**Article:**

Ochiai, O. orcid.org/0000-0002-2543-3262, Poulter, B., Seifert, F.M. et al. (22 more authors) (2023) Towards a roadmap for space-based observations of the land sector for the UNFCCC global stocktake. iScience, 26 (4). 106489. ISSN 2589-0042

https://doi.org/10.1016/j.isci.2023.106489 iScience

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Review

# Toward a roadmap for space-based observations of the land sector for the UNFCCC global stocktake

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## SUMMARY

**Space-based remote sensing can make an important contribution toward monitoring greenhouse gas emissions and removals from the agriculture, forestry, and other land use (AFOLU) sector, and to understanding and addressing human-caused climate change through the UNFCCC Paris Agreement. Space agencies have begun to coordinate their efforts to identify needs, collect and harmonize available data and efforts, and plan and maintain a long-term roadmap for observations. International cooperation is crucial in developing and realizing the roadmap, and the Committee on Earth Observation Satellites (CEOS) is a key coordinating driver of this effort. Here, we first identify the data and information that will be useful to support the global stocktake (GST) of the Paris Agreement. Then, the paper explains how existing and planned space-based capabilities and products can be used and combined, particularly in the land use sector, and provides a workflow for their harmonization and contribution to greenhouse gas inventories and assessments at the national and global level.**

## SPACE-BASED OBSERVATION SUPPORTING THE PARIS AGREEMENT IN THE LAND SECTOR

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (PA),[1] adopted by 196 countries in 2015 and which came into force on 4th November 2016, sets a limit for countries to keep global warming to well below 2°C above pre-industrial levels, with the aim of limiting it to 1.5°C. Signatory parties communicate through their nationally determined contributions (NDCs), the actions they will take to reduce their greenhouse gas (GHG) emissions to reach the goals of the PA. Anthropogenic activities have led to increases in atmospheric carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). From 1959 to 2019, 19% of the net total $CO_2$ emissions were attributed to land use change (sources) and 32% of the total emissions were taken up by the land (sinks)[2]; for $CH_4$ from 2000 to 2017, over half of the emissions were from fossil fuel burning and agricultural activities[3]; and for $N_2O$, from 2007 to 2016, almost half of the emissions were from agriculture.[4]

Article 14 of the PA mandates a collective assessment of progress toward its goals, known as the global stocktake (GST),[5] which follows the PA's 5-year cycle and informs every new set of NDCs. Reports from Parties to the UNFCCC are a source of input to the GST. Parties report their GHG emissions to the UNFCCC secretariat using standardized Intergovernmental Panel on Climate Change (IPCC) guidelines.[6–8] Under the PA, Parties have agreed standardized tables to report GHGs through the enhanced transparency framework starting in 2024 and biennially thereafter. Information reported in biennial transparency reports will be considered at a collective level as an important input into the GST.

Based on the IPCC guidelines, anthropogenic emissions of GHGs (including $CO_2$, $CH_4$, and $N_2O$) reported by countries through their GHG inventories comprise the following components: (i) energy, (ii) industrial processes and product use, (iii) agriculture, forestry, and other land use (AFOLU), (iv) waste, and

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Continued

(v) other (e.g., indirect emissions from nitrogen deposition from non-agriculture sources). In its simplest form, the AFOLU process of reporting fluxes from land requires two types of information[6,8]: (i) activity data for land cover/use and hence derived land use and land cover change, and (ii) so-called ''emission factors'', which are the quantities of GHG emitted per unit area of activity or change from one category to another. A matrix of known emission factors is required to allow calculation of emissions arising from conversion of one land use to another. Satellite sensor data can contribute significantly to the identification of activity data for land use and land cover change between the categories described in the IPCC guidelines. It is also increasingly feasible that the emission factors can be determined, or at least improved, by the inclusion of information derived from satellite sensor data on the carbon content of each cover type through, for example, estimates of biomass.

This paper describes current and planned capabilities from space-based data and products for supporting AFOLU estimation and assessments. It presents a plan for harmonization of these products and more coordinated activities across space agencies and partners that will enable increasing uptake of Earth observation (EO) data and support both GHG inventories in national reporting and the GST as a global assessment process in the coming years.

## UNDERSTANDING THE GST NEEDS AND PROCESS FOR EARTH OBSERVATION

EO satellites have been acquiring global data on the state and dynamics of the global landscape for over 40 years, and their role in understanding climate change, GHG emissions, and mitigation and adaptation needs has increasingly been recognized. The most recent update of the IPCC guidelines on AFOLU[8] noted the significant advances in the use of EO for monitoring land use and land cover change, as well as directly quantifying GHGs in the atmosphere. Generic guidance on the use of biomass density maps for GHG inventories was also provided. However, the widespread uptake of these EO products in domestic GHG inventories requires substantive collaboration between space agencies, national teams, and GHG inventory experts with understanding of EO satellite limitations.

The GST is a fundamental component of the PA and will assess the collective progress toward achieving the purpose of the PA and its long-term goals, including those for mitigation, adaptation and finance, response measures and loss and damage, and cross-cutting issues, such as science and equity. The GST thus links aggregate implementation of NDCs with the overarching goals of the PA and includes the aim of raising climate ambition, where EO satellite data could play a role in supporting decision-makers by providing alternative data and information. The first GST takes place in 2020–2023. Decision 19/CMA.1 outlines the modalities of the GST. The first GST will operate in 3 phases[5]:

i) **Information collection and preparation (2020–2023):** In this phase, the information necessary to conduct the GST will be collected and compiled from a wide range of sources to prepare for the technical assessment component of the GST. Information includes synthesis reports by the UNFCCC secretariat, such as those estimating the state of GHG emissions by sources and removals by sinks, mitigation efforts undertaken by Parties, NDCs, scientific studies, country reporting efforts, and other initiatives or actions. This includes contributions from the systematic observation community.
ii) **Technical assessment (2022–2023)**: In this phase, there will be an assessment of the implementation of the PA to gauge collective progress toward achieving the purpose and long-term goals of the PA, as well as opportunities for enhanced action and support. This includes international cooperation for climate action through technical dialogs and joint contact groups.
iii) **Consideration of outputs (2023):** This phase will discuss the implications of the findings of the technical assessment with a view to achieving the outcome of the GST of informing Parties in updating and enhancing, in a nationally determined manner, their actions and support. This is in accordance with relevant provisions of the PA, as well as enhancing international cooperation for climate action.

The space agencies and CEOS have a major interest in providing EO for mitigation and adaptation, and in better understanding opportunities to enhance finance and support equity through:

i) Mitigation (i.e., reporting, measurement and tracking the progressive decrease in national GHG emissions)

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https://doi.org/10.1016/j.isci.2023.106489

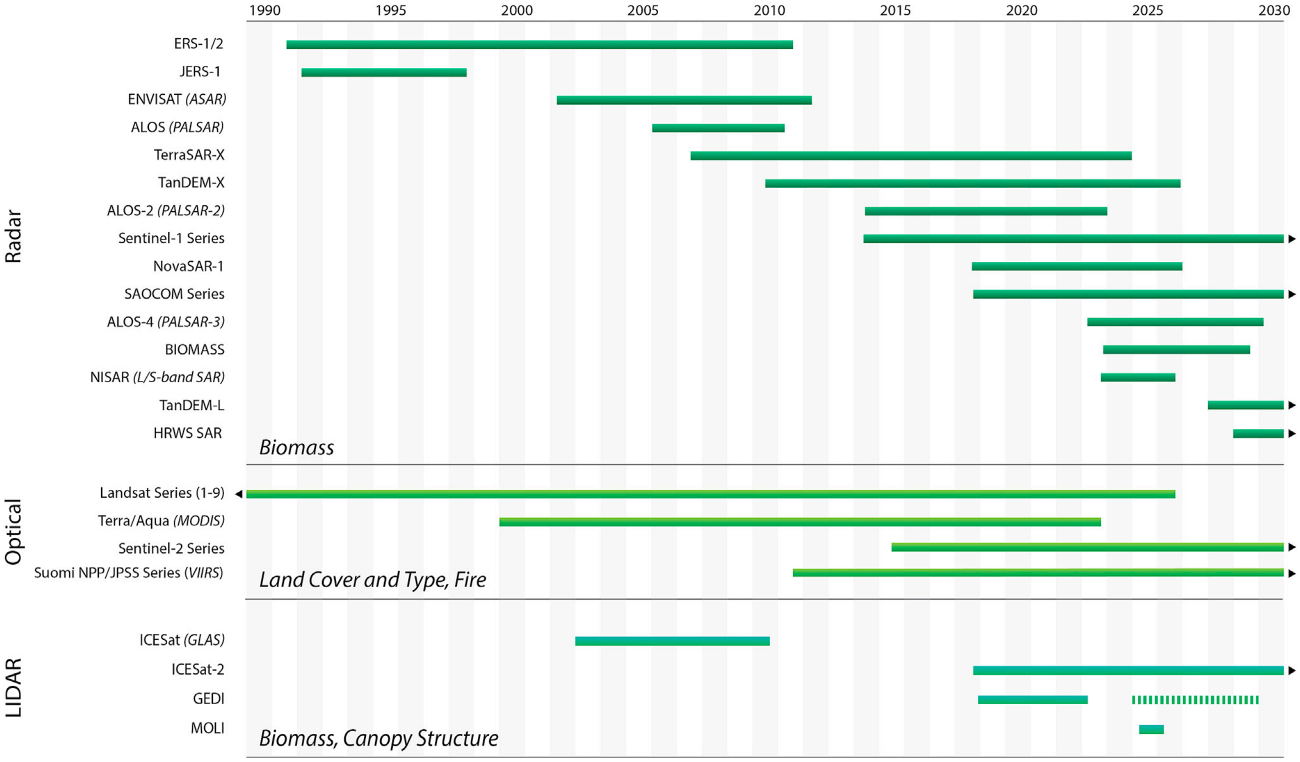


**Figure 1. Earth observation satellite sensor types (CEOS member space agencies) supporting AFOLU information needs, and their (estimated) lifespans**

ii) Adaptation to ongoing climate change and its consequences and impacts

iii) Finance of mechanisms to support the PA

iv) Equity among Parties for implementation, with this being implicit in the overall process.

Satellite data also inform top-down estimates of emissions through measurements of atmospheric composition and through provision of information on both land cover change and emission factors to the AFOLU process. All these comprise elements of the CEOS Roadmap in support of the PA and GST.

In preparation for the first phase of the GST,[5] CEOS agreed to form dedicated teams and to develop a GST Roadmap for GHGs and AFOLU to i) identify the substantive benefits of using EO data, ii) provide satellite products that need to be communicated to the policy community, and iii) understand potential barriers to the effective use of EO data in support of the PA.

