The boundless carbon cycle

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Tom J Battin
École Polytechnique Fédérale de Lausanne

Sebastiaan Luyssaert
Vrije Universiteit Amsterdam

Louis A Kaplan
Stroud Water Research Center

Anthony Audfenkampe
LimnoTech

commentary

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Tom J. Battin, Sebastiaan Luyssaert, Louis A. Kaplan, Anthony K. Aufdenkampe, Andreas Richter and Lars J. Tranvik

The terrestrial biosphere is assumed to take up most of the carbon on land. However, it is becoming clear that inland waters process large amounts of organic carbon and must be considered in strategies to mitigate climate change.

Atmospheric carbon dioxide concentrations increased from ~280 ppm before the industrial revolution to over 384 ppm in 2008 (ref. 1). This increase reflects only about half of the CO_2 emissions from human activities; the other half has been sequestered in the oceans and on land[2,3] (Box 1). Although the location and magnitude of continental carbon sinks remain uncertain[4], they are assumed to lie within the terrestrial biosphere. We argue that inland waters have a significant role in the sequestration, transport and mineralization of organic carbon. Integration of these fluxes into the traditional carbon cycle is needed for appropriate CO_2 management and climate change mitigation.

Inland waters — such as ponds, lakes, wetlands, streams, rivers and reservoirs — permeate terrestrial ecosystems and often shape the Earth's landscapes. Although only about 1% of the Earth's surface is assumed to be covered by inland waters, their collective contribution to global carbon fluxes is substantial compared with terrestrial and marine ecosystems[5–10]. Specifically, current estimates suggest that inland waters transport, mineralize and bury ~2.7 Pg C yr^{-1} (ref. 5; Fig. 1). This is similar to the size of the terrestrial carbon sink for anthropogenic emissions of 2.8 Pg C yr^{-1} (ref. 3).

So far, carbon fluxes into and out of inland waters have received little attention in global-scale analyses. However, their quantification could prove critical for constraining estimates of terrestrial ecosystem fluxes, adequately integrating all vertical and lateral carbon fluxes over regional and global scales, and predicting feedbacks to climate change[6,11,12]. For example, because inland water fluxes are lateral, their consideration may reconcile the often large discrepancies between estimates of continental carbon balance measured at different scales (Box 1); such discrepancies are pronounced when it comes to the European[11] and Amazon[12] carbon budgets, for example. Furthermore, because the water cycle is exceptionally sensitive to climate change, water-borne carbon fluxes will inevitably respond to climate change. For example, larger storms will mean more intense erosion–deposition fluxes, which will transport a greater proportion of terrestrial carbon to inland waters.

Box 1 | Balancing the carbon cycle

Carbon dioxide sinks

Since 1750, continuously increasing anthropogenic CO_2 emissions and land-use change have perturbed the natural carbon cycle. Of the 9.1 Pg C yr^{-1} (1 Pg C = 1 petagram or 10^9 metric tons of carbon) emitted in this way between 2000 and 2006, 4.1 Pg C yr^{-1} have accumulated in the atmosphere, 2.2 Pg C yr^{-1} have been assigned to marine sequestration and the residual 2.8 Pg C yr^{-1} have been assigned to sequestration within the terrestrial biosphere[3]. At regional and continental scales the terrestrial carbon sink has been evaluated by top-down and bottom-up carbon balances[20,21].

Estimating from the top down

In the top-down approach, the carbon balance from an atmospheric perspective is compiled by running an atmospheric transport model (the so-called inverse model) back in time. The distribution of sources and sinks at land and ocean surfaces is then optimized for observed atmospheric CO_2 concentrations. This approach has confirmed the location of the residual carbon sink over continents. However, state-of-the-art inverse models have a spatial resolution too coarse to account for most inland waters. Therefore, CO_2 outgassing from inland waters is assigned to terrestrial ecosystem respiration, blending the carbon sink in inland waters with the terrestrial carbon sink.

Scaling from the bottom up

The bottom-up approach compiles the carbon balance by scaling up site-level observations of sinks and sources of croplands, grasslands and forests as the main land-use types. Inland waters are usually not considered among the main land-use types, with the exception of reservoirs for the carbon sink of the coterminous US[4]. Furthermore, study sites are typically located in uplands to catch a terrestrial signal with little interference from aquatic ecosystems. Consequently, carbon export from terrestrial ecosystems to inland waters is not typically accounted for in regional estimates that scale-up from the bottom-up approach. This in turn contributes to the discrepancy between estimates based on the bottom-up and top-down approaches.

