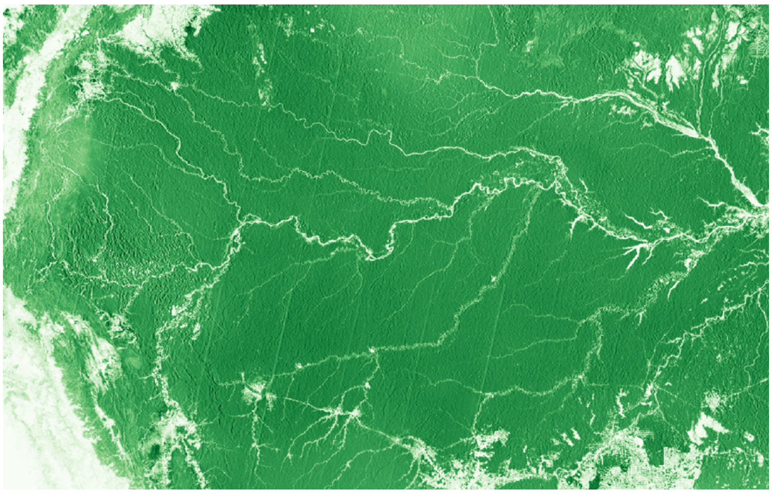

Figure 3-12: Example of seams in the AGB dataset appearing as diagonal bright lines. AGB in this region (western Amazon) was based on the ALOS-2 PALSAR-2 mosaic only and the seams correspond to the point of intersection of two adjacent strips of data.

Seams tend to disappear when averaging to coarser resolution, e.g., 1 km or more.

3.4.3. Topography

The retrieval of AGB was based on images of C- and L-band SAR backscatter, which is affected by geometric distortions due to the side-looking configuration of the radar instrument. As such, sloped terrain facing the radar is characterized by stronger backscatter than sloped terrain looking away from the radar. If untreated at the level of pre-processing, this would turn into AGB estimates being systematically higher on the slopes facing the radar. The ALOS-2 PALSAR-2 mosaics and the Sentinel-1 images were both treated to compensate for slope-induced distortions of the backscatter [RD-3]. Ideally, the backscatter after compensation should be the same regardless of the orientation of the terrain. In practise, imperfections in the Digital Elevation Model (DEM) used to mimic the terrain slope and assumptions made to simplify the correction procedure have the consequence of a residual slope-induced backscatter, which translates into incorrect AGB values. Figure 3-13 shows an example of AGB estimates affected by residual topographic effects. The impact of topography is evident because all slopes facing the radar (observing in this case from the left hand side) have higher AGB than slopes looking away from the radar. The impact of slope-induced biases on AGB was particularly evident in the wet tropics where AGB was based solely on ALOS-2 PALSAR-2 mosaics for which the compensation for topography in the SAR images was undertaken with a simpler approach compared to the processing applied to Sentinel-1 data. Given the poor estimates by Sentinel-1 in the wet tropics, preference was given to the ALOS-2 estimates in spite of topography-induced biases.