## SPACE-BASED CAPABILITIES AND DATASETS IN SUPPORT OF AFOLU

EO satellite sensors operating in different modes (primarily optical, radar, thermal, and lidar) can provide information on biomass, land cover and type, fire, and canopy structure (Figure 1). Combining data from different sensors provides more information on agriculture (crop type and its change), forests and mangroves (extent, height, and canopy structure), and their biomass. This information can contribute significantly to the methodologies set out in the IPCC guidelines but cannot provide all the land use information required by the IPCC (e.g., soil biomass) except within preliminary research. Therefore, ensuring accurate and comprehensive representation of these capabilities in the AFOLU sector is crucial to developing their contribution to the GST and their take-up by countries.

The CEOS AFOLU team organized four dedicated dataset sub-teams of experts (Agriculture, Land Cover and Forests, Aboveground Biomass, and Wetlands and Mangroves) who have already played long-standing and active roles in producing space-based datasets that can contribute to the GST. Each sub-team has summarized current capabilities and identified harmonizing efforts that could provide more consistent and robust datasets fulfilling the requirements of the GST process. It should be noted that current capabilities do not provide fully consistent support for AFOLU needs but the roadmap being developed by CEOS aims at steady development of more comprehensive support.

## Agriculture

The food system has been estimated to contribute 18%–37% of historical GHG emissions.[9] Agriculture accounted for 25% of the global GHG emissions in 2018 and this percentage is rising.[9,10] However, for agriculture to meet the nutrition requirements of a growing global population, it is estimated that production must increase by 60% above 2006 levels by 2050.[11]

Contributions from EO include land use, land cover, and land management state and change information. Global datasets on agricultural crop production systems (including crop types, crop condition, rotations, cover utilization/duration/biomass accumulation, and tillage practices), and rangeland grazing areas (including quality, intensity of use and management) can make a significant contribution to the AFOLU component of agricultural NDCs and as part of the GST.

To address the need for more quantitative information on agricultural land cover, land use, and management practices, a set of Essential Agricultural Variables (EAVs) are being developed by the GEO Global Agricultural Monitoring (GEOGLAM) initiative to address the needs of multiple global policy and program actions at international and national scales. Based on the EAV work, Table 1 identifies which climate-critical measurements can be provided by EO, along with the characterization of each in terms of coverage, spatial resolution, and revisit frequency. Many current missions meet the needs of AFOLU, and several are already employed in operational systems. Using the requirement categories in Table 1, Table 2 provides a list of the current and future satellite missions that can be used to derive climate-relevant variables in support of AFOLU.

Over the last couple of decades, considerable effort has been devoted to developing moderate to coarse scale global land cover products (summarized in Table 3) based on imagery from a single year or accumulated over several years. Most of these treat agriculture as a single class, without providing information on crop type, agricultural management, field sizes, seasonality, crop rotations, etc. Evolution of multiple satellite sensors, data availability, and methods hinder comparison between products, which limits their use in change detection. However, more recent work by the Copernicus Land Service is focused on developing annual assessments and 5-year change products. The first change product was released in 2020 based on 2016 to 2019 annual products and at 100 m resolution. This work approaches the requirements of the IPCC and the needs for AFOLU on land cover change in the GST.

A major step toward global land cover monitoring was realized by the European Space Agency (ESA) WorldCover project which demonstrated that land cover maps can be produced within 3 months of the end of a year. The dataset has 11 classes at 10 m resolution and has an overall accuracy of 74.4% (WorldCover Product Validation Report v1.1). In the WorldCover product, agriculture can be a component of cropland, grassland (pasture, uncultivated cropland in reference year), shrubland, or tree cover classes (greenhouses are considered built-up). In the cropland class, it is seen as a general yearly class (WorldCover Product User Manual v1.0). This does not reflect the dynamic nature of agriculture, which can have between one and three cropping seasons within any year. To provide more information for the agriculture class, the WorldCereal project is currently working on the first seasonally updated cropland and crop type map at 10 m resolution. Perhaps more important for monitoring purposes, ESA's WorldCereal project is developing the first open-source and cloud-agnostic (implementable on any cloud infrastructure provider) systematic approach to create global seasonal cropland extent and crop type maps. This will be used to produce maps at the end of each season per agro-ecological zone that include 10 m crop extent, as well as maize and wheat crop type maps based on the current open and freely available datasets from Sentinel 1, Sentinel 2, and Landsat 8. The first large-scale demonstrations of the products have been produced and validated. These span 1.5 M km$^2$ over five different countries (Argentina, Spain, France, Ukraine, and Tanzania) on three continents. WorldCereal is also building the first global reference database for agricultural monitoring. Data collection and gathering efforts are streamlined and harmonized in close collaboration with the GEOGLAM *In Situ* Data Working Group, and the WorldCereal datasets will be managed by the GEOGLAM community when the initiative ends. The project will produce multi-temporal/seasonal

**Table 1. GEOGLAM Core Essential Agricultural Variables (EAVs) and actual/potential capacity to monitor from EO satellites**

| GEOGLAM Core Essential Agricultural Variables | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Resolution | | When | Mapping | | | | | Attributes classes | | | |
| Req# | Spatial | Spectral (Range) | Effective observation frequency (cloud free) | Agriculture mask | Rangeland mask | Crop mask | Crop type area and growing calendar | Field boundaries | Crop condition | Crop yield | Crop biophysical variables | Agricultural management practices |
| Coarse Resolution Sampling (>100 m) | | | | | | | | | | | | |
| 1 | >500–2000 m | OP | D | | | | | | ▣ | | □ | |
| 2 | 100–500 m | OP | 2 to 5 per week | ▣ | ▣ | ▣ | ▣ | ▣ | ▣ | □ | □ | □ |
| 3 | 5–50 km | MW | D | | | | | | ▣ | ▣ | ▣ | |
| Moderate Resolution Sampling (10 to 100 m) | | | | | | | | | | | | |
| 4 | 10–70 m | OP | M (min 2 out of season +3 in season). Every 1–3 years. | ■ | ■ | ▣ | ░ | ░ | | | | ▣ |
| 5 | 10–70 m | OP | ~W (8 days; min. 1 per 16 days) | | | ▣ | ▣ | ░ | ▣ | ▣ | ▣ | ▣ |
| 6 | 10–100 m | MW (DP) | ~W (8 days; min. 1 per 16 days) | ☁ | ▣ | ▣ | ▣ | ░ | ▣ | ▣ | ▣ | ▣ |
| Fine Resolution Sampling (5 to 10m) | | | | | | | | | | | | |
| 7 | 5–10 m | VIS, NIR, SWIR | M (min. 3 in season) | | | ■ | ■ | ▣ | | | | |

(*Continued on next page*)

**Table 1.** ***Continued***

| GEOGLAM Core Essential Agricultural Variables | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Resolution | | When | Mapping | | | | | Attributes classes | | | |
| Req# | Spatial | Spectral (Range) | Effective observation frequency (cloud free) | Agriculture mask | Rangeland mask | Crop mask | Crop type area and growing calendar | Field boundaries | Crop condition | Crop yield | Crop biophysical variables | Agricultural management practices |
| 8 | 5–10 m | VIS, NIR, SWIR | ~W (8 days min. 1 per 16 days) | | | | ◩ | | ▣ | | ▣ | ▣ |
| 9 | 5–10 m | SAR (DP) | M | | | ◩ | ◩ | ◩ | | | | ◩ |
| Very Fine Resolution Sampling (<5 m) | | | | | | | | | | | | |
| 10 | <5 m | VIS, NIR | 3 per year (2 in season +1 out of season) Every 3 years | | | ■ | ■ | ■ | | | | |
| 11 | <5 m | VIS, NIR | 1 to 2 per month | | | | ▣ | | | ▣ | | ▣ |

OP, Optical; VIS, Visible; NIR, Near InfraRed; VNIR, Visible/Near InfraRed; SWIR, Short Wave InfraRed; MW, Microwave; DP, Dual Polarization; D, Daily; W, Weekly; M, Monthly.

▣, All sizes; □, Large (>15 ha); ▨, Medium (1.5–15 ha); ■, Small (<1.5 ha); ◩, Small/Medium; ▢, Medium/Large; ☁, High cloud.

**Table 2. Satellite missions that derive climate-relevant variables for agriculture in support of AFOLU monitoring**

| | Satellite missions | | Resolution and spectral range | | Timing | |
|---|---|---|---|---|---|---|
| Req# | Core missions | Contributing missions | Spatial resolution | Spectral range | Effective observ. frequency (cloud free) | Growing season calendar |
| Coarse Resolution Sampling (>100 m) | | | | | | |
| 1 | Aqua/Terra (1000 m) | Suomi-NPP/JPSS (750 m)<br>Proba-V (1000 m)<br>SPOT-5 (1150 m) | >500–2000 m | OP | D | all year |
| 2 | Aqua/Terra (250/500 m)<br>Sentinel-3A (500 m) | Suomi-NPP/JPSS (375 m)<br>Proba-V (100/333 m) | 100–500 m | OP | 2 to 5 per week | all year |
| 3 | Aqua<br>GCOM-W1/W2 | SMOS<br>SMAP | 5–50 km | MW | D/W | all year |
| Moderate Resolution Sampling (10 to 100 m) | | | | | | |
| 4 | Landsat 7/8 (30 m)<br>Sentinel-2A/2B (10–20 m) | ResourceSat-2 (56 m)<br>CBERS-4 (20–40 m) | 10–70 m | OP | M (min 2 out of season +3 in season). Required every 1–3 years. | all year |
| 5 | Landsat 7/8 (30 m)<br>Sentinel-2A/2B (10–20 m) | ResourceSat-2 (56 m)<br>CBERS-4 (20–40 m) | 10–70 m | OP | ~W (8 days; min. 1 per 16 days) | growing season |
| 6 | Sentinel-1A/1B (C)<br>Radarsat-2 (C), RCM (C)<br>ALOS-2 PALSAR-2 (L) | RISAT-1/1A (C)<br>RISAT-3 (L) | 10–100 m | MW (DP) | ~W (8 days; min. 1 per 16 days) | growing season |
| Fine Resolution Sampling (5 to 10 m) | | | | | | |
| 7 | | SPOT-7<br>CBERS-4 | 5–10 m | VIS, NIR, SWIR | M (min. 3 in season) | growing season |
| 8 | | SPOT-7<br>CBERS-4 | 5–10 m | VIS, NIR, SWIR | ~W (8 days; min. 1 per 16 days) | growing season |
| 9 | Sentinel-1A/1B (C)<br>Radarsat-2 (C),<br>RCM (C)<br>ALOS-2 (L) | RISAT-1/1A (C)<br>RISAT-3 (L) | 5–10 m | MW (DP) | M | growing season |
| Very Fine Resolution Sampling (<5 m) | | | | | | |
| 10 | | Pleiades,<br>SPOT-7 | <5 m | VIS, NIR | S (3 per year; 2 in season +1 out of season); Required every 3 years | all year |
| 11 | | Pleiades,<br>SPOT-7 | <5 m | VIS, NIR | ~~M (1–2 per month) | growing season |

OP, Optical; VIS, Visible; NIR, Near InfraRed; VNIR, Visible/Near InfraRed; SWIR, Short Wave InfraRed; MW, Microwave; DP, Dual Polarization; D, Daily; W, Weekly; M, Monthly; S, Seasonal; C, C-band; L, L-band.

