DEEP-C Consortium: Carbon sink or methane source - local to global scale assesment of lentic waters' role in the climate system

Jean-Philippe Jenny[‡], Laurent Millet[§], Ronny Lauerwald[|], Fanny Colas[§], Hélène Masclaux[§], Yves Prairie[¶], Pierre Regnier[#], Adam A. Ali[¤], Fabien Arnaud[«], Nuno Carvalhais[»], Vincent Chanudet[ˆ], Emmanuel Chapron[ˇ], Patrick Durand[¦], Isabelle Domaizon[‡,ˀ], Etienne Dambrine[‡], Mathieu Dellinger[«], David Etienne[‡], Jérome Gaillardet[ˁ], Didier Galop[ˇ], David Gateuille[«], Charline Giguet-Covex[«], Olivia Itier-Desgué[‡], Didier Jezequel[‡], Emilie Lyautey[‡], Laurent Marquer[¢], Florence Mazier[ˇ], Théo Mazure[‡], Erwan Messager[«], Jérôme Poulenard[«], Damien Rius[§], Pierre Sabatier[«], Georges-Marie Saulnier[«], Anaëlle Simonneau[ℓ], Laura Melo-Vieira Soares[‡], Viet Tran-Khac[‡], Valérie Verneaux[§], Philippe Ciais[ঌ]

‡ Université Savoie Mont Blanc, INRAE, CARRTEL, 74200 Thonon-les-Bains, France
§ Laboratoire Chrono-environnement - UMR 6249, CNRS Université de Franche-Comté, Besançon, France
| Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, Palaiseau, France
¶ UNESCO Chair in Global Environmental Change, Université du Québec à Montréal, Montréal, Canada
# Biogeochemistry and Modeling of the Earth System, Université Libre de Bruxelles, Bruxelles, Belgium
¤ ISEM, Université de Montpellier, CNRS, IRD, Montpellier, France
« Université Savoie Mont Blanc, CNRS, EDYTEM, 73100 Chambéry, France
» Biogeochemical Integration Department, Max Planck Institute for Biogeochemistry, 07745 Jena, Germany
ˆ EDF, Environment and Social Department, Hydro Engineering Centre, 73290 La Motte-Servolex, France
ˇ GEODE, UMR 5602 CNRS-Université Toulouse, Toulouse, France
¦ INRAE, Institut Agro, SAS, 35000 Rennes, France
ˀ R&D pole ECLA, 74200 Thonon-les-Bains, France
ˁ Institut de Physique du Globe de Paris, Paris, France
¢ Department of Botany, University of Innsbruck, Innsbruck, Austria
ℓ ISTO, UMR 7327, Univ Orleans, CNRS, BRGM, OSUC, F-45071 Orléans, France
ঌ Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-SCE32UVSQ, Université Paris Saclay, 91191 Gif-sur-Yvette, France

Corresponding author: Jean-Philippe Jenny (jean-philippe.jenny@inrae.fr)

Abstract

Lentic waters are biogeochemical reactors, producing and receiving carbon (C) originally fixed by the terrestrial and aquatic biosphere, which is then buried in sediments or respired back to the atmosphere in the forms of carbon dioxide (CO_2) and one of the more potent greenhouse gas (GHG) methane (CH_4). Additionally, lakes serve as archives of terrestrial and aquatic carbon processes within their sediments, enabling the reconstruction of historical changes spanning thousands of years. These changes encompass alterations in land cover, indicated by pollen records, soil carbon erosion, and shifts in lake productivity resulting from changes in land use and climate. Both the burial of C in lakes and the emissions of GHGs are recognized as an important components of Earth's climate system, yet they remain poorly understood and

constrained due to inadequate quantities and qualities of observations. In the case of GHG emissions from lakes, observations are often sporadic, failing to capture the significant spatial and temporal variations in emissions across diverse lentic systems. To address this challenge, process-based models that incorporate the interconnected biogeochemical processes occurring within lakes and their watersheds would arguably be the best tool to extrapolate from site-level observations to regional and finally global scales, to quantify the anthropogenic impact on these fluxes, and to reconstruct long-term shifts in emissions and burial due to changes in land cover and climate. But the development and evaluation of such models is hampered by the lack of observations in sufficient quality. In this project, we bring together a unique consortium of specialists in aquatic ecology, biogeochemistry, palynology, sedimentology and modelling of terrestrial and aquatic biogeochemistry. This project will put forth a national program of systematic, long-term observations of lake GHG and C cycling processes of unmet detail, consistency and quality. First, at 40 pilot sites spanning typological and environmental gradients, there will be a comprehensive data acquisition endeavor to evaluate biological processes and mesological factors influencing the sequestration or recycling of organic carbon. This effort will be complemented with a synthesis of existing data (WP1). Second, based on well-dated sediment records, which include both newly acquired and synthesized existing data, variability of lake C burial and their climate and land use controls will be reconstructed over the past 150 years (WP2). For 15 of these pilot sites, reconstruction will go back until the mid-Holocene (5,000 years BP), allowing to shed light on the anthropogenic perturbation of the C cycle in this earlier part of human history, which is commonly excluded from this type of research due to lack of information. The activities of these two first WPs will result in an open-source national database, guaranteeing valorization of our research far beyond this project. In WP3, we will use the land surface model (LSM) ORCHIDEE C-lateral to assess C cycling in the terrestrial biosphere and the mobilization of biospheric C into lakes, which is possible due to an explicit representation of soil C leaching and erosion processes and a downscaling scheme permitting to assess C exports from watersheds at sub-grid scale. While LSMs are used to assess evolution of biospheric C budgets from the beginning of the Industrial Period, we will use it to hindcast the evolution since the mid-Holocene, using lake sediment record for model validation. Moreover, we develop a new process-based lake C model supported by the database established in WPs 1 and 2, which we will couple to ORCHIDEE C-lateral to simulate lake C burial and GHG emissions in response to climate and processes in the lake watershed. This model set-up will first be used to better constrain contemporary large-scale lake GHG emissions and to disentangle the anthropogenic perturbation of these fluxes from the natural background flux. These estimates will be revolutionary, as they will allow attributing part of lake GHG emissions to anthropogenic emissions for national GHG budget reporting. Then, these models will be emulated to reconstruct evolution of lake GHG budgets and C budgets of the whole lake watershed since the mid-Holocene. While simulations will first be performed at the scales of France and Europe, the development of international partnerships to implement observations from other biomes (WP4) will finally support simulations at the global scale.

Keywords

Land to ocean aquatic continuum, Lentic waters, Lakes and reservoirs, C stocks and fluxes, Exports from watersheds, Soil erosion and C-exports, biological processes, CO_2-CH_4 emissions, C accumulation in sediments, Model-data integration, Land surface models, Global estimates, Regional synthesis, Local validations for lake-watershed systems, Sediment records, Sensors, Integrated approaches, Temporal trends (centuries to millennia)

Significance of the Interdisciplinary Consortium

The DEEP-C project, a pivotal component of the PEPR FairCarboN initiative spanning from 2023 to 2028, assembles an unparalleled consortium of specialists in studies of aquatic ecology, biogeochemistry, palynology, sedimentology, but also in modeling of terrestrial and aquatic biogeochemical processes at local to global scales. This innovative interdisciplinary collaboration aims to establish a comprehensive national program, marked by systematic and long-term observations of greenhouse gas (GHG) emissions from lakes, precise measurements of carbon burial in sediment cores, and an in-depth examination of carbon cycling processes that have previously lacked detailed examination. Notably, this effort extends beyond experimental approaches to incorporate modeling techniques for spatial extrapolations and historical hindcasts. Importantly, the project will enable the synergy between experimentalists and modelers, emphasizing their collaborative efforts as a central strength of the endeavor.

Encompassing 40 pilot sites across France and integrating existing national data to complement observational efforts, this project sets the stage for novel model-data integration approaches. The model set-up derived from this interdisciplinary synergy not only aims to enhance the precision of contemporary large-scale lake GHG emissions and carbon burial constraints but also strives to differentiate anthropogenic perturbations from the natural background fluxes. Notably, the retrospective approach, extending back to the mid-Holocene (5,000 years BP), adds a unique temporal dimension to the investigation.

Although the initial focus is on France and Europe, the simulations are set to go beyond geographical boundaries through the establishment of international partnerships. These collaborations will facilitate observations in diverse biomes, ultimately scaling the project's impact to a global level. The originality and benefit of this interdisciplinary consortium lie in its holistic and innovative approach to comprehensively understanding and addressing the complexities of lake-watershed carbon biogeochemistry.

Context, objectives and previous achievements

Context and objectives

Over the past 15 years, the inland water network has received growing attention in global carbon (C) cycle research: as direct link between terrestrial and ocean components of the C cycle, as important source of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere, and as potentially important sink of C on the continents (Cole et al. 2007 Lauerwald et al. 2015 Liu et al. 2022 Raymond et al. 2013 Tranvik et al. 2009). Numerous regional to global scale estimates on inland water C fluxes have been published, but most progress has been made for emissions of CO_2 from flowing waters (Cole et al. 2007 Lauerwald et al. 2015 Liu et al. 2022 Raymond et al. 2013 Tranvik et al. 2009), while emissions from standing water bodies such as lakes and reservoirs, and in particular emissions of CH_4, are much less constrained. Filling this knowledge gap is crucial because, in terms of climate impact, lake CH_4 emissions could be of similar importance as total inland water CO_2 emissions (Lauerwald et al. 2023). At the same time, due to their efficient sedimentary C burial, standing water bodies are potentially important sinks of C, but the magnitude of this flux also remains poorly constrained, with estimates ranging over one order of magnitude (Mendonça et al. 2017). The impact of C cycling in standing water bodies on the climate system largely depends on the ratio between net-C burial in sediments as long-term CO_2 sink and the emissions of CO_2 and the more potent greenhouse gas CH_4, both recognized as key uncertainties in the last assessment reports of the IPCC (Canadell 2023). Both fluxes, just as the overall cycling of C in standing water bodies, is influenced by allochthonous terrestrial inputs of sediments, C and nutrients, and thus by physical and biogeochemical processes in the watershed and their anthropogenic perturbations. The extent to which these fluxes have been perturbed by human activities however remains difficult to constrain quantitatively (Regnier et al. 2013 Regnier et al. 2022). Although these fluxes are conventionally viewed as natural components of terrestrial carbon and greenhouse gas budgets, their precise quantification remains elusive (IPCC AR6) (Canadell 2023). Studies on lake sediment records have found that C burial and sediment accumulation rates have accelerated between 5,000 and 2,000 years BP due to anthropogenically caused land cover change and soil erosion (Kastowski et al. 2011 Jenny et al. 2019). The anthropogenic perturbation of those fluxes goes thus back until the Mid-Holocene. Eutrophication of lakes, caused largely by the increase of land use nutrient inputs in the 20th century, has been found to substantially increase CH_4 production and emission from lakes (Li et al. 2021 Rinta et al. 2016), a trend which is expected to further increase over the 21st century (Beaulieu et al. 2019).

