EYE-CLIMA
Verifying emissions
of climate forcers

Report on existing biomass and biomass change datasets

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Summary

This report is aimed at reviewing existing biomass and biomass change datasets, their suitability to be used in preparing greenhouse gases inventories or for being a benchmark (common denominator) for countries' UNFCCC reporting. Drivers of biomass change are also considered for understanding which changes are related to human activities and which are the natural process. We consider three biomass datasets as the most relevant for the EYE-CLIMA project.

(1) ESA CCI Biomass and biomass change maps have a large potential to be used in context of EYE-CLIMA project. The advantage lies in the utilisation of various relevant remote sensing instruments, including radar, lidar, and optical sensors provided by different space agencies such as ESA, NASA, and JAXA. These maps not only report accuracy of estimations of both AGB and AGB change but also continually improve over time through reprocessing of early products (e.g., for the year 2010) with plans for ongoing enhancements and continuing the time series. A noteworthy feature is the successful comparison of CCI Biomass maps to national or regional ground observations, effectively removing bias and enhancing accuracy (Schepaschenko et al., 2021; Avitabile et al., 2023). However, differences between the maps from 2010 and the latest years due to sensors differences impact the reliability of biomass change analysis from the stock change approach.

(2) Biomass change maps based on L-VOD (Vegetation Optical Depth) also demonstrate great potential due to their relatively long observation period starting from 2010, all with the same sensor. Noise in the calibration of L-VOD to biomass and the use of a space for time method to infer change impact the reliability of biomass change analysis from the stock change approach.

(3) Avitabile et al. (2023) offer a European biomass map 2020 that is calibrated to sub-national statistics. This calibration ensures the map’s consistency and is unbiased concerning both national statistics and UNFCCC national reporting.

(4) The visual interpretation of very high-resolution imagery indicates that CCI Biomass tends to overestimate the area of changes. However, the direction of changes is recognized correctly. Notably, 72% of biomass loss is associated with forest management, while 92% of biomass gain occurs within forest areas.

(5) For biomass change, flux-based methods have been developed based on recovery rates from disturbances to infer changes of AGB for secondary forests, with applications in Europe, Boreal and Tropical forests where long term disturbance maps from Landsat exist. The European analysis was done with the support of EYE CLIMA

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1. Introduction

This report aims to review biomass and biomass change datasets that are available or might be made available during the course of the project. These datasets should be suitable for direct utilisation in UNFCCC reporting or for benchmarking greenhouse gas (GHG) inventories at European scale. Our primary focus has been on the remote sensing-based products that facilitate wall-to-wall mapping at regular (annual) intervals.

Biomass definitions vary across datasets. From a biological standpoint, the living biomass of a forest encompasses trees (stem, bark, branches, foliage, roots), understory and green forest floor biomass. Remote sensing-based products typically estimate above-ground woody biomass of trees (in units of dry matter) with a diameter at breast height greater than 10 cm. Other components, such as roots, foliage, smaller trees, shrubs, and herbaceous cover, are not included. This divergence is acceptable as long as the definition is consistently applied for time series analysis or cross-dataset comparison. A conversion of dry matter to C requires conversion factors from the C content of biomass, close to 0.48.

Direct measurement of biomass is unattainable, barring destructive methods involving cutting trees, dividing them into pieces, and weighing them. Even in the destructive method, a sampling approach is employed to select representative trees, branches, and wood density samples. Consequently, biomass estimations are inevitably associated with uncertainties. Remote sensing methods rely on various forest features obtained through optical, radar or lidar instruments. Each feature and its corresponding biomass estimation method have inherent advantages and shortcomings. Notably, the most relevant instruments (L/P-band radar and lidar) have a relatively short history of measurements, rendering biomass change detection particularly challenging when different instruments are employed over time.

An additional critical question we aim to address concerns the drivers of biomass change. This knowledge is crucial for distinguishing changes linked to forest management from those attributable to natural processes. Quantifying drivers of change should enhance our understanding of the effectiveness of forest management practices and identify major threats.

