A CEOS AFOLU Initiative for the UNFCCC Global Stocktake Process

A Discussion Paper for CEOS Plenary to explore
the development of a CEOS AFOLU Roadmap

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Issues for Plenary Discussion and Decision

1. **CEOS Plenary is asked to recognise the magnitude of the opportunity for satellite Earth observations in support of the Global Stocktake (GST) process** - noting it as a new and significant dimension to the nature of space agencies support of climate policy processes.

2. **CEOS agencies involved in the operation and data processing for missions identified as relevant to the proposed GST1 inputs are asked to support the preparation of those inputs in 2021**, in parallel to and in coordination with the equivalent efforts of the GHG Roadmap aimed at GST1. These agencies include EC, ESA, JAXA, NASA, and USGS amongst others.

3. **These same key agencies are asked to decide at Plenary whether they are willing to provide representation and resources going forward to support the development of a full CEOS AFOLU (Agriculture, Forestry and Other Land Uses) Roadmap in support of the GST process.** Representation and resources to proceed will be paramount regardless of the institutional way forward agreed by CEOS. The effort in 2020 has been made possible through the contributions of the LSI-VC Forest and Biomass subgroup with a number of volunteer experts, many of whom are not CEOS agency personnel, and the LSI-VC GEOGLAM subgroup. We envision that increased participation of CEOS agency personnel will be needed given the nature of the task ahead.

4. The CEOS-CGMS GHG Roadmap already envisions a number of deliverables targeting support to the GST1. **The AFOLU Roadmap and the GHG Roadmap deliverables will likely require a degree of coordination and collaboration and the AFOLU team will commit to that effort in 2021,** including with the overarching support provided by the SIT Chair's ongoing priority for Carbon and Biomass activities. The AFOLU team can no doubt learn from the architecture approach undertaken by the GHG team and should apply lessons learned from that pioneering effort.

5. During the CEOS TW in September, **CEOS has appointed three focal points to the UNFCCC SEC GST process:** Osamu Ochiai (for AFOLU issues), David Crisp (GHG issues), Jörg Schulz (general issues). These focal points will keep CEOS informed on GST developments.

Based on an agreement by Plenary to proceed towards a CEOS AFOLU Roadmap, it is assumed that the established core team (see point 3 above) - expanded with additional resources - will lead the effort in 2021. This will include the CEOS internal relationships with WGClimate - as lead for the CEOS interface to UNFCCC - and with the GHG Task team and WGCV LPV, and the external relations to GFOI and GEOGLAM. Sustained institutional arrangements within CEOS will be necessary to underpin a substantial AFOLU activity and proposals for these will be developed during 2021.

1. Introduction

1.1 Overview

The 2015 UNFCCC Paris Agreement (PA), which came into force on 4th November 2016, is aimed at holding global warming well below 2° C above pre-industrial levels with the aim of limiting to 1.5° C. Parties that were signatories committed to the nationally determined contributions (NDCs) that they intend to achieve in order to reduce their future Greenhouse Gas (GHG) emissions reductions.
The Paris Agreement includes a collective assessment, known as the Global Stocktake (GST). This key process aims to

a) understand how effective the combined efforts are in cutting GHG emissions over time,
b) determine how close we are collectively to achieving its long-term temperature goals, and
c) create the momentum for countries to increase their ambitions in each new set of NDCs.

A common timeframe for NDCs, which is still being negotiated, will facilitate the assessment of collective efforts. The process of the first GST begins in 2023 and follows a 5-year cycle which is timed to inform every new set of NDCs.

The GST represents a significant opportunity for the Committee on Earth Observation Satellites (CEOS) and Space Agencies (SA) to support the climate policy process and demonstrate the value of Earth observation (EO) satellite datasets in that process, both globally and on national scales. Key areas where support can be provided relate to the extent of land use and change (forestry, agriculture and other land uses) and the above ground biomass (AGB; as an indicator of carbon stocks) of vegetation.

EO satellites have been acquiring global data on the state and dynamics of the global landscape for over 40 years and its role has been increasingly recognised. The IPCC Special Report on Climate Change and Land (SRCCL), which highlights the multiple interactions between climate change and land use and the social dimensions of land degradation, desertification and food security in a changing climate, also references the strengths and limitations of EO data. As examples, the recent update of the IPCC guidelines on Agriculture Forestry and Other Land Use (AFOLU; 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories on AFOLU) referred to the significant advancement of the use of EO data for monitoring **land use and land change**.

In the UNFCCC COP-25, CEOS stated that they were in the process of "coordinating the use of multiple satellite missions with novel capabilities to determine **above ground biomass**" and noted that EO data *"offer new prospects and will enable more direct estimates in support of forest and carbon emission reporting – including for global stocktake. …".* Within the Paris Agreement, several articles make reference to EO data, with these including Art 3,4 (the National Determined Contributions; NDCs), Art 5 (Conserve and enhance sinks and reservoirs of GHG including forests, Art 13 (Transparency framework and GHG reporting, and Art 14 (Global Stocktake (GST) - assessment of collective process).

Of immediate concern is that the Paris Agreement has presented a significant opportunity for CEOS to consolidate, present evidence of and showcase the value of EO to parties and other stakeholders, but steps need to be taken to achieve this. On this basis, the 35th CEOS Strategic Implementation Team (SIT) met in March 2020 and agreed that the Japan Aerospace Exploration Agency (JAXA) and the European Space Agency (ESA) explore the development of a CEOS AFOLU Roadmap. The aim of the Roadmap is to assess the will, direction and capability of the relevant CEOS Agencies, with the SIT Chair team supporting communications with Principals and identifying team nominees.

A team of expert volunteers has worked since SIT-35 in order to scope out a possible CEOS AFOLU Roadmap and to track the progress evolving in the GST process being established by the UNFCCC Secretariat. The approach taken by this team has been:

- to document the possible technical contributions of satellite Earth observations to the different aspects of AFOLU and the policy frameworks evolving in support of the GST - with the rationale that it is vital to ensure that CEOS agency capabilities are understood, recognised and represented in the Systematic Observations (SO) Synthesis Report that the UNFCCC SEC is seeking to have developed through an ad-hoc process, in which CEOS will engage;

- to identify the deployment of these technical capabilities via the main datasets which are available at a global or national level to assist the GST process;

- to make the case at both SIT TW and CEOS Plenary for CEOS agency support to the development of a full CEOS AFOLU Roadmap as a management framework and guide to steer and optimise long-term space agency support to the GST process and its AFOLU aspects.

This effort is documented in this first deliverable from the team - framed as a White Paper in support of debate and decision at the CEOS Plenary, with the goal of supporting agreement to proceed with the development of a full AFOLU Roadmap exercise through 2021 and beyond.

1.2 Purpose

In 2018, CEOS developed a White Paper that is focused on the provision of atmospheric GHG datasets to the GST process (Crisp et al., 2018). This White Paper for an AFOLU Roadmap builds on the GHG Roadmap and provides a CEOS contribution that firmly establishes the role of EO data and derived products that are available to support this sector.

CEOS and CGMS have put significant emphasis on support for the GCOS Essential Climate Variables and the coordination of a managed response, including development of an ECV inventory system to track progress. As the climate policy framework evolves with the implementation of the Paris Agreement, including the GST, we will see increased emphasis on mitigation, adaptation and on national-level reporting and data. Many of the issues will be relevant to the land sector and the AFOLU Roadmap should seek to ensure that space agencies are fully alerted to the opportunities and that a coordinated and managed response is assembled, with full awareness of all assets and plans to be provided by each CEOS space agency such that gaps and overlaps can be addressed with maximum efficiency and the policy relevance of CEOS agency data is maximised.

The main objectives of this White Paper are to:

- Establish the issues and context around the development of an AFOLU Roadmap and provide the case to CEOS and its agencies for investing in its development.

- Communicate the opportunity presented by the GST process and ensure a coordinated and comprehensive response from CEOS and space agencies.

- Provide a mechanism for further engagement and iteration between CEOS and the GST processes, including support of the Synthesis Reports, and with UNFCCC SEC.

- Provide a clear statement of the technical capabilities of CEOS agency EO satellite data and their characteristics so that these are clearly understood, both by stakeholders in the GST process and by countries.

- Propose a specific way forward for 2021 and deliverables for GST1 as the critical first deadline.

If supported by CEOS agencies, a full CEOS AFOLU Roadmap will identify opportunities for using EO data to quantify the extent and dynamics of land activities and impacts at the global level and in relation to the NDCs that individual countries are engaged in and which national-level datasets might support. It would assess the EO data and derived products that are available or anticipated over the next five years and beyond, and identify further work needed to maximise opportunities presented by the GST for CEOS agency data; this may include data production activities, but also education and capacity-building measures.

The Roadmap would necessarily identify and engage with a broad range of stakeholders, including:

- national and international bodies: such as the national inventories communities who are charged with the compilation of the GST, and the UNFCCC, who will be collecting and validating the GST inputs;
- space agencies as key investors in the remote sensing capabilities needed at both convention and national levels; the Roadmap should outline the nature of spatial information on agriculture, forestry and vegetation biomass that can be provided to space agencies and contribute to their activities.
- existing CEOS organisations - that will be required to manage, progress and contribute to the roadmap implementation if agreed by CEOS.

1.3 Scope and Structure of the Report

This Discussion Paper is a first step for CEOS and its agencies towards formulating a coordinated response to support the AFOLU aspects of the UNFCCC, and in particular the GST process. To date, CEOS has tended to place greater emphasis on the physical climate through development of the Global Climate Observing System (GCOS) Essential Climate Variables (ECVs) and coordinated support for them. The importance of NDCs to the Paris Agreement, and specifically the GST, raises new challenges around understanding country needs and the implications for using EO space data. CEOS does have country-focused activities in specific domains through the GEO flagships for forest monitoring (the Global Forest Observation Initiative (GFOI) and agricultural monitoring (GEO Global Agricultural Monitoring Initiative; GEOGLAM). Such country-focused efforts will need to be expanded significantly if CEOS and the SA wish to make the most of the opportunity presented by the GST process for the space data community. A CEOS AFOLU Roadmap will be a living document and will have to evolve as this process develops and as opportunities for observations to support the policy become clear.

Section 2 provides more detail on the steps and milestones involved in this process. A key milestone for the CEOS community is the production of a Synthesis Report on Systematic Observations in late 2021 or early 2022. Ensuring accurate and comprehensive representation of remote sensing capabilities in providing policy-relevant information in this Synthesis Report is considered to be a key objective for this first stage of work on an AFOLU Roadmap by CEOS.

Section 3 provides an expert overview for the layman in terms of the contribution of EO to AFOLU aspects of the UNFCCC, with contributions described in relation to forests, vegetation biomass (primarily above ground), agriculture and other land uses.

Section 4 provides an understanding of the major programmes through which these capabilities are deployed, including by production of major national and/or global datasets that can aid the UNFCCC and individual countries. Such programmes include a range of stakeholders, such as space agencies, UN agencies and NGOs. One example is the periodic global Forest Resources Assessment (FRA) of the UN Food and Agriculture Organisation (FAO), which relies heavily on data provided by CEOS agency missions.

Section 5 presents actions that could be undertaken as part of a CEOS AFOLU Roadmap, with these including improved awareness and understanding of EO datasets (e.g., for national forest monitoring through partners and country users in GFOI); support for the CEOS Biomass Protocol to accelerate the uptake and policy relevance of the data from the new generation of CEOS missions; and gap-filling and coordination to ensure the coverage and continuity which is essential for countries to plan with confidence to integrate EO data into their national accounting and reporting systems. We would expect these actions to evolve significantly as the GST process unfolds and the CEOS engagement deepens.

Section 6 suggests the next steps, in terms of CEOS processes and organisations that would lead to further development and implementation of an AFOLU Roadmap and engagement with stakeholders including the UNFCCC SEC. It focuses on the debate and decision at CEOS Plenary in October 2020 as a key decision point on whether to invest further effort in this direction.

References are listed in **Section 7**.

2. Opportunity of the Global Stocktake

2.1 The Global Stocktake

The GST will operate in 3 phases (UNFCCC, 2019):

1) Collecting and preparing information to take stock of progress (starting in mid-2022 for the first stocktake). This will commence one session before the start of the technical assessment, which will take place during the two (or depending on the timing of the publication of the IPCC reports, three) successive sessions of the subsidiary bodies preceding the CMA/COP in 2023 (i.e., mid- to late 2022). Furthermore, Phase 1 should end no later than six months before the consideration of outputs to ensure timely consideration of inputs. The sources of input for Phase 1 of the GST are detailed in the Paris Rulebook (paragraph 37; UNFCCC, 2019c).
2) A technical assessment period (Phase 2) consisting of dialogues and gatherings held over the course of a year through UN climate conferences, and the production of summary reports by the co-facilitators.
3) Consideration of outputs according to the Paris Rulebook (UNFCCC, 2019c). Phase 3 will take place at the Conference of the Parties (COP) to the Paris Agreement (CMA) in the year of the stocktake itself (i.e., 2023, every five years thereafter and coincident with the Conference of the Parties; COP). Country representatives will gather to reflect on the outcome of the technical assessment.

Given the announcement of the UK Government postponing COP26, now set to take place in Glasgow in November 2021, the dates mentioned for the different phases of the first GST may need to be adjusted. For the GST, information on the changing extent of forestry, agriculture and other land uses (settlements, wetlands) and quantities of biomass contained (as a minimum, in forests) is needed.

2.2 Engagement by CEOS

For the GST, there are considerable opportunities and reasons for CEOS to link with the GST as outlined in the following sections. As part of the Systematic Observation Community (SOC), CEOS can play a key role in supporting countries in their long-term progress on mitigation and adaptation, including through the GST process. In this regard, the UNFCCC Secretariat has presented initial proposals for key partners to support and assess collective progress under the first GST, and a concept note with further details on these (Reference, 0000) has been prepared. These include:

- Establishing an informal ad hoc working group on systematic observation and collective progress to develop the report.

- Developing a structured work programme to better enable support the systematic observation community for Parties and the GST.

- Providing a consolidated contribution of the SOC in a synthesis report.

