1st ESA CARBON SCIENCE CLUSTER MEETING

TERRESTRIAL CARBON

23–24 JUNE 2021
REPORT

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Introduction

The carbon cycle is central to the Earth system, being inextricably coupled with climate, the water cycle, nutrient cycles and the production of biomass by photosynthesis on land and in the oceans. Understanding the patterns of exchanges of carbon between the atmosphere, ocean and land and the processes associated to them such as CO_2 fertilization, ocean acidification, changes in surface runoff of sediments, changes to wetlands and peatlands, warming of permafrost, and changes to natural disturbance regimes, are critical to improving knowledge of the carbon cycle, its direct and indirect impacts on society and identifying approaches to mitigate and adapt for its consequences.

In the last few years ESA has launched a critical mass of projects addressing different and complementary aspects of the Carbon cycle over land, ocean and atmosphere. Those projects, today more than 20 (see annex 2 for current list), represent the core of the ESA Carbon Science Cluster. The Cluster has been established with the belief that it would be extremely beneficial to establish a technical forum for all teams and ESA to present the work done, encourage exchange between these projects, discuss opportunities and define potential ways to strengthen the European carbon cycle research area, in close collaboration with the European Commission Directorate General for Research and Innovation and other European and international partners. The ESA Carbon Science Cluster will be supported by a number of research opportunities and networking actions. These are aimed at promoting collaborative research, and fostering international collaboration and bringing together different expertise, data and resources to ensure that the final result is bigger than the sum of the parts.

Workshop Objectives

The 1st ESA Carbon Science Cluster Coordination Meeting represents the initiation of the ESA Carbon Science Cluster and had the following key objectives to:

- present the status and results of ESA's science supported activities in Terrestrial Carbon Research, so that all teams are informed about plans and outcomes of the different projects.
- identify synergies and potential collaboration and cross-fertilization among the different teams.
- strengthen coordination and collaboration of different activities where needed.
- discuss and propose a way forward in terms of scientific gaps and requirements, science questions, and new ideas that may be used as guidelines for ESA to define a Carbon science plan for 2023-2025.
- Explore options to strengthen the community

The focus of this first meeting was to provide a panorama of all the different terrestrial carbon projects that are being run in ESA currently, initiating a discussion on what to do next, capitalising on the current assets and projects and identifying gaps and opportunities for cross-linkage, in particular in view of the satellite missions that will be in space in the next few years, developing the community and planning for the next round of funding. The objective is to be ambitious in developing a larger initiative on carbon to exploit the expanding numbers of satellite missions directly relevant to terrestrial carbon.

These initial discussions will be further expanded at the 4th Carbon from Space meeting in October 2022 jointly convened with EC RTD, NASA, Global Carbon Project and CEOS (**http://4thcarbonfromspace.esa.int**).

Context

DAY 1
SESSION 1

The opening session featured presentations on the landscape within and beyond ESA covering the three principal components ocean, atmosphere and land.

- The ESA Scientific Exploitation and the Carbon Science Cluster (Diego Fernandez)
- Carbon in the Atmosphere (Christian Retscher)
- Carbon in the Ocean (Marie-Helene Rio)
- Current Challenges in Terrestrial Carbon Science (Ana Bastos, Stephen Sitch)
- AFOLU – A CEOS Roadmap and Initiative (Frank Martin Seifert)
- Workshop objectives and logistics, (Stephen Plummer)

Terrestrial Carbon Projects:
Understanding Primary Production

DAY 1
SESSION 2

The characterisation of gross primary production (GPP) using modelling, data-driven approaches and the combination of satellite, aircraft and in situ observations still represents a challenge and different approaches exist each with their strengths.

- Land Surface Carbon Constellation - Lund University (Marko Scholze)
- Sentinels4Carbon - Noveltis SAS (Cedric Bacour)
- TerrA-P – VITO (Roel van Hoolst)
- Vad3emecum – MPI-BGC (Sophia Walther)
- Sentinel 5P Innovation SIF - Noveltis SAS (Luis Guanter)
- Photoproxy - Forschungszentrum Jülich (Uwe Rascher)
- Multi-Flex - University of Milano Bicocca (Marco Celesti)

The possibility to conduct some form of systematic intercomparison potentially at sites is a major area of interest. Key to this would be the selection of sites, the time period and standardisation of the procedure for assessment, not as a single time period but as part of an ongoing effort with multiple layers of detail. The overlap period of 2018-2019 was identified as it also corresponds to both a key extreme event in Europe (2018 drought) as well as a major effort on in situ data collection and standardisation at the ICOS flux tower infrastructure sites. Of particular interest were the most highly instrumented sites (e.g. Sodankyla, Majadas) as it is here that Eddy covariance, Vegetation Optical Depth (VOD) and Fluorescence observations are being routinely collected. However, some of the more experimental data (especially SIF) was collected at sites that are different to other projects there is therefore a need to consider the establishment of a more extensive network of sites where in situ observations for the interpretation of EO products are routinely made, a sort of 'gold' standard in terms of reference sites which would subsequently attract further research efforts, researchers and potentially airborne and satellite campaigns.

Linkage with activities on standardised validation e.g. CEOS Land Product Validation subgroup (LPV) or through the Copernicus Global Land Service was considered important as it not currently available for GPP.

RD1

Conduct systematic intercomparison of observations/products at both 'gold' standard most instrumented sites and a more extensive network of sites for defined time periods and following community protocols for assessment as part of an ongoing effort.

DAY 1
SESSION 2

In addition to the intercomparison need there was further observation on opportunities and challenges presented by new observations, in particular Solar Induced Fluorescence (SIF) and VOD. These could provide a lot of complementarity but at the same time introduce redundancy and it was suggested that there is a need to establish an 'ideal' set of complementary products for the carbon cycle that allows progress to be made in a structured manner. However, there needs to be caution in this approach as different aspects of the carbon budget require different resolutions and hence products. For example, for global carbon budget studies it may be sufficient to have a combination of flux observations and biomass increment measurements while for understanding photosynthesis (and hence SIF) there is a need for greater detail in both spatial and temporal terms as well as in the product set required. It is important to consider spatial and temporal scales in tandem and the question being targeted in order to assess the data sets needed, what each brings to the quantification of carbon sinks and how complementary and/or redundant they actually are.

RD2

Conduct work to establish an 'ideal' set of complementary satellite products for specific purposes/challenges in carbon cycle research e.g. global carbon budget or for understanding photosynthetic processes.

It is clear that different levels of detail in the measurements are still valuable even when we the objective is to have a global product that might not need the resolution of the original values because there are processes that happen at fine scale which control larger scale impacts e.g. water stress or disturbance. While we may think we have a reasonable understanding of fire, the same cannot be said of pathogens, insects or windthrow events which are all important in terms of the carbon stored in ecosystems. This means there is an opportunity to to see how the scales fit together and what measurements are needed at different scales whilst retaining information about the processes.

RD3

Examine the impacts of scale of observations in relation to the scales of carbon processes to assess how processes operating at fine scale impact global scale carbon pools and fluxes

There are many issues associated with the consistency of satellite products, not just differences between estimates of the same variable but also across different variables even when they may have the same root (the original satellite radiances, brightness temperatures or backscatter). There is, therefore, a strong scientific argument that these original observations (the actual satellite 'Level 1' data given that vegetation variable estimates (Level 2) are all derived) should be used together with models rather than going through the full set of processing steps (Level 2, Level 3, Level 4 etc) to generate products that are comparable/consistent with the model outputs to then assess the information content of each product.

Terrestrial Carbon Projects:
Understanding Primary Production

DAY 1
SESSION 2

Such an approach intrinsically is sensible as it removes the assumptions and model dependencies that are innate in the generation of any given product and that may lead to physical inconsistency between individual products (even those based on the same original observations (Level 1) as well as structural inconsistency with land surface models that use them for benchmarking. This can partially be accommodated by developing appropriate characterisation of uncertainties and ensuring traceability in the processing chains. However, there is a need to reassess approaches on both sides.

On the product side this means efforts to ensure that products generated from Level 1 observations are consistent for a given variable and more importantly between variables e.g. VOD, LAI, biomass, LST, soil moisture etc. Consideration of multiple observations from different parts of the EM spectrum (microwave, optical, thermal etc) in a synergistic manner is also a valuable way of improving the product consistency, in particular given that the actual observations (radiances, brightness temperature, backscatter) are at best indirectly related to carbon.

