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Aquatic Carbon-Nutrient Dynamics as Emergent Properties of Hydrological, Biogeochemical, and Ecological Interactions: Scientific Advances

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Abstract

Carbon and nutrient dynamics in aquatic systems often emerge as the result of hydrological, biogeochemical, and ecological interactions. Due to the multiscale and multidisciplinary nature of these process interactions, research into aquatic carbon and nutrient dynamics is becoming increasingly interdisciplinary. The motivation for this special issue came from an international workshop titled "*Hydro-Biogeochemical Processes: Mechanisms, Coupling, and Impact*," which took place from 27 to 31 October 2015 at China University of Geosciences, Wuhan, China. During this workshop, scientists from various countries and disciplines met to discuss current work and future advances on topics such as the hydro-biogeochemistry of Earth's critical zone, stream-groundwater interaction zones, aquatic ecosystem processes, and dynamics at land-atmosphere, land-ocean, and human-natural interfaces. Contributions to this special issue on "*Emergent aquatic carbon-nutrient dynamics as products of hydrological, biogeochemical, and ecological interactions*" include papers from authors who attended the workshop and from those who responded to the open solicitation for papers. Our aim in organizing this special issue is to stimulate continued discussion and collaboration across disciplinary boundaries in order to further our collective understanding of aquatic carbon-nutrient dynamics.

1 Introduction

Carbon and nutrient dynamics affect the fundamental structure and function of aquatic ecosystems, including rivers, estuaries, lakes, and wetlands. These dynamics emerge from complex interactions among hydrological, biogeochemical, and ecological processes. For example, factors such as hydrologic flow paths and residence times often play key roles in the rates, magnitude, and spatial extents or locations of aquatic carbon and nutrient (e.g., nitrogen, phosphorous, and sulfur) processing. These factors, together with other interconnected processes (e.g., human activities and aquatic ecological dynamics), lead to organized biogeochemical patterns—in space and time—across various aquatic systems.

In human-dominated watersheds, carbon and nutrient dynamics are modified by elevated nutrient delivery to surface waters, which in turn, affects aquatic ecosystem health. In agricultural watersheds, nutrients may accumulate in the upper soil horizons during dry periods after fertilization and nitrogen fixation, leading to rapid flushing to deeper soil horizons and into rivers via macropore or tile drainage networks during subsequent rainfall events (e.g., Bechtold et al., 2003; Li et al., 2010). Correspondingly, urban watersheds are hydrologically *flashy* due to increased imperviousness, reduced surface roughness, and channelized streams. These conditions lead to rapid pulses of nutrients to streams and limited opportunity for in-stream nutrient processing and removal (e.g., Beaulieu et al., 2015). In both instances, excess nutrients react with organic carbon in the fluvial network, potentially causing aquatic ecosystem degradation, including acidification of streams and lakes (Driscoll et al., 2003), over-enrichment of estuaries, and consequently eutrophication (Diaz & Rosenberg, 2008) and hypoxia (Rabalais et al., 2002). Human activities can therefore fundamentally change aquatic ecosystem composition and function (as can natural disturbances, e.g., loss of canopy cover) that affect carbon and nutrient dynamics.

It is clear that multiple interacting processes across a range of spatiotemporal scales influence carbon and nutrient dynamics and therefore functions of aquatic ecosystems. However, a coherent understanding synthesized across physical and biological disciplines to interpret and predict the complex and often nonlinear ecobiogeochemical behavior of aquatic systems and improve potential watershed management is currently lacking. In this special issue on "*Emergent aquatic carbon-nutrient dynamics as products of hydrological, biogeochemical, and ecological interactions*" we highlight novel research findings, future research needs, and potential paths toward improved understanding of carbon and nutrient dynamics that are the result of hydrological, biogeochemical, and ecological interactions, as well as other factors such as water management.

2 Special Issue on Emergent Aquatic Carbon-Nutrient Dynamics

The motivation for this special issue came from an international workshop titled "*Hydro-Biogeochemical Processes: Mechanisms, Coupling, and Impact*," which took place from 27 to 31 October 2015 at China University of Geosciences, Wuhan, China. During this workshop, scientists from various countries and disciplines met to discuss current research, challenges, and future research directions in ecosystem hydro-biogeochemistry. Research topics included the hydro-biogeochemistry of Earth's critical zone, the permeable layer from the tops of trees to the bottom of the groundwater. Research examined stream-groundwater interactions and dynamics at land-atmosphere, land-ocean, and human-natural interfaces. This special issue thematically builds upon the presentations and initial discussions that occurred during the international workshop. With this special issue, we hope to stimulate further discussion and interdisciplinary collaboration on these topics and synthesize emergent themes from the papers published herein (Figure 1).

