CCI Biomass: Status and developments for global mapping of aboveground biomass and change

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ESA's Climate Change Initiative Biomass project

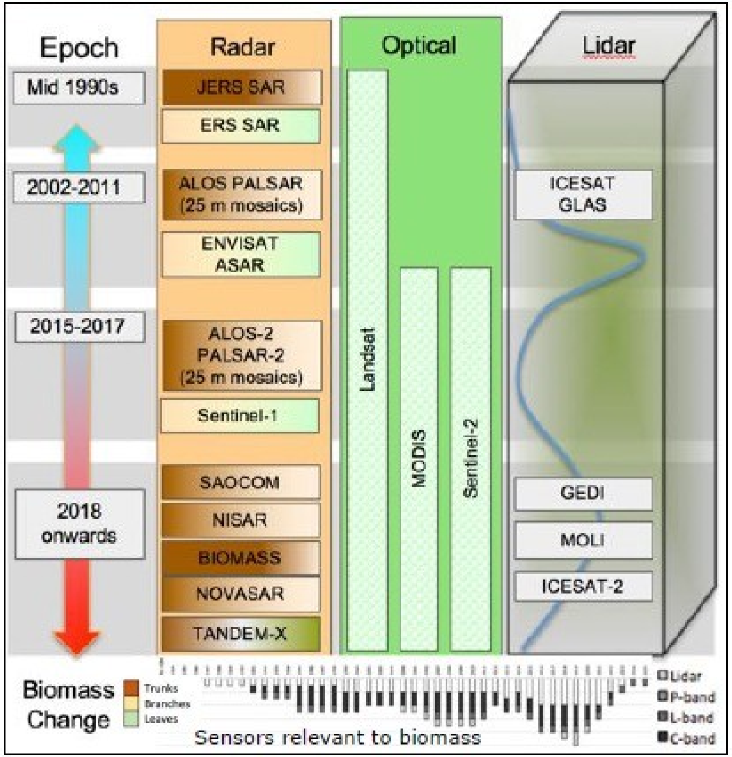
CCI aims at *realizing the potential of the long-term global EO archives that ESA, together with its Member states, has established over the last thirty years..... as a significant and timely contribution to the ECV databases required by the United Nations Framework Convention on Climate Change*

Phase 1 of **CCI BIOMASS** *aimed at the generation of three global* ***AGB maps for 2010, 2017 and 2018 with a suite of EO data*** *and assessment of* ***AGB changes*** *with an evaluation in climate and carbon models.*

In Phase 2 maps for the years 2010, 2017, and 2018 are reproduced / improved and new maps for the years 2016, 2019-2022 will be produced

Measurement domain	Essential Climate Variables
Atmospheric	Surface: air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget Upper-air: temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget, lightning Composition: carbon dioxide (CO2), methane (CH4), other long-lived greenhouse gases, ozone, aerosol, precursors for aerosol and ozone
Oceanic	Physics: temperature: sea surface and subsurface; salinity: sea surface and subsurface; currents, surface currents, sea level, sea state, sea ice, ocean surface stress, ocean surface heat flux Biogeochemistry: inorganic carbon, oxygen, nutrients, transient tracers, nitrous oxide (N_2O), ocean colour Biology/ecosystems: plankton, marine habitat properties
Terrestrial	Hydrology: river discharge, groundwater, lakes, soil moisture Cryosphere: snow, glaciers, Ice sheets and Ice shelves, permafrost Biosphere: albedo, land cover, fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire, land surface temperature Human use of natural resources: water use, greenhouse gas fluxes

Spaceborne EO relevant to AGB estimation

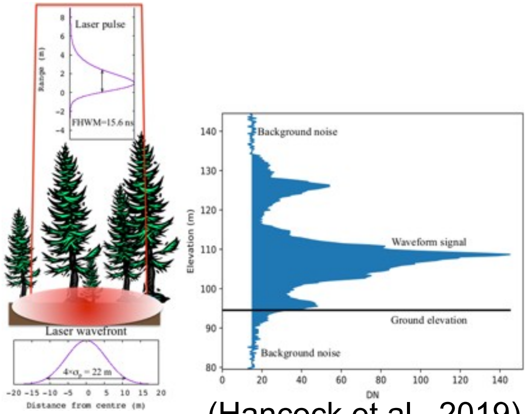


(Courtesy R. Lucas)

SAR

CCI Biomass relies on spaceborne C- and L-band Synthetic Aperture Radar data acquired globally in the last decades by the ESA C-band missions ENVISAT ASAR & Sentinel-1 and the JAXA L-band missions ALOS-1 PALSAR & ALOS-2 PALSAR-2.

