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Dynamic modeling of organic carbon fates in lake ecosystems

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ABSTRACT

Lakes are active processors of organic carbon (OC) and play important roles in landscape and global carbon cycling. Allochthonous OC loads from the landscape, along with autochthonous OC loads from primary production, are mineralized in lakes, buried in lake sediments, and exported via surface or groundwater outflows. Although these processes provide a basis for a conceptual understanding of lake OC budgets, few studies have integrated these fluxes under a dynamic modeling framework to examine their interactions and relative magnitudes. We developed a simple, dynamic mass balance model for OC, and applied the model to a set of five lakes. We examined the relative magnitudes of OC fluxes and found that long-term ($>$ 10 year) lake OC dynamics were predominantly driven by allochthonous loads in four of the five lakes, underscoring the importance of terrestrially-derived OC in northern lake ecosystems. Our model highlighted seasonal patterns in lake OC budgets, with increasing water temperatures and lake productivity throughout the growing season corresponding to a transition from burial- to respiration-dominated OC fates. Ratios of respiration to burial, however, were also mediated by the source (autochthonous vs. allochthonous) of total OC loads. Autochthonous OC is more readily respired and may therefore proportionally reduce burial under a warming climate, but allochthonous OC may increase burial due to changes in precipitation. The ratios of autochthonous to allochthonous inputs and respiration to burial demonstrate the importance of dynamic models for examining both the seasonal and inter-annual roles of lakes in landscape and global carbon cycling, particularly in a global change context. Finally, we highlighted critical data needs, which include surface water DOC observations in paired tributary and lake systems, measurements of OC burial rates, groundwater input volume and DOC, and budgets of particulate OC.

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1. Introduction

Lakes are dynamic components of the landscape that actively process, store, and transport terrestrially derived organic carbon (OC) (Cole et al., 2007; Tranvik et al., 2009; Tanentzap et al., 2017), as well as emit inorganic carbon to the atmosphere (Arvola et al., 2002; Raymond et al., 2013; Weyhenmeyer et al., 2015), making them important in global carbon (C) cycling. Owing to few ecosystem-scale studies that fully balance OC budgets (Cole et al., 1989; Hanson et al., 2014, 2015), there remains a considerable knowledge gap in lake OC dynamics, and thus in fully understanding the role of lakes in the global C cycle. Global estimates of CO_2 emissions (i.e., evasion) from lakes and reservoirs are 0.32 Pg (petagrams) C yr^{-1} (Raymond et al., 2013), whereas anywhere from 0.02–0.07 Pg C yr^{-1} (Tranvik et al., 2009) to 0.06–0.25 Pg C yr^{-1} are stored in sediments (Mendonça et al., 2017). These estimates, however, are highly uncertain, and models that dynamically account for major OC fluxes and storage terms in lakes and that explore uncertainties around those terms are needed to advance our understanding of lake OC cycling and their contribution to global C budgets (Hanson et al., 2015; Reed et al., 2018). Existing mass balance models are generally based on low spatio-temporal frequency data, confined to single lakes, and are often from boreal regions (Jonsson et al., 2001; Urban et al., 2005; Andersson and Sobek, 2006; Cremona et al., 2014). In a first step in overcoming some of these limitations, we developed and applied a dynamic mass balance model to examine the relative magnitudes of OC fluxes across a set of five lakes with whole-ecosystem OC budget data. Our goal was to build a simple OC model that could be applied in a range of lake ecosystems to capture seasonal and annual variation in OC concentrations.

1.1. Overview of concepts of key OC fluxes in lake ecosystems

For lakes, the term "mass balance" has been broadly used to quantify carbon or nutrient budgets as the combination of inputs, outputs, and changes to standing stocks in the water column and sediments (Pace and Lovett, 2013). Inputs to lake ecosystem OC budgets are the sum of allochthonous (externally derived) dissolved (DOC) and particulate OC (POC) inflows from surface and groundwater sources, atmospheric deposition via precipitation, dry deposits, and litterfall, and autochthonous (internally derived) DOC and POC (Kawasaki and Benner, 2006) and phytoplanktonic primary production. Outputs from the OC pool reflect mechanisms that mineralize (i.e., photo-oxidation and respiration) and export OC via surface and groundwater outflows. Here, for simplicity, all mineralization processes that convert OC to CO_2 are collectively modeled as respiration. The mass change in OC in the water column and lake sediments is considered as change in storage. Outputs and storage are the fates of OC loads, and their balances define the role of lakes in broader C cycling (Box 1, Fig. 1).

