CCI

BIOMASS

PRODUCT USER GUIDE

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Document Change Record (from Year 1 to Year 2)

VERSION	DATE	DESCRIPTION	APPROVED
2.0	2020-10-07	Updated the description of the year 1 data product (AGB map for the year 2017). Added the description of the year 2 data products (AGB maps for the years 2010 and 2018)	
3.0	2021-07-05	Updated the description of the year 2 data products (AGB maps for the epochs 2010, 2017 and 2018). Added the description of the year 3 data products (AGB change maps for 2010-2018 and 2017-2018).	

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5.0	2024-06-17	Edited the description of AGB and AGB change products.	

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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
SD	SD
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	5.0	
RD-2	Users Requirements Document	2.0	
RD-3	Algorithm Theoretical Basis Document	5.0	
RD-4	End-to-End ECV Uncertainty Budget	5.0	
RD-5	Product Validation & Intercomparison Report	4.0	

1 Introduction

The aim of the European Space Agency (ESA) 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 listing above-ground biomass (AGB, typically expressed in tonnes (or Mg) per hectare) as an ECV is that this variable is crucial to understand both the source and sink terms in the global carbon cycle (which is fundamentally what drives climate change by controlling levels of carbon dioxide (CO_2) in the atmosphere). The source term comes from carbon emissions when vegetation biomass (including below ground components) is lost through events (e.g., fire) and primarily human activities leading to land use change; the sink term arises because growing forests extract CO_2 from the atmosphere and tie it up in long-lasting wood (including roots) and soil stores.

Although satellite sensor 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 forest AGB have been demonstrated (noting that the below ground components cannot be observed). In addition, the coming years will see a wealth of missions targeting the retrieval of AGB as one of the primary objectives. As such, this CCI project sets out not only to produce the best possible validated maps of AGB suitable for climate modelling with existing data, but also ensures that AGB estimation methods being developed are sustainable to include new and additional data streams towards progressively more accurate AGB products.

1.1 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 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 fifth year of the CCI BIOMASS project and are referred to as Version 5.0 (V5). Starting with V5 of the CRDP, CCI BIOMASS also distributes AGB and AGB change maps at coarser spatial resolution.

1.2 Contents

The document consists of the following sections:

- Section 2 provides an overview of the CCI BIOMASS project.
- Sections 3 and 4 describe the full resolution data products provided as part of the CRDP.
- Section 5 describes the spatially averaged maps part of the CRDP.

- Section 6 gives an indication of how to use the CCI BIOMASS datasets.
- Section 7 summarizes changes between versions of the datasets.
- Section 8 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.

For correct use of the CCI BIOMASS datasets, it is strongly recommended to refer to Section 6.

Please contact the data producer (Maurizio Santoro, Gamma Remote Sensing, santoro@gamma-rs.ch) for questions related to the use of the AGB maps and the AGB change maps.

2 CCI BIOMASS Project

2.1 AGB and Earth Observation

According to the Food and Agriculture Organization (FAO), 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, while below-ground biomass (BGB) refers to the amount of biomass stored in vegetation roots below the soil. AGB is sometimes differentiated depending on whether it is stored in woody or non-woody vegetation. AGB stored in woody vegetation requires a definition of the minimum size of trees used to define vegetation as woody. Non-woody vegetation consists of trees smaller than a given threshold on size (e.g., diameter, height, cover), shrubs, and all other non-herbaceous live vegetation. For the definition adopted in this work, refer to Section 3.1.

In this context, AGB is here referred to in terms of biomass 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., Mg ha^{-1} (Megagrams per hectare).

Precise estimates of AGB require destructive sampling. This is not viable when the aim is to quantify the overall biomass pool on Earth, so alternative methods that predict AGB from *in situ* measurements and model-based approaches come into play. Allometries derived from felled sample trees, i.e., equations linking various structural parameters of a tree to biomass, permit non-destructive sampling. Yet they require ground surveys, which can be costly, imply non-trivial logistics and are time consuming. To overcome some of these issues, terrestrial, airborne and spaceborne remote sensing techniques have been developed in recent years as an alternative or complement to local surveys. Accordingly, models relating remote sensing observables to measurements collected *in situ* have been developed. A major advantage of airborne and spaceborne remote sensing as tools to estimate AGB is their ability to cover large areas at less cost than ground surveys. However, a map of AGB obtained from remote sensing observations is an estimate of the true biomass on the ground and relies heavily on the accuracy of the models used to convert measurements of the observables to AGB.

The remote sensing community has made continual efforts to generate wall-to-wall datasets of AGB 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 gave a significant boost to generation of global climate data records from space. The CCI Programme added the ECV AGB to its suite of CCI+ projects, with the primary objective of generating climate-relevant time records of AGB 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 User requirements

The CCI BIOMASS project was built on the requirements set by GCOS in terms of the spatial detail, temporal resolution and thematic accuracy of AGB datasets. The requirement is for AGB to be provided wall-to-wall over the entire globe for all major woody vegetated biomes, with a spatial resolution between 500 m and 1 km (based on satellite observations of 100-200 m), and a relative error of less than 20% where AGB exceeds 50 Mg ha^{-1} and an error of 10 Mg ha^{-1} where the AGB is below 50 Mg ha^{-1}. Furthermore, the AGB data products delivered by the CCI BIOMASS project need to consider 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. 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 both the modelling and policy communities.

Table 2-1 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 different (text in *italic*). The climate and carbon modelling community, which is the primary focus of CCI BIOMASS, requires unbiased AGB estimates but is more relaxed on the spatial resolution because of the coarse grid-cell size of climate models. The community concerned with United Nations Framework Convention on Climate Change (UNFCCC) reporting and the UN Reducing Emissions from Deforestation and Forest Degradation (UN-REDD+) Programme emphasises the needs of individual countries and requires resolutions of 1 ha or better. Notwithstanding the sensitivity of EO data to AGB and the capability of retrieval models to infer biomass from EO observations, the requirements in Table 2 imply that the project should deliver data products at the highest possible resolution and provide aggregates at coarser spatial resolution that have better accuracy and precision than full spatial resolution pixels.

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, refer to the Algorithm Theoretical Basis Document (ATBD) [RD-3] and the End-to-End ECV Uncertainty Budget (E3UB) [RD-4] documents.

Table 2-1: Requirements for an AGB product formulated by the modelling and the policy communities as reported in the CCI BIOMASS URD. 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 Resolution	*1 km x 1 km* (M) *100x100 m / 1 ha or finer* (P)	*100 m resolution is desirable, and 30 m resolution data could be used* (M) *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)	Annual
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 be unbiased and with known precision
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) *GeoTIFF* (P)	*NetCDF for global products* (M) *GeoTIFF - for regional products* (M) *other country-preferred formats* (P)

Other Requirements	Fully documented mapping methods Robust and standardised validation scheme with protocol Metadata available Free and open access *Full reporting of validation results and implications for product bias and precision* (M)	Fully documented mapping methods Metadata available, Robust and standardised validation scheme with documented protocol Full reporting of validation results and implications for possible product bias and precision 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* (P) *Full reporting of validation results and implications for product bias and precision* (P) *Clear and transparent reporting of regional accuracy / uncertainty* (P) *Consistent spatial-temporal coverage* (P)

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 (https://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 (Santoro *et al*., 2021). CCI BIOMASS currently aims to a) generate annual global estimates of AGB for several epochs between 2005 and 2022, and b) quantify AGB changes between epochs. The AGB map produced in the context of the GlobBiomass project is replaced by the map produced in CCI BIOMASS.

This document presents the data products of the CRDP and an assessment in terms of their accuracy and reliability. The v5 CCI BIOMASS data products consist of global maps of AGB for the years 2010, and for each year between 2015 and 2021. Each AGB estimated is paired with an estimate of its precision expressed by the standard deviation. The difference of AGB maps for two epochs together with an estimate of their standard deviation forms the dataset of AGB change products. Each AGB change map is accompanied by a quality flag map, detailing the level of reliability of the AGB change estimate.

Because of the different types of remote sensing data available for each year, the AGB change maps may be affected by substantial biases. We strongly encourage referring to the quality flag layer to ensure that the data are used correctly (Section 4).

3 AGB Maps

3.1 Product description

The CCI BIOMASS project delivers spatially explicit estimates of AGB for three epochs and related standard deviations (SDs) as separate map products. The AGB product consists of global datasets with estimates of AGB (where the unit of Mg ha^{-1} = tons ha^{-1}). 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 SD product is a separate data layer providing per-pixel SD of the AGB estimates in Mg ha^{-1}.

The data products currently provided by the project (Year 5, V5.0) consist of maps of AGB and AGB SD based on EO data acquired in 2010 and for each year between 2015 and 2021. Maps are provided at:

- Full spatial resolution, i.e., with a pixel size of 1 ha, equivalent to an area with dimensions 100 m x 100 m,
- Coarse spatial resolution, after spatial averaging of the full resolution maps.

Generation of the AGB datasets at full spatial resolution and technical specifications are presented in this Section. For the AGB datasets at coarser spatial resolution, refer to Section 5.

Figures 3-1 and 3-2 show one example of the CCI BIOMASS AGB products and the corresponding map of relative SD. To enhance image contrast, the AGB map in Figure 3-1 has been clipped between 0 and 500 Mg ha^{-1}. The AGB SD map (Figure 3-2), expressed in the form of a relative SD with respect to AGB, has been clipped between 0% and 100% of the estimated AGB.

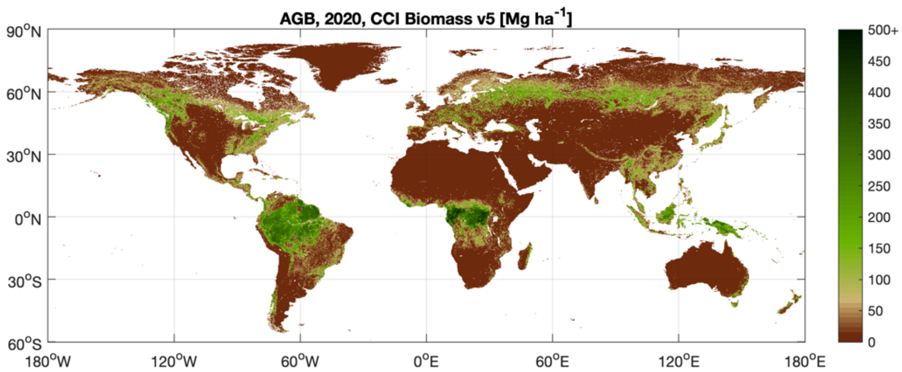


Figure 3-1: Global AGB estimates for the year 2020. Spatial resolution: 100 m.

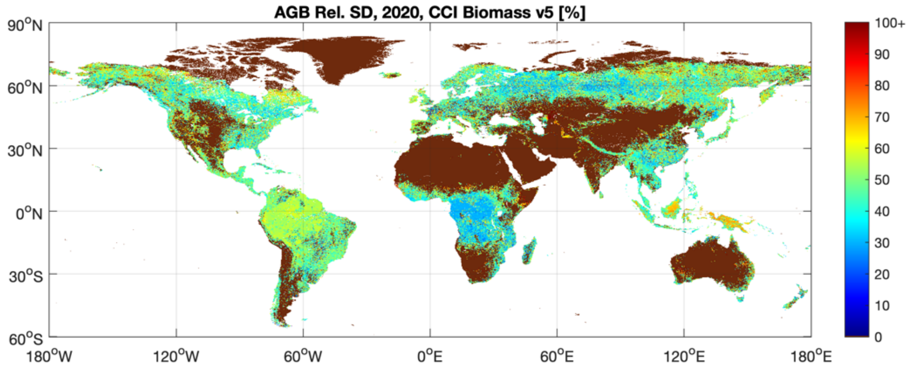
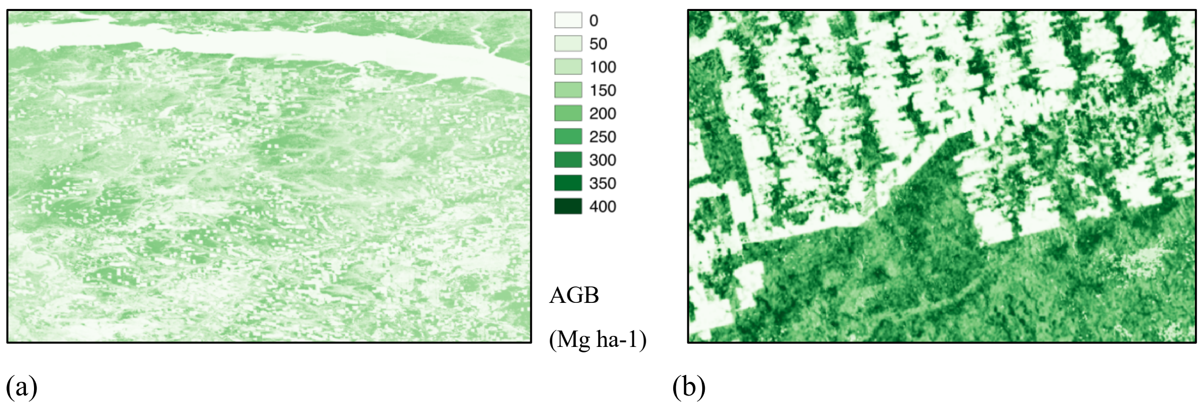


Figure 3-2: Relative SD of global AGB estimates for the year 2018 in Figure 3-1. Spatial resolution: 100 m.

Figure 3-3 shows two examples of AGB maps, each covering an area of approximately 50 km × 50 km, that highlight the spatial detail in the AGB dataset. 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. Forests are dominated by boreal coniferous species with AGB up to 200 Mg ha^{-1} and the region has undergone intensive logging. 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} (for woody vegetation). The panels on the righthand side of Figure 3-3 show a detail of the forest along the Trans-Amazonian Highway, between the cities of Uruará and Altamira. While the forest north of the highway has been extensively logged to be replaced by agriculture, forests to the south have remained intact.



(c) (d)

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 that serve as reference for each of the AGB maps.

Processing chain

EO datasets

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

Requirements on global coverage during each of the three epochs, open access to the data and sensitivity of the observations to forest structural parameters restricted the useful pool of remote sensing observations to images acquired by SAR C-band (Envisat ASAR for 2010 and Sentinel-1 starting with 2015) and L-band (ALOS-1 PALSAR-1 for 2010 and ALOS-2 PALSAR-2 starting with 2015).