The poorly constrained estimates on CO_2 and CH_4 emissions from standing water bodies are due to the sparsity and insufficient quality of observations, the complexity of the physical and biogeochemical processes constraining these fluxes, and the lack of suitable process-based models for spatio-temporal upscaling. Flowing waters typically exhibit thorough mixing, facilitating the measurement of representative greenhouse gas (GHG) concentrations. In contrast, standing water bodies often exhibit greater internal heterogeneity, influenced by factors such as lake bed geometry and proximity to terrestrial inflows of sediments, carbon, and nutrients (Colas et al. 2020). In addition, seasonal lake stratification alternating with periods of lake turn-over complicates the relation between GHG production and emissions in lakes and may lead to short periods of intense water-atmosphere gas exchange. Unfortunately, most sampling campaigns on standing water bodies are not designed to account for this internal spatial and temporal variability, which easily leads to large uncertainties and even biases in estimates of CO_2 and CH_4 emissions - even for individual water bodies (Colas et al. 2020). Further, uneven geographic distribution of observations and underrepresentation of specific systems, such as small lakes and impoundments (Downing et al. 2008) mandate caution towards observation based regional to global scale estimates of CO_2 and CH_4 budgets of standing water bodies. Also the C burial in aquatic sediments remains poorly quantified at regional to global scales for similar reasons (Mendonça et al. 2017).

The arguably best strategy to extrapolate from local observations across ranges of types and sizes of standing water bodies, as well as across biomes and intensity of land use of the lakes' watershed would be a process-based modelling framework that represents the coupled biogeochemical cycling between the water bodies and their watershed. In fact, simple, process-based models have recently been used to re-estimate present-day CO_2 and CH_4 emissions from lakes and reservoirs (Johnson et al. 2022 Soued et al. 2022).

While the approach is promising, the predicting capability of these models is limited. One reason for this is that quantitative process understanding from experimental field studies is not yet available in sufficient quantity and quality. The other reason is that existing model approaches have not yet succeeded in coupling C dynamics within the water body to physical and biogeochemical dynamics of their catchment which control the inflows of water, sediments, C and nutrients. Finally, the difficulty also stems from the inability of models and data to capture the temporal evolution across scales, from single events to seasonal to long-term changes, hence motivating the coupling between current, centennial and millennial approaches.

The main objective of this project is to substantially improve our understanding of C cycling in standing water bodies, ranging in types from agricultural ponds and gravel pits to large lakes and reservoirs, and focussing on fluxes of long-term (i.e. both centennial and millennial) C burial in sediments and emissions of CO_2 and CH_4 in response of environmental change in the watershed. We seek to use that knowledge to quantify the contribution of standing water bodies to terrestrial C and GHG budgets at local to global scales. First, we strive to come up with better constrained estimates for present day. Moreover, to implement these estimates into anthropogenic C and GHG budgets at policy-relevant national, European (Petrescu et al. 2021) and global scales (Friedlingstein 2022 Saunois 2020), we will quantify the natural background component of these fluxes and their anthropogenic perturbations, which results from centennial changing inputs of sediments, C and nutrients. Placing our work on a long-term perspective will allow to investigate main environmental drivers on C fluxes and stocks: atmospheric CO_2 levels, land cover change and climate change (Fig. 1).

Second, in addition to the centennial timescale, we seek to reconstruct the millennial evolution of local to global C cycling within standing water bodies in response to land cover and climate change over the past 5,000 years. This will allow us to assess the long-term impacts of human land use and land cover change since the late mid-Holocene.

With this attempt, we defy common views of the so-called Anthropocene that focus the analysis of anthropogenic perturbation of the land-inland water connexion of global C cycle starting with the Industrial period, and tending to view pre-Industrial state of the global C cycle as nearly natural.

DEEP-C would therefore provide new answers to fundamental questions: What is the contribution of lentic waters to the land C budget across annual to millennial timescales? What are the impacts of land use and climate change on GHG emissions and C stock formation in lentic waters across timescales? What are the rates of change in soil C exports, C burial in lentic waters and C emissions to the atmosphere over the period 1850-2100 and over the past millennia? How has the ratio emissions:burial rates in lentic systems changed over time? What are the main controls across spatial and timescales? What are the rates of change in C turnover in lake catchment systems over the past centuries and millennia?

In this research project, we would like to test the following hypotheses:

• **Hypothesis H1**: The implementation of new data collection aimed at refining constraints on lentic CH_4 emissions, identified as the most uncertain factor in the budget according to the latest IPCC AR6 , combined with the advanced assimilation of paleolimnological records into terrestrial and aquatic modeling approaches, is anticipated to result in a substantial decrease in uncertainties within the global carbon (C) budget.

• **Hypothesis H2**: Annual C burial in standing water bodies is relatively modest (~0.5 Pg C a-1) but C stocks in aquatic sediments are well preserved from degradation. This long-term burial escapes the short-term C cycle, and is probably one of the least constrained terms in the global C budget. It will potentially lead to relatively large geological C stocks over centennial to millennial timescales that need to be considered in global C estimates.

• **Hypothesis H3**: Anthropogenic activities have altered C cycling on the continental surface, including stock changes in terrestrial biosphere (biomass and soils) and aquatic sediments - for thousands of years, and not only since the Industrial revolution. Landscape opening due to human activities have accelerated soil C erosion and C burial in sediments, which partly counterbalances the concomitant decrease of C stocks in plant biomass. Eutrophication of standing waters, which is largely due to land use related mobilisation of nutrients since the 20th century, has led to a turning point in the role of standing waters in greenhouse gas cycling of continents, with enhanced CH_4 emissions increasingly outweighing the effects of the C sink.

To achieve our research goals and test the hypothesis outlined above, we bring together a unique consortium of specialists from various, complementary fields including aquatic ecology, biogeochemistry, palynology, sedimentology as well as modelling of terrestrial and aquatic biogeochemical cycling at local to global scales. Together, we coordinate our efforts to achieve new standards in field research, process understanding and modelling of C cycling in standing water bodies and their watersheds.

This project will put forth a national program of systematic, long-term observations of lake GHG and C cycling processes of unmet detail, consistency and quality. First, extensive data collection will be conducted at 40 pilot sites spanning typological and environmental gradients across France. This endeavor will focus on assessing biological processes and mesological factors associated with the sequestration or recycling of organic carbon. (WP1). Further, based on well-dated sediment records from these sites, variability of C burial in standing water bodies and their climate and land use controls will be reconstructed over the past 150 years (WP2). For 15 of these pilot sites, reconstruction will go back until the mid-Holocene (5,000 years BP), allowing to shed light on the anthropogenic perturbation of terrestrial C cycling in this earlier part of human history. A third work package (WP3) focussing on modelling approaches will support this experimental work by providing estimates of water, sediment, C and nutrient inputs from the surrounding landscape. In this first step, the local simulations on pilot sites will include a reconstruction of land cover change in the watersheds over the past 5,000 years and their impact on these terrestrial matter inflows. In a second step, WP3 will upscale these local scale reassessments of C and GHG budgets of standing waters first to the European and finally the global scale, developing and using a lake C model which will be coupled to a land surface model simulating terrestrial C cycling in response to rising atmospheric CO_2 levels, land cover change and climate change. This upscaling will further be supported by a review of existing field observations from publications and grey literature (also WP2) and international collaboration with experts working on high and low latitude systems (WP4). Finally, we will run simulations over the past 5,000 years, allowing for the assessment of long-term land use and land cover change impacts on C cycling on continents, including both C stock changes in terrestrial biosphere as well as in lake sediments.

Main previous achievements

The reserach objectives and hypotheses of the project DEEP-C are supported by 1) previous achievements in assessment of C cycle in lentic waters from sites around the world, but also improvement of technics for measurement of C fluxes, stocks, and metabolism in lentic systems, 2) a decade of development and progressive collection of paleo-observations conducted in France (which had not yet been synthesised), 3) development of methods for local to regional scale reconstruction of land cover based on pollen records from lake sediments, and 4) recent developments of process-based lake biogeochemical models for large scale application and the implementation of reactive fluvial C transfers into the land surface model ORCHIDEE.

More specifically, the methodological approaches in WP1 (c.f. WPs detailed in section 2.2.) will mainly beneficiate from long experience within the consortium (i.e. Dr. Fanny Colas, Dr. Yves Prairie) in assessing temporal and spatial variability in **CO_2 and CH_4 surface water concentrations and diffusive fluxes** combining both a high temporal and spatial resolution monitoring (Prairie et al. 2017, Colas et al. 2020, Soued et al. 2022). The **retro-observation approaches** developed in WP2 using lake sediment records will be supported by bringing together five French units (CEN, EDYTEM, CARRTEL, GEODE, ISTO) with strong expertise in reconstructing past centennial to millennial variations in land cover (pollen-based), soil erosion (terrigenous accumulation rates), C exports from land (allochthonous C sources), water C primary productivity (autochthonous C sources). Access to well-equipped platforms, lab and coring facilities (c.f. section 5, *Partners' Commitment)* will unsure WP2 objectives.

The model development proposed for WP3 will profit from experience within the project consortium concerning development and application of models simulating CH_4 (Maisonnier et al. in prep., used in the European CH4 budget by Petrescu et al. 2022) and CO_2 budgets as well as physics and oxygenation (Desgué-Itier et al. 2023) of standing water bodies. These model developments comprise already most of processes that will be required for the lake C model to be produced here, and can directly be adapted for this project.

In addition, members of the project consortium took a leading role in the development of a new version of the land surface model ORCHIDEE (ORCHIDEE C-lateral) to be used in this project for its representation of C leaching and erosion from soils into the river network as well as the reactive transport of C through network of rivers and floodplains (Lauerwald et al. 2017). Land surface models are used to simulate the strength of the land C sink in response to increasing atmospheric CO_2, as well as to changes in climate and land cover, but usually ignore inland water C fluxes. It could be shown that fluvial C transfers have a non-negligible effect on the simulated land C sink, and classical land surface models not representing these fluvial C transfers are biased by underestimating the terrestrial net-uptake of atmospheric CO_2 and/or overestimating the accumulation of C in the terrestrial biosphere (Lauerwald et al. 2020). What is however urgently missing in these land surface models are the representations of standing water bodies and of inland water CH_4 emissions. In this project, we will finally close that gap by coupling the new lake C model to ORCHIDEE C-lateral.