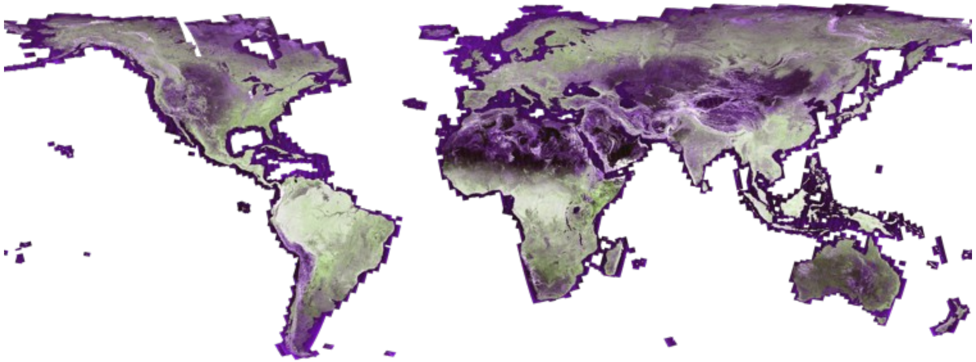
LiDAR



(Hancock et al., 2019)

Forest structural information provided by spaceborne LiDAR (ICESAT GLAS, ICESAT-2, GEDI) supports modelling of SAR backscatter as function of biomass.

ENVISAT ASAR & Sentinel-1 C-Band SAR



Sentinel-1 IW for years 2015-2021

Ca. 250,000 scenes per year considered (no 6-day repeat-pass images)

Almost full annual IW coverage since 2017 from S1A&B

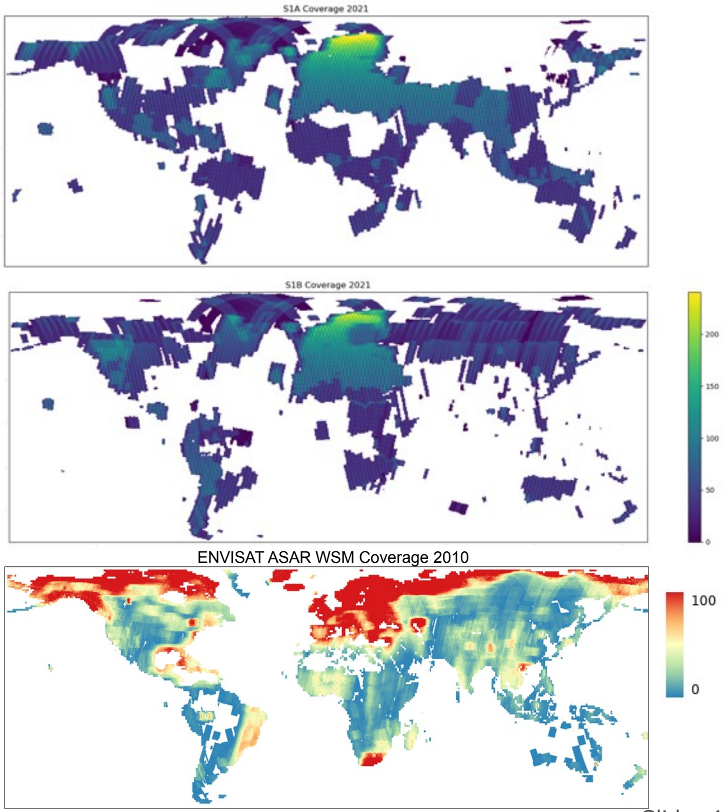
With few exceptions >30 observations per year in two polarizations

