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SYMBOLS AND ACRONYMS

AGB	Above Ground Biomass
AGC	Above Ground Carbon
ALS	Airborne Lidar Scanning
CCI	Climate Change Initiative
COP	Conference of the Parties
ECV	Essential Climate Variable
ESA	European Space Agency
FREL	Forest Reference Emissions Level
GCOS	Global Carbon Observing System
GFZ	Germany's Helmoltz Centre for Geosciences
INPE	Brazil's National Institute for Space Research
LiDAR	Light Detection And Ranging
NFI	National Forest Inventory
NGHGI	National Greenhouse Gas Inventory
SAR	Synthetic Aperture Radar
SynCER	Synthesising post-disturbance carbon emission and removals across Brazil's Biomes
TMF	Tropical Moist Forest
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

The aim of the European Space Agency (ESA) Climate Change Initiative (CCI) Programme is to advance scientific understanding of the climate system and climate change by producing long-term datasets that meet climate data quality conditions (IPCC, 2003) and that can be readily linked to climate models. A basic input to this process is the series of reports by the Global Carbon Observing System (GCOS) that set out a continually reviewed set of Essential Climate Variables (ECVs) and a process to implement the acquisition of these ECVs.

The CCI Biomass Team has provided a major contribution to the CEOS Harmonisation Exercise, to the GFOI biomass/NFI integration work and in the engagement with countries. In line with CEOS AFOLU recommendation for developing best practice guidance for the use of EO-derived AGB at national levels and exploring links with national definitions and needs for inventories, we implemented a dedicated Brazil case study to be able to showcase tangible outcomes.

1.1 Purpose of document

This deliverable outlines the main tasks for the Optional Work Package 1000 (OP1) of the ESA CCI Biomass project (Phase 2), requested in the Statement of Work (SoW). The development of the Brazil case study included (i) a Synthesis of removal factors (Task 1.1); Country Engagement (Task 1.2); and international presentation and outreach (Task 1.3). Task 1.2 was in the form of a workshop dedicated to assessing the key advances made in research concerning "Synthesisng post-disturbance carbon emission and removals across Brazil's Biomes" (SynCER) and assessing the potential to integrate such results into policy and applications purposes for carbon reporting and assessing biodiversity changes. Task 1.3 presented many of these outcomes of the workshop at the 30th Conference of the Parties (COP) in Belém, Brazil held from 10th to 21st November 2025.

1.2 Contents

The document consists of the following sections:

- Section 2 shows the main ongoing outputs from Task 1.1 on Synthesising removal factors.
- Section 3 outlines the main objectives, discussions and conclusions from at the SynCER workshop.
- Sections 4 highlights the main discussions and viewpoints experienced at COP30, as part of Task 1.3

2 Section 2: Task 1.1 Synthesis of removal factors

2.1 Overview of Task

Research into post-disturbance carbon losses and gains in Tropical Moist Forest (TMF) has surged, driven in part by the importance of these forests for mitigating climate change and biodiversity loss (Buma et al., 2024; Lennox et al., 2018). More comprehensive accounting for carbon losses and gains is important for National Greenhouse Gas Inventories (NGHGIs) (Nabuurs et al., 2023; Perugini et al., 2021), notably in the framework of the Paris Agreement's Global Stocktake (UNFCCC, 2022), as well as for results-based payments frameworks (Andrade et al., 2017).
Advances in satellite Remote Sensing since ca. 2015, in combination with field plot and airborne data, are making it increasingly possible to disaggregate AGC losses from degradation versus deforestation, and Aboveground Carbon (AGC) gains from recovery (following partial disturbance) versus regrowth (following complete forest clearance). The recent rise in studies on post-disturbance carbon fluxes has created an opportunity for a comprehensive review (de-Miguel et al., 2025) and synthesis across datasets, disentangling the unique contribution of each disturbance driver and regeneration process to the net carbon budget of TMFs.

2.2 Pan-tropical synthesis of aboveground carbon losses and gains

In light of these research advances, a meta-analysis was performed to synthesize existing estimates of loss and gain from TMF degradation and regeneration across disparate data sources, assessing the extent to which they agree at continental and regional scales. The synthesis showed immediate (within 2.5±2.3 years) AGC losses following partial anthropogenic disturbances (average ±1SD) were greatest for forest fires (AGC loss of 49% ± 26), selective logging (34% ± 20) and edge effects (31% ± 19). Higher frequency and intensity disturbances were found to significantly increase carbon loss.