Detailed project description

Project outline, scientific strategy and innovative features

DEEP-C proposes 3 research innovative avenues:

1. **bridging disciplines** - Despite relatively widespread current use, our understanding of the inland water C-cycle on centennial or millennial timescales is severely limited by the lack in the integration of (paleo)observations with model approaches. DEEP-C opens new frontiers in data-model integration for short and long-term C cycle estimations and combines experts from numerical modelling and field and lab work;
2. **integrating lentic waters in land surface model framework** – a model of lentic water C cycling will be coupled to a land surface model. Integrating lentic waters in land surface model framework will permit for an operational approach of model-data integration to better understand the coupled biogeochemical cycling of

aquatic and terrestrial ecosystems at regional to global scales in response to chnages in climate and land cover;

3. **identifying long-term trends and environmental drivers** of C cascades along the inland water network - Controls of Land cover change and climate will be investigated both temporally and spatially. The new knowledge to be generated in this project – and formalized into new conception of land surface models – will potentially completely redefine our views on the role of human activities and lentic waters in the global carbon cycle and hence will open new horizons in land surface modelling, where long-term changes and lentic C cycle still do not receive appropriate attention.

Adequation with the Call - DEEP-C meets the exploratory PEPR FairCarboN objectives aiming to develop the role of continental ecosystems in climate change mitigation and the attainment of carbon neutrality. DEEP-C will gather a multidisciplinary consortium of 34 carbon (or related fields) experts including national experts from academia and private sectors (e.g. EDF, ECLA), thereby consolidating French leadership in the area of carbon management within continental and inland waters ecosystems. **First, DEEP-C is in line with the open call** topic in FairCarboN « Source, transfer, transformation, and storage of carbon along the terrestrial-coastal-atmospheric continuum » to a better understanding of the key processes governing the carbon cycle, providing

1. empirical and model trends and quantitative estimates on the coupled C cycling along the terrestrial-aquatic continuum of the continents that need to be accounted for in future global C cycle projections, and
2. variations in C stock formation and C vertical fluxes in lentic waters that are critical for estimating the net C effects of lentic waters in the inland water network.

Second, DEEP-C will contribute the fifth target project (PC5), being part of two actions in PC5 (c.f. continental sedimentary C stocks & lentic waters C emissions) with 4 involved members of the consortium in PC5, for the creation of an unprecedented database on the evolution of carbon stocks and fluxes in French lentic waters. Previous data collections, grant access to lakes and reservoirs, and supports from infrastructures and water managers (i.e., Pôle ECLA, EDF-CIH, OLA) will benefit to the consortium for sites selection and data acquisition. Yet, large data acquisition will be made to complete lacking information on current C stocks, transfers and emissions.

Scientific and technical description of the project

<u>Work plan</u>

Four work packages (WP 1-4, see Fig. 2) comprising six individual research projects (RP) have been defined to test hypotheses H1-H3:

1. WP1 and 2 will consolidate (in coordination with PC5) observations of modern and past C fluxes and stocks in lentic waters over large scales through review of existing data and an own monitoring programm,

2. WP3 will integrate data collected in WP1-2 into a land surface model framework to quantify continental C budgets and their long-term response to land cover change at European and global scale, with a specific focus on the role of inland water on the C cycle,
3. finally, WP4 will develop international partnerships to integrate C lentic data from other sites of the world in order to support initiatives in WP1-3 for upscaling C estimates from national to global scales.

The research projects will include a well-balanced mix of observation and modelling. Each project is a highly challenging, stand-alone scientific task. For the success of the project, close collaboration and intensive exchange of information, knowledge and code is foreseen between the projects to maximize the synergies of the different research plans.

Work packages and individual research projects

WP 1: Assessing current carbon stocks, fluxes and drivers in lentic waters at national level

***Leaders** : Fanny Colas (LEHNA) & Hélène Masclaux (CE), **Participants**: 15P*

The objective in WP1 is to provide robust estimates on current C stocks and emissions from lentic ecosystems and to investigate abiotic and biotic controls involved in the fate of stored organic C. To achieve this objective, WP1 will examine 40 lentic systems in France that capture a wide range of land cover, climatic conditions and water types, including natural and artificial lakes, ponds and gravel. Field and lab work in the 40 sites will be complemented with a synthesis of available data published or from the grey literature.

The WP1 is structured into three interconnected tasks: Task 1 (T1.1) focuses on the quantification and characterization of C in the surface sediment; Task 2 (T1.2) will assess the fate of C (i.e., sequestration vs. mineralization), the metabolic pathways and the microbial diversity involved in C transformation; Task 3 (T1.3) focuses on CO_2 and CH_4 emissions from sediments. T1.3 will further assess CO_2 and CH_4 transfers within the benthic and pelagic food webs and its evasion to the atmosphere. The three tasks in WP1 will also investigate the controls and processes involved in the C cycle. Data collections in WP1 will be planned and coordinated with WP2 and 3, and with two actions part of the target project PC5 in FairCarboN.

T1.1: Assessing the origin, quantity and quality of OM stocks in sediments (M1-36)

T1.1 will **quantify current C sediment stocks, the relative contribution of terrestrial vs aquatic C in sediments** , and the controls on C accumulation in sediments within and among lentic water systems. More specifically, the role of environmental drivers on C accumulation will be investigated, including mesological conditions, water quality and human footprints, and will be conducted during field work on the 40 lakes and lab analyses (M1-36). Continuous monitoring and punctual measurements will be achieved in the 40 study sites. Oxygen concentrations and temperatures will be monitored in the water column during over a year using sensor mooring line at the point of maximal depth. Sediment traps (and topmost sediment core samples) will be used to quantify sediment accumulation rates and to analyze C composition, including C organic concentration (Corg), total C, nitrogen (N) and phosphorus (P) concentration (C/N/P), lipid composition and quantitative organic palynofacies characterization (Simonneau et al. 2014, Simonneau et al. 2013). The origin of OM will be assessed with C_{org}:N_{tot} ratio, C isotope signature ($\delta^{13}C$) and palynofacies. Autochtonous C sources related to primary production will be quantified using HPLC carotenoids and chlorophyll a pigments. Deployment of the sensors and traps will be done for each of the 40 study sites in late winter, just after thaw.

T1.2: Estimating the transformation, burial and emissions of C from sediments (M6-48)

GHG production at the water/sediment interface will be quantified in the deepest zone of each lentic systems in late summer using respiration chambers equipped with submersible gas and oxygen/temperature sensors. The respiration chambers are configured to have 10 cm of chamber walls buried inside the sediment. Two non-return valves are placed at the corners of the chambers allowing the water to drain into the chamber during the immersion. The incubation period is 45 minutes during which gas concentrations and temperature will be recorded every minute. Additionally, GHG concentrations and C stable isotope analyses ($\delta^{13}C$-CH_4,$\delta^{13}C$-CO_2) will be quantified in interstitial water at 0.5 m below the sediment surface to examine metabolic pathways and the origin of OC sources associated with GHG production Bastviken et al. 2002 Flury and Ulseth 2019 Rinta et al. 2015) using Picarro analyzer. A research engineer (IE) will be recruited to support T.1.1 (in coordination with WP2 T.1-2). A database of CO_2-CH_4 emissions on 40 French pilot sites is expected for M24 (D1.1) and will be updated until M60.

The microbial community composition and activity involved in GHG production will be assessed using subsurface sediment samples from each pilot site, collected with a gravity corer. Based on CH_4 concentration data, relevant sediment samples will be selected for molecular microbiology analyses. DNA will be extracted using a soil dedicated DNA extraction kit, and quantified fluoretically. Methanogenic and methanotrophic community abundances will be quantified by DNA-based qPCR abundance of the particulate CH_4 monooxygenase gene (pmoA) involved in methanotrophy, and of the methyl coenzyme M reductase (mcrA) involved in methanogenesis. The diversity of both Bacteria and Archaea will be evaluated using high-throughput sequencing targeting 16S rRNA genes (two distinct assays for Archeae and Bacteria). Sequencing datasets will be analyzed to determine the archaeal and bacterial ASVs present in the sedimentary samples. The functional potentialities of microbial communities will be defined using the PICRUSt2 tool, and relationships between the main functions and the productivity of the systems will be sought. It is hypothesized that land cover and eutrophication will affect microbial communities and related GHG production both through the quality and quantity of OC inputs to the surface sediment. The magnitude of this effect would depend on the site typology. Two papers are expected in T1.2 at M24 on microbial communities interaction with GHG production in sediments (D1.2) and on benthic-pelagic transfer of C in lentic ecosystems (D1.3).

T1.3: Transfer and transformation of C in lentic waters (M1-60)

This task aims to **quantify GHG and the proportion of CH_4 vs CO_2 emitted in the atmosphere vs transferred in the food webs**. Recycling of organic C in the sediment leads to the production of CO_2 and CH_4 that can either be transferred to benthic and/or pelagic food webs or emitted in the atmosphere. We plan to evaluate whether biotic and abiotic factors in the sediments and in the water column are likely to modulate the relative proportion of these two transfer pathways.

For this purpose, the **dynamics of GHGs from benthic processes along the water column** will be evaluated by means of concentration profiles using the headspace method (UNESCO/IHA 2010Kampbell et al. 1989) that accounts for the carbonate equilibrium for CO_2 (Koschorreck et al. 2021). Concentration of CO_2 and CH_4 will be quantified along the column water three times a year, in late winter, in late summer and in autumn (Task 2.1). C isotope signature of GHG ($\delta^{13}C$-CH_4,$\delta^{13}C$-CO_2) will be measured at each sampling depth to examine the origin of C sources associated with GHG dynamics along the water column. Additionally, atmospheric gas emissions will be determined for CO_2 and CH_4 using a floating chamber equipped with three-way Luer-lock stopcoks with connection to the Microportable Greenhouse Gas Analyser (MGGA, Los Gatos Research Inc., Envicontrol, France). The floating chamber will be deployed 3 times at the center of the lake and left drifting during measurement to avoid creation of artificial turbulence. Each deployment will be run over about 5 min after an equilibration period with an open vent for 5 min.

At each sampling time, qPCR will be performed on suspended particles of the water column to study **microbial community composition and the importance of Methane Oxydising Bacteria** (MOB). For the same purpose, fatty acids biomarkers of MOB (16:1ω8 and 18:1ω8, Bowman et al. 2011) will be quantified in suspended organic matter. In parallel, the activity of the MOB and the oxidation rate of CH_4 will be evaluated by measuring the isotope signature of CH_4 ($\delta^{13}C$-CH_4). Characterisation of Csources used by benthic and pelagic consumers will be done by measuring their $\delta^{13}C$. As consumer signatures can be very variable during an annual cycle (Essert et al. 2022), the $\delta^{13}C$ of consumers remains found in surface sediment of the autumn field campaign will be used. Chironomid head capsules and carapace remains of zooplankton reflect indeed the signature of the whole consumer at the time they were produced, and reflect a time-integrated average signature of the consumer source population (Perga et al. 2010). Altogether, T1.3. will provide assessment of the GHG dynamics in lentic ecosystems (publication D1.4) and on the abiotic-biotic factors controlling the fate (sequestration vs. transfer/emission) of C in lentic ecosystems (D1.5). The task will be supported by one postdoc M6-24 under the supervision of Emilie Lyautey (CARRTEL) for the microbial communities and one PhD Student (M1-36) supervised by Fanny Colas (LEHNA).

