Decreasing uncertainties in the regional contributions to the global carbon cycle with state-of- the-art Earth observation products

Torbern Tagesson
2021-05-19

Summary

Carbon fixation via photosynthesis is known as gross primary production (GPP), and together with ecosystem respiration it dominates the land-atmosphere exchange of carbon dioxide (CO_2). It is thus one of the main processes driving climate regulation, carbon sequestration and storage as well as being important for a range of ecosystem services, including the production of food, feed, fiber, fuel, biodiversity and the regulation of the habitability of Earth. Given the central role of GPP within the Earth system and within climate change mitigation, accurate monitoring from space is pivotal. Within the global carbon cycle research community, modelling with Earth observation is generally using two approaches; 1) bottom-up approaches with physical relationships based on ground observation applied on global scale, or 2) or top-down approaches where processes within terrestrial biosphere models are constrained to fit the Earth observations. Recently, it was shown that the mismatch between the two approaches matches the global carbon budget imbalance, highlighting key needs in improved understanding in the reasons for this mismatch. The Copernicus Sentinel fleet is a series of next-generation Earth observation missions, and the main aim with the proposed project is to bring the data from the Sentinel fleet into the two main Earth observation approaches for studying global carbon cycling. The project is separated into two different research questions: 1) What is the impact of increasing the spatiotemporal averaging resolution of input Earth observation data for the GPP variability as estimated by empirical light use efficiency upscaling methods? 2) Can we decrease the difference in the spatiotemporal variability within the global-scale estimates of GPP of the top-down and bottom-up approaches by using state-of-the-art Earth observation products? Results and knowledge gained during this project will increase our understanding of the processes driving climate regulation and carbon sequestration, and increase our capability to predict environmental changes. This enhance the possibilities to make informed decision makings, being of high relevance for many of the UN sustainable Development Goals.

Research Project

Carbon fixation via photosynthesis is known as gross primary production (GPP), and together with ecosystem respiration it dominates the land-atmosphere exchange of carbon dioxide (CO_2)[1]. GPP is thus one of the main processes driving climate regulation, carbon sequestration and storage[2] as well as being important for a range of ecosystem services, including the production of food, feed, fiber, fuel, biodiversity and the regulation of the habitability of Earth[3,4]. Human population growth and increased food and fiber consumption have increased the use of global vegetation productivity[5], with severe consequences for services and functions of global ecosystems [3,4]. An improved understanding of spatial and temporal dynamics in regional and global GPP is therefore essential to better understand, quantify, and forecast the effects of current and future climate change[6], also in relation to the design of climate change mitigation policies and in the early detection of ecosystem change[7].

There has been a substantial progress in our understanding of spatiotemporal variability in GPP, thanks to a strong collaboration between different research disciplines such as biogeochemistry, dynamic vegetation modelling, plant ecology, and remote sensing[1,2,8,9]. But there are still major uncertainties in our understanding[1,10,11]. The global carbon budget estimated on atmospheric CO_2 growth rate, fossil fuels emissions, and terrestrial and ocean fluxes cannot be fully closed, highlighting uncertainties in these components[12]. Generally, it is considered that the terrestrial carbon fluxes are the most uncertain components[12]. Within the global carbon cycle research community, modelling terrestrial carbon fluxes with Earth observation is generally using two approaches; 1) bottom-up with physical relationships based on ground observation applied on global scale, or 2) or top-down where processes within terrestrial biosphere models are constrained to fit the Earth observations. Recently, it was shown that the mismatch between the bottom-up and top-down approaches matches the global carbon budget imbalance, highlighting key needs in improved understanding in the reasons for this mismatch[12].

The most common bottom-up approach for estimating GPP from satellite data involves the light use efficiency (LUE) model, where LUE is defined as the conversion efficiency of absorbed photosynthetically active radiation (APAR) into GPP [13-17]. The advantage of the LUE model is its simplicity using a linear relationship, and it has been shown to work well in a range of biomes, and environmental conditions[13-17]. This linearity assumption has been shown reasonable at temporal resolutions larger than weekly and at moderate spatial resolutions[13-18]. However, observations show that the relationship between GPP and PAR generally follows an asymptotic shape, and only by multiplying with fraction of PAR that is absorbed by the green vegetation (FAPAR) does the relationship turn approximately linear[14,19-23]. But, when FAPAR approaches one, this linearization does not occur, and the actual relationship thereby remains asymptotic. Additionally, if the aim is to estimate day-to-day GPP variability, or even diurnal variation, FAPAR at this high temporal resolution is basically static, and the linearity assumption thereby fails. If our aim is to improve our understanding of the GPP variability within the Earth system, increasing the spatial and temporal resolution of the GPP estimates is vital.

