4th CARBON FROM SPACE WORKSHOP

25–28 October | ESA–ESRIN | Frascati (Rome), Italy

RECOMMENDATIONS REPORT

Co-organised by ESA, NASA, CEOS, EC and GCP

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Background

Since the **3rd Carbon from Space workshop** in Exeter in 2016, significant improvements have been made in the estimation of the global **[RD-1]** and regional carbon budgets, especially through the quantification and parameterisation of the terrestrial carbon balance and the second cycle of the Regional Carbon Cycle Assessment and Processes (RECCAP-2) that will publish its assessment of the carbon budget in 2023 **[RD-2][RD-3]**. In addition, advances have been made in the determination of the budgets of the two other major GHGs, methane (CH4) and nitrous oxide (N_2O) as well as better understanding of the interaction between the carbon, water, nitrogen cycles. These budgets provide a global and regional view from a scientific perspective and represent a complement to national carbon balance reporting (e.g. **[RD-4][RD-5][RD-6]**).

At the same time institutional arrangements for realisation of the Integrated Carbon Observing System have started to take shape **[RD-7]** accompanied by the establishment of improved or better coordinated in situ networks (NEON, ICOS, TERN, FOS **[RD-8]**, SAEON etc), as well as major improvements in the availability and frequency of carbon-relevant satellite observations e.g. NASA's GEDI, OCO-2, OCO-3 as well as ECOSTRESS and SWOT for water observations, Copernicus Sentinel series, generation of a proliferation of key EO-based products e.g. CCI **[RD-9]** and planning for detailed plans for new NASA and ESA satellite launches including, in particular, BIOMASS, NISAR, FLEX, PACE all with potential to address specific gaps in data and understanding of the terrestrial carbon cycle, as part of the effort to implement the Committee on Earth Observation Satellites (CEOS) Carbon Strategy **[RD-10]**.

The European Space Agency (ESA), in collaboration with Global Carbon Project (GCP), CEOS, NASA and the European Commission (EC), organised the 4th Carbon from Space Workshop held in late 2022 at ESRIN/ESA to bring together the EO, in situ and Earth system science communities to review progress since the 3rd Carbon from Space Workshop **[RD-11]** (Annex I), identify gaps, challenges and issues to address in understanding the carbon cycle.

External policy context

The Paris Agreement was put in place with the goal to limit global warming to well below 2, preferably to 1.5 degrees Celsius **[RD-12]**, compared to pre-industrial levels and as part of this the Global Stocktake was established, with its first assessment due in 2023. While the implementation of the Global Stocktake and the Glasgow Declaration on Forests and Land Use **[RD-13]** and more recently, the Global Methane Pledge [RD-14], are proceeding, recent reports on progress towards the limitation of global warming indicate that while limiting warming to 1.5°C is possible and may help in achieving the Sustainable Development Agenda **[RD-14]**, the recent evidence indicates that it will be difficult to avoid an overshoot with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020 **[RD-16]**. This is despite a temporary dip in fossil fuel emissions during the COVID19 period and efforts to introduce a more climate smart approach to development and management of land **[RD-17][RD-18]**. The accumulation of GHGs in the atmosphere, which is determined by the balance between anthropogenic emissions and removals, and physical-biogeochemical source and sink dynamics on land and in the ocean **[RD-19]**, has continued to increase from energy use, land use and land-use change, lifestyles and patterns of consumption and production. The impact of these increases in GHGs has been further detailed in special reports of the IPCC on Land **[RD-20]** and on Ocean and the Cryosphere **[RD-21]**.

Advances in understanding the terrestrial carbon cycle – summary of IPCC AR6 WG1

Recent evidence **[RD-19]** from land process-based models and data-driven machine learning indicates that water availability controls the spatial distribution of photosynthesis over a large part of the globe with both observational and model evidence indicating a stronger response to vapour pressure deficit than temperature **[RD-22]**. Droughts may also reduce the land CO_2 sink by decreasing productivity, increasing forest mortality, and promoting wildfire. Plant productivity is highly dependent on climate with cold regions moving toward an earlier growing season due to warming, partly offset by climate variability, water, energy, and nutrients. While air temperature has an impact on tropical and temperate environments, observations and models suggest that the vapour pressure deficit effects on stomatal conductance are stronger than direct temperature effects on enzyme activities **[RD-23]**, and that acclimation of photosynthetic optimal temperature may mitigate productivity losses of tropical forests under climate change.

There have been improvements in reducing global carbon budget uncertainties, specifically through carbon sink estimation for natural terrestrial ecosystems, improved emissions estimates from forestry and other land use **[RD-24]**, better river flux partitioning between hemispheres **[RD-25]**; and the expansion of constraints from atmospheric inversions using more satellite observations.

For methane, progress has been made in better constraining freshwater lake and river emissions and reducing double counting with wetland emissions although there remains large uncertainty due to difficulty in mapping wetland and inland water area and temporal dynamics (**[RD-26]** and **[RD-27]**). More observational data and improved wetland areal estimates have led to revision of inland water CH4 **[RD-28]** but double-counting remains in bottom-up estimates of wetland and inland water emissions. Trees in upland and wetland forests have also been found to contribute to methane production through abiotic production in the canopy and the methanogenesis taking place in stems **[RD-29]**.

For N_2O there has been improved understanding of sources with the largest anthropogenic driver changing the natural nitrogen cycle being use of synthetic fertilizers and manure, as well as nitrogen deposition resulting from land-based agriculture **[RD-30]**. The quantification of biomass burning for both natural and anthropogenic sources has been improved through better inventories and improved modelling of soil processes. However, uncertainty remains in the ability of process-based models to capture the interaction between N_2O emission and weather/climate processes, especially rain and freeze–thaw events **[RD-31]**.

Improvements have been made in models to account for interactive nitrogen cycle dynamics over land which tends to reduce the CO_2 fertilization effect on land carbon storage, while the addition of the effect of phosphorous further constrains this effect **[RD-32]**. Progress has also been made in understanding soil carbon dynamics, specifically the quantification of high-latitude soil carbon feedbacks, soil carbon persistence and soil carbon dynamics in subsurface layers.

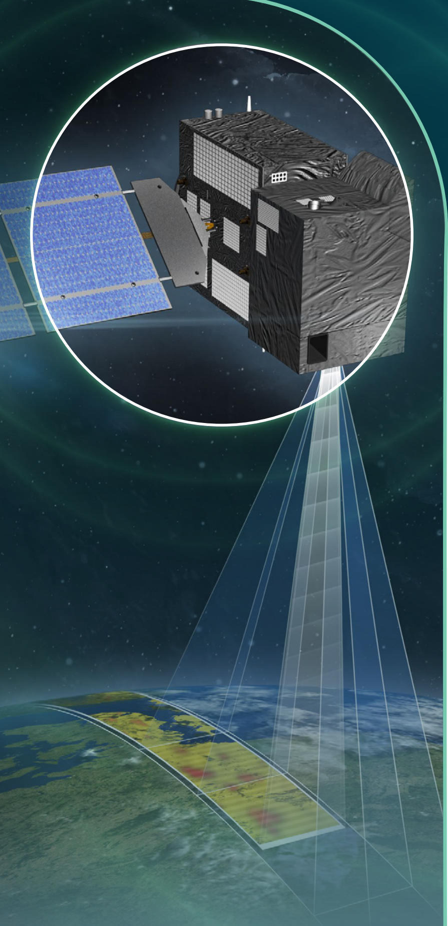
Advances in understanding the terrestrial carbon cycle – summary of IPCC AR6 WG1

In the permafrost region large wintertime carbon (CO_2) losses are being observed during the non-growing season **[RD-33]** potentially driven by increased autumn and winter respiration due to top-down permafrost thaw. While a more active carbon cycle has been observed in the northern high-latitude regions through the increased amplitude of CO_2 seasonal cycles, the CH_4 emissions from this region contribute do not seem to have increased from thawing permafrost.

Climate change has been observed to be playing an increasing role in affecting wildfire regimes through a combination of direct and indirect effects e.g., change in fuel loads including indirectly through fire suppression, increased evapotranspiration, severity recurrence, especially in tropical rainforests **[RD-34]**. Models have increasingly attempted to include wildfire in their calculations. Climate change also drives changes to vegetation composition through disturbances such as forest dieback that may lead to biome shifts in tropical forests, although the introduction of ecosystem heterogeneity and diversity in models reduces the sensitivity of such changes. The evidence for regional abrupt changes in the biosphere such as those related to ecosystems and biogeochemistry, forest dieback or release of greenhouse gases (GHGs) from permafrost remains uncertain.

Key advances for the next period of IPCC **[RD-19]** are needed in:

- Quantifying CO_2, CH_4 and N_2O fluxes from land use, land-use change, and forestry (including gross fluxes), and fossil fuels, especially spatial resolution, and representations of land management, such as forestry, grazing and cropping.
- Diagnosing the variability and trends in the transport of carbon through the land–ocean continuum.
- CH_4 emissions from wetlands and inland waters, especially for the global CH_4 budget including improved observations and process understanding of source responses to climate.
- Understanding and representation in Earth system models of changes in land carbon storage and associated carbon–climate feedbacks (CO_2 fertilization, nutrient-limitations, soil organic matter stabilisation and turnover; land-use change; large-scale and fine-scale permafrost carbon; plant growth, mortality, and competition dynamics; plant hydraulics; and disturbance processes.



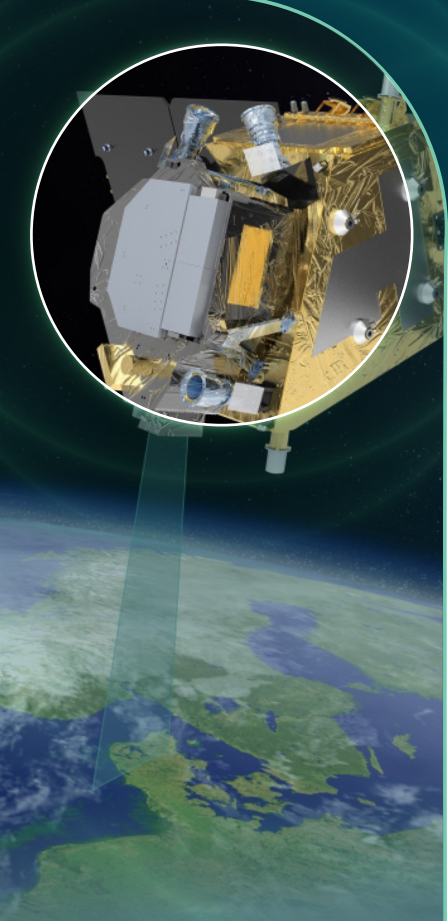
Advances in observations

Since 2016 there has been a major advance in the number of satellites observing the Earth with higher spatial resolution and greater frequency and the targeted observations of key processes. Of particular note for the carbon cycle are the Sentinel series of satellites developed by ESA for the European Commission, the continuity efforts from USGS (Landsat 8/9) and new observations from NASA (OCO-2, OCO-3, GEDI, IceSat2, and ECOSTRESS and SWOT for evapotranspiration estimates and associated water availability constraints on carbon cycle dynamics). In addition, national space agencies have continued to provide better data (e.g., Pleiades, PRISMA, DESIS, TerraSAR, TanDEM-X) while new commercial space operators have proliferated, providing low cost, high frequency and high spatial resolution observations (GHGSat, Planet, SPIRE, Google, MAXAR).

