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Future directions for river carbon biogeochemistry observations

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Rivers carry large quantities of carbon and form an important link between terrestrial, marine and atmospheric biogeochemical cycles, yet our observations of river carbon are severely limited. Here we provide a blueprint to build a global River Observation System that would improve our ability to observe and predict changes in this crucial piece of the global carbon cycle.

Rivers and streams form the largest nexus between the continents, oceans and atmosphere. As such, they play major roles in storing, transporting and transforming carbon alongside other key biogeochemical cycles. The carbon in streams and rivers supports aquatic and riparian food webs, and is thus important for biodiversity (e.g., ref [1,2]). Rivers serve as conduits of inorganic carbon (primarily bicarbonate, HCO_3^-) to the ocean where it can be sequestered into the geologic carbon cycle – an important component of the theorised enhanced weathering negative emissions technology [3]. Rivers also transport particulate organic matter which can be stored in lake, river and coastal ocean sediments where it has the potential to be converted to the greenhouse gases carbon dioxide (CO_2) and methane (CH_4); however, once in the deeper ocean, buried organic carbon can eventually make its way into the geologic carbon cycle [4]. River dissolved organic carbon also poses a significant challenge to water resources, where it can react during water treatment to form harmful byproducts [5].

The amount of carbon transported, buried and emitted by rivers is significant in the context of the global carbon cycle. Rivers receive approximately 3.16 Pg carbon pear year from terrestrial systems, bury ~0.03 Pg, export ~0.81 Pg to the ocean, and emit ~2.3 Pg as CO_2 to the atmosphere [6]. In addition, rivers emit approximately 27.9 Tg of CH_4 to the atmosphere per year [7]. These are substantial fluxes of carbon with the potential to influence global climate. While community estimates of the magnitude of these carbon fluxes are moving towards consensus, the dynamics and underlying processes at play are still largely unknown due to lack of data and inconsistency in the goals (and therefore approaches) of river carbon measurement campaigns. For example, diurnal fluctuations are important for total river greenhouse gas emissions yet little data exists for river CO_2 and CH_4 dynamics over diurnal timescales [8]; and while high-flow events may be the dominant mechanism of particulate export in rivers, particularly in the tropics, to date there are few studies that have been able to accurately capture river carbon dynamics during flood events [9]. Therefore, a global River Observation System (RIOS) has recently been proposed [6]. In this comment, we outline foundational ideas towards the implementation of a globally representative and community-driven RIOS.

Establishing a global River Observation System (RIOS) for carbon

On 14-15 June 2023, a consortium of hydrologists and biogeochemists met at the University of Bristol to discuss what a global RIOS could look like (see Acknowledgements for a full list of contributors). An overarching goal was developed, along with core science and community objectives (Table 1).

With these overarching goals, we hope that RIOS could provide a co-ordinated, standardised, synchronised research infrastructure that the global community can use to answer key research questions of local, regional and global relevance. We hope that RIOS can be flexible and evolve, and include two-way interactions with other networks (e.g., the Global Lake Ecological Observatory Network – GLEON, https://gleon.org/) and infrastructure (e.g., the Integrated Carbon Observation System – ICOS, https://www.icos-cp.eu/). We seek to make the RIOS as accessible as possible from the outset, although these efforts will be constrained by community engagement and funding. Ultimately, we hope the RIOS can provide a step-change in our observations of this key component of the global carbon cycle to understand how it will change in the future and how it might inform us of other wider changes to ecosystems.

The first step to establishing a global RIOS is to harmonise existing data across local and regional river observation systems. We do not attempt to identify all available data and ongoing networks, but we highlight examples as a first step to bringing these together. There are several efforts which have started this process already, particularly for hydrological data and water quality data (e.g., ref [10]). And there are a few efforts for river carbon including CO_2 (ref [11]), CH_4 (ref [12]), and river radiocarbon [13]. However, these are largely synthesis efforts of at times inconsistent data collected for different purposes. More in line with the idea of a RIOS are a few efforts ranging from using sensor networks nested within headwater catchments (e.g., the boreal Krycklan catchment in Sweden https://www.slu.se/en/departments/forest-ecology-management/environment/krycklan/, and the alpine METALP observatory in Switzerland https://metalp.epfl.ch) to more large-scale designs such as the StreamPULSE community (https://streampulse.org/) and the Arctic Great Rivers Observatory (https://arcticgreatrivers.org/).