WP2: Long-term variations in carbon stocks and fluxes in lentic waters

***Leaders** : Laurent Millet (CE) & Jean-Philippe Jenny (CARRTEL), **Participants**: 8P*

WP2's objective is to consolidate (paleo)observations and to assess C stocks, sources and drivers in lentic systems over 1) centennial and 2) millennial timescales (c.f. Fig.2) using well dated sediment archives. Specific objectives will be to

1. collect and analyse new empirical C data (quality & quantity) from short sediment cores,
2. assess the centennial effects of eutrophication and climate on C burial in 40 lentic systems,
3. investigating millennial trends in erosion, C exports and C lentic stocks, and testing the stationarity of these fluxes and potential interactions, such as erosion: C-exports ratio that informs on the relation between erosion and C exports over time.

Datasets on C stocks used for global simulations of the C cycle in inland water network reveals major gaps and disparities (e.g. only four lentic waters in France so far) (Regnier et al. 2022), hence stimulating research in WP2.

T2.1: Assessing the spatial variability of carbon burial rates in lentic waters (M1-24)

The objective in T2.1 is to as assess current C stocks and the C sources in 40 lentic systems: i.e. the amounts of organic matter generated in lentic waters (C uptake from lacustrine photosynthesis) to be discriminated from terrigenous C supplies originating in their drainage basins. Accumulation of C stocks over time in lentic sediments will be calculated in T.1 from elemental C (%) measurements, sediment density and age-depth models derived from ^{210}Pb, ^{137}Cs radionuclides and radiocarbon analysis. In order to build the most comprehensive data-set possible, T2.1 will first carry out a review of existing data in French lentic sedimentary systems, including published and un-published data, and then complement the dataset with new acquisition in 40 French sites. The terrestrial and lacustrine origin of the C will be inferred on the basis of C_{org}:N ratio, C isotope signature, rock-eval pyrolysis, and biomarkers: i.e. algal pigments, lignin derivatives, n-alkanes, methyl ketones and tetraethers. End-member signatures from isotopic and elemental ratios will be used to quantify C sources. The origins of the organic matter will be further investigated by optical characterization. Field and lab work in Task 2.1 will be performed by researchers, by a research engineer and by Master students during the first 3 years (shared with WP1) of the project under supervision of Laurent Millet, Fanny Colas and Jean-Philippe Jenny. Completion of estimations on current C stocks, sources and drivers (D2.1) is planned for M24. Related paper publications and comprehensive database on modern carbon burial rate are planned in M32 (D2.2).

Published data mainly concern natural lakes and still poorly document small water bodies of anthropic origin such as gravel pits, ponds, etc., which nevertheless account for the majority of French water bodies. The ambition of our project is therefore to implement a paleolimnological approach on a selection of 40 sites located in France and in the rest of Europe in order to increase the representativeness of the database. A significant part of our research efforts will be directed towards small anthropogenic water bodies (less than 10ha).

T2.2: Impact of the Great Acceleration of the Anthropocene on C stocks and sources (M1-48)

T2 will apply a paleolimnological approach to 40 lentic systems in order to investigate temporal changes in organic C burial in relation with changes in C sources, lake primary production, and preservation conditions over the past 150 years. The objective of this task is to assess the response of water bodies and the associated Ccycle to the unprecedented increase in human activities and their impacts on the environment that took place in the middle of the 20^{th} century, commonly referred to as the Great Acceleration. The task will provide a pre-Anthropocene state and an assessment of the Ccycle response to perturbation from linear and easily reversible trajectories to more complex dynamics involving rapid shifts to degraded and poorly reversible steady states.

In the 40 sites, development of a paleolimnological approach will be on the past 150 years to assess (quantitatively and qualitatively) the impact of the Great Acceleration and associated anthropic impacts on C burial in water bodies (D2.3). Our hypothesis is that in European lentic waters, the 1950's are characterized by an unprecedented shift in C cycle driven by the accelerated eutrophication. We expect a large increase in organic carbon (C_{org}) burial and a shift from allochtonous to autochtonous dominated sediment organic matter. Interaction between C cycle and biodiversity will be assessed using chironomid community as a good predictor of macro-invertebrate diversity, isotopic signature of subfossils remains of benthic and pelagic consumers.

T2.3: A multi-millennial assessment of the influence of perturbation regime on carbon transfer and sequestration (M1-36)

T3's objective will be to explore variations and sensitivity of C stocks in lentic systems over the past **5,000 years in 15 lake-catchment systems**. The hypothesis is that human activities have increased C exports from land to lentic systems. Consequently, through burial of erdoded soil, C is transfered from the short-term C cycle to the geologic cycle. We will take advantage of the existence of 15 well-dated lake sedimentary records in France where changes in land cover and/or erosion processes have been reconstructed at high chronological resolution. In this case, sediment archives from natural lakes are selected as they are recognised as one of the best continental archives with continuous records of near annual resolution. This existing dataset (not yet published as a set, and especially not for Csignal so far) will be completed with new measurements to harmonize the available dataset. As a result we will provide the first comprehensive reconstruction dataset of land-cover, soil erosion, soil C transfer, and lentic C stocks and sources (Bajard et al. 2015 Bajard et al. 2017 Brisset et al. 2013 Giguet-Covex et al. 2011 Giguet-Covex et al. 2014 Simonneau et al. 2013) that will be analysed and published by a postdoc under supervision of Fabien Arnaud (EDYTEM), Didier Galop (GEODE) and Jean-Philippe Jenny (CARRTEL) (D2.4).

The analytical approach will combine measurements described in T2.1, complemented with high resolution characterisation of C and of the mineral fraction (XRF and MSCL-S hyperspectral analysis). This will be supported by the new MSLC-S hyperspectral at the sedimentological platform USMB-ASTRE managed by EDYTEM funded with MITI INRAE-CNRS subventions in the C-Sensible project at the prefiguration of this call (c.f. Project section). A PhD student will support the analytical part related to C characterisation, hired at EDYTEM on external funds. Terrigenous fluxes derived from dry bulk density and sediment ^{14}C dating will be used to reconstruct temporal variations in the amplitude of soil erosion and will be compared to test the stationarity between erosion and C exports over millennial timescales (D2.5).

Four regions will be considered, mostly in mountainous areas and surroundings, as they are prone to changes in past land cover and soil erosion sediment transfers (Fig.2). In each region two types of sites will be considered: **Reference lakes** with already available well-dated paleo-signal of land cover and soil erosion (Giguet-Covex et al. 2011 Giguet-Covex et al. 2014 Simonneau et al. 2013). T2.3 will complement these time series with C (quality and quantity) data. **Satellite lakes** will be included in some regions, not for erosion and C signal, but in order to improve the number or pollen records necessary for land cover reconstruction made in WP3 (Marquer et al. 2020b Marquer et al. 2020a Plancher et al. 2022). This task will benefit from the input of the large consortium national experts, each with a strong knowledge of the studied regions and related paleo-records. T2.3 will be supported by the above-mentionned postdoc (M1-24) to perform and analyse such unique synthesis of multi-proxy paleo-records.

WP3: Modelling large scale C exports, stocks, emissions

Leaders *: Ronny Lauerwald (EcoSyS) & Pierre Regnier (ULB),* ***Participants****: 7P*

WP3 will quantify continental C budgets and their long-term response to land cover change at European and global scale, with a specific focus on the role of inland water C fluxes. Specific objectives will be to

1. reconstruct land cover change in the basins of 15 pilot sites,
2. the assessment of long-term effects of land cover change on terrestrial C turnover over the last 5,000 years at local to global scales,
3. reassessing inland water C fluxes (CO_2 and CH_4emissions, burial, export to coast) at European and global scale, while quantifying the anthropogenic perturbation of these fluxes (Fig. 3).

T3.1 Reconstructing land cover change at pilot sites (M13-M24)

The main objective of Task 3.1 is to reconstruct the evolution of land cover over the last 5,000 years in the watersheds of the 15 pilot sites where sediment cores will be taken. This reconstruction will be based on pollen analysis and application of the local vegetation reconstruction model LOVE (Sugita 2007). Task 3.1 will be performed by a PostDoc during the first year of the project under supervision of Florence Mazier

(GEODE). The targeted time of completion of vegetation reconstructions (D3.1) is M21, leaving 3 months for finalizing related publications. D3.1 is a major input to T3.2.

T3.2 Simulation of terrestrial C turnover and exports to inland water network (M8-M34)

The main objective of T3.2 is the simulation of C turnover in terrestrial ecosystems, including the mobilization of C into the inland water network at European to global scale. In addition, this task will also provide simulated time series of riverine inputs of water, sediment, Cand nutrients to the lakes of the 40 pilot sites, to be used in WPs 1 and 2, as well as in T3.3. A PostDoc will be hired for 2 years at INRAe/UMR EcoSys and supervised in close collaboration with LSCE, IPG, ULB, SAS and MPI-Jena. A 3 month secondment at MPI-Jena is foreseen.

Riverine inputs to the pilot sites will be simulated using the process-based model SWAT in combination with high-resolution geodata and field level observations of topsoil characteristics for different types of land use (forest, cropland, pasture, near natural grassland), including texture and concentrations of organic C, carbonates, nitrogen and phosphorous. Once the model is calibrated and evaluated against discrete measurements of river water quality, it will be used to obtain continuous time-series of inflows to the pilot sites over the past three decades (D3.2, due M18). For the 15 pilot sites where sediment cores will be taken and analysed, SWAT will then be used to reconstruct water and matter in-fluxes over the last 5,000 years (D3.3, due M32), based on reconstructed land cover (D3.1) and paleo-climate data from general circulation model (GCMs) output to be downscaled and bias corrected against locally observed meteorology. Note that D3.2 and D3.3 are important inputs for WP1 and WP2, respectively, as well as for the development of the inland water C model in T3.3. Moreover, in cooperation with WP2, we will evaluate simulated long-term dynamics in sediment inflows against observations from the dated sediment cores (WP2), and modify the SWAT hindcasts (like adapting assumed crop cover effects for historical land use) until simulated and observed long-term dynamics sufficiently agree.