The Sentinel-1 dataset consisted of images of SAR backscatter acquired 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. Sentinel-1 images acquired in the Interferometric Wide Swath (IWS) mode were used. Some isolated gaps in North America were filled with images acquired in the Extended Wide Swath (EWS) mode [RD-3]. The two Sentinel-1 units became operational in spring 2017, which means that the density of observations was slightly lower prior to 2017 compared to the years following. All images were terrain-geocoded, speckle filtered and corrected for terrain-induced distortions [RD-3]. As a trade-off between processing speed, preservation of features and fulfilling the requirements of spatial resolution for an AGB product (see Section 2), each Sentinel-1 image was processed from the original 20 m to 150 m pixel size. To reduce redundancies and optimize processing times, individual images were combined into monthly averages.

The ALOS-2 PALSAR-2 dataset consisted of individual image strips of SAR backscatter acquired in Fine Beam Dual-polarization (FBD) and Wide Beam (WB) modes [RD-3]. The FBD dataset consisted of multiple observations per year [RD-3]. This unique dataset was provided to the CCI BIOMASS project by the Japan Aerospace Exploration Agency (JAXA) as part of an ongoing collaboration with ESA on satellite-based estimation of biomass. The WB dataset consisted of per-cycle image mosaics and covered the tropics only. The mosaics were produced on a repeat-pass cycle basis, i.e., every 46 days. All mosaics were produced by JAXA (Shimada and Ohtaki, 2010; Shimada et al., 2014). The WB mosaics are available to members of the research community participating in the Kyoto and Carbon (K&C) Initiative, which is led and coordinated by JAXA's Earth Observation Research Center (EORC) (Rosenqvist et al., 2007). The K&C ScanSAR 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. While the WB mosaics were provided with a pixel spacing of 100 m, the FBD images were provided with 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 images were averaged to 100 m. The overall quality of the SAR data for 2015-2021 was high and considered sufficient to generate a global dataset of AGB at a hectare scale on an annual basis.

The Envisat ASAR dataset consisted of terrain-geocoded images of SAR backscatter acquired in the Wide Swath Mode (WSM) between 2010 and 2011 [RD-3]. The dataset has a spatial resolution of 150 m, which is the reason for processing the higher resolution Sentinel-1 images to moderate resolution. The main drawbacks of the ASAR data are the lack of a cross-polarized channel and inhomogeneous coverage of terrestrial land surfaces. Dense sets of observations were achieved over northern regions, while most tropical and sub-tropical regions were not imaged frequently. This has practical implications for the 2010 AGB dataset.

The ALOS-1 PALSAR-1 dataset up to Version 3 (V3) of the CCI Biomass products consisted of terrain-geocoded annual mosaics of SAR backscatter acquired between 2007 and 2010 in the FBD mode [RD-3]. JAXA has now released all individual ALOS-1 PALSAR Fine-Beam images in Level 2.2 format, i.e., images processed to radiometrically terrain-corrected level. Starting with V4 of the CCI Biomass products, the level 2.2 data set, which in contrast to the annual mosaics provide multiple observations per year, was used after aggregating the original images with 25 m resolution to the 100 m target resolution.

Although for the eight epochs the same kind of EO data were available (C- and L-band SAR backscatter), the difference in terms of observation density affected the accuracy of the AGB estimates. The 2010 dataset was based on the few L-band SAR observations from ALOS-1 PALSAR-1 except in areas of low AGB density where the retrieval algorithm weighted the C-band estimates (from single-polarized images) more heavily than the L-band estimates. The 2015-2021 datasets used a larger number of observations of SAR backscatter at L-band in the tropics and wall-to-wall cross-polarized C-band images elsewhere. This leads to improved estimates in the wet tropics and in low AGB regions [RD-5]. These factors need to be considered when attempting any comparison of estimates from the 2010 map and the maps spanning the 2015-2021 epoch. For the latter, fluctuations of the AGB estimates are also likely because of the different ALOS-2 and Sentinel-1 datasets acquired each year.

<u>AGB retrieval algorithm</u>

The estimation of AGB is illustrated by the flowchart in Figure 3-4. Initially, separate algorithms (which share the same theoretical basis) are applied to the C-band and L-band datasets. With each algorithm, referred to as BIOMASAR, a global map of AGB is obtained. The BIOMASAR algorithm inverts a semi-empirical model relating the forest backscatter to canopy density and canopy height; these are replaced by two functions relating canopy density to height (based on spaceborne LiDAR measurements) and canopy height to AGB (based on spaceborne LiDAR height metrics and global statistics of AGB produced by National Forest Inventories) [RD-3]. The model contains three parameters that are unknown *a priori*, and which correspond to specific backscatter components (ground, canopy) and backscattering properties of the forest. 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]. Note that the model training phase does not require *in situ* observations, such as AGB plot data.

The two maps of AGB obtained from the BIOMASAR-C and BIOMASAR-L implementations, i.e., from the C- and L-band data, are merged using a set of weighting rules to reduce systematic estimation errors in one or the other map [RD-3]. Prior to merging, the BIOMASAR-C dataset of AGB is resampled from 150 m to 100 m to be compatible with the pixel spacing of the BIOMASAR-L dataset. In a nutshell, the weighting favours the BIOMASAR-L AGB estimates in regions of high AGB because of the weaker sensitivity of C-band backscatter to AGB in mature and dense forest. The AGB of younger and regrowing forest is often an average of the two values estimated by BIOMASAR-C and -L.

The shaded part in Figure 3-4 indicates that the estimation framework foresees the integration of additional AGB datasets. This will become relevant in the near future with a multitude of global AGB datasets planned for release as part of mission objectives (GEDI, NISAR, BIOMASS) or as part of currently ongoing activities to quantify AGB.

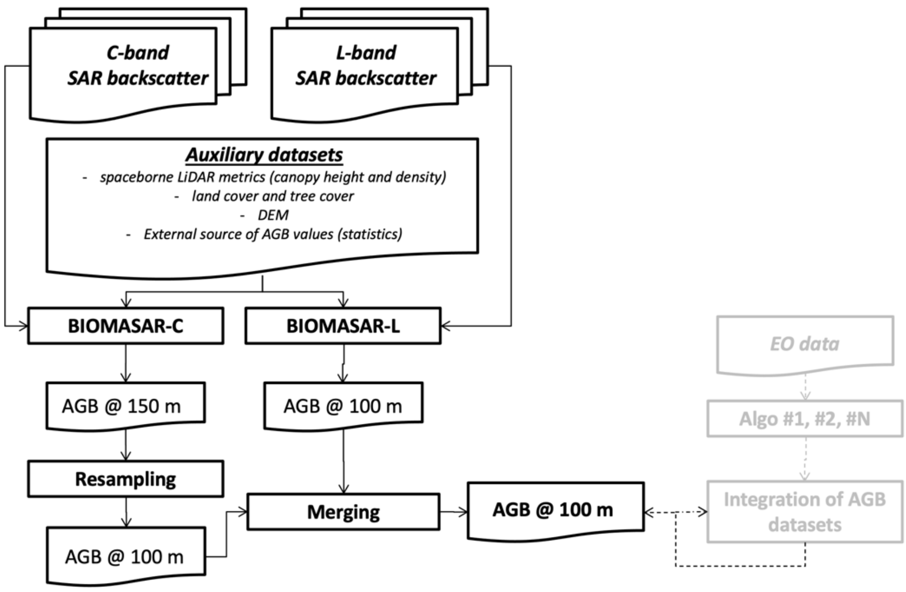


Figure 3-4: Functional dependencies of datasets and approaches forming the CCI BIOMASS global biomass retrieval algorithm. The shaded part of the flowchart represents potential improvements following the implementation of additional retrieval techniques.

Each AGB map part of the CRDP is accompanied by a per-pixel estimate of its SD, which is computed by propagating individual standard deviations of (i) the SAR measurement, (ii) the modelling framework behind the BIOMASAR algorithms and (iii) the merging procedure. Full characterization of the SDs is provided in the E3UB report [RD-4].

Specifications of data products

Current version: V5.

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, ice-capped surfaces, and bare soils according to the Copernicus Global Land service land cover datasets of the same year (Buchhorn et al., 2019; available at https://land.copernicus.eu/global/products/lc), are set to 0 Mg ha^{-1}. For the 2010 AGB dataset, the 2015 land cover dataset was used.

AGB expresses the density of AGB for the area covered by the pixel.

The AGB and AGB SD have not been masked for forest area. Users intending to extract values corresponding to “forests” are advised to use their own forest mask.

Reference system: Lat-long, WGS-84.

Corner coordinates: top left corner of pixel.

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

Timeframe: annual (average) estimate for 2010, 2015, 2016, 2017, 2018, 2019, 2020 and 2021

Data format: NetCDF (one global file) and GeoTiff (10° × 10° tiles)

Format of the NetCDF file

Naming Convention

The filename convention of the global AGB and AGB SD 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 3-1.

Table 3-1: Elements of the NetCDF file name of the CCI BIOMASS AGB and AGB SD data products 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
code	Product code identifier	MERGED (constant)
spatres	Spatial resolution	100 m (constant)

epoch	Year of the product	2010, 2015, 2016, 2017, 2018, 2019, 2020 or 2021
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 names of the global AGB maps in NetCDF format distributed with the current CRDP are:

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2010-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2015-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2016-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2017-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2018-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2019-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2020-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-100m-2021-fv5.0.nc

Each NetCDF file contains the AGB (16-bit integer), AGB_SD (16-bit integer), latitude (64-bit floating point), longitude (64-bit floating point) and time (64-bit floating point) information.

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. The metadata follow the CCI guidelines (ESA Climate Office, 2019).

Estimated size

The size of each annual AGB dataset, including the SD layer, in NetCDF format is approximately 18 GBFormat of the GeoTiff tiles

Naming Convention

The filename convention of the AGB and AGB SD tiles delivered by the CCI BIOMASS project is the following:

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

where <id> = <N/S flag><Latitude><E/W flag><Longitude>_<project>-<level>-<var>-<code>-<spatres>-<epoch>

The dash "-" is the separator between name components. The different name components are defined in Table 3-2.

For the specific case of a tile covering the area between (60°N, 40°E) and (50°N, 50°E), the file names of the AGB maps in GeoTiff format distributed with the current CRDP are:

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2010-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2015-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2016-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2017-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2018-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2019-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2020-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-100m-2021-fv5.0.tif

Accordingly, the file names of the SD layer are:

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2010-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2015-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2016-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2017-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2018-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2019-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2020-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB_SD-MERGED-100m-2021-fv5.0.tif

Table 3-2: Elements of the GeoTiff file name of the CCI BIOMASS AGB and AGB SD data products delivered by the CCI BIOMASS project.

Field	Signification	Value
N/S flag	North/South hemisphere of northernmost row in the tile	N or S
Latitude	Northernmost latitude coordinate of tile	Integer (2 digits, between 00 and 80)
E/W flag	East/West hemisphere of westernmost column in the tile	E or W
Project	Westernmost longitude coordinate of tile	Integer (3 digits, between 0 and 180)
Project	Project acronym	ESACCI- BIOMASS (constant)
Level	Processing level	L4 (constant)
Var	Unit of the product	AGB or AGB_SD
code	Product code identifier	MERGED (constant)
spatres	Spatial resolution	100 m (constant)
epoch	Year of the product	2010, 20215, 2016, 2017, 2018, 2019, 2020 or 2021
version	Incremental, following the successive revisions of the CCI-BIOMASS processing lines	Version of product revision, preferably major.minor, optionally with processing centre [a-zA-Z0-9._]*

Estimated size

For each of the five epochs, the Geotiff dataset consists of approximately 11 GB of AGB estimates and 11 GB of AGB SD estimates.

Format

Short unsigned integer (uint16).

Format of the data product – additional information

Additional information on the data products is reported below. This information is independent of the format in which the maps are stored.

Product layers

AGB and AGB SD. Both are expressed in Mg ha^{-1}.

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 of the AGB corresponds to a number expressed in Megagrams per hectare (Mg ha^{-1}). Valid AGB values are between 0 and 10,000 Mg/ha.

Each pixel value of the AGB SD corresponds to a number expressed in Megagrams per hectare (Mg ha^{-1}). Valid AGB SD values are between 0 and 10,000 Mg/ha.

Spatial Extent

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

Spatial Resolution

0.0008888°, corresponding to nearly 100 m at the Equator

Temporal resolution

Annual

Projection

The Coordinate Reference System (CRS) is a geographic latitude and longitude 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 3-3).

Table 3-3: Description of the coordinate reference system defining the global AGB products.

```
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]]
```

3.2 Qualitative assessment

The level of detail of the CCI BIOMASS maps of AGB has been discussed in Section 3. Each CCI BIOMASS map provides a wall-to-wall portrait of AGB for the corresponding year. The maps correspond with the expected distribution of AGB in woody vegetation on Earth (Figure 3-1).

The highest AGB (> 300 Mg ha^{-1}) is found 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 AGB for decreasing latitude in the northern hemisphere, following the transition from boreal to temperate and tropical forest. In the southern hemisphere, AGB is greatest in the tropical wet forest and decreases in the drier forests and savannahs. AGB increases markedly at the southernmost latitudes corresponding to temperate cool forests.

The SD of the AGB estimates in Figure 3-2 depends on the proportion of C- and L-band estimates used. A map of the weights applied to each of the estimates is shown in the Appendix (Figure 10-1). For the wet tropics, where the estimate depends solely on L-band data, the SD is about 30-40 % of the estimated AGB except for South America, where on average the SD is 50 % of the estimated value, and across undisturbed forests of insular Southeast Asia where the SD is around 70 % of the estimated value. In extra-tropical regions, the AGB estimates combine values from both SAR data streams. The SD is around 30-40 % of the estimated value with the exception of Central Siberia where the value is higher as a consequence of a dominant contribution from the C-band data stream. This region has the smallest number of satellite observations compared to other regions of the world [RD-3].

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 true AGB. Forest field inventory measurements with well-known and well-described reporting protocols represent the primary source for validation. Validation of the AGB maps is described in the Product Validation & Intercomparison Report (PVIR) [RD-5]. Validation confirmed the visual impression that the spatial distribution of AGB is well captured globally (Figure 3-5). The scatterplot for 2020 is representative for all years between 2015 and 2020 as these shared the same type of EO data to estimate AGB.

Each epoch is characterized by increasing variance and discrepancies for increasing AGB. The panel in Figure 3-5 for the 2020 dataset indicates increasing underestimation of AGB with increasing AGB. The different patterns in the two panels are a consequence of the different databases of field inventory measurements. For some regions, inventory data were available for 2010 but not for 2020.