Processed by CCI Biomass Consortium on AWS with support from Earth Big Data LLC

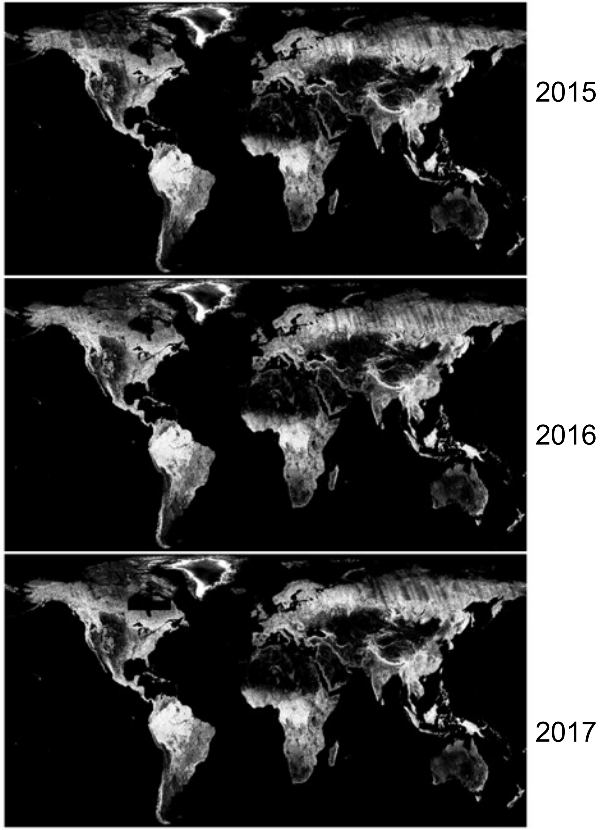
ENVISAT ASAR ScanSAR for epoch 2010

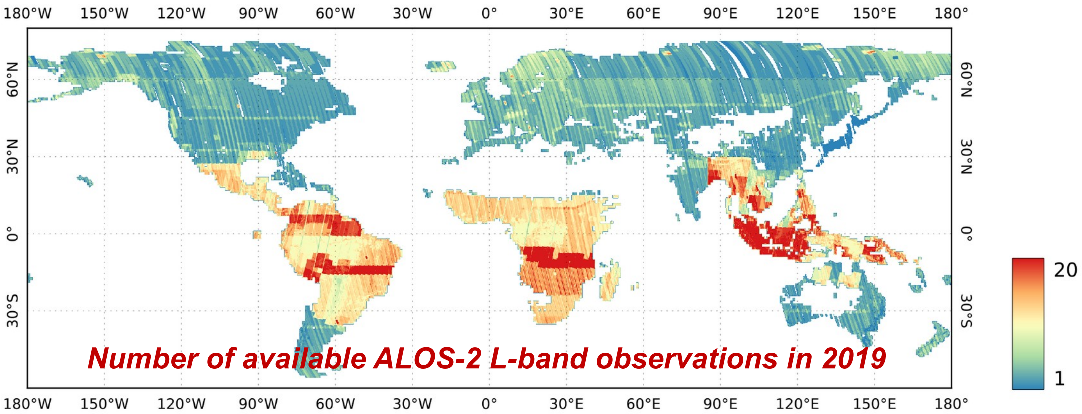
Processed > 200,000 images acquired between 2005 and 2012 on G-POD

More than 100 observations at high latitudes, some gaps over South America, Africa, Australia



ALOS-1/2 PALSAR-1/2 Fine Beam/ScanSAR L-Band SAR





ALOS-1 PALSAR-1:

- Global Fine-Beam Mode Mosaics 2007-2010 (1 mosaic per year)
- L2.2 Fine-Beam Mode (includes all multi-temporal observations)

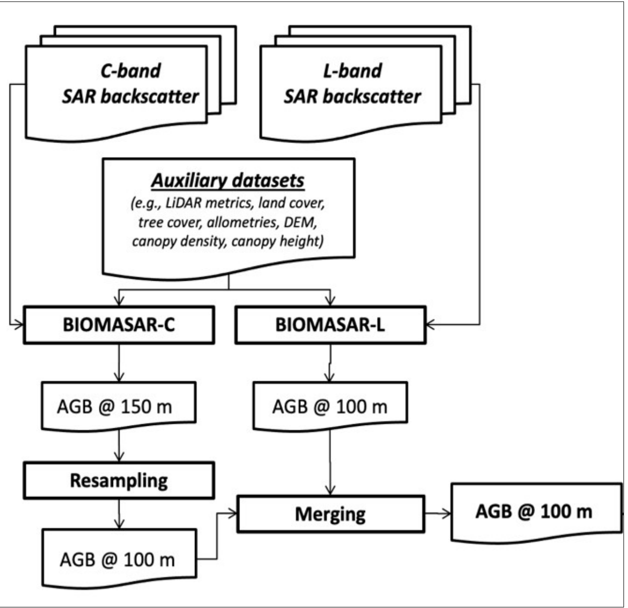
ALOS-2 PALSAR-2

- Global Fine-Beam Mode Mosaics 2015-2021 (1 mosaic per year)
- Per-cycle ScanSAR mosaics (all multi-temporal observations over tropics)
- Access to ALOS2 KC image strips through JAXA-ESA collaboration (all multi-temporal observations)

Processed by JAXA

Processed by CCI Biomass consortium on AWS

CCI BIOMASS CORE algorithm



The BIOMASAR algorithm for C- and L-band SAR (Santoro et al., 2011, 2015, 2021, 2022; Cartus et al., 2011) is the CCI Biomass CORE algorithm.

BIOMASAR algorithm aims at modelling SAR backscatter as function of above-ground biomass based on a simple semi-empirical model which is **calibrated without forest inventory plot data** because such information is not available across most of the worlds forest areas to support:

1) adaptive calibration of models for each individual SAR observation with respect to the effects of spatially and temporally changing environmental imaging conditions,
2) capture forest structural differences.