2. Biomass and Biomass Change Datasets

Remote sensing-based above-ground biomass and biomass change maps serve as critical independent sources of information regarding carbon stocks and fluxes. While they may exhibit somewhat lower accuracy compared to ground-based national inventories, they offer several distinct advantages, including:

- Consistent Cross-Border Approach: Remote sensing allows for a uniform approach across borders, facilitating standardized assessment methods.
- Wall-to-Wall Estimation: One of the notable strengths is the ability to provide comprehensive, wall-to-wall estimations, offering a holistic view of the biomass distribution.
- Timely (Annual) Estimates: Remote sensing methods enable timely assessments with annual estimates, ensuring a more dynamic and up-to-date understanding of biomass changes over time.

These advantages make remote sensing an invaluable complement to ground surveys, enhancing our ability to monitor and understand the dynamics of carbon stocks and fluxes in a more comprehensive and efficient manner.

Table 1 comprises a list of biomass and biomass change datasets that have been considered in this report.

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Table 1. Major biomass and biomass change datasets

Dataset name	**Spatial resolution**	**Spatial coverage**	**Temporal coverage**	**Biomass change**
Baccini	25 m	global	2000	no
CCI Biomass	100 m	global	2010, 2017, 2018, 2019, 2020	yes
CTREES JPL	10 km	global	2000-2020	yes
GEDI L4 gridded biomass	1 km	up to 51.6° N	2020	no
ICESat-2 Boreal Biomass	30 m	50°-75° N	2020	no
Harmonised Forest Biomass dataset 2020 for Europe	100 m and sub-national statistics	Europe, 38 countries	2020	no
LVOD	25 km	global	2010-2019	yes

2.1. Biomass datasets

2.1.1. ESA CCI Biomass

The ESA CCI Biomass dataset offers estimates of forest above-ground biomass for the years 2010, 2017, 2018, 2019 and 2020. These estimates are derived from a blend of Earth observation data, varying by year and sourced from the Copernicus Sentinel-1 mission, Envisat's ASAR instrument, and JAXA's Advanced Land Observing Satellite (ALOS-1 and ALOS-2). Additional information from Earth observation sources is also incorporated. Developed as part of the European Space Agency's (ESA's) Climate Change Initiative (CCI) programme by the Biomass CCI team, the current release of the data is version 4. The AGB maps rely on revised allometries which are based on a longer record of spaceborne LiDAR data from the GEDI and ICESat-2 missions. The data products consist of two (2) global layers that include estimates of: 1) above ground biomass (AGB, unit: tons/ha i.e., Mg/ha) (raster dataset). This 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) per-pixel estimates of above-ground biomass uncertainty expressed as the standard deviation in Mg/ha (raster dataset). In addition, files describing the AGB change between two consecutive years (i.e., 2018-2017, 2019-2018 and 2020-2010) and over a decade (2020-2010). Each AGB change product consists of two sets of maps: the standard deviation of the AGB change and a quality flag of the AGB change. Note that the change itself can be simply computed as the difference between two AGB maps, so is not provided directly. There are biases due to the use of different sensors between 2010 and other years that limit the use of the CCI Biomass data to analyse change. Data are provided in both netcdf and geotiff format (Santoro et al., 2021; Santoro & Cartus, 2023).

The dataset is accessible at: https://dx.doi.org/10.5285/af60720c1e404a9e9d2c145d2b2ead4e

2.1.2. GEDI gridded biomass 2020

The GEDI gridded biomass dataset is derived from the Global Ecosystem Dynamics Investigation (GEDI) L4B product, offering 1 km estimates of mean aboveground biomass density (AGB). NASA's GEDI, a full waveform lidar instrument aboard the International Space Station, conducted data collection between April 2019 and August 2021, covering global regions between 51.6° N and 51.6° S latitudes. Each laser