RD4

Conduct work on the consistency of observations/products from Level 1 upwards to ensure variability at product level (Level 2 and beyond) is not introduced during single sensor processing. This should be undertaken on products representing the same variable as well as between different variables and should include traceability and quantitative characterisation of uncertainties.

RD5

Conduct work on synergistic use of observations from different parts of the EM spectrum as a way of improving product consistency.

On the model side there is a need for improvement such that models are more capable of representing the interaction processes with electromagnetic radiation that the satellite observations measure. This would allow progress towards use of level 1 observations in models including assimilation but also in understanding how well models represent processes at multiple spatial and temporal scales (level 2).

Terrestrial Carbon Projects

DAY 1
SESSION 3

As well as EO sensors commonly associated to carbon research a number of other sensors not traditionally considered to provide information on terrestrial carbon also offer value potentially. In addition, satellite sensors are becoming of increased interest for understanding the dynamics of the terrestrial carbon cycle and how that is impacted by anthropogenic activities.

3.1 New observations for terrestrial carbon

- SMOS+ Vegetation – Univ Toulouse 3 (Nemesio Rodrigues-Fernandez)
- Albiom - Deimos Space UK Ltd (Maria-Paola Clarizia)
- Biomascat - Gamma Remote Sensing AG (Maurizio Santoro)

3.2 Dynamics, disturbance, carbon management

- Sentinel4Carbon - TUD (Theme 2) (Matthias Forkel)
- S14Science Amazonas – GISAT, Agresta, NMBU, NLS (Neha Joshi)
- SHRED – TU Vienna (Mariette Vreugdenhil)
- F-DTE, Assesscarbon, Forest Carbon Monitoring (Matti Mottus)

3.3 Discussion on new observations and dynamics

While there are satellite missions where there is an obvious, albeit, indirect association to observation of the carbon cycle there are others which were not considered in their mission objectives to be of clear value for terrestrial carbon cycle understanding but which subsequently have been found to be of potential value. The classic case in remote sensing is AVHRR which was initially designed for meteorology and climate use (clouds and thermal emission) but has become a major instrument in vegetation dynamics. There are many examples of such instruments e.g. GOME and Sentinel 5P for Solar Induced Fluorescence, SMOS for Vegetation Optical Depth, scatterometry for biomass and altimetry for biomass.

RD6

Encourage exploratory work on the contribution of satellite data not originally conceived for carbon cycle research.

Of particular recent interest is L-band passive microwave Vegetation Optical Depth, a by-product of the soil moisture processor, which has been seen to provide value in aspects of carbon cycle modelling particularly for tracking changes in vegetation over time. It therefore becomes important to understand exactly what the product represents (vegetation optical depth is a function of water content and biomass), what the dependencies are and thus be aware of what the strengths and weaknesses of product are and how they are best used and at what spatial and temporal scales. L-VOD for example equates more to biomass at annual and longer scales while at seasonal scales the response is more to variability in vegetation water content. Furthermore, there may be regional differences and variation in response to temperature that are not due to VWC or biomass.

RD7

Encourage further work on understanding what L-band VOD corresponds to in space and time and on how to separate out variability due to water content from that due to biomass.

In addition, future study is needed on understanding of VOD not just from L-band but also other wavelengths (X-, C-, etc) whilst also considering the complementarity of these products with other vegetation products derived from satellite observations (LAI, biomass, vegetation structure, phenology etc). This latter therefore represents an area where interaction between individual projects and more generally the cluster becomes of interest. The cluster has as part of its objectives to support and facilitate community interaction.

RD8

Encourage activities on understanding of existing VOD products and multiple wavelength retrievals of VOD and their complementarity with vegetation products derived from other satellite observation domains (optical, thermal etc).

In addition to VOD, understanding of signal returns and the development of products which may be related to biomass is important in the context of new missions e.g. BIOMASS, NISAR, ROSE-L but also in terms of extending observation records back in time using instruments that were not designed with biomass in mind. There is therefore a need to prepare for the advent of the ‘biomass’ missions (BIOMASS, NISAR, ROSE-L), understanding what the different observation types provide in terms of characterising the vertical structure of forest and what the best combination of these observations might be in tandem with existing and 'older' L- and C-band systems (e.g. Sentinel-1, SAOCOM, ALOS) and sensors that vary with biomass (altimetry, passive microwave, GNSS reflectometry) or vegetation structure such as lidar (GEDI etc).

RD9

Encourage activities focussed on understanding what different multi-frequency missions offer for biomass estimation in preparation for and, as an addition to work dedicated to, the BIOMASS mission. This in particular should look at active and passive microwave missions, existing data sources to characterise biomass in the temporal record before BIOMASS/NISAR etc, regions that will not be covered by BIOMASS and vegetation types for which P-band is less appropriate but which are important for the carbon cycle.

While mission studies will look at the individual systems there is a need and an opportunity to look across missions and observation domains, supported by dedicated aircraft and ground campaigns, to help understand what the contribution of each measurement is to the characterisation of e.g. vegetation structure and the appropriate use of different data streams in a synergistic manner. Further, it is important to look across missions to overcome limitations in both temporal and spatial domains, e.g. BIOMASS will not be able to provide global observations while a focus on the next new mission does not provide the temporal context needed for carbon cycle studies. Before a mission is launched one role for the cluster is in the area of preparatory activities on potential synergistic use and the combination/extension back in time to provide a longer temporal sample with larger uncertainty (assuming this will be fully characterised).

RD10

Take advantage of synergies between missions to characterise vegetation with support from and coordination with aircraft and ground campaigns

RD11

Conduct preparatory activities on combinations of satellites to generate longer temporal samples including characterisation of the uncertainties in doing so.

These activities should also look to datasets and missions beyond ESA, for example NISAR, GEDI and take advantage of ongoing data collections e.g. lidar data collection in the Amazon that is planned to be released soon (see talk by N. Joshi) or ongoing infrastructure systems – NEON, iLTER, TERN, ICOS, FOS, ISMN etc. for the purposes of understanding our datasets. The cluster should also act as a forum to encourage work across traditional spectrum domains (optical, thermal, microwave) and modes (passive,

active). This can be achieved by bringing different expertise within the community/cluster together to investigate how the observations in different domains (and for different products) complement each other in the context of terrestrial carbon cycle quantification. While each domain can and traditionally does work independently it is important to be aware of progress and direction in other domains in particular to better understand the errors and uncertainties in time and space.

RD12

Take advantage of contacts in the Cluster to make in situ/aircraft data collections visible and accessible in coordination especially with infrastructure efforts

RD13

Encourage cross-spectral domain exchange (at product level or focussed on a carbon issue) to benefit from advances made in any one domain as well as introducing common approaches in terms of assumptions/ ancillary data dependences, and specification of uncertainty.

Whilst the objectives of much of the work may be on understanding the data products it is also important to be aware of additional needs that such products could help address. For example, structural information from radar and lidar could help parameterise canopy roughness at multiple scales – this considers the change for climate models in moving from forest to agriculture to pasture in biophysical terms and what impact that has as multiple spatial scales, in particular in terms of forest degradation and fragmentation. This also includes clumping at the landscape level for forest ecosystems because this controls also the amount of light that reaches the ground. Many land surface models are starting to consider gaps in canopies and/or model gaps. The derivation of some form of index of how the vegetation is distributed (clumping) from high resolution products would be very useful for land surface modelling - are the trees very clumped or with a lot of holes between or gaps. Such products would also be very valuable for the biodiversity modelling community for habitat structure and ecosystem fragmentation.

RD14

Revisit existing or planned vegetation structure products to derive appropriately scaled products for canopy roughness, fragmentation and/or, for forest, clumping (and its dynamics linked to degradation).

RD15

Coordinate with ongoing activities on biodiversity to establish differences in need between biodiversity definitions for fragmentation/ structure and those needed for land surface and/or climate models.

In addition to activities on developing consistent and complementary products, there is a need to ensure, especially for data assimilation purposes, that there is a clear quantification of uncertainty around such products with a priority on understanding bias and its scale dependence. While some components of errors are uncorrelated and cancel with scaling, this cannot be assumed. Bias in particular is not lost. There is still a lot of work to be done to have really robust 'uncertainty' estimates including their variation in space and time. This includes the terminology used, the way we communicate 'uncertainty' and share information and the aggregation of such 'uncertainty'. The connection to ground data forms part of this process as it helps to understand which products to trust in any particular location, where and when.