Workflow:

(1) Models are **calibrated and inverted to estimate biomass for each individual SAR image** in the multi-temporal stack of C- and L-band observations.
(2) Biomass estimates from individual SAR backscatter images are **combined multi-temporally** considering each of the images' sensitivity to biomass
(3) C- and L-band derived maps are merged considering 1) sensitivity to biomass locally, and 2) inter-annual consistency of biomass estimates

Model

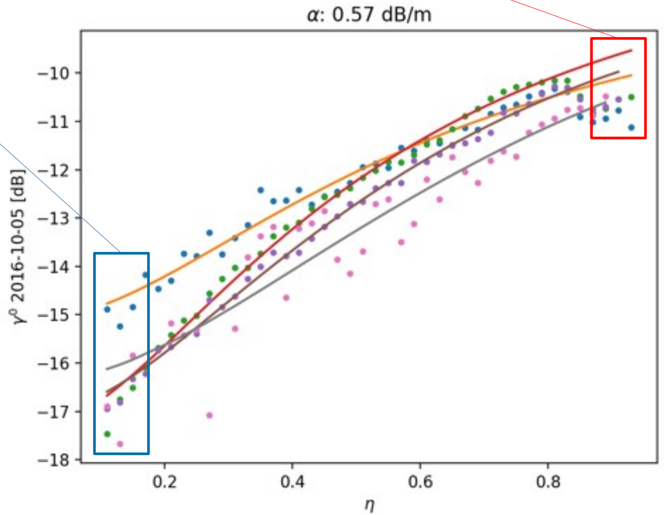
$$\sigma^0_{for} = \left(1 - \eta\left(h\left(B\right)\right)\right)\sigma^0_{gr} + \eta\left(h\left(B\right)\right)\sigma^0_{gr} e^{-\alpha h\left(B\right)} + \eta\left(h\left(B\right)\right)\sigma^0_{veg}\left(1 - e^{-\alpha h\left(B\right)}\right)$$

Backscatter modelled as function of:

1) Canopy density ***η*** and Height ***h:***
Model **calibration** to determine variation of scattering coefficients of forest floor and canopy, $\sigma^0_{gr,veg}$, with changing **environmental imaging conditions** for each backscatter image based on information on provided by optical and Lidar EO data, i.e., calibration **does not rely on *in situ* data.**

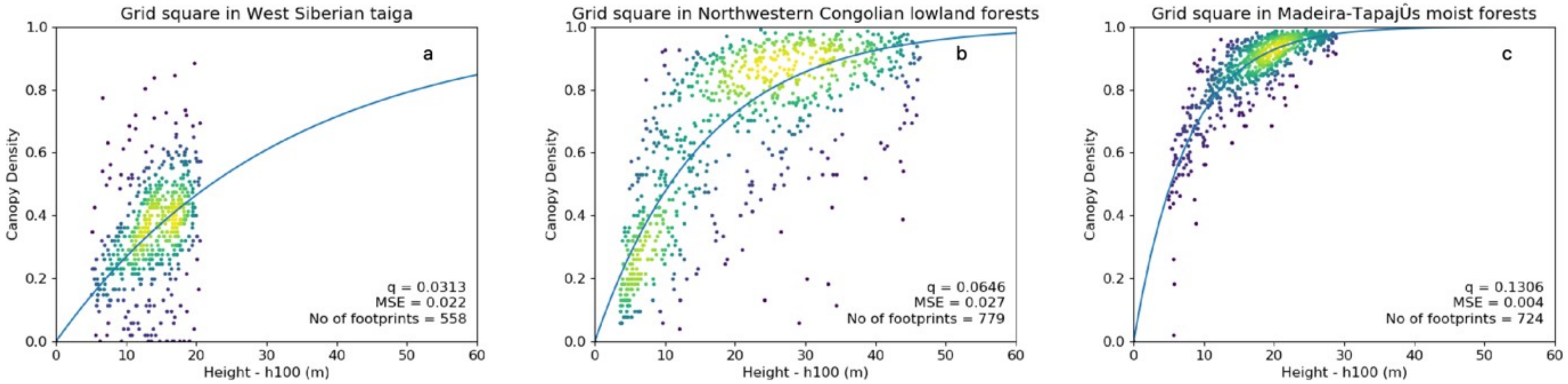
Models calibrated for 10° bins of local incidence angle to account for topography and wide incidence angle range of ScanSAR datasets.

2) Above-ground Biomass:
Allometric functions describing the relationships between canopy density, height, and above-ground biomass are used in the **inversion step to account for forest structural differences.**



ALOS-2 LHV backscatter as function of Landsat canopy density (Hansen et al., 2011) for different incidence angle classes.