(1) Requirement 3 only includes crop-specific parameters (e.g., soil moisture and evaporation) and does not include precipitation.

(2) Missions listed in this table are under consideration and evaluation for long-term GEOGLAM operations due to their accessibility and continuity plans. During the development phase, several other missions will be used for specific focused studies (e.g., TerraSAR-X, COSMO-SkyMed, WorldView-2/3, QuickBird, UK-DMC-II, Formosat-2, NMP-EO1, and China HJ-1).

**Table 3. Description of global agriculture products relevant for AFOLU monitoring**

| Dataset definition | Agriculture relevant classes | Owner | Date of coverage | Currently active | Refresh | Minimum spatial resolution | Target groups applications | Availability |
|---|---|---|---|---|---|---|---|---|
| **European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover** Time series of consistent global land cover maps produced annually from 1992 to 2015 using a multi-sensor strategy (to make use of all suitable data and maximize product consistency; ESA 2018). | **Legend** (based on the Food and Agriculture Organization (FAO) Land Cover Classification System (LCCS):<br>**10:** Cropland, rainfed<br>**11:** Herbaceous cover<br>**12:** Tree or shrub cover<br>**20:** Cropland, irrigated or post-flooding<br>**30:** Mosaic cropland (>50%)/natural vegetation (tree, shrub, herbaceous cover) (<50%)<br>**40:** Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%)/cropland (<50%)<br>**130:** Grassland | ESA, 2010.[a] | 1992– 2015 | YES | An original 3-epoch series of global land cover maps were updated to annual mapping. | 300 m | Climate Community Climate modelers | Open[d] |
| **GlobCover** (ESA, 2009) Map of global land cover extent. | **Legend:** (22 class LC)<br>11: Post-flooding or irrigated croplands<br>14: Rainfed croplands<br>20: Mosaic Cropland (50%–70%)/Vegetation (grassland, shrubland, forest) (20%–50%)<br>30: Mosaic Vegetation (grassland, shrubland, forest) (50%–70%)/Cropland (20%–50%)<br>110: Mosaic Forest/Shrubland (50%–70%)/ Grassland (20%–50%)<br>120: Mosaic Grassland (50%–70%)/Forest/ Shrubland (20%–50%)<br>130: Grassland<br>140: Closed to open (>15%) grassland | ESA, 2009[b] | 2004–2006<br>2009 | NO | Original coverage 2004–06, with open refresh in 2009 | 300 m | Land Cover Community (Global land cover states over two for two time periods | Open[e] |
| **Copernicus CGLS Dynamic Land Cover.** Time series of consistent global land cover maps for 2016–2019 and updated annually. Global change product 2016–19 released in 2020 (Africa available at time of publication). Data from PROBA-V 100 m time series 2016–2019 with Sentinel missions to be used from 2020. | **Legend** (23 class LC):<br>Shrubland, herbaceous, cropland | Copernicus, 2015.[c] | 2016 | YES | Annual, plus global 5-year change products 2016–19 | 100 m | Land cover state and change | Open[f] |

[a] https://www.esa-landcover-cci.org/?q=overview.

[b] http://due.esrin.esa.int/page_globcover.php.

[c] https://land.copernicus.eu/global/products/lc.

[d] http://maps.elie.ucl.ac.be/CCI/viewer/download.php.

[e] http://due.esrin.esa.int/page_globcover.php.

[f] https://lcviewer.vito.be/2015.

datasets for 2022 and, more importantly, will leave a post-project legacy of an open-source system and reference database. The GEOGLAM community is exploring options to operationalize the system, expand the system to cover more crops, and develop change products through time.

There is often a need to develop regional land cover mapping based on open and free multiple EO data sources, for which a cloud-based data analysis platform such as Google Earth Engine is becoming preferred.[12] The challenge is how to harmonize the regional mapping efforts to be consistent with the IPCC guidelines.

## Land cover and forest

Land use and land cover (LULC) and change information is essential for national GHG inventories, activity data estimation, and global AFOLU modeling and assessments. LULC information derived from EO data can support these processes by providing national GHG inventories with improved activity data and land change information for AFOLU assessments. It can also enhance the consistency and comparability of national GHG inventory data and global GHG analyses when global EO-derived LULC data are harmonized with National GHG inventory information. Integration of EO data into National GHG inventories has seen significant progress in recent years, particularly in forest monitoring,[13] but significant challenges remain. These include the consistency of data streams, providing data for different land use types and transitions, definitions (including how managed and unmanaged lands are distinguished), and accounting for natural versus anthropogenic impacts. Moving from land cover to land use is one particular challenge for which multiple data products may be required. The choice of data to support these AFOLU-related assessments depends on the objectives, including the scale of the analysis, type of approach used (i.e., stock-difference or gain-loss), the Tier requirements, and other factors.

LULC products are being developed as part of several ongoing projects and programs (e.g., Figure 2). These include several Land Cover maps such as GlobCover, and the subsequent ESA Climate Change Initiative (CCI) Land Cover, Copernicus Global Land Service, and WorldCover (Table 4). In addition, the data-driven HILDA + product[14] combines several EO-derived LULC datasets and national land use statistics from the Food and Agriculture Organization of the United Nations (FAO) to provide a consistent approach for global- and national-scale assessments of annual global LULC transitions between 1960 and 2019. A longer history of land use data (from 850) is presented in LUH2,[15] which is a required forcing dataset in many Coupled Model Intercomparison Project (CMIP6) experiments. LUH2 connects input datasets on historical land use, crop functional type maps, Landsat-based forest loss, and shifting cultivation estimates with future projections from integrated assessment models. This harmonized dataset serves as an input to Earth system models, enabling them to assess the effects of land use on the global carbon-climate system.

As part of LULC characterization, forest/tree cover derived from EO can contribute to defining forest extent and types, allowing more precise assignment of growth rates, wood densities, biomass expansion factors, and emissions factors. Table 5 highlights the essential forest information requirements, while Table 6 indicates current and future EO missions that can provide supporting data. Several global forest extent and change, and percentage tree cover maps have been generated (Table 7). The most notable is the dataset of Hansen et al. (2013), which is available through the Global Forest Watch (GFW) of the World Resources Institute. GFW provides annual maps of tree cover loss at global level retrieved from Landsat sensor data with 30 m nominal spatial resolution. Tree cover height maps for 2000 and 2020 are also available and, in future, annual maps of tree cover height will allow annual extent, loss, and gain to be derived. Contextual products, such as plantation datasets and primary forest/intact forest maps, allow GFW users to move from tree cover to forest-related land use information. Other relevant forest cover datasets available include global forest age,[16] forest types and plantations,[17] and those with a regional or ecosystem type focus (e.g., mangroves).

There remains, however, a striking divergence in LULC and LULC transitions inferred from the available products, which is reflected in both the magnitude of the extent of LULC classes and the trend of LULC transitions in the past decades.[18,19] For example, for the same historical period, the CCI Land Cover shows a global decreasing trend in forest extent[20] while the GFW[21] shows increasing forest loss.[22] Reconciling the different approaches and definitions and addressing issues of accuracy and consistency of time series are therefore major priorities for the AFOLU Roadmap Land Cover and Forests Team.

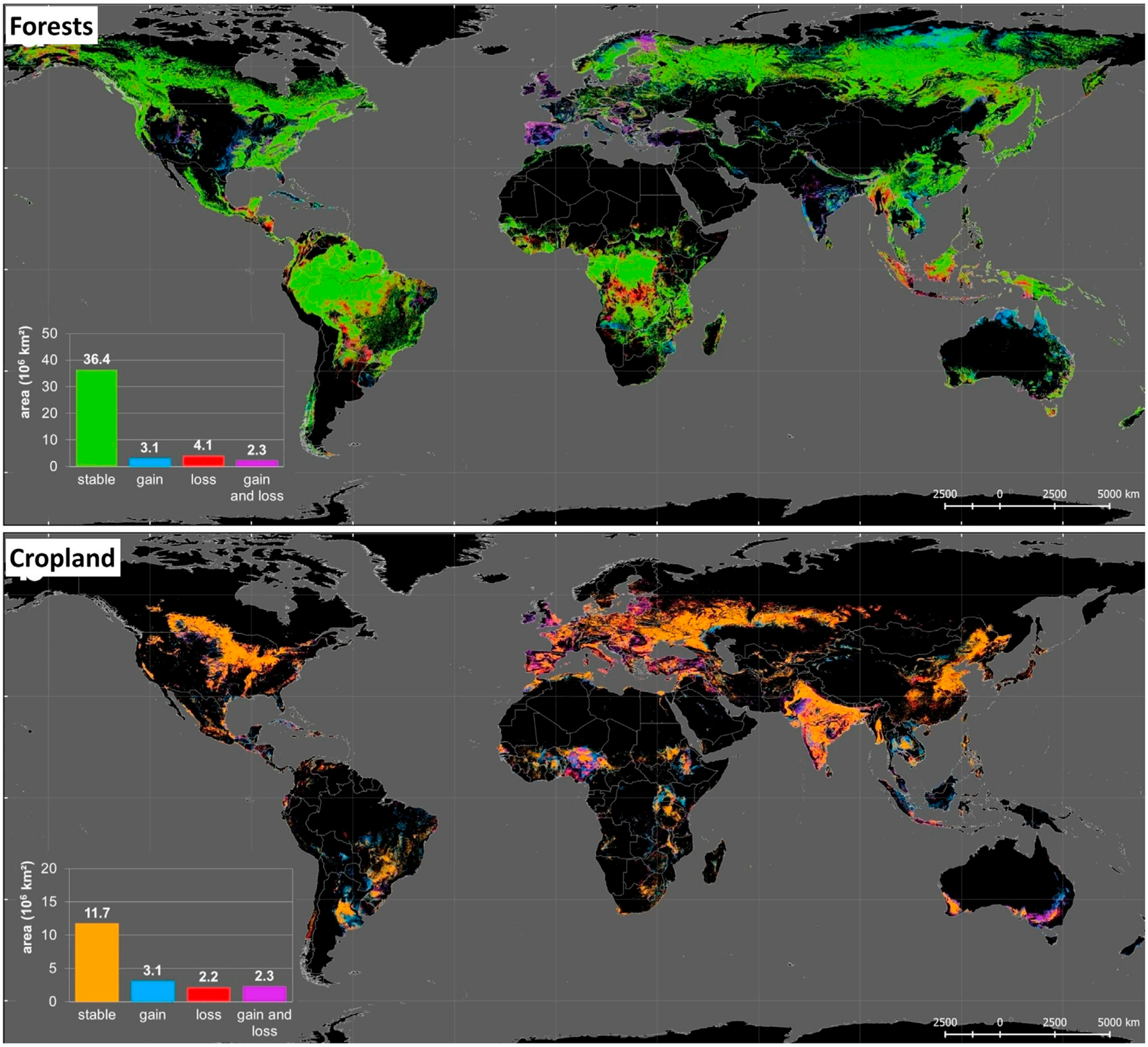


**Figure 2. A visual depiction of two main types of global land cover change from 1960–2020 related to forest and cropland (derived from HILDA + data[14])**