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illuminates ~25 m on the ground, and measures tree heights and volumes within those 25 m areas. GEDI L4A parametric footprint biomass models convert each high-quality waveform to an AGB prediction, and the L4B algorithm uses the sample present within the borders of each 1 km cell to statistically infer mean AGB and the standard error of the mean. The GEDI L4B product is 1 km spatial resolution, and the gridding procedure is described in the GEDI L4B Algorithm Theoretical Basis Document (ATBD). Dubayah et al. (2022) describe the hybrid model-based mode of inference used, where estimates of the standard error of the mean account for both GEDI L4A modeling uncertainty and uncertainty related to how the 1 km cells are sampled by GEDI's observations (as opposed to making wall-to-wall observations). The data themselves are samples, that is, are not spatially continuous.

The dataset is accessible at: https://doi.org/10.3334/ORNLDAAC/2299

2.1.3. ICESat-2 Boreal 2020

The ICESat-2 boreal dataset stems from NASA’s ICESat-2, a photon-counting lidar instrument that launched in 2018. ICESat-2 is dedicated to collecting global 3D structure measurements of Earth’s terrain and vegetation. This provisional product, still in development, utilises samples from ICESat-2’s vegetation height product along with 30m data from Harmonized Landsat Sentinel-2, and the Copernicus DEM. This product focuses on high latitude boreal forests where NASA’s GEDI instrument doesn’t collect data, and is meant to complement the temperate and tropical forest maps from GEDI. Description of the data set available here: https://ceos.org/gst/icesat2-boreal-biomass.html

2.1.4. Harmonised Forest Biomass dataset 2020 for Europe

The Harmonised Forest Biomass dataset is a collaborative effort led by the Joint Research Centre in conjunction with National Forest Inventory representatives from a majority of European countries (Avitabile et al., 2023). This database provides statistics and maps of the forest area, biomass stock in the year 2020, and statistics on gross and net volume increment in 2010-2020, for 38 European countries. The statistics of most countries are available at sub-national scale and are derived from National Forest Inventory data, harmonised using common reference definitions and updated to a common year using a modelling approach. The map originated from the CCI BIOMASS map, which was calibrated with the NFI statistics and depicts the spatial distribution of the AGB at 100 m resolution.

The biomass statistics refer to the aboveground standing biomass of all living trees, including the aboveground stump, the stem from stump to top, branches and foliage (AGB) as total AGB stock (tons) and AGB stock per hectare (AGB/ha) (t/ha) in the forest areas of each country (Avitabile et al., 2023).

The dataset is accessible at: https://doi.org/10.6084/m9.figshare.c.6465640

2.2. Biomass change datasets

Biomass change is being estimated by several methods that involves the integration of various sources of information:

- ground measurements, primarily National Forest Inventories (NFI)
- remote sensing, including optical, radar and lidar instruments
- different models

2.2.1. ESA CCI Biomass

The ESA CCI Biomass project not only provides estimates of forest above-ground biomass for specific years (2010, 2017, 2018, 2019, and 2020) but also offers AGB change maps for consecutive years (2018-2017, 2019-2018 and 2020-2019) and for a decadal interval (2020-2010). Each AGB change product is composed of two sets of maps: the standard deviation of the AGB change and a quality flag of the AGB change. Note that the change itself can be simply computed as the difference between two

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AGB maps, so is not provided directly. The quality flag layer of the AGB change maps 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 (CCI Biomass Product user guide v.4, 2023).

The dataset is accessible at: https://dx.doi.org/10.5285/af60720c1e404a9e9d2c145d2b2ead4e

2.2.2. Machine learning model of AGB change using multiple sensors

Xu et al. (2021) Developed a machine learning model trained using spatial in-situ measurements of AGB with optical and microwave (short frequency VOD) to provide temporal changes of AGB at 10 km resolution since 2000. This product shows areas of loss and gains, but losses in some tropical deforestation areas do not seem to be captured properly, possibly because of the machine learning model trained in space and used in time for change maps.