For the large scale simulation of terrestrial C turnover and mobilisation of C from the terrestrial biosphere into the inland water net-work, we use the land surface model ORCHIDEE-$C_{lateral}$. This model has recently been calibrated and evaluated at European scale (ESD) (Zhang et al. 2022), while global scale calibration and evaluation are undertaken at the time of proposal submission (Zhang et al. in preparation). However, to keep computation time practicable for large scale simulations over the 5,000-year period, we emulate this model. To create an emulator that reproduces the basic model behaviour at global scale and that permits to test the model sensitivity to certain key model parameters, we will run a number of site-level simulations with ORCHIDEE-$C_{lateral}$ which cover a realistic range of environmental drivers and variations of the model parameters in question. For creation and application of the emulator, we reconstructed land cover (HYDE, REVEALS) and GCM paleao-climate reconstructions (e.g. ECHAM6 Stevens et al. 2013) which will be downscaled and bias corrected against observation based meteorological forcing data. For the establishment of the model emulator and the simulations of C turnover we will collaborate closely with Nuno Carvalhais from the Max Planck Institute for Biogeochemistry in Jena/Germany (MPI), for which a three-month secondment of the PostDoc to be hired is planned.

To complement the representation of soil-to-inland water transfers of C, we will in addition use a simple rock-weathering model that simulates trends in weathering related CO_2 consumption and alkalinity production as a function of lithology and time variant runoff and temperature (Goll et al. 2014). For application at the pilot sites, this model will be coupled to runoff simulated by SWAT, and recalibrated against local observations of riverine DIC fluxes. For simulations at European and global scale, we scale weathering rates to runoff, temperature, and soil respiration rates produced by the emulator, following the methodological approach by Simon Bowring (2019, PhD thesis under supervision of P. Ciais and R. Lauerwald). The model will be recalibrated at global scale against observational data (Rotteveel et al. 2022). The European and global scale simulations of yearly terrestrial NPP, respiration, biomass and soil C stock changes, and mobilisation of water, sediments, organic C, CO_2 and alkalinity into the inland water network will be a major deliverable of this task (D3.4, M36).

T3.3 Simulate inland water C and GHG budgets (M32-56)

The main objective of this task is the assessment of inland water C budgets, including terrestrial inputs, C burial in sediments, water-air exchange of CO_2 and CH_4, and C export to the coast. Development and application of a process-based inland water C model (IWCM) will allow extrapolating process-knowledge gained from observations at the pilot sites and from a comprehensive review of existing studies and datasets (WP1, WP4) to European and global scales. The work will be performed by a PostDoc to be hired for 2 years at INRAe/EcoSys, who will be supervised in collaboration with ULB, LSCE, SAS and CARTELL.

The model development will profit from experience within the project consortium concerning development and application of models simulating CH_4 (Maisonnier et al. in prep., used in the European CH_4 budget by (Petrescu et al. 2023) and CO_2 [18] budgets of lakes, as well as lake physics and oxygenation[23], but also with models representing transport and reaction of C in streams and rivers[24,45] as main transport routes from the catchment through the cascade of inland water bodies to the coast. The model will use simulated terrestrial inputs of water, C and sediments from T3.2 (D3.2, D3.3, D3.4), as well as other climate forcings used in that task, as inputs. In addition, we will estimate inflows of nutrients, scaling organic N and P loads to those of C, based on land cover specific stoichiometric ratios, and use estimates of anthropogenic N and P loads (fertilizer, manure, sewage) from the IMAGE-GNM model, an impact model that is based on the HYDE land cover, land use and population data that we also use for global long-term simulations in T3.2.

The IWCM will be applied to achieve spatially explicit, European and global scale estimates of inland water CO_2 and CH_4 emissions, resolving both seasonality and interannual variability, and to quantify the anthropogenic perturbation to these emission fluxes (D3.5).

For the 15 pilot sites with sediment cores, we will then run the IWCM over the last 5,000 years, using the long-term SWAT simulations of water, sediment, C and nutrient inflows (D3.3) as forcing data. We will then evaluate simulated C accumulation in sediments against observations, and recalibrate the sediment C dynamics in the IWCM if necessary.

For European and global scale long-term simulations of inland water C budgets, we will emulate the IWCM to keep computation time practicable. The IWCM emulator will consist of a set of empirical response functions to be derived from simulations of the original model for permutations of stochastically varying model inputs and key model parameters covering the full range of realistic values. A similar meta-modelling strategy has been used in earlier studies of consortium members (Maavara et al. 2017 Lauerwald et al. 2019). Coupling the inland water emulator to outputs of the ORCHIDEE emulator, we will assess the long-term impacts of land-cover change on terrestrial C budgets, including and quantifying the role of inland water C fluxes and stock changes.

WP4: International partnerships: upscaling C estimates

***Leaders** : Adam Ali (ISEM) & Yves Prairie (UQAM), **Participants**: 8P*

The objective in WP4 is to stimulate clustering & collaboration activities to consolidate observation data on C fluxes and stocks in lentic waters on a global scale. DEEP-C consortium will identify the possibilities for clustering with other relevant national, EU non-EU-funded projects and contact the coordinators of the identified projects/initiatives to organise cross-project cooperation, exchange of knowledge and joint activities. This will allow us to capitalise on existing communication/ dissemination channels and networks and contribute to maximising the DEEP-C impact. Prof Adam Ali is the coordinator of the France-funded Strategic Research Consortium on studies of cold forests (IRN cold forests: https://forets-froides.org/en/). One member of this consortium is the Canada and a strong Trans-Atlantic cooperation between France-Canada was established since 2005 with joint research activities developed within the Canadian NSERC-UQAT-UQAM Industrial Research Chair in Sustainable Forest Management (holder by Prof. Yves Bergeron https://chaireafd.uqat.ca/index.php) and the Institut de Recherche sur les Forêts (IRL).

Naturally, DEEP-C consortium will collaborate with the IRL and cited colleagues notably through exchange/comparative of data and approaches, and ultimately by jointed meeting. DEEP-C consortium will also initiate collaboration with the Prof. Paul Del Giorgio, the chair holder of the Canadian NSERC-HYDRO-QUEBEC (URL). This is one of the main international groups working on the impact of climate change on the functioning of boreal lakes. Through Trans-Atlantic collaborations DEEP-C consortium will reinforce the leadership of EU in the field of research of C cycle in inland water systems. WP4 will support exchanges between internal scientists, and will be supported by researchers in WP1-2 to contribute global datasets and upscaled estimates on C cycle. WP4 will also be supported by ongoing data collection conducted by members of the consortium, such as for near-annual C,N and XRF signatures preserved in short sediments from 370 lakes from around the world collected and processed between 2017-2021 by Jean-Philippe Jenny in collaboration with Max Planck (G) and the LACCORE facilities, Minnesota (USA).

Planning, KPI and milestones

KPI and milestones

For each of the 3 following dimension of the project, we identify corresponding work packages (WP), tasks (T), deliverable (D) and key performance indicators (KPI) **Fig. 4**.

· ***Observations and current estimates***

KPI 1: At Month 24 and 36 (see WP1 Tasks 1.1 & Task 1.3), we will aggregate multiple sources of current C fluxes data (i.e. CO_2-CH_4 emissions, C burial, metabolism) and microbial communities to analyse these data for the 40 studied lentic sites leading to **1 database** and to between **1 to 2 publications**.

· ***Paleo-observations and past estimates***

KPI 2: At Month 24 (see WP2 Task 1.3)**,** we complete characterization of the benthic and pelagic transfer of OC in lentic, leading to at least **2 publications**. This will allow the identification of drivers and hotspots of C fluxes. **KPI 3: At Month 24** (see WP2 Task 2.1)**,** we will complete quantification of current C stocks in lentic sediments and identification of main drivers of spatial variability between sites, leading to **2-4 publications**. **KPI 4: At Month 24** (see WP2 Task 2.2) sediment dating and C accumulation rates are calculated for the past 150 years, trends of proxies are completed and analysed, leading to **1 database** and to between **1-2 publications. KPI 5: At Month 24** (see WP2 Task 2.3) we achieve land cover, erosion signal, C trends and sources reconstructions, we analyse drivers for past 5,000 years, leading to **1-2 publications**.

· ***Pilot, European and global simulations***

KPI 6: At Month 24 (see WP3 Task 1.1) we complete simulations to reconstruct land cover trends for the past 5,000 years**. KPI 7: At Month 24 and 36** (see WP2 Task 2.3) we simulate C exports, deposition and emissions from lentic inland waters leading to **2-3 publications**. **KPI 8: At Month 32** (see WP3 Task 1.2-3)**.**

Risks that might endanger reaching the action objectives and the contingency plans

The risk challenge of DEEP-C will be the integration of numerous and highly heterogeneous data streams in the model approaches, specifically regarding the paleo-records. There is a risk that in some cases, paleo-records cannot be interpreted or integrated to model-data approach due du poor preservation of the archives. This risk will be minimised by the coupling expertise of the large and reactive paleo team in WP2 with granted access to numerous lakes and reservoirs who will ensure to synthesis and valorise the reconstructions and the integration of past C fluxes and stocks. As regard the model approach for past trends, different models will be developed and tested in order to adapt the model complexity and sensitivity to the sediment archives. Land surface model is a key expertise of the WP3 experts. Furthermore, without appropriate coordination, there is a risk of delay during the data collection phase that may compromise data sharing within groups, particularly with WP3 which needs C fluxes and stocks for the modelling phase. Hence, as contingency measure, regular meetings between filed/lab experts will be set up by the coordination team to control advancements in the data collection during the 2 first years of the project. In addition, consequent support will be dedicated to achieving the database in time: this includes recruitment of an IE in DEEP-C for field work; strong interactions and resources sharing with 2 actions in PC5 FairCarboN dedicated to the consolidation and harmonization of C fluxes/stocks in lentic systems (these groups are note restricted to only lentic waters). Full granted accesses to lakes & reservoirs (from OFB and EDF) will further guarantee the collection of a dataset at the national Level. The database will be designed on the existing Information System (SI) structure & semantic of the SI OLA (AnAEE) to complement for lentic waters what already exists and be applied for soils data in FairCarboN (i.e. INFOSOL), which will help data management/ sharing during the project.

Project organisation and management

Organization of the partnership

The DEEP-C consortium is a multidisciplinary team of 10 French partners and 3 partners from different countries (Belgium, Germany, Canada). Implementing this ambitious research project requires an efficient management structure.

Management framework

DEEP-C Scientific coordination

Dr. Jean-Philippe JENNY (INRAE) and Dr. Laurent Millet (CNRS) will supervise the overall coordination of the project.

Dr. Jean-Philippe JENNY is researcher, coordinator of the Lake Biogeochemistry Group (URL) at the center of limnology INRAE CARRTEL, member of the scientific board of the Franco-Swiss "International Commission for the Protection of the Water Lake Geneva" (CIPEL) since 2020. Using sedimentological and geochemical proxies complemented by multi-disciplinary approaches, his principal interests are in understanding the long-term interactions between land uses, lateral transport of sediments and carbon (C) and lake system responses. His current projects examines the dynamic of land vegetation and soil erosion over the last centuries to millennia using radionuclides and ^{14}C data. Over the last 3 years his team has been coupling 1D lake modelling, limnological observations (OLA sites) and sediment proxies of oxygen conditions, C primary production and nutrient inputs, to address local lakes management challenges. He has contributed to 28 publications (1,500 citations, H-Index: 21; Google Scholar 2022-12-03), 5 of which in journals with an impact factor>10. Since 2019 he has supervised 2 PhD students, 1 PostDoc, 2 engineers and 4 Master Students.