## Aboveground biomass

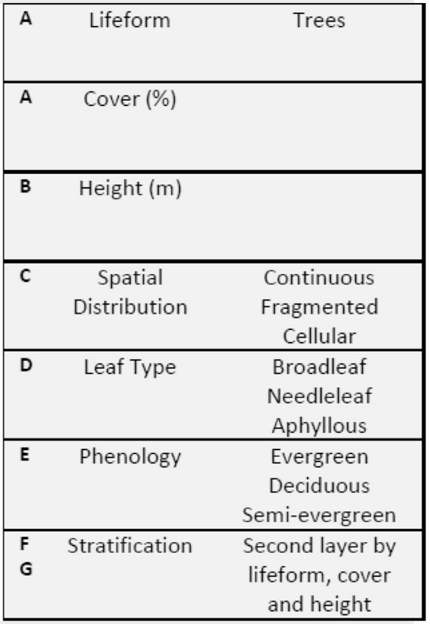
Aboveground biomass (AGB) of forests, defined as the dry-weight of the live standing woody component of vegetation situated above ground, has been recognized by GCOS as an Essential Climate Variable.[23] Knowledge of the global distribution of AGB in forests is limited due to multiple factors, such as inaccessibility of remote and dense forests, inability to directly measure AGB without destructive harvesting, and constant changes to forests and land use.[24,25] EO data provide information on forest structure, which can be used to infer biomass, and many teams have worked to produce maps of forest AGB using a range of methods.[26–29] As a result, the maps and levels of uncertainty generated vary for the same locations, including as a function of forest type and prevailing environmental conditions.[30]

A summary of forest AGB datasets relevant to the GST that are generated from EO data, together with their characteristics and access information, is given in Table 8. This only includes continental to global-scale datasets, but numerous other AGB products have been derived from EO data at country or local

**Table 4. Land use and land cover datasets available to support the GST and generated from EO data**

| Dataset name | AFOLU relevant area | Description | Sensors | Temporal coverage (frequency) | Spatial resolution | Reference |
|---|---|---|---|---|---|---|
| GlobCover | Land Cover and Use<br>Forest Cover | Global land cover maps | ENVISAT MERIS | Dec 2004–Jun 2006<br>Jan–Dec 2009 | 300 m | Arino et al. 2010 |
| CCI Land Cover | Land Cover and Use<br>Forest Cover | Global land cover maps | ENVISAT MERIS, AVHRR, SPOT Vegetation, PROBA-Vegetation, Sentinel-3 OLCI and LSTR | 1990s, 2000, 2005, 2010, 2015 | 300 m | |
| Copernicus Global Land Service Land Cover map | Land Cover and Use<br>Forest Cover | Global land cover maps | PROBA-Vegetation | 2015 – present (annual) | 100 m | Buchhorn et al.,[51] |
| WorldCover | Land Cover and User<br>Forest Cover | Global land cover maps (available in June 2021 with 5 classes) | Sentinel-1, Sentinel-2 | 2020 (one-time product) | 10 m | Winkler et al. 2020 |
| HILDA+ | Land Cover and Use (Seven generic land use/cover categories) | Global land cover change maps | Various data, based on existing RS-derived datasets including GlobCover and CCI Land Cover. Also integrates models and statistical data. | 1960–2019 (annual) | 1 km | Hurtt et al. 2020 |
| LUH2 | Land Use (Twelve land use classes, transitions between classes and agricultural management layers) | Global land use maps | Various data based on existing RS-derived datasets including Hansen et al. (2013). Also incorporates models and statistical data. | 850–2100 (annual) | 0.25° | University of Maryland 2021 |

**Table 5. Essential forest information requirements based on the FAO Land Cover Classification System (LCCS))**

| | | Forest variables - information requirements | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Environmental descriptors included in the FAO LCCS taxonomy | | | | | Additional environmental descriptors | | |
| | | Forest cover and spatial distribution[ha] | | Forest structure and functional elements | | | | | |
| Req# | Sensor type | Forest area [ha] (LCCS: A) | Canopy closure (%) (LCCS:A) spatial distribution (LCCS: C) | Forest height (m) (LCCS:B) | Vertical structure (LCCS:F, G) | Forest type Leaf type (LCCS: D) phenology (LCCS: E) | Dominant plant species (incl. natural/ plantations) | Above-ground biomass (Mg $ha^{-1}$) | FAO LCCS categories |
| Coarse resolution sampling (>100 m) | | | | | | | | |  |
| 1 | O | – | – | – | – | – | – | | |
| 2 | MW | – | – | – | – | – | – | | |
| Moderate resolution sampling (10–100 m) | | | | | | | | | |
| 3 | VNIR, SWIR | RL(2): Once (Ref year) AD(3): Annual | | – | – | EF(4): Once<br>ΔEF(5): Annual | RL: Once<br>AD: Annual | | |
| 4 | MW Long (L-band, P-band) | RL: Once<br>AD: Annual | | – | EF: Once<br>ΔEF: Annual | EF: Once<br>ΔEF: Annual | RL: Once<br>AD: Annual | ΔEF(5): Annual (singularly or in combination) | |
| 5 | MW Short (S-band, C-band, X-band) | – | – | Annual (Digital Elevation) | – | – | – | | |
| Fine & Very Fine resolution sampling (< 10 m) | | | | | | | | | |
| 6 | PAN, VNIR, SWIR | RL: Once<br>AD: Annual | | – | – | EF: Once<br>ΔEF: Annual | EF: Once<br>ΔEF: Annual | | |
| 7 | MW | – | – | – | – | – | – | | |
| Point sampling | | | | | | | | | |
| 8 | LiDAR | – | – | EF: Once<br>ΔEF: Annual | EF: Once<br>ΔEF: Annual | – | – | EF: Once<br>ΔEF: Annual | |
| (9) | *In situ* | – | EF Once<br>ΔEF: Annual | EF: Once<br>ΔEF: Annual | EF: Once<br>ΔEF: Annual | EF: Once<br>ΔEF: Annual | – | EF: Once<br>ΔEF: Annual | |

| | | |
|---|---|---|
| **A** | Lifeform | Trees |
| **A** | Cover (%) | |
| **B** | Height (m) | |
| **C** | Spatial Distribution | Continuous<br>Fragmented<br>Cellular |
| **D** | Leaf Type | Broadleaf<br>Needleleaf<br>Aphyllous |
| **E** | Phenology | Evergreen<br>Deciduous<br>Semi-evergreen |
| **F**<br>**G** | Stratification | Second layer by lifeform, cover and height |

Note: For national forest monitoring and early warning, forest area and ideally environmental descriptors need to be tracked at least weekly.

**KEY:** OP, Optical; VIS, Visible; NIR, Near InfraRed; VNIR, Visible/Near InfraRed; SWIR, Short Wave InfraRed; PAN, Panchromatic; MW, Microwave; RL, Reference Level; AD, Activity data (change in forest area); EF, Emission Factor (Mg $CO_2$-e $ha^{-1}$; representing C stock in all pools, incl. AGB).

**Table 6. EO missions with capacity to support requirements for forest information**

| Operational missions | | Future missions | Resolution | | | |
|---|---|---|---|---|---|---|
| Core missions | Contributing missions | | Spatial resolution | Spectral (range) | Temporal (capacity) | Observation strategy |
| Coarse resolution Optical (>100 m) | | | | | | |
| Terra/Aqua (MODIS) | | | 250–1000 m | VNIR/SWIR | 0.5 days/2 sat | Global |
| Sentinel-3 (OCLI) | | Sentinel-3C/3D | 300–1000 m | VNIR/SWIR/TIR | 2 days/2 sat | Global |
| Suomi-NPP (VIIRS) | | | 375–750 m | VNIR/SWIR | Daily | Global |
| Coarse resolution Microwave (>100 m) | | | | | | |
| SMOS (L-VOD) | | | 15 km | L-band radiometer | 1–2 days | Global |
| SMAP | | | 10–40 km | L-band radiometer | 1–2 days | Global |
| | | BIOMASS (2023) | 200 m | P-band SAR | 7 months | Continental |
| Moderate resolution Optical (10–100 m) | | | | | | |
| Landsat 7 (ETM+)<br>Landsat 8 (OLI) | | Landsat 9 | 30–100 m | VNIR/SWIR/TIR | 8 days/2 sat | Global |
| Sentinel-2 (MSI) | | Sentinel-2C/2D | 10–20 m | VNIR/SWIR | 5–10 days/2 sat | Global |
| CBERS-4 (MUXCam + WFI-2) | | | 20 + 73 m | VNIR/SWIR | 26 days | Regional |
| | ResourceSat-2 (LISS-3 + AWiFS) | | 23.5 + 56 m | VNIR/SWIR | 5–24 days | Regional |
| Moderate resolution Microwave (10–100 m) | | | | | | |
| ALOS-2 (ScanSAR) | | ALOS-4 (2022) | 50 m | L-band SAR | 42 days | Pan-tropical |
| | ALOS-2 (Fine Beam) | ALOS-4 (2022) | 25 m | L-band SAR | Annual mosaics | Global |
| | SAOCOM-1A/1B | SAOCOM-2 | 10–50 m | L-band SAR | 4 times/year | Global |
| | | NISAR-L (2023) | 10 m | L-band SAR | 12 days | Global |
| Sentinel-1 | | Sentinel-1C/1D | 20–50 m | C-band SAR | 6–12 days/2 sat | Global |
| | RCM | | 10 m | C-band SAR | 4 days/3 sat | National |
| | NovaSAR | NISAR-S (2023) | | S-band SAR | 12 days | National |
| | TanDEM-X | | | (Digital Elevation) | | Global |
| Fine & Very Fine resolution Optical (<10 m) | | | | | | |
| Planet (Through Norway) | | | <5 m | VNIR | Monthly mosaics | Pan-tropical |
| | Pleiades, SPOT-6/7 | | (1.5 m), 6 m | (PAN)/VNIR | | On demand |
| LiDAR | | | | | | |
| ICESat-2 | | | 13 m footprint | Photon count LiDAR | 91 days | Global |
| GEDI | | MOLI (2025) | 25 m footprint | Full waveform LiDAR | ISS non-repeat orbit | <52o latitude |

**KEY:** VNIR, Visible/Near InfraRed; SWIR, Short Wave InfraRed; PAN, Panchromatic; TIR, Thermal InfraRed Radiometer.

scales. To date, most biomass estimates have been generated using sensors (radar, lidar, and/or optical data) with limited sensitivity to the biomass of forest components. Common problems in estimating biomass include signal saturation (common to optical and synthetic aperture radar (SAR) and varying as a function of radar frequency and polarization) and partial observations (lidar, as a function of footprint size and sampling relative to the distribution of plant elements in the vertical and horizontal dimensions). These problems have limited the operational use of past sensors, particularly in areas of high biomass. However, the knowledge gained has informed the design of the next generation of biomass missions and products (e.g., GEDI, ICESat-2, NISAR, and BIOMASS), that will reduce AGB uncertainties and provide valuable data for country level and global forest carbon monitoring. Next-generation CEOS biomass products, and pilot studies highlighting their uptake for policy, can be explored at https://earthdata.nasa.gov/maap-biomass/.