2.1 Small-Scale Processes as Drivers of Large-Scale Patterns

Hydrological, biogeochemical, and ecological patterns observed at the stream reach (hundreds of m^2) to landscape (hundreds of km^2) or larger extents often demonstrate emergent properties wherein large-scale patterns arise from smaller scale processes (Cheng & Basu, 2017; Li et al., 2017; Roche et al., 2017). Furthermore, characteristics of a system expressed at a broad spatial or temporal scale are not necessarily evident at finer spatial scales (Corning, 2002).

In this special issue, Li et al. (2017) highlight how fine-scale (<25 cm) patterns of hyporheic flow and microbially mediated denitrification can affect nitrogen removal rates at the stream reach (hundreds of meters) and larger spatial scales. Azizian et al. (2017) demonstrate how nitrogen processing in stream hyporheic zones can also be influenced by the spatiotemporal structure of groundwater flow, whereby higher rates of vertical groundwater flux generally diminish stream nitrogen processing. Accordingly, turbulence-driven hyporheic flow dynamics at the submeter scale, and groundwater flow at the riffle-pool sequence scale, represent nested processes that simultaneously modulate stream nitrogen processing (Azizian et al., 2017; Li et al., 2017).

While landscape level hydro-biogeochemical patterns can be driven by physical (Azizian et al., 2017) and microbial (Roche et al., 2017) processes occurring at subcentimeter scales, measuring, understanding, and modeling these fine-scale processes present extensive challenges. Azizian et al. (2017) detail one observational challenge: although subcentimeter processes have importance to stream denitrification rates, we have limited ability to measure, or at least adequately represent, process heterogeneity at subcentimeter scales. Roche et al. (2017) describe a second challenge: identifying how small-scale biofilm structure controls fine particle retention at the stream reach scale. Because it is impossible to measure the full extent of fine-scale heterogeneity of processes and characteristics in streams and watersheds, scientists are required to determine the acceptable spatial granularity of measurements based on the scientific objective or management target.

Complementary to observations, modeling approaches can assist in understanding how small-scale processes emerge as larger scale patterns and provide insight beyond observational data alone. For example, fine-scale heterogeneity not captured by observations can be represented using probabilistic models (Azizian et al., 2017). From these integrated measurement and modeling approaches applied at fine scales, a new, more *complete* set of information is derived that can then be linked to empirical or process-based models at larger scales to facilitate scaling submeter processes to landscape biogeochemical patterns. While this procedure may seem theoretically clear, coupling processes and patterns across scales in realistic, predictive models remains a challenge for interdisciplinary studies of aquatic ecosystems from hydrological, biogeochemical, and ecological perspectives.

2.2 Process Understanding at Multiple Spatial Scales

The papers in the special issue evaluate processes across multiple spatial scales and highlight complex interactions among hydrological, biogeochemical, and microbial processes that influence aquatic carbon and nutrient dynamics. Roche et al. (2017) describe the physical structure of benthic biofilms at fine spatial scales (μm), which can control fine particle retention but not deposition rates. The authors describe how biofilm-mediated retention of fine particulate organic matter affects stream organic carbon cycling and watershed carbon export. However, these fine-scale processes are often not considered in models that quantify or simulate hydrological transport and biogeochemical processes at large spatial scales (e.g., at the reach or watershed scale; Roche et al., 2017).

Ye et al. (2017) demonstrate that larger rivers may be more important for nutrient processing than previously recognized. This is in contrast to work that has underscored the importance of small streams in regulating fluvial nitrogen dynamics at river network to continental scales (Alexander et al., 2000; Gomez-Velez et al., 2015; Peterson et al., 2001). The importance of larger rivers in nitrogen removal processes has been traditionally underappreciated due, in part, to the lack of field data on nitrogen processing in large river systems (Ensign & Doyle, 2006). In fact, most field studies, and data generated from them, have been limited to a relatively narrow range of spatial measurements (Roche et al., 2017) and have typically excluded fine-scale (μm) and larger river measurements (Ye et al., 2017).

This special issue further highlights emergent carbon and nitrogen processes at catchment (Kasurinen et al., 2016), river network (Ye et al., 2017), national (Destouni et al., 2017), and global scales (Cheng & Basu, 2017). Kasurinen et al. (2016), for example, show that multiple mechanisms, including soil temperature, catchment water storage, and land-cover, can influence landscape level dissolved organic carbon (DOC) dynamics in boreal catchments in Sweden. Additionally, the timing of DOC release from soils varied between forest-dominated and mire-dominated catchments (Kasurinen et al., 2016). Specifically, in forest-dominated catchments, DOC release was greatest when soil temperature was low, while the opposite was true in mire-dominated catchments. This highlights the need to capture process heterogeneity in field data and modeling in order to properly represent variability in mechanisms of DOC export among catchments.