In developing an AFOLU Roadmap, the substantive benefits of using Earth observation data and derived products need to be communicated to the policy community, as well as potential barriers to the effective use for supporting the Paris Agreement. This includes a) the scarcity of relevant ground-based observation networks for algorithm development and validation, b) gaps in observations by mode (e.g., optical, radar, lidar), c) disparities between spatial resolutions and observations frequencies, and c) the costs of the data and also processing and limited knowledge and skills exchange, which collectively limit use in many developing countries. Progress on these measures can be tracked just as space agencies have tracked our coordinated efforts towards satisfying GCOS requirements and the ECVs. CEOS must also communicate the need for continuity and consistency of observations and short to long-term coordination of acquisitions and product generation and use. These barriers are not insurmountable and there is an increasing drive (supported by the Roadmap) to address these given the increasing impacts of GHG driven climate change and public awareness and the political importance of this issue. We might envision that future CEOS engagement of UNFCCC and annual reporting to SBSTA could take on a broader scope as such issues are tracked in a coordinated fashion to ensure that space agency data is of optimal value to the policy process.

2.3 Global data

To assist the UNFCCC policy process, CEOS can provide global level datasets and inventories relating to the changing extent of forests, agriculture and other land uses and, in many cases, their condition (e.g., as represented by AGB). Many of these have been generated using global data from satellite sensors that have been specifically developed to provide data that can be used to address key environmental challenges. Most focus has been on separate retrieval of environmental variables that describe or can be used to classify different land covers, and a wide range of datasets have already been generated or algorithms already exist. However, observations have taken place over different periods, spatial resolutions and temporal frequencies. Hence, using these in combination is often problematic. In this regard, there is a requirement to ensure global coverage and alignment of observation strategies and modes to ensure consistent, systematic observations and integrative capacity. Whilst it is commonly recognised that global products are often not usable at the national level, this is changing with the acquisition of global data at higher spatial resolution and the development of globally applicable retrieval and classification algorithms. Furthermore, harmonisation of processing systems and capabilities has been increased through the development of open platforms that allow processing of global and openly available satellite sensor data, such as the Google Earth Engine, the European DIAS, the Open Data Cube and others. In developing global products, recognition of national needs is essential.

2.4 Country-level data

Global classifications (e.g., of land cover) or retrievals need to be relevant to meet national needs but also be usable within the infrastructures available to a range of organisations. For this to be achieved, the definitions (e.g., of forest cover, agricultural area extent), spatial resolutions and temporal frequencies of observations need to be at least commensurate with past, current or proposed national approaches. Hence the relative value of the global and national methods and whether these can be aligned depends on careful national engagement and knowledge exchange and, in many cases, capacity building, technology transfer and scientifically-based justification.

3. EO Capabilities in support of AFOLU

3.1 Introduction

The Systematic Observation Synthesis Report being developed (by an *ad hoc* Working Group overseen by the UNFCCC SEC) is a key milestone for CEOS and its agencies in relation to the GST. **Ensuring accurate and comprehensive representation of CEOS agency capabilities** is a key objective in working towards an AFOLU Roadmap. This section seeks to provide a clear and expert overview of these capabilities in a way that might easily be imported into the Synthesis Report and these are described in relation to **Agriculture**, **Forests** (cover and biomass) and **Other Land Uses**. Each case focuses on:

- An overview of EO capabilities in relation to each domain; a sense of the length of the heritage, what progress has been made, and the current scale and capacity of the observing assets that can be deployed;
- Measurements that can be provided and characterisation of each in terms of, for example, coverage, spatial resolution, revisit frequency and precision.
- Comparisons (if any) with known IPCC methods in relation to these characteristics (e.g., spatial resolution and user requirements);
- Clear graphical representations of spatial coverage and time history of each archive (in so far as it can be simplified), given the importance of time series and consistency for national reporting;
- A future outlook in terms of key measures of capability and coverage and how improvements will be introduced and by which missions.

A generic explanation of capabilities is provided in order to convey a broad understanding of what EO can provide in each area, based on available and planned technology. Section 4 elaborates on the deployment of these capabilities by the major dataset production programmes and indicates those that might be applied in support of the GST and the NDCs.

3.2 Current and future sensors

Earth observation sensors operating in different modes (primarily optical, radar, thermal and lidar) either singularly or in combination provide information on agriculture, forests and vegetation biomass (Figure 3.2.1).

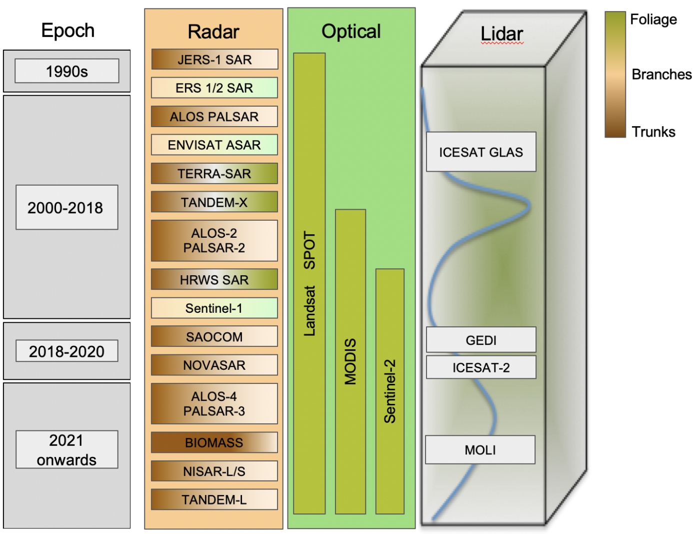

Figure 3.2.1. Earth observation sensor types supporting AFOLU information needs

3.3 Agriculture

For agriculture to meet the food and nutrition requirements for a growing global population, it is estimated that production must increase by 60 % by 2050 (FAO 2016). These increases must occur on an increasingly constrained and degraded land resource that is experiencing climate change marked by increasing extremes. Further, agriculture provides livelihood for approximately two thirds of the global population, the majority of which are smallholders who are among the most vulnerable populations to climate-related extreme weather events.

Beyond food security concerns, agriculture already accounts for 11 % of the global GHG emissions and is rising (FAOSTAT). Of this, agriculture is the primary anthropogenic contributor of methane and nitrous oxide. At the same time, there exist agricultural practices and technologies that can reduce GHG emissions and, in some cases, sequester more carbon than they emit. For both adaptation to and mitigation of climate change impacts, accurate and timely information is critical for meeting the challenge of addressing nutritional needs while reducing GHG contributions from the sector. EO and derived information is already a major asset for climate adaptation and mitigation information, and opportunities for expanding its use in agricultural land use monitoring are increasing.

Agriculture has been a major objective for EO research and operational development for over 40 years. The effort has evolved from a discovery research focus utilizing scientific missions (e.g. LACIE and AgRISTARS, Pinker et al. 2003), to the current day where operational monitoring systems employing operational EO mission data are supporting policy and program decisions around the world (e.g., the Group of 20 GEOGLAM). The IPCC has identified many information and knowledge gaps required for food availability, food system resilience, mitigation, and trade-offs between GHG emissions and food production (IPCC 2014 and IPCC 2019). Taken together, the over 40 year legacy of research and development in EO, the existing EO for agriculture communities (including GEOGLAM) that are well-organized and collaborative, the availability of open EO data, advances in computing systems, and openly available analytical applications means that many of these gaps can now be addressed in whole or part by operational EO solutions. Among the largest remaining challenges to large-scale EO-application is achieving sufficient access to high quality *in situ* data, particularly for less developed nations.

Monitoring the state and change in land use and management practices is a fundamental requirement to understanding the complex web of social and bio-physical challenges associated with agriculture. This understanding is necessary for the development of appropriate policy, program, and reporting responses that support effective GHG reduction and climate change mitigation and adaptation, while maintaining an adequate food supply. Contributions from EO may include monitoring land cover, land use, and land management state and change. These global data sets of agricultural crop production systems (including crop rotations, cover crop utilization/duration/biomass accumulation, and tillage practices), rangeland grazing areas (including quality, intensity of use, and management) can make a significant contribution to the AFOLU, agricultural NDCs as part of the GST. The main areas in which EO can contribute are crop productivity, agricultural land cover and use, management practices and biomass burning.

- **Crop Productivity:** Satellite methods to resolve information on AGB generation in cropping systems are well-established, and models to relate ABG to soil carbon sequestration are becoming increasingly robust (e.g., EPIC and DNDC). At the same time, near-real time monitoring of crop productivity is critical to understanding the impact of climate shocks on local and global food chains within season and throughout time. The IPCC's report on Climate Change and Land (IPCC, 2019) identifies key knowledge gaps around food availability, resilience, mitigation, and trade-offs in decision making. Operational EO is already important in the support of proactive climate adaptation decision making.

- **Agriculture Land Cover and Land Use** state and change monitoring is critical for understanding AFOLU dynamics and their impact on climate change, and *vice versa*. The IPCC identified this type of information as a major gap and highlighted the need for improved global high-resolution data sets of crop production systems and grazing areas (IPCC 2014). Besides global crop productivity monitoring (*via* condition assessment and yield forecasting), cropland and crop type mapping are among the most mature applications of EO for agriculture.

- **Agriculture Management Practices:** Information about agricultural land management practices have also been flagged by the IPCC as a major gap. Information requirements relate to nutrient application, pest management, irrigation, cover crop utilization, structural conservation management (e.g. strip and buffer cropping), and crop residue management (tillage and burning, see next sub-bullet). The IPCC points out that this information provides "improved understanding of the mitigation potential, interplay, and costs as well as environmental and socio-economic consequences of land use-based mitigation options such as improved agricultural management" (IPCC 2014). This has become one of the most active arenas of EO application research and development, particularly with the advent of commercial satellites with increased temporal and spatial resolution coupled with the adoption of sustainability commitments by actors throughout the agricultural value chain.

- **Agricultural biomass burning** is a widely used practice globally during harvesting, post-harvesting, and preparatory (pre-planting) periods that has profound effects on local and regional air quality (Korontzi et al., 2006). Agricultural land use is responsible for at least 8-11 % of global fire events worldwide (ibid) and at least 3 % of carbon emissions worldwide (van der Werf et al, 2010). Even so, current methods under report and therefore underestimate the agricultural emissions from agricultural burning by missing small and short duration fires (Lasko et al., 2017; highlighting this as an important area for further research). Satellite sensor data have revolutionized the field of burned area mapping, active fire mapping, and fire emissions estimation (Boschetti et al., 2020), but further work is needed to close the gap in understanding agricultural fire dynamics and their impacts on carbon (dioxide and monoxide), methane, nitrogen dioxide, sulfur dioxide, and particulate matter emissions. Their impacts on microclimate and human health also need to be recognised.

To address the need for more quantitative information on agriculture 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 action at international and national scales (including UNFCCC and UN 2030 Agenda for Sustainable Development). The EAV concept is consistent with the GCOS Essential Climate Variables (ECVs). Further, many of the variables essential for agriculture are addressed by ECVs, and where they do intersect the EAVs reference the ECV definitions, minimizing new effort and amplifying the voice behind core variable requirements. EAV definitions are in development during 2020, and once complete, they will be used to define the requirements for operational systems to generate information products in support of AFLOU, the Global Stocktake and higher resolution NDC's.

Based on the EAV work, Table 3.3.1 identifies which climate critical measurements can be provided by EO along with the characterisation of each in terms of coverage, spatial resolution, and revisit frequency.

Table 3.3.1: Critical agricultural variables from EO

				GEOGLAM Core Essential Variables								
	Resolution		When ?	Mapping					Attributes Classes			
Req#	Spatial	Spectral (Range)	Effective observ. frequency (cloud free)*	Agriculture Mask	Range-land Mask	Crop Mask	Crop Type Area and Growing Calendar	Field Boundaries	Crop Condition	Crop Yield	Crop Biophysical Variables	Agric. Management Practices
	Coarse Resolution Sampling (>100m)											
1	>500-2000 m	optical	Daily						X		L	
2	100-500 m	optical	2 to 5 per week	X	X	X	X	X	X	L	L	L
3	5-50 km	microwave	Daily						X	X	X	
	Moderate Resolution Sampling (10 to 100m)											
4	10-70m	optical	Monthly (min 2 out of season + 3 in season). Every 1-3 years.	M/S	M/S	X	L/M	L/M				X
5	10-70m	optical	~Weekly (8 days; min. 1 per 16 days)			X	X	L/M	X	X	X	X
6	10-100m	SAR Dual Polarisation	~Weekly (8 days; min. 1 per 16 days)	C	X	X	X	L/M	X	X	X	X
	Fine Resolution Sampling (5 to 10m)											
7	5-10 m	VIS, NIR, SWIR	Monthly (min. 3 in season)			M/S	M/S	X				
8	5-10 m	VIS, NIR, SWIR	~Weekly (8 days; min. 1 per 16 days)				M/S		X		X	X
9	5-10 m	SAR Dual Polarisation	Monthly			M/S	M/S	M/S				M/S
	Very Fine Resolution Sampling (<5m)											
10	< 5 m	VIS, NIR	3 per year (2 in season + 1 out of season); Every 3 years			S	S	S				
11	< 5 m	VIS, NIR	1 to 2 per month				X			X		X

X = for all field sizes   Optical = VIS, NIR, SWIR, TIR
L = large field (>15 ha)
M = medium field (1.5 ha-15 ha)
S = small field (<1.5ha)
C = high Cloud

Observations in Support of AFOLU

Many current missions meet the needs of AFOLU, and several are already employed in operational systems. Using the requirements categories employed in Table 3.3.1, Table 3.3.2 provides a list of the current and future satellite missions that can be used to derive climate relevant variables in support of AFOLU.

