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Spatial patterns and environmental controls of particulate organic carbon in surface waters in the conterminous United States

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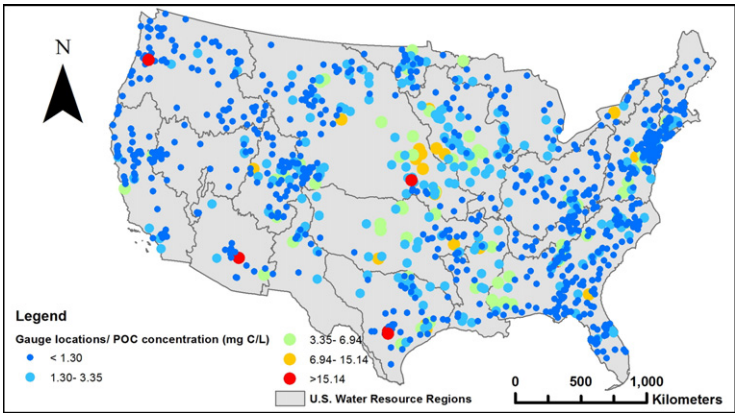
HIGHLIGHTS

- POC concentration varies substantially across surface waters in the United States.
- Suspended sediment and chlorophyll-a explain 26% and 17% of the POC variability.
- Twenty one environmental factors explain ca. 40% of the spatial variance in POC.

GRAPHICAL ABSTRACT



The 1145 U.S. Geological Survey gauge stations and concentration of particulate organic carbon.

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ABSTRACT

Carbon cycling in inland waters has been identified as an important, but poorly constrained component of the global carbon cycle. In this study, we compile and analyze particulate organic carbon (POC) concentration data from 1145 U.S. Geological Survey (USGS) gauge stations to investigate the spatial variability and environmental controls of POC concentration. We observe substantial spatial variability in POC concentration (1.43 ± 2.56 mg C/L, mean ± one standard deviation), with the Upper Mississippi River basin and the Piedmont region in the eastern U.S. having the highest POC concentration. Further, we employ generalized linear models (GLMs) to analyze the impacts of sediment transport and algae growth as well as twenty-one other environmental factors on the POC variability. Suspended sediment and chlorophyll-*a* explain 26% and 17% of the variability in POC concentration, respectively. At the national level, the twenty-one environmental factors combined can explain ca. 40% of the spatial variance in POC concentration. At the national scale, urban area and soil clay content show significant negative correlations with POC concentration, whereas soil water content and soil bulk density correlate

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positively with POC. In addition, total phosphorus concentration and dam density correlate positively with POC concentration. Furthermore, regional scale analyses reveal substantial variation in environmental controls of POC concentration across eighteen major water resource regions in the U.S. The POC concentration and associated environmental controls also vary non-monotonically from headwaters to large rivers. These findings indicate complex interactions among multiple factors in regulating POC concentration over different spatial scales and across various sections of the river networks. This complexity, together with the large unexplained uncertainty, highlights the need for considering non-linear interplays of multiple environmental factors and developing appropriate methodologies to track the transformation and transport of POC along the terrestrial-aquatic interfaces.

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1. Introduction

Carbon cycling along the terrestrial-aquatic interfaces have been identified as an important, but poorly constrained component of the global carbon cycle (Regnier et al., 2013; Butman et al., 2016). In the Fifth Assessment Report of the International Panel on Climate Change (IPCC), carbon export, burial, and outgassing from inland waters are highlighted as critical but insufficiently investigated processes that may affect the global carbon budget (Ciais et al., 2013). However, inclusion of these processes into regional and global carbon cycling investigations is jeopardized by the significant uncertainties in the magnitude, variability, and environmental controls of riverine carbon (Butman and Raymond, 2011; Regnier et al., 2013; Rodríguez-Murillo et al., 2015).

Riverine carbon is mainly composed of three groups of carbon species including dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) (Cole et al., 2007). Synthesis of the global riverine carbon data suggests that magnitudes of riverine POC (0.2 Pg C/year) and DOC (0.18–0.33 Pg C/year) fluxes are comparable at the global scale (Cole et al., 2007; Galy et al., 2015). However, the underlying mechanisms controlling the two species are distinct from each other and vary over different spatial scales (Zhang et al., 2009). Therefore, it is necessary to explore the impacts of a wide range of environmental factors on POC concentration to discover knowledge contributing to the explanation of carbon cycling along the terrestrial-aquatic continuum.