Another tool of relevance for estimating carbon budgets on different scales (landscape, regional, and global) are process-based terrestrial biosphere models. They enable the study of long-term adjustments in biogeochemical exchanges as a response to climatic and environmental changes, as well as changes in land cover and management[24,25]. They use a mechanistic representation of the main ecosystem processes to simulate biogeochemical cycling and, this approach makes them applicable to investigate the effects of changing conditions[25]. Terrestrial biosphere models have been shown to reproduce broad-scale patterns and inter-annual trends in terrestrial ecosystem carbon exchanges well[24], but the process parameterizations introduce possible errors and result in the loss of landscape variation in the models. Hence, purely model-based quantification of carbon fluxes and dynamics of stocks exhibit large uncertainties[2,26]. However, Earth Observation data provide spatial and temporal patterns in the vegetation dynamics and structure, whereas the biosphere models provide insights into the reasons behind these patterns. These two methods thereby complement each other. In a data assimilation approach, Earth observation data is used for assimilation in terrestrial biosphere models to constrain and improve the process parameterizations, with the aim to consistently reproduce the spatial and temporal patterns in terrestrial carbon cycling[27-29].

One of the main reasons for the mismatch between the bottom-up and top-down approaches was uncertainty in the land use change emissions[12]. Recently, Tagesson, et al. [6] showed diverging trends in the net terrestrial carbon sink for boreal and tropical forests by using a state-of-the-art Earth observation land cover data set. These diverging trends were not observed when applying a conventional land use dataset, but were also evident in satellite passive microwave estimates of aboveground biomass (Enclosure 3)[6]. These datasets thereby converge on the conclusion that the land use and land cover change have had a greater impact on tropical forests than previously estimated[6].

Given the central role of GPP within the Earth system and within climate change mitigation, accurate monitoring from space is pivotal. Hence, forming an ensemble of Earth observation based independent approaches is key in better understanding and addressing the uncertainties in our global GPP budget. The Copernicus Sentinel fleet is a series of next-generation Earth observation missions, and with these we now have the possibility to generate a novel independent Earth observation based global GPP product. Additionally, the very high spatiotemporal resolution can generate improved understanding of the regional distribution, as well as in the model parameterization of the global carbon exchange processes.

The main aim with this project is to bring the data from the Copernicus Sentinel fleet into the two Earth observation approaches applied within the global carbon cycle research community for studying global-scale GPP; bottom-up and top-down modelling. This project proposal is separated into two different research questions:

1) What is the impact of increasing the spatiotemporal averaging resolution of input Earth observation data for the GPP variability as estimated by empirical light use efficiency upscaling methods?
2) Can we decrease the difference in the spatiotemporal variability within the global-scale estimates of GPP of the top-down and bottom-up model approaches by using state-of-the-art Earth observation products?

We aim at responding to these research questions by first studying the difference in the linear LUE approach versus the asymptotic light response function at local scale. The most accurate model will be used for upscaling the field observations of GPP globally using Sentinel-3 data. A terrestrial biosphere modelling and carbon cycle data assimilation (CCDAS) system[27] will also be parameterized, and applied using data from Sentinel-3 and a state-of-the-art Earth observation data set of land use and land cover change emissions[6]. In this combined approach, we will be able to compare the main differences in their simulations of GPP, providing insights into main uncertainties in the regional distributions of the global carbon cycle. The GPP simulations will be evaluated against independent products of vegetation productivity, such as inter-annual variability in biomass, Vegetation Optical Depth (VOD), solar induced florescence, and other Earth observation products of GPP. The variability in the GPP will also be analysed against explanatory variables such as soil moisture (SM), land surface temperature (LST), meteorology, land cover, and atmospheric CO_2 levels, providing insights into the processes affecting the CO_2 uptake by terrestrial vegetation.

Project proposal

The overall workflow of the proposed project is shown in figure 1 below. The objectives will be reached via five inter-linked work packages (WP) (Figure 1; Table 1).

