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Volume reduction outweighs biogeochemical processes in controlling phosphorus treatment in aged detention systems

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ABSTRACT

Stormwater detention areas (SDAs) play an important role in treating end-of-the-farm runoff in phosphorous (P) limited agroecosystems. Phosphorus transport from the SDAs, including those through subsurface pathways, are not well understood. The prevailing understanding of these systems assumes that biogeochemical processes play the primary treatment role and that subsurface losses can be neglected. Water and P fluxes from a SDA located in a row-crop farm were measured for two years (2009–2011) to assess the SDA's role in reducing downstream P loads. The SDA treated 55% (497 kg) and 95% (205 kg) of the incoming load during Year 1 (Y1, 09–10) and Year 2 (Y2, 10–11), respectively. These treatment efficiencies were similar to surface water volumetric retention (49% in Y1 and 84% in Y2) and varied primarily with rainfall. Similar water volume and P retentions indicate that volume retention is the main process controlling P loads. A limited role of biogeochemical processes was supported by low to no remaining soil P adsorption capacity due to long-term drainage P input. The fact that outflow P concentrations (Y1 = 368.3 μg L^{-1}, Y2 = 230.4 μg L^{-1}) could be approximated by using a simple mixing of rainfall and drainage P input further confirmed the near inert biogeochemical processes. Subsurface P losses through groundwater were 304 kg (27% of inflow P) indicating that they are an important source for downstream P. Including subsurface P losses reduces the treatment efficiency to 35% (from 61%). The aboveground biomass in the SDA contained 42% (240 kg) of the average incoming P load suggesting that biomass harvesting could be a cost-effective alternative for reviving the role of biogeochemical processes to enhance P treatment in aged, P-saturated SDAs. The 20-year present economic value of P removal through harvesting was estimated to be $341,000, which if covered through a cost share or a payment for P treatment services program could be a positive outcome for both agriculture and public interests.

1. Introduction

Intensification of agriculture to fulfill increasing demand for food is predicted to have the greatest impact on freshwater given the need for nitrogen (N), phosphorus (P), and water resources (Tilman et al., 2001, 2011). With agriculture accounting for 70% of the global fresh water consumption (Gössling et al., 2012), its high contribution to water resources' degradation is understandable. The environmental footprint of agriculture, based not only on its use of limiting nutrients but also on their release, is significant, with an estimated 2.4 and 2.7 times increase in N and P induced eutrophication by 2050, respectively (Tilman et al., 2001). Striking a balance between agricultural production and its environmental footprint is a challenge and calls for an improved, sustainable approach which can increase agricultural production while minimizing its detrimental impacts (Foley et al., 2011). Most freshwater systems are P limited (Holman et al., 2008) and due to absence of volatile losses, the extent of redistribution of P is less compared to N (Peñuelas et al., 2013), which makes treating P driven eutrophication of freshwater systems, a more challenging issue.

Nutrient transfer via surface water has been the focus of most studies in the past (Holman et al., 2008). One of the major reasons for the lack of research on groundwater nutrient transport is the complexity in measuring subsurface fluxes given their spatio-temporal variability (Rosenberry et al., 2015; Shukla et al., 2015). Because of the complexity in accurately quantifying seepage, its role in nutrient budgets is often ignored (Deitchman and Loheide, 2009; Rosenberry et al., 2015), and the fate of the nutrients lost through seepage remains unknown (Powers et al., 2013; Ramírez-Zierold et al., 2010). However, recent studies have

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highlighted that the nutrients lost through subsurface pathways cannot be disregarded (Holman et al., 2008; Jolly et al., 2008; Ackerman et al., 2015; Rosenberry et al., 2015), scrutinizing the term 'nutrient retention' in treatment systems. Furthermore, it is assumed that soluble reactive P is adsorbed by the subsurface soil and rendered immobile (Holman et al., 2008). This assumption has been questioned in recent studies suggesting that P transported through groundwater could be a significant source of eutrophication (Holman et al., 2008; Kröger et al., 2013; Meinikmann et al., 2015), especially in shallow water table environments (Sklar et al., 2005).

Reducing P loses from production systems located in low-lying areas with poorly drained soils and tropical/sub-tropical climate are even more challenging from a water quality standpoint (Hendricks et al., 2014). To take advantage of the year-round warm subtropical climate while minimizing the environmental footprint, it is important that nutrient losses from croplands be strategically reduced. This is accomplished by Best Management Practices (BMPs), both on-farm (e.g. applying fertilizers at a recommended rate) and edge-of-the-farm (e.g. stormwater detention areas (SDAs)). Given that nutrient leaching losses are inevitable (Shukla et al., 2010), edge-of-the-farm treatment strategies assume a major role by serving as the last point of nutrient treatment before the drainage leaves the farm.

The SDAs are ubiquitous structures, irrespective of the climate regime, known by various names such as agricultural runoff wetlands (Kovacic et al., 2006), constructed farm ponds (Baker et al., 2012), detentions ponds (Fiener et al., 2005), etc. Area of SDAs as a percent of drainage (farm) area is a function of annual average precipitation (Downing et al., 2006). For example, given the large annual precipitation, Florida in United States has approximately 10% of the farm area under SDAs compared to 0.2% in Nebraska (Downing et al., 2006). The SDAs are typically aboveground systems, originally constructed to prevent downstream flooding. An SDA is designed on the "fill to spill" concept such that it at least stores the first 2.5 cm of runoff from the farm before discharging to a public canal, large stormwater treatment areas, or another SDA. A typical SDA is surrounded by an embankment/dike that is formed between two borrow ditches that surround the inner and outer perimeter of the SDA. The inner borrow ditch is a result of excavation to build the embankment while the outer borrow ditch is connected to a network of ditches in the farm serving as a collector for farm drainage. "Throw-out" pumps are installed in the outer borrow ditch to pump the drainage into the enclosed SDA. The outlet structure is usually a weir or an orifice.