In the coming few years EO will provide a unique capability to advance towards a complete dynamic reconstruction of the terrestrial carbon cycle at unprecedented scales in space and time driven by synergistic observations from the Sentinels (Next Generation, Expansion – CIMR, LSTM, CHIME, ROSE-L, CO2M) and Earth Explorers (FLEX, BIOMASS) together with missions from NASA (NISAR, MTI, SBG) and JAXA (e.g. ALOS-4, GOSAT-GW) and other national agencies (Trishna, MERLIN, MicroCarb) will open a new potential to better characterise the Earth's terrestrial carbon cycle from space.

At the same there has been investment in the generation of a greater variety of estimates of key variables (Biomass, Tree cover, Fire disturbance, Land cover at high resolution) plus the exploitation of existing observations for new uses that show promise for the carbon cycle (e.g. SIF, VOD). This increase in observation has also been accompanied by greater attention to characterisation of uncertainty in the estimates and efforts to improve consistency both between estimates of the same variables and across variables. This is supported by ongoing and increasingly coordinated transatlantic aircraft sampling such as Aircore, Hippo, ATOM, JAL of atmospheric trace gases and joint activities such as AfriSAR, AboVE and AMPAC, FIREX-AQ dedicated to understanding specific regions, processes and/or observations such as forest structure and biomass retrieval, permafrost change and methane, fire and air quality.

Improvements in the Earth System models e.g., ORCHIDEE, JULES, BETHY/DALEC, GISS-E, E3SM, CESM, ESM4 and the interface between models and data and data assimilation techniques e.g., the Land Carbon Constellation, WCRP/Data Assimilation and AIMES data assimilation have also been made supported by benchmarking activities bringing together data products above e.g., iLAMB, CoCO2/Verify, model intercomparison activities such as TRENDY, OCO2MIP, AgMIP.



Institutional Arrangements

While individual multiple agencies have made specific investments in satellites and supporting in situ observations and/or campaigns there has also been an increasing realisation that coordination of activities makes for a much more effective return both economically and scientifically. Of particular importance have been the investments in:

- research infrastructure in Europe, Australia, China, Japan and America to create a more stable platform for in situ observation (through ICOS, NEON, Ameriflux, ChinaFlux, JapanFlux or TERN),

- the Copernicus Programme and the development of the European Digital Twin Earth **(https://digital-strategy.ec.europa.eu/en/policies/destination-earth)** (joint between ESA, EC, and Eumetsat),

- use of cloud computing resources to process the greater flow of EO data (Google, Amazon, European DIAS systems),

- to analyse data streams innovatively through machine learning methods e.g. FluxCom, FluxSAT

- better coordination of funding streams e.g. through the EC-ESA Earth System Science Initiative: **(https://eo4society.esa.int/communities/scientists/ec-esa-joint-initiative-on-earth-system-science/).**

These investments support the international research communities to be able to develop the global budgets of the main GHGs (GCB, RECCAP), engage more effectively in methodological and model developments (MIPs, AIMES) and to contribute information in support of mechanisms such as the Global Stocktake, the European Green Deal, REDD+, Global Methane Pledge or the Glasgow Declaration.

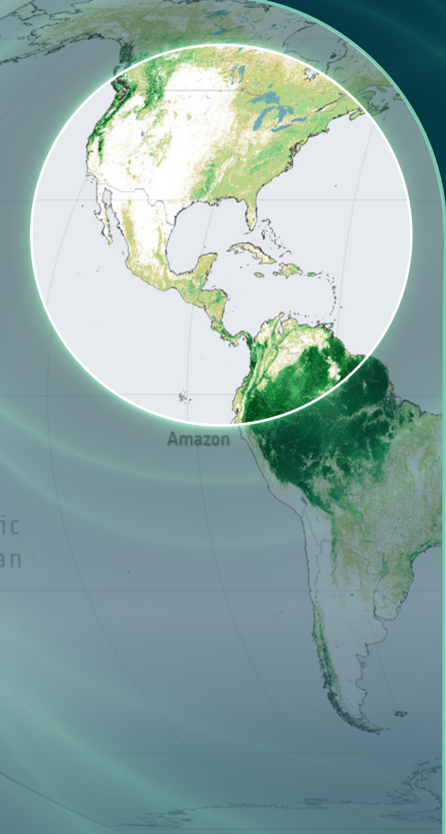
New opportunities arising

The combination of advances in understanding of the terrestrial carbon cycle, better, more frequent and more secure observations in the long term allied with improvements in institutional arrangements and a better coordination of activities within Europe e.g. EC-ESA Earth System Science Initiative (ESSI) and the Copernicus Services, and across the Atlantic improve the prospects for advances in Earth system science and its contribution to respond to the global challenges that society is facing in the onset of this century.

While there are number of different projects and activities funded today by e.g., ESA, NASA, JAXA and the EC, there is a need to structure activities to exploit the unique set of complementary missions and sensors that will arrive in the near future (together with in-situ observations, enhanced models), emerging technologies e.g. through targeted model development, Digital Twin activities and collaborations e.g. ESSI, AMPAC, RECCAP-2 and -3 to significantly advance the way we observe and assess the terrestrial carbon cycle.

Fundamental to this is the interface between models and both in situ and space-based observations. However, there are several challenges that need to be addressed to ensure this interface is appropriate for the flux of observations in the near future. In particular, improvements are needed in:

- modelling of processes especially those that models do not currently adequately capture supported by key process studies in target regions.
- understanding of the observations (in situ and EO) with an emphasis on consistency in space and time.
- the interface between models and data especially towards the compatibility of model structures and EO observations. This may require development of new models as well as improvement of existing ones.
- the integration of in situ observations and EO to provide better understanding of several priority gaps. Examples include land use in a carbon neutral context, permafrost carbon, disturbance dynamics including extremes, blue carbon, climate-driven biome shifts or the separation of natural and anthropogenic contributions.



Recommendations

This report provides a summary of the recommendations for action identified during the 4th Carbon from Space Workshop with the intention to contribute to the establishment of a strategic plan of research and development activities. This strategic plan is needed to help the Space Agencies and major funders to develop programmatic calls for research and application on the terrestrial carbon cycle, in particular, in view of the Global Stocktake and wider commitments made under the Paris Agreement and subsequently COP26 in Glasgow, the Global Methane Pledge and the European Green Deal. This includes improved coordination across the co-sponsors to guide the programmatic actions and investments on terrestrial carbon research and related application development for the time frame 2023–2028.

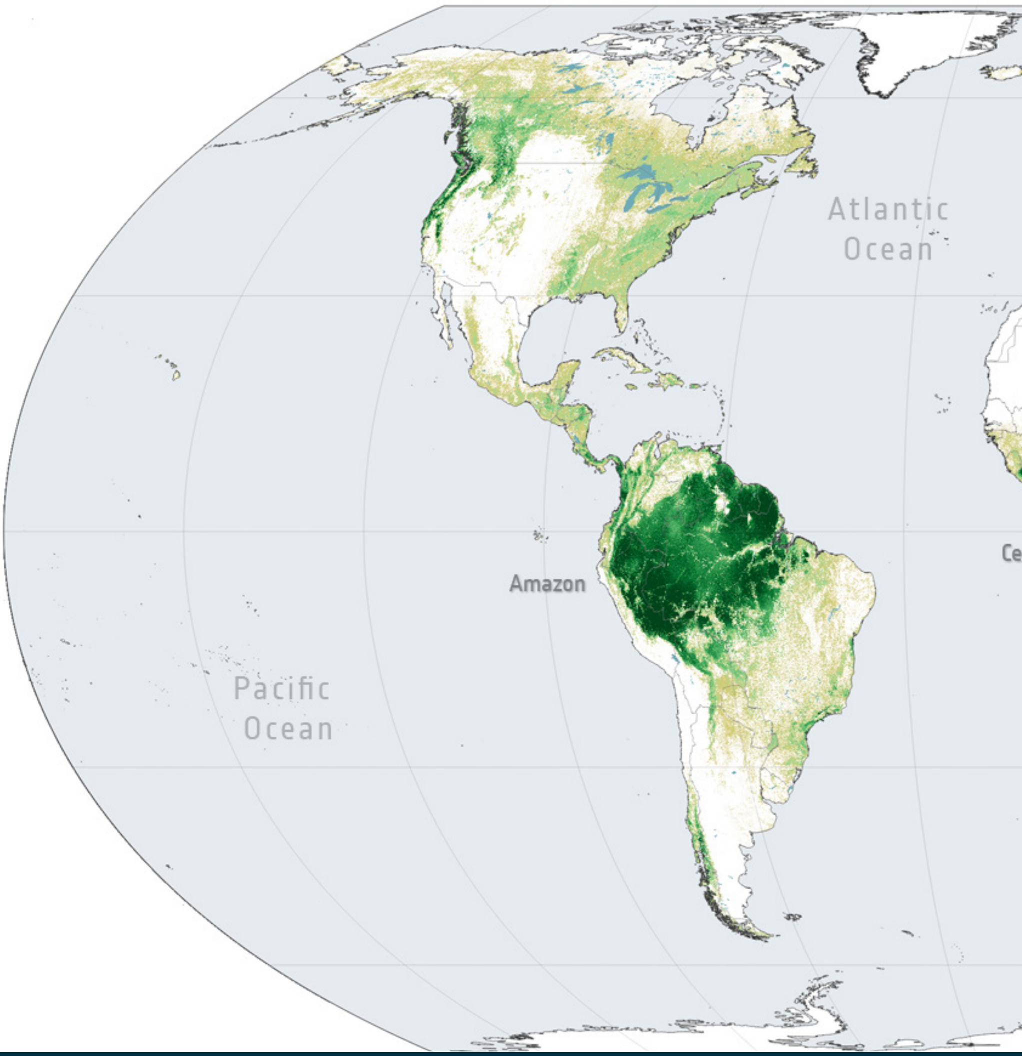
To provide a mechanism for rapid review of progress the report is divided into the following sections and the recommendations summarised in the form of tables under the following sub-headings:

1. **Carbon budgets, RECCAP-2 rapid updates and linkage to National Determined Contributions**
2. **Data Issues**
3. **Models and their interfaces with data/appropriateness**
4. **Attribution/Natural-Anthropogenic**
5. **Extremes, disturbance, and vegetation response - carbon-climate interaction/feedback**
6. **Key regions/challenges (Now & Future)**
7. **Training, Education, Outreach, Engagement across Communities and with Early Career Scientists**
8. **Improve coordination across Research Infrastructures, Space Agencies, other major science funders,**
9. **Processing structures, computing, data access**

1 Carbon budgets, RECCAP-2 rapid updates and linkage to National Determined Contributions

While the Global Carbon Budget Annual Updates and the RECCAP regional carbon budget exercises represent an important scientific benchmark for the Global Stocktake they offer complementary information for the NDC process. Improvements in the interface between the scientific budget calculations and the NDC process could be valuable to those organisations charged with NDC reporting. Discrepancy exists in time and in detail between the GCB and the RECCAP processes which needs to be addressed given they are generated with different approaches and at different spatial detail. In addition to CO_2, CH_4 and N_2O are two other important GHGs for which budgets have recently been produced and for which updates are required with additional advances in understanding to reduce the spatial and temporal uncertainties.