Relative to undisturbed forest, and after 20 years of regeneration, AGC stock was higher in recovering degraded forests (41-117%) than in secondary regrowth forests after complete deforestation (1-74%), indicating greater regeneration potential when forest structure is preserved. The compiled database and associated meta-analysis improve accuracy and completeness for carbon inventory reporting and modelling. Substantial AGB losses and gains from distinct degradation and recovery processes are now better characterized, serving as a contributory evidence base for policies to halt degradation and foster recovery for climate mitigation.

Most of the studies were for America, and the Brazilian Amazon more specifically. A detailed detailed analysis of absolute carbon gains was possible for young Amazonian secondary regrowth forests for which there was substantial data (Figure 1). Data sources were compared to ascertain whether rates from different methodologies agree, despite potential variability in the regrowth ages used to derive the growth rates, especially in the field data (Figure 1).

At the Amazon biome scale, the average of all data sources falls within the standard deviation of the IPCC Tier 1 estimate for young secondary regrowth forests in North and South American tropical rainforests (Figure 1a). Satellite-derived AGC growth rates were consistently lower (average: 1.75 Mg C ha^{-1} yr^{-1}) than those measured in field sites (average: 2.56 Mg C ha^{-1} yr^{-1}) and from data integration (average: 3.97 Mg C ha^{-1} yr^{-1}) (Figure 1a). We also compared field-site and data-integration regrowth rates from the State of Pará (Brazil) and around the city of Manaus with regionally derived satellite estimates (Figure 1b and c). The average secondary regrowth rates converged for field and satellite-derived estimates, and the greatest difference was for data integration (Tukey's HSD test $p < 0.05$). This discrepancy may be linked to the fact that the data integration studies used in the synthesis (Cook-Patton et al., 2020; Robinson et al., 2025) are themselves based on machine learning approaches that integrate a variety of climate and ecosystem data, together with field data that may not be directly from the area in question. At biome scale (Figure 1a), there is lower agreement between the data sources, compared to at the regional scale (Figure 1b and 1c), this may in part be attributed to the uneven spatial distribution of field site data that are also in part reflected in data integration data sources.

2.3 Research outcomes currently in the second round of peer-review at Science Advances:

Heinrich, Holcomb et al. *A meta-analysis of carbon losses and gains from tropical moist forest degradation and regeneration. (In Review)*