Dr. Laurent Millet is Director of Research at the CNRS. His initial field of expertise is paleolimnology and the reconstruction of paleoclimate and ecological trajectories of lake ecosystems on decadal, secular and millennial time scales. He is now developing innovative approaches that combine neo and paleo-limnology, and the calibration of proxies to assess the carbon cycle in lakes. Its study sites are located in France (Jurassic massif, Vosges, Pyrenees, Alps), in southwestern Greenland and in the boreal zone of Quebec and Labrador. His most recent work focuses on the sources and transfer pathways of carbon in aquatic food webs and the influence of climate and human activities. He has contributed to 57 publications (2,313 citations, H-Index: 27; Scopus 2022-12-04). He has co-supervised 5 PhD students and 1 PostDoc.

In the frame of DEEP-C, several types of research data are expected to be collected, processed and/or generated (e.g. ensemble climate data, spatial disturbance risk data, guideline for managers and policy-makers, etc.). For each one of those research data, the DEEP-C consortium will carefully study the possibility and pertinence to make them findable, accessible, interoperable and reusable. A **Data Management Plan (DMP)** will be delivered at M6 by the PMT and regularly updated. In this document the partners will determine the handling of research data during and after the end of the project, the list of the data collected, processed and generated, the methodology and standards to be applied, which data will be made openly available and how, the measures undertaken to facilitate the interoperability and reuse of the research data and how the data will be curated and preserved. The DMP will be drafted following the guidelines on FAIR data management using the French application OPIDoR. Several standards and trusted archiving repository options (according to OpenAIRE criteria) will be used. **Jean-Philippe Jenny** in collaboration with the WPL, will be in charge to collect and stored all data in the INRAE Dataverse site (https://data.inrae.fr) and OLA SI (AnAEE CARRTEL https://si-ola.inrae.fr).

Knowledge management and protection: The management of Intellectual Property Rights (IPRs) as well as the use of the project results and their exploitation by external stakeholders (e.g. OFB, SILA, CIPEL) will be discussed during the Steering Committee meetings (M12) and will comply with the related clauses in the Grant and Consortium agreements. Any key results will be protected whenever relevant for an appropriate period and with appropriate territorial coverage. **The Consortium Agreement (CA):** to be signed by each partner prior to the project starting date, will complement the clauses of the Grant Agreement and address all relevant issues related to IPR and to the results generated in the frame of the project (access rights to background and foreground needed for the implementation of the project, rules for dissemination and use of own knowledge). The identification of the IPR on the project result is essential to perform a freedom to operate analysis and establish a suitable exploitation plan for the project results. **Project progress reporting:** The work plan is comprised of 5 work-packages (WP) and 15 tasks. Each WP leader, acting as a sub-project coordinator, is responsible for the monitoring of the project progress within his/her WP and is expected to regularly inform and report to the PMT about this. In particular, WP leaders should provide to the PMT every 6 months a short report (status of the activities, ressouces spent, status of Deliverables and Milestones).

Reduced carbon footprint plan – Transports, field Campaign over long distances, can considerabely increase the C footprint. In DEEP-C transports will be reduced: the extensive data collection and field works will then be conducted at the national level, and international collaboration will be encouraged to access and share observation from other parts of the world.

Institutional strategy

DEEP-C consortium is largely composed of scientists from the National Center for Scientific Research (CNRS) and the National Research Institute for Agriculture, Food and Environment (INRAE), both being programme leaders of the 'FairCarboN' (carbon) exploratory PEPR.

DEEP-C is structured around the first stated INRAE2030 strategic priority for the next 10 years is **research on climate change mitigation** (URL). More specifically, DEEP-C fits to the scientific priority (SP) *SP #1: Responding to **environmental challenges and their associated risks*** and to policy priorities as it addresses the global challenge of identifying ecological, agronomic and socio-economic levels and trajectory scenarios within groundbreaking model-data integration approaches to reach carbon neutrality and restore natural resources within continental ecosystems. DEEP-C also fits to some extent to policy priorities (PP) *PP#2 Placing science, innovation and expertise at the centre of **society-policy dialogue***, a s it will provides fundamental and operational knowledge on **C cycling within continental ecosystems** and also because DEEP-C gather a solid network of national stakeholders (i.e. EDF, OFB) and scientists working together.

The challenge of the CNRS in the National research strategy France Europe 2020 is to meet the permanent challenge of knowledge and the unprecedented socio-economic **challenges of our century related to climate change**. Furthermore, DEEP-C fits the strategic plan for 2019 – 2024 of the CNRS that encourages the understanding the dynamics of Earth's fluid envelopes. CNRS is a large institute that has identified arounds 50 thematic priorities thatare grouped into six broad domains. DEEP-C fits in the Planet and Universe (c.f. 1.4) domain, and more specifically the sub-domain "understanding the dynamics of Earth's fluid envelopes". The CNRS priority in this domain is to ensure the development of our societies, the dynamic and biogeochemical processes in the ocean, the **continental hydrosphere**, the cryosphere and the atmosphere must be known on a wide range of spatial and temporal scales, and more largely to promotes the understanding the dynamics of Earth's fluid envelopes, among which DEEP-C evolves. CNRS encourage **multidisciplinary research** which is the basis in DEEP-C with more that 30 national experts dedicated to C the study of cycling in the continental zone.

Within the same domain, the important modelling component in DEEP-C will fit to CNRS strategy to implement mathematics for humans and its interaction with planet Earth Climate change, impacts on ecosystems linked to human activities.

Partners' Commitment – DEEP-C' success will require an important engagement of all partners to achieve the ambition of the extensive data collection on 40 lentic sites (both for current and paleo observations in WP1-2). Furthermore, secured access to equipment, field and lab facilities are important for the success of DEEP-C. In this perspective, DEEP-C overall achievements will be fully supported by the analytical platforms at EDYTEM (CNRS-USMB), LEHNA (CNRS), Chrono-environnement (CNRS) or CARRTEL (INRAE), with access to numerous field facilities (platform PINTE, URL) sedimentology (platform ASTRE; CPEP, URL), geochemistry (platform ACE, URL, PTAL, URL) and biological facilities (platform B2ME, URL; and PRECCI, URL). Within these platform and partners, DEEP-C will benefit from dedicated human resources with a total of about 250 months and 170 months committed by permanent and non-permanent researchers to the program during the 5 years of the project for the empirical part in DEEP-C. The modelling part in DEEP-C will beneficiate from 52 months committed by postdoc researchers to the project and will be supported by the leader experts in the field.

Expected outcomes of the project

DEEP-C is expected to generate several exploitable outcomes.

- **Main outcomes in WP1.** Using 40 pilot sites in France from WP1 complemented with national data synthesis we will estimate CO_2-CH_4 emissions and C stocks and forms in lentic systems in France, including the new knowledge gain related to main drivers of the spatial distribution of these fluxes and stocks. This is an important outcome as it will refine National C inventories in aquatic ecosystems and support data integration in modelling tools.
- **Principal outcomes in WP2.** Using 40 pilot sites, WP2 will shed lights on the current and centennial effects of human activities and ongoing climate change on lentic ecosystem functioning and impacts on lentic carbon cycling. We will develop and consolidate national observations on the temporal variations in C stocks formation and transfers in lentic environments. Further, WP2 will use 15 pilot sites to provide coherent synthesis on millennial trends in geological C stocks formation, C exports from lands, C in-lake contribution to sedimentary stocks formation. WP2 sill advance our knowledge on the long-term effects of human land uses on the C cycling at lake-catchment scales. National datasets produced in WP2 will be unique and will allow to constrain local to large-scale model approaches in WP3.
- **Outcomes in WP3.** We will reconstruct the evolution of land cover over the last 5,000 years in watersheds of 15 pilot sites in France where sediment cores will be taken. WP3 will provide simulations of C turnover in terrestrial ecosystems, including the mobilization of C into the inland water network at European to global

scale. WP3 will produce assessment of inland water C budgets, including terrestrial inputs, C burial in sediments, water-air exchange of CO_2 and CH_4, and C export to the coast.

Funding justification

DEEP-C' will require important funding to support the empirical ambition to consolidate large spatial and temporal scales' observation of C stocks and fluxes in lentic waters, to be valorized in a national database of carbon and in local to global C cycle modelling (WP1-2). DEEP-C will require 70k€ for instrumental costs to secure radionuclide dating for 40 short sediments cores (part of the analysis will also be subcontracted). Staff expenses (~50% of the total costs) will cover for modelling (250k€), field and lab work (122k€) and valorization (300k€) as many outcomes are planned in DEEP-C. It is planned that field and lab work will require additional resources to achieve the data collection on the 40 sites. As such, DEEP-C will adapt the sampling/field strategy with coordinators in Target project 5 (PC5) of the FairCarboN program, in which staff supports (IE engineer) and field equipment (CO_2-CH_4 emissions) are anticipated to be grouped with efforts in DEEP-C. Previous funds (c.f. MITI-INRAE-CNRS C-Sensible, prefiguration to FairCarboN, PI: JP Jenny) will secure high frequency carbon data acquisitions (MSCL-S hyperspectral) on sediment cores in complement to other analytical costs both within subcontracting and internal billing.

Funding program

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Grant title

ANR-22-PEXF-0009

Hosting institution

INRAE - Institut national de recherche pour l'agriculture, l'alimentation et l'environnement

Conflicts of interest

The authors have declared that no competing interests exist.