A watery grave

Approximately 0.6 Pg C yr^{-1} is buried in inland water sediments[5] — this is equivalent to approximately 20% of the carbon assumed to be buried in terrestrial biomass and soils. Still, these estimates do not include long-term net carbon burial in floodplains and other near-water landscapes — a poorly constrained, but most probably significant, flux[13]. Sedimentary carbon often accumulates over thousands of years[5,14] and thus represents a long-term carbon sink. Furthermore, in stable continental sedimentary basins some of the buried carbon may eventually enter the lithosphere. The greater prevalence of bottom-water anoxia in inland waters, compared with the ocean, inhibits sedimentary carbon decomposition and the release of carbon back into the atmosphere.

The loss of organic carbon from terrestrial ecosystems and its subsequent burial in inland waters represents a redistribution of carbon sinks that must be taken into account in climate change mitigation strategies. The first step in managing carbon sequestration is to understand where it occurs and the processes that enhance and maintain it. For example, in regions with high erosion rates one might underestimate whole-watershed carbon sequestration by focusing exclusively on carbon accumulation rates in soils and terrestrial biomass. Furthermore, carbon buried in aquatic sediments will probably respond very differently to regional climate and land-use changes than carbon stored in soil. For example, when soil erosion is high, carbon sinks are more likely to shift from the land to inland waters. Consequently, sediment loads to inland waters increase, but reservoirs and impoundments retain and bury the sediments and their associated carbon[5,9], ultimately reducing their transport to the ocean. It remains unclear, however, whether burial in inland waters represents a net increase in carbon sequestration rather than simply a translocation of a sink that would otherwise have occurred on land or, eventually, in the oceans[15].

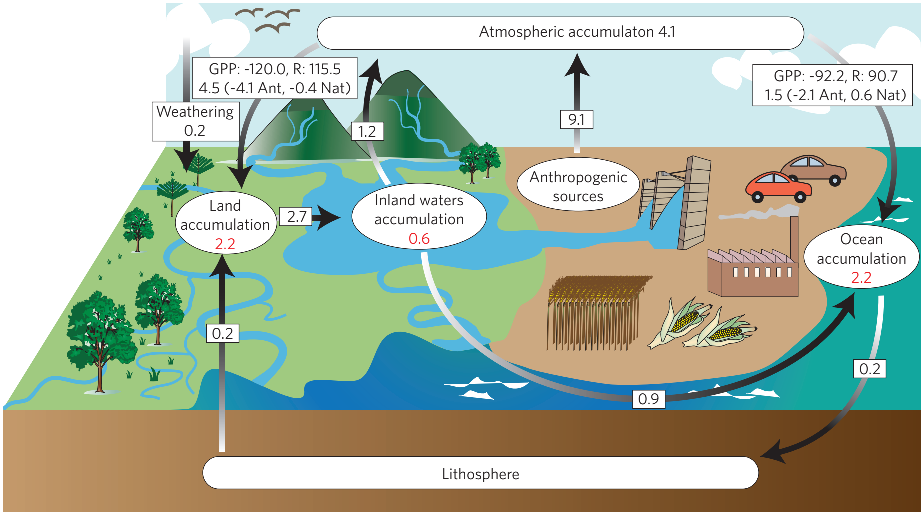

Figure 1 | The 'boundless carbon cycle'. The schematic highlights carbon fluxes through inland waters[5], and also includes pre-industrial[2] and anthropogenic[3] fluxes. Values are net fluxes between pools (black) or rates of change within pools (red); units are Pg C yr^{-1}; negative signs indicate a sink from the atmosphere. Gross fluxes from the atmosphere to land and oceans, and the natural (Nat) and anthropogenic (Ant) components of net primary production — the net uptake of carbon by photosynthetic organisms — are shown for land and oceans. Gross primary production (GPP) and ecosystem respiration (R) are poorly constrained[18,19]; we therefore modified respiration to close the carbon balance. Non-biological dissolution of anthropogenic carbon dioxide by the oceans is included in these fluxes[2]. Fluxes to the lithosphere represent deposition to stable sedimentary basins, and the flux from the lithosphere to land represents erosion of uplifted sedimentary rocks[2].

