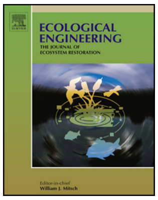
Ecological Engineering xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Relative importance of external and internal phosphorus loadings on affecting lake water quality in agricultural landscapes

Keunyea Song[a,*], Craig J. Adams[b], Amy J. Burgin[a]

[a] *University of Kansas and Kanas Biological Survey, University of Kansas, 2101 Constant Ave., Lawrence, KS, 66047 USA*
[b] *School of Natural Resources, University of Nebraska-Lincoln, 3310 Holdrege Street, Lincoln, NE, 68583 USA*

ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form 5 June 2017
Accepted 5 June 2017
Available online xxx

Keywords:
Agricultural reservoir
Eutrophication
External P loading
Internal P loading
Flow-through sediment core incubation

ABSTRACT

Internal phosphorus (P) loading from the sediment poses a high risk of being an additional P source to deteriorate water quality. Previous studies hypothesized that internal P loads can be as high as external P inputs, especially in P enriched landscapes such as agricultural areas. However, internal P loadings in eutrophic conditions are rarely quantified or compared with external P loads. In this study, we aimed to answer these three questions; 1) how much P is internally released from the sediment of hypereutrophic lakes? 2) how much do internal P loads contribute to lake water quality compared to external loads? and 3) what factors regulate the release and retention of P in the sediment? We selected four hypereutrophic lakes located in Eastern Nebraska. In the study lakes and watersheds, internal and external P loads were quantified in 2014. Total P concentrations of inflow water collected from primary water channels feeding the study lakes and daily inflow water discharge rates were used to calculate external P loads. Internal P loads were quantified from flow-through soil core incubation experiments. External TP loads varied temporarily depending on the changes in discharge, and were highest during spring storm events. The majority of internal P loading (i.e. P release from sediment) occurred in the summer when lakes experience strong stratification (i.e. anaerobic conditions). This is likely associated with oxygen availability in the sediments and chemical dissolution of P. By comparing the annual-scale of external and internal P inputs, external P loadings were still the dominant P source to the lakes, contributing up to 98% of the total P input whereas internal P loadings accounted for 4–12% of the total P input. Although internal P loads were relatively minor on an annual time scale, we found that summer internal loadings in some of study lakes exceeded their external loadings. Our results confirmed the dominant influence of external P loadings on water quality in the reservoirs. This suggests that non-point source controls and watershed management strategies to reduce external loadings should be implemented prior to internal P loading controls. Internal P loadings can be a significant P source, even if just temporarily, worsening water quality of agricultural reservoirs and downstream ecosystems in the summer.

1. Introduction

Eutrophication is one of the most common water quality problems in the world. Nearly half of all US lakes are impaired by eutrophication, mainly from excessive phosphorus (P) loading (Carpenter et al., 1999; Dodds et al., 2009; Smith and Schindler, 2009). Eutrophication results in harmful algal blooms, hypoxia in coastal areas and loss of biodiversity. Such water quality deterioration is estimated to cause an annual loss of approximately $ 2.2 billion in the US (Dodds et al., 2009).

Agricultural activity is one of the major contributors of P to aquatic ecosystems (Kleinman et al., 2011; Royer et al., 2006; Schippers et al., 2006). The use of P in agricultural fertilizer has increased 3.5 times since 1960 and is expected to continue increasing (Smil, 2000; Tilman et al., 2001). Phosphorus is a necessary nutrient for crop production, and also the limiting nutrient for primary productivity in freshwater (Elser et al., 2007; Smil, 2000; Smith and Schindler, 2009). Phosphorus carried with water through rivers and stream channels in watersheds to downstream, lakes or reservoirs, is called external P loading. Variation in external P loading to lakes is driven by the timing of fertilizer application, crop production, soil type, and rainfall patterns (Royer et al., 2006). Once P enters into lakes, it can go through an internal cycle within food-webs or be retained in the sediment, which accumulates over time, creating P and organic matter enriched sediment (Das et al., 2012;

---

[*] Corresponding author.
E-mail address: keunyea@gmail.com (K. Song).

http://dx.doi.org/10.1016/j.ecoleng.2017.06.008

Søndergaard et al., 1993). Inorganic P can be chemically bound and deposited in sediments. Sediments also contain high loads of organic or particulate P, which can be released from decomposition (Song and Burgin, 2017). Sediment P concentrations can be 100X higher than water column concentrations, especially when excessive external P loads persist over time, such as in agricultural watersheds (Diaz et al., 2006; Reddy et al., 1999).

Phosphorus enriched sediment is problematic because sediment P can be released back into the water column, a phenomenon termed internal loading. Lack of oxygen, pH changes, or decomposition can trigger internal P loading (Hupfer and Lewandowski, 2008; Jensen and Andersen, 1992; Pettersson, 1998). For example, in summer when strong stratification prevents the vertical exchange of materials in lakes and creates hypoxia in the sediment, chemically bound P is released (Nürnberg, 1987; Pettersson, 1998). Decomposition, mainly under aerobic conditions breaks down organic matter and releases inorganic or dissolved organic P into water columns (Hupfer and Lewandowski, 2008; Song and Burgin, 2017). As lakes eutrophy, internal P loading becomes a potentially large P source compared to external P loading (Coveney et al., 2005; Hamilton, 2012).