Table 3.3.2: Current & future satellite missions that derive climate relevant variables in support of AFOLU

	Existing Missions		Resolution		Timing	
Req#	**Core Missions**	**Contributing Missions**	**Spatial Resolution**	**Spectral Range**	**Effective observ. frequency (cloud free)***	**Growing Season Calendar**
	Coarse Resolution Sampling (>100m)					
1	Aqua/Terra (1000m)	Suomi-NPP (750m) Proba-V (1000m) SPOT-5 (1150m)	>500-2000 m	optical	Daily	all year
2	Aqua/Terra (250/500m) Sentinel-3A (500m)	Suomi-NPP (375m) Proba-V (100/333m)	100-500 m	optical	2 to 5 per week	all year
3	Aqua GCOM-W1/W2	SMOS SMAP	5-50 km	microwave	Daily	all year
	Moderate Resolution Sampling (10 to 100m)					
4	Landsat 7/8 (30m) Sentinel-2A/2B (10-20m)	ResourceSat-2 (56m) CBERS-4 (20-40m)	10-70m	optical	Monthly (min 2 out of season + 3 in season). Required every 1-3 years.	all year
5	Landsat 7/8 (30m) Sentinel-2A/2B (10-20m)	ResourceSat-2 (56m) CBERS-4 (20-40m)	10-70m	optical	~Weekly (8 days; min. 1 per 16 days)	growing season
6	Sentinel-1A/1B (C) Radarsat-2 (C), RCM (C) ALOS-2 PALSAR-2 (L)	RISAT-1/1A (C) RISAT-3 (L)	10-100m	SAR Dual Polarization	~Weekly (8 days; min. 1 per 16 days)	growing season
	Fine Resolution Sampling (5 to 10m)					
7		SPOT-7 CBERS-4	5-10 m	VIS, NIR, SWIR	Monthly (min. 3 in season)	growing season
8		SPOT-7 CBERS-4	5-10 m	VIS, NIR, SWIR	~Weekly (8 days; min. 1 per 16 days)	growing season
9	Sentinel-1A/1B (C) Radarsat-2 (C), RCM (C) ALOS-2 (L)	RISAT-1/1A (C) RISAT-3 (L)	5-10 m	SAR Dual Polarization	Monthly	growing season
	Very Fine Resolution Sampling (<5m)					
10		Pleiades, SPOT-7	< 5 m	VIS, NIR	3 per year (2 in season + 1 out of season); Required every 3 years	all year
11		Pleiades, SPOT-7	< 5 m	VIS, NIR	1 to 2 per month	growing season

(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, China HJ-1).

3.4 Forests

Forests cover approximately 4 billion hectares, or one third of the Earth's land surface, with 45 % located in the tropics (FAO, 2020). Land-use change accounted for about 14 % of anthropogenic CO_2 emissions in the last decade, largely as a result of deforestation. At the same time, forests can act as a powerful GHG sink, working as an efficient, safe, natural, long-lasting and cost-effective carbon capture and storage technology. Consequently, mitigation actions in the forest sector are strategically important to achieve the long term goal of the Paris Agreement (IPCC 2019). It is therefore not surprising that the sector plays a key role in the pledges made by many countries towards meeting the Paris Agreement targets. In particular, if the Land Use, Land Use Change and Forestry (LULUCF) targets involved in the initial NDCs were implemented in full, this would represent approximately a quarter of pledged mitigation efforts up to 2030 (Grassi et al., 2017).

Additionally, around 80 % of all the vegetation biomass on Earth is contained in the world's forests, and growing forests continually accumulate biomass. Loss of forest biomass caused by deforestation and forest degradation is second only to fossil fuel emissions as a major source of GHG emissions to the atmosphere, either immediately (e.g., through burning) or in the longer term (through long-term decomposition, including of wood products). At the same time, uptake of CO_2 from the atmosphere by forest growth makes up a large part of the land sink. Accurate biomass data, generally in conjunction with forest change data, are therefore essential in quantifying GHG emissions (e.g., for national and international reporting). For the processes under the UNFCCC, and specifically the operationalization of the Paris Agreement, the availability of biomass information presents opportunities for the update and enhancement of NDCs, for national reporting under the Enhanced Transparency Framework (ETF, Art 13), for REDD+ (Art 5), and for the GST (Art 14).

Key areas in which EO can contribute with quantitative information to these processes relate in particular forest cover and forest biomass:

Forest Cover

- Information about forest cover is essential to support countries in the development of forest reference levels (RL) and forest activity data (AD). The former includes both estimation of the total area of land cover belonging to the forest class (parameterised by, for example, canopy closure), as well as information about the spatial distribution, or macro patterns, of the forest cover, which is required for higher tier reporting. Canopy closure, typically estimated from optical fine- or medium resolution EO data, is also an indicator of the state or health of the forest cover.

- Activity data can be estimated using time-series of EO data, where information about changes to the forest class from/to other land uses (i.e. afforestation, reforestation, deforestation) can be derived. Optical medium resolution sensors are most commonly used, but long wavelength band (L-band) SAR sensors are particularly efficient in detecting and delineating changes as they are unaffected by cloud cover and illumination conditions. Both sensor types are also useful for detecting within class changes (a.k.a. forest remaining forest), caused by degradation events and processes, regrowth or forest management practices. These are typically slower processes than those driving forest removals and require longer time-series of data for detection and quantification.

Biomass

- Biomass products from EO – specifically derived from Lidar and SAR sensors – can be used to estimate Emission Factors (EF) for higher tier reporting and will need to meet requirements of the IPCC in order to contribute successfully to National Greenhouse Gas Inventories (NGGI) (IPCC, 2019). In particular, the ground data need to be available for calibration and validation of EO products and characterisation of uncertainty including the manner in which bias and precision are reported. It is also essential that consistency is maintained in relation to each individual country's definitions of forest and biomass.
- EO-derived forest data can also contribute to NGGIs through the development of biomass change products, with these allowing estimation of emissions from change events (e.g., deforestation) or processes (degradation, growth). Central to this is, again, the need for consistent products and supportive in-situ data. Considerations need to be made in the separation between anthropogenically and naturally driven changes and their different contributions to emissions. The sensitivity of EO data to subtle changes in forest biomass (e.g., through progressive removal or growth of woody components) also needs to be carefully assessed. In addition, compatibility must be maintained between different EO data sources and processing methods through time. This requirement for consistent and well-calibrated multi-temporal biomass maps and change mapping could be achieved in future years with launch of new sensors alongside increased contributions to in-situ data across the globe.
- Important to note is that, to date, there have not been any global-scale biomass products that have been developed with satellite data streams designed specifically for measuring forest structure. We are now at the very beginning of a new wave of biomass products that use Lidar and SAR data designed

for this purpose. These new biomass products are anticipated to be of much higher quality than previous biomass products that used data designed for other purposes (e.g. for measuring ice), which was the only data available at the time

Forest data can also contribute to Goal 15 of the UN Sustainable Development Goals (SDGs), which aims to promote sustainable forest management in all types of forests by increasing afforestation, restoring degraded forests and halting deforestation globally by 2020 (Herold and Carter, CEOS Biomass Protocol, 2020). Biomass maps can contribute to GHG inventories but it is also important to highlight the role of forest cover, *in situ* data and other forest EO products in producing these (e.g., by defining forest area). Forest data derived from EO can also contribute to defining forest types allowing more precise assignment of growth rates, wood densities, biomass expansion factors, or emissions factors, and can inform policy making in their own right. Table 3.4.1 highlights these essential forest information requirements, whilst Table 3.4.2 indicates current and future EO missions that can provide supportive data.

Table 3.4.1. Essential forest information requirements.

		Forest Variables - Information Requirements						
		Spatial distribution		**Biophysical characteristics**			**Other**	
		Forest Cover [ha]		**Above-Ground Biomass [Mg/ha]**				**NFMS**
Req#	**Sensor Type**	**Forest Area (LCCS:A)[1] [ha]**	**Canopy Closure, Macro-pattern (LCCS:C) [%]**	**Forest Height (LCCS:B) [m]**	**Vertical Structure (LCCS:F, G)**	**Forest Type (LCCS:D & E)**	**Dominant Plant Species (incl. Natural/ Plantations)**	**Early Warning**
	Coarse resolution sampling (>100 m)							
1	Optical	-	-	-	-	-	-	< Weekly
2	Microwave	-	-	-	-	-	-	-
	Moderate resolution sampling (10-100 m)							
3	VNIR, SWIR	RL[2]: Once (Ref year) AD[3]: Annual		-	-	EF[4]: Once ΔEF[5]: Annual	RL: Once AD: Annual	< Weekly
4	Microwave Long (L, P)	RL: Once AD: Annual		-	EF: Once ΔEF: Annual	EF: Once ΔEF: Annual	RL: Once AD: Annual	< Weekly
5	Microwave Short (S, C, X)	-	-	Annual (Digital Elevation)	-	-	-	< Weekly
	Fine & Very Fine resolution sampling (< 10 m)							
6	PAN, VNIR, SWIR	RL: Once AD: Annual		-	-	EF: Once ΔEF: Annual	EF: Once ΔEF: Annual	< Weekly
7	Microwave	-	-	-	-	-	-	-
	Point sampling							
8	LiDAR	-	-	EF: Once ΔEF: Annual	EF: Once ΔEF: Annual	-	-	-
(9)	(In situ)	-	EF Once ΔEF: Annual	EF: Once ΔEF: Annual	EF: Once ΔEF: Annual	EF: Once ΔEF: Annual	-	-

(1) FAO Land Cover Classification System (LCCS) Codes:

A	*Cover [% (of area)]*
B	*Height [m]*
C	*Macro-pattern [continuous, fragmented, cellular, etc]*
D	*Leaf type [broadleaf, needleleaf, etc.]*
E	*Phenological type [evergreen, deciduous, etc.]*
F, G	*Stratification [second layer type, cover, height]*

(2) RL - Reference Level (Forest Area for reference year)
(3) AD - Activity Data (change in Forest Area)
(4) EF - Emission Factor [Mg CO_2-e ha^{-1}] (representing C stock in all pools, incl. AGB)
(5) ΔEF - Change in EF (or AGB).

Table 3.4.2. EO missions with capacity to support forest information requirements.

	Operational Missions		Future Missions	Resolution			
Req#	Core Missions	Contributing Missions		Spatial	Spectral (range)	Temporal (capacity)	Observation strategy
	Coarse resolution Optical (>100 m)						
1	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)						
2	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)						
3	Landsat 7 (ETM+) 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)						
4	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
5	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
6		TanDEM-X			(Digital Elevation)		Global
	Fine & Very Fine resolution Optical (<10 m)						
7	Planet (through NICFI)			< 5 m	VNIR	Monthly mosaics	Pan-tropical
		Pleiades, SPOT-6/7		(1.5 m), 6 m	(PAN), VNIR		On demand
	LiDAR						
8	ICESat-2			13 m footprint	Photon count LiDAR	91 days	Global
	GEDI		MOLI (2024)	25 m footprint	Full waveform LiDAR	ISS non-repeat orbit	<52° latitude

Missions specifically supporting biomass

The Second GCOS Adequacy Report (GCOS, 2003) unequivocally stated that “satellite systems capable of measuring global vegetation biomass are required”, and successive GCOS reports refined this requirement, specifying the need for spaceborne lidar and L- and P-band radars (~23.5 and 69 cm wavelength respectively), fostering systematic acquisition of observations from multiple sensors needed for biomass mapping, and increasing the amount, access to, and quality of in situ biomass data for validating biomass measurements from space. The response of the space agencies to these requirements has been outstanding: all of them have been met, though the *in situ* component needs further development.

The rationale for the GCOS stipulation of lidar and radar as key technologies is that most of the forest biomass is below the leafy canopy, information which can only be retrieved using active sensors (i.e., those that do not rely on solar or thermal radiation but which transmit a signal and measure the return); in addition, longer radar wavelengths are needed as these penetrate further into the forest volume. From space, AGB can be measured (for most practical purposes, this is also true for in situ measurements), so GCOS defines AGB as the relevant ECV.

Developing missions dedicated to measuring biomass (and more generally, forest structure) has taken time simply because of the processes by which missions get selected. However, we are entering a phase of unparalleled capabilities, with three sensor types - Lidar, P-band and L-band SAR – specifically designed to measure forest structure and biomass in space or expected to be there by 2023/2024. The NASA Global Ecosystem Dynamics Investigation (GEDI) Lidar mission, has been on the International Space Station (ISS) since December 2018 and is already providing data products. NASA’s Ice Cloud and Land Elevation Satellite-2 (ICESat-2) launched a few months prior to GEDI, in September 2018, and is collecting global photon counting lidar data suitable for height and biomass estimations in lower biomass systems. It is particularly useful for providing boreal forest structure data to fill GEDI’s spatial gap north of 52 latitude. Finally, the Multi-footprint Observation Lidar and Imager (MOLI) is under consideration by JAXA for deployment on the ISS around 2024, potentially providing important continuity to the GEDI mission.

JAXA’s ALOS-2 PALSAR-2 is currently in operation, and it has together with ALOS PALSAR and JERS-1 SAR, collected a valuable long-term systematic global archive of historical L-band SAR data going back to the mid 1990s. The CONAE/ASI SAOCOM-1 constellation is also operational, collecting systematic polarimetric L-band data with focus on the Southern Hemisphere, the tropics and Siberia (similar to the coverage for ESA’s BIOMASS).

The ESA BIOMASS P-band SAR mission, the NASA/ISRO NISAR L- and S-band SAR mission, and JAXA’s ALOS-4 PALSAR-3 L-band mission all have nominal launch dates around 2023. In addition, significant resources have been devoted to making available in situ and airborne lidar data to calibrate and validate products from these missions. Furthermore, an unprecedented level of cooperation between NASA and ESA is producing a common structure for sharing and analysing satellite and ground data, the joint Multi-Mission Algorithm and Analysis Platform (MAAP). This open access platform gives all users free access to all satellite and reference data (in situ and airborne).

The combined data from these three sensor types will mark a major step forward. All three are designed to measure AGB, but they cover different regions and retrieve different components of AGB at different spatial and temporal scales. Their complementary nature is illustrated in Fig. 4, which shows their coverage on a map indicating approximate mean AGB. BIOMASS will focus on tropical and subtropical woodlands at 4 ha resolution and bi-annual coverage, though will also cover the temperate and boreal forests of Asia and the southern hemisphere. NISAR will give 12-day global coverage at 1 ha resolution but with AGB estimates limited to areas where AGB < 100 t/ha. GEDI covers the full range of AGB, but with sample footprints limited to within ± 51.5° latitude, with this coverage being built up throughout the mission. ICESat-2 is still in research phase for biomass, and likely will have high uncertainties in high biomass forests, but collects global data. Hence, the data from all three sensor types will need to be combined to generate wall-to-wall estimates of global forest AGB.