Figure 3-6 shows the spatial distribution of the estimation errors. We identify both over- and underestimation, even within a region, which contributes to the variance and the bias in the scatterplots of Figure 3-5. Overall, the tendency to slight underestimation is a combination of the approximations in the retrieval models and the allometry that relates canopy height to AGB. Because of the decreasing sensitivity of the SAR backscatter to increasing AGB, the retrieval models implement rules that avoid the estimation of unrealistically high values of AGB, thus leading to rather conservative values of AGB in regions where the AGB approaches its maximum and, accordingly, the SAR backscatter is characterized by weak sensitivity to AGB. Large underestimation was often a consequence of the constraint applied in the inversion to a maximum AGB that is lower than reality (e.g., Madagascar, Mexico, Tasmania, Croatia). The maximum AGB is derived from an estimate of maximum height from spaceborne LiDAR and a structural function relating canopy height to AGB. The structural function relating canopy height and AGB evolved; however, it remained in many regions of the world too generic causing AGB biases locally. Another reason for underestimation was the effect of the weak sensitivity of the backscatter to AGB. The simple formulation of the inversion rules from backscatter to AGB was found to weight incorrectly the estimates of AGB from the individual SAR scenes in dense rainforest such as in Guyana and Vietnam. Overestimation was sporadic.

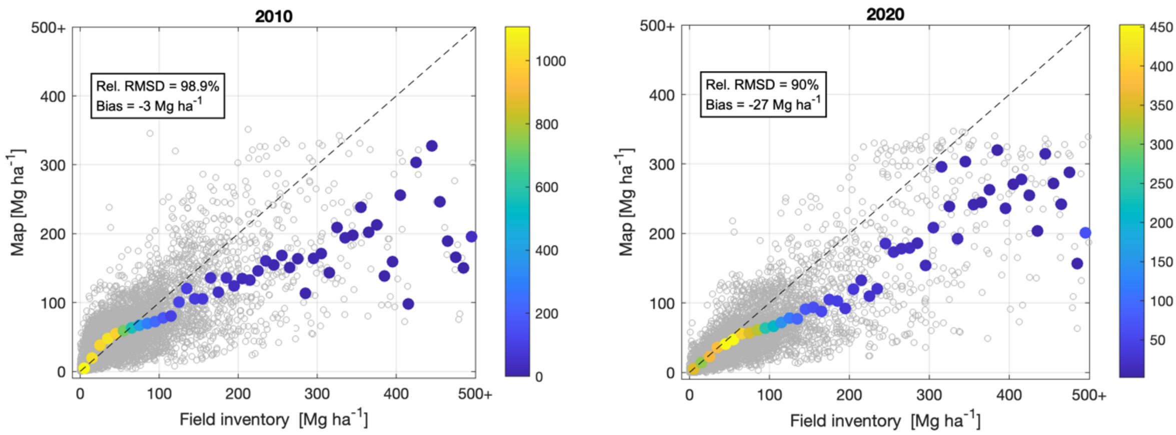


Figure 3-5: Scatterplots of average AGB from field inventory data (x axis) and corresponding values from the AGB map (y axis) using a 0.1° (i.e., 10 km) grid for the years 2010 and 2020 (year 5, V5.0). In each scatterplot, the coloured circles represent the average map value for binned reference AGB (10 Mg ha^{-1} wide intervals). The colour represents the number of grid cells within a specific bin. The scatterplots are based on data provided by Wageningen University and used to compile the CCI BIOMASS PVIR [RD-5].

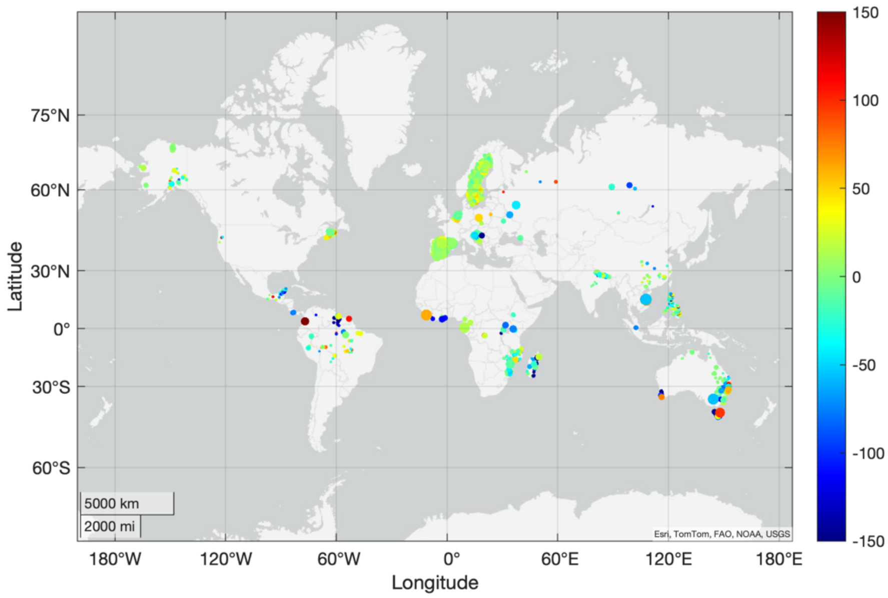


Figure 3-6: Map of the spatial distribution of estimation errors. Errors are defined as the difference between map-based and plot-based average AGB per grid cell. The colour bar is constrained between +/- 150 Mg ha^{-1} to enhance the contrast. The AGB differences are displayed for the 2010 dataset. The size of the circle is proportional to the number of field inventory measurements within a grid cell.

One of the intrinsic limitations of validation with inventory data is that the inventory samples are an opportunistic collection of measurements gathered for other reasons than validating AGB estimates from remote sensing data. Hence, trends identified by the validation need to be understood before coming to conclusions.

The same concept applies if the source of reference AGB measurements is a high-resolution map. Before applying the map in local to regional- scale applications, users may want to evaluate the accuracy of the map in their own area of interest, for instance with the aid of locally available *in situ* information on AGB. A frequent scenario may be that forest inventory data collected from small diameter plots (e.g., 10-20m diameter) are used, despite the mismatch with respect to the spatial resolution of the CCI AGB maps (100 m x 100 m). It is then important to understand that (i) this spatial mismatch poses limits on the possibility to quantify the local error and overall bias of the CCI AGB maps and (ii) comparisons of map and *in situ* AGB estimates need to be interpreted with caution.

With the aid of AGB maps derived from an airborne laser scanner (ALS), we demonstrate below the limitations associated with assessing the precision and bias of a coarser 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 smaller plots is revealed not only in the form of 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 geolocation and measurement errors in the *in situ* data or the allometric equations used to estimate AGB from 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., a boreal and a tropical forest site. 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 forest's vertical structure and to produce high-resolution AGB maps. The maps, with a spatial resolution of 20 m (Figure 3-7), 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.

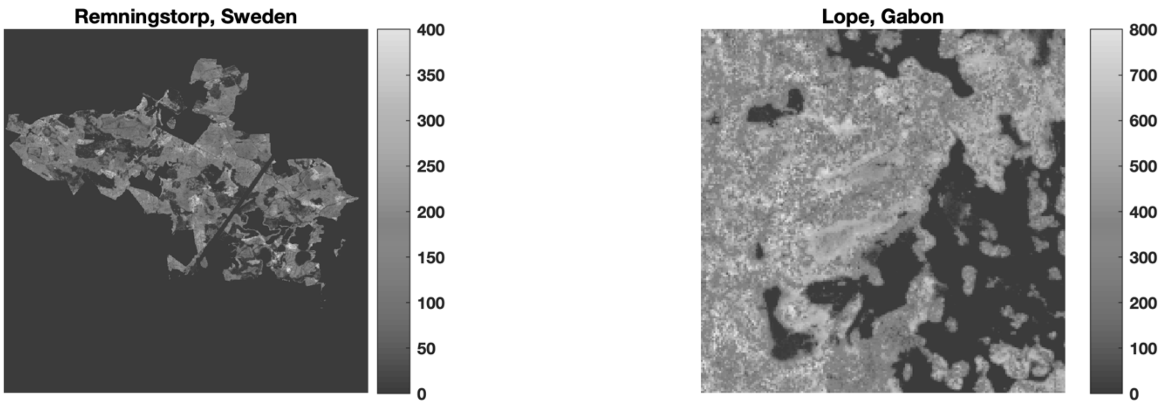


Figure 3-7: AGB maps with a resolution of 20 m × 20 m derived from ALS data acquired over the test sites Remningstorp, Sweden, and Lope, Gabon.

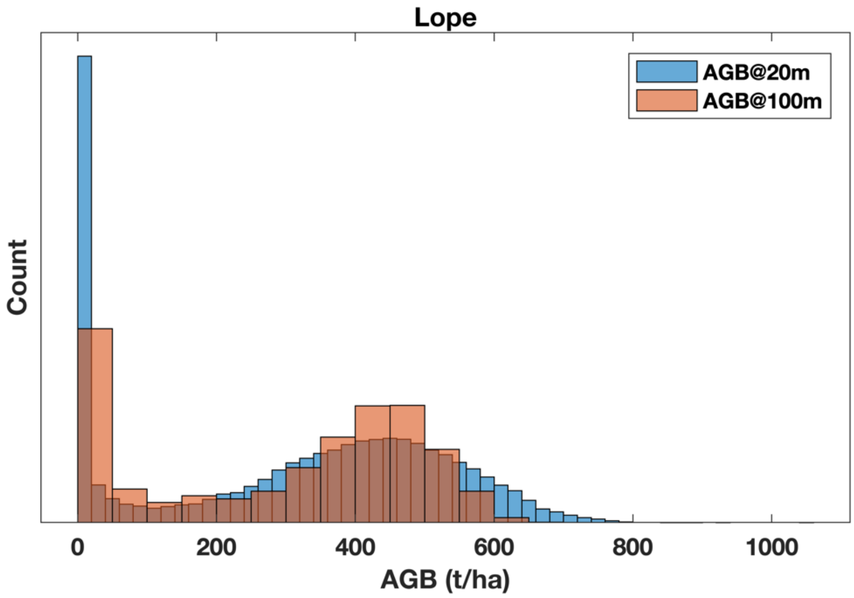


Figure 3-8: Histograms of AGB in Lope at 20 m × 20 m and 100 m × 100 m pixel size.

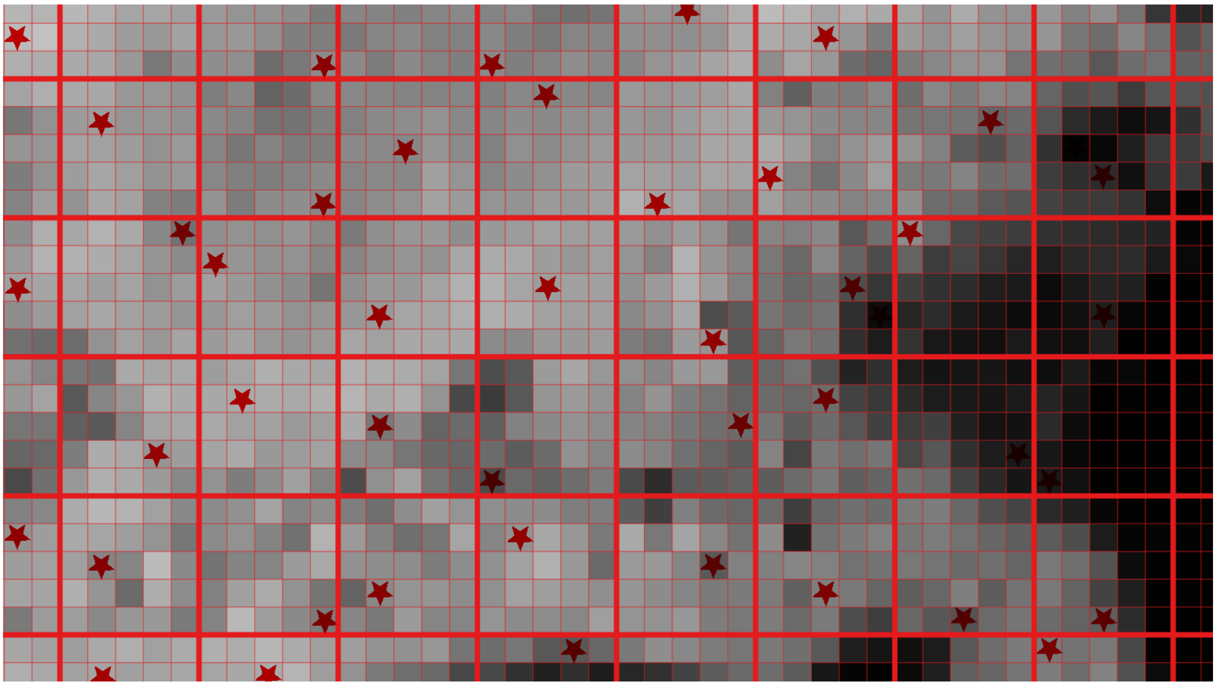


Figure 3-9: 20 m × 20 m pixel grid of an ALS-derived AGB map nested into a 100 m × 100 m pixel grid representing the global AGB map. The 20 m pixels labelled with a star are used to simulate 20 m plot level AGB information for evaluating the errors in the 100 m AGB map.

The ALS AGB maps are used to simulate 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 20 m x 20 m to 100 m x 100 m pixel size. The histograms of AGB at 20 and 100 m scale are illustrated in Figure 3-8 for Lope. The aggregation leads to a reduction in the maximum AGB. At 20 m scale, the maximum AGB is around 800 Mg ha^{-1}, while at 100 m scale AGBs rarely exceed 600 Mg ha^{-1}. Subsequently, any of the 20 m pixels located within a 100 m pixel is treated as if it were a plot used to evaluate the error of the 100 m map. For Lope, plotting the AGB in the 100 m map against a randomly selected 20 m pixel inside each 100 m pixel (indicated in Figure 3-9) yields the scatterplot in Figure 3-10. The RMS error is of order 100 Mg ha^{-1} (30 % of the mean AGB) and there are deviations from the 1:1 line that depend on the AGB level. These deviations are systematic and not limited to a given test site, as is clear when repeating the comparison for 100 random samples of 20 m x 20 m and plotting the 100 m AGB against the 20 m AGB as curves that reflect the mean trend (average 100 m AGB in 20 Mg ha^{-1} intervals of against the 20 m AGB) (Figure 3-11). Despite the 100 m maps simply representing the averaged version of the 20 m map, the comparison suggests that the 100 m map is biased, in that low AGB ranges seem to be overestimated and high AGB ranges underestimated.