While EO cannot provide a complete record for these budgets, improvements in the contribution of EO can be envisaged and EO can potentially provide a rapid update to the regional budgets using data-driven methods which could be of value for the actual budget calculations at Regional and Global scales. Table 1 summarises the recommendations for activity related to the carbon budget issues.



Global Carbon Project

REgional Carbon Cycle Assessment and Processes Phase 2

RECCAP2

Recommendations from 4th Carbon from Space for Carbon Budget calculations

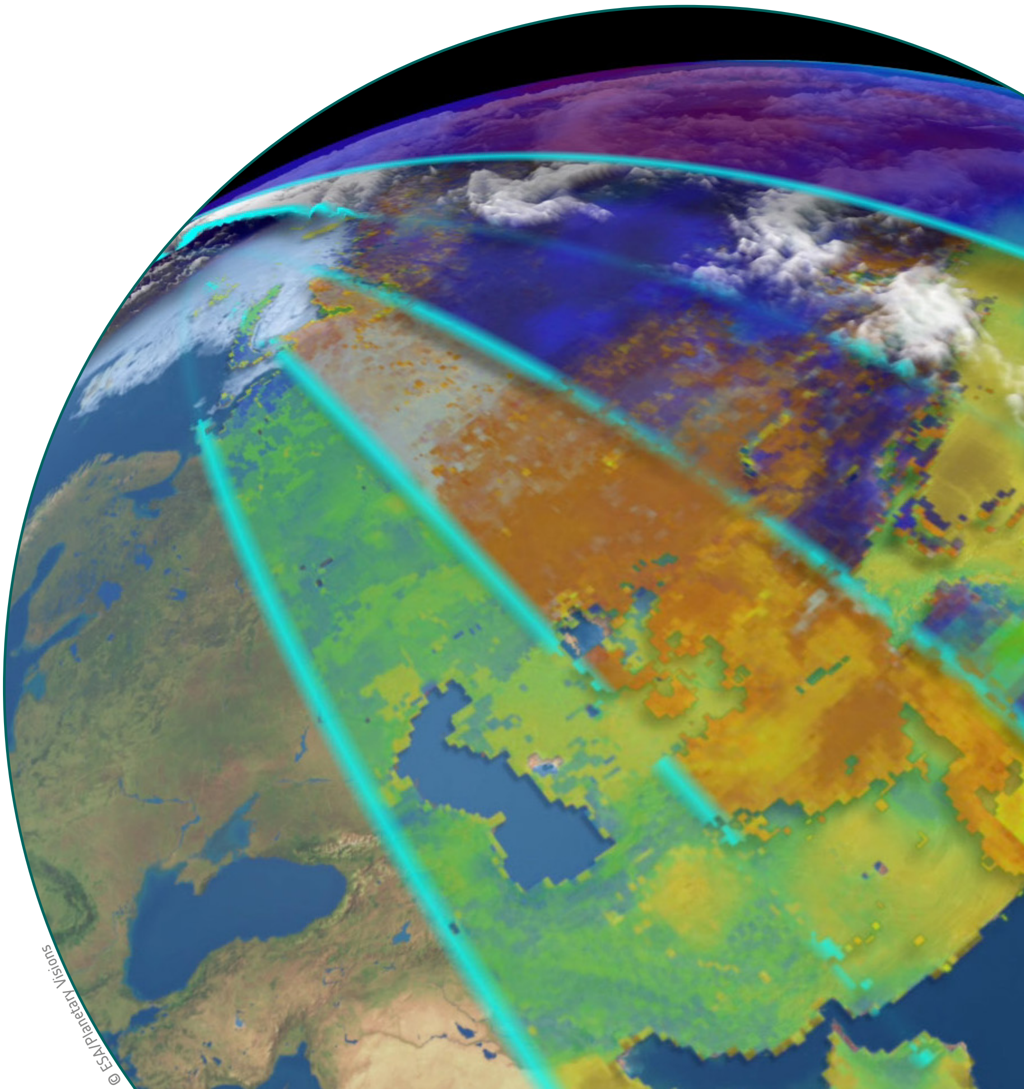
TABLE 1

Nº	Description	Recommendation
1	Characterisation and reduction in the spatial and temporal uncertainty in the global budget, for CO_2, CH_4 and N_2O, and quantification and understanding of the imbalance in emissions and removals.	Identify and improve quantification of the major unknown or uncertain components for the three global budgets with an emphasis on the terrestrial component.
2	Increased contribution of EO (land, ocean,and atmosphere) to the global annual update for CO_2, bi-annual CH_4 and N_2O budgets.	Identify the specific components of the global budgets where EO could contribute. Assess the current approaches used (model ensembles, in situ etc) and prioritise, with the GCP, elements to target specifically on model constraints/fidelity with 'real' world.
3	Increased consistency (or characterisation of the discrepancy) between RECCAP-2 regional estimates and the global budgets with alignment in estimates and update generation targeted at bi-annual reporting.	Budgets estimates generated by/coordinated by GCP globally and regionally need to be consistent or their differences explainable. This requires alignment of budget releases and provision for 'rapid' updating for components of RECCAP without removing the regional expert participation. Generation of baseline RECCAP products (for use by regional contributors) and their rapid (annual) updating is needed. Move toward higher spatial resolution product development and activities to support smaller national-scale studies. This requires coordinated actions across space agencies and development of a RECCAP repository
4	Increased dialogue between carbon science community and those responsible for policy, specifically reporting requirements for Nationally Determined Contributions (NDC) for the 'Global Stocktake'. This should include generation and provision of products/capacity building for NDC with an emphasis on improved consistency between and/or traceability of differences national, regional, and global budgets.	Links between the carbon science community and the authorities (i.e., IPCC and National Greenhouse Gas Inventories and Reporting community) responsible for NDC reporting should be improved. This dialogue is intended to identify where EO products could help those doing NDC reports in both Annex I and non-Annex I countries. NB: the Science Community does not do NDC reporting but may help the Task Force on Inventories (IPCC)/UNFCCC
5	Improvement in data latency and assured continuity of products to ensure data are both consistent and availability is aligned to budget (Regional and global) schedules.	Provision of data products in time for use to update regional and global budgets should be prioritised.
6	Establish a monitoring mechanism from a scientific perspective for the Global Methane Pledge (COP26, COP27, **(https://www.globalmethanepledge.org)** in liaison with the International Methane Emissions Observatory **(https://www.unep.org/)**.	Coordinate activities between IMEO and ESA, NASA, EC RTD on methane release estimation (focussed on both anthropogenic and natural source monitoring) and its reduction.
7	Characterise and eliminate double counting for global methane budget, in particular for wetlands	Establish a new intercomparison of methods and models for wetland characterisation and methane emission with an emphasis on improved spatial resolution and constraints from EO. This should include intercomparison of different EO estimations of wetland extent and their dynamics (optical, radar, PMW, GNSS).
8	EO at site-scale/regional scale as a mechanism for rapid update/tracking for RECCAP regions between periods of the RECCAP process (nominally every 5 years)	Establish a mechanism to pull together all EO observations for RECCAP-2 regions to provide an annual update of the of change taking place in the given region in alignment with the Global Carbon Budget release. These data/products should made available for use by the Regional experts for each cycle of RECCAP.

2 Data Issues

The increased availability of observations that are relevant for the terrestrial carbon cycle represents an opportunity for improved understanding of the carbon cycle and this is important given that new types of observation will arrive in the near future. However, increased attention is needed to deal with persistent gaps in the observational record (in situ and EO) e.g., Global South, continuity of the records themselves, improved consistency for individual variables and/or observation types and across variables.

There also remain issues with processing the data effectively and with ensuring that the outputs are appropriate to the temporal and spatial variability of processes in the carbon cycle (both fast and slow).