Ye et al. (2017) highlight variability in the dominant mechanisms controlling retention of various solutes (e.g., nitrate, ammonium, and phosphorous) within a single river network. For example, ammonium uptake was not significantly correlated with any environmental variables, but nitrate uptake was associated with chlorophyll *a* concentration and land use. Soluble reactive phosphorous uptake was linked with agricultural land use and suspended sediment concentration, likely reflecting phosphorus-sediment sorption dynamics (Ye et al., 2017). The lack of relationships between ammonium uptake and various environmental characteristics might be a consequence of biological preference for ammonium relative to nitrate. Thus, biological processing can mask land cover and land use impacts particularly when the nutrient of concern is in high demand.

Cheng and Basu (2017) synthesized data from 600 lentic systems (lakes, reservoirs, and wetlands) around the globe and found that nutrient (total nitrogen, total phosphorus, nitrate, and phosphate) removal rate constants in these systems were inversely proportional to water residence time. The inverse relationship between reaction rate constants and residence time was related to lentic system morphometry and volume to surface area relations. In smaller lentic systems with shorter residence times, more of the water and solutes are in contact with sediment boundaries, thus promoting higher processing rates. Further, upscaling empirical data revealed the importance of small wetlands in nutrient removal processes. Specifically, 50% of the landscape-scale nitrogen removal occurred in wetlands smaller than 350 m^2, underscoring the important role of small wetlands in nutrient processing across the landscape (Cheng & Basu, 2017).

2.3 Linking Science and Management

A goal of many projects across the basic to applied science continuum is using scientific understanding to guide real-world action (Stokes, 1997). While the importance of this broader impact is increasingly emphasized, linking science and management remains a challenge. This is particularly true, as Destouni et al. (2017) emphasize, because data are often limited to conduct complete assessments on the effectiveness of management approaches to improve water quality. For instance, in Sweden monitoring data necessary to evaluate ecosystem status is available for only 1% of the stream and lake water bodies classified under the EU Water Framework Directive (WFD) (Destouni et al., 2017). Accordingly, there is a need for multiscale experimental and monitoring data, incorporated into a multidisciplinary framework, to improve understanding and upscaling capabilities and to determine how finer-scale processes result in larger-scale patterns.

Multiple other challenges for linking science with management objectives exist, some of which are highlighted in this special issue. For example, although small wetlands may play a disproportionately large role in nutrient retention (Cheng & Basu, 2017), wetland area-function relationships are not yet fully integrated into mitigation strategies. Approaches that incorporate the nutrient retention and water quality improvement potential of small wetlands, lakes, and reservoirs can help enhance mitigation strategies. Additionally, nutrient water quality assessment frameworks that evaluate loads, as opposed to concentrations, may not be able to assess human-driven impacts on inland water quality (Destouni et al., 2017). As such, use of concentration data may be more appropriate to reveal human-driven water quality impairment and nutrient impacts on coastal receiving bodies. In addition to determining the *best* data to evaluate water quality impacts, these monitoring data need to be of adequate resolution in both space and time. Even in developed countries such as Sweden, data availability limits these types of assessments (Destouni et al., 2017), and these data limitations are even greater in developing countries (Riveros-Iregui et al., 2018).

3 Summary and Outlook

The majority of the papers in this special issue highlight the need for a multiscale, interdisciplinary measurement and modeling approach, which would assist in improved aquatic resource management. For example, the multiscale approach will allow for µm-cm scale processes to be evaluated at larger scales (1–100 m) where ecobiogeochemical patterns are typically observed. Further, research that involves measuring and modeling emergent carbon and nutrient dynamics, as well as other biogeochemical processes, needs to cross scientific disciplines in order to be useful in supporting management objectives. For example, Li et al. (2017) recommend *increased synergy of hydrological, biogeochemical, and microbiological field investigations*. A multidisciplinary and multiscale framework on ecobiogeochemical processes and patterns will likely deepen our understanding of aquatic ecosystems and should generate new data to both inform and improve larger scale models and guide aquatic resource management. Future research should aim to incorporate this multifaceted approach, as all of these components will be necessary to develop a coherent understanding to interpret and predict the complex and often nonlinear ecobiogeochemical behavior of aquatic systems.

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