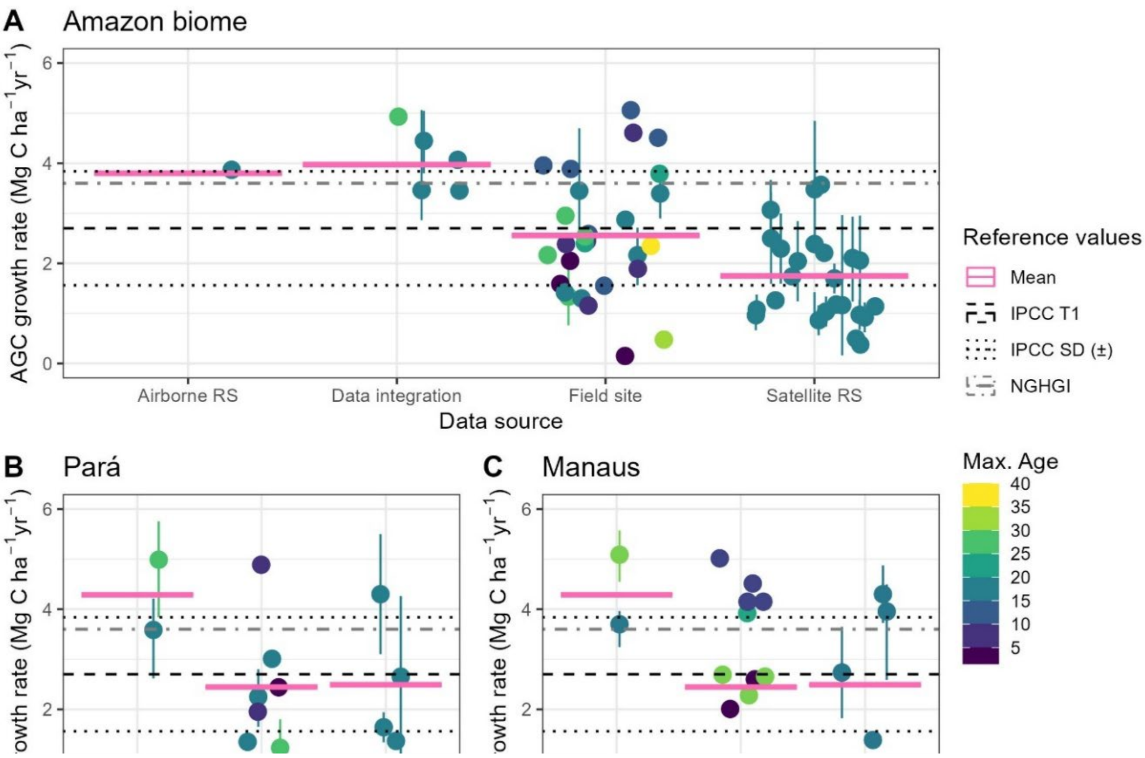

Figure 1. Regional and locally relevant mean absolute aboveground carbon (AGC) accumulation rates (in Mg C ha^{-1} yr^{-1}) for young (≤ 20 yrs) secondary regrowth forest. Studies are from within (a) the Amazon, and more specifically (b) Para, and (c) Manaus. Max. Age refers to the maximum included in the respective studies, note the Max. Age may be higher than 20 years if the growth rate was described to be linear in the study. For the field site data, we determined the location of the data based on the information given in the site descriptions. For the satellite data and data integration studies we used region specific growth curves or clipped spatially explicit data to within a 50km of field site locations to extract the mean growth rate. The cross bar for each data source is the mean for the respective data sources. Error bars denote the uncertainties given in each study, when available. We acknowledge that there may be overlaps in the datasets used by each study, especially the data integration and field site studies. Figure from Heinrich, Holcomb et al. (in Review).

2.4 Ongoing Tasks in Year 2

Brazil provides a unique case study to further assess the ability of the 18-year record of global AGB maps to track carbon dynamics of secondary forest regrowth through time in a "stock-change" approach, rather than a space-for-time-substitution approach, which has been used in most Earth Observation studies assessing secondary forest regrowth (Heinrich et al., 2021; Xu et al., 2026).

The latest release of the ESA CCI Biomass dataset (version 7.0), significantly extends previous data records (covering the period 2005-2012 and 2015-2024) and reduces temporal inconsistencies caused by the diverse set of satellite observations required to construct such a long time series.

Early results include:

- Spatially consistent biomass accumulation in tropical secondary forests was identified in Brazil, in agreement with sample-based estimates derived from in situ measurements where available (Figure 2). Spatially resolved growth trends, combined with forest age information from the MapBiomas dataset (Souza et al., 2020), indicate higher growth rates in the western Amazon, with peaks of up to 10 Mg ha^{-1} yr^{-1} at approximately 10–15 years of forest age. In contrast, growth rates in the eastern Amazon did not exceed 5 Mg ha^{-1} yr^{-1} (Figure 2). Comparing this to prior data and AGB data from an ALS campaign shows generally good agreement. One notable exception is in the North West region, were ALS and CCI-change derived rates agree less. This discrepancy may be linked to (i) the low area of secondary forest in the NW area (Heinrich et al. 2021); and (ii) additionally the lower number of ALS flights overlapping these secondary forest areas. These results thus highlight the benefit of using wall-to-wall maps in areas with low ALS/field data coverage.
- Contrasting biomass trends were observed in primary forests of the Brazilian Amazon. Below a biomass threshold of 250 Mg ha^{-1}, forests exhibit an average accumulation of approximately 1–2 Mg ha^{-1} yr^{-1}, whereas above this threshold high-biomass forests show a decline of around −1 Mg ha^{-1} yr^{-1}. These findings are consistent with recent evidence suggesting a weakening of the Amazon carbon sink. However, they remain unconfirmed and will need further investigation, particularly with respect to statistical significance, given the substantial pixel-level uncertainty in the CCI Biomass estimates.
- A comparison among several global AGB datasets derived from satellite data (e.g., Xu et al., Boitard et al., Li et al., Santoro et al.), including CCI Biomass, reveals broad agreement in the spatial distribution of biomass. However, absolute AGB estimates can differ by up to 100% among datasets, irrespective of geographic location. Moreover, temporal biomass trajectories often diverge, showing differences in the magnitude of fluctuations and, in some cases, opposing growth trends. Overall, the analysis underscores the need for a systematic intercomparison of remote-sensing-based AGB datasets using a common framework to assess their accuracy and uncertainty.