RD16

Conduct work to improve the specification of 'uncertainty' including their variation in space and time to improve the trust in products in any particular location at any specified time.

In addition, further work is needed on the most appropriate methods for the assimilation given that each data stream increases the complexity of the assimilation including when uncertainty/bias is added. This complexity incorporates the need to ensure that any new data stream is consistent with the other ones that are assimilated but also with the model, the representation of process understanding in the model and the model trajectory. Coherence between data streams becomes more important as more products become available e.g. biomass products, VOD, SIF, phenology, land cover etc. These products have to be coherent both in time and space but ideally also in the retrieval schemes used to obtain them from Level 1 data. The objective is to obtain, from the retrieval, a consistent set of geophysical parameters across the spectrum, from optical extending also to microwaves, rather than one parameter at one wavelength. Some attempts have been made e.g. MULTIPLY but it is a challenge and one approach may not work for all data streams and/or all scientific challenges e.g. requirements/approaches for agriculture may be different to those for an LSM. In addition, the observation operators used must incorporate radiative transfer formulations and accept that there are likely to be correlated uncertainties that need to be accounted for.

RD17

Improve the capability of assimilation schemes to deal with multiple data streams whilst incorporating uncertainty ensuring consistency between data streams and process understanding and trajectory of the model used.

RD18

Improve the specification of observation operators, incorporating radiative transfer ideally with applicability across the spectrum from optical to microwave.

While there is a need to think across the spectral domain it is also important to work across missions and sensors as traditionally the tendency is to be mission/sensor focussed. Multi-mission/sensor approaches are more complex the data is recorded at different times, at different spatial resolutions and is often not available at the times (temporal extent) or in the same places desired. Encouraging communal efforts to identify the closest observations for a particular point (or series of points) in time and space that are appropriate to estimate the parameters needed for a particular carbon challenge is one aspect that has been mentioned previously, along with approaches such as data assimilation of joint retrieval schemes discussed above. These approaches should also be developed in tandem with approaches based on machine learning such as FluxCom.

RD19

Continue and extend activities based on machine learning, in particular hybrid methods that incorporate process understanding, in tandem with more traditional data assimilation, process understanding/model-based schemes.

Open discussion on project status, cluster, new mechanisms for working, new call for cluster

The sessions and discussions above highlighted the potential value of the cluster concept as a mechanism for engaging the community but also communicating about all the activities that are being undertaken by ESA and beyond. This applies both within the community of cluster members but equally within ESA as well. It is clear from the participation that the wide range of projects funded by ESA that are relevant to the terrestrial carbon cycle was not well known and as a consequence there is also a need to digest that information and then develop ideas of collaboration. The current list of project is available at: https://eo4society.esa.int/communities/scientists/esa-carbon-science-cluster

The key to a successful cluster will be the active engagement of the community (including ESA participants). This also means that the cluster needs to be managed in a way that is not onerous on the community or the organisers. The intention here is to be very light in terms of information provision and requests for input. It is intended from ESA to use this mechanism to provide/request the information on:

- the way we work
- what we offer or what we look to make a call for in the cluster ITT
- the opportunities that ESA believes the cluster might be interested in
- how best can we join existing projects together
- gaps between projects/overlaps between projects that we can exploit.

Terrestrial Carbon Projects

DAY 1
SESSION 3

RD20

Circulate meeting report and list of current projects, in particular, key contacts, description, publications to all participants.

RD21

Make all talks at this meeting accessible on website, subject to agreement with presenters.

It is the intention to have a cluster meeting regularly, taking account of opportunities also at planned conferences, open to all projects to discuss and potentially define what the next opportunities are, identify recommendations to shape the work in a more structured manner. It is hoped that this will stimulate/identify synergies between teams to make proposals for joint additional work packages following the model of the Polar Cluster. This is also extended to projects that are not ESA [funded] e.g. those by EC. The mechanisms to support will come via both targeted and open research calls dedicated to the cluster (traditional ITT) but the cluster should also think about other opportunities as teams both from ESA but also wider. Examples from within ESA include the Open Call system and the Living Planet Fellowship Scheme.

RD22

Develop a dedicated call for research for the Carbon Science Cluster and encourage teams to look for other opportunities both within ESA e.g. open call, LP Fellowship call and wider.

Future Missions, Campaigns, Tools and other ESA activities in support of Carbon science

DAY 2
SESSION 4

As well as the specific scientific activities grouped around the Carbon Science Cluster, ESA is developing missions, tools, conducting campaigns and other projects from different programmes that are all relevant to the Cluster. The missions FLEX and BIOMASS fall under the Earth Explorer programme, while the planning for the expansion of the Sentinel series is also highly relevant to carbon (CHIME, CIMR, ROSE-L, LSTM, Cristal, CO2M). Dedicated planning for campaigns in preparation for such missions as well as tools such as ESDL and other programmes such as CCI and Applications, also provide additional value to the Cluster.

- Biomass, FLEX, status and plans (Klaus Scipal, Matthias Drusch)
- Sentinel Expansion Missions (Malcolm Davidson)
- Land Surface data campaigns – what is there, where, what is planned (Dirk Schuettemeyer)
- Earth System Data Laboratory (Anca Anghelea)
- CCI and carbon activities (Clement Albergel)
- Applications – The 'World' projects (Frank Martin Seifert)

RD23

Engage with other activities, sites and programmes across ESA as part of the Carbon Science Cluster to ensure individual activities at different ESA sites and across programmes/projects are coordinated to maximise return for the terrestrial carbon community.

DAY 2
SESSION 5

5.1 Towards a European Terrestrial Carbon Constellation project

Background

In the coming few years Europe will rely on one of the most comprehensive and sophisticated space-based observation infrastructure in the world, through the suite of sensors on board of the Copernicus Sentinels series (including S1, 2, 3 and S5P), the ESA's Earth Explorers (including new missions such as BIOMASS and FLEX), the upcoming meteorological missions and different EO observation satellites planned to be launched by national space agencies and private operators in Europe. This will be complemented by novel observations provided by partner space agencies around the world (SAOCOM, NISAR, GEDI…), together with in-situ observations, enhanced models and emerging technologies to offer unprecedented opportunities to advance the way we observe and assess the terrestrial carbon balance from space.

This discussion session aimed at advancing in the definition of the opportunities in front of us and at drafting collectively the main potential goals and scientific elements of an ambitious scientific endeavour to be promoted by ESA in collaboration with other partners (e.g., EC DG-RTD) starting in 2023. This initiative will be also discussed with EC (DG-RTD) as one of the potential joint Flagship actions to be implemented together as part of the EC-ESA Earth System Science Initiative. This initiative, launched in 2020, aims at joining forces to face major scientific challenges with a societal impact through the alignment and coordination of scientific actions funded under Horizon Europe and ESA's FutureEO programme.

Outcomes

Coordination and engagement
As indicated elsewhere, the lack of integrated awareness of all ESA activities in the meeting and in the discussion, there is a need to organise and communicate what ESA does in terrestrial carbon prior initiating thinking about a wider European activity. The carbon cluster is an important step in this direction in particular in the context of the generic information explosion from EO satellites. A key problem is that the community is not prepared for amount data that will be coming at them and it needs to think strategically about how to exploit them best.

[RD24]

Develop a strategic vision for Carbon Science Cluster to ensure the carbon science community is prepared better and informed better about what ESA activities are, what funding opportunities are and how projects can interact within and beyond ESA

DAY 2
SESSION 5

One key area for activity, in particular in relation to the data flow, concerns the provision of training especially for early career scientists/researchers both in understanding of models and in situ data but also satellite data and the last of these is where ESA can play an active role. At the moment there is no coherent connected training available on these three aspects and ESA should consider aligning specific masters courses, tailoring summer schools or providing training events. ESA has had these in the past and continues to provide training through specific summer schools, MOOCs etc but these may need to be reactivated or tailored more to the terrestrial carbon community.

RD25

Review existing and past ESA training events, summer schools, MOOCs and linkage with universities generically to examine how to tailor them more effectively towards the terrestrial carbon community.

In addition to early stage researchers it was also recognised that there training for modelling groups at a higher research level to understand satellite data better. A specific exercise with the model community should be considered.