Inland outgassing

The 'conventional carbon cycle'[2] blends outgassing from inland waters with fluxes of terrestrial ecosystem respiration, and underestimates the potential for lateral transport (Box 1). But terrestrially sourced organic carbon can also fuel secondary production by heterotrophic biota in inland waters. Globally, these biota respire 1.2 Pg of terrestrial carbon each year and release it to the atmosphere[5,6,8,10]. This flux is not recognized in the 'conventional carbon cycle', which pipes organic carbon from the land to the oceans, rather than processing it through biologically active inland waters[2,8].

When this outgassing source is considered in the continental carbon balance, ecosystem production — that is, the difference between annual terrestrial photosynthetic uptake and respiratory release — must be increased from the conventional estimate of 3.2 Pg C yr^{-1} (ref. 2) to 4.5 Pg C yr^{-1} to offset this release and close the carbon budget (Fig. 1). However, present emission estimates from inland waters are provisional and low because of difficulties associated with measuring the areal extent of inland waters and the partial pressure of CO_2 and gas exchange rates[16,17]; all these factors contribute to the underestimation of CO_2 outgassing. Improved and higher estimates of CO_2 emissions from inland waters will thus require even higher ecosystem production to close the carbon balance. A larger flux to the land would fit better with current independent regional estimates of net CO_2 uptake by terrestrial ecosystems using bottom-up approaches[18] (Box 1).

Furthermore, expected land-use changes could exacerbate the climatic impact of inland outgassing. Most carbon mineralized in inland waters is released as CO_2, but lakes, wetlands, and particularly reservoirs, also release methane — a potent greenhouse gas that traps heat more efficiently than an equal amount of CO_2. The creation of reservoirs for hydroelectric power and agriculture will increase methane production[5]. However, dam removal to restore fisheries and riparian-zone reforestation, with subsequent stream widening to improve water quality, may have the opposite effect.

Opportunities and challenges

The significance of inland waters to carbon fluxes on land needs to be recognized. Rivers, lakes and wetlands are important factors for climate change, which should have a place in conceptual models of the global carbon cycle. A broader concept of a 'boundless carbon cycle' should motivate future working groups of the Intergovernmental Panel on Climate Change to place inland waters on the map of global carbon cycling. The contribution of inland waters to global carbon cycling is not recognized within the Kyoto protocol. Based on our assessment, though admittedly preliminary, we argue that post-Kyoto negotiations should include inland waters as part of the 2009 United Nations climate change conference in Copenhagen.

Our concept of a 'boundless carbon cycle' would encourage policymakers to better appreciate the couplings between land and water and between the hydrological cycle and the carbon cycle. This would be a necessary step towards subsuming traditional land management under integrated watershed management as a tool to mitigate climate change. Integrated watershed management connects land and water when considering the effects of soil erosion, urbanization, riparian-zone restoration and dam construction or removal, on carbon burial in — and outgassing from — inland waters.

The 'boundless carbon cycle' would also promote the scientific exploration of fluxes of organic carbon across the terrestrial–aquatic interface, its fate in inland waters and feedbacks with climate change. Collaborative investigations augmented by new observatories and experimental platforms for long-term research are necessary to achieve this. Specifically, we need to improve remote sensing of the global inland water surface area, water residence time and concentrations of organic carbon in these ecosystems. Furthermore, tropical and boreal ecosystems, potential sinks or sources of CO_2, and polar ecosystems prone to loss of organic carbon from melting permafrost should receive more attention. This would address the current bias of our global estimates of aquatic carbon fluxes towards temperate ecosystems.

If we decide to take up the challenge of managing the Earth's surface carbon cycle as a way of mitigating anthropogenic carbon emissions, we cannot ignore the contribution of inland water any longer. Much work lies ahead for scientists to quantify carbon fluxes in streams, rivers and lakes, and for policymakers to incorporate these aquatic ecosystems into strategies for land-use regulations. ❐

Tom J. Battin[1,2], Sebastiaan Luyssaert[3], Louis A. Kaplan[4], Anthony K. Aufdenkampe[4], Andreas Richter[5] and Lars J. Tranvik[1] are at [1]Limnology, Department of Ecology and Evolution, Uppsala University, 752 36 Uppsala, Sweden, [2]Department of Limnology, University of Vienna, 1090 Vienna, Austria, [3]Department of Biology, University of Antwerp, 2610 Wilrijk, Belgium, [4]Stroud Water Research Center, Avondale, Pennsylvania 19311, USA and [5]Department of Chemical Ecology and Ecosystem Ecology, University of Vienna, 1090 Vienna, Austria.*
*e-mail: *tom.battin@univie.ac.at*

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