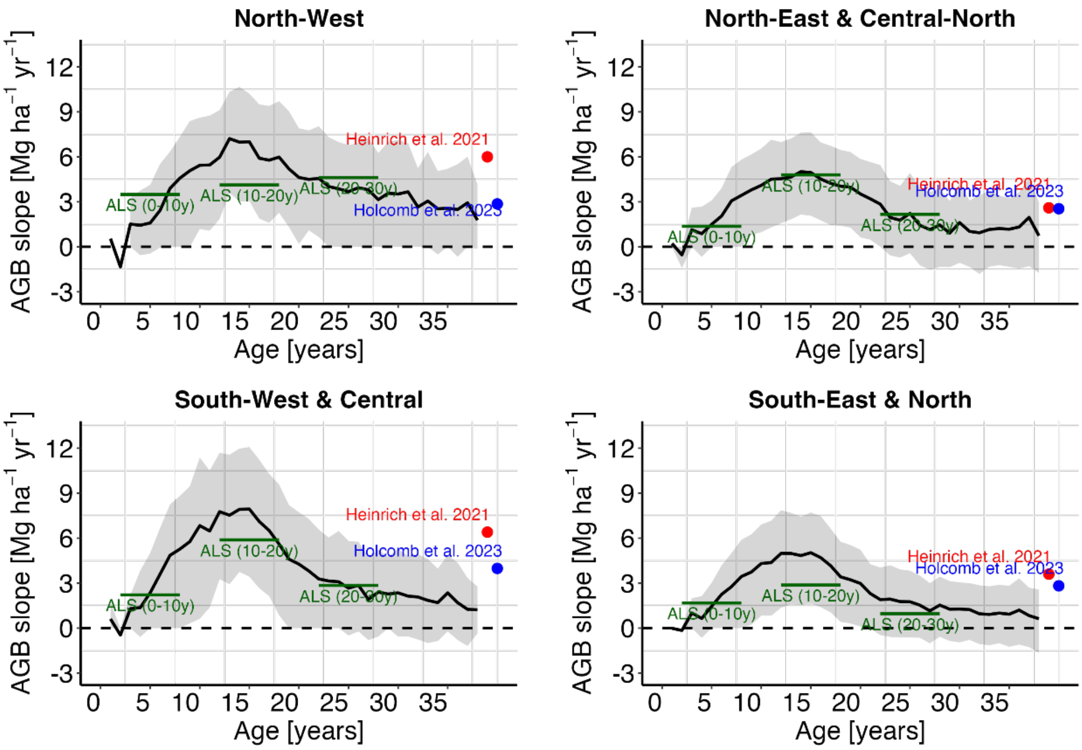

Figure 2. Abovground Biomass accumulation for different secondary forest ages across four climate regions of the Brazilian Amazon. Black line denotes the mean slope derived from a regression approach of taking all available CCI Biomass maps available (v7) for the period 2005 – 2023 for available secondary forest ages in 2023, and the associated interquartile ranges. Green lines represent regrowth rates derived by combining AGB data from ALS data and forest age data from MapBiomas v9. Red and Blue points show the average regrowth rate in the first 20 years of regrowth derived from previous studies, using a space-for-time substitution approach, and making use of satellite data (Heinrich et al., 2021; Holcomb et al., 2023). See Heinrich et al., 2021 for the climate regions.