RD26

Examine scope for developing an EO-model interface course targeted at land surface modellers developing models for the terrestrial carbon community.

It is important to bring the in-situ experts, the modelling experts and the remote sensing community together regularly to discuss differences and break down some of the conceptual/transparent barriers that exist between them. The intention of the Carbon form Space series is precisely this and the next meeting is in October 25-28th 2022.

RD27

Continue the Carbon from Space series of meetings to bring the model, in situ and satellite communities together in the context of terrestrial (and wider) carbon understanding.

The novelty of and opportunities represented by the Earth System Data Laboratory were considered valuable but currently limited in terms of data provision. Further effort would be useful on developing the structure, the data provision and its promotion specifically to the carbon community in Europe and more widely. Engagement with this community would be welcome to put together a list of priority datasets that could be included. The new ESA project, Deep ESDL, will have a mechanism for users to request specific datasets to be added but of course these datasets need to go through a curation process and so for this it would be good to have a priority list. A good start may be all the data that were used in the recent RECCAP-2 Initiative project, split off into the RECCAP regions

DAY 2
SESSION 5

RD28

Develop the Earth System Data Laboratory concept to make it more attractive to the terrestrial carbon community by involving them in its development.

for example to allow investigations on specific regions and it is easily done in the ESDL. Beyond ESDL the establishment of improved provision of datasets from different sensors perhaps through a single point of access is something that ESA needs to reflect on. This is useful for exploring what the data actually means and its complementarity but also for the non-EO terrestrial carbon community provision of more easily digestible data volumes to exploit.

In doing so it was reiterated that satellite datasets do not actually measure a specific product for carbon, rather they make measurements which are associated to land surface processes, which in turn are associated to the carbon cycle. The EO data are in some respects complementary to each other but also overlap in terms of information content and hence consistency in the processing from raw data (Level 1) to generate different products is fundamental to avoid that the end product is not determined by the assumptions that were made in the processing and they are consistent with another product developed similarly.

With respect to subsequent assimilation of multiple datasets there is a need to think in terms of using datasets at a lower level of processing but to do so the difficulty becomes then in the construction of the observation operators, given they need to include radiative transfer code, and ensure that the uncertainty in the products is characterised

RD29

Target generation of data products at Level 1 and Level 2 across the different frequency domains coordinated with existing infrastructure and or targeting specific processing and signal understanding.

RD30

For data assimilation development of improved observation operators that are consistent across different Level 1 products is needed.

RD31

Also, for data assimilation, improved specification of uncertainty is needed, both in terms of its specification and separation into components AND provision of products with an associated error covariance matrix that is consistent and traceable.

appropriately especially the bias.

Benchmarking in general for existing models has seen a slowly increasing use of satellite products (Level 2 and above). Various tools/approaches were mentioned including iLAMB, ESMVal and planned ECMWF-CoCo2 activity for land models. These activities need coordinating to ensure benchmarking is done effectively and consistently rather than having three different systems in use, all valid, but all doing different things with different data and different model variants.

RD32

Encourage development of communication between benchmarking approaches for land models and in particular the provision of data products for use in them. This should emphasise consistency between data products and appropriate aggregation of products to model resolutions for benchmarking processes.

Research directions

As well as consideration of how to make data and models talk more effectively together, a number priority areas where process understanding could be augmented using satellite data were identified. Four areas were briefly considered:

Efficacy of carbon impacts of land-based mitigation

This relates to the potential for satellite data to be used to assess the impacts of positive anthropogenic mitigation activities which act at small scale but potentially have an impact at larger scales. In particular, forest management, regrowth, re-wetting of peatlands could be targeted.

Vegetation dynamics and extremes

Vegetation dynamics in general and specifically to understand how EO can actually observe disturbance, especially beyond fire, is a key area which will probably require using all the high-resolution missions. From a process perspective the triggers for disturbance remain not well understood and as a consequence also their impact on carbon and vegetation dynamics as well as the interaction in time and space between different forms of disturbance. This implies the need to monitor disturbance cycles and mortality in relation to the interaction between the carbon and water cycle. A better understanding of the dynamics of disturbance over longer time scales is also needed to separate trends that are climate induced from natural cycles and/or anthropogenic perturbation.

This should also be considered in tandem with the efficacy of the land-based mitigation because if for example tropical forest which is expected to provide a long-term sink could be compromised if there is a higher frequency of droughts and extremes. This potentially offers an opportunity to examine if present-day remote sensing data can provide information on the sensitivity of ecosystems to extremes, to monitor what is the response of the vegetation and then inform the longer-term efficacy side. Generation of dynamic functions from satellite data which can be used in DGVMs and ESMs would be very helpful.

DAY 2
SESSION 5

Land Use and Land Cover

Improved knowledge of land use as distinct from land cover, namely management practices and type of crop in agriculture, forestry management and tree type. Whilst land use is the primary target, it should be noted that land cover remains extremely important and consistency between approaches in land cover and land use needs to be ensured. The focus on land use is a consequence of the greater availability of high-resolution data (Sentinel-1 and -2, Landast-8) which opens up new opportunities to see processes/practices that we were difficult to look at before and, as a consequence, providing improvement in how models resolve them.

Carbon, Nitrogen and Water Cycle Interactions

As indicated above for disturbance is important to think about not just about the carbon cycle but also to consider that the carbon cycle is implicitly linked with and interacts with other cycles, specifically water and nutrients. This then extends and links back to the disturbance issue above to examine the impacts on the carbon cycle of climatic extremes e.g. droughts. A focus on extremes could be driven from both a rapid assessment from society/government for quick assessment in relation to carbon as well as serving identification of anomalous events in long-term observations because that is what the models need.

Scale Consistency

Sentinel datasets/products come at different resolutions and at slightly different times of day which represent both a challenge to use them appropriately but also an opportunity to investigate impacts of scale both in space and time for models and for data with an objective to ensuring consistency. One of the aspects the Sentinel4carbon (http://sense4fire.eu and http://sen4gpp.noveltis.fr) was to look at this issue of the consistency with data as you move up different resolutions for the cases of fire and GPP but more widely it is important to think about how those different resolutions are appropriate for the models that we use the data in and we need to make sure that they talk to one another effectively. This in turn relates to the issue of complementarity of the data.

Campaigns, coordination and access

Throughout the meeting it is clear there exists a rich variety of campaign data and in situ data and making it more accessible and coordinated would be valuable. The implementation of a structure linked to 'super' sites has been discussed but other directions exist, in particular, because at least in ESA Campaigns (in situ, airborne, satellite) are decided in terms of a given mission. Therefore, it does not necessarily mean that the super sites would be completely appropriate for campaign activities. However, making campaign activities/preparation more visible to the carbon community could bring mutual benefit.

RD33

Pursue development of a strategic approach to assessment of terrestrial carbon processes, taking advantage of the increasing data provision at multiple scales, coupled to existing research infrastructure and taking advantage of campaign opportunities in a coordinated manner which also takes into account improved model-data interfaces and work on consistency of data products.

5.2 Science needs in preparation for Copernicus Sentinel Expansion Missions

Background

In approx. 5 years from now, ESA and the EC plan to start launching the Copernicus Sentinel Expansion missions and Sentinels NG series. These new sets of missions together with Earth Explorer and Meteorological missions will open a completely new panorama in the way to observe and monitor our planet.

Several activities are planned already to support the scientific preparation for each of the different missions. However, we do not have today a dedicated plan to prepare for the synergistic opportunities that those missions will offer in terms of new science and novel applications or to fully explore their potential beyond primary products and mission goals. To ensure the scientific community takes full advantage of this unique opportunity will require dedicated scientific efforts. In particular, for the carbon cycle there are a large number of relevant satellite missions that will be launched, including the Copernicus Sentinel Expansion Missions (CO2M, CHIME, CIMR, ROSE-L and LSTM).

However, while all the missions have a science plan and some missions are looking at synergistic aspects with other missions there is no current preparatory plan for science that goes beyond what the specific mission plans are preparing. This is not covered by the Copernicus funding and a preparatory programme to prepare for new applications, products and services has been advocated by the European Association for Remote Sensing Companies (EARSC) to be ready when all those missions with all that increasing huge capability will be available. A programme to have dedicated funding to address this issue is therefore being prepared by ESA at the next Ministerial but clearly must include the scientific community in its development.

