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Characterizing nutrient distributions and fluxes in a eutrophic reservoir, Midwestern United States

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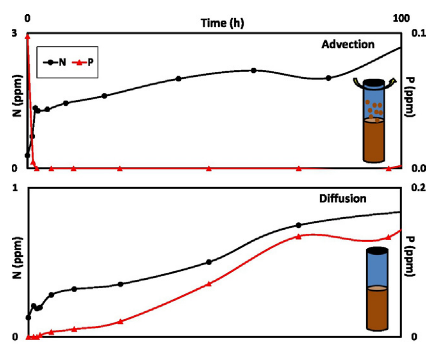
HIGHLIGHTS

- The role sedimentary nutrients play in triggering algal blooms is poorly understood.
- Spatial sampling of sediment and water was conducted in an agricultural reservoir.
- Core experiments examined nutrient behavior via diffusion and sediment resuspension.
- Diffusion releases sediments N and P; resuspension releases N but promotes P storage.
- Sediments may be an endogenous nutrient source contributing to algal blooms.

GRAPHICAL ABSTRACT



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ABSTRACT

Harmful algal blooms are increasingly common in aquatic ecosystems and have been linked to runoff from agricultural land. This study investigated the internal nutrient (i.e., phosphorus (P) and nitrogen (N)) dynamics of a eutrophic reservoir in the Midwestern United States to constrain the potential for sedimentary nutrients to stimulate harmful algal blooms. The spatial distribution of nutrients in the water column (soluble reactive P (SRP), nitrate/nitrite-N (NO_x-N), and ammonium-N (NH_4^+-N)) and sediments (total P, total carbon (C), total N, and organic matter (OM)) were quantified and mapped. Water column nutrients varied spatially and temporally, with generally higher concentrations near the dam wall during normal lake levels. The upper portion of the lake, near the inlet, was sampled during a flood event and had overall higher nutrient concentrations and lower chlorophyll levels compared to normal lake level samples. Mean sedimentary total P (936 mg/kg) was ~30% higher in the reservoir than the surrounding upland soils, with the highest concentrations near the dam wall (1661 mg/kg) and a significant positive correlation found between sedimentary total P, total C, and OM. Additionally, 15 intact sediment cores were manipulated ex situ to examine mechanisms of nutrient flux across the sediment-water interface (SWI) that may trigger algal blooms. Core treatment conditions included advection (i.e., simulating potential nutrient fluxes during wind events through sediment resuspension) and diffusion. Core experiments indicated both advective and diffusive conditions at the SWI may trigger the flux of nutrients important for algal growth from lake sediments, with diffusion contributing both N and P to the water column, while intense advection increased water column N, but decreased P. Release of P to the water column may be more diffusion-driven than advection-driven, whereas N release to the water column appears to be both diffusion- and advection-driven.

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1. Introduction

Globally, intensive agriculture has been linked to eutrophication, declining water quality, and algal blooms, resulting in more than $2 billion in annual damage in the United States alone (Paerl et al., 2011). Algal blooms are triggered by excess inputs of the normally limiting nutrients nitrogen (N) and phosphorus (P), and can be responsible for a range of human health and environmental risks, from liver toxic *Microcystis* blooms in Lake Erie (Kane et al., 2014) to the expanding Dead Zone in the Gulf of Mexico (Yaeger et al., 2013). Harmful algal blooms are predicted to increase in magnitude and frequency, exacerbated by increasing pollution and climate change (Paerl et al., 2011; Paerl and Paul, 2012). Systems vulnerable to harmful blooms include lakes and reservoirs, particularly those in highly agricultural areas. River impoundments may further affect watershed-scale biogeochemical processes (Powers et al., 2013): eutrophic reservoirs have been shown to be sites of N loss and co-occurring P storage (David et al., 2006; Grantz et al., 2014). Extensive denitrification in large, shallow reservoirs may be beneficial, leaving less N to contribute to downstream hypoxia. However, large impoundments may not be enough to mitigate downstream hypoxia, and N pollution is problematic for reservoirs (David et al., 2006).

Accumulated P in lakebed sediments may result in a system of self-perpetuating eutrophication through endogenous loading of stored P (Reddy et al., 1996; Grantz et al., 2014). Significant P loading from sediments has been observed in environments as diverse as estuarine (Roy et al., 2012), boreal (Tammeorg et al., 2015), and subtropical (Xie et al., 2003; Grunwald et al., 2006; Torres et al., 2014), and in bodies of water as large as the Laurentian Great Lakes (Kane et al., 2014) and Lake Taihu in China (You et al., 2007). Excess P inputs are often stored in lentic systems as "legacy" P (Sharpley et al., 2013), which is P that has been accumulating in sediments over time and may take tens to thousands of years to flux out of the system (Kleinman et al., 2011). Algal blooms fed by internally stored P fluxing into the water column would not be affected by nutrient runoff mitigation and could continue in near-perpetuity, as reflected by some systems that have naturally high P inputs (e.g., Kilinc and Moss, 2002). In fact, algae like *Mycrosistis* can stimulate P release from the sediments through raising water column pH via photosynthesis (Xie et al., 2003).