Factors affecting POC in surface waters can be generally categorized into two groups based on their influences on the supply and/or transport of POC. POC mainly originates from two sources including erosion of soil organic carbon (Kirkels et al., 2014), and autochthonous production (Hatten et al., 2010). Impacts of these two sources on riverine POC vary with distance from headwaters, land use types, and hydrological conditions. Soil erosion mobilizes as much as 4–6 Pg C $year^{-1}$ of sequestered carbon in soils at the global scale, and plays a dominant role in POC export (Galy et al., 2015). It was estimated that autochthonous production provides approximately 8–28% of POC in large rivers (Howarth et al., 1996; Veyssy et al., 1998). In streams with enriched nutrients, algae growth could be the primary source of carbon input to water bodies (Royer and David, 2005). Contributions of the two POC sources vary over different temporal and spatial scales, resulting in significant variability in POC concentration.

Riverine POC is also controlled by transport-related factors. Carbon cycling is closely coupled with water cycling since water movement from soils to rivers contributes to POC transport (Kirkels et al., 2014). Rain drops provide energy and runoff for detaching and mobilizing soil organic matter through erosion, especially during heavy rainfalls (Gomez, 2003; Nearing et al., 2005). Meanwhile, intensive rainfalls and associated high streamflow increase the capacity of rivers in carrying high concentrations of POC (Neitsch et al., 2009). Remobilization of bottom sediment and bank erosion by floods also increase riverine POC (Adams et al., 2015; Merritt et al., 2003; Smith et al., 2003).

Human activities have dramatically altered riverine POC through land conversions, damming, and chemical fertilizer use (Butman et al., 2015; Kirkels et al., 2014; Syvitski et al., 2005; Zhou et al., 2009). Land-use change influences riverine carbon cycling either by altering water cycling or by changing the production of carbon leachates (Farley et al., 2005; Piao et al., 2007). Agricultural activities enhance soil organic carbon (SOC) erosion through mobilizing organic matter aggregates in top soils during tillage and irrigation (Kirkels et al., 2014). Dam constructions have dramatically altered the natural flow regimes and resulted in high sedimentation and burial of POC (Li et al., 2014). Excessive nutrient discharge to rivers and lakes from urban areas and agricultural lands stimulates autochthonous POC primary production, therefore increases concentration of river carbon (Rabalais, 2002).

Recent efforts have been devoted to unraveling the complex controls of riverine POC. However, most studies examining regional scale POC dynamics were mainly focused on quantifying the magnitude of POC export (Tian et al., 2015), but paid insufficient attention to exploring mechanisms governing POC (Schlunz and Schneider, 2000). Local scale investigations provide detailed descriptions of how riverine carbon dynamics are affected by input, in-stream decomposition, and deposition (Webster et al., 1999), and demonstrate contrasting results among different watersheds (Hope et al., 1994), reflecting the complex interplays of multiple processes in controlling the generation, transport and deposition of POC. Furthermore, it is uncertain whether the mechanisms identified through watershed-scale studies are applicable and transferable to broader scales that include complex climate conditions, land use types and geophysical settings (Hatten et al., 2010). The reported large uncertainties call for comprehensive analyses of factors influencing POC in surface waters.

Investigating how POC concentration in surface waters is affected by multiple environmental factors is a necessary and critical step towards better understanding of riverine POC fluxes. In this study, we compile POC concentration data from 1145 of the U.S. Geological Survey (USGS) gauge stations. Statistical analysis is employed to explore impacts of climate factors, hydrological conditions, soil properties, and anthropogenic activities on the spatial variability of POC concentration. The objectives are to: 1) characterize the spatial patterns of POC concentration across the U.S riverine systems; 2) identify key variables controlling riverine POC concentration over different spatial scales and river orders; and (3) provide insights into future investigations of riverine POC related carbon sources and sinks.

2. Method

2.1. Data compilation and statistical analysis

We compiled field POC concentration data from 1145 USGS gauge stations (Fig. 1) listed in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES-II) dataset (Falcone, 2011). The GAGES-II dataset provides geospatial attributes, such as climate conditions, geomorphological characteristics, and soil properties, for stations with long-term streamflow records (>20 years). POC refers to carbon that cannot pass membrane filters with a 0.45 μm pore size (https://water.usgs.gov/admin/memo/QW/qw00.08.html).We first checked the availability of POC concentration data for each GAGES-II station. Stations with available suspended organic matter (with USGS water quality parameter code of 00689), or paired total organic carbon (TOC, 00680)

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