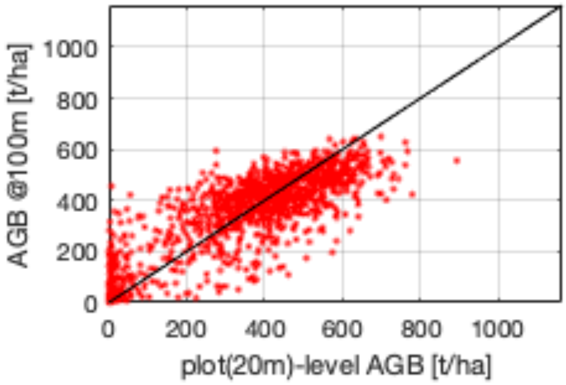


Figure 3-10: AGB estimates at 100 m × 100 m scale vs. sub-pixel random samples of AGB at 20 m × 20 m scale.

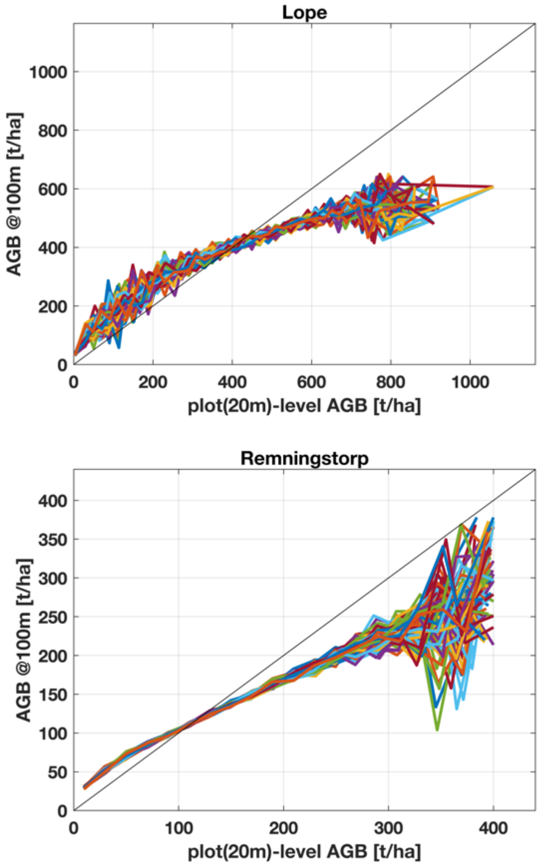


Figure 3-11: 100 m AGB plotted vs. sub-pixel samples of AGB at 20 m scale in Lope and Remningstorp.

This false indication of bias may be compensated by using more than one random sub-sample of 20 m AGB pixels per 100 m AGB pixel (Figure 3-12). Forest inventory data are generally not collected at such high spatial density. However, when, for example, comparing AGB maps with reference AGB information derived from small-footprint LiDAR, such a strategy may be feasible.

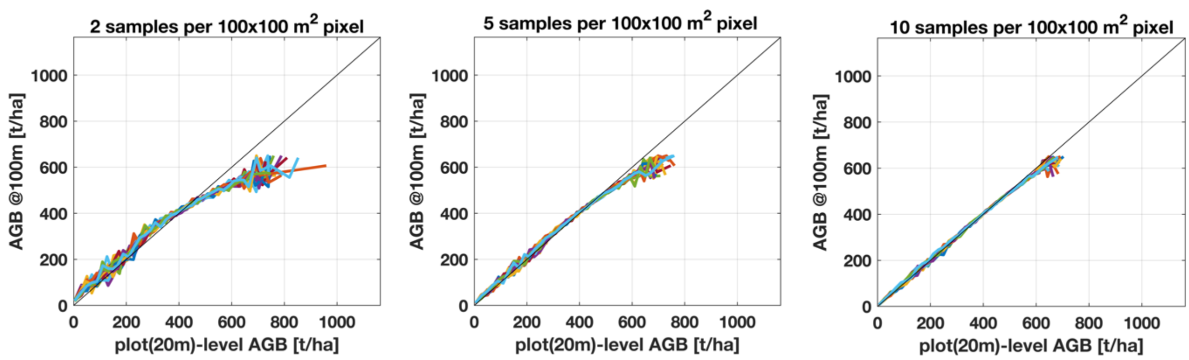


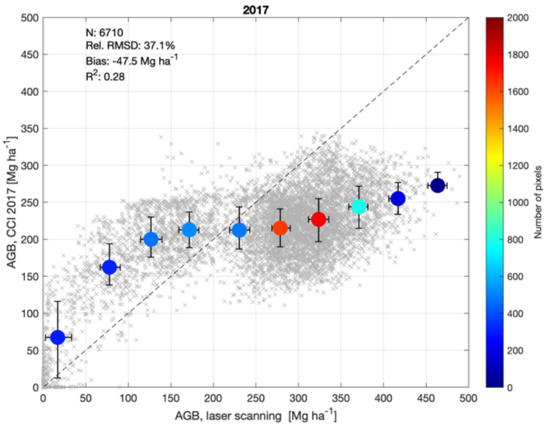
Figure 3-12: 100 m AGB plotted vs. sub-pixel samples of AGB at 20 m in Lope and Remningstorp when averaging for each 100 m AGB pixel more than one (two, five, ten) 20 m AGB pixels.

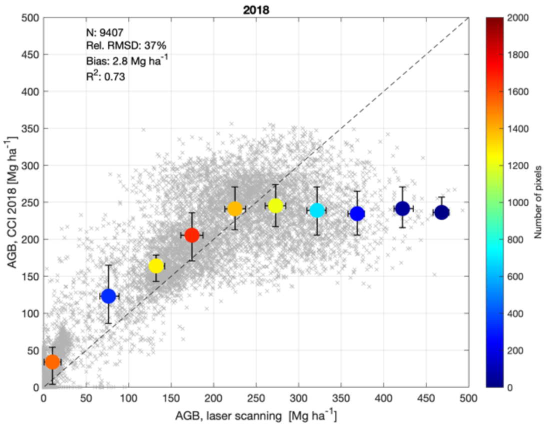
To build up confidence in the CCI BIOMASS AGB estimates, an additional comparison with estimates of AGB from ALS data and part of a dataset of *in situ* measurements of CCI BIOMASS is reported. Data available from the Sustainable Landscapes Brazil project (Longo et al., 2018), the Carbon Monitoring System (CMS) Kalimantan project (Ferraz et al., 2018), the United States National Ecological Observatory Network (NEON) (https://data.neonscience.org/home) program and the Australian Terrestrial Ecosystem Research Network (TERN) (https://www.tern.org.au) were processed to generate LiDAR-based maps of AGB with a pixel size of 100 m x 100 m (courtesy of N. Labriere and J. Chave, CCI BIOMASS consortium). Although laser-based estimates are themselves estimates of AGB and therefore do not qualify as reference data, they cover regions not represented in the plot inventory database and provide valuable indications with respect to potential systematic errors in the AGB retrieved in CCI.

Figure 3-13 shows scatterplots comparing ALS-based and map-based estimates of AGB at the level of individual pixels, each pixel covering 1 ha. To aid interpretation, we also included median values per AGB bin of the ALS-based values and inter-quartile ranges of the map-based AGB per AGB bin. For the Brazilian and U.S. datasets the comparison is undertaken at sites for which LiDAR data were acquired in the same year as the CCI datasets (Brazil: 13 sites in 2017 and 14 in 2018; U.S.: 33 sites in 2017 and 27 in 2018). The CMS dataset of Kalimantan was acquired in 2014 and is compared with the map-based estimates of 2017 (86 sites).

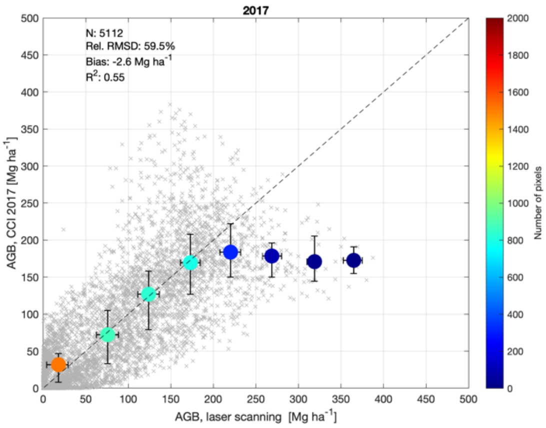
Overall, the spatial distribution of AGB is captured but the scatterplots show large variance of the estimated AGB and, for the tropical sites, a tendency to first over- and then underestimate AGB for increasing AGB. Overestimation typically occurs in mixed landscapes of primary and secondary forest. We associate overestimation with imperfect representation of the maximum AGB, because of the model relating height to AGB that is tailored to undisturbed forest and generalized to represent large geographic areas including multiple types of vegetation structure [RD-3]. Underestimation both in Brazil and Kalimantan is explained by the imperfect model between height and AGB, which in our case was set to predict substantially smaller AGB than the model (based on *in situ* measurements) used to convert the LiDAR top-of-canopy height to AGB. Overall, however, the strong biases that are particularly evident in Kalimantan, are caused by the rather simple modelling framework and the assumptions behind the model training that do not allow capture of the small-scale heterogeneities of the landscape described in Ferraz et al. (2018). For the U.S. sites, the agreement is better than for the tropical sites because of the correctly estimated allometries and, thereof, the maximum AGB. The deviation of the median values of AGB from the identity line above 250 Mg ha^{-1} should not be interpreted as underestimation in the CCI maps because these AGB bins are very scarcely populated. For the Australian sites, the agreement is moderate except for AGB > 500 Mg ha^{-1} where the map underestimates AGB. This result is attributed to the maximum AGB, which was set too low compared to the values estimated from the LiDAR data.

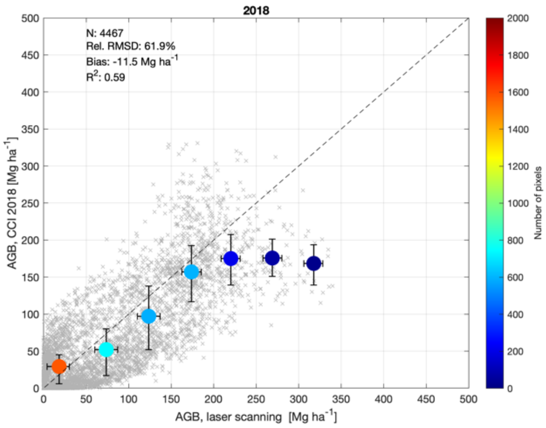
Sustainable Landscapes Brazil



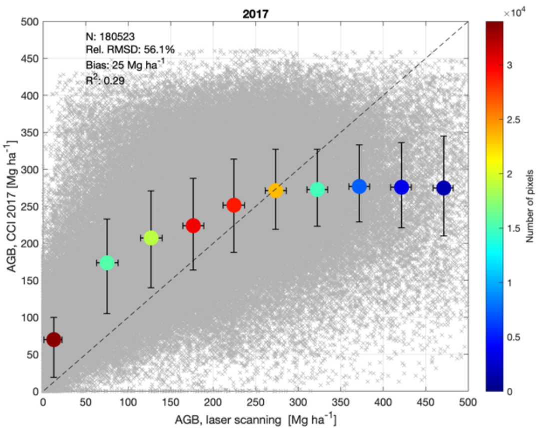


U.S. NEON program





CMS Kalimantan



TERN Australia

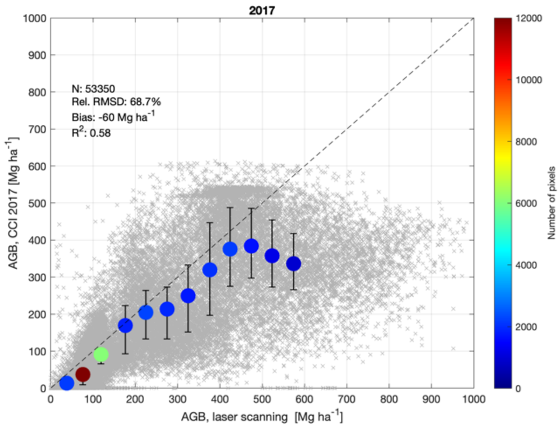


Figure 3-13: Scatterplots comparing LiDAR-based AGB and estimated AGB. The coloured circles and the bars represent the median and inter-quartile ranges of AGB for 50 Mg ha^{-1} wide bins. Retrieval statistics reported in this figure include the number of pixels, relative RMSD, bias and R^2 coefficient of determination.

3.4 Limitations

As a result of the validation process and additional analysis undertaken with averages at administrative level, which were reported in the ATBD [RD-3], the limitations of the CCI BIOMASS datasets of AGB 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 the 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 into the remote sensing image by the data provider. A description of errors affecting the remote sensing data is provided in the ATBD [RD-3]. The effect of local errors can be easily spotted 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.

Local biases

An AGB estimate based on C- and L-band backscatter is prone to errors and large inaccuracy in regions where the backscatter has limited sensitivity to AGB This is typically the case in moderate to high biomass forest (i.e., for large biomass density) and when the environmental conditions alter the SAR backscatter so that the sensitivity to above ground components 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 Envisat ASAR) and L-band backscatter (from ALOS-1/2 and PALSAR-1/2) are used to reduce noise and errors. Still, at the level of a single pixel, the error can be very large. Even aggregates may be biased if the retrieval did not perform well (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 similarly at all locations. We give a summary of areas prone to errors and their explanation below:

- Underestimation in moderate-to-high AGB forest occurs locally. The weak sensitivity of L-band backscatter to moderate-to-high AGB and the conservative rules implemented in the BIOMASAR algorithm to estimate AGB partly explain this [RD-3]. We also identified an issue with the height-to-AGB allometry implemented in the retrieval algorithm, which appears to generate lower or higher AGB estimates than reality, depending on the quality and the number of reference samples available to train the allometric function (e.g., Mexico, Southwest Australia, Tasmania, Croatia, Guyana, Southeast Africa).
- The effect of topography on backscatter and thus on the estimated AGB should have been reduced compared to past mapping efforts. For V4, several SAR datasets were accessible at an unprocessed level so that a rigorous handling of distortions induced by the terrain slope could be applied. This is in contrast to previous versions of the CCI BIOMASS maps that were based on SAR image mosaics where a simpler handling of backscatter distortions was implemented resulting in unnatural backscatter values. Nonetheless, we still observe underestimation in regions characterized by moderate to strong topography (e.g., Nepal) where the models used to compensate for distortions of the SAR backscatter due to sloped terrain may not be optimal.
- Overestimation is seldom and usually a local feature due to an incorrect setting of the model relating AGB to canopy height. Although based on multiple observational datasets [RD-3], the maximum AGB layer does not account for small-scale discontinuities corresponding to transitions in forest cover. The coarse resolution at which the model is currently trained causes it to be locally biased. Continual advances in characterizing the relationship between LiDAR height metrics and AGB will help to improve the structural model implemented in the CCI Biomass retrieval models.