The dataset is accessible at: https://doi.org/10.5281/zenodo.4161694

2.2.3. Vegetation Optical Depth based change map

The Vegetation Optical Depth based change map provides a time series of AGB products spanning from 2010 to 2019. This analysis is derived from the L-band Vegetation Optical Depth (LVOD) signal acquired by the Soil Moisture and Ocean Salinity (SMOS) mission (Yang et al., 2023). The LVOD signal serves as a valuable indicator for monitoring changes in vegetation properties. The retrieval of above-ground biomass from LVOD is complemented by referencing a high-resolution AGB product, for instance the GlobBiomass, developed by Santoro et al. (2021) and the calibration of LVOD into biomass is performed using different reference maps. Advantage of LVOD is that the same sensor provides estimates of change. Further, the fusion of SMAP and SMOS (Li et al., 2022) data allows a continuous AGB dataset even beyond the SMOS lifetime. Uncertainties are induced by saturation of LVOD at very high biomass > 250 t ha^{-1}, impossibility to retrieve VOD in frozen soils and flooded areas (filtered in the data), noise from Radio Frequency Interference (filtered in the data but in Northern China, no data is available) and sensitivity to water content per unit biomass volume (filtered in the data with a statistical model, but inter-annual water content changes might still alias with annual AGB retrieved from LVOD).

Reference: https://dx.doi.org/10.1038/s41561-023-01274-4

3. Uncertainties of biomass and biomass change datasets

The uncertainties linked to biomass and biomass change datasets are essential for ensuring their accuracy. Data producers estimate these uncertainties, and independent efforts, like Araza et al. (2022), contribute insights.

For example, The CCI Biomass dataset includes a standard deviation layer for pixel-level uncertainties in biomass values. For AGB change, it reports a quality flag indicating if confidence intervals of consecutive AGB estimates overlap.

Independent validation of biomass datasets is crucial to ensure diverse data sources are employed in map production and validation. However, challenges in validating biomass maps arise from several factors:

- Size Discrepancy: Ground plots, like those from National Forest Inventories (NFIs), are often too small compared to map pixels. This size discrepancy can affect the representativeness of ground data.
- Coarse Geolocation: The geolocation of ground data, particularly from NFIs, is often too coarse. This limitation can hinder precise alignment with finer-resolution map pixels.
- Spatial Distribution Issues: The spatial distribution of ground data may not meet statistical requirements. This can lead to uneven coverage and affect the reliability of validation efforts.

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- Temporal Mismatch: Ground data may suffer from a temporary mismatch, being too old for current map validation. This temporal misalignment can impact the relevance of ground data for assessing contemporary biomass maps.

Addressing these challenges requires concerted efforts in improving ground data quality, refining geolocation accuracy, enhancing spatial distribution representativeness, and ensuring temporal alignment. Initiatives like GEO-TREES (https://geo-trees.org/) and methodologies proposed by Labrière et al (2023), Duncanson et al. (2021) contribute to advancing the field of biomass dataset validation.

Araza et al. (2022) propose an uncertainty framework designed to address biases in existing Above-Ground Biomass (AGB) maps. This framework, when applied, corrects for biases along with their associated standard deviations at coarser scales. The method allows for the utilisation of small plots by aggregating data to a coarser resolution and averaging values from multiple small plots. However, the effectiveness of spatial uncertainty modeling is impacted by the uncertainty associated with plot-level Above-Ground Biomass (AGB). This uncertainty primarily arises from measurement and sampling errors. In regions where only small plots are available, this uncertainty tends to be particularly pronounced. In summary, Araza et al.'s framework aims to enhance the reliability of AGB maps by addressing biases and associated uncertainties, especially when dealing with data from small plots and aggregating to coarser scales.

In the study conducted by Avitabile et al. (2023), a calibration approach is employed to align map values with sub-national statistics. This calibration process aims to ensure that maps are not only consistent but also unbiased in comparison to both national statistics and the reporting requirements of the United Nations Framework Convention on Climate Change (UNFCCC) at the national level.