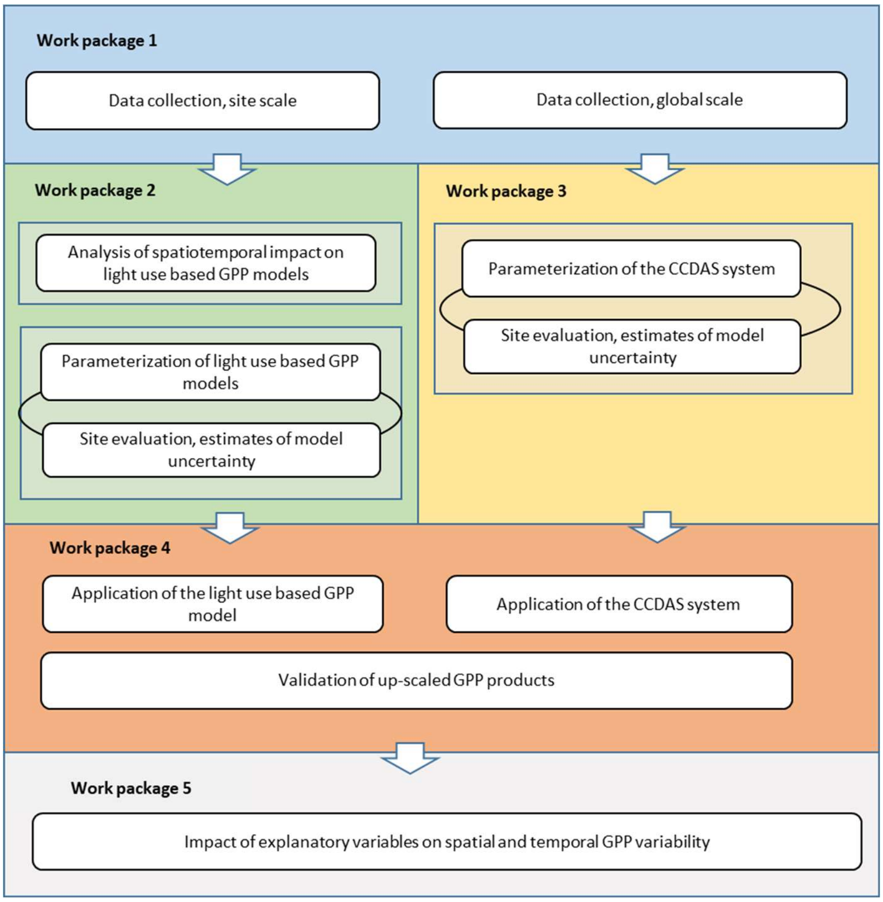

Fig 1. Flow chart showing the logic of the work to be undertaken.

Table 1. Schedule for the proposed project indicating the duration of the work packages (WP), and the milestones of the project. T_0 is the start of the project and the numbers are quarters of a year. M1-4 are the milestones given in the work package descriptions.

Tasks	**Start**	**End**	**2022**				**2023**				**2024**				**2025**			
Quarter			**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
WP 1 Data Collection and Preparation	T_0+0	T_0+8			▨	▨	▨	▨	▨	▨	▨	▨						
WP 2.1 Scaling effects on Light use based approaches	T_0+0	T_0+5			▨	▨	▨	▨	▨									
WP 2.2 Parameterisation of Light use based approach	T_0+1	T_0+6				▨	▨	▨	▨									
WP 3 Parameterisation of data assimilation system	T_0+2	T_0+7					▨	▨	▨	▨	▨	▨						
WP 4 Upscaling and validation	T_0+5	T_0+10							▨	▨	▨	▨	▨	▨				
WP 5 Impact on Global Carbon Cycle	T_0+8	T_0+12										▨	▨	▨	▨	▨		
Milestones	T_0+0	T_0+12							M1			M2		M3		M4		
Writing of Journal articles	T_0+0	T_0+12			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		

WP 1. Data collection and preparation

During the project, the focus will be a site-wise analysis over eddy covariance tower sites, and an analysis at global scale. All data to be collected for this project are listed in Table 2. Data that require some additional preprocessing are:

1) For some eddy covariance sites data of net ecosystem exchange have not been partitioned into the respiration and GPP components. For those cases, standard partitioning methods will be used for estimating GPP[30].
2) From the Sentinel-2 and Sentinel-3 reflectance data; standard vegetation indices (VI) will be calculated. The VIs to be used are the normalized difference vegetation index (NDVI); the enhanced vegetation index (EVI2); and the plant phenology index (PPI). In order to smooth and gap fill the time series, TIMESAT will be used[31].
3) The land cover data of the European Space Agency (ESA) Climate Change Initiative (CCI) will be used to produce a map of different land cover classes. The following separation will be done: 1) deciduous broad-leaf; 2) evergreen broad-leaf; 3) deciduous needle-leaf 4) evergreen needle-leaf; 5) deciduous shrub; 6) evergreen shrub; 7) grasslands; 9) bare soil/urban/water (non-vegetation); 10) crops; 11) moss or lichen; and 12) wetlands.