3 Section 3: Task 1.2 Country Engagement

3.1 Background

The Brazilian NGHGI aims to have a thorough inclusion of carbon gains in secondary forest across its diverse biomes, with considerable motivation to improve the spatial and temporal resolution further. Over the last few years, there has been a surge in research quantifying carbon losses and gains following different types of disturbance, from large-scale deforestation to degradation processes, that cause partial forest losses, such as through fire, selective logging, fragmentation, edge effects, and natural processes including drought and windthrow (see Task 1.1). Much of this research has been focused on the Amazon and Brazilian Biomes such as the Atlantic Forest, but is increasingly pan-tropical through the careful integration of remote sensing estimates. The increased availability of remote sensing data has spanned from local-scale terrestrial/aerial data to regional estimates from satellite-based data such as Light Detection and Ranging (LiDAR) and Synthetic Aperture Radar (SAR) data, often integrated with long time series of optical sensor data. Additionally, there has been a movement towards integrating these remote sensing data with long-standing, single National Forest Inventories (NFIs) and other permanent field plots with repeated measurements to provide details on post-disturbance carbon dynamics at higher spatial resolution. Such estimates are crucial to improve the complete representation of the carbon budget, and the integration of these processes in national reporting, such as NGHGIs and Forest Resources Emission Levels (FRELs), can influence potential local and regional protection and restoration efforts.

With the emergence of new estimates of carbon losses and gains following disturbance comes the need to understand how these estimates compare across various data sources, regions, and forest types and to highlight how and for what practice methods and associated estimates can be best applied. The aim and title of the workshop was therefore "Synthesising post-disturbance carbon emissions and removals across Brazil's Forest Biomes" – SynCER. The primary workshop objectives were to:

1. **Strengthen partnerships** between research scientists and the applications community to enhance future collaborations for outstanding, novel and diverse research integrated into application-based science concerning forest degradation and regrowth.
2. **Explore** the **development and remaining knowledge/information gaps** in the research on post-disturbance forest dynamics.
3. **Follow up studies/papers** exploring the points found in (2), such as synthesizing the best available estimates of carbon losses and gains following disturbance/regrowth across Brazil's biomes.

3.2 Summary of workshop

Overall, the workshop brought together 56 in-person participants (Table 1; Figure 3), from 14 international and 14 Brazilian institutes, bridging the gap between researchers and applications scientists and policy experts. The workshop took place from 29th to 31st October 2025, and included a full agenda of scientific talks and breakout discussions (Table 2).

Day 1 focused on introducing current satellite-derived datasets that identify secondary forests, their extent and ages, and how different sensing platforms e.g., Airborne LiDAR and field data can be integrated. Keynotes speeches gave an overview of the challenges around climate finance mechanism and carbon accounting in a world where forests are increasingly threatened by climate change and human disturbance. ESA's CCI Biomass Project and BIOMASS mission was introduced extensively, highlighting the possibilities and expected contribution of the satellite data to reduce uncertainties in estimating the global carbon sink in forests.

Day 2 focused on AGB datasets and associated missions and how such data can be used to help identify various metrics of secondary forest success, but also the importance of considering biophysical processes. Field data scientists discussed the unique position of their work to explore important biodiversity and species composition developments and secondary forest recovery.

Day 3 saw talks from policy and inventory experts such as the Food and Agricultural Organisation (FAO), the Global Forest Observations Initiative's (GFOI) Research & Development Component, and Brazil's Ministries and associated partners. They provided insights to scientists to help advance how results from research on secondary forest carbon accumulation can be better integrated into national and jurisdictional carbon credit reporting and National Greenhouse Gas Inventories.

The workshop highlighted five potential avenues for further exploration and addressing Objective 3:

- Discrepancies in secondary forest and age datasets in Brazil and advances and drawbacks of using remote sensing products to assess AGB in secondary forests.
- Comparing AGB regrowth rates from multiple data sources across Brazil's biomes
- Assessing the permanence of current regrowth rates due to temporal and spatial patterns of climate change and ongoing disturbances.
- Using ESA BIOMASS data in combination with reference data to show feasibility in Brazil and beyond for assessing disturbance and regrowth.
- Considering the integration of sub-biome, non-linear regrowth rates in future NGHGIs of Brazil.

Figure 3. Group photo of the in-person participants

The outcomes of the workshop were disseminated and distributed:

1. Event summary and presentation slides on the GFOI website.
2. Event news bulletin on the ESA CCI Biomass website.
3. Presentation held at COP30 (see section 4).