By calibrating map values to sub-national statistics, the study seeks to enhance the accuracy and reliability of the maps, making them more aligned with actual on-the-ground conditions and improving their utility for national-level reporting, particularly in the context of climate change assessments and commitments.

Hunka et al. (2023) conducted a comparative analysis of NASA’s GEDI and ESA’s CCI biomass maps. The comparison revealed strong relations between both products and NFI estimates in four countries. However, the study emphasised the importance of validating these correlations with independent reference data. Despite the identified relations, direct comparisons were limited by dissimilarities in the uncertainty estimation frameworks employed by NASA GEDI and ESA CCI Biomass. The study advocates for active collaboration among map producers, as well as engagement with policy experts. Formalising approaches for the operational use of Above-Ground Biomass Density (AGBD) maps in national-level reporting is crucial. Furthermore, the study underscores the need for transparent and comprehensive public releases of AGBD estimates, including associated variances. This approach aligns with guidance from the Intergovernmental Panel on Climate Change (IPCC) and ensures that the information is both actionable and impactful for policy decisions.

4. Drivers of biomass change

Understanding and quantifying drivers of biomass change are important to attribute changes related to management or natural processes. Existing dataset mostly focussed on biomass losses, which are easier to detect.

Senf C. and Seidl R. (2021) used satellite data to map three decades of forest disturbances across continental Europe. Between 1986 and 2016, 17% of Europe’s forest area was disturbed by anthropogenic and/or natural causes. The majority of disturbances were stand-replacing. Storm- and fire-related disturbances each accounted for approximately 7% of all disturbances recorded in Europe. Storm-related disturbances were most prevalent in western and central Europe, where they locally

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accounted for >50% of all disturbances. Fire-related disturbances were a major disturbance agent in southern and south-eastern Europe. The dataset available here: https://zenodo.org/records/8202241. It contains three classes of disturbances: (1) bark beetle or wind disturbances, (2) fire disturbances, (3) other disturbances, mostly harvest at 30 m resolution.

The second version of the map is available for browsing, but not for downloading at the moment of compiling this report (https://albaviana.users.earthengine.app/view/european-forest-disturbance-map). In the new version, the timeline is extended until 2021 (Viana-Soto and Senf, in prep).

Curtis et al. (2018) produced a global map of drivers of forest cover loss for the period 2001 to 2015. Despite tree cover losses observed at 30 m spatial resolution, the drivers dataset indicates only primary driver at 10 km spatial resolution. This resolution is too coarse for our purposes. Basically, the entire Europe is represented by “Forestry” driver, while Asian Russia by “Wildfire”.

Using LVOD AGB change, Yang et al. (2022) Inferred drivers of change from the Curtis et al. dataset and other data like annual forest loss map and attributed 25 km AGB change to fires, deforestation, regrowth and forestry. The key result is that northern forests that show an increase of AGB change are young or middle aged, opposite to what global simulation models predict, as these models mostly lack the effect of forest demography on C sinks from recovery of past natural disturbances and harvest.

4.1. Own study on the drivers of biomass change

Analysis of AGB change from CCI maps since 2017 indicate that most European areas are losing biomass, which is incorrect, compared to national forest inventories. This is possibly because of striped patterns from the ALOS orbits that are not yet fully corrected in the algorithm, and because CCI may underestimate biomass and biomass increments in old forests. We are working with the group producing the maps to improve these effects.