What and when to measure

We propose a three-layer sampling scheme to local and regional RIOSs (Figure 1). A first layer should establish long-term time series of discharge and concentrations of dissolved organic carbon (DOC), particulate organic carbon (POC) and dissolved inorganic carbon (DIC), as the most important lateral carbon fluxes to observe. Emissions of CO_2 and CH_4 are the most important vertical carbon fluxes. We also propose measurement of water temperature, dissolved oxygen and photosynthetic active radiation, which will serve to model ecosystem gross primary production and respiration – the internal engines of a river's carbon cycle. For most of these measurements, commercial sensors are available for continuous monitoring; they should serve as platform for additional targeted intensive campaigns and 'snapshot' or 'grab' sampling. The second layer would include desirable additional observations, such as nutrients (e.g., NO_3, NO_2, NH_4, soluble reactive phosphorus, silicate), major cations and anions, alkalinity, and carbon isotopes. In the third layer, these efforts would be supported by regular hydro-geomorphological surveys for rating curves (e.g., discharge, gas exchange) and remote sensing observations of river (e.g., geometry, water colour and temperature) and catchment (e.g., land cover) characteristics.

We propose that understanding where river carbon comes from is the most valuable asset to any given RIOS site as it informs on terrestrial processes contributing to lateral losses. Carbon isotopes, including stable isotopes and radiocarbon derived from baseflow and stormflow snapshot sampling, provide valuable insights into carbon sources and transformations (e.g., CO_2 production and CH_4 oxidation), and how these change under different river flow conditions. These second-layer observations would provide important additional information to contextualise the first-layer core observations.

Clearly, there are frontiers and challenges associated with RIOS. For instance, gas transfer velocities (including CH_4 ebullition) through the turbulent water surface must be better constrained as this is critical to better estimate vertical fluxes. Novel modelling approaches that take into account high gas exchange and fluctuating discharge in headwaters, or those that capitalise on both dissolved oxygen and CO_2 data, are on the way and should improve estimates of ecosystem metabolism and evasion rates. A challenge common to numerous observation systems is data sharing and open science. Lessons learned from the National Ecological Observatory Network (NEON) in the USA and the global GLEON network, for example, should guide RIOS efforts on an inclusive and successful path.

Our three-layer approach to a RIOS will enable the establishment of multi-annual regimes of relevant biogeochemical fluxes and ecosystem metabolism. These regimes and their underpinning temporal resolution (from hours to seasons) can be used to identify river ecosystem phenology (i.e., recurrent seasonal biogeochemical patterns), which can be studied in the context of climate change. The layers also serve to understand and predict effects of hydrological events and land cover alterations on river biogeochemistry and ecosystem metabolism. Seasonal and annual fluxes of the various carbon species will be helpful for Earth system modelers.

Where to measure

In an ideal world, we would aim for a global RIOS that integrates over some of Earth's major fluvial networks from their headwaters to their estuaries. However, it is easiest to initiate the effort by harmonising and integrating existing gauged river systems with their infrastructure and personnel, including reviving and extending long-term river network studies particularly in the Arctic and boreal regions [14]. As is frequently recognised, most existing infrastructure is in temperate regions, while sites in the tropics and global south tend to be less well represented.

To identify new RIOS sites, we propose a strategic approach based on biomes and regional necessities, depending on global change drivers. For example, the unprecedented tropical peat deterioration in southeast Asia would call for RIOS sites to quantify and predict the substantial lateral loss of old peat carbon into rivers, atmosphere and ultimately the ocean. Permafrost and glaciers of Tibetan Plateau and the Himalaya are being lost at a rapid pace due to climate change, while also providing freshwater resources to hundreds of millions of people, which calls for RIOS sites in these regions. Finally, we also propose to prioritise the integration of rivers in some of the world's fastest growing megacities in an urban RIOS. We believe that these strategic steps help build critical mass and ensure continuous funding, both of which are critical to the longevity and success of a global RIOS.

