

Global Significance of the Changing Freshwater Carbon Cycle

As human activities continue to pump carbon into the atmosphere, the backbone of our understanding of the resulting warming is our knowledge of where that carbon is going: into the atmosphere, into the land, and into bodies of water. When it comes to accounting for the carbon absorbed and emitted by water, the role of inland freshwater may appear quite small compared to the vastness of Earth's oceans. After all, inland lakes, rivers, streams, reservoirs, wetlands, and estuaries cover less than 4% of Earth's surface [Downing, 2010; Verpoorter et al., 2014].

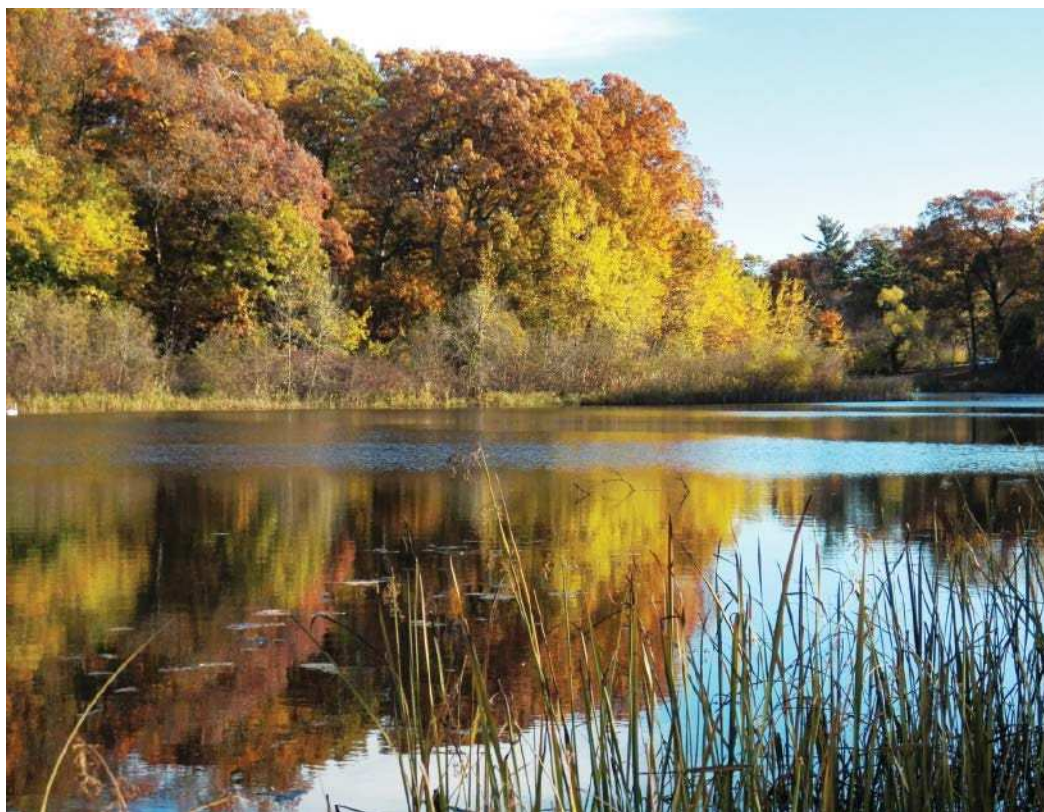
But recent research shows that the roughly 200 million bodies of inland water play a much larger role in the global carbon cycle than their small footprint suggests. Inland streams and rivers move vast amounts of carbon from the land to the ocean, acting as carbon's busy transit system. They also play a disproportionately large role in the global carbon cycle through their high rates of carbon respiration and sequestration [Cole et al., 2007; Tranvik et al., 2009].

According to recent estimates, the amount of carbon that inland waters emit is comparable to the net amount of carbon absorbed by living organisms on Earth's land surface and in its oceans. Moreover, bodies of freshwater bury more carbon in sediments each year than the vast ocean floor [Battin et al., 2009; Aufdenkampe et al., 2011].

Nevertheless, there is great uncertainty in these figures, and scant data exist on continental and global scales. The changing climate is putting freshwater ecosystems at great risk: They are warming at an alarming rate, outpacing warming of the atmosphere and oceans. It's crucial that scientists dedicate more resources to understanding the global impact of the freshwater continuum on the carbon cycle.

Emerging Role of Freshwater in the Global Theater

The latest models of the carbon cycle in land, ocean, and atmosphere show that the biosphere exchanges more than 400 billion metric tons of carbon every year: The land and oceans absorb 212 billion metric tons of carbon each year, and they release 206 billion tons [Schlesinger and Bernhardt, 2013]. Human activities emit around 10 billion metric tons of carbon each year, of which about half accumulates in the atmosphere. The other half is absorbed by the land and the ocean, 80% of



Small inland freshwater bodies play a large role in the global carbon cycle. Here Ruddiman Lagoon, a small freshwater lake, joins Muskegon Lake, a freshwater estuary in Michigan that drains the extensive Muskegon River watershed into Lake Michigan. This North American Great Lake feeds the Saint Lawrence River, which drains into the Atlantic Ocean. Credit: Janet H. Vail

which is accounted for, but the rest is still unknown.