This discussion aimed at addressing the needs for specific preparatory scientific activities to support the community to prepare for such a novel and unprecedented capacity and to ensure a fast and more effective preparation for them.

Outcomes

General thoughts

- *Basic research*

  Better understanding on where is the signal is coming from and what are we actually measuring in the different domains. This point applies for active and passive microwave but is also valid for the optical including thermal domains.

- *Multiple sensitivity that needs to be exploited at mission scale*

  Signal observed at the satellite is a function of multiple variables (e.g., vegetation / soil moisture / surface temperature for SMOS). Having a real approach on how to how to deal with that is crucial

- *For each parameter there are already existing products*

Some of them need additional development efforts to capture especially dynamics (e.g. no support yet for surface water extent and limited support for 'all weather' LST)

- *Multi-mission approach is required already in the mission design phase*

  Consideration of multi-mission approaches would be beneficial for mission design phase and for Sentinel Expansion should start soon. For work on synergy part of the design should be on ensuring compatibility of observations across missions, for example, common grids.

- *Consistency between missions needs to be established*

  We need an approach that systematically takes care of all the processing including ancillary data for every single but also multi-missions. This should be traceable and available as a guideline. should be handled systematically along guidelines.

- *Common framework for forward modelling for both active and passive microwave missions and optical-thermal missions.*

- *Constellation should really improve spatial and temporal resolutio*n

Data-model interfaces

The issue of whether it is preferable to concentrate on the interface with models at level 1 (satellite observation) or Level 2 (derived product) is an ongoing discussion and both directions are likely to be fruitful. A common framework for both synergistic level 1 and level 2 products would be desired perhaps in terms of the data cubes or consistent gridded datasets. However, such a common grid may need to vary for different types of users.

The current Earth System Data Cube logic is designed with climate scientists and modellers in mind but could be extended to bring data together in a form that it is easily useable for many. This, in particular, requires a focus on data at finer [spatial] resolution and more and upstream products, such as reflectance, backscatter, temperatures, than currently. Such an expansion would be useful to facilitate synergy and compatibility between the different sources of data, specifically data of the Expansion missions.

The development of a consistent interface between Level 1 and/or Level 2 products and Earth System Model requires:

- uncertainties to be specified at pixel level for the different types of modellers.
- a science effort to develop more complex observation operators potentially including multi-frequency radiative transfer modelling for Level 1.
- a major effort to develop consistency for Level 2 complete with traceability in the processing and inclusion of error propagation.

Campaigns

RD34

Develop improved specification and quantification of uncertainty, complete with traceability, for different types of modellers.

DAY 2
SESSION 5

RD35

Encourage development of more complex observation operators potentially including RT models to assimilate Level 1 data

RD36

Improve consistency between Level 2 products in particular across EM domains.

Experiments are needed in order to prepare for future missions. These experiments or campaigns should be advertised more widely before the actual experiment and ESA should make efforts to also solicit contributions from science community. While not the direct focus for a campaign, establishing an interface to the science communities in a synergistic way would be potentially beneficial to ensure:

- the science community is on site and really measuring the right things in the field to really enlarge the scope of the experiment.
- provide training and engagement for early career researchers not necessarily linked to EO
- improved connection between the in-situ measurement (flux, ecosystem) community, and those people interested in parameterising radiative transfer models.

For the purposes of Cal/Val and signal understanding there is a need to generate 'Golden standard validation sites' that have an extended and consistent set of instruments. Examples already are Sodankyla and Majadas but others may exist. The objective would be to have well-equipped sites with an almost complete set of measurements for the upcoming missions. Here, the focus should be on coordination with sites where instrumentation already exists e.g. ICOS, NEON, TERN, FoS, iLTER and to make sure that for the datasets we generate at least there are cut-outs available whenever we pass over. These can be at Level 1, Level 2 or somewhere in between [so-called analysis ready data], where all the corrections have been done, so that people can pick them up and actually use them for that given site.
In addition to these 'golden' sites, sites of opportunity from a scientific viewpoint would

RD37

Coordinate campaigns activities with in situ research infrastructure.

also be desirable and could lead to innovative products that the community could really benefit from. This may require the development of sites dedicated to particular types of applications, putting together in situ data, dedicated campaigns associated to a synergistic experiment, commercial satellite products for simulation of future satellites that are appropriate to that application e.g. agriculture/land use, terrestrial carbon dynamics, disturbance, the land-ocean interface, specific issues for process understanding etc. Such sites could be new but could also be developed in a manner linked to and including research infrastructure. The objective would be to build those sites open to the scientific community with datasets that simulate the wealth of data that we will have and try to promote somehow collaborative research across those sites.

Satellite combinations in time and space

RD38

Include the terrestrial carbon community where possible in the identification of sites for dedicated campaigns.

Overpass time matters a lot in retrievals for carbon cycle processes and has to be carefully analysed in the context of the temporal characteristics of missions. Daily global datasets will be possible in the near future given all sensors that should available in a number of years. For example, for LST the combination of LSTM and Sentinel-3 will allow a better characterisation of the diurnal cycle if we combine different sensors. Similarly, synergy there for microwave and optical sensors, should also be considered.

The combination of SAR missions or radar missions, unlike optical/thermal, should not have a too large time delay to really exploit these kind of data. For example, for Sentinel-1 and ROSE-L the information content might be really limited if it is more than 3 days apart, to an extent that it is not possible to be used synergistically so there is a need activity in methods for combining systems is therefore needed.

In addition, rather than focussing on high-level separate products there might be some intermediate level for instance with missions that have already several frequencies and several capacities. There should be an emphasis on evaluating, within a mission, all the frequencies to derive several products that are compatible instead of adding separate chains to produce each product e.g. SMOS VOD and SM. This is naturally extendable to e,g the combination of passive and active microwave with similar spatial resolution e.g. ASCAT and passive microwave. The emphasis here would be on a framework which is consistent at Level 1 to produce, for instance, vegetation properties rather than focussing on data assimilation complex observation operators required for e.g. ECMWF models.

Commercial missions

RD39

Encourage investigations across EM domains in the generation of products.

DAY 2
SESSION 5

Commercial missions were also thought to offer high value for the spatial resolution and ESA could potentially facilitate the access. This might be through the third-party mission programme with the objective to give access to scientifically useful commercial data. Doing this is not just an issue of data buy but also to recognise that the carbon community may not need access to the full product but maybe to parts of it.

While commercial data have an obvious value spatially, they could also be used for gap-filling of time series. However, to do so, a common standard of calibration from these commercial missions should be developed because the quality of these sensors is unknown and hence it is very tough to develop use them in a consistent way.

In parallel with coordination on sites and campaigns the extension of one-off activities for commercial data currently done by ESA, should be considered. Such data would be very useful scientifically even in a degraded form (not the original resolution).

RD40 *Investigate the potential for acquisition of data from commercial missions (VHR) in support of research at research infrastructure and other sites of opportunity.*

RD41 *Investigate provision of degraded versions of commercial data at such sites that are free-to-use for research purposes.*

RD42 *Develop a common approach to calibration for commercial missions to permit use in combination with Agency data.*

Scale Consistency

Models do not represent reality very well since that they cannot capture the fine scale variability that can be seen in satellite data but likewise, in the observation process and subsequent processing to level 1 and beyond a lot of fine scale structure that is important for biosphere functioning is aggregated at e.g. 300m. For satellite data it is very important to understand that aggregation cannot be simple averaging because the connection between the observation, say, radiances, and the level 2 product is non-linear and similarly moving to a gridded level 3 is similarly non-linear (brightness temperature to VOD to biomass as an example). The only upscaling that is done properly is at the instrument level using the point spread function or the antenna gain function. This means the concepts of common grids, common resolutions and analysis ready data need to be treated with caution.

Similarly, it is fundamental to understand that the output of the inversion of a radiative transfer code at 300m will not be the same as the average of the same processor at 20m and similarly nor will a fluorescence retrieval at 300m (with Flex) averaged to 5km (S5P) be the same as the retrieval at 5km.

The process of incorporating or assimilating products should really be done at the footprint level (Level 1 or Level 2) using the models then to do any subsequent integration or aggregation e.g. the approach in the Land Carbon Constellation. While this does not solve the scaling problem it at least accounts for it with a common framework. While this works for the detail of a site conceptually there is still a need to bring useable information to a scale more amenable to models. This may require re-engineering of models to make them more compatible with the observation scale as well development of observation operators incorporating radiative transfer and is a long-term objective.