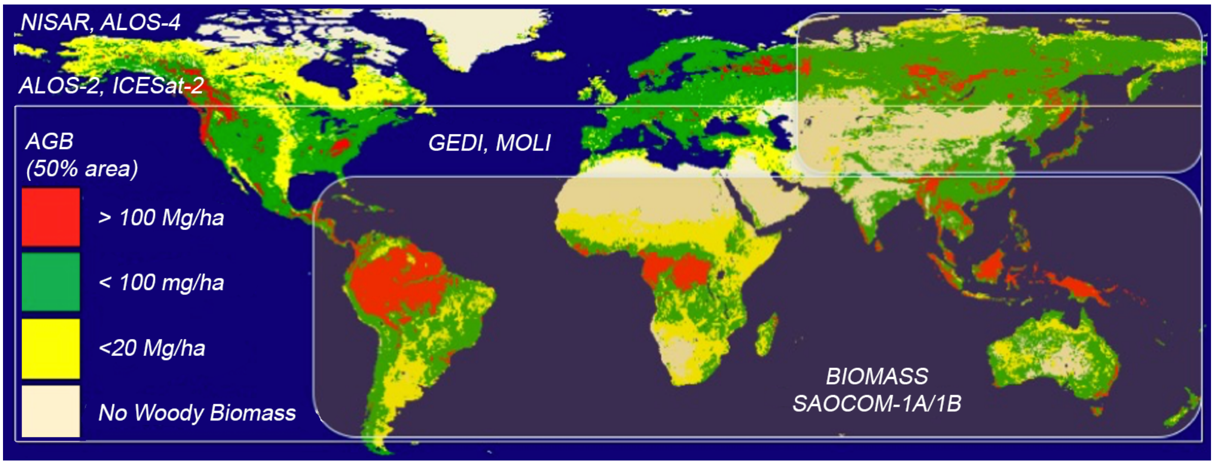

Figure 3.4.1. Map indicating the approximate areas where AGB > 100 t/ha (red), 20 t/ha < AGB < 100 t/ha (green), AGB < 20 t/ha (yellow) and there is no biomass (grey). Also shown is the access range or planned coverage of key current and near future CEOS agency missions related to AGB.

3.5 Other Land Uses

Other Land Uses (OLU) comprises the remaining four land-use categories in the 2006 IPCC Guidelines:

- Grasslands (including rangelands)
- Wetlands
- Settlements (all developed land, incl. transportation infrastructure and human settlements)
- Other Land (bare soil, rock, ice, and all land areas not belonging to any other IPCC category)

Requirements relating to the Grasslands category are included (as rangelands) in the Agriculture (Cropland) section (3.3) above, while Settlements and Other Land are not covered. Our focus for OLU here is on the Wetlands class, which is diverse enough to warrant its own section.

The IPCC (2006) defines Wetlands as *"areas of peat extraction and land that is covered or saturated by water for all or part of the year, and that does not fall into any of the other Land Use categories"*. It also includes hydroelectric reservoirs, natural rivers and lakes.

The Ramsar Convention on Wetlands applies a very broad definition of wetlands, as *"…areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, …" (Wetlands Convention, Art. 1.1), and which "may incorporate riparian and coastal zones adjacent to the wetlands" (Art. 2.1).*

The significance of EO data for addressing the information needs of the Ramsar Convention has been duly recognised by the Convention, which states that *"New [Earth observation] capabilities in terms of spatial, temporal and spectral resolution of the data have enabled more efficient and reliable monitoring of the environment over time at global, regional and local scales. These developments provide a myriad of new opportunities for the monitoring and reporting on indicators for the Sustainable Development Goals (SDGs), Nationally Determined Contributions, under the Paris Agreement, and the UN Reducing emissions from deforestation and forest degradation scheme (REDD+), under the UN Framework Convention on Climate Change (UNFCCC)."* (Rebelo et al., 2018).

Whereas practically all ecosystems where there is water, permanently or temporary, can be categorised as "wetlands", focus here is limited to three types of vegetated wetlands which may be considered by countries for inclusion in their NDCs and are relevant for reporting on SDG Task 6.6 (Protect and restore water-related ecosystems) and its Indicator 6.6.1 (Change in the extent of water-related ecosystems over time):

- Mangroves
- Peatlands
- Riparian (floodplain) forests.

Mangroves

Mangroves are estuarine wetlands, which also include river deltas and tidal marshes. These are commonly referred to as "Blue Carbon" ecosystems due to their coastal influence. Blue Carbon ecosystems have the capacity to sequester and store large amounts of carbon due to the extremely slow decomposition rates of organic matter produced by wetland plants that occur under conditions created with 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 [Beers et al, 2020]. Mangroves are furthermore of critical importance as breeding and nursery sites for birds, fish, and crustaceans, and perform critical landscape-level functions related to regulation of freshwater and coastal protection (Lucas et al., 2014).

Mangroves are in decline, with about four to five percent of the global coverage lost during the past two decades (FAO 2015; Bunting et al. 2018). Significant drivers of change include removal for aquaculture, agriculture, energy exploitation and other industrial development (Thomas et al. 2017), with an unknown proportion of the remaining mangroves fragmented and degraded. Mangroves are also sensitive to climate change effects such as sea level rise (Duke et al., 2017), temperature extremes and geographic range, and changes in hydrology.

Mangroves are relatively straight-forward 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 has consequently commonly been used in the past for baseline mapping (e.g. Spalding et al., 2010; Giri et al., 2010; Bunting et al., 2018). Cloud cover however puts limitations on optical data availability in certain areas of the tropics. Long wavelength band (L-band) SAR sensors provide complementary information and constitute a key tool to map mangrove structure and changes over time (Lucas et al., 2014; Rosenqvist et al., 2007). To estimate parameters such as mangrove height, which relates to AGB, spaceborne LIDAR and interferometric SAR have been used (Simard et al., 2019; Lucas et al., 2020).

Peatlands

Peatlands are palustrine (swampy) wetlands and 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 below-ground biomass, with exceptionally slow decomposition rates due to the anoxic conditions in the permanently waterlogged soil. Peatlands occur worldwide, but most commonly in the boreal zone (Siberia, Fennoscandia, Canada and Alaska) and in the tropics (Indonesia, Malaysia, PNG, Amazon Basin, Congo Basin). While peatlands cover only about 3 % of the Earth's land surface, they are estimated to hold between 113 and 612 Pg of carbon, corresponding to a staggering 18–89 % of global terrestrial C biomass (Köchy et al., 2015; Jackson et al., 2017; Minasny et al., 2019). Notable is the considerable uncertainty in the estimate, partly due to that peat carbon stock is proportional to peat depth, which typically can only be measured directly *in situ*. As peatlands furthermore are fragmented ecosystems that occur in localised pockets, mapping is challenging and detailed information about their global distribution is lacking.

Peatlands are in many areas of the world under severe threat, often mined as biofuel or drained and converted to agriculture or plantations, in the tropics commonly to oil palm or Acacia. It has been estimated that for the first 25 years after an oil-palm plantation is established in a peat swamp forest, about 60 tonnes of CO_2 are released per hectare every year, with more than half of those emissions coming from the peat itself (Murdiyarso et al., 2010; Vaidyanathan G., 2011). Wielaard (2018) reports that in 2015, peatlands were estimated to be responsible for 42 % of Indonesia's total emissions; approximately 1.62 billion metric tons of GHG emissions have been released by forests and peat fires, and the total costs for the Indonesian economy were estimated at USD 16 billion. Due to their high sensitivity to disturbances and their enormous amount of stored carbon, very high emissions can occur from small areas. But this also means that peatland conservation and restoration can be a very effective climate change adaptation and mitigation measure, even in small peatland areas.

With peatland carbon mainly stored below ground, direct measurements by EO sensors is not possible. EO data can however be used to map indicators associated with peat depth, such peatland forest phenology using multi-temporal optical coarse- (MODIS) or medium resolution (Landsat/Sentinel-2) data (Shimada et al, 2016). With L-band SAR sensitive to forest inundation, Hoekman (2007) used JERS-1 SAR time-series to map the spatial and temporal characteristics of flooding in tropical (Indonesian) peatlands, modelling peat depth as a function of flooding intensity. Peat dome elevation and shape are furthermore important predictors of peat depth and Digital Elevation Models derived from EO can be used to model carbon storage and changes (Jaenicke et al., 2008).

In the EU, member states are from 2021 required to report on the emission and removals of greenhouse gases from wetlands, which requires detailed information about peatland extents, conditions and carbon stocks. Knowledge about peatland regional and global distribution and extents is as mentioned above however poor, highlighting a critical need for the development of consistent EO-based methods for peatland mapping and monitoring.

Riparian (floodplain) forests

Riparian, or floodplain, forests are characterised as riverine wetlands. They are a dominant ecosystem in meandering river basins with moderate topography, where they provide important habitats for aquatic flora and fauna, and critical ecosystem services – such as sustaining local fish production – for communities on and along the rivers. 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 (Devol et al., 1990).

Floodplain forest biomass varies in strata across the floodplain as a function of (average) annual duration of inundation, with increasing biomass when moving from the river's edge towards the edge of maximum inundation extent where dryland *terra firme* forest types gradually take over. In river basins with low topography, floodplain forests can constitute more than 10% of the total basin area, e.g. corresponding to around 600,000 km^2 in the Amazon basin alone (Hess et al., 2003, Rosenqvist et al., 2020).

Maps of floodplain forest extent and biomass are however scarce or lacking, partly due to that riparian ecosystems can occur over extensive areas while occupying only narrow corridors along the rivers. In coarse resolution global biomass maps (see Table 4.3.2) they may be represented by only a few pixels, if identified at all. The general lack of information about floodplain biomass distribution can also be attributed to biomass close relationship with flood duration, which represents a challenge to detect, in particular across tropical and sub-tropical wetlands where flooding for the most part occurs under a closed evergreen canopy. Detailed geospatial information about both inundation extent and duration is thus required to accommodate full stratified mapping of floodplain forest biomass.

From the perspective of SDG (6.6.1) reporting on inundation spatial extent, and the Ramsar Convention focus on wetland conservation and wise use, in turn, there is also a critical need for long-term systematic monitoring and mapping of riparian floodplain forests and the effects of anthropogenic activities on these. A particular threat comes from the rapid expansion of hydropower across the world. Apart from the ecological impact and carbon emissions caused by the reservoir itself, damming can alter the river flows and significantly disturb the seasonal inundation cycle for all wetlands downstream, causing irreversible damage to the flora and fauna and the ecosystems services they sustain, and trigger a release of carbon from dried out and dead floodplain forest. In the Greater Amazon Basin – encompassing parts of Bolivia, Brazil, Peru, Ecuador and Colombia – more than 400 reservoirs are planned the coming decades, with more than a third of those involving five of the six main rivers that drain into the Amazon river from the Andes (Little, 2014). In the Congo river, a mega power station with twice the capacity of the Three Gorges Dam in China is being planned, while in Southeast Asia, 12 new dams are planned or are under construction on the Mekong river main channel.

Regular monitoring and mapping of wetland distributions and inundation dynamics in major river basins across the world are thus of critical importance both from the perspective of carbon and biomass, as well as to map the effects of these monumental changes and understand their effects on climate, environment and ecosystem services.

Wetlands EO information requirements

Common for the three wetland types discussed above are that they are all under threat from human activities and in need for comprehensive geospatial information to map their extents, health and special characteristics, including their water regimes, and changes to those.

Optical and microwave sensors provide complementary information, with optical medium resolution data primarily required for characterisation of the wetland vegetation (e.g. vegetation type, dominant species, canopy closure, etc.) and indicators of plant health (e.g. NDVI), and medium resolution microwave for mapping of the wetland water regimes – specifically for determination of the inundation state (flooded/non-flooded). L-band SAR has a proven long track record in mapping and detection of forest inundation, going all the way back to SEASAT (MacDonald et al., 1980), thanks to the capacity of the long wavelength signal to penetrate a forest canopy and interact with the ground or a 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 JAXA's systematic acquisition strategies for ALOS PALSAR and ALOS-2 PALSAR-2, L-band SAR data have been acquired across the entire pan-tropical zone on a regular (every 6 weeks) basis since the 2006, with additional historical coverage by JERS-1 SAR in the mid 1990s. Continuity of into the end of the decade is assured with ALOS-4 PALSAR-3. NASA's NISAR L-band SAR comprises a comprehensive acquisition plan for wetlands monitoring with global L-band observations every 12 days during the mission.

Table 3.5.1 below outlines the Earth observation requirements for the three wetlands types discussed above. The EO missions corresponding to the numbers in the first column of the table ("Req#") are identical with those listed in Table 3.4.2 in the Forest section above, and thus not repeated in this section. Please refer to Table 3.4.2.

Table 3.5.1. EO information requirements for Mangroves (M), Peatlands (P) and Floodplain forest (F)

(M) – Mangroves (P) – Peatlands (F) – Floodplain forest		Wetlands Variables - Information Requirements						
		Spatial distribution		Biophysical characteristics			Water regime	Other
		Wetland Cover [ha]		Above-Ground Biomass [Mg/ha]				NFMS
Req#	**Sensor Type**	**Area (LCCS:A)[1] [ha]**	**Canopy Closure, Macro-pattern (LCCS:C) [%]**	**Height (LCCS:B) [m]**	**Vertical Structure (LCCS:F, G)**	**Vegetation Type (LCCS:D & E), Dominant Species**	**Inundation state**	**Early Warning**
	Coarse resolution sampling (>100 m)							
1	Optical	Monthly (P)	Monthly (P)	-	-	Monthly (P)	-	-
2	Microwave	-	-	-	-	-	-	-
	Moderate resolution sampling (10-100 m)							
3	VNIR, SWIR	RL[2]: Once (M, P, F) AD[3]: Annual (M, P, F)		-	-	EF[4]: Once (M, P, F) ΔEF[5]: Annual (M, P, F)	-	< Weekly (M, P, F)
4	Microwave Long (L, P)	RL: Once (M, P, F) AD: Annual (M, P, F)		-	?	-	< Bi-weekly (P, F)	< Weekly (M, P, F)
5	Microwave Short (S, C, X)	-	-	Annual (DEM) (M, P, F)	-	-	-	< Weekly (M, P, F)
	Fine & Very Fine resolution sampling (< 10 m)							
6	PAN, VNIR, SWIR	RL: Once (M, P, F) AD: Annual (M, P, F)		-	-	EF: Once (M, P, F) ΔEF: Annual (M, P, F)	-	< Weekly (M, P, F)
7	Microwave	-	-	-	-	-	-	-
	Point sampling							
8	LiDAR	-	-	EF: Once (M, P, F) ΔEF: Annual (M, P, F)		-	-	-
(9)	(In situ)	-	EF: Once (M, P, F) ΔEF: Annual (M, P, F)				Daily (river height) (P, F)	

[1] FAO Land Cover Classification System (LCCS) Codes:

A	*Cover [% (of area)]*
B	*Height [m]*
C	*Macro-pattern [continuous, fragmented, cellular, etc]*
D	*Leaf type [broadleaf, needleleaf, etc.]*
E	*Phenological type [evergreen, deciduous, etc.]*
F, G	*Stratification [second layer type, cover, height]*

[2] RL - Reference Level (Forest Area for reference year)

[3] AD - Activity Data (change in Forest Area)

[4] EF - Emission Factor [Mg CO_2-e ha^{-1}] (representing C stock in all pools, incl. AGB)

[5] ΔEF - Change in EF (or AGB).