Canopy Density-to-Height allometry, v4

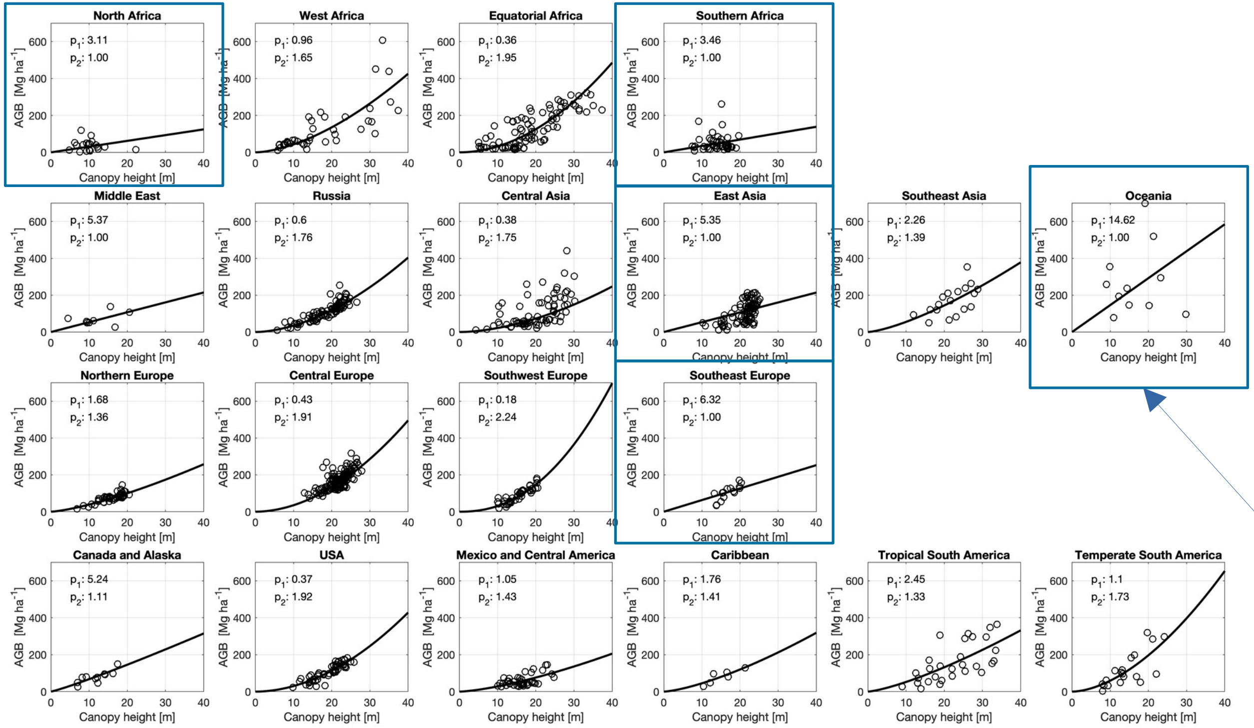


- Model fitted to each of the 883 WWF ecoregions (Olson et al., 2001) using ICESat GLAS canopy density, CD, and RH100 metrics (Kay et al., 2021)
- Ongoing: Re-evaluation of allometry considering GEDI