A 'happy intermediate level' is therefore likely needed to allow progress, aiming to keep the integrity of the raw observations while ensuring any grid product is accompanied by the appropriate uncertainty that reflects the unknowns passing from the point spread function to the gridding etc. Such an approach should be traceable back to the original scales of observation. In addition, the approach taken should be not just product dependent but also considered to be process dependent. Sampling at multi-scale is needed to understand to what extent the variability at fine scale translates to the process at larger scales and hence whether transfer functions can be created for this, spatially, spectrally and temporally.

Fundamental to this is that these 'analysis ready products' should not be rolled out as a form of service, rather they are developed jointly by the technical experts on the data side and those on the ground with expertise in process understanding on the ground (vegetation growth, form, dynamics). The whole concept of ARD depends on what is needed by the 'user' of the products, with one product not necessarily being suitable for all applications.

RD43

Conduct multi-scale experiments to understand how processes scale in space and whether transfer functions can be developed for aggregation of processes rather than products.

General Discussion

DAY 2
SESSION 6

Campaigns and Gold standard sites

Coordination between campaigns and the existing research infrastructure at regional and national scales would provide mutual benefit when this is practical and achievable. Existing research infrastructure exists e.g. ICOS and initiatives are under way to develop validation networks for satellite observations e.g. GBOV. This is not limited to flying instruments over sites or gathering data at those sites but looking at organising work around those site and engaging the in-situ community in doing so, particularly the early career scientists. Such a coordination allows for synergy to be explored by collecting information at multiple scales, supporting sites to sample in a manner more appropriate to the satellite observation, and augmenting observations on ground. Such advantages are only obtained over longer terms, at least 5-10 years, and thus need strategic thought with respect to funding cycles.

See RD-1, RD-12, RD-37, RD-38, RD-40

However, again it is important not to think just about fixed sites but also to think about climate impacts e.g. efficacy of land mitigation. For example, if Brazil will rely on sinks in southern Amazonia for its carbon reporting, either secondary regrowth or maintenance of intact forest then it will need to know what happens if that area is under threat from e.g. drought or potentially fire. Therefore, it is important to include study areas involving important processes from a climate or a mitigation viewpoint. Characterisation of the temporal dynamics with remote sensing can provide an indication of the sensitivity and the response of the ecosystem. Such information can then be used in a DGVM forward model to look for feedbacks etc in the context of near-term climate change. This also allows engagement with in situ communities not based around tower sites who have existing knowledge that can benchmark some of the remote sensing.

See See RD-1, RD-2, RD-3, RD-28, RD-33, RD-38, RD-43

Model-data interfaces

There has been significant investment and history in the development of models for the carbon cycle and as a consequence most models parameterised with in situ experiments or observations and rather than remote sensing. However, the increase in data provision, product availability and its spatial and temporal resolution is making remote sensing a more attractive proposition for model optimisation or constraint e.g. land use forcing, burned area, and benchmarking.

While the data are now more easily accessible initially through NASA but now also through ESA there is still room for improvement to facilitate the access of these data and collocation of data at supersites in particular would be interesting because the model community is used to evaluate models at site level, especially the flux tower measurements e.g. there is the [Land Surface Model Benchmarking Evaluation Project, Phase 2] Plumber-2 exercise (https://researchdata.edu.au/plumber2-forcing-evaluation-surface-models/1656048) where most people contribute. This is managed by the Fluxnet sites and if that could be augmented some satellite observations at all sites to compare and evaluate against, then it would be would be welcome as a first step as a benchmarking of models using more of these satellite data. For the data assimilation and the parameter optimisation, the interface to remote sensing it is still quite complex and model dependent and advances in this direction depend on all model groups.

See RD-30, RD-31, RD-32

It should also be noted that the models themselves are in continuous development so while the current typical resolutions are with 50km resolution tile structure there are many activities looking at sub-grid heterogeneity e.g. hydrology and hence, if the focus is preparation for the Expansion missions in 5-10 years, then land surface models will also have moved towards landscape scale processes. The prospect of a move to 10km is already real along with development of vertical structure in the model (vegetation inter-dependence e.g. for light and water) with vegetation having different fluorescence, different humidity characteristics/responses. If the objective is to tackle that sub-grid scale in the model there is a vital need for spatially coherent information about these systems to allow model developments to be evaluated against datasets/observations at much finer scales [than 50km].

See RD-33, RD-34

Next Steps for the Carbon Science Cluster
The following set of direction will be explored as mechanisms for the Carbon Science Cluster:

Meetings

- A regular meeting, perhaps once per year for one day focussed on dedicated topics with all the different projects together.
- Meetings taking advantage of existing opportunities e.g. LPS in 2022 with a dedicated day for the carbon science cluster, where this community would actually gather anyway naturally.

Action taken: Carbon Science Agora at LPS22

- The identification of the important activities in view of new instruments, instrument-instrument comparison/joint use, model-data interfaces. Such activities should leverage from other ongoing efforts e.g. an activity on the model-data interface and data assimilation is already undertaken by AIMES (https://aimesproject.org/ldawg/).

Action taken:

Identify and link Cluster to AIMES activity. See 4th Carbon from Space Models and Data session.

See RD-27

General Discussion

DAY 2
SESSION 6

Funding opportunities with ESA

- Specific calls for synthesis activities and collaborative research activities engaging this community e.g. bringing two different teams addressing a common area or bring different resources/expertise together to propose an additional work package. This should be not just ESA projects but other projects/activities carried out outside ESA such as at national level or funded by the European commission.
- More open-ended calls, rather than the existing very directed ITT process, to allow teams to propose new ideas from different project area with different ranges of project on a specific subject on say vegetation or open water but where with some liberty to define/drive the project scope. Especially in terms of synergy between instruments/observations. There are different ways to explore data and we need freedom to test hypotheses.
- Better use of/visibility the Open call and the Living Planet Fellowship Scheme in addition to specific cluster calls.

Actions taken:

o Invitations to Tender under Carbon Cluster

o Living Planet Fellowship Programme: https://eo4society.esa.int/search/living+planet+fellowship

o Open Call Opportunities: https://eo4society.esa.int/open-call-innovation

o Coordination with EC under the Earth System Science Initiative

Communication with the cluster

- Improved clarity in terms of points of contact for the Cluster, the Science Hub, for instruments, for projects both in ESA and outside.
- A dedicated communication channel about things of this carbon cluster between these yearly meetings, newsletter or social feeds etc could work well in this case. This could be in the form of a digest (quarterly) on what is going on - relevant calls, meetings that are coming in ESA and/or in the Commission given planned coordination.
- A continuous dialogue that remains light but informative – this should be not just community to ESA but also within the cluster. A mechanism for highlighting latest developments, opportunities, datasets etc.
- Activities to improve links between ESA staff and this community – visiting fellows/scientists either through the Science Hub at ESRIN or elsewhere in ESA. This though needs feedback from this community.

Action taken:

o Production of this Recommendations report

o Annex 2 to the report listing current projects

o ESA Science Hub

ANNEX 1

DAY 1 AGENDA

9:30 – 10:45	**Introduction and Welcome – Stephen Plummer**
	The ESA Scientific Exploitation and the Carbon Science Cluster (Diego Fernandez)
	Carbon in the Atmosphere (Christian Retscher)
	Carbon in the Ocean (Marie-Helene Rio)
	Current Challenges in Terrestrial Carbon Science (Ana Bastos, Stephen Sitch)
	AFOLU – A CEOS Roadmap and Initiative (Frank Martin Seifert)
	Workshop objectives and logistics, (Stephen Plummer)
10:45-11:00	Coffee break
11:00 - 12:30	**Terrestrial Carbon Projects - Stephen Plummer**
Understanding Primary Production	
11:00	Land Surface Carbon Constellation - Lund University (Marko Scholze)
11:15	Sentinels4Carbon - Noveltis SAS (Cedric Bacour)
11:30	TerrA-P – VITO (Roel van Hoolst)
11:45	Vad3emecum – MPI-BGC (Sophia Walther)
12:00	Sentinel 5P Innovation SIF - Noveltis SAS (Luis Guanter)
12:15	Photoproxy - Forschungszentrum Jülich (Uwe Rascher)
12:30	Multi-Flex - University of Milano Bicocca (Marco Celesti)
12:45-13:00	Discussion on GPP
13:00-14:00	Lunch break
14:00-15:30	**Terrestrial Carbon Projects – Stephen Plummer**
New observations for terrestrial carbon	
14:00	SMOS+ Vegetation – Univ Toulouse 3 (Nemesio Rodrigues-Fernandez)
14:15	Albiom - Deimos Space UK Ltd (Maria-Paola Clarizia)
14:30	Biomascat - Gamma Remote Sensing AG (Maurizio Santoro)
Dynamics, disturbance, carbon management	
14:45	Sentinel4Carbon - TUD (Theme 2) (Matthias Forkel)
15:00	S14Science Amazonas – GISAT, Agresta, NMBU, NLS (Neha Joshi)
15:15	SHRED – TU Vienna (Mariette Vreugdenhil)
15:30	F-DTE, Assesscarbon, Forest Carbon Monitoring (Matti Mottus)
15:45-16:15	Discussion on new observations and dynamics
16:15-16:45	Open discussion on project status, cluster, new mechanisms for working, new call for cluster