The SDAs are event driven systems which calls for intensive monitoring to understand water and nutrient processing, particularly because they differ from traditional detention systems (e.g. constructed wetlands, urban stormwater detention areas, etc.) with regards to flow rates, incoming nutrient concentrations, speciation of incoming nutrients, and type of inflow (pumped/gravity fed).

The major P removal, biogeochemical processes in retention/detention systems such as wetlands include soil adsorption, plant biomass and microbial assimilation, and sedimentation (Dong et al., 2012). The role of aforementioned processes in treating nutrients in traditional detention systems has been discussed in detail in past studies (Zedler, 2003; Reinhardt et al., 2005; Verhoeven et al., 2006; Eveborn et al., 2012; Kynkäänniemi et al., 2013; Beutel et al., 2014; Pietro and Ivanoff, 2015). A majority of these studies suggest that soil is the long-term sink for P, however, it remains unknown whether this is true for SDAs given the limited data available on water and nutrient fluxes. Although, studies have reported traditional detention/retention systems to be an excellent practice for treating nutrients, majority of such studies were conducted within first five years of operation (Gottschall et al., 2007). There are concerns regarding the P removal performance of aged systems since the primary P treatment processes are expected to change over time (Gottschall et al., 2007). It has been postulated that detention systems can get saturated with P over time and become ineffective for nutrient removal, and subsequently contribute P to downstream waterbodies (Dong et al., 2012; Sharpley et al., 2013).

Specifically, this paper is an effort towards answering the following research questions: 1) what is the P treatment efficiency of a SDA located in a vegetable farm when considering groundwater P losses?; 2) what are the primary factors affecting the P treatment potential of the SDA?; and 3) which engineering/managerial modifications can be implemented to increase or sustain the P treatment efficiency of the SDA? In this study, we did not neglect the subsurface P transport and estimated the P treatment efficiency of SDAs, both with and without P losses through groundwater, allowing prediction of the future role of SDAs as P sinks/sources using water quantity, quality, soil, and vegetation data.

2. Methods and materials

2.1. Study site

The SDA used in this study is located in a vegetable farm in the C-139 basin in south Florida (Fig. 1). With agriculture as its primary land use, the C-139 basin is a sub-watershed of the Everglades basin. The SDA releases the farm drainage to the Everglades through a series of other SDAs and a larger stormwater treatment area. The SDA was instrumented to monitor water and P fluxes for two years. Year 1 refers to July 20, 2009 to July 20, 2010 and Year 2 refers to July 21, 2010 to July 20, 2011.

The SDA has been in use since 2000, covers an area of 14.85 ha and was designed to receive drainage from 112 ha of a vegetable farm. Major crops cultivated in the farm include tomato, bell pepper, eggplant and herbs such as basil. Based on the irrigation needs, the drainage from the farm is routed to the outer borrow ditch (collector ditch) through a network of ditches. Drainage from the outer borrow ditch is pumped into the SDA via three (3) diesel operated axial flow pumps (throw-out pumps), each designed for a maximum flow rate of $37.85\ \mathrm{m^3\ min^{-1}}$. Pump 1 and 2 (P1 and P2) are located on the west side of the SDA and pump 3 (P3) is located on the east (Fig. 1). The majority of pumping takes place in the wet season (June–October). The outer borrow ditch surrounding the SDA on the east and west receives drainage from the drip irrigated and seepage irrigated parts of the farm, respectively.

The discharge site is located at the southern end of the SDA (Fig. 1). The discharge structure is a combination of two corrugated aluminum culverts (Diameter = 1.22 m) each fitted with a sharp crested rectangular weir with a control elevation set at 5.52 m (AMSL, NAVD88[1]). A "borrow ditch", although discontinuous, surrounds almost the entire interior perimeter of the SDA. The remaining interior of the SDA is characterized by flat, nearly level ground (average elevation = 5.49 m) with an exception of four depressions, three of which are jurisdictional wetlands (average elevation = 5.06 m).

The predominant soil types within the SDA are Myakka fine sand and Basinger fine sand. The SDA is covered by a variety of vegetation types, including Torpedo Grass and Smartweed (*Panicum repens* and *Polygonum hydropiperoides*), Water Lettuce (*Pistia stratiotes*), Primrose Willow (*Ludwigia peruviana*), Cattail (*Typha* spp.), and Carolina Willow (*Salix caroliniana*).

2.2. Hydrologic monitoring

2.2.1. Pumped drainage

Volume of farm drainage pumped into the SDA by the three pumps (P1, P2, and P3; Fig. 1) was estimated by developing flow equation for each pump using an ultrasonic flowmeter (Sontek, Dan Diego, CA, USA). Pumps were operated at variable impeller *RPMs* (Rotations per

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[1] AMSL, NAVD88 is the height above mean sea level as per North American Vertical Datum established in 1991.