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Modeling phosphorus retention at low concentrations in Florida Everglades mesocosms

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ABSTRACT

Reducing phosphorus (P) concentration in surface water is a primary component of the ongoing effort to restore the Florida Everglades. Engineered wetlands are currently being used to retain P from stormwater inflows but are not consistently achieving outflow P concentration goals. A three-year mesocosm study was performed investigating the effects of different plant communities on P retention within engineered wetlands. A dynamic model was constructed in the high-level simulation software STELLA, using water, soil, weather, and plant data from this mesocosm study. The model consists of three interconnected submodels: plant growth, hydrology, and P dynamics. The model simulates processes in water and soil related to all four forms of P: dissolved organic, dissolved inorganic, particulate organic, and particulate inorganic. Model verification and subsequent calibration was performed using biweekly outflow water quality data from a mesocosm containing a submerged aquatic vegetation (SAV) community consisting of *Najas guadalupensis* and the algae *Chara* sp. Model validation was then conducted using data from separate mesocosms with three different plant communities: monocultures of *Typha domingensis* or *Cladium jamaicense*, and a combination of *Nymphaea odorata* and SAV. The model was able to simulate outflow concentrations of total phosphorus from all four plant communities with average relative errors of less than 35%. A sensitivity analysis revealed the relative importance of the various processes involved in the retention of all P forms and the effects of different vegetation communities on these processes. Further simulations were run to predict the outflow total P concentrations for an additional year beyond the end of the mesocosm study.

1. Introduction

Reduction of total phosphorus (TP) concentrations in surface water is a primary component of the ongoing Florida Everglades restoration. Increased TP concentrations along with altered hydrology patterns have been shown to cause a shift in dominant vegetation type in areas of the Florida Everglades from the native *Cladium jamaicense* (sawgrass) to the invasive *Typha domingensis* (southern cattail) (Koch and Reddy, 1992; Urban et al., 1993; Newman et al., 1996; Richardson et al., 2008). Part of the ongoing Florida Everglades restoration effort includes the use of 23,000 ha of engineered wetlands known as stormwater treatment areas (STAs) that receive inflow from the Everglades Agricultural Area (EAA) located north of the Everglades (SFWMD, 2015). These STAs are designed to retain nutrients from stormwater flows; an ecosystem service that wetlands have been known to effectively provide (Walker, 1995; Fisher and Acreman, 1999; Mitsch and Gosselink, 2015). In the 2005, the Florida government established a five-year geometric mean concentration criterion of 10 ppb TP for water in the Water Conservation Areas (WCAs), which receive inflows from the STAs (FDEP, 2005). In 2014, the STAs had mean outflow TP concentrations ranging from 14 to 41 ppb (SFWMD, 2015) suggesting the need for further improvement in TP retention rates. The South Florida Water Management District (SFWMD) has supported many studies over the years focusing on how to achieve better retention rates. The Mitsch et al. (2015) mesocosm experiment that this modeling study is based on was supported in this way. Since then, the SFWMD has funded additional research efforts on the topic of how to improve the TP retention by the existing STAs. However, we see little interest in designing additional treatment wetlands that the mesocosms were meant to simulate that receive the outflow from the existing STAs as inflows.

Mathematical models can be an integral tool in the pursuit of better functioning constructed wetlands by improving

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understanding of ecosystem processes and predicting outcomes of different management scenarios. Early phosphorus (P) retention modeling often used empirical equations based on observed data, treating the wetland as a 'black-box' (Mitsch et al., 1995; Kadlec, 1997; Moustafa, 1998). The STAs themselves were in fact designed using a mass-balance P retention model based on data from Water Conservation Area 2A (WCA-2A) (Walker, 1995). However, P retention and release within wetlands are complex processes with both biotic and abiotic mechanisms. Biotic retention processes include uptake from the soil or water by plants, plankton, algae, and microbes; while abiotic retention processes include sedimentation, adsorption by soil, and coprecipitation (Reddy et al., 1999). Biotic processes that release P include the decomposition of plants and microbes, while abiotic process that release P include low pH releasing previously precipitated P, and the reduction of metal ions that P typically reacts with (Mitsch and Gosselink, 2015). Because of this complexity, mechanistic models, which aim to simulate these processes with systems of differential equations, have become increasingly popular. Mechanistic models have the potential to more accurately predict the performance of wetland systems with regards to nutrient removal and also to provide better insight into the relevant retention and release dynamics of the system (Robson, 2014).

Models have been used for decades to describe P retention in wetlands (Mitsch, 1976, 1983, 1988; Mitsch et al., 1982; Jørgensen et al., 1988; Kadlec and Hammer, 1988; Mitsch and Fennessy, 1991). Mitsch and Reeder (1991) developed a model that described P retention by a coastal wetland on Lake Erie in Ohio. That model was upgraded and refined by Christensen et al. (1994) and then by Wang and Mitsch (2000) to describe P retention in created riverine marshes in Illinois. This model utilized 4 submodels: hydrology, primary productivity, sediments, and phosphorus. Wang and Mitsch (2000) validated this model with data sets from four created marshes collected over 3 years of data.