Recommendations from 4th Carbon from Space for Issues with Data

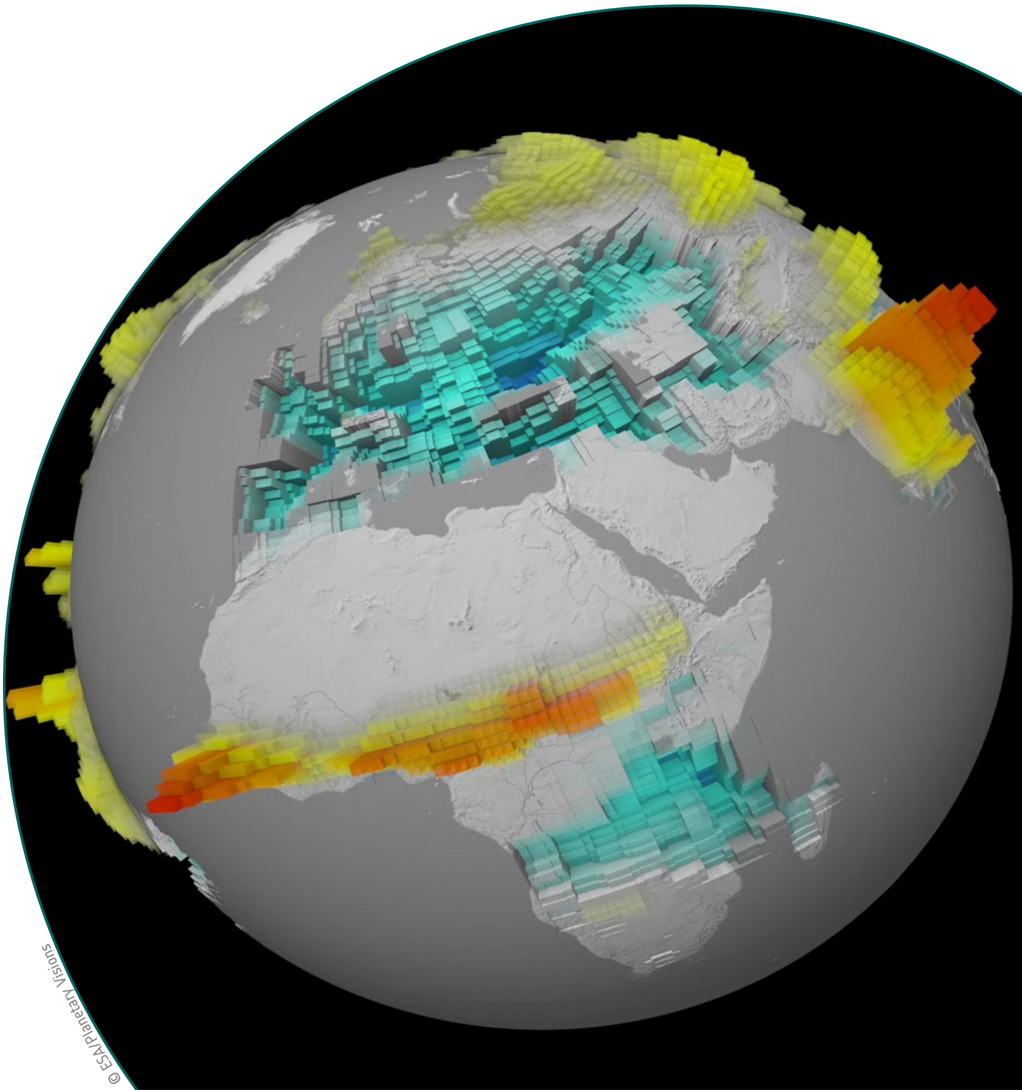
TABLE 2

Nº	Description	Recommendation
9	Increasing data richness and new types of observation will arrive soon which will provide improved understanding of the carbon cycle. The data richness and opportunity provided by upcoming data needs to be planned appropriately to maximise understanding of the carbon cycle. In addition, planning is needed immediately to address missing observations, new observation opportunities (for specific carbon processes) given the time between concept and satellite launch.	• Establish wider collaboration mechanisms (e.g. like MAAP) to take advantage of current and upcoming data across variables and for variables from different data types. • Identify gaps in terms of spatial and temporal provision. • Plan for new observations with priorities for 2027 timeline e.g. **COS (Carbonyl Sulphide)** **HR SIF** **Canopy roughness/canopy structure** **HR Disturbance (fire) – temporal** **LST temporal** **Imaging spectroscopy** **GNSS reflections for wetland**
10	There remain persistent data gaps both in situ and EO which need to be filled. These include flux tower and EO observations in the tropics, the global south generally and the northern high latitudes (cloud presence, polar winter).	• Improve distribution of in situ observations in the global south/tropics and/or NHL, targeting key processes (water availability, degradation, regrowth, plantations, tundra/taiga boundaries, wetlands etc). • Focus on established sites (could be Fluxnet/ICOS/NEON/TERN or LTER or FOS etc) and target locations that improve network representativeness. • Provide observation consistency with mix of SAR, lidar and optical and multi-sensor combinations for polar winter, persistent cloud, complex vegetation structure) • Support studies at sites with aircraft/UAV campaigns and additional in situ instrumentation (mobile as necessary) to overcome spaceborne limitations (i.e. cloud cover, low-sun angles).
11	There are issues of consistency both for individual variables/observation types and across variables. To understand the EO data, reconcile/understand differences in variable estimates and across variables there is a need for a concerted effort to provide complete and appropriately provided coverage of research infrastructures with all data forms (Level 1 (EO data) and Level 2 (Variable estimate)) as well as key locations where processes are active. In addition, there is a need to improve communication and collaboration between research infrastructures and the EO carbon community and improve/augment sites for understanding EO data.	• Identify key sites from existing research infrastructure (ICOS, Fluxnet, NEON, TCCON, COCCON, SAEON, tall Towers etc) augmented with key process locations to address issues with EO data understanding. • Establish priority listing based on budget and importance (primary and secondary sites, key processes), accessibility (physical logistics, geopolitical, cultural, etc), network consistency/funding. • Establish collaboration (supersites for flux/processes/EO validation/data) including augmentation of instrumentation. • Develop flexible science-data platform for data enquiry for selected sites (as a minimum key ESA-NASA data and products) • Focus campaign efforts with in-situ support on research infrastructure and key process site
12	While there is an increasing amount of data and products from different parts of the EM spectrum, these data come at different spatial and temporal resolutions and temporal extent which may not match Stakeholder needs.	• For each key Stakeholder group e.g. GCB, RECCAP-2, EO understanding for carbon, Policy (NDC) implementers identify the current data provision and future need. • Establish protocols/mechanisms/structures to develop required products in a consistent manner (cross-agency)
13	Carbon cycle changes take place at both fast and slow timescales and their interaction with other cycles (water-energy-nitrogen) are also complicated. To understand these there is a need for a detailed set of observations, as well as a consistent and long-term observational approach over time and space.	• Establish historical estimates that are consistent over time and space and for different satellites (all space agencies) • Provide clear intercomparison and validation outcomes that are globally representative. • Conduct exercises on consistency across different spatial scales for given variables and across variables e.g. biomass and VOD • Ensure long term planning for estimate continuity including ongoing commitment to validation and intercomparison (individual variables and between variables).

3 Models and their interfaces with data/appropriateness

Whilst improvements in data availability, data characterisation and consistency are all important the interfaces between models and these data products are appropriate to ensure that the data can be used effectively with models. Current ESM/DGVM models were not designed originally with EO data in mind and consequently are not structured to represent what satellites observe.

There are several options for progress to be made, specifically development of models that are better aligned to observation scales/mechanisms, models that are capable of assimilating radiance and backscatter observations rather than derived quantities, models that are comprehensive in capturing processes, and establishment of experiments over key regions with top-down and bottom-up data available for both model and data testing.



Recommendations from 4th Carbon from Space for Model-Data Interfaces

TABLE 3

Nº	Description	Recommendation
14	The current main ESM/DGVM models were not designed originally with EO data in mind but are increasingly confronted/tested against or constrained by EO products. The models are not structured in the same way as satellites observe (e.g., PFT) and if the intention is increase model resolutions towards Stocktake type needs then the model-data interface needs improvement and appropriate models are needed (with EO in mind).	Progress with the development modelling systems better WWWaligned to observation scales and mechanisms to: · facilitate the synergistic exploitation of the new and existing EO data sets. · help in the identification of inconsistencies among these EO data sets. · assist the design of in-situ networks and planning of field campaigns for calibration/validation. · help explore which EO and in situ data are required to address questions relevant to decision makers, e.g., to support the Global Stocktake.
15	EO does not directly measure products required by the current models, but the models are also not formally set up to 'simulate' EO exiting radiance. Development of biogeochemical models that simulate EO are starting e.g. NASA GISS ENTS model **(https://www.giss.nasa.gov/)** and while this has significant potential the debate on the appropriateness of models for this is still open and not much progress has been made. Thus, parallel improvements are needed on understanding the existing provision of relevant variables (assumptions, uncertainty, representativeness etc) as constraints in relation to current models.	· Explore the usefulness of assimilating L1 observations (TOC radiances/backscatter) in contrast to assimilating retrieved biophysical products. · Develop observation operators suitable for L1 assimilation. The observation operators should be developed in a modular way so that they can be plugged into alternative modelling systems. · Assess inconsistencies among these EO data sets of individual variables and across variables using a combination of models and EO conversion algorithms.
16	While existing models do a good job of capturing carbon cycle variability most of them have gaps in their 'structure', specifically missing processes (disturbance, permafrost, agriculture, land-ocean interfaces).	· Develop modules to incorporate missing processes into current ESM/DGVM · These modules should be based around the available data from satellites as the 'best' measures of dynamics and should adequately consider the spatial and temporal variability contained within the EO data. · Model modules shall be extensively inter-compared to assess their capacity to capture the spatial and temporal variability using benchmark data.
17	Both models and data have a limited approach for characterising or reporting uncertainty in terms of individual processes or collectively. Models generally rely on uncertainty expressed as a function of model ensembles while data products generally do not track uncertainty in the original measurements through to the final output. For data assimilation purposes a more complete characterisation is required on both sides since despite progress in this area uncertainty figures are often quite conservative which requires artificially inflating the observation errors to compensate.	· Establish protocols for quantifying and representing uncertainty in models and for data products. · For data products generate uncertainty fields ommensurate with needs for data assimilation. Monte Carlo uncertainty tracing should be conducted where possible. · Ancillary data used in any products/models should come with uncertainty expressed.
18	Data assimilation with terrestrial models has seen a large increase in activity. However, the infrastructure needed to run many of the big models is getting increasingly complex, and DA often requires significant computational power and thus most data assimilation schemes treat data products singularly and independently when the original data may not be independent. Assimilation of new observations. e.g., SIF, VOD and ASCAT slope in tandem with more traditional approaches (albedo, biomass, fAPAR, LAI) shows promise for constraints on processes in both the water and the carbon cycle. Data assimilation schemes that are capable of assimilating multi-species/multiple EO datasets are needed. Funding of workshops and small studies has been conducted within the AIMES Global Research Project of Future Earth and should be built upon.	· Develop community models and DA tools that are easier to use. · Provide better access to existing models – experiments, emulators. · Explore links with ongoing work in AIMES. · Conduct multi-dataset assimilation experiments especially those with new data products e.g., SIF, VOD and ASCAT slope.
19	Approaches towards characterising carbon budgets from top-down (atmospheric observations of carbon gases) and bottom up (observation of the surface characteristics and the resulting emissions) can differ because of issues with models and data provision/comprehensiveness (in space and time and height and including uncertainty) with resulting disagreement in the budget calculations.	· Experiments over key regions with top-down and bottom-up data available needed – possibly RECCAP size areas. · Target also key areas where major discrepancies exist e.g., dry tropics, drylands, permafrost. · Integration of land-ocean-aquatic fluxes from inland waters, estuaries, and continental shelf processes.