4. Deployment of Capabilities

4.1 Introduction

This Section provides a reference summary of the main datasets and sources that may be of value to UNFCCC and to countries in support of the GST process. Using the headings adopted in Section 3 to explain EO capabilities (agriculture, forests, biomass, other land uses), known programmes are identified and information provided on:

- The nature of the dataset in question, including which measurements are included;
- The dataset producer and provider;
- The key technical characteristics, including spatial resolution, coverage and temporal frequency;
- Access and format information for potential users;
- Known example applications of the data of relevance to the GST and/or NDCs;
- Depth of the archive in terms of years of interest to UNFCCC.

An indicative overview of datasets that are available to support the GST is provided in Figure 4.1.1, noting that there is potential to combine these within integrating frameworks to better understand and quantify transitions within and between land cover categories and their impacts on changing AGB amount and distributions.

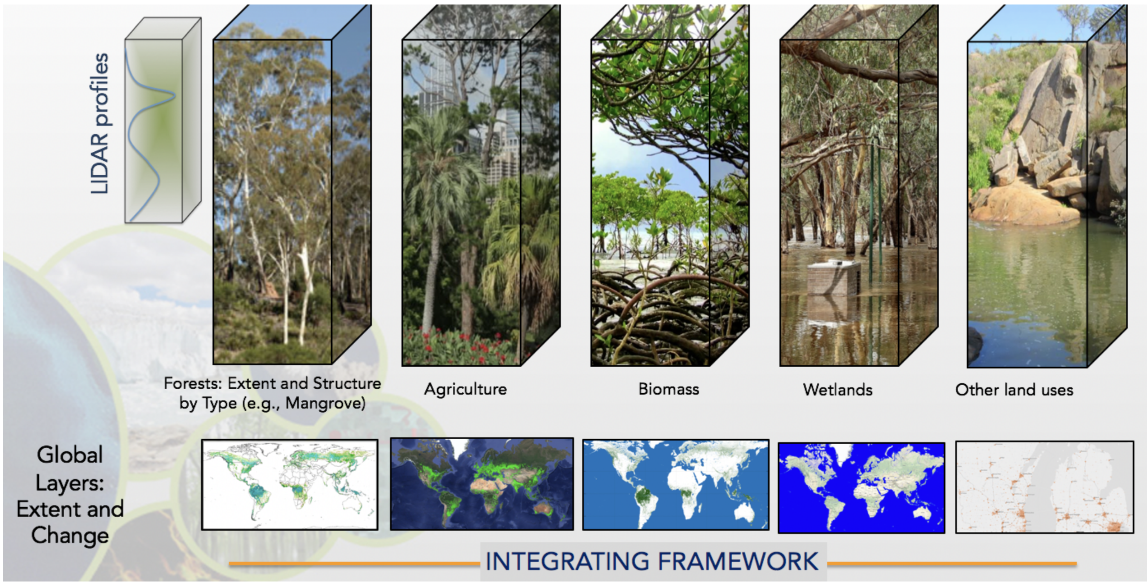

Figure 4.1.1. Broad overview of global datasets generated from EO that can support the GST

4.2 Agriculture

There are many past, current, and planned initiatives that can contribute to AFOLU NDCs by providing state and change information in support of climate change mitigation and adaptation measures. These contributions are grouped and discussed in terms of crop production, agricultural land cover and land use, and crop management activities.

Crop Production

Near-real-time crop production information supports climate adaptation programs and policy by helping to stabilize global commodity markets and give early warning for international and national food security agencies on climate impacts, such as drought, disease, and pests. At the global level, GEOGLAM operates two monthly crop conditions assessments that contribute to the needs for crop production monitoring (cropmonitor.org).

The GEOGLAM Crop Monitor for AMIS (CM4AMIS) provides near real-time crop conditions for the four major commodity crops (maize, rice, wheat, and soybean), in major exporting nations (80-90% global production). This information supports the Agricultural Market Information System (AMIS) and helps to stabilize markets by providing independent, reliable information on production prospects. The crop monitor is based on a synthesis of EO data and regional expertise and has produced monthly reports since 2013.

The Crop Monitor for Early Warning (CM4EW) provides timely information on crop conditions for regionally important food crops in food insecure regions of the world. Like the CM4AMIS, the CM4EW is produced through a synthesis of EO data and on the ground expertise. Partners include the major international food security agencies (WFP, FAO, FEWSNET, USAID), regional authorities and several national agencies. CM4EW reports have been produced monthly since 2016.

Together the crop monitors provide near global coverage (Figure 4.2.1). GEOGLAM has also worked with national agencies in food-insecure nations to co-develop national level crop monitoring, and these have proven to be effective for driving policy and program response to climate disasters, such as flood and drought. GEOGLAM is in discussions with the UNFCCC Adaptation Programme to get crop monitoring into the National Adaptation Planning (NAP) process.

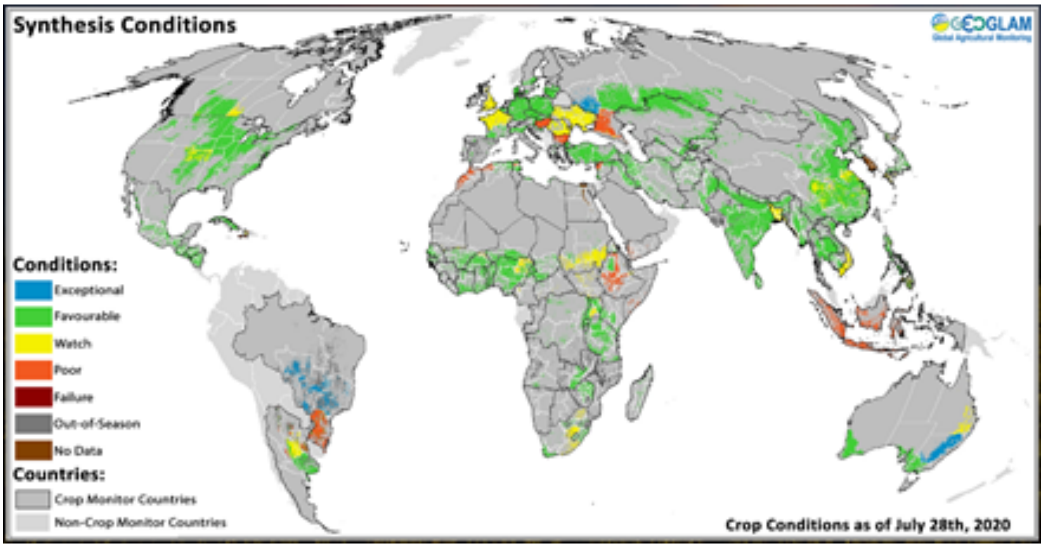

Figure 4.2.1. AMIS and CM4EW Synthesis Conditions, July 2020

Agricultural Land Cover and Land Use

Considerable effort has been directed at the development of global land cover products (summarised in Table 1) over the last couple of decades. They have been coarse scale created for one year or based on imagery accumulated over several years. Over the years the sensors used, data availability and methods used have evolved, so comparison between products is difficult, and will not support accurate change detection. However more recent work by the Copernicus Land Services is focussed on developing annual assessments along with 5 year change products. The first change product will be released in 2020 based on 2016 to 2019 annual products, at 100m resolution. This work is approaching the requirements of the IPCC and the needs for the AFOLU in the GST.

Table 4.2.1. Summary overview of global land cover products

Dataset Definition	Agriculture Relevant Classes	Owner	Date of Coverage	Currently Active?	Refresh	Spatial Resolution - minimum pixel size (m)	Target Applications	Availability
Climate Change Initiative (CCI) Land Cover The CCI-LC team produced and released 3-epoch series of global land cover maps. These maps were produced using a multi-year and multi-sensor strategy in order to make use of all suitable data and maximize product consistency (ESA 2014).	**Legend** (based on the LCCS**):** • 10 Cropland, rainfed • 11 Herbaceous cover • 12 Tree or shrub cover • 20 Cropland, irrigated or post-flooding • 30 Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%) • 40 Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%) • 130 Grassland	**ESA, 2010**[1].	2008-2012, 2003-2007, 1998-2002	**No**	3-epoch series of global land cover maps where each epoch covers a 5-year period	**300**	Intended to match the needs of key users' belonging to the climate change community	**Open** http://maps.elie.ucl.ac.be/CCI/viewer/download.php
GlobCover (ESA, 2009) .Land cover map of global extent	**Legend:** (22 class LC) • 11 Post-flooding or irrigated croplands • 14 Rainfed croplands • 20 Mosaic Cropland (50-70%) / Vegetation (grassland, shrubland, forest) (20-50%) • 30 Mosaic Vegetation (grassland, shrubland, forest) (50-70%) / Cropland (20-50%) • 110 Mosaic Forest/Shrubland (50-70%) / Grassland (20-50%) • 120 Mosaic Grassland (50-70%) / Forest/Shrubland (20-50%) • 130 Grassland • 140 Closed to open (>15%) grassland	**ESA, 2009**[2]	2004-2006, and 2009	**No**	Original coverage 2004-06, with opne refresh in 2009	**300**	The state of global land cover for two time periods	**Open** http://due.esrin.esa.int/page_globcover.php
Copernicus CGLS Dynamic Land Cover A global land cover product updated annually. Global change product 2016-19 to be released in 2020 (Africa available now). Data from PROBA-V 100m time series 2016-2019, Sentinel missions to be used from 2020 o	**Legend** (23 class LC): Shrubland, herbacious, cropland	**Copernicus, 2015**[3].	2016	**Yes**	**Annual, plus global 5 year change products** 2016-19	**100**	Land cover state and change	**Open DOI:** 10.5281/zenodo.3243509

1 https://www.esa-landcover-cci.org/?q=overview
2 http://due.esrin.esa.int/page_globcover.php
3 https://land.copernicus.eu/global/products/lc

In Development

Dataset Definition	Agriculture Relevant Classes	Owner	Date of Coverage	Currently Active?	Refresh	Spatial Resolution - minimum pixel size (m)	Target Applications	Availability
WorldCover								
WorldCereal								

Some new products are in the development stages from the World Cover and World Cereals projects. World Cover will provide 10 class IPCC Level 1 global land cover data, including cropland and grasslands at 10 m resolution, with an overall minimum accuracy of 75 %. The first 10 % of the world land area is complete and under review in August 2020, and the project will be completed by late 2021.

The World Cereals project has a much higher resolved legend that breaks cropland into specific crop categories with an initial focus on wheat and maize and will identify irrigated and non-irrigated croplands. It will produce annual crop extent maps based on seasonal updates 10 m resolution. These products make use of the higher spatial resolution and revisit time of the Sentinel 2 missions. They are also utilizing the Sentinel 1 missions, as the SAR data overcome observation constraints in regions with high prevalence of clouds. This is particularly important for highly dynamic agricultural landscapes that require multiple images for 1-3 crop seasons annually Once these high resolution products (including change) are moved to operations, they will revolutionize the availability of data to support land cover, land use state and change metrics for the GST, and provide detailed country level data that will support national level programs and monitoring for the NDCs.

Agriculture Management Practices

Beyond land cover, the IPCC has identified many information and knowledge gaps required for food availability, food system resilience, mitigation, and trade-offs between GHG emissions and food production (IPCC 2014 and IPCC 2019). The way farmers interact with the land and soil has a significant impact on the release of GHGs. Optimizing management practices for crop productivity while reducing GHG emissions and increasing carbon storage can contribute towards NDCs. Agriculture management practice information is essential to developing programs that support adaptation and mitigation measures towards meeting and monitoring NDCs. However, to effectively implement metrics in a systematic way will require significant development of new analytical tools.

EO can play an important role in filling these data gaps, but unlike land cover and except for a few nations, there is little systematic generation of land management information. Exceptions include the Canadian Annual Crop Inventory; the US Cropland Data Layer; and European Common Agricultural Policy (CAP) mapping products. Work is underway to develop best practices for these essential variables.

To address information gaps, GEOCLAM's EAVs will provide the roadmap to developing quantified metrics that can in part support UNFCCC NDCs and the GST. The EAVs will define the minimum set of EO-derived variables for monitoring key aspects of agricultural state and change that are relevant to climate adaptation and mitigation. These essential variables follow along the work undertaken in other science domains such as the ECVs (GCOS 2016), Biodiversity EBVs (Proença et al 2017), and water (Lawford, 2014)

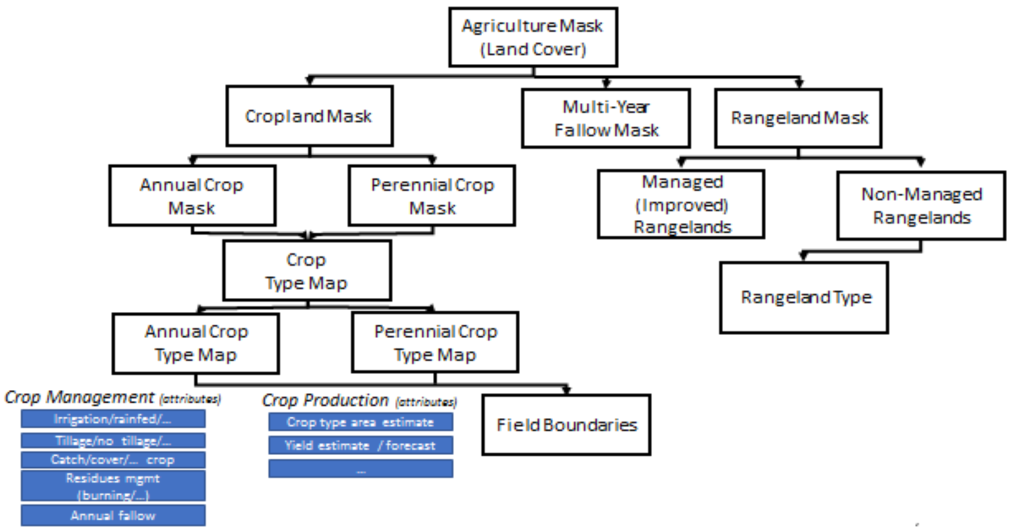

Figure 4.2.2. Essential Agricultural Variables, Mapping Hierarchy

To provide some insight into how GEOGLAM's EAVs can contribute, at the highest level in Figure 4.2.2, the "Agriculture Mask" corresponds to the "A" in AFOLU. Detailed ECV descriptions are being developed for each level in the hierarchy, and crop management and production attributes, and will be completed in 2020. As NDCs are defined, these EAV descriptions will allow us to map the lower level EAVs and their corresponding products to national needs.