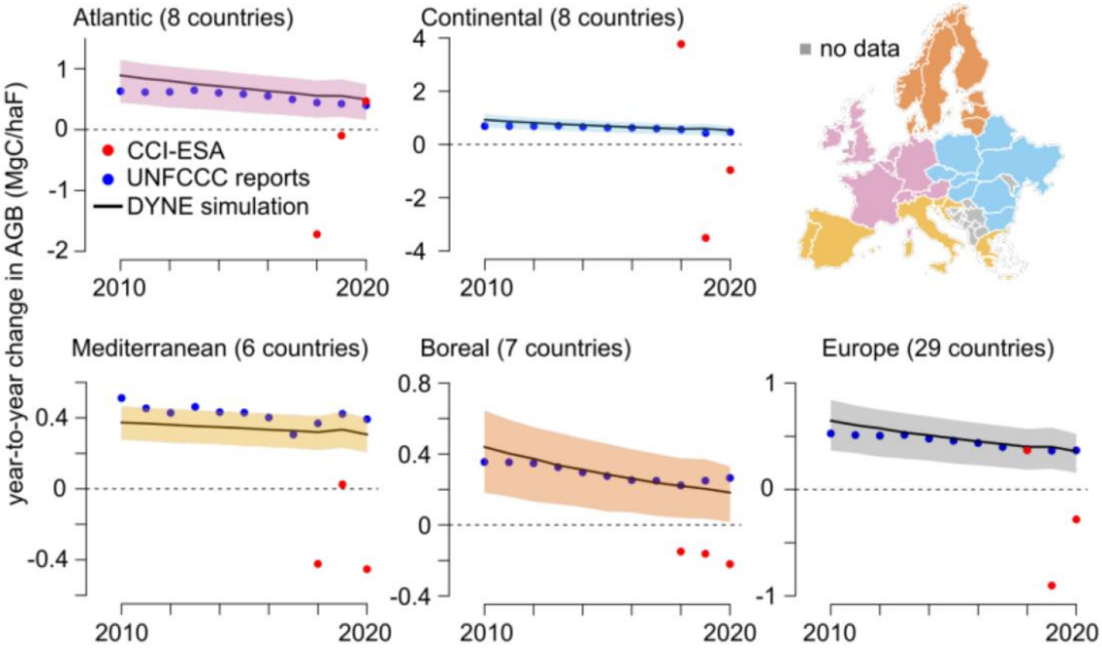

Figure 1. Biomass change from ESA CCI maps since 2017 obtained by taking the year-on-year difference of AGB between subsequent years (red dots) indicating an unrealistic biomass loss and a too large inter-annual variation. The blue dots are the NFI based AGB change submitted to UNFCCC based on ≈ 5 years revisits of thousands of forest plots and the black line is the result of a data driven model of regrowth and loss of AGB at 18 km resolution, calibrated to NFI data for the first year by adjusting the ratio of disturbance severity to AGB loss (Ritter et al. in review 2024)

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Existing drivers of change datasets focus solely on biomass losses, whereas our objective encompasses both loss and gain. Additionally, we aim to validate the CCI Biomass and drivers of tree loss datasets. We use the Geo-Wiki approach (Laso Bayas et al., 2022; Lesiv et al., 2022). This method involves visual interpretation of very high-resolution imagery and vegetation indices by trained experts. They examine images to confirm biomass changes (loss or gain) between 2010 and 2020, specifying possible reasons such as clearcutting, fire, land use change, forest regrowth, etc. The target resolution is aligned with CCI Biomass maps (100 m) for recent changes (2010-2020).

For our assessment, we implemented a random stratified sample design with two-fold stratification: geographic regions (Nordic countries, Mediterranean countries, Eastern/central Europe, Western Europe, European Russia, Asian Russia) and magnitude of biomass changes (0-50, 50-100, 100-150, >150) in both directions (biomass losses and gains). In 2023, experts checked and classified approximately 4,000 locations. This ongoing effort will continue into the next year to achieve a more statistically robust assessment. The distribution of locations is presented in Figure 2. The results of visual interpretation are presented in Table 2.