At the global scale, lakes are thought to be net sources of C to the atmosphere based on the mean CO_2 (Kortelainen et al., 2006; Tranvik et al., 2009; Raymond et al., 2013) and methane (Bastviken et al., 2011) concentrations at higher than atmospheric levels in lake surface waters. OC export is less frequently considered, but equally important, in terms of the quality and quantity of OC ultimately reaching the ocean via tributaries (Raymond and Bauer, 2001; Santoso et al., 2017). Because lakes store OC in sediments, they can also act as sinks in the global C cycle (Mulholland and Elwood, 1982; Dillon and Molot, 1997; Einsele et al., 2001; Einola et al., 2011).

We synthesized existing knowledge of lake OC budgets into a model that integrates these important mechanisms, including both in-lake as well as external (i.e., watershed) processes (Fig. 1). Below we described these processes in three main categories of the dominant processes that influence long-term lake OC budgets: 1) allochthonous inputs, 2) autochthonous inputs, and 3) storage and export.

1.2. Allochthonous inputs

Allochthonous inputs include all externally derived OC, including terrestrial DOC and POC from surface and groundwater inflows, litterfall, and direct-fall precipitation (Box 1). Although surface water inflows regularly deliver DOC to lake ecosystems, the uncertainties around their sources and magnitudes are perhaps the most commonly overlooked aspect in OC budgets, largely owing to data limitations (Hanson et al., 2015; Duffy et al., 2018). Prior studies have included direct measurements of inflow stream concentrations of DOC when available (Schindler et al., 1997; Jonsson et al., 2001; Urban et al., 2005; Klump et al., 2009), but other approaches have included literature-derived input estimates (Striegl and Michmerhuizen, 1998), equations based on watershed area (Sobek et al., 2006), watershed-wetland area ratios (O'Connor et al., 2009), precipitation (Hanson et al., 2004; Staehr et al., 2010), or GIS-based estimates based on land cover and distance-weighted hydrological flow paths (Canham et al., 2004). In lakes without surface inflows, including closed-basin and seepage lakes, groundwater can be the dominant hydrological input (e.g., Gaiser et al., 2009) and can deliver DOC to lakes, especially in organic-rich soils (Schindler and Krabbenhoft, 1998). Empirical measurements of groundwater discharge and DOC concentration, however, are rare and difficult to estimate (Hanson et al., 2014). POC inputs from litterfall, and wet and dry atmospheric deposition are typically small and are generally estimated as a function of lake size and literature- or expert-based loading coefficients (Hanson et al., 2004).

1.3. Autochthonous inputs

Autochthonous DOC and POC originate within lakes through bacterial exudates and photosynthesis by primary producers. Since gross primary production (GPP) is difficult to measure at the ecosystem level, net primary production (NPP), considered the difference between GPP and autotrophic respiration, is measured instead (Pace and Lovett, 2013; Box 1). Approaches to estimate NPP include bottle incubations (Urban 2005, Yang et al., 2008) and high frequency measurements of dissolved oxygen or CO_2 concentrations (Cole et al., 2002; Staehr et al., 2010). Statistical relationships have also been developed to estimate NPP from lake temperature and total phosphorus (TP; Hanson et al., 2004), chlorophyll-a (chl-*a*; Jonsson et al., 2001; Ramlal et al., 2003), or static proportions of the overall OC pool (Åberg et al., 2004).

1.4. Storage and export

Long-term burial of POC in lake sediments is the mechanism by which lakes remove C from the global C cycle, and is therefore a critical component of our understanding of the fate of both allochthonous and autochthonous POC (Cole et al., 2002; Tranvik et al., 2009; Mendonça et al., 2017). POC burial in lakes is a product of in-lake POC

Box 1
Mass balance conceptual equations for organic carbon (OC) in lake ecosystems.

<u>*OCALLOCHTHONOUS*</u>: surface and groundwater inflows + litterfall + atmospheric deposition
<u>*$OC_{AUTOCHTHONOUS}$*</u>: gross primary production - autotrophic respiration
<u>*Full budget*</u>: <u>*OCALLOCHTHONOUS*</u> + <u>*OCAUTOCHTHONOUS*</u> = respiration + burial + export + ΔOC (in water column)