Table 2. List of data to be used within this project.

Data	Sensor/data source	Period	Temporal resolution	Pixel size /instrumental resolution	Analysis*	Data access
Earth observation Data						
Surface reflectance	Sentinel-2/-3	2016-2021	5 and 2 days	10, 20, 60 and 300 m, 1.2 km	SW, BU, TD	https://scihub.copernicus.eu/
FAPAR	Sentinel-2/-3, MERIS, JRC-TIP MODIS	2002-2021	5 and 2 days	20, 300 m, 1.2 km, 0.01°	SW, BU, TD	Nadine Gobron**
Land cover	ESA-CCI	1992-2018	annual	300 m	SW, BU, TD	http://www.esa-landcover-cci.org/
Soil Moisture	SMOS	2011-2021	3 days	43 km	TD, V	Yann Kerr***
Vegetation Optical Depth (VOD)	SMOS, VODCA	2011-2021	3 days	43 km	V	Jean Pierre Wigneron, Leander Moesinger***
Atmospheric CO_2 concentrations	CAMS	2003-2018	daily	1.29 km x 2.25 km	TD, V	https://ads.atmosphere.copernicus.eu/#!/home
Solar Induced Flourescence (SIF)	Sentinel-5	2018-2021	daily	7 km	TD,V	https://s5p-troposif.noveltis.fr/data-access/
Earh observation based GPP products	MOD17, SMAP, VPM, LRF, p-model, Kolby-Smith	1980-2021	various	various	V	https://earthdata.nasa.gov/, Tagesson et al 2021
Ground data						
Eddy data	NEON, ICOS, Africa, AmeriFLUX, FLUXNET	2016-2020	half-hourly	few 100 m	SW, BU, TD, V	https://www.neonscience.org/, https://www.icos-cp.eu/, https://ameriflux.lbl.gov/, https://fluxnet.org/, Cooperations in Africa***
Model data						
Climate data	ERA5	1979-2021	hourly	30 km	SW, BU, TD, V	https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5
Fossil fuel emissions background flux	ICOS	1970-2021	monthly	various	TD	https://data.icos-cp.eu/portal/
Ocean background flux	Carboscope	1970-2021	monthly	various	TD	http://www.bgc-jena.mpg.de/CarboScope/?ID=oc
Biomass burning background flux	GFED4	1970-2021	monthly	various	TD	https://globalfiredata.org
Land use change background flux	Global Carbon portal, ESA-CCI	1970-2021	monthly	various	TD	https://www.globalcarbonproject.org/, Tagesson et al 2020
GPP and C fluxes	TRENDY DGVM ensamble	1959-2019	Monthly	0.5°×0.5°	V	http://dgvm.ceh.ac.uk/node/21/

* SW: Site-wise, BU; bottom-up; TD: top-down (Biosphere Model Assimilation); V: validation

** See letter of support by Nadine Gobron.

*** See Research connections below.

WP 2 The light use based upscaling approaches

WP 2.1 Scaling effects on Light use-based approaches

Vegetation heterogeneity in the vicinity of a flux tower strongly affect the measured fluxes, and for accurate matching tower fluxes and its surrounding areas, footprint models must be used[32]. We will use the footprints of the eddy covariance towers to extract average Sentinel-2 based FAPAR and VIs for each measurement point in time. Next, we will separate the GPP, FAPAR and VIs for different sizes in the spatial averaging scale (various sizes in footprints). Also, different averaging scales in the temporal resolution will be used to average the parameters hourly, daily, weekly, semi-monthly, monthly, quarterly, and annually. This will generate time-series with the different temporal resolutions, for each of the spatial averaging resolutions. For each of these spatiotemporal resolutions, we will fit the LUE model and the light response function against FAPAR/VIs and incoming photosynthetically active radiation. Bootstrapping will be used to include and omit sites in the analysis, where the omitted sites will be used in a model evaluation. Finally, we will use the output of the model evaluation (root-mean-square-error (RMSE), wellness of fit, bias, Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC)) to study at what spatiotemporal averaging scale the asymptotic relationship seen at plant scale and at high temporal resolution is converted towards a more linear relationship.