4.3 Forests

An extensive survey of stakeholders' data needs for estimating forest area and change, AGB and emission factors as well as overall AFOLU GHG emissions is reported in Romijn et al. (2018). The stakeholder group consisted of 557 participants drawn from the governmental (Annex-I and Non-Annex-I countries), intergovernmental, local stakeholder, NGO, company, research institute and university, donor and media sectors.

Forest Cover

A number of global forest extent and cover maps have been generated (Table 4.3.1), with the most notable being the Global Tree Cover dataset of Hansen et al. (2013), with this forming the basis of the Global Forest Watch. The GFW is providing annual maps of forest change at a global level from Landsat sensor data at 30 m spatial resolution. Other datasets are more regional or focused on ecosystem types (e.g., mangroves) or have been generated for years.

Table 4.3.1. Global forest datasets relevant to the GST generated through Earth Observation.

Dataset name	AFOLU relevant area	Description	Sensors	Temporal coverage/ frequency	Spatial resol.	Reference
Treecover2010 (Global Tree Cover dataset by Univ. Maryland GLAD - Global Land Analysis & Discovery)	Forest (cover)	Pixel estimates of circa 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 2010	30 m	https://glad.umd.edu/dataset/global-2010-tree-cover-30-m. Hansen, M. C., at al., 2013.
GLAD Primary Humid Tropical Forests (Primary forests in the tropics, dataset by Univ. Maryland GLAD - Global Land Analysis & Discovery)	Forest (cover)	Extent in global pan-tropical regions 2001.	Landsat	2001	30 m	https://glad.umd.edu/dataset/primary-forest-humid-tropics Turubanova, S. et al, 2018.
Intact Forest Landscapes (dataset by Univ. Maryland GLAD - Global Land Analysis & Discovery)	Forest (cover)	Identifies World's remaining unfragmented forest landscapes, 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	https://glad.umd.edu/dataset/intact-forest/overview Potapov, P., at al. 2017.
Global Forest Watch	Forest (cover and change)	Pixel estimates of forest cover loss	Landsat	Current	30 m	https://www.globalforestwatch.org

Global Forest Canopy Height, 2019	Forest (cover and biomass)	Global Landsat analysis-ready data were used to extrapolate GEDI footprint-level forest canopy height measurements, creating a 30m spatial resolution global forest canopy height map for the year 2019.	GEDI and Landsat	2019	30 m	https://glad.umd.edu/dataset/gedi/ P. Potapov, et al., 2020 (*in review)* Preprint: doi.org/10.5281/zenodo.4008406
Global Forest/ Non-Forest maps (dataset by JAXA from L-band SAR series satellites)	Forest (cover)	Forest extent map accompanying JAXA's L-band SAR mosaic products. Provided as 1x1 degree tiles	ALOS PALSAR & ALOS-2 PALSAR-2	2007-2010 & 2015-2016	25 m	https://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm Shimada et al. 2014

Biomass

A summary of forest AGB datasets relevant to the GST and generated from EO data, together with their characteristics and access information is given in Table 4.3.2. This only includes continental-scale datasets, though numerous other AGB products have been derived from EO data at the country scale. Note that the majority of existing biomass products were made with data that either saturates with biomass (optical data, C and L band SAR), or was a sparse spatial sample of forests (GLAS). These past products have been very informative in the design of the next generation of biomass missions, but have had large uncertainties that have limited their utility for operational applications. We anticipate the new generation of biomass missions, and associated products, to have much lower uncertainties and provide useful data for country-level and global forest carbon monitoring.

An assessment of some of these past biomass products is given in the survey of stakeholders' data needs for estimating forest AGB and emissions factors in Romijn et al. (2018). The survey, inter alia, asked them to assess the utility of two selected tropical forest AGB datasets derived from EO data: Saatchi et al. (2011) and Baccini et al. (2012). They were also asked to assess the utility of Harris et al. (2012), which combined the Saatchi et al. (2011) dataset with the Hansen et al. (2010) forest change dataset to estimate emissions. Around 79% of the 215 participants who had used the Baccini et al. (2012) dataset had found it useful for AFOLU purposes; for the 204 participants using the Saatchi et al. dataset, 70% found it useful. Fewer (134) directly used the emissions from Harris et al. (2012) and around 66 % of these found them useful. Several aspects of these findings are particularly noteworthy: (1) about the same number of stakeholders had used the EO-derived biomass information and the Hansen et al. (2013) maps of forest change, but the biomass information was found to be more useful (> 70 % for the former, 64 % for the latter); (2) there was no evaluation of more recent datasets, such as Zarin et al. (2016) or Baccini et al. (2017) probably, in part, because of the delay between their becoming available and their being evaluated by stakeholders; (3) the GEDI, BIOMASS and NISAR datasets are expected to significantly improve all current estimates of biomass particularly in the tropics, so their utility for AFOLU purposes is likely to be much higher, as outlined by Romijn et al. (2018).

Two specific examples of the use of EO-derived AGB data include the adjustment of the total emissions estimate in Guyana's submitted Forest Reference Emission Level using Baccini et al. (2012), and use and comparison of both the Baccini et al. (2012) and Saatchi et al. (2011) pan-tropical biomass maps by the Republic of Congo. Such use is only expected to rise with the increasing availability of spatially explicit and increasingly accurate AGB and AGB change data and improved technical capacity in developing countries.

An example of how greater technical capacity allows more sophisticated use of EO data is given in Vol. 2, Box 2.0E, of the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories (IPCC, 2019). This describes how Brazil is turning its huge investment in airborne lidar measurements into an AGB map for the whole of Brazilian Amazonia by using several types of satellite measurement to extrapolate AGB estimated along lidar transects. The methodology is likely to be transferable to use of GEDI data, because of its high density sampling, and hence offers an opportunity for other countries to adopt a similar approach.

Summary of past biomass products (prior to 2018)

In the tropics, the most significant developments have been based on the Geoscience Laser Altimeter System (GLAS) onboard the NASA Ice, Cloud and land Elevation Satellite (ICESat) which operated from 2003-2009. Combining GLAS data with other EO and environmental datasets and in situ AGB measurements allowed two pan-tropical AGB maps to be produced (Saatchi et al. 2011; Baccini et al. 2012) at grid scales of 1 km and 500 m respectively. In order to reduce biases and discrepancies between these two maps, Avitabile et al. (2016) used a data fusion procedure with an extensive database of in situ data to produce a refined pan-tropical map at a grid scale of 1 km. Further refinements to the Baccini et al. map include that by Zarin et al. (2016) at a grid scale of 30 m and Baccini et al. (2017) at a grid scale of ~460 m, based on essentially the same satellite datasets and methodology. In each case, a critical input was in situ AGB data from plot networks and inventory data, needed for product calibration and validation.

For boreal and temperate forests, very long time series of Envisat C-band radar data have been used to estimate Growing Stock Volume (defined as the volume of wood in all living trees in an area with diameter at breast height above a given threshold) (Santoro et al. 2011). Combining this with wood density information allowed Thurner et al. (2014) to estimate the carbon stock of forests north of 30°N and, on the basis of carbon models, to estimate above-ground carbon. The use of C-band may seem surprising, since this 6 cm wavelength typically does not penetrate far into the forest canopy, but when the forest freezes the canopy becomes almost transparent to the radar, even at shorter wavelengths. Even C-band can then penetrate deep into the forest and gain access to the major biomass-bearing elements of the canopy. The BIOMASAR algorithm used by Santoro et al. (2011) implicitly exploits this property. An important feature of the algorithm is that it requires no training data, but is based on a simplified physical model that automatically adapts to local conditions.

The ESA GlobBiomass project extended the boreal coverage in Santoro et al. (2011) to global coverage for the year 2010 by the key step of combining C-band data from Envisat with L-band data from ALOS PALSAR. The AGB estimates from PALSAR used the same physical model as C-band but, being based on annual mosaic PALSAR data from JAXA, could not exploit the time series approach used for BIOMASAR. Separate AGB estimates were made with the C-band and L-band data and these were combined using adaptive weighted averaging that automatically gave larger weight to the most reliable sensor at a given location (Santoro et al., 2020). At the global scale, the GlobBiomass map with 100 m grid scale is consistent with the large scale pattern of AGB revealed by field inventory, but comparison of the GlobBiomass map with regional data from several different biomes shows that it tended to overestimate low AGB and underestimate high AGB.

ESA's CCI-Biomass project is a natural successor to GlobBiomass that is providing global maps of AGB for 2017 and 2018 with 100 m grid spacing, based primarily on Sentinel-1A & -1B and ALOS-2 PALSAR-2 data (the biomass map for 2017 and an associated map of its per-pixel standard deviation are already available at https://catalogue.ceda.ac.uk/uuid/bedc59f37c9545c981a839eb552e4084). Several ancillary datasets are used to support the model-based approach. These include satellite-based products, viz. height from GLAS, MODIS Vegetation Continuous Fields, a global gap-free DEM (de Ferranti, 2009), the CCI Land Cover map, and global maps of canopy density and density changes (https://earthenginepartners.appspot.com/science-2013-global-forest), together with maps of bioclimatic variables, ecological zones and terrestrial eco-regions. An important feature of CCI-Biomass is the effort being made to construct a comprehensive validation of the products. This has implications well beyond CCI-Biomass, as it provides a much-needed assessment of the reference data suitable for validation and exposes significant weaknesses in the available data. Processing of 2019 data and reprocessing of 2010 data should lead to a consistent time series of global AGB data.

Summary of new and upcoming biomass products (post 2018)

GEDI, ICESat-2, BIOMASS, NISAR and ALOS-4 PALSAR-3 mark a huge improvement in the capabilities discussed above. These will likely be further complemented with missions such as MOLI and ROSE-L. Each of these missions will release biomass products, but we anticipate many other products will be created through data fusion, such as via the CCI Biomass approach. Here we summarize the main technological capabilities of these first four missions. For more specific information of expected upcoming products and associated uncertainties please refer to the CEOS biomass protocol (Duncanson, L. et all, 2020).

The GEDI lidar instrument has been deployed onboard the ISS since December 2018, and there are plans to extend its operation to 2023. Its mission is focused on tropical and temperate forests and it is providing the first sampling of forest vertical structure across all forests between 51.6° S and 51.6° N, from which estimates of canopy height, ground elevation and vertical canopy profile measurements are being derived. A major improvement compared to the GLAS lidar is that it provides 25 m diameter footprints (less affected by slopes), and order of magnitude more measurements than GLAS. GEDI lidar measurements separated by 60 m along-track and 600 m across track, enabling estimates of the mean and variance of AGB on a 1 km grid across the tropical and temperate zones.

ICESat-2 launched in September, 2018, and while similar to its precursor the primary science goals are for solid earth and ice, a formal vegetation height and land elevation product is already publicly available. ICESat-2 is a green photon counting lidar system that collects continuous transects of photon data capable of resolving ground elevations and canopy heights. Early validation results suggest that ICESat-2 vegetation heights are highly accurate in areas of moderate canopy cover, with higher uncertainties in dense and sparse systems (Neuenschwander et al., 2020). Two NASA funded projects are currently developing a boreal biomass map to complement GEDI's products by mapping biomass north of 52 degrees. Thus, a global lidar-derived forest biomass product combining both GEDI and ICESat-2 will be representative of 2019 conditions and ongoing through the GEDI and ICESat-2 mission lifetimes.

BIOMASS will carry the first P-band SAR in space. This frequency was chosen because it gives the highest possible sensitivity to AGB feasible from space. It will also measure forest height using polarimetric interferometric SAR techniques, and will provide 3-D imaging of forests using SAR tomography. While it has the capability for global imaging, it will be subject to restrictions imposed by the US Department of Defence Space Object tracking radar (SOTR) system, so will not provide data over N America or Europe. Though the sensor resolution is ~50 m, gaining sufficient sensitivity to AGB requires the resolution to be reduced to 4 ha. The planned mission lifetime is 5 years.

NISAR is a joint project between NASA and ISRO to fly the first dual-frequency SAR satellite, with NASA providing the L-band and ISRO the S-band (9.5 cm wavelength) sensors. The L-band sensor will measure AGB and its disturbance and regrowth globally in 1 ha grid-cells for areas where AGB does not exceed 100 tonnes per hectare (t or Mg/ha). Such lower biomass forests constitute a significant portion of boreal and temperate forests and savanna woodlands. L-band coverage in space and time provided by this sensor will be unprecedented, with HH and HV observations every 12 days in ascending and descending orbits and global coverage of forests every 6 days during its 10-year lifetime.

ALOS-4 PALSAR-3 is planned for launch by JAXA in 2023, providing continuation to the long legacy of global systematic L-band SAR observations over almost three decades by the JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2 missions. PALSAR-3 will provide wider observation swath and finer spatial resolution than its predecessors, and in important complement to NISAR, capacity for operational observations in full polarisation mode. The planned mission lifetime is 7 years.