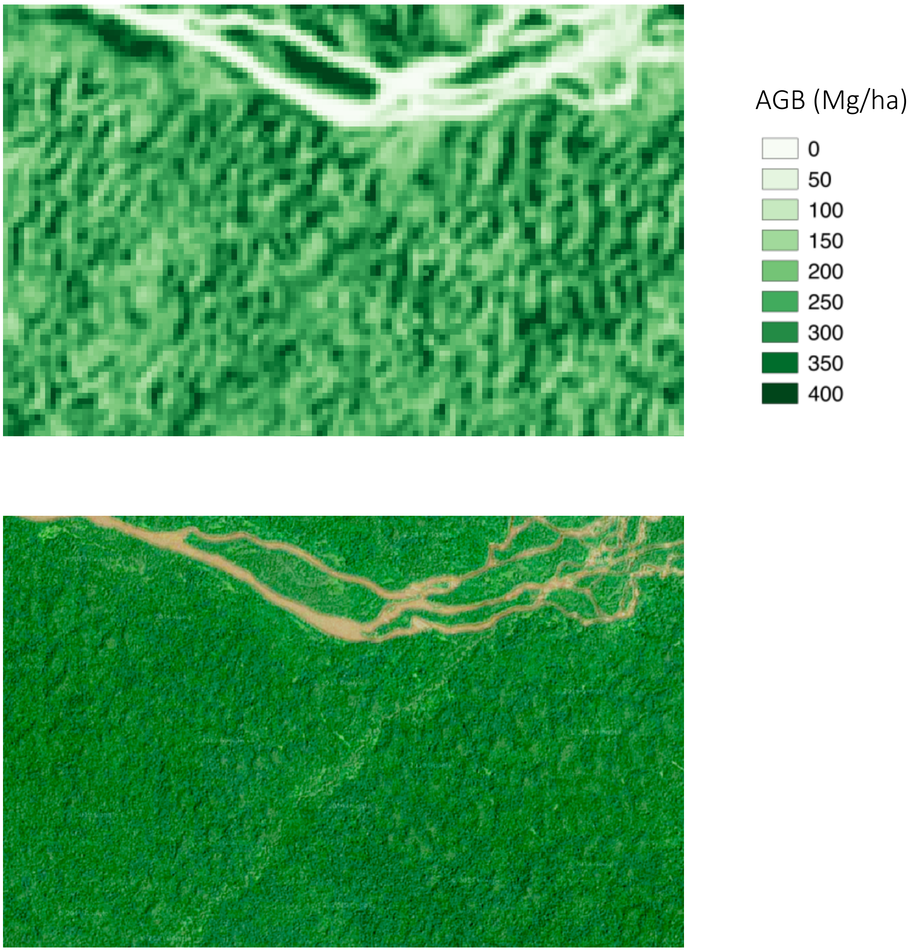

Figure 3-13: Example of topography-induced modulation of AGB estimates (top) and corresponding optical image from Google Earth to be considered as reference for the landscape (bottom). Uncompensated topography caused a variability of up to 200 Mg ha^{-1} between slopes facing the radar (light green areas) and slopes looking away from the radar (dark green areas).

Topography-induced distortions strongly decrease the level of confidence of the AGB estimates at the original spatial resolution of 1 hectare. By averaging over several adjacent pixels, the effect of topography reduces; however, the AGB level is somewhat lower than in reality, which needs to be accounted for when interpreting the averaged AGB maps.

3.4.4. Mangroves

The BIOMASAR algorithms rely on a simplified model that describe the behaviour of the SAR backscatter as a function of biomass. The performance of this model, referred to as Water Cloud Model, to reproduce the relationship between SAR backscatter observations and biomass has been demonstrated in a large variety of forest types. Whenever this functional dependence does not hold true, the model is not able to provide correct estimates of AGB. By cross-checking with other datasets of forest variables (canopy height, biomass etc.), we identified a clear modelling issue in mangrove forests. Mangroves are often characterized by a strong decrease of backscatter for increasing biomass

[RD-5], which contrasts with the assumption that the backscatter increases with biomass. The result of applying an incorrect model is strong underestimation as demonstrated by the CCI BIOMASS map displayed in Figure 3-14 when compared to an AGB data product specifically tailored for mangroves and based on elevation data and allometries (Simard et al., 2019). The CCI BIOMASS dataset does not appear to follow the spatial distribution of the mangroves AGB map generated by Simard et al. (2019) and remains often well below the level estimated. Estimation of AGB from canopy height and regional height-to-biomass allometry appears to be more reliable than the solution implemented in CCI BIOMASS, but the lack of a DEM for 2017 implied that the approach proposed by Simard et al. (2019) could not be implemented. Understanding, however, how signal changes in EO data can be related to the original map by Simard et al. could be a way to provide an updated estimate of AGB for mangroves in order to avoid such strong biases. The alternative would be to rely on different models to retrieve AGB specifically in mangrove forests.