WP 2.1 Parameterisation of Light use based approach

The model performing best at the spatial and temporal scale of Sentinel-3 will be selected to be parameterized for a global scale bottom-up upscaling approach. A large fraction of the GPP variability caused by meteorological and hydrological variability is already captured by the variability in the FAPAR/VI data, and is therefore already included in a first estimate of GPP[11]. However, in order to capture GPP variability that is not captured by the Sentinel-3 FAPAR/VI, we will calculate a scalar by taking the ratio of measured and modelled GPP. Relationships between this GPP scalar and meteorological and hydrological variability will be fitted to study and upscale impact of daily variability in meteorological and hydrological conditions[11]. The explanatory variables employed will be land surface temperature, atmospheric CO_2 concentrations, and meteorological variables from ERA5[11]. When fitting functions, the Eddy tower sites will be grouped into the selected land cover classes suggested in WP1. Again, bootstrapping will be used in the parameterization, and the average and standard deviations of the model parameters for each of the land cover classes will be selected as final model parameters and their uncertainty.

The major deliverables of WP1 and WP2 will be done at the first milestone (M1); data in Table 2 will be collected and pre-processed, the parameterization of the light use based approaches for upscaling GPP based on Sentinel-2 and Sentinel-3 data will be done; and a manuscript regarding impact of scaling effects on light use based approaches will be submitted.

WP3 The Carbon Cycle Data Assimilation approach

In a close collaboration with Marko Scholze and Guillaume Monteil, a top-down approach using the Carbon Cycle Data Assimilation (CCDAS) methodology will be employed[27,33]. In this CCDAS system, process parameters and background fluxes feed the Biosphere Energy Transfer and HYdrology (BETHY) model and produce surface-atmosphere CO_2 fluxes[27,33]. These are then used via the atmospheric transport model TM3[34] to predict atmospheric CO_2 concentrations, which can be compared to satellite derived CO_2 observations[33]. In the present study the CCDAS system will be operated for the land cover classes defined in WP1, and the meteorological driving data are temperature, precipitation, and incoming solar radiation from ERA5. The Earth observation driving data will be FAPAR from Sentinel-3, but the use of further Earth observation data streams as additional drivers (land surface temperature, soil moisture, and solar induced fluorescence) will be explored.

The background fluxes from fossil fuels emissions, oceans, and biomass burning will be prescribed as in Wu, et al. [29]. However, as above mentioned one of the main reasons for the mismatch between bottom-up and top-down approaches was uncertainties in the land use change emissions[12]. Hence, to study the impact of input of land use and land cover change emissions on the GPP simulations of the top-down approach we will apply two data sources as background flux. First by using conventional data[2,29], and then also a novel state-of-the-art Earth observation based data set[6].

Process parameters and their uncertainty as well as the initial atmospheric CO_2 concentration will also be specified similarly as in Wu, et al. [29]. The model-data misfit term in the cost function will be specified, and the assimilation system will be employed to optimize the model parameters. Next, the inclusion of further Earth observation data (land surface temperature, soil moisture, and solar induced fluorescence) as additional drivers will be explored and alternative GPP test data sets generated.

The major deliverables of WP3 should be done at the second milestone (M2); the parameterization of the CCDAS system for global carbon cycle studies based on Sentinel-3 data, and a manuscript submitted about the process parameterization and the impact of different land use and land cover data sets.

WP4 Upscaling and validation of the GPP modelling approaches

The parameters from WP2 for the bottom-up GPP model will be used for upscaling GPP globally. The parameters will depend on and be applied according the land cover classes. The exact input data will be based on the results of WP2, but will at least be Sentinel-3 and meteorological variables from ERA5. The CCDAS system will also be applied using the parameterization from WP3. Both approaches will be applied at the spatial and temporal resolution of Sentinel-3.

Both GPP estimates will be evaluated against the Eddy covariance based GPP. However, since the models originally are parameterized using the Eddy covariance data, the GPP simulations will also be compared against: 1) existing GPP products[11,16,35-39]; 2) solar induced fluorescence[40]; 3) simulations from the TRENDY ensemble[41]; biomass estimates from the ESA-CCI[42]; and 4) VOD from the Soil Moisture and Ocean Salinity (SMOS) sensor[43] and the VOD Climate Archive (VODCA)[44]. Inter-annual variability in the biomass proxies will be used, as this can be an indicator of vegetation productivity. The validation will be carried out by using a standard set of benchmark metrics, such as RMSE; wellness of fit (using least square linear regressions) and bias.