4 Attribution and the separation of Natural and Anthropogenic contributions

Scientific progress on understanding the terrestrial carbon cycle and the role of humans in affecting it, requires attribution of changes in sources and sinks to both natural and anthropogenic processes. This is complicated by definitions of what constitute anthropogenic and natural contributions, the processes, and their importance for the different GHG budgets (methane, CO_2 and N_2O), the spatial and temporal variability of those contributions and finally how the impacts land management change the balance between them.

Improvements are being made on quantification of point source emissions, on improvements in stocks and in determination of dynamics but there remains the need to improve observation resolutions to the those of policy implementation and likewise improve models to incorporate such processes.

TABLE 4

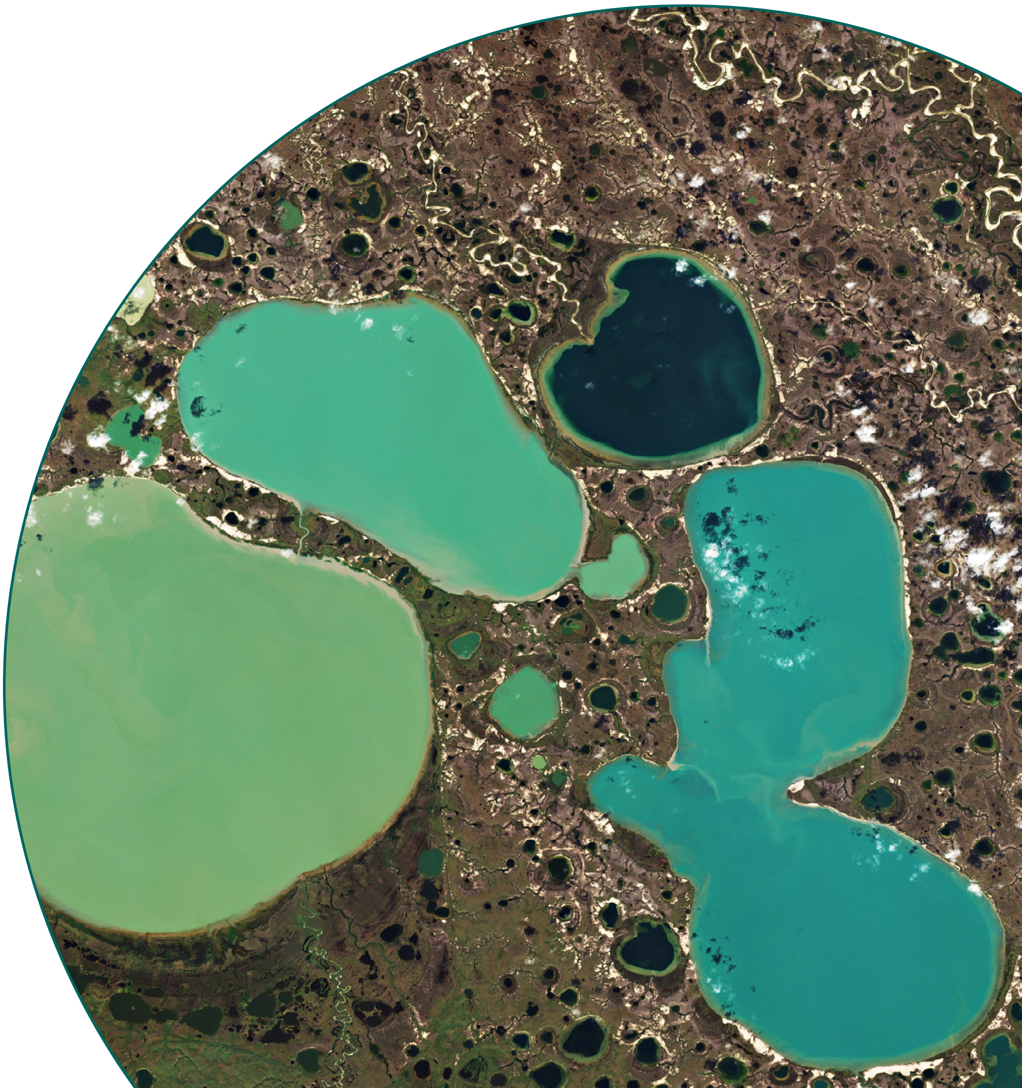
Recommendations from 4th Carbon from Space for Attribution and separation of natural and anthropogenic contributions

Nº	Description	Recommendation
20	Most land on the globe is managed yet for the purposes of UNFCCC managed land has a more limited definition and a clarity is needed. Land use change represents a major emission source in carbon budgets but land use once a gross change has occurred is not well characterised and this is where policy intervention is also prominent. A better understanding of management impacts is needed as current land use/book-keeping models are very limited in incorporating land management (intensity, crop type, rotation etc) and EO data can contribute increasingly especially in terms of the distributions of C3 and C4 crops, management type and intensity (grassland and cropland, plantation, biofuels, silviculture, degradation etc). The scale of observation of land management impacts is also very important.	· Improve bookkeeping models by using more specific types of cropland. · Conduct experiments on the impact of land use type and land management using a combination of book-keeping and EO. · Assess the impact of detailed information on land use type (beyond crop, grass, forest, and change) on carbon emissions including spatial distribution of C3 and C4 crops and impacts of policy intervention/regulation (fertilizer use, cover cropping etc.) and the scale at which such processes are observable. · Assess the role of disturbance processes especially in respect of forestry in land use terms and at what scale these processes can be best observed. · Assess the impact of uncertainty of the products; error propagation on the ability to observe land use change and policy impacts.
21	Forests and the Glasgow Declaration	· If EO should be used in the policy context we need to intensify efforts to produce consistent maps with proper uncertainties. · AGB stocks is good and important, but what we really need is change. Harmonisation in time is a major challenge. Even in case of unique products like the CCI AGB, time consistency is not given. · EO must invest in the collection of ground data. It is essential for product validation in space and in time. Most ground networks are in a critical situation and risk running dry of funds. Initiatives like GEO-TREES have been established but need the buy-in of Space Agencies. · The tendency of the EO community to harvest ground data without contributing to its collection is perceived extremely critically. · We need to better integrate field and spaceborne AGB estimates and link them to practical land/forest monitoring solutions and policy needs. · We need new tools to monitor and document mitigation and adaptation efforts and their impact. · We should support/incubate services for forest management and assessments on biodiversity, ecosystem sustainability and environmental degradation.
22	The identification and separation of natural from anthropogenic contributions to the carbon budget is needed for all three GHG but with different components/processes being important. In addition, the ability to attribute sources of emission will vary with spatial resolution and temporal sampling from the perspective of identifying discrete and ephemeral sources as well as diffuse versus point sources.	· CH_4 point source emission monitoring are rapidly improving with commercial systems and Sentinel-2 and for future Merlin lidar (for NHL winter). Temporal sampling (diurnal) still needed. · Focus is needed on CO_2 anthropogenic emissions (in preparation for CO2M) and CH_4 natural emissions and their dynamics. · N_2O addressed by proxy aiming at improving budgets especially agriculture, forest loss reduction, natural soil oxidation, atmospheric concentrations (NH3, NO2) especially for underrepresented regions and non-anthropogenic processes.
23	While urban carbon, land-ocean flux or blue carbon were not discussed during the meeting, given the impact of urbanisation of the land surface (physical, through trade flows and through impact on non-urban environment), changes in fluxes between land and ocean through land management and the potential of the land-ocean interface for processing carbon, their contribution to the carbon budget needs to be addressed.	· Assess impact of urban carbon as a special case of land use including its wider impact on trade flow · Characterise land-ocean flux including the impact of urbanisation of hydrological routing and carbon inputs from agriculture/silviculture. · Assess impact of anthropogenic activity on blue carbon dynamics (sea grass, macroalgae, mangrove, tidal flats)

5 Extremes, disturbance, and vegetation response-carbon-climate interaction/feedback

Understanding the dynamics of vegetation growth in relation to the carbon cycle is fundamental for improved determination of the carbon budget and its change in response to changes in climate especially shifts in terms of anomalous climate events (extremes) and change imposed by anthropogenic processes. Modelling of the carbon cycle needs to include natural dynamics including natural turnover, disturbance from fire, pests, changes in weather and climate and anthropogenic activities (land management, resource exploitation) and their combination. Observation of these processes are improving but there is a need to effectively combine different data streams over time and data from different resolutions in both space and time to differentiate different disturbance/dynamic processes.

In addition, targeted studies are needed in different biomes to establish a better understanding of the potential for irreversible change in the carbon cycle especially in regions with a large legacy pool of carbon or that are important for carbon cycle stability.



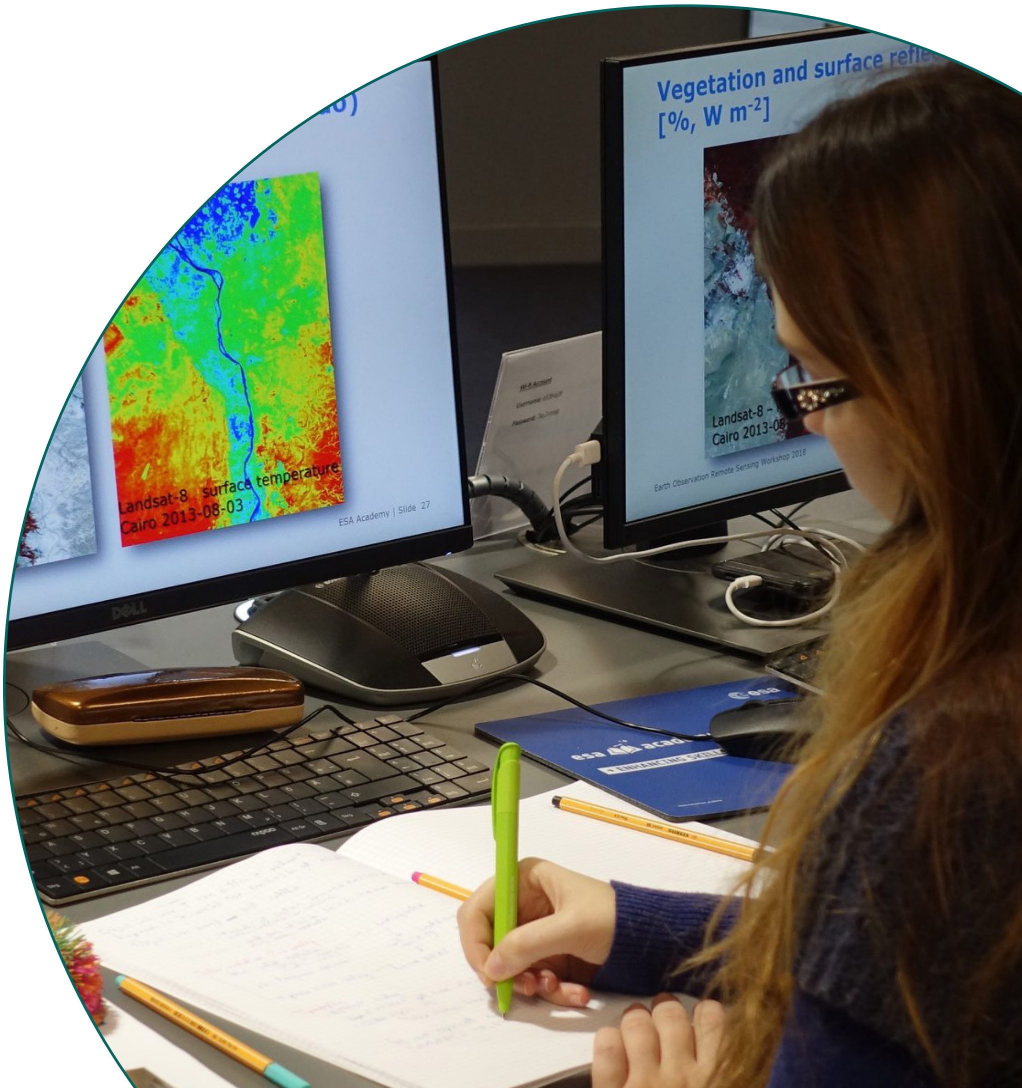
Recommendations from 4th Carbon from Space for dynamics and carbon-climate feedbacks

