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Vegetation effects on floating treatment wetland nutrient removal and harvesting strategies in urban stormwater ponds

Chih-Yu Wang [a], David J. Sample [b,*], Cameron Bell [b]

[a] Ecological Engineering Research Center, National Taiwan University, No.1, Section 4, Roosevelt Road, Taipei, 10617, Taiwan
[b] Department of Biological Systems Engineering, Hampton Roads Agricultural Research and Extension Center, Virginia Polytechnic Institute and State University, 1444 Diamond Springs Road, Virginia Beach, VA 23455, USA

HIGHLIGHTS

- We investigated nitrogen and phosphorus storage and distribution in plant tissues.
- Floating treatment wetland plant management strategies are recommended.
- Pickerelweed aerial tissues should be harvested at vegetation stage (summer).
- Harvest of the whole plants in the fall will likely remove the most nutrients.
- The study used microcosms flushed with water from a nearby urban retention pond.

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ABSTRACT

Floating treatment wetlands (FTWs) consist of emergent macrophytes that are placed on a floating mat in a pond for water treatment and aesthetic purposes. FTWs may have unique advantages with respect to treating urban runoff within existing retention ponds for excess nutrients. However, research is lacking in providing guidance on performance of specific species for treating urban runoff, and on timing of harvest. Harvesting is needed to remove nutrients permanently from the retention pond. We investigated vegetation effects on FTWs on nitrogen (N) and phosphorus (P) removal performance and storage in above-ground FTW macrophyte tissues. The study evaluated pickerelweed (PW, *Pontederia cordata* L.) and softstem bulrush (SB, *Schoenoplectus tabernaemontani*) over time in microcosms flushed with water obtained from a nearby urban retention pond in northern Virginia near Washington, DC. While the literature exhibits a wide range of experimental sizes, using the term mesocosm, we have chosen the term microcosm to reflect the small size of our vessel; and do not include effects of sediment. The experiment demonstrated PW outperformed SB for P and N removal. Based upon analysis of the accumulated nutrient removal over time, a harvest of the whole PW and SB plants in September or October is recommended. However, when harvesting only the aerial parts, we recommend harvesting above-ground PW tissues in July or August to maximize nutrient removal. This is because PW translocates most of its nutrients to below-ground storage organs in the fall, resulting in less nutrient mass in the above-ground tissue compared to the case in the summer (vegetative stage). Further research is suggested to investigate whether vegetation can be overly damaged from multiple harvests on an annual basis in temperate regions.

1. Introduction

Population migration to cities and the urban development to accommodate it has caused numerous impacts to the environment. Urban development results in the increased production of runoff, consequently increasing discharges of nutrients, metals, and other pollutants (Carey et al., 2013; Hatt et al., 2004). In excess, nutrients may cause eutrophication of lakes and estuaries (Anderson et al., 2002; Dodds, 2010). Nonpoint source pollution from urban runoff (including excessive nutrients such as nitrogen (N) and phosphorus (P)) is one of the largest uncontrolled sources of pollution to receiving waters (Novotny, 2003). In the U.S., the Clean Water Act requires states to develop a total maximum daily load (TMDL) to remediate those impairments. A TMDL defines the amount of a given pollutant a water body can assimilate without violating water quality standards adopted by each state. A recent example of this is the Chesapeake Bay TMDL, issued by the U.S. Environmental Protection Agency (EPA) which addresses excess nutrient and sediment loading (U.S. EPA, 2010).

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* Corresponding author. Tel.: +1 703 3633835.
E-mail addresses: cywang.ee@gmail.com (C.-Y. Wang), dsample@vt.edu (D.J. Sample), cbell147@vt.edu (C. Bell).

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A TMDL requires affected stakeholders to develop an implementation plan, which uses controls, also known as best management practices (BMPs) to reduce or eliminate hydrologic and water quality impacts. BMPs use a variety of physical, chemical, and biological processes to restore receiving waters. Low impact development (LID) practices are BMPs that predominately utilize infiltration and filtration to both reduce and treat urban runoff, and have emerged as the practice of choice for new development. However, development from the mid-70s through the 2000s predominately used retention ponds as their treatment BMP (National Research Council, 2009). Wet ponds, which are retention ponds that maintain a pool volume even during dry conditions, provide storage and some water quality treatment through sedimentation, and are effective at settling coarse and/or heavy particles with attached pollutants. However, they are much less effective at treating pollutants in dissolved form (Shilton, 2005). While these legacy ponds may only be partially effective at remediating water quality, there are many of them, at least one in each urban development (if required by regulation) from the 1970–2005 era (Schueler, 2011). Finding means of improving wet pond water quality performance could represent an opportunity to provide real reductions in nutrient and sediment loads to receiving waters without requiring additional space. This would help municipal government achieve required TMDL reductions at lower costs. One new potential means of achieving this goal, floating treatment wetlands, or FTWs, is described in the following section.

1.1. Floating treatment wetlands (FTWs)

Floating treatment wetlands (FTWs) are a relatively new stormwater treatment practice that could enhance the effectiveness of retention ponds. FTWs consist of macrophytes growing on floating mats which can be deployed in many existing water bodies (Hubbard et al., 2011). The first recorded case of a "floating field," similar in design to an FTW, was built in Taiwan, before the Year 1717 (Zhou, 2005). Recently, FTWs have been evaluated for water quality improvement across the world with different plant species in various environments, from tropical to temperate regions (Chua et al., 2012; Headley and Tanner, 2012). Biofilms develop within the root mass hanging below the mat and provide a large treatment area (Headley and Tanner, 2006; Tanner and Headley, 2011). N is removed through assimilation and denitrification, and phosphorous (P) is removed through assimilation and sorption (Stewart et al., 2008).