Table 4.3.2. Forest above-ground biomass datasets relevant to the GST generated from EO data, together with 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 and cover)	Above-ground forest biomass map. Pan-tropical coverage.	GLAS, MODIS, SRTM, QSCAT	Early 2000s	1 km	Saatchi et al., 2011 https://drive.google.com/drive/folders/11z2qm7Q6Rtley1tz3tRU4cxNW8iX_2Xd?usp=sharing
(Commonly referred to as) **Baccini 2012 AGB Map**	Forest (biomass and cover)	Above-ground forest biomass map. Pan-tropical coverage.	GLAS, MODIS, SRTM	2007-2008	500 m	Baccini et al., 2012 https://developers.google.com/earth-engine/datasets/catalog/WHRC_biomass_tropical
(Commonly referred to as) **Avitabile AGB Map**	Forest (biomass and cover)	Fusion of Saatchi and Baccini products using more extensive ground data to reduce bias. Pan-tropical coverage.	GLAS, MODIS, SRTM, QSCAT	Mid-2000s	1 km	Avitabile et al. 2016 http://lucid.wur.nl/datasets/high-carbon-ecosystems
	Forest (biomass and cover)	Above-ground forest biomass map. Pan-tropical coverage.	GLAS, Landsat, SRTM	Early 2000s	30 m	Zarin et al. 2016 https://www.globalforestwatch.org/map/
(Commonly referred to as) **Baccini 2017 AGB Map**	Forest (biomass and cover)	Maps of above-ground forest biomass and change. Pan-tropical coverage.	GLAS, MODIS, SRTM	2003-2014	463 m	Baccini et al., 2017 http://www.thecarbonsource.org/
GlobBiomass (ESA project)	Forest (biomass and cover)	A global terrestrial biomass map with specified requirements to spatial resolution (150-500m) and accuracy below 30% (relative root mean square error) with reference year 2010.	ALOS PALSAR ENVISAT ASAR	2010	100 m	Santoro et al., 2020 https://globbiomass.org
CCI Biomass (ESA)	Forest (biomass and cover)	Global above-ground forest biomass maps with associated maps of precision.	ALOS PALSAR ENVISAT ASAR ALOS-2 PALSAR-2, Sentinel-1 SAR	2010, 2017, 2018	100 m	http://cci.esa.int/biomass
GEDI	Forest (biomass)	Mean and variance of above-ground forest biomass in each 1 km grid-cell. Coverage: 51.6° N to 51.6° S	GEDI 1064 nm waveform lidar	2019 - present (ongoing until mission end)	1 km	https://lpdaac.usgs.gov/news/release-gedi-data-products/
ICESat-2 Boreal	Boreal Forest (biomass)	Mean and variance of above-ground forest biomass maps for forests north of 52°	ICESat-2 532 nm photon counting lidar	2019-2022	100 m	https://above.nasa.gov/profiles_/above_projects.html

4.4 Other Land Uses

Of the three Wetlands types discussed in section 3.5 above, i.e. mangroves, peatlands and riparian (floodplain) forest, global maps have been generated only for one of them (mangroves), illustrating the poor availability of updated geospatial information of key wetland ecosystems.

Recognising the potential of Earth observation to support Ramsar information needs however, the Ramsar Science and Technology Review Panel (SRTP) notes in a 2018 report to the Ramsar COP that *"the increasing availability of systematic and frequent satellite observations at high spatial resolution over all land surfaces and coastal areas enables better representation of seasonally and intermittently flooded areas and their changes, which are essential information sources for assessing the health of wetland ecosystems".*

The STRP furthermore highlights the importance of public open EO data in this context, stating that "*The open and free data policies of government-funded satellite data, along with assurance of long-term continuity of observations, are important incentives for the Ramsar Convention's Contracting Parties and wetland practitioners to routinely integrate EO into their work. With the increasing availability of 'analysis ready' datasets, the level of expertise required for basic wetland applications has decreased"* (Rebelo et al. 2018).

Mangroves

There are presently four datasets showing global mangrove distribution available in the public domain. Three are nominally single-year datasets, derived from medium resolution Landsat data (Spalding et al., 1997 & 2010; Giri et al., 2010).

The fourth dataset, produced by the Global Mangrove Watch, is a series of mangrove extent maps covering seven annual epochs between 1996 and 2016, derived using a combination of Landsat and ALOS PALSAR data for the baseline year 2010, and L-band SAR only for the other six epochs. Annual maps for 2017 and 2018, derived from ALOS-2 PALSAR-2 are scheduled for release in late 2020, to be followed by annual maps (Bunting et al., 2018). Supported by JAXA, the Global Mangrove Watch (GMW) dataset is used by UNEP as the official mangrove dataset for SDG 6.6.1 reporting. The GMW dataset is also the mangrove dataset used by the Global Forest Watch.

Based on the 2000 mangrove extent map by Giri et al. (2010), Simard and colleagues et al. (2019) generated maps of mangrove height and AGB, using Digital Elevation Data from the 2000 SRTM mission.

The mangrove datasets are described below in Table 4.4.1.

Peatlands

There are presently no global peatland maps available.

Floodplain forest

There are no maps available showing global extent of riparian floodplain forests. Regional-scale maps have however been generated over the Amazon basin, using L-band SAR from JERS-1 SAR (Hess et al., 2003), ALOS PALSAR (Chapman et al., 2015) and ALOS-2 PALSAR-2 (Rosenqvist et al., 2020).

Generic Land Cover maps

The main global dataset describing other land uses is the GlobCover, which was generated from the ENVISAT MERIS, its follow-on CCI land cover, the Copernicus Global Land Service and WorldCover (Table 4.4.1).

Table 4.4.1. 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 resolut ion	Reference
Mangroves (global)						
Global Mangrove Watch	Forest (cover); Other Land Use (Wetlands - Mangroves)	Global extent of mangrove forests for seven annual epochs.	JERS-1 SAR ALOS PALSAR ALOS PALSAR & Landsat ALOS-2 PALSAR-2	1996 2007, 2008, 2009, 2010 2015, 2016 (2017 & 2018 to be released Q4/2020)	25 m	Bunting et al. 2019 https://www.globalmangrovewatch.org
(Commonly referred to as) **Giri 2000 mangrove map**	Forest (cover); Other Land Use (Wetlands - Mangroves)	First globally consistent remote-sensing-based map of mangrove extent	Landsat	2000	30 m	Giri et al., 2010
World Atlas of Mangroves	Forest (cover); Other Land Use (Wetlands - Mangroves)	Composite extent map of mangrove extent	Landsat	2000 (range between 1999-2003)	30 m	Spalding et al., 2010
Mangrove Height and Biomass	Forest (biomass); Other Land Use (Wetlands - Mangroves)	Canopy height maps based on SRTM DEM and Lidar altimetry	SRTM	2000	30 m	Simard et al., 2019 doi.org/10.3334/ORNLDAAC/1665
Riparian floodplain forest (regional)						
Amazon Max and Min Inundation Extents 2014–2017	Forest (cover); Other Land Use (Wetlands - Floodplain forest)	Regional dataset 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 J. et al, 2020 doi.org/10.3390/rs12081326
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., 2015 doi.org/10.3390/rs70505440
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 1996 high water	100 m	Hess et al., 2003 doi.org/10.1016/j.rse.2003.04.001
Generic Land Cover (global)						
GlobCover	Forest (cover); Other Land Use (General)	Global land cover maps	ENVISAT MERIS	Dec 2004 - Jun 2006 & Jan - Dec 2009	300 m	Arino et al. (2010)
CCI Land Cover	Forest (cover); Other Land Use	Global land cover maps	ENVISAT MERIS, AVHRR, SPOT Vegetation, PROBA-Vegetation, Sentinel-3 OLCI and LSTR	1990ies, 2000, 2005 2010, 2015	300 m	http://cci.esa.int/landcover
Copernicus Global Land Service - Land Cover map	Forest (cover); Other Land Use	Global land cover maps	PROBA-Vegetation	2015 - present (yearly)	100 m	Buchhorn, M. et al. (2019) https://land.copernicus.eu/global/products/lc
WorldCover	Forest (cover); Other Land Use	Global land cover maps (available in June 2021 with 5 classes)	Sentinel-1, Sentinel-2	2020 (one-time product)	10 m	https://esa-worldcover.org/

4.5 Cross links in the AFOLU Sector

Within the domains of agriculture, forestry and biomass, a number of global products exist or are currently being developed and these provide a platform upon which to build future activities. However, activities in these domains are interrelated and hence an integrative approach is recommended. An example is ESA's Climate Change Initiative (CCI), which is coordinating climate data records for 21 of 54 ECVs to provide the evidence base to support the UNFCCC process, improve prediction of future change, and assess progress towards Paris Agreement targets geared at averting serious global warming. Other frameworks have also been developed that directly use continuous or categorical descriptors of the environment to generate land cover and change maps. However, in the past and also currently, focus has been on using the products as standalone with a few used in combination. However, there are considerable advantages in planning for more focused, coordinated and coherent integration. Mechanisms that take different inputs from EO datasets and use these to support the GST are therefore recommended.

5. Potential Roadmap Actions

This Section serves to provide a flavour to CEOS agencies as to the nature of the measures required by CEOS and space agencies to take full advantage of the opportunity presented by the GST and to ensure EO capabilities and their deployment are in step with the needs of UNFCCC and its Parties. We envision that a CEOS AFOLU Roadmap might comprise a range of different types of measures, including:

- **Improving EO capabilities to better meet the needs of the Convention** or Parties for monitoring and reporting; this may include improvements in precision, in coverage, or in repeat frequency;
- **Providing new measurements** that do not currently form part of CEOS agency capabilities;
- **Engaging with countries and stakeholders (such as GFOI and GEOGLAM) to improve understanding and uptake** of EO data by countries;
- Taking **actions to assure the policy relevance of new capabilities** (e.g., through measures such as the CEOS Biomass Protocol) to guarantee consistency in application of new CEOS missions anticipated in the coming years;
- **Increasing efficiencies and effectiveness in the process by which climate data requirements are set** (e.g., by GCOS) and to which CEOS and CGMS space agencies respond. This would inform policy processes and how these might benefit from confidence in the nature and continuity of the EO data contribution.

In addition, activities are required in relation to engagement in the GST process and the working teams and deliverables anticipated for Systematic Observations which CEOS is expected to support. Further, efforts to integrate the CEOS activities in relation to GHG emissions and AFOLU are expected, including support for dialogue between the respective communities. Current and future CEOS capabilities should be clearly communicated through the GST process, including making best use of the Synthesis Report for Systematic Observations planned by UNFCCC Secretariat.

GST1 Deliveries in 2021

The GHG Roadmap has a very pragmatic focus on the major milestones of GST1 and subsequently for GST2 and the production of prototype inventories in support of those milestones. We would envision that the AFOLU Roadmap would have a similar pragmatic focus on GST1 and GST2 and what can be delivered effectively to support these and the national reporting to them. Given the urgency in meeting the 2021 deadline for inputs to GST1, the AFOLU Roadmap team has provided suggestions as to what CEOS might consider as achievable and useful targets for AFOLU in relation to GST1 prior to the development of a full AFOLU Roadmap.

The primary expected outcome of the AFOLU Roadmap is an enhanced uptake of EO satellite data sets in support of the first GST in 2023 on a global and country level. Our conservative view on pilot data sets for GST1 is based on existing capabilities and takes into account that 2021 will be a reference year for the GST1. These deliverables include:

Agriculture (in cooperation with GEOGLAM):

- Global crop productivity maps
- Country cases for agricultural land use and change, agriculture management practices and agricultural biomass burning supporting reporting of NDCs

Forests:

- Global forest cover and tree density maps (in cooperation with GFW and UMD)
- Global above ground biomass maps in GST1 reference year 2021 with 2020 as backup and historical datasets from previous years (Contributions of CCI biomass with inputs from GEDI and IceSat-2 missions and WGCV LPV team)
- Country cases of carbon stock in forests supporting reporting of NDCs (in cooperation with GFOI)

Other Land Use: (TBC)

- Global mangrove extent maps annually (in cooperation with Global Mangrove Watch)

Strong need for global/regional peatland maps and floodplain forest biomass, but partner organisations need to be identified

It is expected that during the development of the AFOLU Roadmap advances of these deliverables will be available (e.g. activity data on forest cover might include differentiation of natural forest and plantation and different forest types). Upcoming missions, such as the NISAR and BIOMASS, will further enhance the capabilities to assess the AFOLU sector. Dedicated developments to match the evolving needs of the stakeholders to the GST are most welcome and will shape the operational input to future GSTs.

The country cases for agriculture and forestry will support mitigation activities and contribute to the NDCs. They are expected to facilitate technology transfer and capacity building within the countries and will lead to further refinements of the countries' requirements.

We expect that all these actions will continue to evolve as the GST process unfolds and the dialogue among systematic observation providers, UNFCCC, and countries develops and lessons are learned from GST1. This will be taken into account for a more operational contribution to the second GST in 2028.

6. Summary and Next Steps

In response to an action from the CEOS SIT-35 meeting, a team of expert volunteers, led by JAXA and ESA, has developed this Discussion Paper in support of the development of a CEOS AFOLU Roadmap. The team considers that there is significant opportunity for space agencies to support the evolution of the climate policy framework of the UNFCCC, through its GST process. This evolution is expected to see greater emphasis on mitigation, adaptation and on national reports - with many of the issues being relevant to the land sector. In parallel, CEOS agencies are investing heavily in significant new capabilities, including for the measurement of AGB that offer unparalleled potential to support the reporting processes. This Section makes recommendations for the way forward within CEOS for the further development of an AFOLU Roadmap, including for the decisions from the 2020 CEOS Plenary.

1. **CEOS Plenary is asked to recognise the magnitude of the opportunity for satellite Earth observations in support of the Global Stocktake (GST) process** - noting it as a new and significant dimension to the nature of space agencies support of climate policy processes.
2. **CEOS agencies involved in the operation and data processing for missions identified as relevant to the proposed GST1 inputs are asked to support the preparation of those inputs in 2021**, in parallel to and in coordination with the equivalent efforts of the GHG Roadmap aimed at GST1. These agencies include EC, ESA, JAXA, NASA, and USGS amongst others.
3. **These same key agencies are asked to decide at Plenary whether they are willing to provide representation and resources going forward to support the development of a full CEOS AFOLU (Agriculture, Forestry and Other Land Uses) Roadmap in support of the GST process.** Representation and resources to proceed will be paramount regardless of the institutional way forward agreed by CEOS. The effort in 2020 has been made possible through the contributions of the LSI-VC Forest and Biomass subgroup with a number of volunteer experts, many of whom are not CEOS agency personnel, and the LSI-VC GEOGLAM subgroup. We envision that increased participation of CEOS agency personnel will be needed given the nature of the task ahead.
4. The CEOS-CGMS GHG Roadmap already envisions a number of deliverables targeting support to the GST1. **The AFOLU Roadmap and the GHG Roadmap deliverables will likely require a degree of coordination and collaboration and the AFOLU team will commit to that effort in 2021,** including with the overarching support provided by the SIT Chair's ongoing priority for Carbon and Biomass activities. The AFOLU team can no doubt learn from the architecture approach undertaken by the GHG team and should apply lessons learned from that pioneering effort.
5. During the CEOS TW in September, **CEOS has appointed three focal points to the UNFCCC SEC GST process:** Osamu Ochiai (for AFOLU issues), David Crisp (GHG issues), Jörg Schulz (general issues). These focal points will keep CEOS informed on GST developments.

Based on an agreement by Plenary to proceed towards a CEOS AFOLU Roadmap, it is assumed that the established core team (see point 3 above) - expanded with additional resources - will lead the effort in 2021. This will include the CEOS internal relationships with WGClimate, as lead for the CEOS interface to UNFCCC, the GHG Task team and WGCV LPV, and the external relations to GFOI and GEOGLAM. Sustained institutional arrangements within CEOS will be necessary to underpin a substantial AFOLU activity and proposals for these will be developed during 2021.