TABLE 5

Nº	Description	Recommendation
24	Dynamics of disturbances and their activity in combination or in sequence requires special attention especially considering changes in climate that may favour changes in fire regimes and pest ranges. Most of the work on disturbance to date has been on fire and this needs to continue but further work on pest impacts on especially forest and windthrow processes need attention singly and in combination with other disturbances as well as anthropogenic activities (forest opening, selective logging, forest management, deforestation/fragmentation). In addition, studies on the impacts of fire emissions on other ecosystems is needed e.g., phytoplankton fertilisation in the Pacific from fire in Australia.	• Dynamics of disturbance can be addressed leveraging multiple EO data sets to study global and individual events. This requires coordination across satellite sensors to estimate emissions, fuel load, combustion completeness, type, size etc. • Studies on carbon impacts of pest occurrence and windthrow are sparse and need increased attention focussed on earlier detection of pest impacts/stress (SIF, vegetation structure changes, growth dynamics etc) • Work needed also on impacts of fragmentation, forest degradation and forest management and windthrow. • Studies on sequential disturbance (pest and fire etc) also needed.
25	As well as dynamics of disturbance, longer term observation of key regions is needed to observe vegetation dieback and/or forest regrowth as a function of shifts in climate and abandonment/positive interventions in terms of reforestation. This includes change in vegetation composition and structure and observation of recovery dynamics.	• Research is needed on observation of change in vegetation structure/composition, vegetation long-term growth decline/change and recovery dynamics and their impact on the carbon cycle especially in response to climate shifts.
26	Change in climate whether anthropogenic or natural may lead to increased atmospheric variability/instability due to greater energy in the atmosphere with the potential for development of anomaly events which can be widespread, short but rapid or long and sustained. Examples include intense rainfall, megafires, long-term and short term drought, windstorms, snow, and ice storms. The impact of these on carbon cycle functioning and understanding of carbon cycle processes needs study.	• While these cannot be planned, dedicated efforts to study carbon cycle impacts of such events requires planning pre and post-event to look at emissions, recovery and change in vegetation composition in response. Studies of atmospheric dynamics and determination of anomaly events for large regions and local areas (streamers etc) should be conducted to identify regions 'at risk'. • Strategic planning for provision of data-driven estimates of impact with model efforts for immediate aftermath and then for long term recovery research. ESA and NASA should have a strategic approach to make data rapidly available for the region affected (a form of Charter for carbon science)
27	The existence of tipping points in carbon cycle and their reversibility is a widely debated field in particular for regions that either have a large legacy pool of carbon (stable but with potential to become active) or that are important for stability of the carbon cycle (tropical forest, boreal forest, wetlands, peatlands, permafrost). It is not known if such regions could 'tip' to a new state or the impact on the carbon cycle if they do.	• Special studies needed on: -permafrost legacy carbon and dynamics -tropical peatland -northern wetlands and methane -tropical forest carbon uptake change -boreal forest expansion/vegetation change

6 Training, Education, Outreach, Engagement across Communities and with Early Career Scientists

Improvement in the exchange between EO, in situ and modelling communities and between different Space Agencies is an important mechanism for advancing carbon cycle science with a particular emphasis on early career scientists from across these communities. There are currently a number of different but disconnected opportunities that could benefit from some form of coordination and to target better early career scientists and specifically, from a Space Agency perspective, to develop training mechanisms for non-EO communities (in situ and model) as well as communicating better the wider opportunities that can be exploited e.g. Open call, Fellowship schemes, access to campaign activities and resources (models, data collections, documentation etc) and targeted training courses (MOOC and in-person).



Recommendations from 4th Carbon from Space for training and outreach

TABLE 6

Nº	Description	Recommendation
28	With the planned exercises around in situ research infrastructures/campaigns and specific regional foci (linked to understanding key processes/where change is taking place) there is. a recognised need for the three communities to improve understanding of the data-model interfaces, especially for upcoming researchers.	NASA-ESA should support existing and develop new training courses oriented to towards the in situ community and the model community to improve understanding of what the EO data observe and how they should be used effectively. This should target Early Career Scientists in particular.
29	To improve interfaces between in situ, model and EO communities there should be targeted calls for proposal from new investigators/early career scientists with a focus on recommendations identified in this report.	A specific scheme to encourage new investigators/Early career scientists should be organised ideally as a collaboration between ESA and NASA focused on the ESA Carbon Science Cluster and linked to the NASA equivalent opportunities.
30	The ESA Living Planet Fellowship schemes is an annual call but the call is limited to ESA Member States. Similarly, the ESA Open Call also offers opportunities for science (150-200kEuro-12 months) but is limited to ESA Member States, is not dedicated to Early career scientists and is very competitive.	• ESA and NASA should explore mechanisms for exchange for researchers focussed around the ESA Science Hub (Carbon Science Cluster, in particular) and/or including provision for co-sponsorship/coordination of research calls (same call themes) targeted to Early career scientists. • A Visiting Scientist exchange to work on the schemes/ opportunities in Science Hub is open to the international community
31	Exchange of ideas and knowledge across the terrestrial carbon community could be helped by the availability of targeted online learning materials possibly linked to formal Credit schemes (this would require University sign-up as ESA does not have a scheme) focussed on the issues raised in the meeting and expressed in these recommendations.	• Develop an Online course (MOOC) targeted towards Early Career Scientists/post-docs/postgraduates and focussed on the interface between land surface carbon models, in situ and EO data. • his should be a joint effort also with other sponsors of Carbon from Space (CEOS, EC and GCP).
32	The complexity of land carbon models/DGVMs means there are few groups actively developing them. Although these are often in collaboration across different organisations, the numbers of contributing organisations is limited and access to models by community members as a consequence can be difficult. While not intentional this means models may move forward more slowly and the interfaces between models and data (EO and in situ) develop inefficiently. Without limiting this approach there is a need also for development of community models or model versions that can be accessed by a larger and more diverse community (EO, in situ and model together).	• There should be an effort to improve access to land surface models to allow more efficient development of data-model interfaces and improved process testing and understanding. • Development of Community Model versions of existing major models is recommended especially to facilitate greater exchange between the model and data communities.
33	It is recognised that there would be significant benefit from coordination between ESA and NASA focussed on exchange opportunities for early career scientists. This should focus on improved exchange between Space Agencies through adaptation of existing mechanisms to be more inclusive.	• Fellowship e.g., ESA Living Planet Fellowships should incorporate options to allow visits to laboratories beyond the current approach. • Exchange mechanisms to allow especially early career and key scientists to work for periods in a new environment should be explored. • This can be done by establishment of science/challenge clusters (either at agency or community level) and can operate both in-person and virtually.
34	EO products, EO data, in situ data and land carbon models all suffer from the complexity and lack of transparency in the way they have been developed or processed especially on the in-built dependencies on ancillary data and assumptions. If improvements in the interfaces between models and data and increase in uptake and use of models and data by the land carbon community are objectives then improvements in documentation are required.	• Simple guideline documentation should be produced which describes especially the dependencies and assumptions that are inherent in both models and data. • This should complement not replace detailed theoretical baseline documentation and should be page limited with an emphasis on how the data was processed or the model works, what its strengths and weaknesses are and what its dependencies/assumptions are.

Recommendations from 4th Carbon from Space for training and outreach

TABLE 6

Nº	Description	Recommendation
35	To move forward on understanding the carbon cycle requires coordination across the carbon community and cannot be unilaterally pursued by the Space Agencies (ESA and NASA in particular). This requires a joint approach with the carbon cycle science community and active engagement with Future Earth generically. There is also a need to ensure coordination across different parts of Future Earth (and its sister organisations) to be effective.	Activities by the Space Agencies should be coordinated with Future Earth activities related to the carbon cycle: • GCP, • iLEAPS, • AIMES in Future Earth and • WCRP.
36	Provision of EO data both as radiance/backscatter observations and as derived products has increased significantly along with temporal frequency and spatial resolution. However, the provision of these products relies strongly on scientific literature knowledge, contacts and programme profile rather than there being a concerted effort to provide a maintained listing of data products and coordinated access points. This also works against appropriate use of data in combination and or assessment for a given variable of data consistency. Some efforts have been made e.g. CEOS **(https://gis.csiss.gmu.edu/)** or ECV inventory **(https://climatemonitoring.info)** these are not well known to the carbon community. The development needs to be coordinated with the in situ and model community and Future Earth.	• Simple guideline documentation should be produced which describes especially the dependencies and assumptions that are inherent in both models and data. • This should complement not replace detailed theoretical baseline documentation and should be page limited with an emphasis on how the data was processed or the model works, what its strengths and weaknesses are and what its dependencies/assumptions are.