Table 1. Participant list of the SynCER workshop.

	Name	Organisation	In-person/Online
1	Alexandre Avelino	MMA	In-person
2	Aline Daniele Jacon	UFSCar	In-person
3	Aline Pontes Lopes	re.green	In-person
4	Ana Talita Galvão Freire	UFMA	In-person
5	Andre Giles	UFSC	In-person
6	Angélica Faria de Resende	USP	In-person
7	Barbara Costa	MapBiomas/IPAM	In-person
8	Bruna Henrique Sacramento	INPE	In-person
9	Carla Ramirez	FAO	In-person
10	Catarina Jakovac	UFSC	In-person
11	Celso Silva Junior	UFMA/IPAM	In-person
12	Daniela Requena Suarez	GFZ	In-person
13	Débora Giancola Tomiatti	INPE	In-person
14	Erison C. S. Monteiro	INPE	In-person
15	Fabricio Pires Chagas	UFMA	In-person
16	Frank Martin Seifert	ESA	online
17	Graciela Tejada	Geonoma	In-person
18	Hannah Graham	GFZ	In-person
19	Henrique Luis Godinho Cassol	Geonoma	In-person
20	Igor Santiago Broggio	Vale Institute of Technology	online
21	Iris Roitman	PNUD	In-person
22	Isabela Noronha	Geonoma	In-person
23	Isadora Haddad	INPE	In-person
24	Jean Ometto	INPE	In-person
25	Juliana Leroy Davis	PUND	In-person
26	Liana Anderson	INPE	In-person
27	Luan Moldan Motta	MMA	In-person
28	Luiz Aragão	INPE	In-person
29	Martin Herold	GFZ	In-person
30	Matheus Pinheiro Ferreira	ESALQ/USP	In-person
31	Mikhail Urbazaev	GFZ	In-person
32	Pedro Brancalion	USP	Online
33	Polyanna Bispo	University of Manchester	In-person

34	Ricardo Dalagnol	Ctrees	In-person
35	Rita Von Randow	INPE	In-person
36	Roberta Cantinho	MMA	In-person
37	Rodrigo Lacerda Brito Neto	INPE	In-person
38	Rodrigo Oliveira do Nascimento	UFRA	In-person
39	Scott Barningham	University of Exeter	In-person
40	Silvana Amaral Kampel	INPE	In-person
41	Thais Rosan	University of Exeter	In-person
42	Thelma Krug	INPE	In-person
43	Vinicius Peripato	INPE	In-person
44	Viola Heinrich	GFZ	In-person
45	Yhasmin Mendes	FAO	In-person
46	Savanah Freitas	INPE	In-person
47	Marcos Longo	INPE	In-person
48	Renata Francoso	Serviço Florestal Brasileiro	In-person
49	Gilney Bezerra	Gamma	In-person
50	Clement Bourgoin	JRC	online
51	Danielle Celentano	ISA	online
52	Gabrielle Pires	Universidade Federal de Viçosa	online
53	Joao Carrieras	JRC	online
54	Lais Rosa Oliveira	Universidade Federal de Viçosa	online
55	Maurizio Santoro	Gamma	online
56	Rene Beuchle	JRC	online
57	Sassan Saatchi	Ctrees	online
58	Simon Besnard	GFZ	online
59	Susan Cook-Patton	TNC	online
60	Flavia de Souza Mendes	Planet	online
61	Yidi Xu	LSCE	online