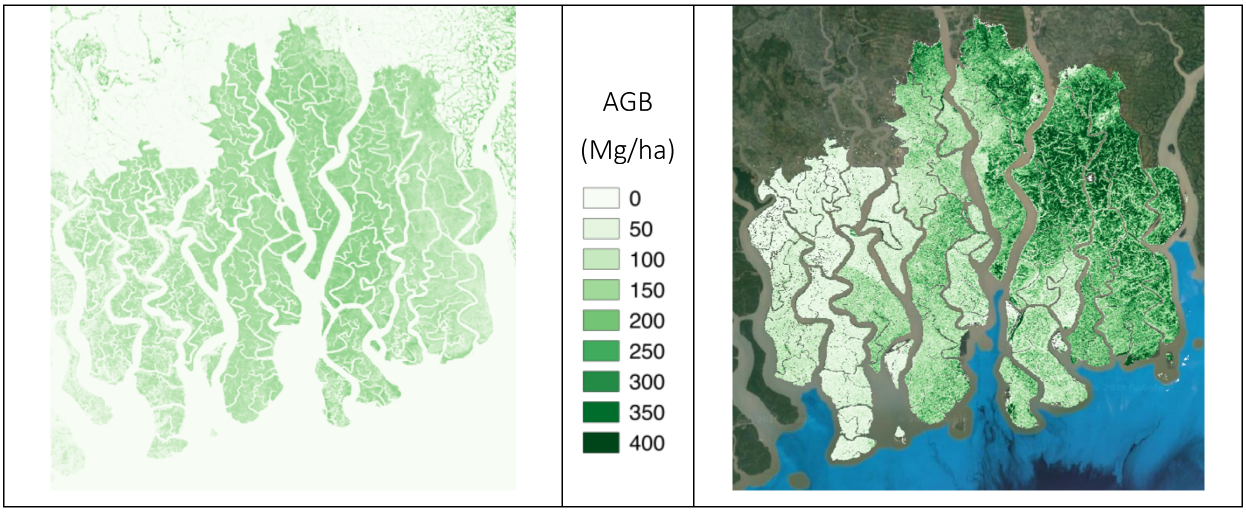

Figure 3-14: Estimates of AGB for mangrove forests of Bangladesh from the CCI BIOMASS dataset of 2017 (left) and the global mangrove AGB dataset for the year 2000 by Simard et al. (2019).

4. AGB change maps

CCI BIOMASS also delivers AGB change maps. These are foreseen for Years 2 and 3 of the project and, therefore, are not discussed in this version of the PUG.

Note: The comparison with the GlobBiomass AGB dataset to estimate AGB changes between 2010 and 2017 is discouraged. Although the two datasets share the same retrieval algorithms and type of EO data, the spatial and temporal resolution of the EO data are different, thus leading to estimates that are not comparable.

5. Data access and policy

The CCI BIOMASS products are made available through the CCI data portal (http://cci.esa.int/data).

At the end of Year 1 of the CCI BIOMASS project, the following data products are available

- AGB map for the year 2017, including per-pixel standard error, version 1.0;

6. References

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ESA Climate Office, CCI Data Standards, CCI-PRGM-EOPS-TN-13-0009, version 2.1, date 02/08/2019

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Shimada, M. and Ohtaki, T., 2010. Generating large-scale high-quality SAR mosaic datasets: Application to PALSAR data for global monitoring. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 3 (4), 637-656.

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Ulander, L.M.H., Gustavsson, A., Flood, B., Murdin, D., Dubois-Fernandez, P., Dupuis, X., Sandberg, G., Soja, M.J., Eriksson, L.E.B., Fransson, J.E.S., Holmgren, J., Wallerman, J., 2011. BioSAR 2010 - Technical assistance for the development of airborne SAR and geophysical measurements during the BioSAR 2010 experiment.

7. Appendicies

7.1. Appendix 1 – NetCDF attributes

The description of the CCI Biomass global aboveground biomass (AGB) products is based on the structure of the NetCDF files. The global attributes of the biomass map are described in Table A1.

Table A1: Global attributes of the global AGB map delivered by the CCI Biomass project, following the structure of the NetCDF files.

Attribute Name	Format	Value	Description
title		ESA CCI above-ground biomass product level 4, year 2017	Product identifier
institution		Gamma Remote Sensing	Where the data has been produced
source		ALOS-2 PALSAR-2 FB and WB mosaics, Sentinel-1 GRD	Source of the original data
history		GSV estimation with BIOMASAR-L, v201906 GSV estimation with BIOMASAR-C, v201906 Merging of GSV estimates, v201906 Conversion of GSV to AGB, v201711	List of applications that have modified the ALOS-2 PALSAR-2, Sentinel-1 data, with time stamp, processor and parameters
references		http://cci.esa.int/biomass	References that describe the data or methods used to produce it.
tracking_id		4e618436-c170-3165-8781-046b3aff5bf3	UUID, Universal Unique Identifier
Conventions		CF-1.7	Name of the conventions followed
product_version		1.0	Version of AGB product
summary		This dataset contains a global map of above-ground biomass of the epoch 2017 obtained from L-and C-band spaceborne SAR backscatter, placed	