7 Address key regions/challenges (Now & Future)

As well as understanding the interfaces between EO, in situ and model communities there are a number of challenges in understanding that require special effort to address both current change and potential for future change in specific regions of the planet subject to anthropogenic pressure and to change in climate e.g., the tropical rainforest or potential for future change e.g., legacy carbon in permafrost. Each of these poses challenges in process understanding, data availability/quality and consistency and continuity of data sufficient to allow the region to be assessed comprehensively. Beyond the 'pure' science issues there are also challenges involved in the policy domain. Examples include major policy interventions e.g., Paris Agreement and understanding how science can contribute to the Global Stocktake, or examination of the efficacy of regulations e.g., European Green Deal (land use and agriculture) or the Glasgow Declaration (forest protection, reforestation, and deforestation).

Such research foci call for coordinated responses from Space Agencies, Research Infrastructures and the carbon cycle science and policy communities ranging from community engagement through to dedicated experiments/campaigns.

Recommendations from 4th Carbon from Space for research foci

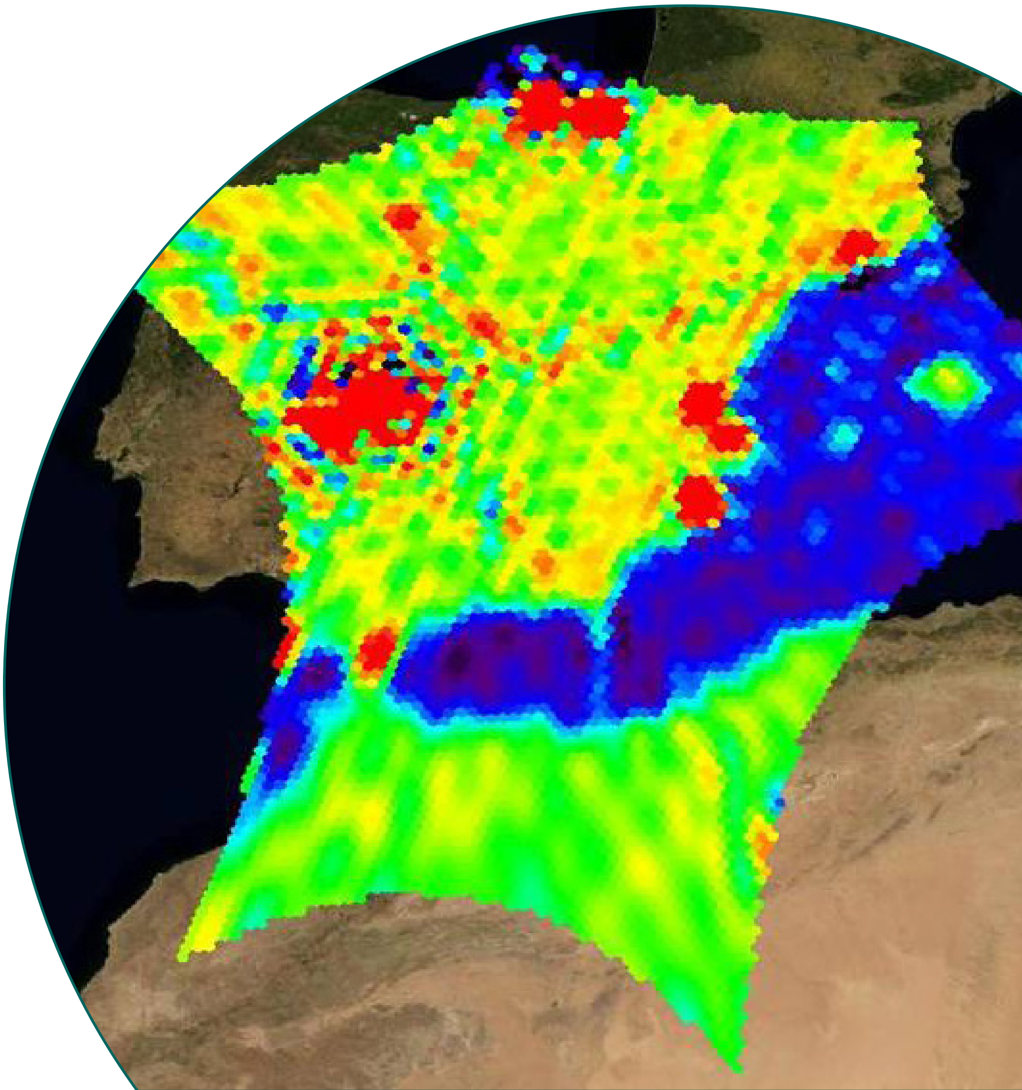
TABLE 7

Nº	Description	Recommendation
37	The first Global Stocktake under the Paris Agreement takes place in 2023 and will be repeated in 2028 with the objective to move towards being monitoring, carbon loss reduction etc. Provision of inputs are the responsibility of National agencies not the science community but latest advances in science can have an impact (RECCAP, GCB etc). Improved links between the carbon science community and the national reporting agencies is needed to improve consistency from global-regional-national level budgets or explain divergence. EO has a clear role to play at the Regional-National level but cannot provide definitive answers to the needs of Stocktake reporting.	• Establish/improve exchange between the carbon cycle science community and the agencies responsible for reporting for the Global Stocktake • Conduct work to understand and reduce differences between National reporting and Regional and Global science assessments of carbon budgets. Note significant work is needed on Global-Regional consistency. • In collaboration with National Reporting agencies develop products of value from EO of value to those agencies.
38	There are a large number of potential areas to target for improvement in understanding the carbon cycle and the impact of anthropogenic pressure in changing the cycle. Each of these has significant challenges. A number pf these already have activities and others are planned at national/regional level – how can these be more effectively coupled to maximise return, where are they important and what are the individual challenges (see also other recommendations). These include: • Land Use and Agriculture -> Responding to need to be carbon neutral. • Land use and Forests -> Responding to the objectives of the Glasgow Declaration and its implementation. • Permafrost carbon -> improved quantification of amount, potential for release, mechanisms. • Tropics especially forest and peatland in Amazon basin (CEOS), Africa and tropical Asia -> impact on uptake/loss. • Blue carbon -> quantification of individual components and their dynamics (mangroves, seagrass, macroalgae, tidal flats, land-ocean aquatic continuum lateral flows). • Disturbance and its dynamics globally. • Drylands – 50% of land surface and growing but carbon processes are not well characterised. • Extreme impacts (drought, temperature etc). • Climate driven biome shifts -> over what time scale and where? • Natural vanthropogenic -> separation v combined • effects? • Urban Carbon -> characterisation, carbon neutral approaches, wider impact than urban bound?	• ESA-NASA-GCP to generate a roadmap needed for each to identify the challenges, how each can be addressed (combination of models, in situ and EO), observations needed (and if these are already available) • Identify priorities based on a) need, b) ongoing or planned activities, c) opportunities to address challenge, d) available resources (in situ, model, EO), e) community

Improve coordination across Research Infrastructures, Space Agencies, other major science funders.

The individual space agencies and other major science funders including those funding major research infrastructures (e.g. EC or NSF) invest in carbon cycle relevant projects through a series of programmes and funding lines dedicated to science, campaigns, missions, policy assessment and/or infrastructure support. Coordination of some of these programmes would increase the benefits to be accrued through individual projects/funding lines, with the money spent more effectively and the returns in terms of scientific understanding and outputs increased.

This is particularly relevant for new mission preparation by Space Agencies as well as cross-mission activities to get additional value from existing satellite sensors and coordination of multi-agency campaigns/experiments.



Recommendations from 4th Carbon from Space for improving funding coordination and return.