Seams

Seams are unnatural AGB variations that are related to the SAR imagery and correspond to the overlap between adjacent image strips or at the border between image tiles (for mosaics). Seams in the tropics are a consequence of the pre-processing of the L-band datasets undertaken by the Japan Aerospace Exploration Agency (JAXA) [RD-3]. JAXA generated mosaics per orbital cycle. i.e., consisting of images acquired in a time interval of 44 days. Images acquired on different dates, possibly characterized by different environmental conditions, were stitched together to obtain a wall-to-wall coverage within each orbital cycle. When the feathering was sub-optimal, it introduced radiometric offsets between one image and the adjacent one. Although SAR pre-processing tried to reduce such seams [RD-3] and the models used to retrieve AGB are strongly spatially adaptive [RD-3], some of the seams remained at the end of the processing chain. These become visible in regions of weak sensitivity of the backscatter to AGB (e.g., dense tropical forest). Seams appearing in the form of a small radiometric offset (of the order of 0.1-0.2 dB) translate to a clear AGB offset > 10 Mg ha^{-1} and show up as unnatural features (Figure 3-14). One approach to overcome seams would be to flag image strips characterized by radiometric offsets with respect to adjacent strips. This process, however, would be time consuming because it would involve considerable operator intervention.

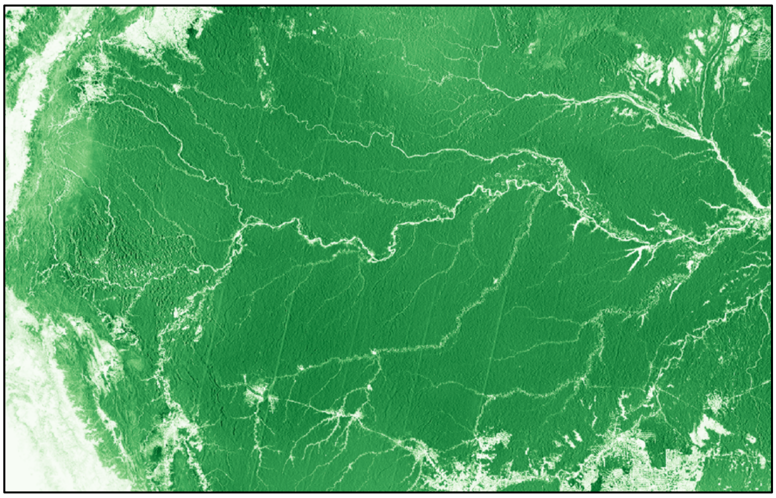


Figure 3-14: Example of seams in the AGB dataset appearing as diagonal bright lines due to image-related issues in the L-band SAR data. AGB in this region (western Amazon) was based on the ALOS-2 PALSAR-2 mosaics only and the seams correspond to the point of intersection of two adjacent strips of data.

The Sentinel-1 datasets were also affected by seams. These are related to incorrect characterization of the noise floor, which comes as part of the image metadata and is subtracted from the original backscatter image. These seams propagate throughout the AGB estimation to the final AGB map in regions where the contribution by the C-band AGB estimates is predominant. Figure 3-15 shows an example of such seams for the Southeast U.S. Similar patterns were also observed over Southeast China.

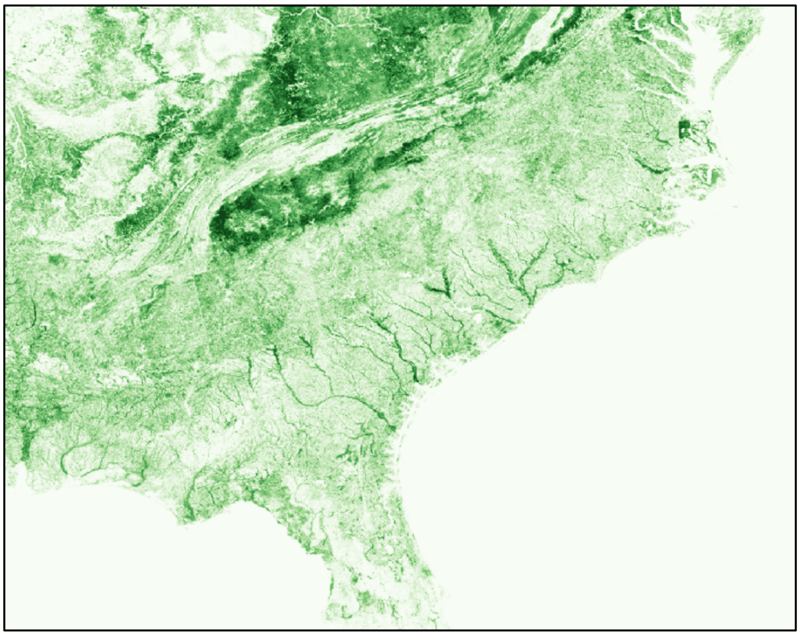


Figure 3-15: Example of seams in the AGB dataset appearing as diagonal bright lines due to image-related issues in the C-band SAR data. AGB in this region (southeast U.S.) was based on the Sentinel-1 images and the seams correspond to the point of intersection of two adjacent strips of data.

Topography

The retrieval of AGB was based on images of SAR backscatter, which are affected by geometric distortions due to the side-looking configuration of the radar instrument. Sloped terrain facing the radar is characterized by stronger backscatter than sloped terrain facing away. If untreated in the pre-processing, this would cause AGB estimates to be systematically higher on the slopes facing the radar. Both the ALOS-1/2 and the ASAR/Sentinel-1 SAR images were treated to compensate for slope-induced distortions of the backscatter [RD-3] and ideally the backscatter after compensation should be the same regardless of the orientation of the terrain. In practice, imperfections in the Digital Elevation Model (DEM) used to mimic the terrain slope and assumptions made to simplify the correction procedure result in a residual slope-induced backscatter error which translates into incorrect AGB values.

Although we have introduced a model-based framework to adjust the backscatter to local incidence angle as a function of canopy cover [RD-3], topography-induced distortions in the map of AGB are still visible whenever the model was not able to capture the relationship between these variables (poor correspondence) or because of errors in the DEM or the canopy cover dataset used as reference. Figure 3-16 shows an example of AGB estimates affected by residual topographic effects. All slopes facing the radar (observing in this case from the left-hand side) have higher AGB than those 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 was undertaken with a simpler approach than in the processing applied to Sentinel-1 data. Given the poor estimates by Sentinel-1 in the wet tropics, it was still preferred to favour the ALOS-2 PALSAR-2 estimates despite topography-induced biases.

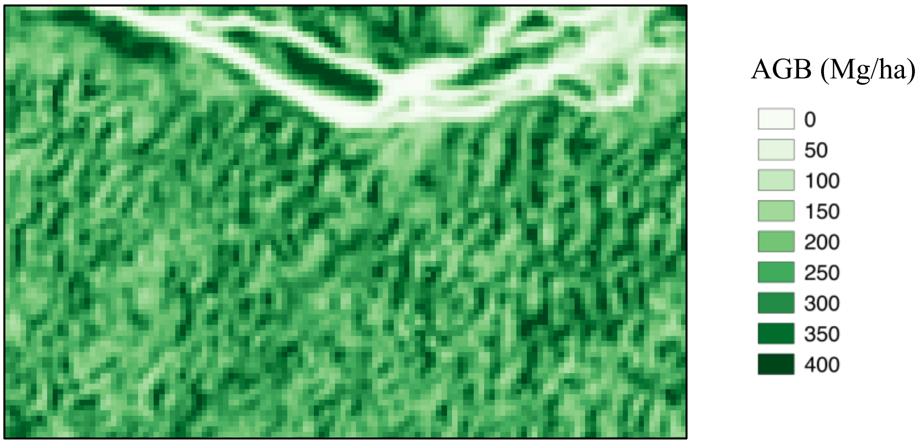


Figure 3-16: Example of topography-induced modulation of AGB estimates (top) and corresponding optical image from Google Earth to be considered as reference for the landscape (bottom). Uncompensated topography caused a variation of up to 200 M g ha^{-1} between slopes facing the radar (light green areas) 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 might be somewhat lower than in reality, which needs to be accounted for when interpreting the averaged AGB maps.

Mangroves and inundated forests

The BIOMASAR algorithms rely on a simplified model (the Water Cloud Model) that describes the behaviour of the SAR backscatter as a function of AGB. The ability of this model to reproduce the relationship between SAR backscatter observations and AGB has been demonstrated in a large variety of forest types. However, when this functional dependence does not hold true, the model is not able to provide correct estimates of AGB. By checking against other datasets of forest variables (canopy height, biomass etc.), we identified a clear modelling issue in mangrove forests. Mangroves often exhibit a strong decrease of backscatter with increasing biomass at L-band, which is the opposite of what the retrieval model predicts. This causes strong underestimation of AGB by BIOMASAR-L. For this reason, the CCI BIOMASS map is set to the estimate by BIOMASAR-C in mangrove forest, according to the mapping by the Global Mangrove Watch dataset (https://www.globalmangrovewatch.org).

In the example of Figure 3-17 the CCI BIOMASS map is compared to an AGB 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 mangrove AGB map and often lies well below the AGB estimated in the latter. Although estimation of AGB from canopy height and regional height-to-biomass allometry appears to be more reliable than the solution implemented in CCI BIOMASS, the lack of a DEM for the epochs targeted by CCI BIOMASS implies that the approach proposed by Simard *et al*. (2019) cannot be implemented. Understanding, however, how signal changes in EO data can be related to the original map by Simard *et al*. (2019) could be a way to provide an updated estimate of AGB for mangroves that avoids such biases. The alternative would be to rely on different models to retrieve AGB specifically in mangrove forests.

The same concept applies to permanently and seasonally inundated forests. The backscatter signals at C- and L-band depend on the presence of standing water below the canopy. Standing water causes an increased trunk-ground backscatter resulting in a different type of relationship between biomass and backscatter. The unavailability of reference data from inundated forests impedes a more detailed assessment of the effect of flooding on the CCI BIOMASS maps. As a consequence of the spatially and temporally dense sets of observations by spaceborne LiDAR missions in recent years, it is, in principle possible to investigate the relationship between radar signals and forest parameters of flooded forests and therefore identify alternative approaches to estimate AGB.

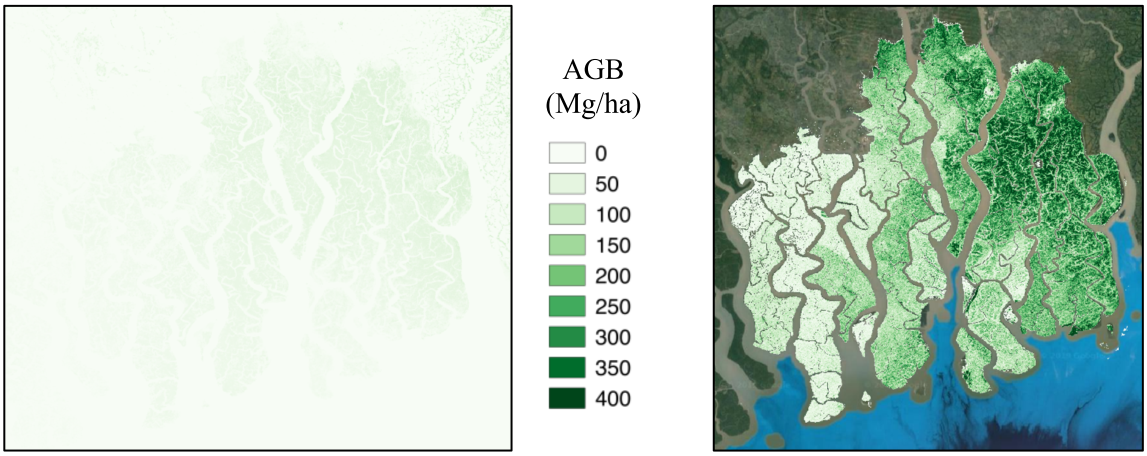


Figure 3-17: Estimates of AGB for mangrove forests of Bangladesh from the CCI BIOMASS dataset of 2010 (left) and the global mangrove AGB dataset for the year 2000 by Simard *et al*. (2019).

4 AGB change maps

The Climate Research Data Package (CRDP) of the CCI BIOMASS defines AGB change products as the difference between AGB maps from two years y_2 and y_1, with $y_2 > y_1$. AGB change is expressed in Mg ha^{-1}. Positive values represent a gain of AGB, negative values represent a loss of AGB.

The standard deviation of the AGB change estimate is defined as the square root of the sum of the variances of the two individual AGB values. The standard deviation is expressed in Mg ha^{-1}.

As a result of the different setting of data available for each year included in the CRDP, a quality flag for the change value is provided. The quality flag expresses whether the AGB histograms associated with a pixel at the two epochs overlap or are disjoint.

Assuming that AGB1 and AGB2 are two estimates at epoch 1 and epoch 2, with epoch 1 prior to epoch 2. The follow scenarios can occur:

- Realistic negative difference (AGB2<<AGB1), i.e., disjoint histograms, corresponding to an AGB loss
- Potential negative difference, loss (AGB2<AGB1) i.e., partially overlapping histograms
- Unreliable magnitude of change, i.e., overlapping histograms

- Potential positive difference (AGB2>AGB1) i.e., partially overlapping histograms
- Realistic positive difference (AGB2>>AGB1), i.e., disjoint histograms, corresponding to an AGB gain

The data products currently provided by the project (year 5, Version 5.0) consist of maps of AGB change and AGB change SD based on EO data acquired in 2010 and 2015 through to 2021. The spatial resolution of the map products is 100 m.

The AGB difference between two epochs is not provided as part of the CCI BIOMASS data package. Users interested in AGB changes between two epochs compute the difference by subtracting one map from the other. The CRDP provides the standard deviation of the AGB difference and the quality flag layer for a selected type of AGB change products.

- Annual change, i.e., 2016-2015, 2017-2016, 2018-2017, 2019-2018, 2020-2019 and 2021-2020
- Decadal change, i.e., 2020-2010

The quality flag layer is stored in byte format and adopts the following legend:

0: AGB=0 in both maps

1: AGB loss

2: Potential AGB loss

3: Improbable change

4: Potential AGB gain

5: AGB gain

With respect to class 3, a pixel is also labelled as improbable change when the conditions leading to a gain are satisfied but the difference is larger than the largest potential growth. For largest potential growth we assumed a value of 10 Mg ha^{-1} year^{-1}, which includes all types of natural forests and most plantations (IPCC, 2019).

It is strongly advised to use the quality flag map of the AGB change product when evaluating the AGB change data products (AGB difference and AGB difference standard deviation)! The AGB change products are indeed characterized by large uncertainties.