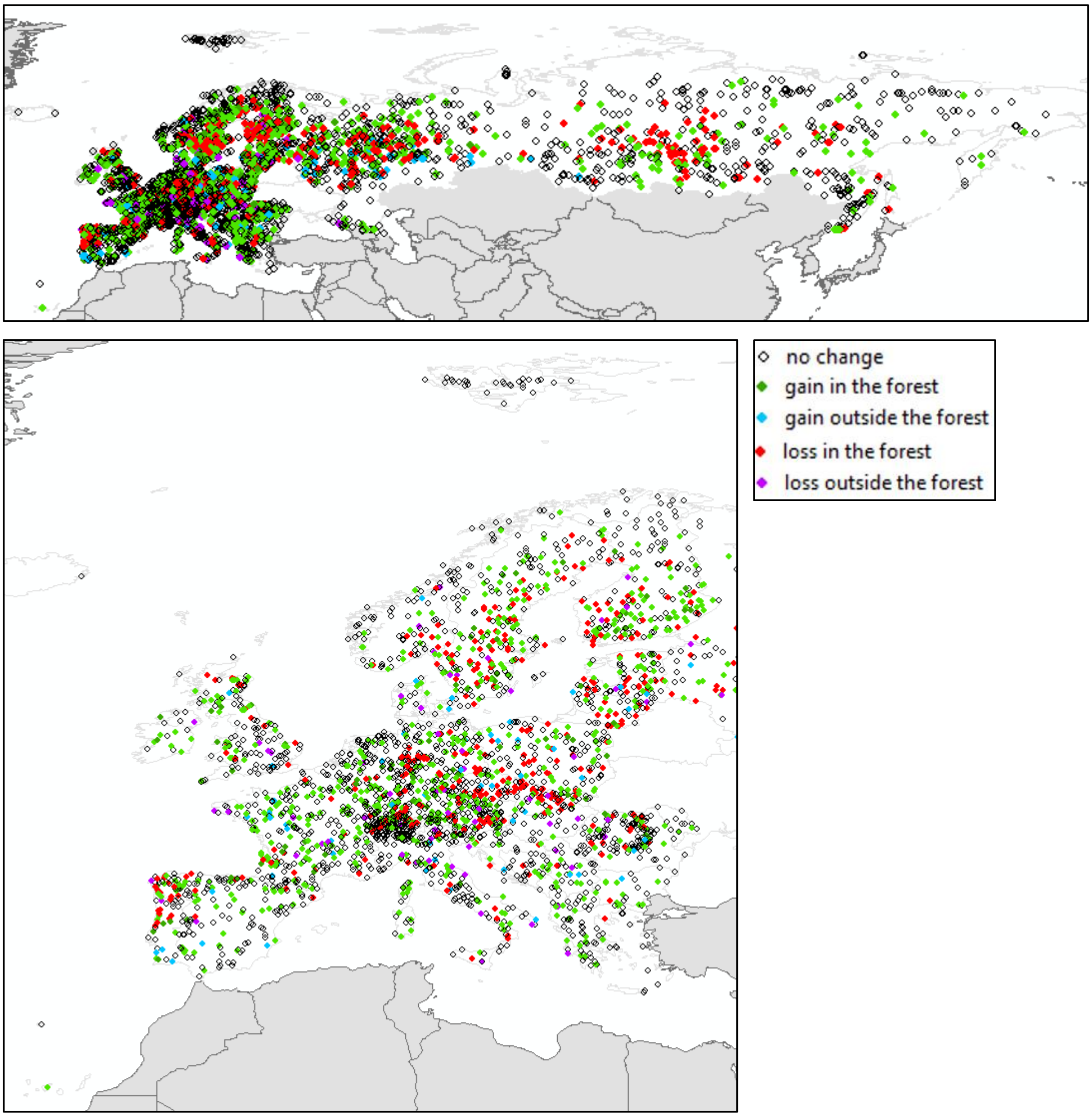

Figure 2. Distribution of the sample location for visual interpretation

Table 2. Results of classification of drivers of biomass change

Drivers of change	**Number of locations**	**Share, %**
Gain: afforestation	62	1.6
Gain: forest growth	842	21.1
Gain: reforestation	98	2.5
Gain: tree crops, agroforestry	19	0.5
Gain: urban trees	2	0.1
Loss: cropland	26	0.7
Loss: forest management	410	10.3
Loss: insects and diseases	21	0.5
Loss: mining and crude oil extraction	2	0.1
Loss: other natural disturbances	5	0.1
Loss: roads/trails/buildings	31	0.8
Loss: tree/shrub crops	9	0.2
Loss: wildfire	63	1.6
Loss: windthrow	5	0.1
No, remains forest	1649	41.3
No, remains non-forest	657	16.5
Not clear, not good imagery	67	1.7
Not sure, difficult case	21	0.5
Grand Total	3989	100.0

Forest gain was confirmed at 1,023 locations, with 92% attributed to reforestation or forest growth, 6% to afforestation, 2% urban areas, tree crops, and agroforestry. Biomass losses were confirmed at 572 locations, revealing that 72% are associated with forest management (harvesting or thinning), 12% with land use change or activities outside of the forest (infrastructure, cropland, tree crops), 11% with wildfires, 4% with insects and deceased, 1% with windthrow, and 1% with other natural disturbances.

Results of the visual check of reported biomass change in the CCI biomass product are shown in Table 3. The visual inspection of the CCI Biomass change product reveals that in approximately 50% of cases, changes are not visually discernible. This observation holds even when applying a high threshold for changes (>50 t/ha), which should theoretically be visible. This suggests that CCI Biomass overestimated the area of changes. A portion of reported changes comes from the different set of space instruments in 2010 and 2020.

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Table 3. Results of visual validation of CCI biomass map (changes exceeding ±50 t/ha)

CCI Biomass quality flag	**share of locations at visual interpretation, %**			
	Not visible	**gain**	**loss**	**total**
AGB loss	54	1	45	100
Potential AGB loss	65	2	33	100
Improbable change	50	39	11	100
Potential AGB gain	37	62	2	100
AGB gain	47	52	1	100
Total	52	28	20	100

The collected data will serve the following purposes:

- Calculating regional statistics on the drivers of biomass change.