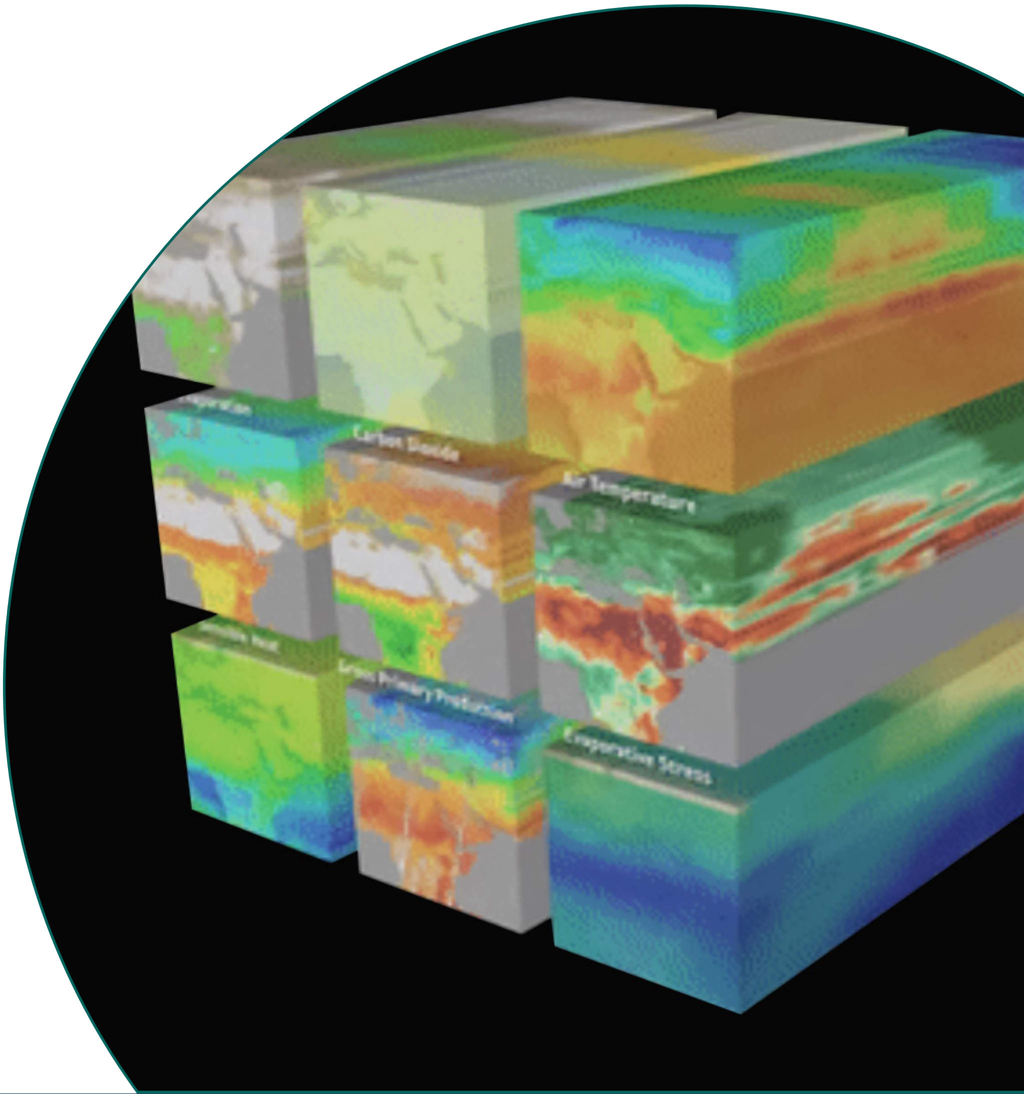
TABLE 8

Nº	Description	Recommendation
39	The Space Agencies and other key funders/actors have programmes on addressing the land carbon cycle and the challenges that exist. This work could benefit from coordination of programmes strategically and internationally to maximise the opportunities that exist.	· The meeting co-sponsors should identify elements at multiple timescales where joint activities can be coordinated. · These should be linked to existing and new missions and cross-mission combination, research infrastructure needs and challenges identified.
40	Flight/campaign planning, exchange programmes	· EO mission developments include campaigns to test algorithms and observation technology but are generally organised by Space Agencies independently. · Where possible these should be coordinated to ensure a larger number of observations of different types for a given science objective.
41	EO development, product development and data analysis are programmatically separated from in situ provision (research infrastructure, scientific investigation) yet for product validation, science insight these should be coordinated to ensure the science is addressed effectively both on the ground and from air and space.	· Space Agencies and research infrastructures need to coordinate activities to ensure in situ observations are appropriate for science as well as being useful for calibration/validation of space observations. · Campaign organisation by Space Agencies should be oriented around the research infrastructures where appropriate or targeted to a specific science challenge in coordination with in-situ programmes.
42	Most EO satellite missions are built around a scientific need that is self-contained, but the data can be used for other objectives and with appropriate planning the science return can be much larger especially if the scientific challenges are mission drivers. Mission development should be coordinated more effectively to address science needs (mission combinations, observation continuity etc).	· In development of missions the scientific objectives should be traceable, achievable and in the context of the challenges. · An emphasis on quality, comprehensiveness of observation and longer-term continuity should be drivers. · Beyond the priority science objectives that drive the mission, opportunities to be accrued through cross-agency mission combinations, mission continuity and additional scientific objectives should be considered as part of mission exploitation plans.

9 Processing structures, computing, data access funders.

The increase in availability, variety, resolution, and volume of data in the recent period brings with it the need to consider how to effectively process and exploit the data streams singularly and in combination. In line with the data volumes there have been concomitant improvements in processing speeds, availability of machine learning methods, availability of improved data access and access to 'in-the-cloud' high performance computing. These resources can and should be exploited by the carbon cycle community and represent a major opportunity to address the challenges above at higher resolutions and frequencies e.g. for updating carbon budgets.

There should be a conscious effort to make multiple data products available easily for scientists to use, provide Open access to those data and provide support in terms of computing resources and algorithms to allow the data to be effectively exploited (Open Science). Such access applies to models (or emulators), EO data and products and aircraft and in situ observations.



Recommendations from 4th Carbon from Space for data exploitation

TABLE 9

Nº	Description	Recommendation
43	The increasing volume (frequency and spatial resolution) of satellite data requires fast processing systems to allow annual updates on either specific regions or globally with low latency. This comprises bringing together public and privately operated satellites as well as multi-frequency observations (optical, thermal, microwave etc) at multiple spatial resolutions to obtain appropriate diurnal, seasonal, interannual and long time-series.	Cloud computing should be used to: • bring cross-agency datasets together. • give quick updates on current year e.g., for Amazon, Africa etc.
44	The proliferation of data means new approaches to data handling are also required constrained by scientific understanding. In addition new approaches to handling the increasing resolution and complexity of land surface/carbon models are needed to allow faster scenario assessment	• Space Agencies need to undertake exercises in data exploration with AI using appropriately prepared data cubes for process understanding e.g., DeepESDL **(https://www.earthsystemdatalab.net)**. • There is a need for model emulators to allow rapid testing of scenarios and to examine model behaviour against data-driven equivalents. This requires coordination between model teams, AI expertise and data experts (in situ and EO
45	There is a rapidly increasing availability of large hardware facilities in the private sector (GEE, AWS etc) which offer processing resources in the cloud that are superior in performance and availability to those in the public sector and it is likely this will continue into the next generation systems. Such processing power should be exploited wherever possible subject to terms and conditions/respect for Open Science etc. However, the full range of options should be available at any given time to ensure processing can be done using any machine cloud service (no software lock-in).	• Space Agencies and large funding organisations (EC) should provide access to data and computer resources in the cloud in an Open Science context to allow high resolution, multi-dataset analysis.
46	The RECCAP exercise involves significant effort in gathering together models, in situ, air and satellite observations to compile a large area assessment of the carbon cycle and by synthesis arrive at a global budget. A major strength is the compilation of assessment by experts in each region. However, this exercise takes significant time and is not considered practicable annually especially if 3 GHGs are planned (N_2O, CO_2, CH_4). Space agencies can improve the turnaround if they produce RECCAP-Ready Data for regions, with appropriate latency, which can supplement the assessment and be used to provide updates.	• Space Agencies should develop a Data-based characterisation of the carbon cycle for RECCAP regions in the form of RECCAP-Ready Data (RRD) to allow annual updates of RECCAP in parallel to the expert assessment.

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Annex I

Recommendations for Action from the 3rd Carbon from Space Meeting (Land)

1. Budgets – Regional

a. Improve partitioning between land and ocean at the regional scale
b. Reduce discrepancies between methods to estimate regional carbon sinks and uncertainties in models at the regional level.
c. mprove understanding of actual drivers of sinks at both global and regional levels;
d. Reduce uncertainty in emissions (both fossil and LUC) and generate annual estimates of LUC to account for important processes (e.g., ENSO-related variability);
e. Improve understanding and characterise the CO_2 versus the effect of climate (and land-use).
f. Explicitly include transport of carbon from land to the oceans
g. Address inconsistency within inversions for both natural CO_2 and CH_4 fluxes needs to be addressed
h. nvestigate regional differences between satellite and in-situ observation inversions for natural CO_2 fluxes.
i. Estimates of the global terrestrial carbon sink need to be explicitly derived rather than being based on the residual derived from the difference of the other components

For long-term (decadal) carbon balance, improve information on disturbance and regrowth, for an assessment of the site history:

j. Biomass and biomass change (e.g., from BIOMASS, GEDI lidar observations);
k. High resolution atmospheric CO_2 concentrations
l. Fluorescence (e.g., GOSAT, FLEX),
m. Soil moisture
n. Diurnal cycles;

2. Fluxes – Regional

a. There remains a lack of consensus between top-down and bottom up estimates for the regional distribution of fluxes despite the inclusion of satellite data to complement for the sparseness of the ground observations
b. There is a need to identify and quantify anthropogenic emissions consistently for policy-making and management, particularly given at least 70% of fossil-fuel CO_2 emissions are from urban areas.
c. There is an urgent need to develop advanced systems combining satellite and in-situ observations providing significantly more spatial information to resolve the sub-national and city scale

3. Fluxes - Land-atmosphere

a. There remains a lack of consensus between top-down and bottom up estimates for the regional distribution of fluxes despite the inclusion of satellite data to complement for the sparseness of the ground observations
b. There is a need to identify and quantify anthropogenic emissions consistently for policy-making and management, particularly given at least 70% of fossil-fuel CO_2 emissions are from urban areas.
c. There is an urgent need to develop advanced systems combining satellite and in-situ observations providing significantly more spatial information to resolve the sub-national and city scale

4. Attribution

a. Need to improve the spatial resolution in attribution of natural sinks of CO_2 from global/continental to regional or local level.
b. Understand the causes of observed increases in the amplitude of the northern hemisphere seasonal cycle in CO_2 and the role of terrestrial primary productivity.
c. Improve understanding of changes in the global growth rate of methane, the locations of (changes in) sources, and the causes of these changes.
d. Improve the spatial and temporal distribution of measurements for methane concentration and isotopes to understand and resolve the divergence between top-down and bottom-up estimates.

5. Extremes

a. Observational case studies show that the impacts of climate extremes can be identified via remote sensing. However, further studies are needed to understand spatial extent and duration of the impact on the carbon cycle.
b. The interconnected processes through which climate alters the carbon balance are poorly understood and it is important to assess both the impact of extremes on the carbon cycle but also to fully understand the different processes involved.

6. Tipping Point/Sensitive Regions

a. Need for long-term, high precision observations in the atmosphere and at the ocean and land surface both in situ and from space.
b. Extend >30-m spatial resolution record and increase frequency from bimonthly to weekly
c. Add regional samples of high (< 1 - 10m) spatial resolution imagery
d. Augment 2-D data with (sub-metre) vegetation vertical structure

e. Quantify photosynthetic rates and vegetation condition (global, sub-km)
f. Improved spatial and temporal coverage and resolution (< 250 m) of coastal margins to constrain carbon/nutrient export from land to ocean
g. Global measurements of CO_2 and CH_4 at 2-5 km2 resolution, weekly
h. Time resolved observations of CO_2 over the diurnal cycle
i. Other trace gas measurements for attribution (CO, NOx, DMS, H2S, OCS)
j. International cooperation incorporating both broad swath, high resolution low earth orbit missions that cover the entire globe and geostationary missions to capture the full diurnal cycle and rapidly varying feature

7. Fossil fuel CO_2

a. Increase in the density and spatial resolution of atmospheric CO_2 measurements from satellites, since fossil fuel emissions are concentrated over small areas.
b. Before 2025, a high-resolution global imaging carbon mission to provide the capacity of quantifying fossil CO_2 emissions (≈3 km in size, precision of ≈ 1 ppm and systematic errors < 0.5 ppm.
c. By 2030 a set of carbon missions for the frequent detection, quantification and monitoring of emissions including combined active and passive space-borne sensors and the close coordination internationally of space-based resources to provide continuity and resiliency to losses of data from individual satellites.
d. Close coordination of space-based measurements with each other and with the surface in-situ monitoring network will provide greatest benefit if measurements are calibrated against internationally recognized standards.
e. The development of a Fossil Fuel Data Assimilation System (FFDAS) combining: Emission inventory information, Column integrated satellite CO_2 measurements, combustion tracers related to fossil CO_2 emissions (e.g., CO) and in-situ atmospheric measurements of CO_2 and tracers (e.g., CO, 14C).

8. Address key areas

a. Wetland emissions
b. Carbon in the tropics
c. Carbon dynamics in the boreal permafrost region
d. Carbon exchange of semi-arid regions

9. To coordinate between existing structures e.g. NASA CMS, WMO IG3IS, and research efforts of GCP e.g. RECCAP, UCRM and infrastructural networks such as ICOS, NEON and TERN