$$\eta = \mathrm{f(h)}$$

$$CD = 1 - e^{-qh}$$

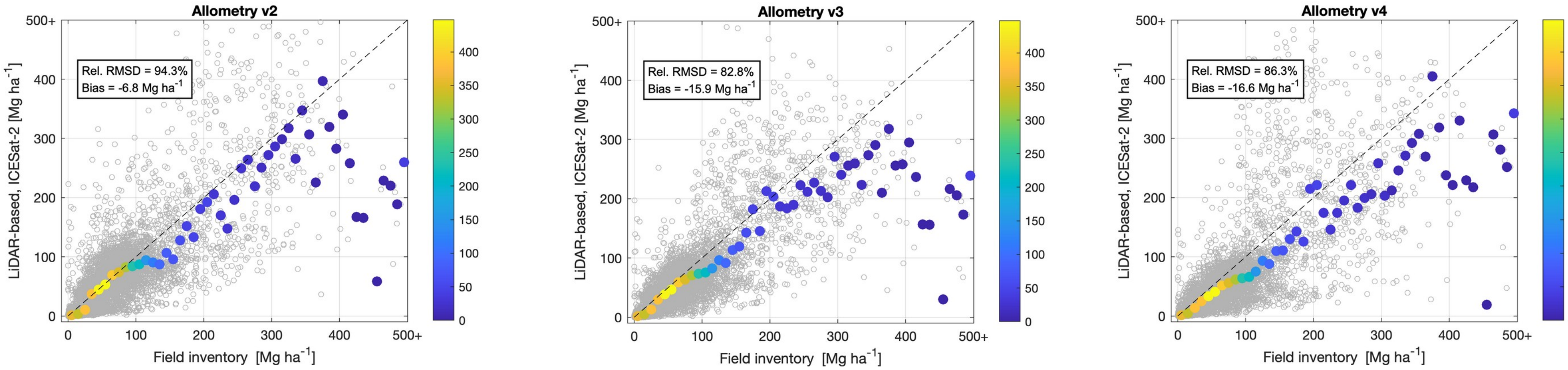
Height-to-AGB allometry, v4



$$AGB = p_1 * h^{p2}$$

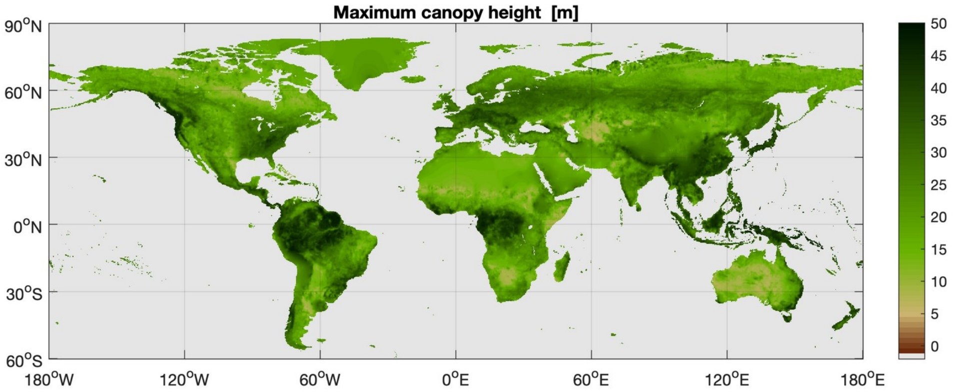
- Allometric functions determined based on average ICESAT-2 LiDAR heights, and biomass statistics reported by 106 countries per administrative (country, states, counties, etc.) or ecological unit (e.g., broadleaf, needleleaf forests), or in the FAO Forest Resources Assessment for 2020
- World stratified into 20 regions to account for similarity in terms of ecological traits, forest management and amount of NFI-based statistics
- Regression to training data fails when data points are scarce or poorly estimated --> linear function

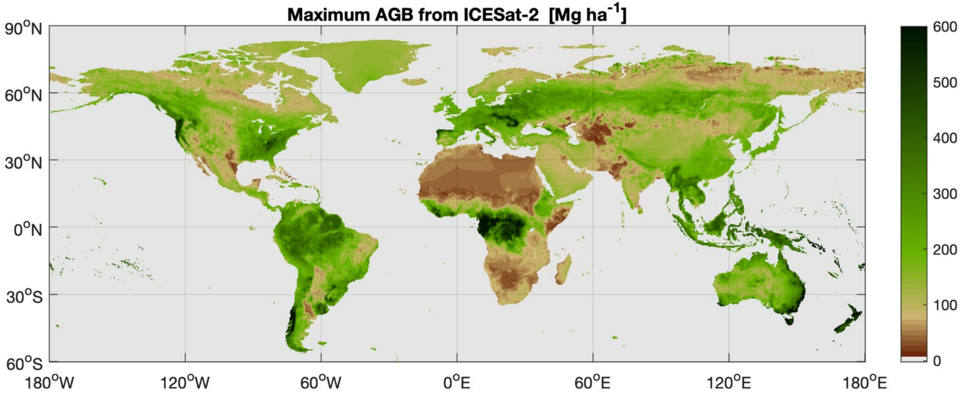
Height-to-AGB allometry, v4



- Allometry evaluated with NFI statistics and plot-level information (plots not used in the CCI Biomass validation)
- The allometry is evolving but the large spread in the scatter plot shows that regionally there are still significant biases
- Allometric equations will be refined further for the next release (v5) of the CCI Biomass products using ICESAT-2 as well as GEDI LiDAR data