FTWs have been demonstrated to be effective at treating agricultural wastewater (Hubbard et al., 2011) and polluted surface water (Billore et al., 2009). Stewart et al. (2008) evaluated a proprietary FTW substrate known as a BioHaven® Floating Island and found significant removals of nitrate, ammonium, and orthophosphate. Hubbard et al. (2004) applied FTWs in a wastewater lagoon treating swine wastes; the species with highest performance (cattail) removed 534 and 79 g/m^2 of N and P, respectively. While only a few studies have focused on urban runoff (Borne et al., 2014; Borne et al., 2013; Headley and Tanner, 2012; Ladislas et al., 2013; Wang and Sample, 2014; Winston et al., 2012), interest is increasing. The dilute nature of stormwater presents an issue to overcome as this can leave plants malnourished in contrast with other, more nutrient-rich waters, such as domestic wastewater or agricultural runoff, i.e., the total phosphorus (TP) and total nitrogen (TN) concentrations of runoff from mixed urban land uses typically are 0.26 and 1.8 mg/L, respectively (US EPA, 1999).

FTWs may enhance the performance of existing retention ponds in urban areas without significant land acquisition (Headley and Tanner, 2012; Winston et al., 2013). However, FTWs pose a challenge to evaluate because they are integrated with the wet pond, and both provide treatment, thus evaluating the treatment contributions from each can be difficult. One means of separation is through modeling. Wang and Sample (2013) present a first order kinetic model that separates the characteristics of a wet pond from an FTW. Another method to isolate treatment factors is the use of mesocosm scale experiments. Mesocosms allow more complexity than column studies or laboratory scale experiments and simplify the system (compared to a full scale field study) to a finite number of factors (Pop et al., 2012). Thus, they provide a means of studying individual factors in integrated systems such as FTWs' effects in wet ponds (Stewart et al., 2013). Mesocosms originated in the horticulture industry (Pop et al., 2012), but have been applied to bioretention research (Lucas and Greenway, 2011a; Lucas and Greenway, 2011b) and FTWs (Chang et al., 2012). Through replication of identical mesocosms, variability with respect to individual factors can be studied in controlled conditions (Pop et al., 2012).

1.2. FTW mesocosm experiments

A wide variety of mesocosm experiments have been applied to the study of FTWs. A review of these experiments was conducted, and is contained in Tables 1 and 2. Table 1 lists the attributes of the study conditions, including the type of control, the type of water treated, the plant species tested, FTW coverage, hydraulic residence time (HRT), air and/or water temperature (when given), raft area, water depth, tub geometry and dimensions, and plant density. Water tested ranges in quality from river water to swine farm wastewater. The purpose of the control (when present) was to separate the effectiveness of the FTW from that of the water body. An open control simply has no raft in it at all, whereas a coverage control has a raft without vegetation. In many cases, water and/or air temperatures were not provided, limiting the ability to generalize results, as all biological processes are a function of temperature (Wang and Sample, 2014). Table 2 lists the nutrient removal effectiveness of each study, in terms of water quality changes, and plant nutrient content, if provided, was also reviewed. Nutrient removal is described in terms of units of mass of the nutrient per unit area of the raft and time, or g/m^2-day; study results varied from 0.008 to 66.3 for N and from 0.002 to 1.8 for P. This varies by plant species and water temperature, however the largest contributors of variability may stem from the source of water and its quality and, perhaps more importantly, loading rate. For example, Xian et al. (2010) used swine farm wastewater (see Tables 1 and 2) with a high nutrient concentration, whereas White and Cousins (2013) used lake water supplemented with nutrients at approximately 1/5th the concentration; yet the latter's nutrient removal rate was greater than the former, on the order of 8-33X for N and 2-15X for P. The difference may be due to the different hydraulic retention times, at 7 days for Xian et al. and vs. 3 days for White and Cousins, respectively, the potential bioavailability of the nutrients in the added fertilizer, and/or the plant species used.

A key consideration is the use of a control. Generally, a control is used to simulate the behavior of the wet pond without the presence of FTWs. Without the control, performance of the FTWs and wet ponds is lumped; Boonsong and Chansiri (2008); Hubbard et al. (2004) and Sun et al. (2009) are studies of this type. Uncovered controls simply use a separate vessel with an open water surface, examples of this type of experiments are Karnchanawong and Sanjitt (1995), Li et al. (2010), Van de Moortel et al. (2010) and White and Cousins (2013). A covered type control uses the FTW raft without the plants, so essentially the difference between the planted FTW mesocosms and control is the contribution from the plant. Examples include Chang et al. (2012); Li et al. (2011); Li et al. (2012); van Oostrom (1995); Wang et al. (2012); Xian et al. (2010); Zhao et al. (2012); Zhou and Wang (2010); and Zhou et al. (2012).

Many FTW mesocosm studies focus exclusively upon the nutrient uptake of the plant, and do not evaluate the temporal variation in nutrient content. Information on plant nutrient distribution in different plant organs is essential to optimize harvesting, a management strategy to remove nutrients from the pond-FTW system. Macrophytes adjust growth and nutrient distribution according to external conditions and growth stages (Ruiz and Velasco, 2010). While similar studies of wetlands provide data on vegetative behavior, the information may not adequately evaluate plant performance in the soilless and low nutrient