- Validating existing biomass datasets, such as ESA CCI Biomass.
- Providing feedback to the ESA CCI Biomass project to contribute to dataset improvement.
- Validating datasets on biomass loss, for example Viana-Soto and Senf (in preparation).

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Conclusions

ESA CCI Biomass and biomass change maps appear to be valuable sources of information, although change maps still have large uncertainties. The advantage lies in the utilisation of various relevant remote sensing instruments, including radar, lidar, and optical sensors provided by different space agencies such as ESA, NASA, and JAXA. These maps not only report accuracy of estimations of both AGB and AGB change but also continually improve over time through reprocessing of early products (e.g., for the year 2010) with plans for ongoing enhancements and continuing the time series. A noteworthy feature is the successful calibration of CCI Biomass maps to national or regional ground data collections, effectively removing bias and enhancing accuracy (Schepaschenko et al., 2021; Avitabile et al., 2023).

Biomass change maps based on L-VOD (Vegetation Optical Depth) also demonstrate great potential due to their relatively long observation period starting from 2010, all with the same sensor, but effects of water content changes and radio frequency interference (RFI) need to be carefully considered. Further the rather coarse resolution of this dataset limits attribution in Europe where harvest, natural disturbances and regrowth operate on smaller spatial scales. The perspective of downscaling LVOD to 100 m change maps should improve the attribution and will be addressed in Europe in the EYE CLIMA project.

Avitabile et al. (2023) offer a European biomass map for 2020 that is calibrated to sub-national statistics. This calibration ensures the map's consistency and is unbiased concerning both national statistics and UNFCCC national reporting.

The visual interpretation of very high-resolution imagery indicates that CCI Biomass tends to overestimate the area of changes. However, the direction of changes is recognized correctly. Notably, 72% of biomass loss is associated with forest management, while 92% of biomass gain occurs within forest areas and associated with reforestation and forest growth.

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