The major deliverables of WP4 will be ready at the third milestone (M3); Sentinel-3 based GPP and carbon cycling products deposited at an open repository, and a manuscript regarding global GPP and the differences in the two up-scaled products submitted.

WP 5. Dynamics in the contributions to the global carbon cycle

By using exactly the same input data to both the bottom-up and top-down approaches, we aim at improving our understanding to the causes of differences in their simulations. For the regions of the world where the two approaches differ the most, we will perform additional regional scale evaluations against the independent data sources to see which of the approaches are closest. Relationships with explanatory variables (land cover change; meteorology and hydrology) will also be studied to assess reasons for the discrepancies, and uncertainties in the process parameterizations.

Next the CCDAS system will be used to study explanatory variables to the GPP dynamics via a sequence of different factorial model simulations. A number of sensitivity experiments will be conducted omitting in turn one of the driving input data. First, we run the model keeping all predictors static. Secondly, we run the model concurrently keeping one of the predictors dynamic whereas the remaining variables will be kept static. The contribution of a specific predictor will be quantified by taking the difference in the carbon dynamics between the static run and the runs with the dynamic predictor. We will separate the effect of meteorological forcing, fertilisation due to increased atmospheric CO_2 concentrations, and land cover change on the carbon dynamics.

Finally, in order to study the contribution of the different biomes and the different drivers to the global GPP we will compare GPP aggregated for the different land cover classes with the global carbon budget. We will separate the contribution to the mean, the trend and the inter-annual variability following the method in Ahlström, et al. [24] and Tagesson, et al. [6]. At the fourth milestone (M4) the major deliverable of this WP will be a submitted manuscript regarding contributions of land cover classes and processes to the global GPP and its variability.

Research connections

In the proposed project, I will cooperate closely with Marko Scholze at Lund University. We will combine our expertise using bottom up Earth observation models and top-down data assimilation systems for improving our understanding of the global carbon cycle. I have previously cooperated with Marko both in research[29], teaching and in an ESA proposal together with researchers at iLAB, Centre dEtudes Spatiales de la Biosphere (CESBIO; Yann Kerr and Nemesio Rodriguez-Fernandez), and University of Helsinki. These contacts will assure data access to SMOS data, expertise on the CCDAS system and solar induced fluorescence. Nadine Gobron at the Joint Research Centre (JRC) have also promised to share her FAPAR data (See her Letter of Recommendation). I am also cooperating with the producers of the SMOS VOD (Jean-Pierre Wigneron) and the VODCA data sets (Leander Moesinger; Wouter Dorigo), granting access to these data. I will also have a Postdoc, Guillaume Monteil, aiding me with the global-scale data preparation and parameterisation of the CCDAS system. Guillaume Monteil is an expert in CCDAS systems and CO_2 inversions.

Currently, I am also cooperating with Gerard Margarit Martin at GMV on an ESA proposal for Rangeland monitoring for Africa using Earth Observation (RAMONA). If we will be given the grant, we will be developing a prototype for an Earth observation based rangeland monitoring system for Africa based on synergetic utilisation of Sentinel-1 and Sentinel-2 data. In this consortium we are also cooperating with researchers at VITO, University of Twente, University of Milano, GISAT, and IIASA. This cooperation will assure connections and data access to several products applicable also within the applied project.

I am also leader and principal investigator for the Dahra field site in Senegal, which is a ground observation site with a focus on Earth Observation purposes. In this role I am a part of several ground observation sharing communities such as Specnet, the International soil moisture network; SoilTemp, and Fluxnet. In Senegal, I also collaborate with Université Cheikh Anta Diop de Dakar-Sénégal, L'Institut Sénégalais de Recherche Agricole (ISRA), and Centre International la Recherche Agronomique pour le Développement (CIRAD); and I am cooperating with Eddy covariance partners across Africa. This network is a strong asset, and Eddy covariance partners across Africa have promised to share their flux data.

I am currently also working at University of Copenhagen within the Earth observation group, and even though my future position would be fully at Lund University, a close collaboration with this group will continue. We have a fruitful cooperation, sharing data, research ideas, funding, supervision, research network, and teaching activities.

In my current project, I was on a research exchange to the Numerical Terradynamic Simulation Group at University of Montana, generating several research connections across the world. Also. several PhD students, postdoc and researchers in current and past research groups that I have been associated with, have generated cooperation with people across the world.