7. References

Arino O., J. Ramos, V. Kalogirou, P. Defourny and F. Achard. GlobCover 2009. ESA Living Planet Symposium, 27 June . 2 July 2010, Bergen, Norway.

Arvidson, T., Goward, S., Gasch, J., Williams, D. (2006). Landsat-7 long-term acquisition plan. Photogramm. Eng. Remote Sens. 72 (10), 1137–1146. https://doi.org/10. 14358/PERS.72.10.1137.

Avitabile V, Herold M, et al. (2016). An integrated pan-tropical biomass map using multiple reference datasets, Global Change Biology, 22, 1406–1420, doi:10.1111/gcb.13139.

Baccini A, et al., (2012). Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps, Nature Clim. Change, 2, 182-185, doi:110.1038/nclimate1354

FAO (2020). Global Forest Resources Assessment 2020: Main Report, Rome, https://doi.org/10.4060/ca9825en

Baccini, A., et al. (2017). Tropical forests are a net carbon source based on aboveground measurements of gain and loss, Science, doi: 10.1126/science.aam5962

Beers, L., S. Crooks, and S. Fennessy (2020). Desktop Study of Blue Carbon Ecosystems in Ramsar Sites. Report by Silvestrum Climate Associates [in press].

Buchhorn, M. ; Smets, B. ; Bertels, L. ; Lesiv, M. ; Tsendbazar, N. - E. ; Herold, M. ; Fritz, S. Copernicus Global Land Service: Land Cover 100m: epoch 2015: Globe. Dataset of the global component of the Copernicus Land Monitoring Service 2019, https://doi.org/10.5281/zenodo.3243509

Bunting, P., Rosenqvist, A., Lucas, R., Rebelo, L., Hilarides, L., Thomas, N., Hardy, A., Itoh, T., Shimada, M., Finlayson, C. (2018). The Global Mangrove Watch—A New 2010 Global Baseline of Mangrove Extent Remote Sensing 10(10), 1669.

Chapman, B., K. McDonald, M. Shimada, A. Rosenqvist, R. Schroeder, L. Hess. Mapping Regional Inundation with Spaceborne L-Band SAR. Remote Sensing 04/2015, 7(5):5440-5470. doi.org/10.3390/rs70505440.

Duncanson, L., Armston, J., Disney, M., Avitabile, V., Barbier, N., Calders, K., Carter, S., Chave, J., Herold, M., MacBean, N., McRoberts, R., Minor, D., Paul, K., Réjou-Méchain, M., Roxburgh, S., Williams, M., Albinet, C., Baker, T., Bartholomeus, H., Bastin, J.F., Coomes, D., Crowther, T., Davies, S., de Bruin, S., De Kauwe, M., Domke, G., Falkowski, M., Fatoyinbo, L., Goetz, S., Jantz, P., Jonckheere, I., Jucker, T., Kay, H., Kellner, J., Labriere, N., Lucas, R., Morsdorf, F., Phillips, O.L., Quegan, S., Saatchi, S., Schaaf, C., Schepaschenko, D., Scipal, K., Stovall, A., Thiel, C., Wulder, M.A., Camacho, F., Nickeson, J., Roman, M., Margolis, H. (2020). Global Aboveground Biomass Product Validation - Best Practices Protocol. Version 1.0. In L. Duncanson, M. Disney, J. Armston, D. Minor, F. Camacho, and J. Nickeson (Eds.), Best Practice Protocol for Satellite Derived Land Product Validation, (p. 222): Land Product Validation Subgroup (WGCV/CEOS), doi:10.5067/doc/ceoswgcv/lpv/agb.001

Devol, A. H., Richey, J. E., Forsberg, B. R., and Martinelli, L. A., 1990, Seasonal dynamics in methane emissions from the Amazon River oodplain. Journal of Geophysical Research, 95, 16 417–16 426.

Duke, N. C., J. M. Kovacs, A. D. Griffiths, L. Preece, D. J. E. Hill, P. v. Oosterzee, J. Mackenzie, H. S. Morning and D. Burrows (2017). Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. Marine and Freshwater Research, 68 (10): 1816-1829. http://dx.doi.org/10.1071/MF16322

FAO (2020). Global Forest Resources Assessment 2020: Main Report, Rome, https://doi.org/10.4060/ca9825en

GCOS (2003). The Second Report on the Adequacy of the Global Observing Systems for Climate In Support of the UNFCCC, GCOS – 82 (WMO/TD No. 1143), World Meteorological Organization

Giri, C.; Ochieng, E.; Tieszen, L.L.; Zhu, Z.; Singh, A.; Loveland, T.; Masek, J.; Duke, N. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 2011, 20, 154–159.

Global Forest Observations Initiative (2020). Integration of remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests: Methods and Guidance from the Global Forest Observations Initiative, Edition 3.0. https://reddcompass.org/mgd-material

GOFC-GOLD (2016), A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation. GOFC-GOLD Report version COP22-1, (GOFC-GOLD Land Cover Project Office, Wageningen University, The Netherlands).

Grassi, G. et al. (2017). The Key Role of Forests in Meeting Climate Targets Requires Science for Credible Mitigation. Nature Climate Change **7**(3): 220–26, doi:10.1038/nclimate3227.

Hess, L.L.; Melack, J.M.; Novo, E.M.; Barbosa, C.C.; Gastil, M. (2003). Dual-season mapping of wetland inundation and vegetation for the central Amazon basin. Remote Sens. Env. 2003, 87, 404–428.

Hansen, M. C., Stehman, S. V., and Potapov, P. V. (2010). Quantification of global gross forest cover loss, PNAS, **107** (19) 8650-8655; https://doi.org/10.1073/pnas.0912668107

Hansen, M. C., at al. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change, Science 342 (15 November): 850–53.

IPCC (2014). Agriculture, Forestry and Other Land Use (AFOLU). Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N.H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello,. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC (2019): Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]

IPCC (2019). “2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.” Intergovernmental Panel on Climate Change, https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gasinventories/

Jackson, R.B., Lajtha, K., Crow, S.E., Hugelius, G., Kramer, M.G., Piñeiro, G., (2017). The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. Annu. Rev. Ecol. Evol. Syst. 48, 419–445.

Jaenicke, J., Rieley, J.O., Mott, C., Kimman, P., Siegert, F., 2008. Determination of the amount of carbon stored in Indonesian peatlands. Geoderma 147, 151–158.

Köchy, M., Hiederer, R., Freibauer, A. (2015). Global distribution of soil organic carbon–part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. Soil 1, 351–365.

Lucas, R.M., Mueller, N., Siggins, A., Owers, C., Clewley, D., Bunting, P., Kooymans, C., Tissot, B., Lewis, B., Lymburner, L. and Metternicht, G. (2019). Land cover mapping using Digital Earth Australia, 4, 143.

Lucas, R.M., Mitchell, A.L. and Armston, J. (2015). Measurement of forest above ground biomass using active and passive remote sensing at large (subnational to global) scales. Current Forestry Reports ((DOI 10.1007/s40725-015-0021-9).

Lucas, R., Rebelo, L.-M., Fatoyinbo, L., Rosenqvist, A., Itoh, T., Shimada, M., Simard, M., Souza-Filho, P.W., Thomas, N., Trettin, C., Accad, A., Carreiras, J. & Hilarides, L. (2014). Contribution of L-band SAR to systematic global mangrove monitoring. Marine and Freshwater Research, 65(7), 589-603.

Lucas, R.M., Van De Kerchove, R.,Otero, V., Lagomasino, D., Fatoyinbo, L., Hamdan, O., Satyanarayana, B. and Dahdouh-Guebas, F. (2020). Structural characterisation of mangrove forests achieved through combining multiple sources of remote sensing data. Remote Sensing of Environment, 237, 111543. https://doi.org/10.1016/j.rse.2019.111543

MacDonald, H. C., Waite, W. P., and Demaricke, J. S., 1980, Use of Seasat satellite radar imagery for the detection of standing water beneath forest vegetation. Annual Technical Meeting of the American Society of Photogrammetry, Niagara Falls, NY, 7–10 October 1980.

Masek, J. G., Wulder, M. A., Markham, B., McCorkel, J., Crawford, C. J., Storey, J., & Jenstrom, D. T. (2020). Landsat 9: Empowering open science and applications through continuity. Remote Sensing of Environment, 248, 111968. doi:10.1016/j.rse.2020.111968

Minasny, B., Berglund, Ö., Conolly, J., Hedley C., et al.. Digital mapping of peatlands – A critical review. Earth-Science Reviews 196 (2019) 102870. doi.org/10.1016/j.earscirev.2019.05.014

Murdiyarso, D., K. Hergoualc'h, and L. V. Verchot. (2010). Opportunities for reducing greenhouse gas emissions in tropical peatlands. PNAS Nov 16, 2010 107 (46) 19655-19660; doi.org/10.1073/pnas.0911966107.

Potapov, P., M. C. Hansen, L. Laestadius, S. Turubanova, A. Yaroshenko, C. Thies, W. Smith, I. Zhuravleva, A. Komarova, S. Minnemeyer, and E. Esipova. 2017. "The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2016." Science Advances 3: e1600821.

Potapov, P., X. Li, A. Hernandez-Serna, A. Tyukavina, M.C. Hansen, A. Kommareddy, A. Pickens, S. Turubanova, H. Tang, C.E. Silva, J. Armston, R. Dubayah, J. B. Blair, M. Hofton (2020) Mapping and monitoring global forest canopy height through integration of GEDI and Landsat data. In review. Preprint: doi.org/10.5281/zenodo.4008406

Rebelo, L.-M., Finlayson, C.M., Strauch, A., Rosenqvist, A., Perennou, C., Tøttrup, C., Hilarides, L., Paganini, M., Wielaard, N., Siegert, F., Ballhorn, U., Navratil, P., Franke, J. & Davidson, N. (2018). The use of Earth Observation for wetland inventory, assessment and monitoring: An information source for the Ramsar Convention on Wetlands. Ramsar Technical Report No.10. Gland, Switzerland: Ramsar Convention Secretariat.

Romijn, E., de Sya, V., et al. (2018). Independent data for transparent monitoring of greenhouse gas emissions from the land use sector – What do stakeholders think and need? Environmental Science and Policy, 85 101–112, doi.org/10.1016/j.envsci.2018.03.016

Rosenqvist J., Rosenqvist A., Jensen K., and McDonald K. (2020). Mapping of Maximum and Minimum Inundation Extents in the Amazon Basin 2014–2017 with ALOS-2 PALSAR-2 ScanSAR Time-Series Data. Remote Sens. 2020, 12, 1326, doi.org/10.3390/rs12081326

Rosenqvist, A., Finlayson, M., Lowry, J. and Taylor, D. The potential of long wavelength satellite borne radar to support implementation of the Ramsar Wetlands Convention. Journal of Aquatic Conservation, Marine and Freshwater Ecosystems, Vol 17, 2007, pp 229-244. doi.org/10.1002/aqc.835

Rosenqvist, A., Forsberg, B, Pimentel, T., Rauste Y. and Richey J., 2002. The Use of Spaceborne Radar Data to Model Inundation Patterns and Trace Gas Emissions in the Central Amazon Floodplain. International Journal of Remote Sensing, 2002, Vol. 23, No. 7, pp. 1303-1328. doi.org/10.1080/01431160110092911

Saatchi S S, et al. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. Proceedings of the National Academy of Sciences, 108(24), 9899–9904

Santoro, M., et al., (2011). Retrieval of growing stock volume in boreal forest using hyper-temporal series of Envisat ASAR ScanSAR backscatter measurements. Remote Sensing of Environment, 115, 490–507

Santoro, M., Cartus, O., Carvalhais, N., Rozendaal, D., Avitabile, V., Araza, A., de Bruin S., Herold, M., Quegan, S., Rodríguez Veiga, P., Balzter, H., Carreiras, J., Schepaschenko, D., Korets, M., Shimada, M., Itoh, T., Moreno Martínez, A., Cavlovic, J., Cazzolla Gatti, R., da Conceição Bispo, P., Dewnath, N., Labrière, N., Liang, J., Lindsell, J., Mitchard E. T.A., Morel, A., Pacheco Pascagaza, A. M., Ryan, C. M., Slik, F., Vaglio Laurin, G., Verbeeck, H., Wijaya, A., and Willcock, S., 2020. The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations, JSTARS (in review)

Scarth, P., Armston, J., Lucas, R. and Bunting, P. (2019). A structural classification of Australian Vegetation using ICESAT/GLAS, ALOS PALSAR and Landsat Sensor Data, Remote Sensing, 11, 147.

Shimada, M., Itoh, T. Motooka, M. Watanabe, S. Tomohiro, R. Thapa, and R. Lucas, "New Global Forest/Non-forest Maps from ALOS PALSAR Data (2007-2010)," Remote Sensing of Environment, DOI=10.1016/j.rse.2014.04.014.

Shimada, S., Takada, M., Takahashi, H., 2016. Peat Mapping, Tropical Peatland. Ecosystems. Springer, pp. 455–467.

Simard, M., T. Fatoyinbo, C. Smetanka, V.H. Rivera-monroy, E. Castaneda-mova, N. Thomas, and T. Van der stocken. 2019. Global Mangrove Distribution, Aboveground Biomass, and Canopy Height. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1665

Spalding, M.; Kainuma, M.; Collins, L. World Atlas of Mangroves (Version 3); Routledge: London, UK, 2010.

Spalding, M.; Blasco, F.; Field, C. World Atlas of Mangroves; The International Society for Mangrove Ecosystems: Okinawa, Japan, 1997.

Thurner, M., et al., (2014). Carbon stock and density of northern boreal and temperate forests. Global Ecology and Biogeography 23, 297–310

Turubanova, S., Potapov, P.V., Tyukavina, A. and Hansen, M.C., 2018. Ongoing primary forest loss in Brazil, Democratic Republic of the Congo, and Indonesia. Environmental Research Letters, 13(7), p.074028.

Vaidyanathan G (2011). Counting the carbon cost of peatland conversion. Nature, doi:10.1038/news.2011.139

Wielaard, N. (2018). EO for tropical peatland mapping. In Ramsar Technical Report No.10. Rebelo & Finlayson [Eds.]. Gland, Switzerland: Ramsar Convention Secretariat.

Zarin D J, Harris N L, et al. (2016). Can carbon emissions from tropical deforestation drop by 50% in 5 years?, Global Change Biology 22, 1336–1347, doi: 10.1111/gcb.13153

http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Publication_Draft2_20181111.pdf