Table 7. Global forest cover datasets relevant to the GST generated through Earth observation

| Dataset name | AFOLU relevant area | Description | Sensors | Temporal coverage/ frequency | Spatial resol. | Reference |
|---|---|---|---|---|---|---|
| **Treecover2000 and 2010**[a] Global Tree Cover dataset generated by Univ. Maryland Global Land Analysis & Discovery (GLAD) | **Forest** (Cover) | Pixel estimates of circa 2000 and 2010 percent maximum (peak of growing season) tree canopy cover derived from cloud-free annual growing season composite of Landsat 7 ETM + data. | Landsat 7 | Circa 2000 and 2010 | 30 m | Hansen et al.,[21] |
| **Primary Humid Tropical Forests**[a] Primary forests in the tropics, dataset generated by Univ. Maryland Global Land Analysis & Discovery (GLAD) | **Forest** (Extent) | Extent in global pan-tropical regions 2001. | Landsat | 2001 | 30 m | Turubanova et al. 2018 |
| **Intact Forest Landscapes**[a] Dataset generated by Univ. Maryland Global Land Analysis & Discovery (GLAD) | **Forest** (Extent) | World's remaining unfragmented forest landscapes identified; large enough to retain all native biodiversity and showing no signs of human alteration as of 2016. Shows reduction in IFL from 2000 to 2016. | Landsat | 2016 | 30 m | Potapov et al. 2017 |
| **Forest Cover Loss**[a] Global year of Forest Cover Loss. Dataset generated by Univ. Maryland Global Land Analysis & Discovery (GLAD) | **Forest** (Extent Change) | Pixel estimates of forest cover loss | Landsat | 2001–2020 (annual) | 30 m | Hansen et al. 2013 |
| **Forest Cover** | **Forest** (Cover, Height) | Global Landsat analysis-ready data used to extrapolate GEDI footprint-level forest canopy height measurements, creating a 30 m spatial resolution global forest canopy height map for 2019. | GEDI and Landsat | 2019 | 30 m | Potapov et al. 2020 |
| **Copernicus Global Land Service - Land Cover map** | **Forest** (Tree Canopy Cover, Change) | Annual global tree canopy cover maps | PROBA-Vegetation | 2015–2019 (annual) | 100 m | Buchhorn et al. 2019<br>Masiliūnas et al. 2021 |
| **Global Forest/Non-Forest maps** Dataset generated by JAXA from L-band SAR series data | **Forest** (Extent) | Forest extent map accompanying JAXA's L-band SAR mosaic products. Provided as 1 x 1° tiles | ALOS PALSAR & ALOS-2 PALSAR-2 | 2007–2010 & 2015–2016 | 25 m | Shimada et al. 2014 |

[a] Datasets are available through the Global Forest Watch, www.globalforestwatch.org/.

A survey of over 300 stakeholders[31] showed that, despite familiarity with IPCC guidance, there was a lack of awareness, knowledge, and uptake of biomass maps among stakeholders. Furthermore, two biomass products (i.e., the pan-tropical maps[27,32]) were not used in GHG reporting by countries, and a significant gap was noted between stakeholders' awareness of data sources and their views on their usefulness.[30] A conclusion was that uptake of biomass products might be encouraged by providing a single harmonized map, accompanied by guidance and example case studies. Efforts to produce such a harmonized map are ongoing through CEOS activities. This is becoming ever more pressing as further maps become available, potentially increasing confusion over which products to use and for what purpose. Similarly, methods to transparently intercompare and validate biomass products with publicly available reference data are crucial toward their uptake by countries.[33,34]

**Table 8. Forest aboveground biomass (AGB) datasets relevant to the GST generated from EO data, their characteristics, and access information**

| Dataset name | AFOLU relevant area | Description | Sensors | Temporal coverage/frequency | Spatial resolution | Reference |
|---|---|---|---|---|---|---|
| Commonly referred to as **Saatchi AGB Map** | Forest (biomass) | Pan-tropical Forest AGB map. | GLAS, MODIS, SRTM, QSCAT | Early 2000s | 1 km | Saatchi et al.,[27] |
| Commonly referred to as **Baccini 2012 AGB Map** | Forest (biomass) | Pan-tropical Forest AGB map. | GLAS, MODIS, SRTM | 2007–2008 | 500 m | Baccini et al.,[32] |
| Commonly referred to as **Avitabile AGB Map** | Forest (biomass) | Fusion of Saatchi and Baccini products using more extensive ground data to reduce bias. Pan-tropical Forest AGB map. | GLAS, MODIS, SRTM, QSCAT | Mid-2000s | 1 km | Avitabile et al. 2016 |
| Commonly referred to as **Baccini 2017 AGB Map** | Forest (biomass and cover, change) | Pan-tropical Forest AGB map and change | GLAS, MODIS, SRTM | 2003–2014 | 463 m | Baccini et al. 2017 |
| **GlobBiomass** (ESA project) | Forest (biomass) | Global AGB map with specified spatial resolution (150–500 m), accuracy below 30% (relative root-mean-square error) and 2010 as reference year. | ALOS PALSAR ENVISAT ASAR | 2010 | 100 m | Santoro et al. 2020 |
| **CCI Biomass**[a] (ESA project) | Forest (biomass) | Global AGB maps with associated maps of precision. | ALOS PALSAR ENVISAT ASAR ICESAT GLAS<br>ALOS-2 PALSAR-2, Sentinel-1 SAR ICESAT GLAS GEDI | 2010<br>2017, 2018, 2020 | 100 m | |
| **GEDI**[b] | Forest (biomass) | Mean and variance of forest AGB in each 1 km grid-cell. Coverage: 51.6° N to 51.6° S | GEDI (1064 nm waveform lidar) | 2019–2021 | 1 km | |
| **ICESat-2 Boreal**[c] | Boreal forest (biomass) | Mean and variance of forest AGB maps for forests. Coverage: 50° N to 75° N (Boreal) | ICESat-2 Landsat | 2019–2021 | 30 m | |
| **NCEO Africa**[d] | Forest (biomass) in Africa | Aboveground woody biomass in African forests and woodlands | ALOS-2 PALSAR-2, Landsat | 2017 | 100 m | |

[a] http://cci.esa.int/biomass.

[b] https://lpdaac.usgs.gov/news/release-gedi-data-products/.

[c] https://above.nasa.gov/profiles_/above_projects.html.

[d] https://leicester.figshare.com/articles/dataset/Africa_Aboveground_Biomass_map_for_2017/15060270/1.

New and upcoming biomass missions will (post 2019) mark a huge improvement in capability. The GEDI, ICESat-2, BIOMASS, NISAR, and ALOS-4 PALSAR-3 missions are likely to be complemented by missions such as MOLI and ROSE-L. Each of these missions will release biomass products, but many other products are anticipated through data fusion, as demonstrated in the approach adopted by ESA CCI Biomass where biomass retrievals from C- and L-band are supported by spaceborne optical and lidar data. More specific information on upcoming products and associated uncertainties is available in the CEOS Aboveground Woody Biomass Validation Protocol.[35]

## Wetlands

Inland and coastal wetlands can play an important role in both climate mitigation and adaptation. Hence there is an urgent need for comprehensive and up-to-date geospatial information on their extent (including by type), biomass and health, to produce reliable estimates of emissions and removals from these ecosystems. Wetlands, in the context of the CEOS AFOLU team (and similarly to the IPCC Wetlands Supplement[7]), can occur under any IPCC land use category. Examples include mangrove forests (Forest Land IPCC category), peatlands (Forest Land or Wetland IPCC category, depending on their management), and seagrass meadows (Wetlands IPCC category). This thematic area can complement and contribute to the other AFOLU thematic areas, specifically land use and biomass, providing scientific information (data and methods) that consider the special characteristics of these important and carbon-rich ecosystems.

Optical and microwave sensors provide complementary information, with optical medium resolution data primarily required for characterizing wetland vegetation (e.g., by functional type, dominant species, canopy closure, etc.) and indicators of plant health (e.g., proportions of photosynthetic/non-photosynthetic plant material), while wetland water regimes/hydroperiods can be quantified from a time series of medium-resolution optical and microwave data.

L-band SAR has a long track record in detection and mapping of forest inundation, going back to SEASAT,[36] thanks to the capacity of the long wavelength signal to penetrate a forest canopy and interact with the ground or water surface below. Using time series of L-band SAR data, the temporal and spatial distribution of inundation can be mapped in detail. As part of systematic acquisition strategies for ALOS PALSAR and ALOS-2 PALSAR-2 developed by Japan Aerospace Exploration Agency (JAXA), L-band SAR data have been acquired across the entire tropical zone on a regular 6-weekly basis since 2006, with additional historical coverage by JERS-1 SAR in the mid-1990s. Continuity to the end of the decade will be assured with JAXA's ALOS-4 PALSAR-3, scheduled for launch in 2023. NASA's forthcoming NISAR L-band SAR mission includes a comprehensive acquisition plan for wetlands monitoring with global L-band observations every 12 days during the mission. Table 9 below outlines the EO requirements for the three wetland types: mangroves, peatlands, and floodplain forest.