Table 2. Summary of the Agenda

Time	Topic	Moderator (Speakers)
Day 1		
9-9.30	Session 1.1: Welcome and Objectives	Luiz Aragao (Lúbia Vinhas & Frank Martin Seifert, Viola Heinrich)
9.30 - 10.45	Session 1.2: Mapping Secondary Forest - where are they regrowing according to what dataset	Viola Heinrich (Silvana Amarall, Bárbara Costa, Joao Carrieras & Clement Bourgoin, Hannah Graham, Ricardo Dalagnol)
11.15 - 12.30	Session 1.3: Linking Field, ALS + satellite data of secondary forest	Mikhail Urbazaev (Pedro Brancalion, Aline Pontes-Lopes, Aline Jacon, Thais Rosa,Matheus Ferreira)
14.00 - 15.30	Session 1.4: Keynote addresses	Viola Heinrich (Thelam Krug & Frank Martin Seifert)
15.30 - 17.00	Workshop breakout groups	Luiz Aragao, Thais Rosan & Martin Herold
Day 2		
9.00 10.30	Session 2.1: (1) Biomass datasets + missions; (2) Estimates of carbon accumulation from various approaches	Daniela Requena Suarez (Jean Ometto, Pollyanna Bispo, Mikhail Urbazaev)
10.40 - 13.00	Session 2.1: (1) Biomass datasets + missions; (2) Estimates of carbon accumulation from various approaches + Session 2.2 Other metrics for identifying secondary forest success	Hannah Graham (Maurizio Santoro, Yidi Xu*, Scott Baringham, Isadora Haddad, Débora Tomiatti, Gabrielle Pires & Lais Oliveira, Sassan Saatchi) * Due to technical difficulties this talk was not possible, slides available online.
14.00 - 15.30	Session 2.2 Other metrics for identifying secondary forest success	Hannah Graham (Catarina Jakovac, Andre Giles, Rodrigo Oliveira)
15.30 - 17.00	Workshop in plenary	Martin Herold
Day 3		

9.00 - 10.30	Session 3.1: Accounting for carbon removals/fluxes in secondary forests for MRV process - advances, needs and challenges	Daniela Requena Suarez (Carla Ramirez & Yhasmin Mendes, Celso Silva Junior, Iris Roitman, Roberta Cantinho, Henrique Cassol & Graciela Tejada)
11.00 - 12.30	Workshop in breakout groups	Daniela Requena Suarez, Yhasmin Mendes, Celso Silva Junior
14.00 - 15.30	Summary from breakout groups and finary wrap-up	Viola Heinrich & Luiz Aragao

4 Section 4: Task 1.3 International presentation and outreach

4.1 Overview of events at COP30 from the CCI biomass consortium.

The CCI Biomass consortium organised a joint side event with INPE at the UNFCCC COP30 called "State of the Art Forest Monitoring of the Amazon", where the main results from the workshop, the Biomass CCI change work package and synthesis work were presented. The side event explored how advances in satellite missions, such as ESA's Biomass mission, are revealing new insights into the dynamics of tropical forest carbon storage. Other events that members of the CCI biomass consortium presented at included:

- Viola Heinrich at the Coalition of the Rainforest Alliance session: Seeing the Wood for the Leaves: Bringing Clarity to the Role of Forests and why they need protecting".
- Martin Herold at WMO/GCOS side event on research and systematic observation including examples of using the CCI biomass datasets in countries

Joining forces, ESA, University of Leicester and GFZ had an exhibit in the Blue Zone entitled "Space for Climate Action" for four full days during the second week of COP30 (Figure 4). Heiko Balzter, Frank Martin Seifert and Nezha Acil showed technical progresses in space-based aboveground biomass change detection, with case studies of forest change presented to visitors through interactive maps. The event provided an opportunity for more informal and personal discussions and networking for negotiators, observers and United Nations staff alike.

Furthermore, as member of the steering committee of the GCOS and chair of the related terrestrial panel (https://gcos.wmo.int/site/global-climate-observing-system-gcos/panels/terrestrial-observation-panel-climate-topc), Martin Herold prepared and organized a dedicated side event to emphasize how the continuity of systematic climate observations is under growing threat, from declining *in situ* networks, uncertain follow-on satellite missions, and barriers to data access, including historical data.

Figure 4. ESA, University and GFZ's exhibit in the Blue Zone

5 Conclusions

The tasks part of OP1 have highlighted the research advances made in Brazil and pantropically with regard to better understanding of post-disturbance aboveground carbon emissions and removal processes. Further to this, the tasks have highlighted how the work carried out as part of ESA CCI Biomass can move into the operational and applications spheres if the opportunity is created to better connect the research and applications communities (Task 1.2), build a dialogue and understand user requirements. Task 1.3 also highlighted the importance of the representation of research and the scientific community at large international events such as the UNFCCC COP events, providing unique opportunities to further engage with a diverse range of stakeholders.

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