Attribute Name	Format	Value	Description
		onto a regular grid.	
keywords		satellite, observation, forest, biomass	
id		ESACCI-BIOMASS-L4-AGB-MERGED-100m-2017-fv1.0.nc	Product identifier
naming authority		ch.gamma-rs	
keywords vocabulary		NASA Global Change Master Directory (GCMD) Science Keywords	
cdm_data_type		INT	
comment		These data were produced at ESA CCI as part of the ESA Biomass CCI project.	Miscellaneous information about the data or method used to produce it
date_created	yyyy-MM-dd'T'HH:mm:ss'Z'	20190708T000000Z	Creation time of product
creator_name		Gamma Remote Sensing	
creator_url		http://www.gamma-rs.ch	
creator_email		santoro@gamma-rs.ch	
project		Climate Change Initiative - European Space Agency	
geospatial_lat_min	-90.0 ... 90.0	-60	South border of the bounding box
geospatial_lat_max	-90.0 ... 90.0	80	North border of the bounding box
geospatial_lon_min	-180.0 ... 180.0	-180	West border of the bounding box
geospatial_lon_max	-180.0 ... 180.0	180	East border of the bounding box
geospatial_vertical_min		0	
geospatial_vertical_max		0	
time_coverage_start		20170101T000000Z	
time_coverage_end		20171231T235959Z	
time_coverage_duration		P1Y	
time_coverage_resolution		P1Y	
standard_name_vocabulary		NetCDF Climate and Forecast (CF) Metadata Convention version 67	
license		ESA CCI Data Policy: free and open access	

Attribute Name	Format	Value	Description
platform		ALOS-2, Sentinel-1A, Sentinel-1B	
sensor		PALSAR-2, SAR-C	
spatial_resolution		100 m	
geospatial_lat_units		degrees_north	
geospatial_lon_units		degrees_east	
geospatial_lon_resolution		0.000888888	
geospatial_lat_resolution		0.000888888	
key_variables		agb	
format_version		CCI Data Standards v2.1	

The variables and variables' attributes of the global AGB NetCDF file are presented in Table A2.

Table A2. Variables and variables' attributes of the global AGB map delivered by the CCI BIOMASS project, following the structure of the NetCDF files.

Variable	Attribute	Format	Value	Description
crs		int		Coordinate reference system attribute container
	grid_mapping_name		Latitude-Longitude	
	semi_major_axis		6378137.0	
	inverse_flattening		298.257223563	
	false_easting		0.0	
	false_northing		0.0	
	longitude_of_central_meridian		0.0	
	scale_factor_at_central_meridian		1.0	
time		double(time)		Start time of the multi-year period
	standard_name		time	
	long_name		single-year period	
	units		time since reference time	days since 1990-1-1 0:0:0
lon		double (lon)	-180.0 .. 180.0	Longitude coordinate of image

Variable	Attribute	Format	Value	Description
				column
	standard_name		Longitude	
	long_name		WGS84 longitude coordinate	
	units		degrees east	
	valid_min		-180.0	
	valid_max		180.0	
lat		double (lat)	-60.0 .. 80.0	Latitude coordinate of image row
	standard_name		latitude	
	long_name		WGS84 latitude coordinate	
	units		degrees north	
	valid_min		-60.0	
	valid_max		80.0	
agb		int16 (lat,lon)		AGB value
	standard_name		n/a	
	long_name		Above-ground biomass	
	valid_min		0	
	valid_max		10000	
	_FillValue		99999	
agb_se		int16 (lat,lon)		Standard error of AGB value
	standard_name		n/a	
	long_name		Above-ground biomass standard error	
	valid_min		0	
	valid_max		65536	
	_FillValue		99999	