### *Mangroves*

Mangroves occur naturally along shallow coastlines in the tropics and sub-tropics, and have the capacity to sequester and store large amounts of carbon due to the slow decomposition rates of organic matter in their inundated, anoxic soils. Once disturbed and exposed to oxygen through diking and draining, mineralization occurs quickly, and the stored carbon is released rapidly to the atmosphere.[37]

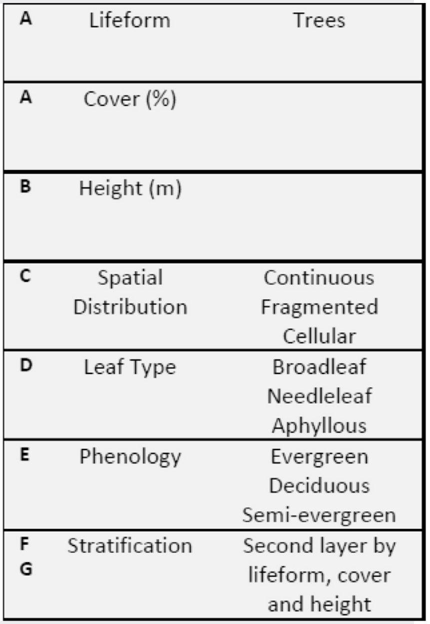
Mangroves are relatively straightforward to map with EO data, due to their flat topography and characteristic homogeneous canopy structure. Optical sensors operating in the VNIR and SWIR bands are useful for distinction of mangroves from other wetland and dryland vegetation types and Landsat data have consequently commonly been used in the past for baseline mapping.[38–40] Cloud cover however puts limitations on optical data availability in certain areas of the tropics. Long wavelength (L-band) SAR sensors provide complementary information and constitute a key tool to map mangrove structure and changes over time.[41]

There are presently four key datasets showing the global mangrove distribution available in the public domain. Two are nominally single-year datasets derived from medium-resolution Landsat data.[38,39] The third, produced by the Global Mangrove Watch (GMW)[42] is a series of mangrove extent maps covering eleven annual epochs between 1996 and 2020, derived using a combination of Landsat and ALOS PALSAR data for the baseline year 2010, and L-band SAR only for the other ten epochs. Maps for 2021 and onward derived from ALOS-2 PALSAR-2 will be generated on an annual basis from 2023.[43] Supported

Table 9. EO information requirements for wetlands (mangroves, peatlands, and floodplain forest)

| | | Forest variables - information requirements | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Environmental descriptors included in the FAO LCCS taxonomy | | | | | Additional environmental descriptors | |
| | | Wetland cover and spatial distribution[ha] | | Forest structure and functional elements | | | | |
| Req# | Sensor type | Forest area [ha] (LCCS: A) | Canopy closure (%) (LCCS:A) spatial distribution (LCCS: C) | Forest height (m) (LCCS:B) | Vertical structure (LCCS:F, G) | Vegetation type Leaf type (LCCS: D) phenology(LCCS: E) | Dominant plant species (incl. natural/ plantations) | Above-ground biomass (Mg ha$^{-1}$) |
| Coarse resolution sampling (>100 m) | | | | | | | | |
| 1 | O | Monthly (PT) | Monthly (PT) | – | – | Monthly (PT) | – | |
| 2 | MW | – | – | – | – | – | – | |
| Moderate resolution sampling (10–100 m) | | | | | | | | |
| 3 | VNIR, SWIR | RL[(2)]: Once (MG, PT, FF) AD[(3)]: Annual (MG, PT, FF) | | – | – | EF[(4)]: Once (MG, PT, FF) ΔEF[(5)]: Annual (MG, PT, FFF) | | < Weekly (MG, PT, FF) |
| 4 | MW Long (L-band, P-band) | RL: Once (MG, PT L, FF) AD: Annual (MG, PT, FF) | | – | M | | | < Weekly (MG, PT, FF) |
| 5 | MW Short (S-, C-, X-band) | – | – | Annual (DEM) (M, PT, F) | – | – | – | |
| Fine & Very Fine resolution sampling (< 10 m) | | | | | | | | |
| 6 | PAN, VNIR, SWIR | RL: Once (MG, PT, FF) AD: Annual (MG, PT, FF) | | – | – | EF: Once (M, PT, FF) ΔEF: Annual (M, PT, FF) | | |
| 7 | MW | – | – | – | – | – | – | |
| Point sampling | | | | | | | | |
| 8 | LiDAR | – | – | EF: Once (MG, PT, FF) | EF: Once (MG, PT, FF) | – | – | |
| (9) | *In situ* | – | | EF: Once (MG, PT, FF) | EF: Once (MG, PT, FF) | | – | |

FAO LCCS Categories



| | | |
|---|---|---|
| **A** | Lifeform | Trees |
| **A** | Cover (%) | |
| **B** | Height (m) | |
| **C** | Spatial Distribution | Continuous<br>Fragmented<br>Cellular |
| **D** | Leaf Type | Broadleaf<br>Needleleaf<br>Aphyllous |
| **E** | Phenology | Evergreen<br>Deciduous<br>Semi-evergreen |
| **F**<br>**G** | Stratification | Second layer by lifeform, cover and height |

KEY: OP, Optical; VIS, Visible; NIR, Near Infrared; VNIR, Visible/Near Infrared; SWIR, Shortwave Infrared; PAN, Panchromatic; MW, Microwave; RL, Reference Level; AD, Activity Data; EF, Emission Factor (Mg $CO_2$-e ha-1; representing C stock in all pools, incl. above ground); MG, Mangroves; PT, Peatlands; FF, Flooded Forest.

by JAXA, the GMW dataset is used by the United Nations Environment Program as the official mangrove dataset for SDG indicator 6.6.1 (Change in the extent of water-related ecosystems over time) reporting for countries without their own national mangrove monitoring systems. The GMW dataset is also the mangrove dataset used by GFW. The fourth dataset is the ESA WorldCover maps[44] for the years 2020 and 2021. The WorldCover maps are derived from 10 m Sentinel-1 and Sentinel-2 data, and include a separate mangrove class that has been derived using the GMW 2020 layer for training and to constrain the classification.

Based on the 2000 mangrove extent map, Giri et al. and Simard et al.[39,45] generated maps of mangrove height and AGB, using digital elevation data from the 2000 SRTM mission. The mangrove datasets are described in Table 10.

### *Peatlands*

Peatlands are characterized by dense, wet layers of dead and partially decomposed organic matter built up over thousands of years. The vast majority of the carbon is stored as belowground biomass, with exceptionally slow decomposition rates due to the anoxic conditions in the permanently waterlogged soil. While peatlands cover only about 3% of the Earth's land surface, they are estimated to hold between 18% and 89% of global terrestrial C biomass.[46]

There is no agreed unique definition of "peatlands", however, and the term as generally used comprises a wide variety of wetland vegetation types (e.g. bogs, fens, mires, forested and non-forested swamps, etc.) and hydrological states (e.g. flooded, non-flooded, frozen, etc.). Uncertainties are consequently very large and there is a scarcity of high-quality maps of global peatland extent.

The US Operational Navigation Charts[47] include peatlands in the wetlands class and have been used to generate coarse scale (1 arc degree) maps of global wetland extent.[48] The Global Lake and Wetlands Database, GLWD-3,[49] which identifies peatlands (bogs, fens and mires) as a separate class, is provided at 30 arc seconds (~1 km) resolution.

Fine-resolution global land cover maps derived primarily from EO data (MERIS, SPOT-VGT, PROBA-V, Sentinel-2, Sentinel-1), such as the 10 m ESA WorldCover,[44] the 300 m CCI Land Cover,[50] and the 100 m Copernicus Global Land Service,[51] do not map peatlands per se, but include generic wetland classes (e.g. tree cover flooded, herbaceous flooded, herbaceous wetlands) that can be expected to also include some peatland types.

Recent maps of global peatland spatial extent released by the Global Peatlands Database (2022), PEAT-ML,[52] and PEATMAP[53] have been assembled from a combination of different data sources, including e.g. soil maps, databases such as GLWD-3, and *in situ* data.

Regional maps at higher spatial resolution, based on parameters derived from EO data (e.g. digital elevation, surface wetness indices, vegetation spectral signatures) and field data, have recently been developed over some of the main tropical peatlands in Indonesia,[54] the Congo Basin,[55] and Peru.[56] With the availability of such baseline datasets of peatland spatial extent, there is significant potential for monitoring changes in peatland extent using time series of both optical and radar EO data.

However, since peatland carbon is mainly stored below ground, direct measurements of peat depth by EO sensors are not possible. EO data can however be used to map proxies and indicators associated with peat depth, such as peatland phenology using multi-temporal optical coarse (MODIS) or medium-resolution (Landsat/Sentinel-2) data.[57] Given the sensitivity of microwave sensors to peatswamp forest inundation, L-band (JERS-1 SAR, ALOS PALSAR) and C-band (Envisat ASAR) SAR time series were used to map the spatial and temporal characteristics of flooding in Indonesian peatlands, modeling peat depth as a function of flooding intensity.[58] Peat dome elevation and shape are furthermore important predictors of peat depth, and digital elevation models derived from EO have been used to model carbon storage and changes.[59]

Recognizing the critical importance of peatlands, and the lack of consistent maps of global peatland extent and composition, the Global Peatlands Assessment was launched at the UNFCCC COP27 in 2022, calling

Table 10. Other land use datasets available to support the GST and generated from EO data