Wang et al. (2003a,b) created a mechanistic model of P dynamics in aquatic soils based on data from the Chesapeake Bay area. This model aimed to simulate complex soil P processes such as sorption, burial, and bioturbation in order to predict flux of P from the soil. As the understanding of wetland ecosystem dynamics has improved, increasingly complex models with more descriptive equations have been created. For example, the recent Submerged Aquatic Vegetation Phosphorus Model (SAVPM) model created by Juston et al. (2013) incorporates detailed processes of P cycling by submerged aquatic vegetation. Often P models are combined with hydrodynamic models to simulate P retention on larger scales. Some examples of these combined models for the Florida Everglades system include the mass-balance models described in Walker and Kadlec (2011), and the model of phosphorus loading, which included soil sorption dynamics, recently developed by Long et al. (2015).

Despite the different forms of P following different biogeochemical pathways within wetlands, few mechanistic P models have split the state variable of total phosphorus (TP) into its four component forms of dissolved organic phosphorus (DOP), dissolved inorganic phosphorus (DIP), particulate organic phosphorus (POP) and particulate inorganic phosphorus (PIP). There have been some recent lake models (Gal et al., 2009) and river models (Garnier et al., 2005; Cole and Wells, 2008) that have incorporated these divisions, but few wetland models that have. It can be valuable to predict the specific forms of P being retained or released from a system, as this can influence downstream impacts (Reynolds and Davies, 2001). This separation is also needed when it is known that inflow waters contain substantial concentrations of two or more of these forms, like those measured in the outflow of the STAs (SFWMD, 2015). When a more accurate breakdown of predicted outflow P forms is needed, a model that simulates processes related to retention of each form is required.

Mesocosm-scale studies have been used in the past decades to experiment with different phosphorus retention treatments and techniques for the restoration of the Everglades. For example, Bays et al. (2001) used mesocosms to investigate the viability of periphyton-based STAs for phosphorus retention. A different study by Dierberg et al. (2002) tested the effects of the presence of different submerged aquatic vegetation (SAV) species on phosphorus retention rates. A study by DeBusk et al. (2004) studied the effectiveness of a flow through system with lime rock substrate and a lime rock filter. Mesocosm studies such as these allow for controlled, cost-effective tests of different phosphorus treatment options that could potentially be brought to full-scale functionality in the STAs.

A more recent mesocosm study was performed from 2010 to 2013 downstream of Stormwater Treatment Area 1-West (STA-1W) in the Florida Everglades to investigate the effects that different vegetation communities could have on P retention at low inflow concentrations. The inflow to the mesocosms was the outflow from STA-1W. The overall results and findings from the study presented by Mitsch et al. (2015) found that the mesocosms did not become sinks of P until late 2012, approximately 2.5 years after the experiment began. This lag in P retention was described as probably being due to P efflux from the mesocosm soil. That study also concluded that "Achieving 10 ppb phosphorus concentrations consistently from created wetlands in the Florida Everglades remains problematic but this research confirms that it may be possible with low loading rates, the right vegetation communities, and low-nutrient soils." Other processes of the mesocosm experiment described in detail in published literature include dissolved organic carbon export (Villa et al., 2014) and aquatic metabolism (Marois et al., 2015).

Based on the data from the 2010–2013 mesocosm study, a dynamic P model was constructed in STELLA^{TM} to better understand the P dynamics in these wetland mesocosms and to assist with management decisions on the full-scale STAs. This study additionally incorporated 5 more months of water quality data (April 2013 to August 2013) that were not part of the Mitsch et al. (2015) study.

The dynamics of each form of P are simulated in the model with the intent of quantifying the relative importance of each in TP retention. The role that different plant communities play in the dynamics of each of these P forms was also investigated by applying the model to four different plant communities. After model calibration, simulations were run to predict future retention rates and test different management scenarios with regards to varying loading of inflow P. Ultimately, we discuss the implications of our findings and how the results of our simulations may be scaled up to larger constructed wetland systems used to retain P in the Florida Everglades region.

2. Site description

Data for model development were gathered from a study site located in south Florida on the southeastern border of the Everglades Agricultural Area within STA-1W. The study site consisted of 18 mesocosms each planted randomly with one of six different plant communities (including a control), with three replications of each community (see Mitsch et al., 2015 for more detail). Data from four of these mesocosms were used for model development: one planted with a mix of submersed aquatic vegetation (SAV) consisting of *Naja guadalupensis* (southern naiad) and *Chara* sp. (charophyte algae); one with *T. domingensis* (southern cattail); one with *Nymphaea odorata* (fragrant water lily), which developed into a mix of water lily and SAV (henceforth called lily/SAV); and one