The biggest absorbers of carbon are terrestrial ecosystems. Each year, they take up roughly 120 billion metric tons of carbon dioxide (CO₂) from the atmosphere and release back only 115 billion metric tons. The net balance of 5 billion metric tons is known as net primary production (NPP), and it represents carbon that is removed from the atmosphere. The oceanic ecosystem NPP is about 1 billion metric tons per year. The large net terrestrial

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carbon sink, together with the slightly smaller oceanic sink, helps mitigate the buildup of anthropogenic CO₂ from fossil fuel and biomass burning.

But the carbon absorbed by land doesn't necessarily stay there. Recent global estimates suggest that more than half of that carbon every year winds up in inland waters, roughly 2.7 billion metric tons. This area is where inland waters play a key role, with both positive and negative effects. Half of the carbon is respired and returned to the atmosphere as CO₂—enough to wipe out the helpful effects of the oceanic sink and on the same order of magnitude as the terrestrial sink [Bastviken et al., 2011; Raymond et al., 2013]. On the other hand, roughly 0.4 billion tons get buried in freshwater sediments. Although this is a much smaller fraction, it amounts to more than all



Freshwater waves lap against dune grass on Lake Michigan's eastern shoreline. The North American Great Lakes are the world's largest contiguous body of freshwater, and their vast continental basin encompasses rivers, lakes, streams, reservoirs, and wetlands. Credit: Janet H. Vail

the carbon burial in oceanic sediments [Battin *et al.*, 2009; Aufdenkampe *et al.*, 2011]. The remaining carbon (roughly 0.9 billion tons) is exported to the oceans.

The global importance of the freshwater carbon cycle has been recognized for some time now [Cole *et al.*, 2007], but scientists rarely identify it separately in diagrams of the global carbon budget. Moreover, the freshwater carbon cycle is usually lumped in with that of the land. Recent textbooks on global biogeochemistry completely overlook the revised role of inland waters in the global carbon cycle [Schlesinger and Bernhardt, 2013].

As a result, we lack adequate data and proper models to evaluate how global warming will affect the ways that freshwater interacts with the land, atmosphere, and oceans. Among these key uncertainties is our understanding of carbon transformations (e.g., NPP, respiration, and storage) taking place in inland waters [Biddanda and Koopmans, 2016].

What We Know and Don't Know About Freshwater's Role

Fortunately, our understanding of the carbon cycle in inland waters has improved since several recent studies have highlighted the issue. In 2013, for the first time, the report

from the Intergovernmental Panel on Climate Change contained a brief description of the highly reactive freshwater ecosystems and included conservative estimates of carbon emission and burial (see <http://bit.ly/IPCC-2013-report>). However, much uncertainty still remains in those estimates for inland waters in general. Especially uncertain is how

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extensively human activity—like land use changes and runoff pollution of fertilizers into freshwater ecosystems—changes the carbon emission and storage process [Regnier *et al.*, 2013].

In general, because rivers and streams import CO₂ from soils and groundwater in their watershed, they emit substantially more CO₂ than lakes do [Raymond *et al.*, 2013]. Furthermore, there is particular concern that climate-sensitive northern lakes and streams are emitting more carbon in response to thawing permafrost and changing hydrology that frees up the movement of carbon from the land [Leach *et al.*, 2016].

Mounting evidence also indicates that agriculture and urbanization-driven pollution are playing an important role. Fertilizers induce algae blooms and plant growth that take up carbon. This uptake decreases the amount of carbon emitted into the atmosphere and increases carbon sequestration in inland and coastal waters [Pacheco *et al.*, 2013; Weinke *et al.*, 2014]. However, as these organisms decay, the process of eutrophication depletes the supply of oxygen above lake beds and riverbeds, which increases the activity of anaerobic microbes that produce greenhouse gases such as methane [Bastviken *et al.*, 2011; Campeau and del Giorgio, 2014; Borges *et al.*, 2015].

Furthermore, the world's reservoirs—an exclusively human construct over the past century or so—are now estimated to collectively bury as much carbon and generate as much methane as the rest of the freshwater ecosystems combined [Clow *et al.*, 2015].

Last, there is justifiable concern that current models don't adequately account for the role of small ponds and streams, which store and transform relatively more carbon per unit area than larger bodies of water [Hotchkiss *et al.*, 2015; Holgersson and Raymond, 2016].

Freshwater Continuum in a Warming World

In recent decades, the surface waters of lakes across the world have been warming at an alarming rate of 0.3°C per decade [O'Reilly *et al.*, 2015]. In a CO₂-rich world with a growing human population, rising heat and per capita water use are placing freshwater ecosystems under increasing stress.

How this will affect the global carbon cycle—and climate change writ large—is still uncertain. Higher temperatures will likely intensify the microbial respiration of carbon, which will increase CO₂ emissions. However, ongoing eutrophication and warming of water bodies around the world may also lead to increased phytoplankton blooms, which would sequester additional carbon.

Because of their newly recognized role as a globally significant processor of carbon, the world's inland waters and what happens in them will play a critical role in the biosphere's feedback on future climate. However, despite the importance of inland waters

as pivotal regulators of the global carbon cycle and as sensitive sentinels of environmental change, very few comprehensive studies of carbon flux among the variety of freshwater ecosystems on continental to global scales exist—and even those are limited [Regnier et al., 2013].

Scientists must coordinate international studies to address the challenge of reducing uncertainty in estimates of carbon emissions from and sequestration in freshwater ecosystems. One way they can do this is by quantifying the rapidly changing carbon cycle among the 100–300 million inland freshwater bodies that bridge Earth's land–ocean continuum.

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