Societal Benefit

The Paris Agreement, adopted in 2015 at COP21[45], strengthened the global effort on climate by requiring all countries to set climate targets, particularly in terms of greenhouse gas reduction. It is within this context that the member states have committed to provide data reports on their greenhouse gas emission, and absorption from all sectors through national greenhouse gas inventories. Knowledge about the greenhouse gas exchange has a wide range of societal benefit areas, including vegetation production estimates, land management, food security and sustainable agriculture, global carbon cycle assessments, climate change related research, disaster resilience, biodiversity and ecosystem sustainability, and monitoring of ecosystem status and environmental change[46]. This project thereby has a strong societal benefit linked to the above mentioned areas and will increases our understanding of earth processes increasing the capability to predict environmental changes. This enhance the possibilities to make better informed decision makings, and is of high relevance for many of the UN sustainable Development Goals (1,2,3,6,12,13,15).

Given the central role of GPP within the Earth system and within climate change predictions, accurate and continuous monitoring from space is pivotal. Currently, there is a large uncertainty in the global GPP budgets. It is commonly accepted to be ~120 PgC year^{-1} globally, but estimates vary from 112 PgC year^{-1} to 169 PgC year^{-1} [8,47]. Given this range of GPP estimates, forming an ensemble of Earth observation-based independent approaches is key in better understanding and addressing the uncertainties in the global GPP budget. Most previous GPP budgets are either based on AVHRR or MODIS data, and with the novel Sentinel-based GPP estimates, we are aiming at establishing a third family of Earth observation global GPP products. This would be a major leap forward in understanding the spatiotemporal patterns in global GPP, and adding to our understanding in its uncertainties.

Global human population growth and thus increased food and fiber consumption increase the appropriation of vegetation production[5], with profound consequences on ecosystems structure and function[3,4]. Land use and land cover changes are particularly ubiquitous since human management impacts ~75% of all ice-free land, replacing natural ecosystems with agricultural land and managed forests[48]. In this project we aim at incorporating a novel Earth observation based data set of emissions from land use and land cover change into a data assimilation approach. Current top-down approaches within the global carbon budget are based on conventional land use and land cover data, and if by incorporating this background flux we would decrease the mismatch between the bottom-up and top-down approaches, this would be a major leap forward in our understanding of uncertainties in the global carbon budget.

Outreach

We will also make sure to communicate our results with the carbon cycle global initiatives. The Global Carbon Project (GCP) integrates knowledge of greenhouse gases for human activities and the Earth system[2]. The generated Sentinel based carbon cycle products, and the knowledge derived from this research will be highly beneficial for global carbon cycle budgeting. GCP is also operating the REgional Carbon Cycle Assessment and Processes', Phase 2 (RECCAP-2) project. I am participating in RECCAP-2, being responsible for collecting Earth observation based GPP estimates. I have included a research exchange to the research group of Benjamin Poulter at NASA, one of the leaders of RECCAP-2, and I will make sure that the created products and knowledge will be transferred to GCP and RECCAP-2.

At Lund University, the communication's coordinators and web-designer will support our outreach activities to transfer the knowledge between academia and society through newspaper articles and website. We will communicate the project to a general public including an outreach website describing the motivation and the issues that the project will examine. Regular updates about the project development on the website and social networks will be performed. Dissemination of results will be targeted the most prestigious peer-reviewed journals within the research area. Results will also be disseminated through attendance at conferences. I will also aim at associating Master and PhD students with the project, and that the research will be implemented in courses at Lund University.

References

1 Ryu, Y., Berry, J. A. & Baldocchi, D. D. *Remote Sens. Environ.* **223,** 95-114 (2019).
2 Friedlingstein, P. *et al. Earth Syst. Sci. Data* **12,** 3269-3340 (2020).
3 Rockström, J. *et al. Nature* **461,** 472 (2009).
4 Steffen, W. *et al. Science* **347** (2015).
5 Krausmann, F. *et al. Proc. Nat. Acad. Sci. U.S.A.* **114,** 1880-1885 (2017).
6 Tagesson, T. *et al. Nat. Ecol. Evol.* **4,** 202-209 (2020).
7 IPBES. The IPBES assessment report on land degradation and restoration., 744 (Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany., 2018).
8 Beer, C. *et al. Science* **329,** 834-838 (2010).
9 Farquhar, G. D., Caemmerer, S. & Berry, J. A. *Planta* **149,** 78-90 (1980).
10 Ciais, P. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley) (Cambridge University Press, 2013).
11 Tagesson, T. *et al. Global Change Biol.* **27,** 836–854 (2021).