7.2. Appendix 2 – Cartographic material

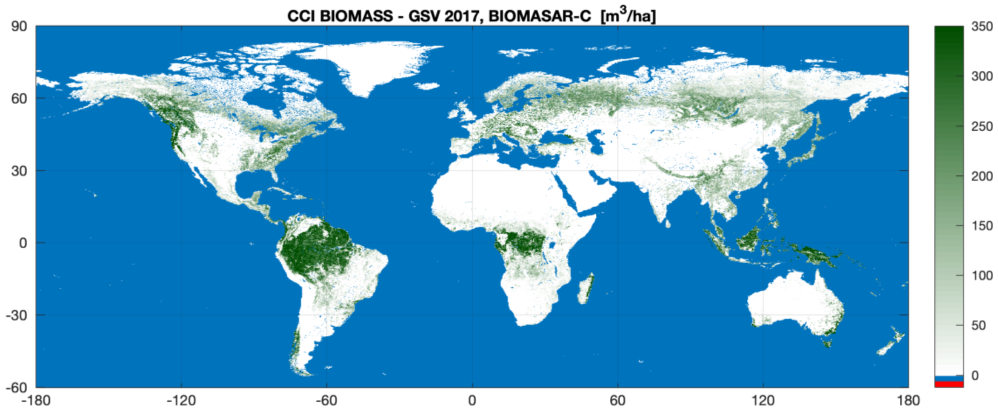

Figure B1. Map of forest GSV obtained with the BIOMASAR-C algorithm using Sentinel-1 SAR data acquired in 2017.

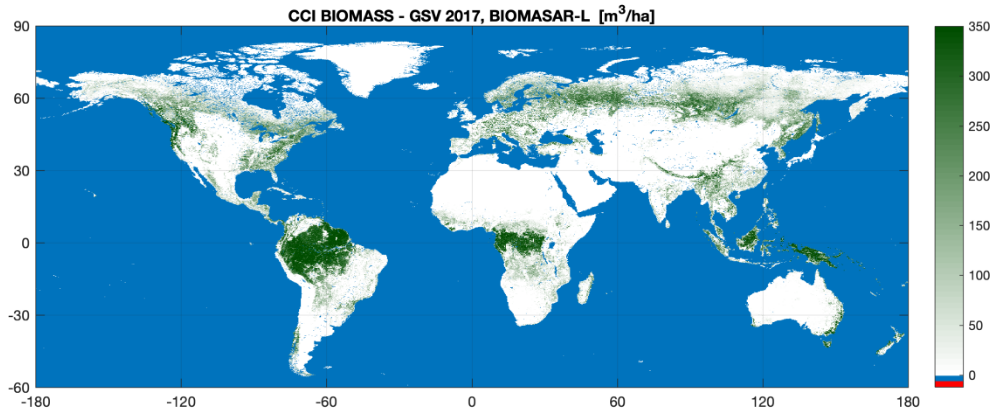

Figure B2. Map of forest GSV obtained with the BIOMASAR-L algorithm using ALOS-2 PALSAR-2 SAR data acquired in 2015-2017.

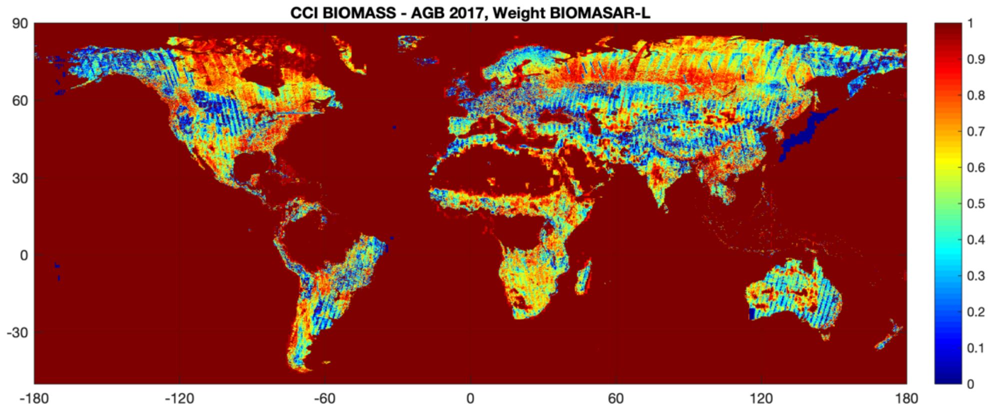

Figure B3. Image of the weights applied to the BIOMASAR-L dataset of GSV in the process of merging with the BIOMASAR-C GSV estimates. Increasing value of the weight indicates increased proportion of the BIOMASAR-L GSV estimate in the final estimate