End of first day

ANNEX 1

DAY 2 AGENDA

9:30-11:00	**Future Missions, Campaigns, Tools and other ESA activities in support of Carbon science**
9:30	Biomass, FLEX, status and plans – Klaus Scipal, Matthias Drusch
9:45	Sentinel Expansion Missions – Malcolm Davidson
10:00	Land Surface data campaigns – what is there, where, what is planned – Dirk Schuettemeyer
10:15	Earth System Data Laboratory – Anca Anghelea
10:30	CCI and carbon activities – Clement Albergel
10:45	Applications – The 'World' projects – Frank Martin Seifert
11:00-11:30	Coffee break
11:30-12:30	**Parallel Technical Discussion sessions**
	1. Towards a European Terrestrial Carbon Constellation project
	2. Science needs in preparation for Copernicus Sentinel Expansion Missions (2026)
14:00-15:30	**Final session**
14:00	Recommendations from Breakouts
14:45	Final Discussion
15:15	Wrap-up and Next Steps

ANNEX 2

ESA Carbon Science Cluster Activity List

Current scientific activities – Terrestrial carbon

Project	Abstract	Prime	Contact	TO
Land Surface Carbon Constellation	The main objective of the Land surface Carbon Constellation (LCC) project is to demonstrate the synergistic exploitation of satellite observations from active and passive microwave sensors together with optical data for an improved understanding of the terrestrial carbon and water cycles.	Lund University	Marko Scholze marko.scholze@nateko.lu.se	Matthias Drusch
SMOS+ Vegetation	This activity aims to increase the scientific return of the SMOS Vegetation Optical Depth data product by preparing and promoting its use for vegetation applications in the fields of agriculture, drought monitoring and land surface modelling.	The Inversion Lab	Thomas Kaminski thomas.kaminski@inversion-lab.com	Matthias Drusch
Photoproxy	With the PhotoProxy project, we address relevant open aspects that are related to the quantitative assessment of vegetation photosynthesis and vegetation stress from space. This activity tests the applicability of fluorescence and reflectance indices CCI and NIRv to track diurnal and seasonal vegetation dynamics.	Forschungszentrum Jülich	Uwe Rascher u.rascher@fz-juelich.de	Dirk Schuettemeyer
Sentinel 5P Innovation SIF	The ESA –TROPOSIF project is one of the seven themes from the Sentinel-5p+ Innovation (S5p+I) activity funded by ESA, which aims at using TROPOMI's spectral and radiometric performance to monitor terrestrial Solar Induced Fluorescence (SIF) with an unprecedented spatial and temporal resolution.	Noveltis SAS	Cedric Bacour Cedric.bacour@noveltis.fr	Christian Retscher
Sentinel4Carbon – Sen4GPP	Objective of this work is to assess time-space variability of terrestrial gross primary production and the contribution to its estimation using observations of land surface temperature, solar induced fluorescence, fraction of absorbed photosynthetically active radiation and land cover offered at multiple resolution as well as other records from other ESA and non-ESA missions.	Noveltis SAS	Cedric Bacour Cedric.bacour@noveltis.fr	Stephen Plummer
Sentinel4Carbon – Sense4Fire	Based on the new possibilities of the Sentinel series of satellites, this project aims to develop a highly novel approach to derive global fire emissions estimates based on the characterisation of individual fires and their behaviour. These data will be combined with bottom-up estimates of fuel and combustion and top-down constraints on total carbon emissions and emissions factors. Furthermore, observations of atmospheric composition will be exploited to provide an uncertainty assessment from top-down emission estimation. The new approach will highlight the power of Sentinels to reduce emissions uncertainty, understand direct and indirect effects of fire on long-term changes in the carbon cycle, and highlight the linkages between fuels, fire behaviour, and emissions with the potential of improved fire predictions.	Technische Universität Dresden	Matthias Forkel matthias.forkel@tu-dresden.de	Stephen Plummer

ANNEX 2

ESA Carbon Science Cluster Activity List

Project	Abstract	Prime	Contact	TO
TerrA-P	Gross primary production (GPP) and terrestrial net primary production (NPP) are fundamental quantities in the global carbon cycle, and for the production of food, fibre and biomass for human use. This project aims at exploiting Sentinel-3 data to develop and validate a productive model, consistent across different regions and ecosystems. The objective of the TerrA-P project is to define, implement and validate a model to derive information on the vegetation productivity based on data from MERIS and Sentinel-3. To reach this goal, knowledge and expertise from three domains need to be combined. These domains are: the ecophysiology of the plants which is expressed in the productivity model, the EO data sets that can be used as input for this model, and the in-situ data that allow the validation of the model outcome using EO-input data.	VITO	Roel van Hoolst roel.vanhoolst@vito.be	Philippe Goryl
SAR4Wild-Fire	To develop a novel and automatic method, using Sentinel-1 SAR time series and a deep learning framework, for near real-time wildfire progression monitoring and burn severity mapping in preselected wildfire sites in Sweden and British Columbia, Canada. Whenever available, Sentinel-2 MSI data will be incorporated in the framework for active fire detection and burn severity mapping.	Kungliga Tekniska Högskolan	Yi Fang yifang@kth.se	Michael Berger
S14Science Amazonas	Forests help offset a quarter of anthropogenic emissions of fossil-fuel, and hold up to 70-90 % of the Earth's terrestrial carbon. Sentinel-1 for Science Amazonas is an exploratory scientific project, funded by the European Space Agency (ESA), looking to assess how Sentinel-1 imagery can be used to estimate forest carbon losses and gains associated with land use and land cover changes in the Amazon basin.	GISAT	Neha Joshi neha.joshi@gisat.cz	Anca Anghelea
FORESTScan	The ForestScan project investigates Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle-based Laser Scanning (UAV-LS) to complement manual plot-based measurements of AGB by collecting and analysing such data for three tropical sites in French Guiana (Paracou), Gabon (Lopé) and Malaysia (Sepilok). In addition, at each of these sites airborne laser scanning data is available. The specific objectives of the study are (i) the development of a protocol for acquiring such measurements in tropical forests; (ii) analysing scaling properties of forest structure in tropical forests and (iii) high precision limited area measurement (plot census, TLS and UAV-LS) with wide area airborne laser scanning.	University College London	Mat Disney m.disney@ucl.ac.uk	Klaus Scipal
Vad3e-mecum	The integration of global land surface remote sensing and in-situ measured ecosystem carbon fluxes through machine learning offers a unique data-driven perspective to diagnose the carbon cycle response to climate change. However, current approaches like ´FLUXCOM' cannot capture drought effects reliably which strongly limits our capability of assessing interactions between global change and biogeochemical cycles. This will be tackled by integrating data streams of the sun-induced chlorophyll fluorescence, land surface temperature and vegetation optical depth into data-driven flux models for a better diagnosis vegetative stress reactions as well as complementary information on soil moisture.	MPI-BGC	Sophia Walther swalth@bgc-jena.mpg.de	LPF