References

- Bajard M, Sabatier P, David F, Develle A, Reyss J, Fanget B, Malet E, Arnaud D, Augustin L, Crouzet C, Poulenard J, Arnaud F (2015) Erosion record in Lake La Thuile sediments (Prealps, France): Evidence of montane landscape dynamics throughout the Holocene. The Holocene 26 (3): 350-364. https://doi.org/10.1177/0959683615609750
- Bajard M, Poulenard J, Sabatier P, Develle A, Giguet-Covex C, Jacob J, Crouzet C, David F, Pignol C, Arnaud F (2017) Progressive and regressive soil evolution phases in the Anthropocene. CATENA 150: 39-52. https://doi.org/10.1016/j.catena.2016.11.001
- Bastviken D, Ejlertsson J, Tranvik L (2002) Measurement of Methane Oxidation in Lakes: A Comparison of Methods. Environmental Science & Technology 36 (15): 3354-3361. https://doi.org/10.1021/es010311p
- Beaulieu J, DelSontro T, Downing J (2019) Eutrophication will increase methane emissions from lakes and impoundments during the 21st century. Nature Communications 10 (1). https://doi.org/10.1038/s41467-019-09100-5
- Bowman J, Skerratt J, Nichols P, Sly L (2011) Phospholipid fatty acid and lipopolysaccharide fatty acid signature lipids in methane-utilizing bacteria. FEMS Microbiology Ecology 8 (1): 15-21. https://doi.org/10.1111/j.1574-6941.1991.tb01704.x
- Brisset E, Miramont C, Guiter F, Anthony EJ, Tachikawa K, Poulenard J, Arnaud F, Delhon C, Meunier J, Bard E, Suméra F (2013) Non-reversible geosystem destabilisation at 4200 cal. BP: Sedimentological, geochemical and botanical markers of soil erosion recorded in a Mediterranean alpine lake. The Holocene 23 (12): 1863-1874. https://doi.org/10.1177/0959683613508158
- Canadell JG, et al. (2023) Global Carbon and Other Biogeochemical Cycles and Feedbacks. Climate Change 2021 – The Physical Science Basis673-816. https://doi.org/10.1017/9781009157896.007
- Colas F, Chanudet V, Daufresne M, Buchet L, Vigouroux R, Bonnet A, Jacob F, Baudoin J (2020) Spatial and Temporal Variability of Diffusive CO₂ and CH₄ Fluxes From the Amazonian Reservoir Petit-Saut (French Guiana) Reveals the Importance of Allochthonous Inputs for Long-Term C Emissions. Global Biogeochemical Cycles 34 (12). https://doi.org/10.1029/2020gb006602
- Cole JJ, Prairie YT, Caraco NF, McDowell WH, Tranvik LJ, Striegl RG, Duarte CM, Kortelainen P, Downing JA, Middelburg JJ, Melack J (2007) Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget. Ecosystems 10 (1): 172-185. https://doi.org/10.1007/s10021-006-9013-8
- Desgué-Itier O, Melo Vieira Soares L, Anneville O, Bouffard D, Chanudet V, Danis PA, Domaizon I, Guillard J, Mazure T, Sharaf N, Soulignac F, Tran-Khac V, Vinçon-Leite B, Jenny J (2023) Past and future climate change effects on the thermal regime and oxygen solubility of four peri-alpine lakes. Hydrology and Earth System Sciences 27 (3): 837-859. https://doi.org/10.5194/hess-27-837-2023
- Downing JA, Cole JJ, Middelburg JJ, Striegl RG, Duarte CM, Kortelainen P, Prairie YT, Laube KA (2008) Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. Global Biogeochemical Cycles 22 (1). https://doi.org/10.1029/2006gb002854

- Essert V, Masclaux H, Verneaux V, Lyautey E, Etienne D, Tardy V, Millet L (2022) Spatial and seasonal variability of the carbon isotopic signature of <i>Daphnia</i> and their ephippia in four French lakes: Implications for the study of carbon transfers in lake food webs. Freshwater Biology 67 (8): 1439-1455. https://doi.org/10.1111/fwb.13952
- Flury S, Ulseth AJ (2019) Exploring the Sources of Unexpected High Methane Concentrations and Fluxes From Alpine Headwater Streams. Geophysical Research Letters 46 (12): 6614-6625. https://doi.org/10.1029/2019gl082428
- Friedlingstein, et al. (2022) Global Carbon Budget 2022. Earth System Science Data 14: 4811-4900.
- Giguet-Covex C, Arnaud F, Poulenard J, Disnar J, Delhon C, Francus P, David F, Enters D, Rey P, Delannoy J (2011) Changes in erosion patterns during the Holocene in a currently treeless subalpine catchment inferred from lake sediment geochemistry (Lake Anterne, 2063 m a.s.l., NW French Alps): The role of climate and human activities. The Holocene 21 (4): 651-665. https://doi.org/10.1177/0959683610391320
- Giguet-Covex C, Pansu J, Arnaud F, Rey P, Griggo C, Gielly L, Domaizon I, Coissac E, David F, Choler P, Poulenard J, Taberlet P (2014) Long livestock farming history and human landscape shaping revealed by lake sediment DNA. Nature Communications 5 (1). https://doi.org/10.1038/ncomms4211
- Goll D, Moosdorf N, Hartmann J, Brovkin V, et al. (2014) Climate-driven changes in chemical weathering and associated phosphorus release since 1850: Implications for the land carbon balance. Geophysical Reseqrch Letters 41 (10): 3553-3558. https://doi.org/10.1002/2014GL059471
- Jenny J, Koirala S, Gregory-Eaves I, Francus P, Niemann C, Ahrens B, Brovkin V, Baud A, Ojala AK, Normandeau A, Zolitschka B, Carvalhais N (2019) Human and climate global-scale imprint on sediment transfer during the Holocene. Proceedings of the National Academy of Sciences 116 (46): 22972-22976. https://doi.org/10.1073/pnas.1908179116
- Johnson M, Matthews E, Du J, Genovese V, Bastviken D (2022) Methane Emission From Global Lakes: New Spatiotemporal Data and Observation-Driven Modeling of Methane Dynamics Indicates Lower Emissions. Journal of Geophysical Research: Biogeosciences 127 (7). https://doi.org/10.1029/2022jg006793
- Kampbell DH, Wilson JT, Vandegrift SA (1989) Dissolved Oxygen and Methane in Water by a GC Headspace Equilibration Technique. International Journal of Environmental Analytical Chemistry 36 (4): 249-257. https://doi.org/10.1080/03067318908026878
- Kastowski M, Hinderer M, Vecsei A (2011) Long-term carbon burial in European lakes: Analysis and estimate. Global Biogeochemical Cycles 25 (3). https://doi.org/10.1029/2010gb003874
- Koschorreck M, Prairie Y, Kim J, Marcé R (2021) Technical note: CO2 is not like CH4 – limits of and corrections to the headspace method to analyse pCO2 in fresh water. Biogeosciences 18 (5): 1619-1627. https://doi.org/10.5194/bg-18-1619-2021
- Lauerwald R, Laruelle G, Hartmann J, Ciais P, Regnier PG (2015) Spatial patterns in CO₂ evasion from the global river network. Global Biogeochemical Cycles 29 (5): 534-554. https://doi.org/10.1002/2014gb004941
- Lauerwald R, Regnier P, Camino-Serrano M, Guenet B, Guimberteau M, Ducharne A, Polcher J, Ciais P (2017) ORCHILEAK (revision 3875): a new model branch to simulate carbon transfers along the terrestrial–aquatic continuum of the Amazon basin.

Geoscientific Model Development 10 (10): 3821-3859. https://doi.org/10.5194/gmd-10-3821-2017

- Lauerwald R, Regnier P, Figueiredo V, Enrich-Prast A, Bastviken D, Lehner B, Maavara T, Raymond P (2019) Natural Lakes Are a Minor Global Source of N₂O to the Atmosphere. Global Biogeochemical Cycles 33 (12): 1564-1581. https://doi.org/10.1029/2019gb006261
- Lauerwald R, Regnier P, Guenet B, Friedlingstein P, Ciais P (2020) How Simulations of the Land Carbon Sink Are Biased by Ignoring Fluvial Carbon Transfers: A Case Study for the Amazon Basin. One Earth 3 (2): 226-236. https://doi.org/10.1016/j.oneear.2020.07.009
- Lauerwald R, Allen G, Deemer B, Liu S, Maavara T, Raymond P, Alcott L, Bastviken D, Hastie A, Holgerson M, Johnson M, Lehner B, Lin P, Marzadri A, Ran L, Tian H, Yang X, Yao Y, Regnier P (2023) Inland Water Greenhouse Gas Budgets for RECCAP2: 2. Regionalization and Homogenization of Estimates. Global Biogeochemical Cycles 37 (5). https://doi.org/10.1029/2022gb007658
- Liu S, Kuhn C, Amatulli G, Aho K, Butman D, Lin P, Pan M, Allen G, Yamazaki D, Brinkerhoff C, Gleason C, Xia X, Raymond P (2022) The importance of hydrology in routing terrestrial carbon to the atmosphere via global streams and rivers. Goldschmidt2022 abstracts https://doi.org/10.46427/gold2022.10470
- Li Y, Shang J, Zhang C, Zhang W, Niu L, Wang L, Zhang H (2021) The role of freshwater eutrophication in greenhouse gas emissions: A review. Science of The Total Environment 768 https://doi.org/10.1016/j.scitotenv.2020.144582
- Maavara T, Lauerwald R, Regnier P, Van Cappellen P (2017) Global perturbation of organic carbon cycling by river damming. Nature Communications 8 (1). https://doi.org/10.1038/ncomms15347
- Marquer L, Mazier F, Sugita S, Galop D, Houet T, Faure E, Gaillard M, Haunold S, de Munnik N, Simonneau A, De Vleeschouwer F, Le Roux G (2020a) Pollen-based reconstruction of Holocene land-cover in mountain regions: Evaluation of the Landscape Reconstruction Algorithm in the Vicdessos valley, northern Pyrenees, France. Quaternary Science Reviews 228 https://doi.org/10.1016/j.quascirev.2019.106049
- Marquer L, Mazier F, Sugita S, Galop D, Houet T, Faure E, Gaillard M, Haunold S, de Munnik N, Simonneau A, De Vleeschouwer F, Le Roux G (2020b) Reply to Theuerkauf and Couwenberg (2020) comment on: “Pollen-based reconstruction of Holocene land-cover in mountain regions: Evaluation of the Landscape Reconstruction Algorithm in the Vicdessos valley, northern Pyrenees, France”. Quaternary Science Reviews 244 https://doi.org/10.1016/j.quascirev.2020.106462
- Mendonça R, Müller R, Clow D, Verpoorter C, Raymond P, Tranvik L, Sobek S (2017) Organic carbon burial in global lakes and reservoirs. Nature Communications 8 (1). https://doi.org/10.1038/s41467-017-01789-6
- Perga ME, Desmet M, Enters D, Reyss J (2010) A century of bottom-up and top-down driven changes on a lake planktonic food web: A paleoecological and paleoisotopic study of Lake Annecy, France. Limnology and Oceanography 55 (2): 803-816. https://doi.org/10.4319/lo.2009.55.2.0803
- Petrescu AMR, McGrath M, Andrew R, Peylin P, Peters G, Ciais P, Broquet G, Tubiello F, Gerbig C, Pongratz J, Janssens-Maenhout G, Grassi G, Nabuurs G, Regnier P, Lauerwald R, Kuhnert M, Balkovič J, Schelhaas M, Denier van derGon HC, Solazzo E, Qiu C, Pilli R, Konovalov I, Houghton R, Günther D, Perugini L, Crippa M, Ganzenmüller R, Luijkx I, Smith P, Munassar S, Thompson R, Conchedda G, Monteil G, Scholze M,

Karstens U, Brockmann P, Dolman AJ (2021) The consolidated European synthesis of CO₂ emissions and removals for the European Union and United Kingdom: 1990–2018. Earth System Science Data 13 (5): 2363-2406. https://doi.org/10.5194/essd-13-2363-2021