Figure captions

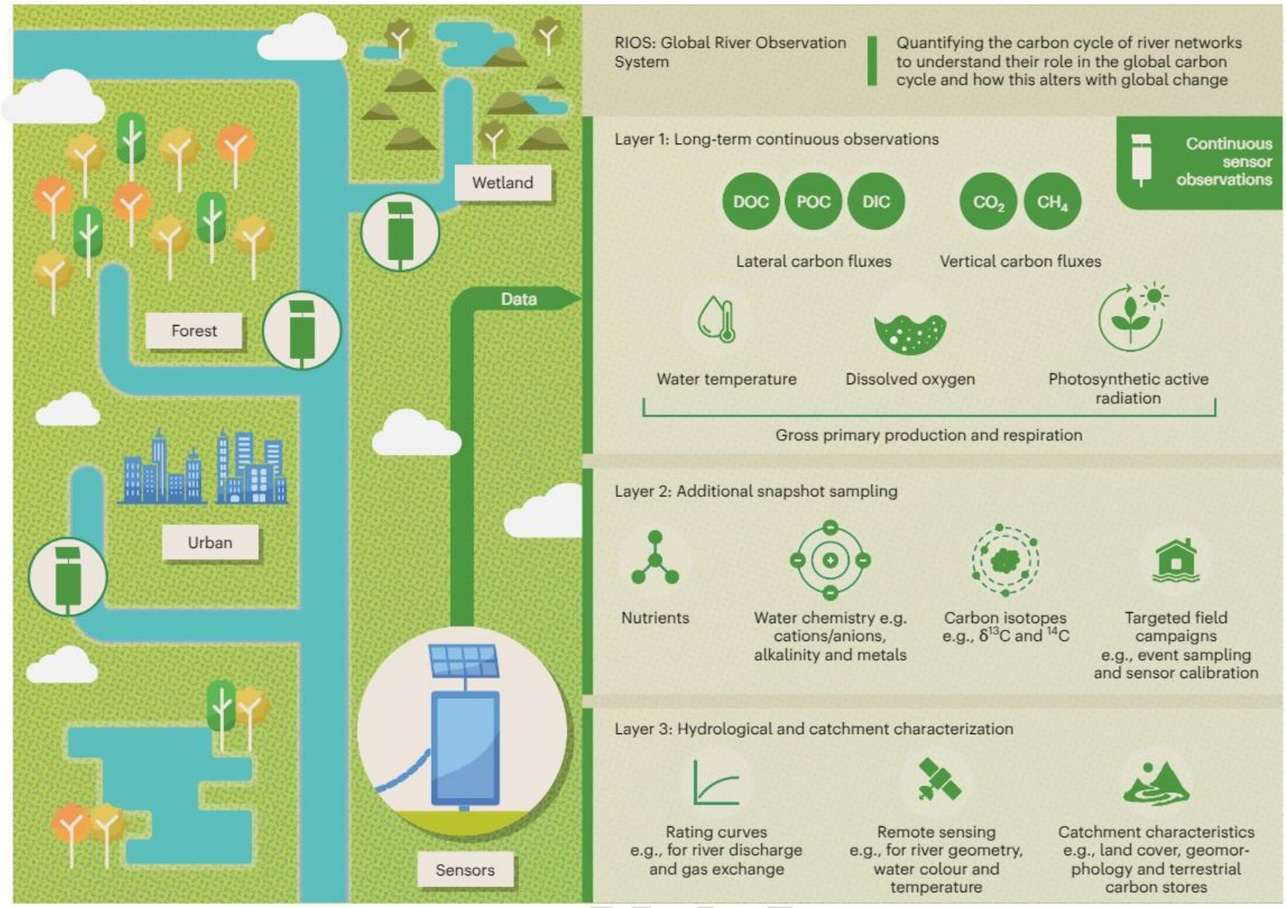

Figure 1. Conceptual figure of the three-layer approach to build a global River Observation System (RIOS). Continuous sensors form the first layer and backbone of the observation system, shown here deployed in three example biomes (left panel). Sensors will be deployed in both small and large catchments to capture both local and regional river carbon dynamics. Continuous data collection will capture the diurnal, event-based and seasonal to annual changes of river biogeochemistry. The second layer will be derived from snapshot sampling campaigns to explore specific scientific questions such as carbon sources and process dynamics. The third layer will provide important wider contextual information to provide critical understanding to the continuous and snapshot observations, such as hydrological and catchment characterisation.

Table 1. The overarching aim of the proposed global River Observation System (RIOS) alongside the core science objectives, and objectives to enhance community benefits and engagement. Here we define ‘science’ objectives to advance our understanding of river biogeochemistry, and ‘community’ objectives to provide a collaborative platform for users who we initially expect to be primarily scientists working on global carbon cycling.

<table>
<tr><th colspan="2">Overarching aim:
To quantify the carbon cycle (coupled to nutrients) of river networks to understand their role in global carbon cycling and how this alters with global change.</th></tr>
<tr><td>Science objectives:</td><td>Community objectives:</td></tr>
<tr><td>• Provide a living observational network to determine long-term trends in river carbon export
• Improve our estimates of the flux of carbon from terrestrial geo- and biosphere into river networks and what reaches the ocean
• Characterise the source and composition of carbon mobilised into river networks
• Understand the role of river networks as biogeochemical reactors
• Understand the role of river networks as sources and sinks of greenhouse gases
• Understand the abiotic and biotic (ecosystem processes) driving carbon fluxes and cycling in river networks
• Determine to what degree these processes can be attributed to direct (e.g., river damming) and indirect (e.g., climate change) anthropogenic perturbations of the global carbon cycle
• Bridge observations from local to regional to global scales
• To bridge temporal observations from event to decadal scales (e.g., impact of zero-flow periods through to floods in the context of multi-year time series).
• Lead to and inform forward modelling of each of these aspects/processes</td><td>• Establish an inclusive network (in all ways) from the beginning
• Co-create a globally representative observational platform to enable whole-community research efforts
• RIOS to quantify flux of carbon from terrestrial biosphere into river networks to inform (e.g.,) the Global Carbon Project
• Identify current observational gaps for the community
• Co-create a minimum package of data collection to answer these questions and participate in the RIOS
• Build an independent global observational data platform that can also support modelling the future of the river carbon cycle
• A forum for knowledge exchange including measurements, modelling and earth observation
• Enable potential contributions from citizen science observations
• Serve as a focal point for policy engagement</td></tr>
</table>

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Competing interests

The authors declare no competing interests.