Figure 4-1 and Figure 4-2 show a full resolution example of AGB and AGB change data products. The examples refer to a standard 10° x 10° tile as distributed by the CCI BIOMASS project, covering the region of Manaus, Brazil (extent of tile: Lat: 0°N, 10°S; Lon: 60°W, 50°W). In the following, we illustrate the AGB dataset (for 2020 only), the AGB standard deviation (for 2020 only) and the AGB change products for 2020-2019 and 2020-2010.

The AGB dataset shows high AGB in undisturbed tropical forest and low values in areas affected by recent deforestation. The Amazon River crosses the image tile from West to East in the northern part of the tile. The image of the SD shows a constant value of about 50% of the estimated value in intact forests. Lower values are observed in deforested regions. This is a consequence of the better sensitivity of the radar backscatter to AGB in areas of low AGB.

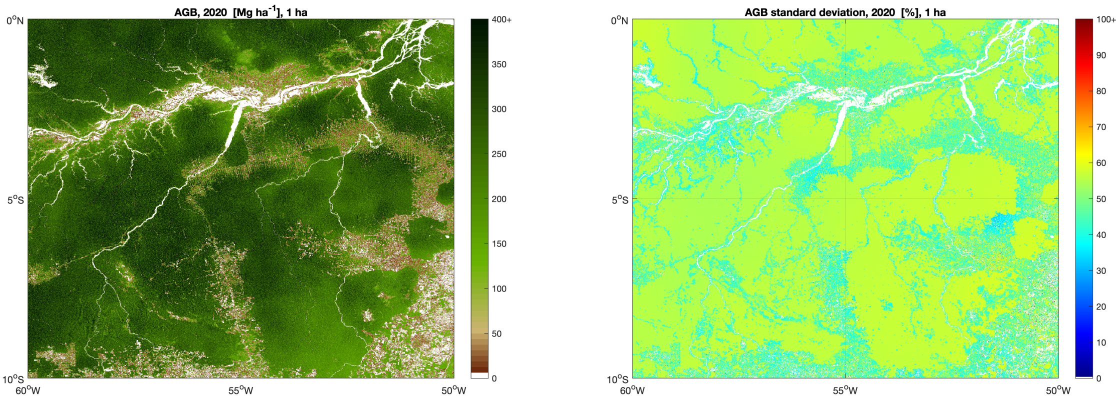


Figure 4-1: AGB (left) and AGB relative SD (right) for 2020. The colour ramps are constrained between 0 and 400 Mg ha^{-1} (AGB) and between 0% and 100% of the estimated AGB (AGB SD) to increase the colour contrast.

By taking the difference of the AGB maps of 2020 and 2019, we obtain the image illustrated in the left panel of Figure 4-2. There is a slight tendency towards positive values, which may either be attributed to growth or to different AGB estimation biases affecting each of the individual maps. The corresponding SD is shown in the right panel of Figure 4-2. The SD of the change is higher than the AGB SDs because variances add. Since the overall SD is mostly above 100% of the estimated change, the SD layer already provides a clear indication of the reliability of the AGB changes. The quality flag in Figure 4-3 gives more direct evidence of the reliability of the AGB change map in Figure 4-2. Most pixels (practically all in intact forests) are labelled as improbable change, meaning that either the distribution of the AGB estimates at the two epochs strongly overlap or the difference is larger than the largest potential growth. AGB losses and gains are concentrated in areas affected by deforestation (Figure 4-3).

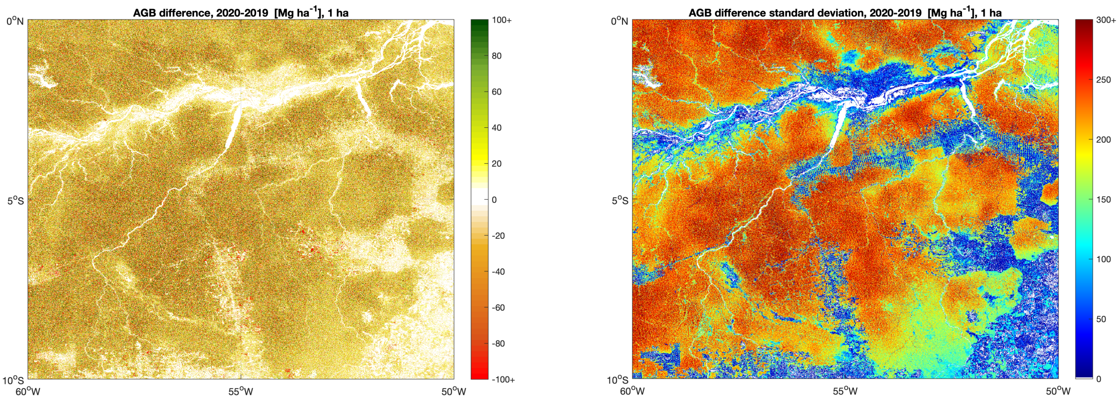


Figure 4-2: AGB change (left) and corresponding SD (right) between 2019 and 2020. AGB change is defined as difference between AGB maps of 2020 and 2019. The colour ramps are constrained between -/+100 Mg ha^{-1} (AGB change) and between 0% and 300% (AGB change SD) to increase the colour contrast.

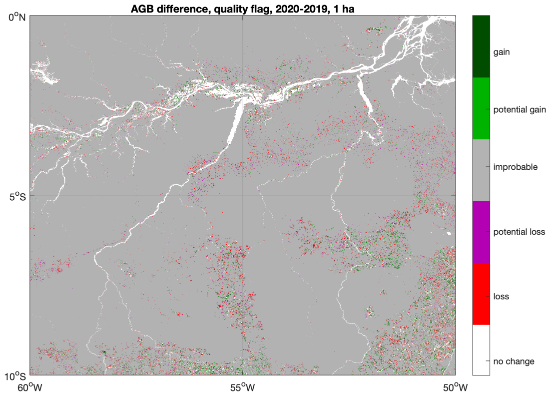


Figure 4-3: Quality flag of AGB change between 2019 and 2020.

The relevance of the quality flag becomes clearer when interpreting the AGB changes between 2010 and 2020 (Figure 4-4). As a result of the different EO datasets, the difference (even in intact forests) is large and corresponds to a change of AGB between 2010 and 2020 of +/- 40 Mg ha^{-1} which is unrealistic. The largest differences occur at the edges of forests affected by deforestation, which is more realistic. The AGB change SD (Figure 4-4) is large but, in principle, not too large to be able to interpret the AGB change correctly in areas affected by true changes. The quality flag (Figure 4-5) provides clear indications that most of the changes are improbable, because the difference was larger than the maximum increment allowed by growth. The quality flag indicates that AGB losses and gains occur in areas of ongoing deforestation. A gain of AGB in these areas is often associated with an increase of AGB from 0 to a very low biomass.

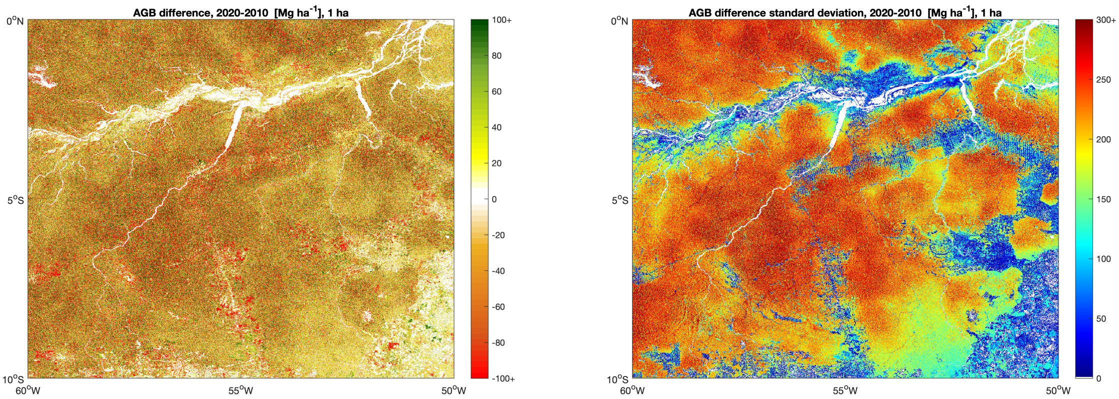


Figure 4-4: AGB change (left) and corresponding SD (right) between 2010 and 2020. AGB change is defined as difference between AGB maps of 2020 and 2010. The colour ramps are constrained between -/+100 Mg ha^{-1} (AGB change) and between 0% and 300% (AGB change SD) to increase the colour contrast.

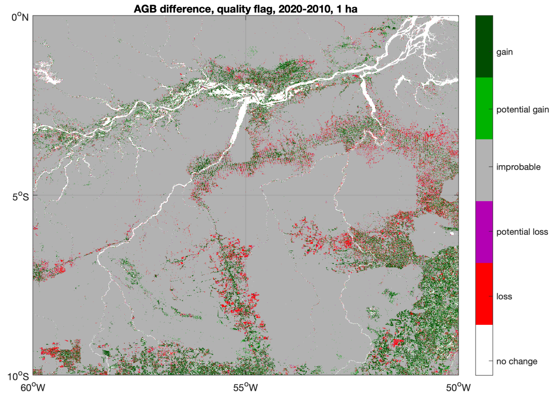


Figure 4-5: Quality flag of AGB change between 2010 and 2020.

Specifications of data products

Current version: V5.

Spatial coverage: Global.

Validity of estimates: Estimates have been generated for each point on Earth for which the remote sensing data were available.

AGB change expresses the difference of AGB values for two different years.

The SD of the AGB change dataset is obtained from the SDs of the two maps being differenced.

The quality flag of the AGB change expresses the reliability of a change value and is derived from the AGB and AGB SD values of the two maps being differenced.

Reference system: Lat-long, WGS-84.

Corner coordinates: top left corner of pixel.

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

Timeframe: annual change estimate for 2016-2015, 2017-2016, 2018-2017, 2019-2018, 2020-2019, 2021-2020 and decadal change estimate for 2020-2010.

Data format: NetCDF (one global file per change dataset) and GeoTiff (10° × 10° tiles for each change dataset)

Format of the NetCDF file

Naming Convention

The CRDP provides the SD and the quality flag of the AGB change maps. The AGB change maps can be generated from the original AGB maps by taking their difference.

The filename convention of the global AGB change SD and quality flag maps delivered by the CCI BIOMASS project is the following:

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

where <id> = <project>-<level>-<var>-<spatres>-<epoch1>-<epoch2>

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 4-1.

Table 4-1: Elements of the NetCDF file name of the CCI BIOMASS AGB change SD and quality flag data products 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-CHANGE
spatres	Spatial resolution	100 m (constant)
epoch1	Year 2	2015, 2016, 2017, 2018, 2019, 2020 or 2021
epoch2	Year 1	2010, 2015, 2016, 2017, 2018, 2019 or 2020
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 names of the global AGB maps in NetCDF format distributed with the current CRDP are:

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2016-2015-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2017-2016-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2018-2017-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2019-2018-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2020-2019-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2021-2020-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-CHANGE-100m-2020-2010-fv5.0.nc

Each NetCDF file contains the AGB_DIFF_SD (16-bit integer), AGB_DIFF_QF (8-bit), latitude (64-bit floating point), longitude (64-bit floating point) and time (64-bit floating point) information.

Format

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

Metadata

The metadata are provided as global attributes in the NetCDF file. The metadata follow the CCI guidelines (ESA Climate Office, 2019).

Estimated size

The size of each dataset in NetCDF format is approximately 11 GB.

Format of the GeoTiff tiles

Naming Convention

The filename convention of the AGB change SD and AGB change quality flag tiles delivered by the CCI BIOMASS project is the following:

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

where <id> = <N/S flag><Latitude><E/W flag><Longitude>_<project>-<level>-<var>-<code>-<spatres>-<epoch1>-<epoch2>

The dash "-" is the separator between name components. The different name components are defined in Table 4-2.

For the specific case of a tile covering the area between (60°N, 40°E) and (50°N, 50°E), the file names of the AGB change SD and QF maps in GeoTiff format distributed with the current CRDP are:

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2016-2015-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2017-2016-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2018-2017-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2019-2018-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2020-2019-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2021-2020-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_QF-100m-2020-2010-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2016-2015-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2017-2016-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2018-2017-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2019-2018-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2020-2019-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2021-2020-fv5.0.tif

N60E040_ESACCI-BIOMASS-L4-AGB-MERGED-DIFF_SD-100m-2020-2010-fv5.0.tif

Table 4-2: Elements of the GeoTiff file name of the CCI BIOMASS AGB and AGB SD data products delivered by the CCI BIOMASS project.

Field	Signification	Value
N/S flag	North/South hemisphere of northernmost row in the tile	N or S
Latitude	Northernmost latitude coordinate of tile	Integer (2 digits, between 00 and 80)
E/W flag	East/West hemisphere of westernmost column in the tile	E or W
Project	Westernmost longitude coordinate of tile	Integer (3 digits, between 0 and 180)
Project	Project acronym	ESACCI- BIOMASS (constant)
Level	Processing level	L4 (constant)
Var	Unit of the product	AGB-MERGED-DIFF (constant)
code	Product code identifier	SD or QF
spatres	Spatial resolution	100 m (constant)
epoch1	Year 2	2015, 2016, 2017, 2018, 2019, 2020 or 2021
epoch2	Year 1	2010, 2015, 2016, 2017, 2018, 2019 or 2020
version	Incremental, following the successive revisions of the CCI-BIOMASS processing lines	Version of product revision, preferably major.minor, optionally with processing centre [a-zA-Z0-9._]*

Estimated size

For each of the change maps, the Geotiff dataset consists of approximately 11 GB of AGB change SD estimates and 11 GB of AGB change QF estimates.

Format

Short unsigned integer (uint16).

5 Aggregated maps

Aggregation consists of spatial averaging of the CCI BIOMASS AGB maps to a coarser spatial scale. The aggregated AGB value corresponds to the mean value of all pixel values within the averaging window. The standard error of the average is obtained from the standard deviations of the AGB estimates. It consists of a variance and a covariance component that are summed. The latter accounts for spatial correlation of errors, which were estimated from airborne LiDAR datasets of AGB [RD-4].

Aggregation is implemented in a Matlab tool available on demand. Input consists of the 10° × 10° tiles of AGB for a given year. The user specifies the target spatial resolution of the aggregated map in km. The tool currently supports only square averaging windows, i.e., it is not possible to specify different averaging factors for longitude and latitude. The output consists of a mosaic of all AGB tiles specified in input averaged to the target resolution and the corresponding map of standard error. The units are Mg ha^{-1}. The averages correspond to AGB per pixel area. The use of a forest mask to provide AGB per forest area is currently not supported.