Maximum Retrievable AGB



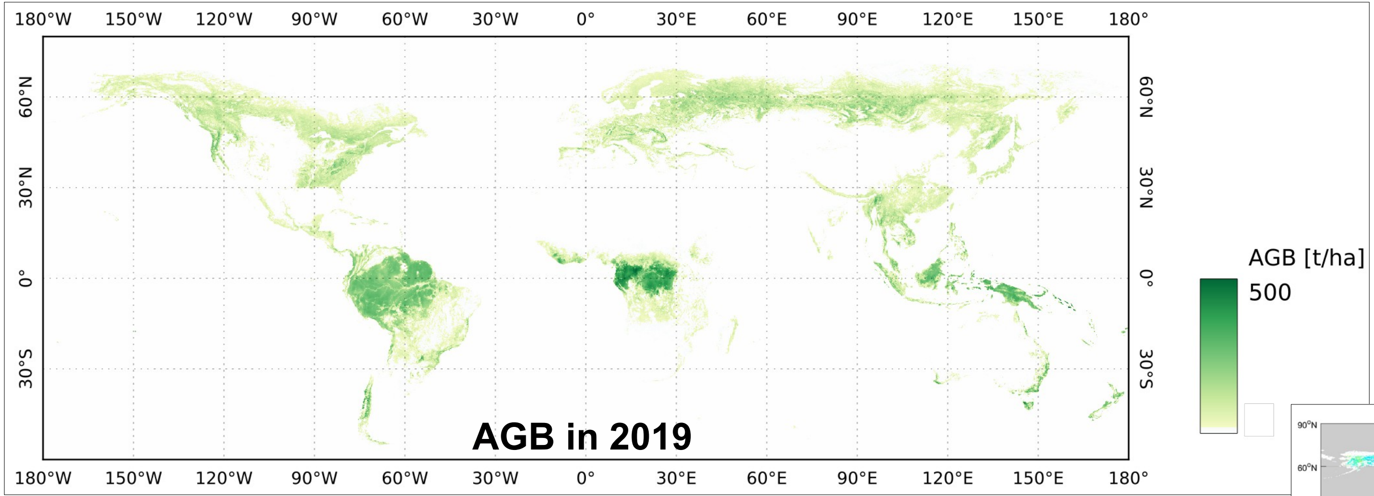


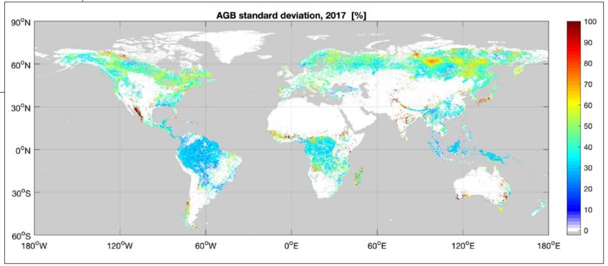
- Due to the non-linear nature of the relationship between radar observables (here backscatter) and AGB, a maximum retrievable biomass needs to be defined to limit AGB estimates to a plausible range of values.

- Maximum AGB currently defined based on gridded estimates of maximum height derived from ICESAT2 Lidar and HGT-AGB allometry.

The CCI Biomass AGB datasets

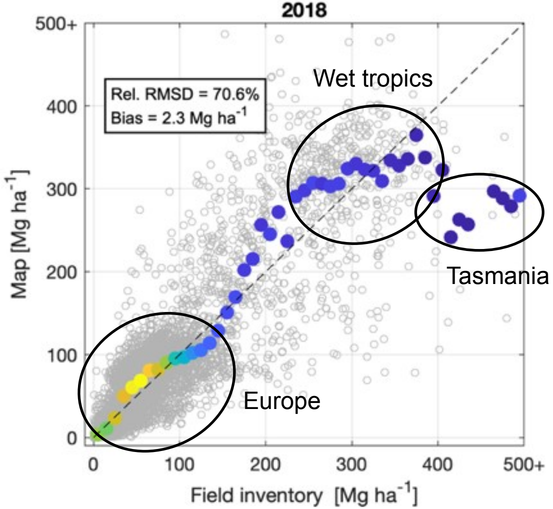
- Global AGB maps @ 100 m for **2010, 2017, 2018, 2019, and 2020** and standard deviation
- Version 4 released in May 2023: https://catalogue.ceda.ac.uk/