Important mechanisms for internal loading in lentic systems are diffusive and advective processes (Reddy and Newman, 1992; Roy et al., 2012; Tammeorg et al., 2015). In detail, eutrophic systems can lead to bottom water anoxia that triggers P release due to reduction of iron (Fe)-bearing minerals. Moreover, water columns depleted of nutrients from high levels of primary productivity in summer may drive molecular diffusion of nutrients from sediments into the water column (Einsele, 1936; Mortimer, 1941; Amirbahman et al., 2003; Amirbahman et al., 2012). In terms of advection (defined here as the transport of sediments and porefluids from the lakebed to the water column via sediment resuspension), P dynamics in shallow lacustrine environments have been shown to be wind-driven (e.g., Søndergaard et al., 1992; Zhang et al., 2011) due to wind-induced wave action causing shear on the bed sediments (Ding et al., 2012). This may result in bioavailable soluble reactive P (SRP) desorption from suspended sediment particles as a response to lower water column P levels or SRP release from enriched sediment porewaters. By increasing shear stress on the sediment, more bioavailable P may be released depending on the composition of the sediment (Dorich et al., 1985; Moore and Reddy, 1994). Indeed, hurricanes, accompanied by intense storms and large shear stresses at the sediment-water interface (SWI), have been reported to stimulate SRP upwelling in lakes and wetlands (Ding et al., 2012; Dunne et al., 2012).

We examined patterns of nutrient loading and storage in Carlyle Lake, Illinois, USA, an impacted agricultural reservoir in the Mississippi River watershed in which algal blooms have been observed, to determine if conditions favorable for algal blooms could be triggered by internal loading alone. This study seeks to answer the following questions: what are the concentrations and spatial distributions of sedimentary and surface water nutrient pools in a shallow reservoir surrounded by intensive agricultural land use, and what drives the exchange of nutrients between the sediments and water column: advective or diffusive flux? By constraining the distribution of the endogenous nutrient load and dominant mechanism of nutrient flux, this study seeks to inform reservoir management for improved remediation of nutrient pollution and the concomitant algal blooms and hypoxia that threaten water security.

2. Site description

Carlyle Lake is the lower of two large impoundments along the Kaskaskia River, which drains central Illinois, USA, and eventually flows into the Mississippi River. The Kaskaskia River watershed is 14,152 km^2 of predominantly agricultural land (i.e., 67%; Chiang et al., 2012). The upper Kaskaskia River watershed has extensive tile drainage, which rapidly conduits nutrient-rich runoff to waterbodies (David et al., 2006; Yaeger et al., 2013). Carlyle Lake was dedicated in 1967, and is managed by the US Army Corps of Engineers for flood control purposes (Illinois State Water Survey, 1975), drinking water supply, and recreation. It is large and generally shallow (105 km^2; mean depth = 3.4 m; Illinois Department of Natural Resources, 2016), with two distinct sections divided by a railway trestle: a much shallower (mostly <1 m) northern portion (referred to here as the "upper lake") below the Kaskaskia River inlet, which features partially submerged trees, and a larger, deeper, and southern portion (referred to as the "lower lake") that extends below the railway to the dam wall. Carlyle Lake can experience high winds and waves due its large fetch. The size and highly agricultural setting of the lake's drainage area (7030 km^2; 73% farmland; Fig. 1) has likely led to the observed high levels of P in Carlyle Lake's water column (e.g., US Army Corps of Engineers, 2006), above the Illinois General Use Water Quality Standard for total P in lakes (i.e., 0.05 ppm; Illinois Environmental Protection Agency, 2016). The lake's compromised water quality is evidenced by anecdotal reports of fish kills and algal blooms, both of which were observed on the shores of the upper lake during sampling for this study.

3. Methods

3.1. Field sampling

To understand the distribution of nutrients within Carlyle Lake, we collected an extensive and high resolution suite of water and sediment samples. Sampling sites were randomly generated in ArcMap 10.1 using a random raster probability surface, and accessed by boat on 4–6 May 2015 and 9 June 2015. The first sampling period was focused on the lower lake with some samples collected at upper lake boat docks. The second sampling period was during flooding conditions when the upper lake was boat-accessible. In situ water quality parameters (dissolved oxygen (DO), pH, specific conductivity, turbidity, and chlorophyll concentration) were measured at each sampling site using a YSI 6600V2 or EXO2 sonde (Yellow Springs Instruments, Yellow Springs, Ohio) and a Hach Turbidimeter (Hach Company, Loveland, Colorado). Water samples for nutrient analysis (SRP, nitrate/nitrite-N (NO_x-N), and ammonium-N (NH_4^+-N)) were taken from the lake surface ("surface water") and close to the SWI ("bottom water") using a Van Dorn water sampler. Samples were stored in acid-washed polyethylene bottles on ice until reaching the lab, whereupon they were filtered through 0.45 μm filters into 20 mL scintillation vials, preserved with sulfuric acid (pH < 2), and stored at 4 °C until analysis. Sediments for total P, total carbon (C), total N, and organic matter (OM) analyses were collected using a Petite Ponar grab sampler (Wildco, Yulee, Florida). The upper 5 cm of sediment was transferred to ziplock bags using a marked trowel and stored on ice until reaching the lab; samples were then refrigerated at 4 °C until analysis. A total of 64 discrete sampling locations in the lake body were utilized for

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