| Dataset name | AFOLU relevant area | Description | Sensors | Temporal coverage/frequency | Spatial resolu-tion | Reference |
|---|---|---|---|---|---|---|
| Mangroves (global) | | | | | | |
| **Global Mangrove Watch** | **Forest** (Extent) **Other Land Use** (Wetlands - Mangroves) | Global extent of mangrove forests for eleven annual epochs. | JERS-1 SAR ALOS PALSAR Landsat 5 & 7 ALOS-2 PALSAR-2 | 1996 2007–2010 2010 2015–2020, 2021+ | 25 m | Bunting et al.,[42,a] |
| **WorldCover** | **Land Cover** (Cover) **Other Land Use** (Wetlands - Mangroves) | Global map of Land Cover (11 classes) | Sentinel-1, Sentinel-2 | 2020 and 2021 | 10 m | Zanaga et al.,[44] |
| Commonly referred to as **Giri 2000 mangrove map** | **Forest** (Extent) **Other Land Use** (Wetlands - Mangroves) | Remote sensing-based map of global mangrove extent | Landsat | 2000 | 30 m | Giri et al.,[39] |
| **World Atlas of Mangroves** | **Forest** (Extent) **Other Land Use** (Wetlands - Mangroves) | Composite extent map of mangrove extent | Landsat | 2000 (range between 1999 and 2003) | 30 m | Spalding et al.,[38] |
| **Mangrove Height and Biomass** | **Forest** (Height, Biomass) **Other Land Use** (Wetlands - Mangroves) | Canopy height maps based on SRTM DEM and Lidar altimetry | SRTM | 2000 | 30 m | Simard et al.,[45,b] |
| Peatlands | | | | | | |
| **Global Peatland Map 2.0 (GPM2.0)** | **Other Land Use** (Wetlands - Peatlands) | Global map of peatlands | Variety of regional maps of peatland extent | Variable | 30 arcsec | UNEP, 2022 |
| **PEAT-ML** | **Other Land Use** (Wetlands - Peatlands) | Global map of peatlands | Variety of regional maps of peatland extent | Variable | 5 arcmin | Melton et al.,[52] |
| **PEATMAP** | **Other Land Use** (Wetlands - Peatlands) | Global map of peatlands | Variety of regional maps of peatland extent | Variable | Variable | Xu et al.,[53] |
| **Global Lakes and Wetlands Database, Level-3 (GLWD-3)** | **Other Land Use** (Wetlands – Peatlands, Floodplain forest) | Global map of lakes and wetlands (12 classes) | Variety of regional maps of peatland extent | Variable | 30 arcsec | Lehner & Döll,[49] |
| Riparian floodplain forest (regional) | | | | | | |
| **GIEMS-D3** | **Other Land Use** (Wetlands - Floodplain forest) | Global maps showing monthly inundation extent | NOAA AVHRR; Passive MW SSM/I; ERS Scatterometer | 1993–2007 | 3 arcsec | Aires et al.,[64] |
| **Amazon Max and Min Inundation Extents (2015–2017)** | **Forest** (Cover) **Other Land Use** (Wetlands - Floodplain forest) | Maps showing maximum and minimum inundation extents in the Amazon Basin for 3 individual years | ALOS-2 PALSAR-2 ScanSAR | 2015 max/min 2016 max/min 2017 max | 50 m | Rosenqvist et al.,[68] |
| **Amazon Inundation Extents (2006–2010)** | **Forest** (Cover) **Other Land Use** (Wetlands - Floodplain forest) | Maps showing average high and low water inundation extents in the Amazon Basin for the period 2006–2010 | ALOS PALSAR ScanSAR | 2006–2010 | 100 m | Chapman et al.,[67] |
| **Amazon Wetlands Map** | **Forest** (Cover) **Other Land Use** (Wetlands - Floodplain forest) | Maps showing wetland vegetation classes in the Amazon Basin | JERS-1 SAR | 1995 low water<br>1996 high water | 100 m | Hess et al., [66] |

[a] https://www.globalmangrovewatch.org.

[b] https://daac.ornl.gov/CMS/guides/CMS_Global_Map_Mangrove_Canopy.html.

CEOS and the UNFCCC Global Stocktake

This page provides an entry point for access to the datasets and guidance being developed by CEOS space agencies and partners in support of the goals of the Global Stocktake process of the Paris Climate Agreement.

The Global Stocktake is a fundamental component of the Paris Agreement, being used to monitor its implementation and evaluate the collective progress made in achieving the agreed goals. The Global Stocktake (GST) thus links implementation of nationally determined contributions (NDCs) with the overarching goals of the Paris Agreement, and has the ultimate aim of raising climate ambition. The first GST will take place in 2023.

$CO_2$ & $CH_4$ Fluxes
Above Ground Biomass
Forests
Mangroves
Agriculture
Land Cover

**Figure 3. CEOS GST portal www.ceos.org/gst/**

for the development of data systems on peatland extent, condition, and uses, to inform policy planning and regulations.[60]

### *Floodplain forest*

Seasonal inundation is a dominant environmental factor affecting floodplain forest ecosystems and the characteristics of flooding, in terms of timing, duration, and amplitude, vary spatially on the floodplain as a function of fluctuations in river stage height and topography. Floodplain forests sequester carbon as they grow, but are also significant sources of methane (CH4) and other trace gases essential to climate regulation as dead trees and litter on the forest floor decompose in anoxic conditions during parts of the year.[61]

The global land cover maps mentioned previously—ESA WorldCover,[44] CCI Land Cover,[50] and Copernicus Global Land Service[51]—provide reasonably good representations of floodplain forests. However, the land cover maps do not capture the seasonal flooding dynamics, which constitute the key drivers of methane emissions.

The 0.25° Global Inundation Extent from Multi-Satellites (GIEMS) dataset was generated from a combination of global coarse resolution optical (NOAA AVHRR), passive microwave (DMSP SSM/I at 37 GHz/0.8 cm), and active microwave (ERS Scatterometer at 5.25 GHz/5.7 cm) data and provides monthly variations of the global surface water extent for the 1993–2007 period. The GIEMS-D15 and GIEMS-D3 datasets are refined versions of the GIEMS dataset, for which topography and hydrography information from the HydroSHEDS[62] database have been used to improve resolution to 15 and 3 arc seconds, respectively.[63,64]

Long wavelength SAR sensors have the potential to provide GIEMS-type global inundation datasets with improved detail and spatial resolution. In an assessment of EO sensors used to map inundation extent in the Amazon Basin,[65] L-band SAR (1.27 GHz/23.5 cm) sensors were found to provide the best results, given their unique capacity to detect water below a closed forest canopy. Regional-scale 50–100 m resolution maps of floodplain forest and inundation extent generated over the Amazon basin from JERS-1 SAR,[66] ALOS PALSAR,[67] and ALOS-2 PALSAR-2[68] are available in the public domain and illustrate what could be achieved at a global scale from forthcoming high-capacity L-band SAR missions such as NISAR and ALOS-4.

## PRODUCT HARMONIZATION ACTIVITIES

Within the domains of agriculture, forestry, and biomass, several global products exist or are currently being developed and these provide a platform upon which to build future activities. A new web portal (www.

**Table 11. CEOS AFOLU datasets harmonization plan**

| | COP-26 (Nov 2021) | GST1 (2023) | Beyond (2024+) |
|---|---|---|---|
| Forest - Aboveground biomass | Individual existing datasets Synthesized biomass product providing estimates at a jurisdictional level globally | *Synthesized, jurisdictional level biomass, emission factors (and prototype biomass change)* | *Synthesized spatially explicit, annual biomass, emission factors and biomass change* |
| Land Cover & Forest (Area) | Copernicus annual global land cover C3S/CCI Land Cover WorldCover, HILDA+ Global Forest Watch tree cover loss and forest fluxes | *Synthesized map products and estimates of land cover and change at regional, and global levels Global tree cover and forest emissions and removals* | *Statistically robust activity data estimates (6 IPCC classes) at national and global levels Global annual forest emissions and removals at 30–100 m resolution.* |
| Wetlands/ Mangroves | Global mangrove extent and change (1996–2020) at 25 m Global mangrove aboveground biomass and height (2000) and 30 m | Global mangrove extent and change at 25 m (1996–2022) Global mangrove aboveground biomass and height at 12 m (2015) | *Global annual mangrove emissions and removals at 10–25 m resolution.* |
| Agriculture | Demonstration WorldCereal products for at least 5 countries (Argentina, Spain, France, Ukraine, and Tanzania) | Initial WorldCereal map and analytical system. *On-going seasonal analysis products* | *Continual system improvement and production of seasonal state and change products* |

***Italic Bold*** indicates additional resources needed.

ceos.org/gst/) has been developed as a single point of access to the EO satellite-based AFOLU datasets and associated guidance (Figure 3). This is a convenient reference for Parties and scientific and other users to access, understand, and apply the data.

However, activities in these domains are interrelated and hence an integrative approach is recommended. An example is ESA's CCI, which coordinates climate data records to provide the evidence base to support the UNFCCC process, improve prediction of future change, and assess progress toward PA targets geared toward averting serious global warming. Other frameworks have also been developed that directly use continuous or categorical descriptors of the environment to generate land use and land cover and change maps. However, in the past and currently, the focus has been on using the products as stand-alone, with a few used in combination. However, considerable advantages will accrue from planning for more focused, coordinated, and coherent integration. The CEOS AFOLU team has developed a plan toward such harmonization for four different product categories on a best effort basis (Table 11).

Global aboveground biomass maps for 2020 have been derived using different input data and different approaches. This causes considerable variation between the products, leading to confusion in the user community and a reduction in their potential application for the estimation of carbon stocks and fluxes.[69] In a harmonization exercise, biomass maps were generated by ESA's CCI, NASA's Jet Propulsion Laboratory, the GEDI and ICESat-2 Science Teams, and the Natural Environment Research Center's National Center for Earth Observation (for Africa). The harmonization activity aims to compare and validate biomass estimates with a view to harmonization with policy needs at a national and subnational level for partner countries. The development of harmonized estimates and open science tools are designed to facilitate uptake by countries for reporting in the GST process (Figure 4).

The harmonization activity is being conducted as an open science activity on the NASA-ESA Multi-Mission Algorithm and Analysis Platform Platform (https://scimaap.net). The products are being both validated through the Plot2Map tool[69] and compared on a continental and biome scale, as well as nationally and subnationally for partner countries. However, the error properties of each of the products vary and considerable effort is required to ensure any comparison or harmonization can account for this.

In addition, a new web-based dashboard (https://earthdata.nasa.gov/maap-biomass, Figure 5) has been developed to allow exploration of the new biomass products and share the experience of product teams and country users (Paraguay, Peru, Wales (UK), Japan, and the Solomon Islands). Each of the country use cases has been developed in collaboration with country stakeholders and enables potential future users to visualize the different methods of incorporating EO-based AGB estimates into their national reporting. This allows the role of these biomass estimates (individual or harmonized) in support of NDCs to be

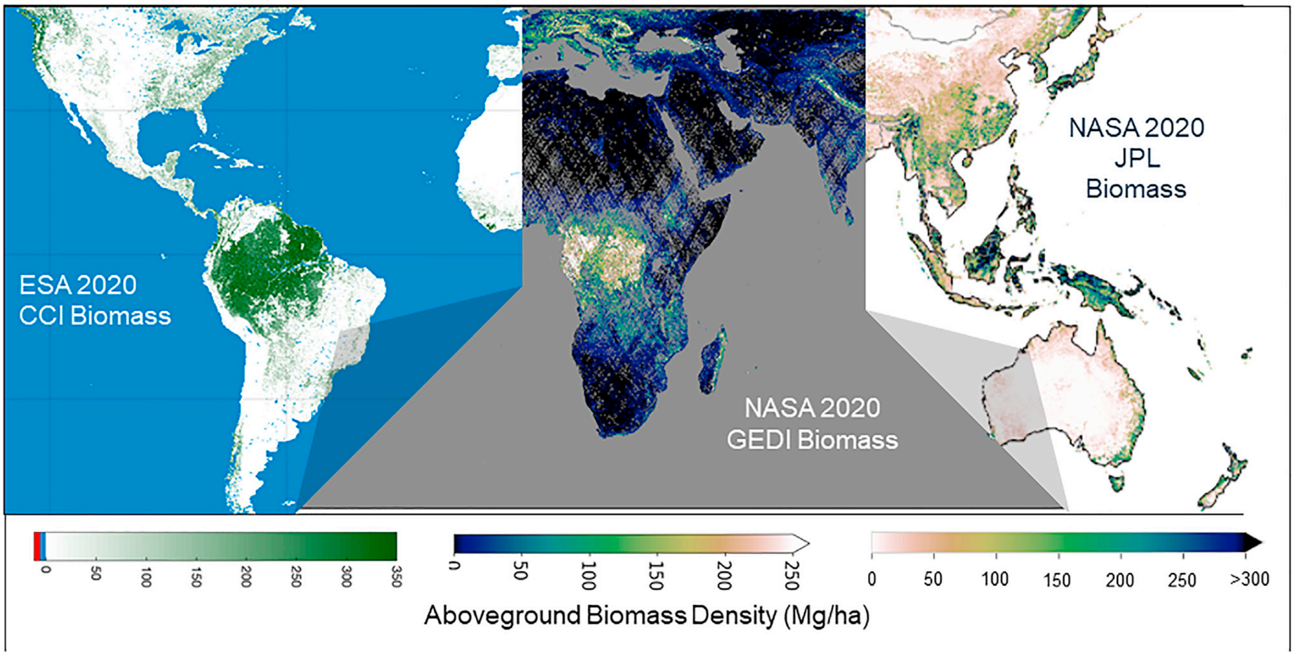


**Figure 4. Intercomparison, validation, and harmonization among biomass maps, including provisional products from the ESA CCI Biomass team (left), and NASA JPL (right), as well as the version 1 GEDI map (center)**