As the computation of the AGB standard error is computationally intense, CCI BIOMASS provides AGB averages for target resolution of 1 km, 10 km, 25 km and 50 km. Starting with v5, the aggregated AGB and AGB change products are also released through the official channel of distribution, i.e., the CCI Open Data Portal (see Section 8). Figure 5-1 shows the AGB maps and the corresponding standard errors for the 0.1° and 0.5° (i.e., 10 km and 50 km) target resolutions. Aggregation reduces the spatial variability of AGB, but it does not alter the spatial distribution. The precision of the AGB estimates increases with the level of aggregation, being mostly below 30 % of the estimated AGB at 10 km. At 0.5°, the standard error reduces below 15 %. Higher values are obtained in sparsely vegetated regions or unvegetated regions because of the very low AGB here.

An example of aggregated AGB change maps is illustrated in Figure 5-2 for 2020-2010 together with the SD and the quality flag. The AGB difference does not differ, apart from extreme values that are averaged out at coarse resolution, but its SD decreases with the aggregation level. Accordingly, a larger proportion of pixels was allocated to either gain or loss of AGB, apart from dense intact tropical forests where the SD of the original AGB estimates was large and the estimated difference was small over the 10 years.

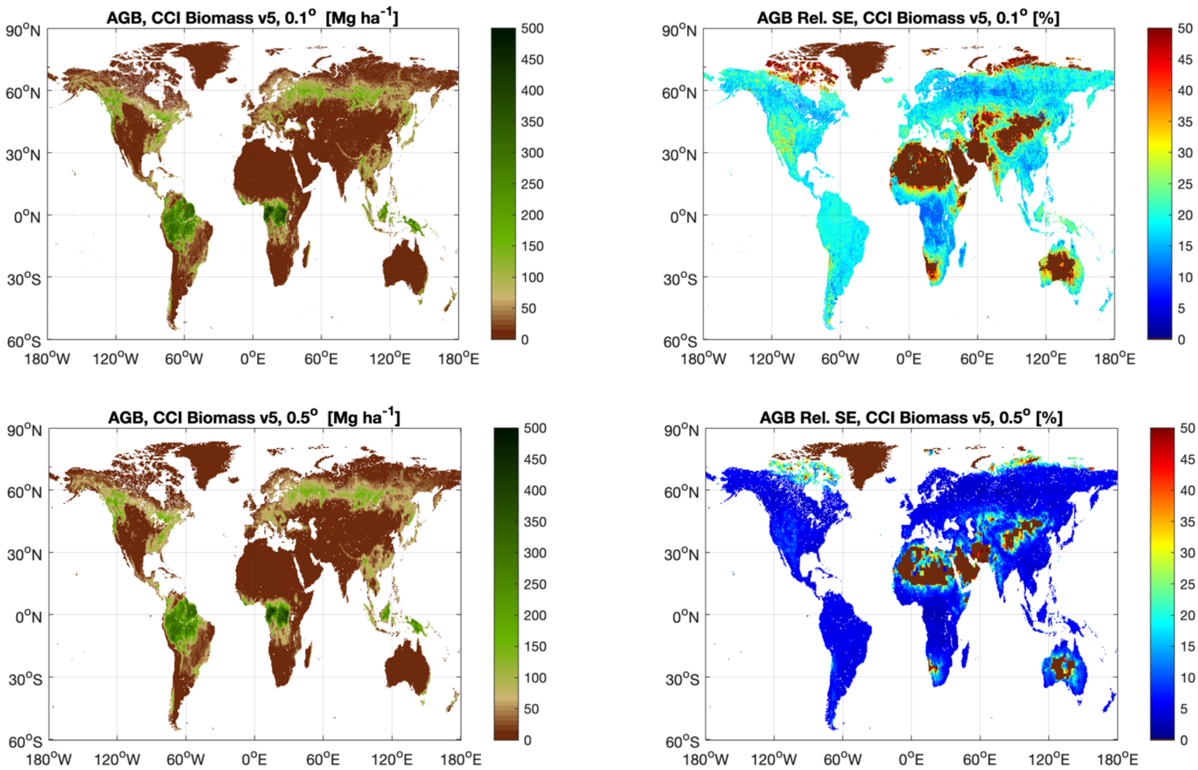


Figure 5-1: Maps of AGB (left) and AGB standard error relative to the AGB value (right) at 0.1° (top) and 0.5° (bottom) obtained by spatial averaging the CCI BIOMASS maps of 2020.

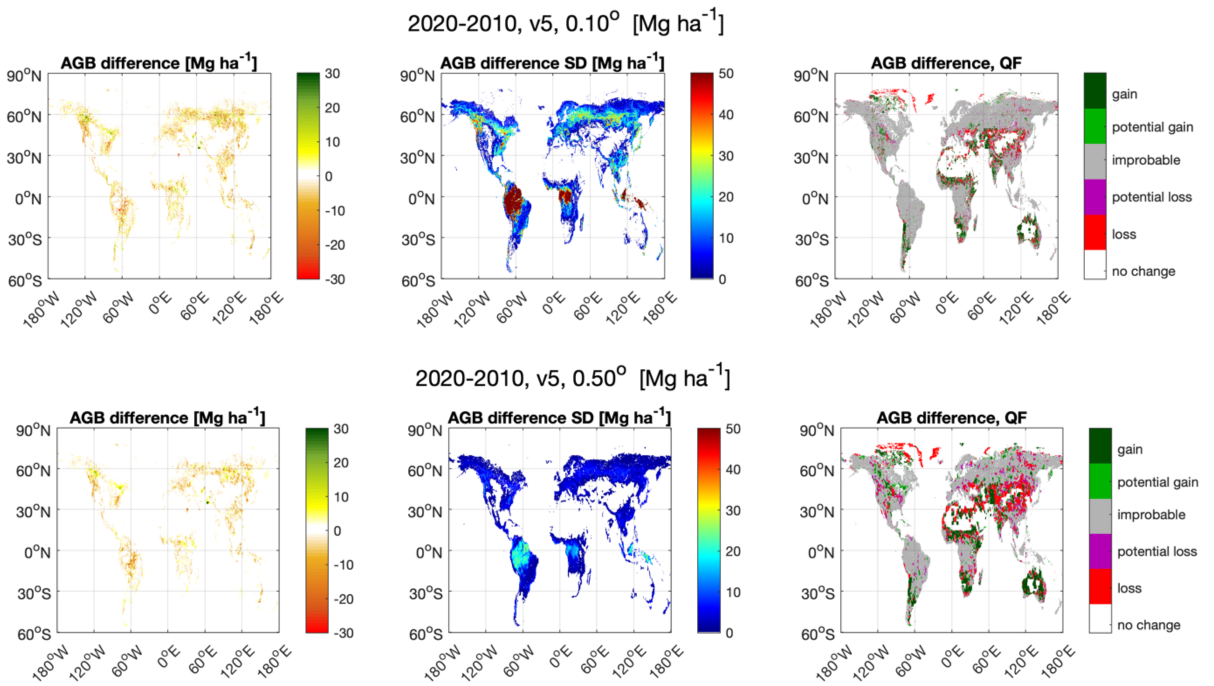


Figure 5-2: Maps of AGB change (left), corresponding standard deviation (middle) and quality flag (right) at 0.1° (top) and 0.5° (bottom) obtained by spatial averaging the CCI BIOMASS AGB maps of 2020 and 2010 and taking their difference.

5.1 Specifications of AGB data products

Current version: V5.

Spatial coverage: Global.

Reference system: Lat-long, WGS-84.

Corner coordinates: top left corner of pixel.

Pixel spacing: The AGB and AGB SD estimates are provided with a pixel spacing of 0.01°, 0.1°, 0.25° and 0.5°

Timeframe: annual (average) estimate for 2010, 2015, 2016, 2017, 2018, 2019, 2020 and 2021

Data format: NetCDF (one global file with all years) and GeoTiff (one global file with all years)

Format of the NetCDF file

Naming Convention

The filename convention follows the same convention of the full resolution data product.

The file names of the global AGB maps in NetCDF format distributed with the current CRDP are:

ESACCI-BIOMASS-L4-AGB-MERGED-1000m-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-10000m-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-25000m-fv5.0.nc

ESACCI-BIOMASS-L4-AGB-MERGED-50000m-fv5.0.nc

Each NetCDF file contains the AGB (16-bit integer), AGB_SD (16-bit integer), latitude (64-bit floating point), longitude (64-bit floating point) and time (64-bit floating point) information.

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. The metadata follow the CCI guidelines (ESA Climate Office, 2019).

Estimated size

The size of the AGB dataset, including the SD layer, in NetCDF format is approximately 1 GB for the 0.01° dataset and less than 1 MB for the 0.5° dataset.

Format of the GeoTiff tiles

Naming Convention

The filename convention of the AGB and AGB SD tiles delivered by the CCI BIOMASS project is the following:

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

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

The dash "-" is the separator between name components. The different name components are defined in Table 5-1.

The file names of the AGB maps in GeoTiff format distributed with the current CRDP are:

ESACCI-BIOMASS-L4-AGB-MERGED-1000m-fv5.0.tif

ESACCI-BIOMASS-L4-AGB-MERGED-10000m-fv5.0.tif

ESACCI-BIOMASS-L4-AGB-MERGED-25000m-fv5.0.tif

ESACCI-BIOMASS-L4-AGB-MERGED-50000m-fv5.0.tif

Accordingly, the file names of the SD layer are:

ESACCI-BIOMASS-L4-AGB_SD-MERGED-1000m-fv5.0.tif

ESACCI-BIOMASS-L4-AGB_SD -MERGED-10000m-fv5.0.tif

ESACCI-BIOMASS-L4-AGB_SD -MERGED-25000m-fv5.0.tif

ESACCI-BIOMASS-L4-AGB_SD -MERGED-50000m-fv5.0.tif

Table 5-1: Elements of the GeoTiff file name of the CCI BIOMASS aggregated AGB and AGB SD data products 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 or AGB_SD
code	Product code identifier	MERGED (constant)
spatres	Spatial resolution	1000 m, 10000 m, 25000 m or 50000 m
version	Incremental, following the successive revisions of the CCI-BIOMASS processing lines	Version of product revision, preferably major.minor, optionally with processing centre [a-zA-Z0-9._]*

Estimated size

The Geotiff dataset consists of approximately 10 GB of AGB estimates and 10 GB of AGB SD estimates at 0.01° and less than 1 MB at 0.5°.

Format

Short unsigned integer (uint16).

Format of the data product – additional information

Additional information on the data products is reported below. This information is independent of the format in which the maps are stored.

Product layers

AGB and AGB SD. Both are expressed in Mg ha^{-1}.

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 of the AGB corresponds to a number expressed in Megagrams per hectare (Mg ha^{-1}). Valid AGB values are between 0 and 10,000 Mg/ha.

Each pixel value of the AGB SD corresponds to a number expressed in Megagrams per hectare (Mg ha^{-1}). Valid AGB SD values are between 0 and 10,000 Mg/ha.

Spatial Extent

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

Spatial Resolution

- 0.01°, corresponding to nearly 1,000 m at the Equator
- 0.1°, corresponding to nearly 10,000 m at the Equator
- 0.25°, corresponding to nearly 25,000 m at the Equator
- 0.5°, corresponding to nearly 50,000 m at the Equator

Temporal resolution

Annual

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.

5.2 Specifications of AGB change data products

Current version: V5.

Spatial coverage: Global.

Reference system: Lat-long, WGS-84.

Corner coordinates: top left corner of pixel.

Pixel spacing: The AGB change, AGB change SD and AGB change quality flag estimates are provided with a pixel spacing of 0.01°, 0.1°, 0.25° and 0.5°

Timeframe: estimates for 2016-2015, 2017-2016, 2018-2017, 2019-2018, 2020-2019, 2021-2020 and 2020-2010.

Data format: NetCDF (one global file with all variables for each difference dataset) and GeoTiff (one global file with all years for each variable)

Format of the NetCDF file

Naming Convention

The file names of the global AGB change maps in NetCDF format distributed with the current CRDP are:

ESACCI-BIOMASS-L4-DIFF-1000m-2016-2015-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-1000m-2017-2016-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-1000m-2018-2017-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-1000m-2019-2018-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-1000m-2020-2019-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-1000m-2021-2020-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-1000m-2020-2010-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2016-2015-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2017-2016-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2018-2017-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2019-2018-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2020-2019-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2021-2020-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-10000m-2020-2010-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2016-2015-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2017-2016-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2018-2017-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2019-2018-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2020-2019-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2021-2020-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-25000m-2020-2010-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2016-2015-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2017-2016-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2018-2017-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2019-2018-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2020-2019-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2021-2020-fv5.0.nc

ESACCI-BIOMASS-L4-DIFF-50000m-2020-2010-fv5.0.nc

Each NetCDF file contains the AGB change (16-bit integer), AGB change SD (16-bit integer), AGB change QF, latitude (64-bit floating point), longitude (64-bit floating point) and time (64-bit floating point) information.

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. The metadata follow the CCI guidelines (ESA Climate Office, 2019).

Estimated size

The size of each file in NetCDF format is approximately 100 MB for the 0.01° dataset and less than 1 MB for the 0.5° dataset.

Format of the GeoTiff tiles

Naming Convention

The file names of the AGB change maps in GeoTiff format distributed with the current CRDP are:

ESACCI-BIOMASS-L4-DIFF-1000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF-10000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF-25000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF-50000m-fv5.0.tif

Accordingly, the file names of the SD and QF layers are:

ESACCI-BIOMASS-L4-DIFF_SD-1000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_SD-10000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_SD-25000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_SD-50000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_QF-1000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_QF-10000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_QF-25000m-fv5.0.tif

ESACCI-BIOMASS-L4-DIFF_QF-50000m-fv5.0.tif

Estimated size

The Geotiff dataset consists of approximately 1 GB at 0.01° and less than 1 MB at 0.5°.

Format

Short unsigned integer (uint16).

Spatial Resolution

- 0.01°, corresponding to nearly 1,000 m at the Equator
- 0.1°, corresponding to nearly 10,000 m at the Equator
- 0.25°, corresponding to nearly 25,000 m at the Equator
- 0.5°, corresponding to nearly 50,000 m at the Equator

Temporal resolution

Annual

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.

6 Usage and release notes

The current release of the CCI BIOMASS data products is version 5, available through the CCI Open Data Portal (https://climate.esa.int/en/odp/#/dashboard). Older versions are superseded. Datasets available on other platforms may be older or unofficial versions of the most recent official release.