12 Bastos, A. *et al. Glob. Biogeochem. Cycles* **34,** e2019GB006393 (2020).
13 Madani, N. *et al. J. Geophys. Res.* **119,** 1755-1769 (2014).
14 Monteith, J. L. *J. Appl. Ecol.* **9,** 747-766 (1972).
15 Monteith, J. L. *Philos. Trans. Roy. Soc. B.* **281,** 277-294 (1977).
16 Running, S. W. *et al. BioScience* **54,** 547-560 (2004).
17 Martínez, B. *et al. ISPRS Journal of Photogrammetry and Remote Sensing* **159,** 220-236 (2020).
18 Tagesson, T. *et al. Int. J. Appl. Earth Obs. Geoinf.* **18,** 407-416 (2012).
19 Baldocchi, D. *Agric. For. Meteorol.* **67,** 291-321 (1994).
20 Falge, E. *et al. Agric. For. Meteorol.* **107,** 43-69 (2001).
21 Lindroth, A. *et al. Tellus B* **59,** 812-825 (2007).
22 Tagesson, T. *et al. Global Change Biol.* **21,** 250-264 (2015).
23 Ruimy, A., Jarvis, P. G., Baldocchi, D. D. & Saugier, B. in *Advances in Ecological Research* Vol. Volume 26 (eds M. Begon & A. H. Fitter) 1-68 (Academic Press, 1995).
24 Ahlström, A. *et al. Science* **348,** 895-899 (2015).
25 Prentice, I. C. *et al.* in *Terrestrial Ecosystems in a Changing World* (eds J.G. Canadell, D.E. Pataki, & L.F. Pitelka) 175–192. (Springer Verlag, 2007).
26 Jupp, Tim E & Twiss, S. D. *J. Geophys. Res.* **111** D19112 (2006.).
27 Kaminski, T. *et al. J. Geophys. Res.* **118,** 1414-1426 (2013).
28 Scholze, M. *et al. Geophys. Res. Lett.* **46,** 13796-13803 (2019).
29 Wu, M., Scholze, M., Kaminski, T., Voßbeck, M. & Tagesson, T. *Remote Sens. Environ.* **240,** 111719 (2020).
30 Reichstein, M. *et al. Global Change Biol.* **11,** 1424-1439 (2005).
31 Jönsson, P. & Eklundh, L. *Comput. Geosc.* **30,** 833-845 (2004).
32 Hsieh, C. I., Katul, G. & Chi, T. W. *Adv. Water Res.* **23,** 765-772 (2000).
33 Kaminski, T. *et al. Remote Sens. Environ.* **203,** 109-124 (2017).
34 Heimann;, H. & Körner, S. Technical Report 5: The global atmospheric tracer model TM3., 131 (Max-Planck-Institut für Biogeochemie, Jena Germany, 2003).
35 Jones, L. *et al. IEEE Trans. Geosci. Remote Sens.* **55,** 6517-6532 (2017).
36 Zhang, Y. *et al. Scientific Data* **4,** 170165 (2017).
37 Stocker, B. D. *et al. Nat. Geosci.* **12,** 264-270 (2019).
38 Jung, M. *et al. J. Geophys. Res.* **116,** n/a-n/a (2011).
39 Kolby Smith, W. *et al. Nat. Clim. Change* **6,** 306 (2015).
40 Christian Retscher, Claus Zehner, Stefano Casadio, Daniele Gasbarra & Espen Volden. Sentinel-5p+ Innovation Theme 6: Solar Induced Chlorophyll Fluorescence (SIF). (Esrin, Italy, 2021).
41 Sitch, S. *et al. Biogeosciences* **12,** 653-679 (2015).
42 ESA-CCI. *ESA-CCI Biomass*, <https://climate.esa.int/en/projects/biomass/>,(2021).
43 Tian, F. *et al. Nat. Ecol. Evol.* (2018).
44 Moesinger, L. *et al. Earth Syst. Sci. Data* **12,** 177-196 (2020).
45 UNFCCC. (2015).
46 Lepers, E. *et al. BioScience* **55,** 115-124 (2005).
47 Anav, A. *et al. Reviews of Geophysics* **53,** 785-818 (2015).
48 Erb, K.-H. *et al. Global Change Biol.* **23,** 512-533 (2017).