- Petrescu AMR, Qiu C, McGrath M, Peylin P, Zaehle S, et al. (2023) The consolidated European synthesis of CH4 and N2O emissions for the European Union and United Kingdom: 1990–2019. Earth System Science Data 15 (3): 1197-1268. https://doi.org/10.5194/essd-15-1197-2023
- Plancher C, Galop D, Houet T, Lerigoleur E, Marquer L, Sugita S, Mazier F (2022) Spatial and temporal patterns of upland vegetation over the last 200 years in the northern pyrenees: Example from the Bassiès valley, Ariège, France. Quaternary Science Reviews 294 https://doi.org/10.1016/j.quascirev.2022.107753
- Prairie Y, Alm J, Beaulieu J, Barros N, Battin T, Cole J, del Giorgio P, DelSontro T, Guérin F, Harby A, Harrison J, Mercier-Blais S, Serça D, Sobek S, Vachon D (2017) Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See? Ecosystems 21 (5): 1058-1071. https://doi.org/10.1007/s10021-017-0198-9
- Raymond P, Hartmann J, Lauerwald R, Sobek S, McDonald C, Hoover M, Butman D, Striegl R, Mayorga E, Humborg C, Kortelainen P, Dürr H, Meybeck M, Ciais P, Guth P (2013) Global carbon dioxide emissions from inland waters. Nature 503 (7476): 355-359. https://doi.org/10.1038/nature12760
- Regnier P, Friedlingstein P, Ciais P, Mackenzie F, Gruber N, Janssens I, Laruelle G, Lauerwald R, Luyssaert S, Andersson A, Arndt S, Arnosti C, Borges A, Dale A, Gallego-Sala A, Goddéris Y, Goossens N, Hartmann J, Heinze C, Ilyina T, Joos F, LaRowe D, Leifeld J, Meysman FR, Munhoven G, Raymond P, Spahni R, Suntharalingam P, Thullner M (2013) Anthropogenic perturbation of the carbon fluxes from land to ocean. Nature Geoscience 6 (8): 597-607. https://doi.org/10.1038/ngeo1830
- Regnier P, Resplandy L, Najjar R, Ciais P (2022) The land-to-ocean loops of the global carbon cycle. Nature 603 (7901): 401-410. https://doi.org/10.1038/s41586-021-04339-9
- Rinta P, Bastviken D, van Hardenbroek M, Kankaala P, Leuenberger M, Schilder J, Stötter T, Heiri O (2015) An inter-regional assessment of concentrations and δ13C values of methane and dissolved inorganic carbon in small European lakes. Aquatic Sciences 77 (4): 667-680. https://doi.org/10.1007/s00027-015-0410-y
- Rinta P, Bastviken D, Schilder J, Van Hardenbroek M, Stötter T, Heiri O (2016) Higher late summer methane emission from central than northern European lakes. Journal of Limnology https://doi.org/10.4081/jlimnol.2016.1475
- Rotteveel L, Heubach F, Sterling S (2022) The Surface Water Chemistry (SWatCh) database: a standardized global database of water chemistry to facilitate large-sample hydrological research. Earth System Science Data 14 (10): 4667-4680. https://doi.org/10.5194/essd-14-4667-2022
- Saunois M, et al. (2020) The Global Methane Budget 2000–2017. Earth System Science Data 12: 1561 -1623.
- Simonneau A, Doyen E, Chapron E, Millet L, Vannière B, Di Giovanni C, Bossard N, Tachikawa K, Bard E, Albéric P, Desmet M, Roux G, Lajeunesse P, Berger JF, Arnaud F (2013) Holocene land-use evolution and associated soil erosion in the French Prealps inferred from Lake Paladru sediments and archaeological evidences. Journal of Archaeological Science 40 (4): 1636-1645. https://doi.org/10.1016/j.jas.2012.12.002

- Simonneau A, Chapron E, Garçon M, Winiarski T, Graz Y, Chauvel C, Debret M, Motelica-Heino M, Desmet M, Di Giovanni C (2014) Tracking Holocene glacial and high-altitude alpine environments fluctuations from minerogenic and organic markers in proglacial lake sediments (Lake Blanc Huez, Western French Alps). Quaternary Science Reviews 89: 27-43. https://doi.org/10.1016/j.quascirev.2014.02.008
- Soued C, Harrison J, Mercier-Blais S, Prairie Y (2022) Reservoir CO2 and CH4 emissions and their climate impact over the period 1900–2060. Nature Geoscience 15 (9): 700-705. https://doi.org/10.1038/s41561-022-01004-2
- Stevens B, Giorgetta M, Esch M, Mauritsen T, Crueger T, Rast S, Salzmann M, Schmidt H, Bader J, Block K, Brokopf R, Fast I, Kinne S, Kornblueh L, Lohmann U, Pincus R, Reichler T, Roeckner E (2013) Atmospheric component of the MPI-M Earth System Model: ECHAM6. Journal of Advances in Modeling Earth Systems 5 (2): 146-172. https://doi.org/10.1002/jame.20015
- Sugita S (2007) Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. The Holocene 17 (2): 229-241. https://doi.org/10.1177/0959683607075837
- Tranvik L, Downing J, Cotner J, Loiselle S, Striegl R, Ballatore T, Dillon P, Finlay K, Fortino K, Knoll L, Kortelainen P, Kutser T, Larsen S, Laurion I, Leech D, McCallister SL, McKnight D, Melack J, Overholt E, Porter J, Prairie Y, Renwick W, Roland F, Sherman B, Schindler D, Sobek S, Tremblay A, Vanni M, Verschoor A, von Wachenfeldt E, Weyhenmeyer G (2009) Lakes and reservoirs as regulators of carbon cycling and climate. Limnology and Oceanography 54: 2298-2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298
- UNESCO/IHA (2010) GHG measurement guidelines for freshwater reservoirs: derived from: The UNESCO/IHA Greenhouse Gas Emissions from Freshwater Reservoirs Research Project. Intern. Hydropower Association (IHA).
- Zhang H, Lauerwald R, Regnier P, Ciais P, Van Oost K, Naipal V, Guenet B, Yuan W (2022) Estimating the lateral transfer of organic carbon through the European river network using a land surface model". preprint https://doi.org/10.5194/esd-2022-4-supplement

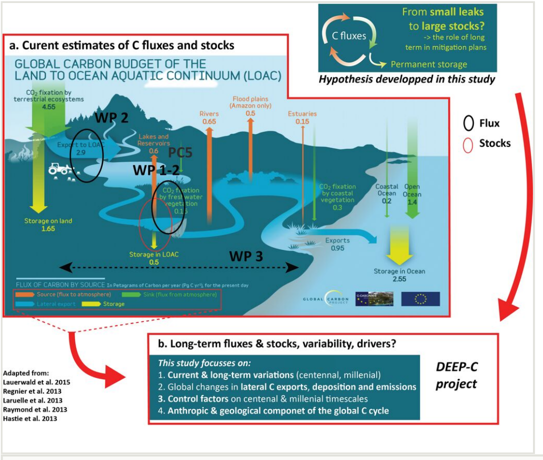

Figure 1.

Overall objectives in DEEP-C to simulate current, centennial and millennial C exports, transfers, deposition and CO2-CH4 emissions in the inland water network (WP3), constrained with new consolidated observations to be collected on C stocks and emissions in lentic water during the project (WP1-2 & PC5).

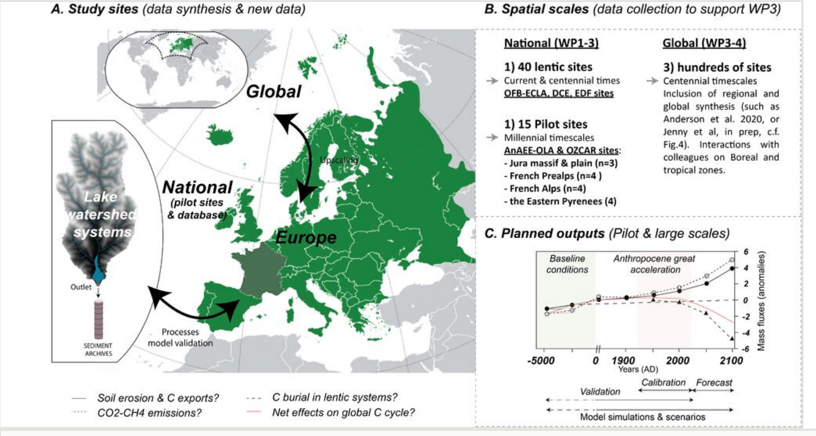

Figure 2.

Study sites (A), input data to constrain land surface and lake models, and observation data collected during DEEP-C for model validation (B), example of planned outputs of trends in C exports, CO2-CH4 emissions and burial of in the inland water network.

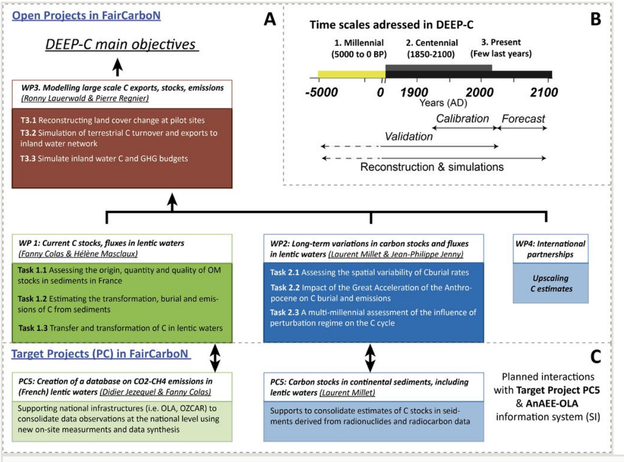

Figure 3.

Overall structure of DEEP-C, A) Work Packages B) Time scales, C) Planned interactions with Target project (PC) in FairCarboN and AnAEE-OLA information system (SI) for data management and database creation in alignment with the call.

	1st Year			2nd Year			3rd Year			4th Year			5th Year		
WP1	Current CO2-CH4 fluxes and C stocks in lentic waters														
T1.1															
T1.2															
T1.3															
D						1,2,3			4,5						1 final
WP2	Temporal variability of C fluxes and C stocks in lentic waters and catchments														
T2.1															
T2.2															
T2.3															
D						1,2		3,4				1 final			
WP3	Modelling large scale C exports, stocks, emissions														
T3.1															
T3.2															
T3.3															
D							4						2,3,4		
WP4	International partnerships and EAB: upscaling C estimates														
D					1										2
	Project management														
M	1		2			3		4,5							6

Table 1. ***WP:*** *Work Package* ***D:*** *Deliverable* ***T:*** *Task* ***M:*** *Milestone*

Figure 4.

Time schedule and working programme.