Users should consider the following usage and release notes:

<u>AGB maps</u>

- The AGB and AGB change maps are not masked for forest. Users wishing to derive statistics for forest land are advised to apply an own forest/non-forest dataset to the CCI BIOMASS data products.
- A pixel with a value equal to 0 means that the AGB is equal to 0 Mg ha^{-1}.
- The AGB and AGB change values are representative of the pixel area, i.e., they do not account for partial or total forest cover within the area of the pixel. The biomass stock in a pixel is obtained from the AGB value multiplied by the area of the pixel (NOTE: the area of the pixel changes with latitude)

- AGB refers to the aboveground LIVE dry biomass. However, given that AGB is derived from radar backscatter observations, which are sensitive to wood density, it is likely that values larger than 0 Mg ha^{-1} occur corresponding to dead standing wood.
- Shrublands/grasslands are in principle not accounted for. All AGB estimates were obtained with a retrieval model tailored to relate the radar backscatter to the biomass of woody vegetation.
- The AGB of understory and lianas is not accounted for because it is assumed that the remote sensing data used to estimate AGB does not contain sufficient signal scattered from layers below the top canopy.
- Use of the AGB estimates of individual full resolution pixels should be avoided.
- The maps have a global scope and may, therefore, be biased at regional level. Users intending to adopt the CCI BIOMASS data product for national or sub-national studies are advised to check the quality of the CCI product by comparing with local data (e.g., from own field survey, National Forest Inventory (NFI), airborne datasets etc.).
- The CCI BIOMASS datasets have not been cross-checked with other CCI datasets.
- The AGB in each annual map corresponds to an average value for the corresponding year. Consequently, the AGB value corresponding to areas that have been affected by changes within a given year may not be representative of the AGB either before or after the change.
- The annual maps for 2017, 2018, 2019, 2020 and 2021 are equally reliable and supersede any previous release.
- The annual maps of 2015 and 2016 have different quality with respect to later years because of the smaller number of satellite observations.
- The 2010 dataset is an improved version of the GlobBiomass AGB dataset (http://globbiomass.org), which is superseded.
- The 2010 dataset may present AGB > 0 in contrast to AGB = 0 in more recent years corresponding to non-forest areas. This is due to the lower quality of the EO data used to estimate AGB in 2010. Users are advised to mask out non-forest areas to avoid incorrect interpretation of temporal trends.
- Fluctuations of the AGB values from one year to the next may occur in mixed landscapes, cropland and arid land due to the inter-annual variability of the number of radar observations.
- Trends in the time series of AGB maps have not been analysed and may therefore need to be critically investigated, in particular when comparing 2010 with more recent years because of the different set of EO observations.

<u>AGB change maps</u>

- AGB change maps are not provided *per se*. Users interested in an AGB change map between two years need to download the AGB maps for the two years of interest and compute the difference.
- For annual intervals and the decadal intervals 2010 vs. 2020, the CCI Biomass CRDP provides the standard deviation of the change value and a quality flag to interpret the reliability of the change value. For other combination of years, please contact the data producer via email santoro@gamma-rs.ch.
- The AGB change maps should be interpreted carefully. It is strongly advised to use the quality flag layer to understand the reliability of the AGB change values. AGB change values corresponding to pixels labelled as “improbable change” may be unrealistic. AGB change

values in corresponding to pixels labelled as “gain” or “loss” are realistic although the standard deviation layer of the AGB change map should be accounted for as well.

- Be extremely cautious when using the CCI BIOMASS maps to assess AGB changes. We strongly advise that changes be validated before further analysis of the data.

Aggregated data products

- AGB and AGB standard error values are for the pixel area.
- AGB change values at coarser resolution are derived from the aggregated AGB maps by differencing. The standard error of the AGB change map is obtained by summing the square of the AGB standard error maps and taking the square root. The quality flag layer for the AGB change at coarse resolution follows the definition proposed in this document.

7 Version updates

7.1 Baseline (V1)

V1 consisted of a map of AGB for the year 2017.

It was derived with the GlobBiomass approach (Santoro et al., 2021). The retrieval inverted a physical model that related canopy density and canopy height to the SAR backscatter. Canopy height and canopy density were replaced with an empirical function relating to forest growing stock volume (GSV). GSV was estimated separately from SAR backscatter at C- band (multi-temporal observations) and L-band (single mosaic dataset) separately. The two GSV maps were merged to a single map. AGB was estimated from GSV with a global raster of Biomass Conversion and Expansion Factors (BCEF). Validation reported systematic underestimation of AGB in high AGB forest (> 250 Mg ha^{-1}) and frequent overestimation in low AGB forest (< 50 Mg ha^{-1}).

7.2 V1 to V2

V2 consisted of three maps of AGB for the years 2010, 2017 and 2018.

In the CCI BIOMASS retrieval algorithm, direct estimation of AGB was implemented. Allometries linking canopy density, canopy height and AGB were developed and replaced the (i) empirical models relating the former to GSV and (ii) the conversion from GSV to AGB. The allometries were based on spaceborne LiDAR observations (ICESat GLAS) and AGB values from v1 of the CCI BIOMASS dataset. This approach reduced underestimation in high AGB forest compared to v1. Nonetheless, the inhomogeneous distribution of LiDAR footprints implied that the allometries were unevenly characterized. Validation indicated underestimation in high AGB forest whenever the allometry was not realistic or the constraint on the maximum retrievable AGB was set incorrectly.

7.3 V2 to V3

V3 consisted of an update of the three maps of AGB for the years 2010, 2017 and 2018 and prototype maps of AGB change for 2018-2017 and 2018-2010.

The CCI BIOMASS retrieval algorithm was consolidated and the allometries were revised thanks to recent spaceborne LiDAR data from the GEDI and ICESat-2 missions. A more precise characterization of the allometries allowed a more correct estimate of the maximum retrievable AGB, which resulted in smaller local biases than V2. The pool of remote sensing data included multi-temporal observations at L-band for the tropics for 2017 and 2018, which also improved the accuracy of the estimates compared to v2. Validation indicated over- and underestimation in regions where the allometry was not realistic. The poorer quality of the EO dataset for 2010 implied that the estimates of AGB were affected by different biases. The bias of the 2010 dataset was larger than for 2017 and 2018. Consequently, the estimates of AGB change were mostly improbable and the use of the AGB maps to quantify AGB changes was discouraged.

7.4 V3 to V4

V4 consists of an update of the three maps of AGB for the years 2010, 2017 and 2018, to which AGB maps for 2019 and 2020 have been added. AGB change maps have been created for annual intervals (2018-2017, 2019-2018 and 2020-2019) and for a decadal interval (2020-2010). An aggregation tool to generate AGB maps at coarser spatial resolution has been created and maps of average AGB and corresponding AGB changes are made available at some selected spatial scales.

The allometries were further revised by including a longer record of spaceborne LiDAR data from the GEDI and ICESat-2 missions, and by replacing AGB from a map product with statistics based on data collected by National Forest Inventories. Temporal information now aids the merging of C- and L-band AGB estimates towards a more reliable sequence of AGB values in time. The pool of remote sensing data now includes multi-temporal observations at L-band for all biomes and for all years. Validation indicates that biases occurring in V3 were corrected for. Validation indicated over- and under-estimation in regions were the allometry was not realistic, pointing to areas of future research. Each map is affected by local biases, which differ in space because of the different types of EO datasets used for 2010 and for 2017-2020. The estimates of AGB change at the original resolution of the maps are mostly improbable and the use of the AGB maps to quantify AGB changes is discouraged. The reliability of AGB values and AGB change values increases with increasing aggregation level.

7.5 V4 to V5

V5 consists of an update of the AGB maps release in the previous version and new maps for the years 2015, 2016 and 2021. AGB change maps have been created for annual intervals (2016-2015, 2017-2016, 2018-2017, 2019-2018, 2020-2019 and 2021-2020) and for a decadal interval (2020-2010). An aggregation tool to generate AGB maps at coarser spatial resolution has been created and maps of average AGB and corresponding AGB changes are made available at some selected spatial scales.

The function relating AGB with canopy height was further revised after including a longer record of spaceborne LiDAR data from the ICESat-2 mission and checking the AGB statistics based on data collected by National Forest Inventories. The use of temporal information aiding the merging of C- and L-band AGB estimates has been reinforced. Validation indicates that several biases occurring in previous versions were reduced. Validation indicated, however, that the maps are still affected by underestimation, which occurs in regions were the constraint on maximum retrievable AGB is not well predicted. This prediction is either due to an incorrect setting of the maximum height (because of undersampling or incorrect filtering of the ICESat-2 data) or to deficiencies in the structural model relating canopy height to AGB because too generalized. For a few regions characterized by underestimation, the caveat was found in the simple formulation of the retrieval rules. Each map is affected by local biases, which differ in space because of the different types of EO datasets used for 2010 and for 2015-2021. The estimates of AGB change at the original resolution of the maps are confirmed to be mostly improbable and the use of the AGB maps to quantify AGB changes is discouraged. The reliability of AGB values and AGB change values increases with increasing aggregation level.

8 Data access and policy

The CCI BIOMASS products are made available through the CCI data portal (https://climate.esa.int/en/odp/#/project).

With the most recent version of the CRDP, the following data products are available:

- AGB maps for the year 2010 and for each year between 2015 and 2021, including per-pixel SD, version 5.0.
- AGB change maps for the years 2016-2015, 2017-2016, 2018-2017, 2019-2018, 2020-2019 and 2021-2020 (annual) and 2020-2010 (decadal) can be computed from the AGB maps. Per-pixel SD and quality flags, QF, version 5.0, are available on the data portal.
- Aggregated AGB and AGB change datasets. Maps are grouped per spatial resolution and per type of map (AGB or AGB change map).

Aggregated AGB and AGB change datasets are available at the following external web link. Maps are grouped per spatial resolution and per type of map (AGB or AGB change map).

The CCI BIOMASS datasets have been processed by the CCI BIOMASS consortium led by the University of Aberystwyth (U.K.). They are made available to the public by ESA and the consortium. You may use one or several CCI BIOMASS products for educational and/or scientific purposes, without any fee on the condition that you credit the ESA Climate Change Initiative and in particular its BIOMASS project as the source of the data:

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Any scientific publication on the results of research activities based on CCI BIOMASS data products should acknowledge the ESA CCI BIOMASS project in the text of the publication and provide the project with an electronic copy of the publication (see https://climate.esa.int/en/projects/biomass/ for contacts).

If CCI BIOMASS data products are to be used in advertising or commercial promotion, the ESA CCI BIOMASS project should be acknowledged and the layout should be submitted to the project for approval beforehand (see https://climate.esa.int/en/projects/biomass/ for contacts).

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10 Appendices

10.1 Appendix A: 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. Values are specific for the year 2020.

Attribute Name	Format	Value	Description
Title		ESA CCI above-ground biomass product level 4, year 2020	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		AGB estimation with BIOMASAR-L, v202311 GSV estimation with BIOMASAR-C, v202311 Merging of AGB estimates, v202311	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		9a24d3e3-61c9-46cb-ab85-333664d1bb92	UUID, Universal Unique Identifier
Conventions		CF-1.7	Name of the conventions followed
product_version		5.0	Version of AGB product
summary		This dataset contains a global map of above-ground biomass (AGB) of the epoch 2020 obtained from L-and C-band spaceborne SAR backscatter, placed onto a regular grid.	

keywords		satellite, observation, forest, biomass	
id		ESACCI-BIOMASS-L4-AGB-MERGED-100m-2020-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
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		20200101T000000Z	
time_coverage_end		20201231T235959Z	
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	
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	
date_created		21-Feb-2024 12:55:22	
EPSG		4326	
proj4		+proj=longlat +datum=WGS84 +no_defs	

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 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 deviation of AGB value
	standard_name		n/a	
	long_name		Above-ground biomass (AGB) standard deviation	
	valid_min		0	
	valid_max		65536	
	_FillValue		99999	

10.2 Appendix B: Weight of L-band AGB estimates

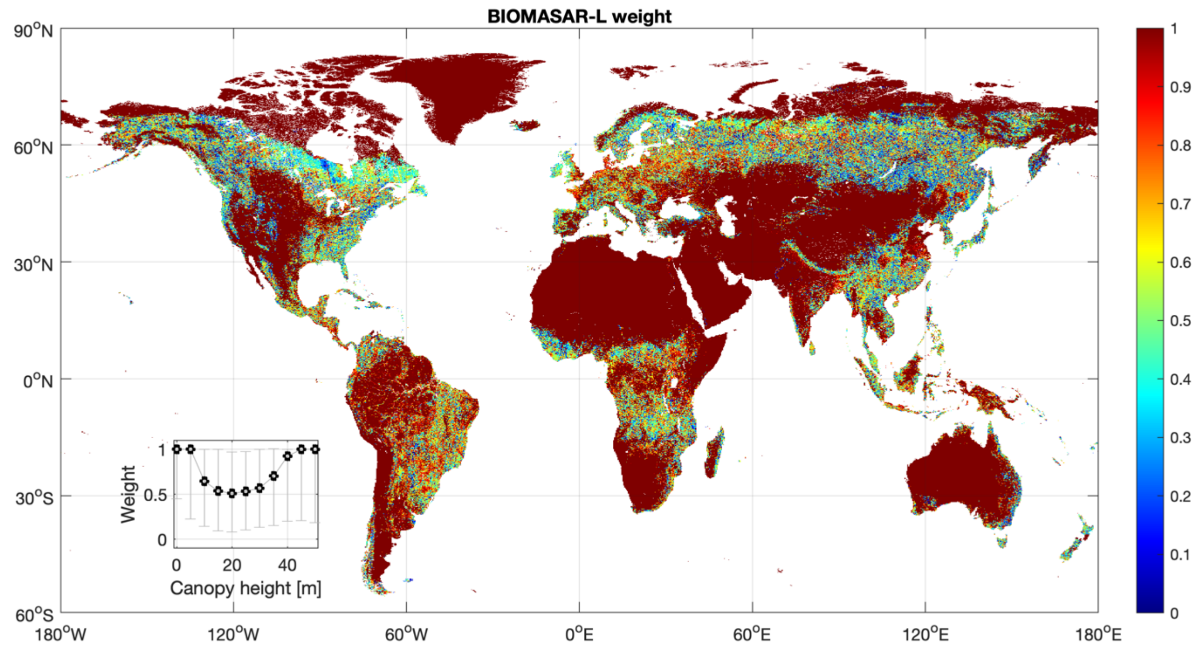

Figure 10-1: Map of the weight applied to estimates of AGB with the BIOMASAR-L approach in v5. Values closer to 1 indicate that the CCI BIOMASS AGB map is based primarily on the L-band estimate. Values closer to 0 indicate that the AGB map is based primarily on the C-band estimate.