ANNEX 2

ESA Carbon Science Cluster Activity List

Project	Abstract	Prime	Contact	TO
Multi-Flex	This project focused on exploiting the potential of fluorescence and reflectance to describe photosynthetic dynamics, by exploiting the dataset acquired within the ATMOFLEX project, developing a flexible tool built on physically based RTMs for retrieving information about vegetation biophysical/biochemical parameters and Sun-induced fluorescence, capable of dealing with multiple spectral and spatial resolution data. High level parameters retrieved from model inversion such as the fluorescence quantum efficiency will be compared with simpler fluorescence- and reflectance-based metrics proposed to track vegetation photosynthetic dynamics or to correct for mixed pixel problems arising at the spatial scale offered by satellite observations.	University of Milano Bicocca	Marco Celesti marco.celesti@unimib.it marco.celesti@esa.int	LPF
SHRED	With the Copernicus Sentinel-1 series, for the first time high temporal and spatial resolution backscatter time series have become available. Studies have demonstrated the sensitivity of the VH/VV Cross Ratio (CR) to vegetation. Here the Sentinel-1 CR with VOD retrieved from EEUMETSAT Metop ASCAT backscatter observations will be combined to develop a global 1 km VOD product. The novel high-resolution VOD will be evaluated using Leaf Area Index from Copernicus Global Land Service (CGLS), ESA's SMOS VOD and VOD from AMSR2. Subsequently, it will used to quantify the impact of water availability on vegetation dynamics. The high-resolution VOD will allow the analysis of variations in impact of water availability on vegetation dynamics between land cover types, e.g. differences between natural and agricultural lands.	Technische Universität Vienna	Mariette Vreugdenhil Mariette.Vreugdenhil@geo.tuwien.ac.at	LPF
Albiom	ALBIOM project (ALtimetry for BIOMass) proposes to derive forest biomass using SAR Altimetry Data from the Copernicus Sentinel-3 (S3) Mission. This is the first use of Sentinel-3 SAR altimeter data to retrieve biomass and generate a Sentinel-3 SAR altimeter backscatter simulator over vegetated areas.	Deimos Space UK Ltd	Maria Paola Clarizia maria-paola.clarizia@deimos-space.com	Jerome Benveniste
Biomascat	This project is combining SAR and scatterometer data collected since the early 1990s to estimate biomass properties. As the spatial resolution of both sensors is consistent with the range of length scales typically used within ecosystem models it is expected that this development will provide a unique contribution to improving ecosystem modelling and assessment.	Gamma Remote Sensing AG	Maurizio Santoro santoro@gamma-rs.ch	Marcus Engdahl

ANNEX 2

ESA Carbon Science Cluster Activity List

Other relevant ESA activities (CCI ECVs, Application projects, DTE Precursors, Tools)

Project	Abstract	Prime	Contact	TO
Biomass_cci	The primary science objective ESA's Climate Change Initiative Biomass project is to provide global maps of above-ground biomass (Mg ha-1) for four epochs (mid 1990s, 2010, 2017 and 2018), with these being capable of supporting quantification of biomass change. The mapping will be at 1km grid spacing with a target relative error of less than 20 % where AGB exceeds 50 Mg ha-1. This will allow more refined information to be inferred (e.g. forest age structure and the disturbance regime) that is relevant for climate and has the potential to be exploited by carbon cycle and climate models as they develop.	Aberystwyth University	Richard Lucas rml2@aber.ac.uk	Frank Martin Seifert
Fire_cci	The Fire project focuses on several issues relating to fire disturbance including analysing and specifying scientific requirements relating to climate, developing and improving pre-processing and burned area algorithms, inter-comparison and selection of burned area algorithms, system prototyping and production of burned area datasets, and product validation and product assessment.	Universidad Al-calá de Henares	Emilio Chuvieco emilio.chuvieco@uah.es	Clement Albergel
RECCAP-2_cci	This project aims to support, in cooperation with the GCP, the scientific synthesis and assessment activities of regional carbon budgets and their drivers of the new RECCAP-2 initiative by making use of EO-data and regional cuts of annually updated global terrestrial and ocean carbon models, and atmospheric CO2 inversions, taking stock of new satellite-based surface monitoring products of climate and ecological variables now available within the framework of ESA-CCI. The data-streams used in ESA-CCI RECCAP-2 are: Atmospheric inversions of concentration measurements based on surface in situ networks and satellite remote sensing, with "high resolution" inversions Output from process-based terrestrial ecosystem models these models being driven by climate fields and land cover change Output of "data-driven" bottom-up approach machine learning methods using satellite data and climate fields These three approaches are largely independent; even though inversions use as prior the output from process-based models, they usually do not use specifically the TRENDY models' output. TRENDY models and data-driven models also share climate forcing as input.	LSCE	Philippe Ciais philippe.ciais@lsce.ipsl.fr	Clement Albergel
Perma-frost_cci	To develop and deliver permafrost maps as ECV products primarily derived from satellite measurements. The required associated parameters by GCOS for the ECV Permafrost are "Depth of active layer (m)" and "Permafrost temperature (K)". Algorithms have been identified which can provide these parameters ingesting a set of global satellite data products (Land Surface Temperature (LST), Snow Water Equivalent (SWE), and landcover) in a permafrost model scheme that computes the ground thermal regime.	Gamma	Tazio Strozzi strozzi@gamma-rs.ch	Frank Martin Seifert

ANNEX 2

ESA Carbon Science Cluster Activity List

Project	Abstract	Prime	Contact	TO
Forest Digital Twin	Goal of the system developed in the project is to bring together forest data and users interested in forests, i.e. Forest DTEP will bring user to the data and data to the user. It will work with EO data to determine the structural and biological properties of forests. This is then used to initialize a set of forest ecosystem models that include processes above and below the ground and develop new interfaces and visualization tools, making the cloud platform easily accessible to end users.	VTT	Mottus Matti Matti.Mottus@vtt.fi	Diego Fernandez
AssessCarbon	The Assesscarbon project, coordinated by VTT Technical Research Centre of Finland and funded by European Space Agency (ESA) demonstrated at a pre-operational level an approach for large area forest biomass and carbon modelling in Forestry TEP. The demonstrated service will combine ground reference data, Sentinel-2 imagery and primary production modelling.	VTT	Jukka Miettinen Jukka.Miettinen@vtt.fi	Frank Martin Seifert
Forest Carbon Monitoring	A forest biomass and carbon monitoring system meeting the requirements of different forestry stakeholder groups piloted in Forestry TEP. This system aims to provide a mechanism for forestry stakeholders (forestry companies, administrative authorities) to respond to increasing carbon monitoring and reporting requirements, e.g. for forest sustainability, carbon compensation, forest certification or for national and international reporting. The focus of the system is initially in Europe, but it can be expanded to other continents in the future.	VTT	Jukka Miettinen Jukka.Miettinen@vtt.fi	Frank Martin Seifert
EO4SD Forest Management	The ESA EO4SD Forest Management Cluster project – aims to demonstrate the utility and benefit of mainstreaming EO-based forest related products and services for improved Forest Management for programmes and stakeholders in specific countries in Latin America, South East Asia and Africa.	GAF	Thomas Häusler thomas.haeusler@gaf.de	Frank Martin Seifert
Earth System Data Laboratory	The main objective of the Earth System Data Lab (ESDL) project is to establish and operate a service to the scientific community that greatly facilitates access and exploitation of the multivariate data set in the ESDL and by this means advances the understanding of the interactions between the ocean-land-atmosphere system and society. To this end, the main tasks of the project fall into four main categories: infrastructure and operations, data sets and tools, use cases and scientific exploitation, and communication and outreach.	Brockmann Consult	Carsten Brockmann carsten.brockmann@brockmann-consult.de	Anca Anghelea
WorldSoils	To develop a global Earth Observation Soil Monitoring System using open source information in situ, EO and reference data to monitor top soil organic carbon (SOC) and implemented in a modular way allowing its future extension to additional soil indices at 100m x 100m globally and 50m x 50m over Europe, and shall allow assessing temporal changes of the global top soil layer at least once per year.	GMV		Michael Berger
Tropical Peat Watch	The Tropical Peat View monitoring system (TPV) provides information on deforestation, forest degradation, development of drainage canals, changes in hydrology, fire and fire damage, through integration of multiple Earth observation data sources from the European Copernicus Programme (Sentinel-1 C-band radar, Sentinel-2 optical imagery) and other missions (PALSAR L-band radar, Landsat optical, MODIS thermal imagery).	Sarvision BV	Wilbert van Rooij <rooij@sarvision.nl>	Frank Martin Seifert


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