Despite the potential for internal P loading to deteriorate water quality, especially in eutrophic or hypereutrophic lakes, internal P loading is rarely quantified and directly compared to external P loading. Therefore, we asked: 1) How much P is internally released from the sediment of hypereutrophic lakes? 2) How much do internal P loads contribute to lake water quality compared to external loads? and 3) What factors regulate the release and retention of P in the sediment? To answer these questions, we quantified both internal and external P loads in four hypereutrophic lakes within agricultural landscapes. Flow-through sediment core incubation experiments under anaerobic and aerobic conditions to quantify internal P loadings.

2. Materials and methods

2.1. Site description

We selected four lakes located in Eastern Nebraska for this study. The study lakes (Table 1) were constructed in the 1960s primarily for water storage and have been restored through sediment dredging and watershed management in the last 20 years. All study reservoirs have similar morphological characteristics-surface area, water depth, and surrounding landscapes (Table 1). Agricultural areas make up 50–75% of their watersheds. All of them are considered to be in eutrophic-hypereutrophic states, as indicated by chlorophyll-a contents and total phosphorus (TP) concentrations in summer (Song and Burgin, 2017).

2.1.1. Lake water quality monitoring

Water samples were collected biweekly at the deepest locations from the epilimnion using a Van Dorn sampler. A Garmin Legend CX-GPS was used for positioning to ensure samples were consistently collected from the same locations. Water sampling was conducted from June to Nov. 2014. Collected water samples were acidified immediately in the field. The samples were then digested in the laboratory using potassium persulfate and analyzed via a Flow Injection Analyzer (Astoria Pacific A2) for TP concentrations using the molybdate blue colorimetric method (USEPA 1993, Method 365.1).

2.1.2. Quantification of external P loadings

Inflow water samples from primary water channels feeding the study lakes were collected through baseflow water sampling and stormwater sampling. Baseflow water samples (flow during dry weather conditions) were gathered biweekly by grab sampling. Storm water samples (flow during and after rain events) were collected using ISCO 6712 auto samplers. The auto samplers were programmed to collect three to eight water samples throughout each storm event depending on the duration of storm events. The samplers were programmed 24 h before the forecasted storm events to take two samples at 12 h intervals before the storm events and three-hr intervals during the storms. Two samples collected prior to the storm events were used as baseflow water samples unless the storm started before the forecasted time; in this case, one or two samples were included with the stormwater samples. This 24 h window increased our chance to capture the first stormwater rainfall flush. Stormwater sampling using autosamplers was conducted from May to December. 2014. Baseflow water was sampled biweekly from May to November in 2014, March to May in 2015, and once a month from December 2014 to February 2015.

Water samples were acidified immediately in the field for subsequent TP analyses, as described above. We calculated daily external P loadings (kg/d) using measured P concentrations (mg/L) in each inflow channel and the daily discharge (L/s). Daily loadings (kg/d) for non-sampled dates were linearly interpolated using gathered data from sampling dates in R with the zoo package. We used daily mean stream flow values from USGS streamgage locations to calculate daily discharge in each lake's watershed using a regression based drainage-area ratio method (Emerson et al., 2006). Daily external P loadings from May 2014-May 2015 (365 days) were summated to estimate the annual P loading (kg/yr).

2.1.3. Quantification of internal P loadings

Quantifying internal loading, although difficult, can be done in several ways (Nürnberg, 1987). In this study, internal P load of each lake was estimated based on Nürnberg (2009). This method includes three components: 1) P release rate ($\mu g/m^2/hr$) measured by flow-through experiments under aerobic and anaerobic conditions, 2) duration (days) of anoxia or aerobic conditions in the sediment, and 3) lake sediment area. To conduct the flow-through experiment, we collected seven to nine replicated sediment cores using an acryl cylinder coring device at each of the study reservoir. The sediment cores were collected on two separate occasions to represent strong stratification with anoxic sediment (July 2014) and lake turn over with aerobic sediment (Oct 2014). The collected cores were immediately moved to the lab to be used for flow-through internal loading experiments.

The flow-through experiment was conducted by placing the cores (8 cm in diameter) in a water bath kept at a relatively constant room temperature. During the flow-through experiment, each core received 1 ml/min flow rate of water collected from its respective lake. We mimicked sediment anaerobic conditions in summer (i.e. stratified lakes) by purging nitrogen into inflow water. Ultrapure nitrogen gas was constantly added through tygon hose to the bottom of the inflow water jar with high pressure to bubbles the surface water (at 20–50 psi). Aerobic conditions were maintained in October cores (i.e., well-mixed lakes) by aerating the inflow water. During the flow-through experiments, dissolved oxygen (DO, mg/L) was measured in the inflow and outflow waters of each core using an YSI-556 MPS at 3–24 h intervals. Dissolved oxygen (DO) in the cores during the experiments reached below 2.0 mg/L during anaerobic conditions whereas DO ranged 8.6 – 9.8 mg/L under aerobic conditions in October (Song and Burgin, 2017).

Inflow and outflow water samples were collected at 3 – 24 h intervals for 14–16 days (up to 384 h). Precise estimation of internal P loads were conducted by frequent water samplings and 4–6 replicates in the incubation experiment. Water samples were filtered immediately through 0.45 μm filters and analyzed via Flow Injection Analyzer (Astoria Pacific A2) for inorganic P concentrations using the molybdate blue colorimetric method (USEPA 1993,

Please cite this article in press as: Song, K., et al., Relative importance of external and internal phosphorus loadings on affecting lake water quality in agricultural landscapes. Ecol. Eng. (2017), http://dx.doi.org/10.1016/j.ecoleng.2017.06.008