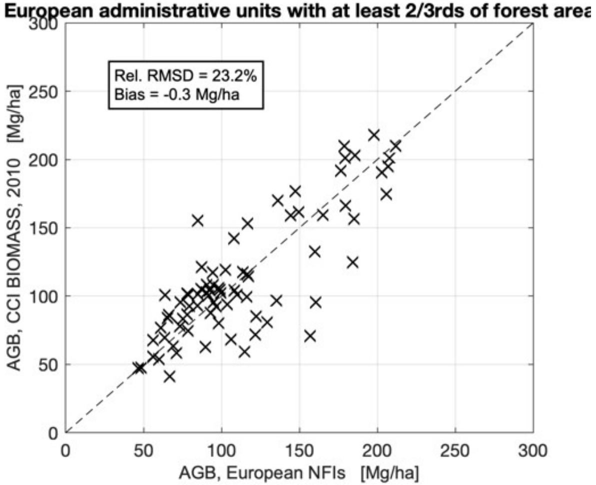


Verification of the CCI AGB estimates

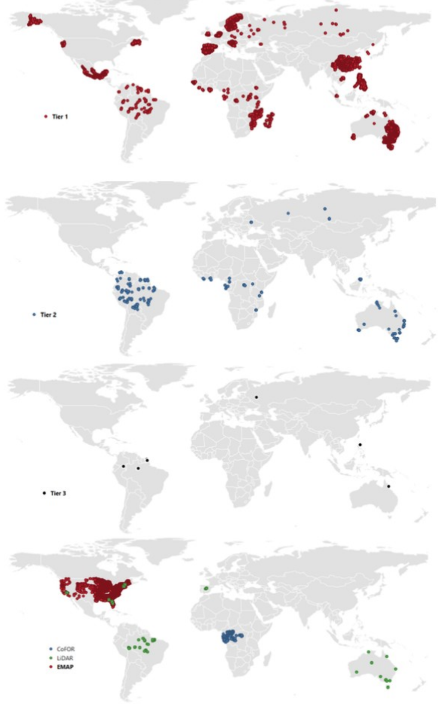
Averages of plot inventory vs. CCI AGBs, year 2018 global dataset (see CCI Product User Guide, v3)



Statistics of European NFI vs. CCI average AGBs, year 2010 (see Santoro et al., RSE, 2015, for NFI sources)



In situ (different Tiers represent different plot sizes) and LiDAR reference datasets

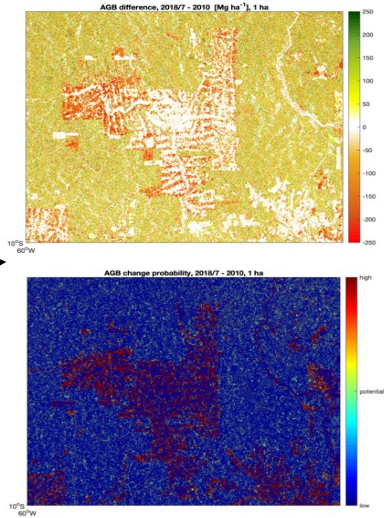


. Geographical locations of plots and footprints of the reference datasets (CoFor = Congo basin Forests, LiDAR and EMAP = Environmental Monitoring and Assessment Program).

- The AGB spatial distribution is well captured but the AGB levels are not everywhere well represented
- Continuous improvements from v1 to v4 of the datasets
- Ongoing: Refinement of CD2H and H2AGB allometry for v5

The CCI Biomass AGB change datasets

- Defined simply as $AGB_{y2} – AGB_{y1}$
- Four datasets have been generated (v4): 2020-2010, 2020-2019, 2019-2018, 2018-2017
- The AGB change maps are provided together with 1) SD defined as the sum of the maps' variances, 2) a quality flag that defines the level of reliability of the AGB change based on confidence intervals



European Space Agency

Limitations of AGB change mapping

- Differences in data availability between years / processing related issues hinder change detection.
- Artifacts in C- and L-band locally
- Limited data availability from different sensors (ASAR, ALOS-1) in 2010 results in systematic biases between 2010 and 2017-2020
- Lack of sensitivity of C- or L-band backscatter to AGB and local errors in backscatter modelling result in local biases.
- The AGB change maps capture both increases and decreases. The decreases are often in line with tree cover losses. Increases are hard to verify given the lack of datasets with similar thematic content. In summary, **we do not know how much biases of the individual AGB maps impact the AGB change estimates**.
- A **direct comparison** of annual maps, in particular 2010 and 2017-2020 maps, is currently **not recommended**
- A quality flag was proposed to ease the interpretation of the AGB changes.
- Our definition is quite strong: the magnitude of the AGB change is ”probable” when two estimates (considering the SD) in time are disjoint.
- Stating that the magnitude of most AGB changes is “improbable”, is a realistic statement on the current capabilities offered by satellite remote sensing to estimate AGB in time.

Data summary & Outlook

- The CCI Biomass project so far produced global maps of AGB for the years 2010, 2017-2020 with a conservative indication of potential changes, with a pixel size of 1 hectare.
- The CCI Biomass datasets are available on the CCI data portal: https://catalogue.ceda.ac.uk/
- All project technical documents available at: https://climate.esa.int/en/projects/biomass/
- Users are advised to read 1) Product User Guide PUG, 2) ATBD to understand limitations of the maps with respect to different applications.
- Feedback and interaction with users is strongly encouraged for mutual benefit.

Outlook:

- Improve inter-annual consistency of maps → Implementation of CCI Biomass activities focussed on change
- Further refine modelling of backscatter as function of AGB with refined allometries (ICESAT-2/GEDI)
- Reproduce 2010/2017-2020 AGB maps, produce maps for all years between 2015-2022