investigated, with the ambition of engaging countries to make maximum and effective use of them. It is unlikely that most countries will use satellite biomass products without national validation and/or updating, with roadblocks including a lack of transparency in product uncertainties, differences in forest definitions between countries and biomass products, and a lack of guidance in the use of biomass products for policy reporting. The 2021–2023 focus of this harmonization activity focuses more on harmonizing biomass products and algorithms with policy requirements, recognizing that a single estimate is unlikely to suit all countries.

## COLLABORATIVE INTERFACE BETWEEN GLOBAL AND NATIONAL LAND MONITORING EXPERTS FOR ENHANCING THE UPTAKE OF SATELLITE-BASED GLOBAL MAPS

National reporting on the AFOLU sector will support mitigation and potentially adaptation activities and contribute to the NDCs. This is expected to facilitate technology transfer and capacity building within countries and will lead to further refinements of national requirements. The coordination framework being developed by CEOS space agencies for AFOLU efforts includes a strong component of engagement with national GHG inventory teams and experts. This collaborative interface will help to i) determine needs and requirements regarding the potential use of space-based data and derived products for specific IPCC variables, following IPCC guidance and principles; ii) test and improve existing datasets to develop harmonized "best available" products; iii) address some of the outstanding issues that hinder the use of products by national teams; and iv) provide examples of the practical implementation of the 2019 Refinement to the 2006 IPCC Guidelines. This activity is led by SilvaCarbon[70] and is leveraged by their partner network and well-established relationship with government institutions responsible for reporting to the UNFCCC. Results from the first year of the CEOS AFOLU team included an overview of the use of LULC maps derived from satellite data in domestic GHG inventories and other reporting to the UNFCCC, a few first examples of the successful uptake of biomass maps derived from EO data (or the practical implementation of the 2019 IPCC Refinement[8]), and the preparation of regional workshops.

In these workshops, national technical teams presented their current methods and their NFIs; invited independent experts, introduced, and discussed the IPCC guidance and requirements; and remote sensing experts and scientists from CEOS agencies showed their different mapping data and methods. The dialog begun in the workshops continues at national scales in working clusters, facilitated by SilvaCarbon, that

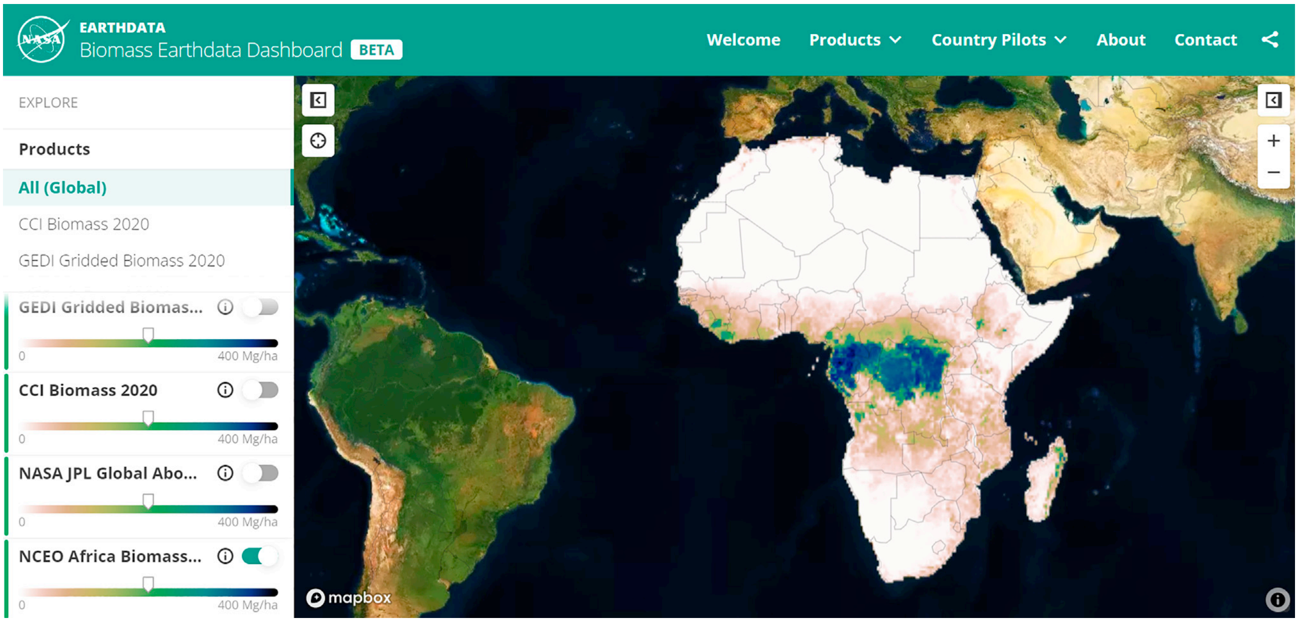


**Figure 5. MAAP Platform aboveground biomass product dashboard**

explore nationally appropriate opportunities for the use of space-based data and maps (biomass is a first case). Each country cluster of selected scientists and national teams includes a champion in the national team and a champion in the CEOS group. At least one member with GHG inventory experience is included in the cluster (e.g., from the UNFCCC roster). The ultimate objectives are i) to invite countries to share their NFI data and expertise to test the maps and contribute to harmonization of global independent maps and estimates that directly contribute to the GST; and ii) to explore opportunities under different national circumstances and different needs to enhance the uptake of satellite data and derived products by national teams in national reporting to the UNFCCC.

Similar activities demonstrating the uptake of remote sensing data-products in national reporting and for climate policy applications can be implemented with teams from developed countries. For example, the new EU forest strategy is envisaging a novel continental monitoring system for the forest sector that increasingly foresees the integrated use of remote sensing data from multiple sensors and technologies with ground observations. In parallel, the European agricultural policy (CAP) foresees a stringent verification phase fully relying on high-resolution radar and optical imagery.

## CONCLUSIONS AND NEXT STEPS

The GST provides a unique opportunity for CEOS, the space agencies, and more generally the systematic observations community to respond to the needs of the UNFCCC and its Parties. Taking full advantage of this process, initial steps were taken at UNFCCC COP-26 by preparing and demonstrating readiness to support GST with early products.

The use of EO to inform policy decisions and track progress, for the AFOLU sector specifically, will become increasingly important in the next 15–20 years. Assuming that the proposed legislative efforts are implemented as planned, the envisaged EO contributions to Monitoring and Verification Support capacities should be able to see fossil GHG emission plumes reduce and eventually disappear over the next two to three decades (depending on the region) and this will subsequently put increased emphasis on monitoring the remaining emissions, in a regime where unavoidable sources (e.g. from agriculture) are compensated by critical carbon sinks (across the AFOLU sectors).

We need to start preparing for this immediately and therefore beyond COP-27, a comprehensive AFOLU Roadmap guiding a sustained coordination framework for AFOLU efforts by space agencies is being developed under the CEOS umbrella. This includes all the major space agencies engaged in land surface and carbon process observation, and supports ongoing efforts toward harmonized products for GST-1 in 2023, provision of data needed for global land emission and removals modeling, and development of EO products that are better matched to the needs of countries in their reporting to the UNFCCC. Moreover, a sustainable architecture in support of the long-term GST process is needed; this must include operational satellite datasets and the integration of atmospheric GHGs and AFOLU in top-down and bottom-up estimates of emissions and removals.

Therefore, features of the AFOLU Roadmap include:

i) Integration of AFOLU variables with GHG data: for example, integration of the managed lands proxy used by the National Greenhouse Gas Inventory, apportioning to sectoral levels, and distribution among the three main greenhouse gases ($CO_2$, $CH_4$, and $N_2O$).

ii) Deepened engagement of users: space agencies can then refine their data products in response to user feedback and lessons learned and ensure increasingly strong cooperation between data providers and users in support of the ambition cycle defined in the Paris Agreement.

iii) Cooperation with the New Space commercial sector, which is planning an increasing number of missions that often complement public programs.

iv) Specification of how space data providers might work together to support the verification and tracking of the various pledges made at COP (e.g., in relation to deforestation, made at COP-26) and to support their implementation and the related incentive schemes.

It is expected that during the development of the AFOLU Roadmap, advances in these EO products will be available; for example, activity data on forest cover might include differentiation of natural forest and plantation and different forest types. Upcoming missions, such as ALOS-4, NISAR and BIOMASS, will further enhance the capabilities to monitor the AFOLU sector. Dedicated developments to match the evolving needs of stakeholders for the GST are most welcome and will shape the operational input to future GSTs. To compare bottom-up AFOLU inventories with top-down atmospheric GHG estimates, we must discriminate fossil fuel/net biospheric exchange/ocean contributions to the net carbon exchange and define "managed land" and what fraction of the observed emissions are from managed/unmanaged land. We must also correct for lateral transport of crops, wood products, and river carbon, because these contributions do not immediately enter the atmosphere.

We expect that all these actions will continue to evolve as the GST process unfolds and the dialog among systematic observation providers, the UNFCCC, and countries develops, and lessons are learned from GST1. These lessons should lead to a more operational contribution from satellite observations to the second GST in 2028.

## ACKNOWLEDGMENTS

The research initiatives described in this paper and preparation of the paper were carried out by integrating activities of all co-authors' host organizations. Submission of the paper was supported by the Japan Aerospace Exploration Agency. Part of the work described in the paper was supported by the ESA-funded CCI Biomass (ESA ESRIN/Contract Number 4000123662) and Forest Carbon Monitoring projects.

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## DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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