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Nitrogen and phosphorus mass balance, retention and uptake in six plant species grown in stormwater bioretention microcosms

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ABSTRACT

Stormwater runoff contains high levels of nutrients, and is regulated by the Federal National Pollution Discharge Elimination System (NPDES) to protect surface water quality. Stormwater bioretention (BR) systems are increasingly used to address these regulations. Planted BR systems remove significantly more pollutants than unplanted systems, but most studies do not attempt to verify a pollutant mass balance and seldom evaluate differences in nutrient uptake among species. This greenhouse experiment proved that an overall 98% recovery of Total Phosphorus (TP) mass over the study period was feasible for six plant species, ensuring accuracy of measurements and analyses. Additionally, it was found that *Phragmites australis*, *Carex praegracilis,* and *Carex microptera* uptake significantly more TP and Total Nitrogen (TN) mass into harvestable tissue than *Typha latifolia, Scirpus validus,* and *Scirpus acutus*. These results confirm that species selection can optimize nutrient retention and recovery from stormwater and decrease pollutant discharge to surface waters.

1. Introduction

As much as half of the US surface waters have excess nutrients disrupting aquatic life (US EPA, 2002). The Federal National Pollution Discharge Elimination System (NPDES) Stormwater Program dictates that states must regulate stormwater runoff, including the regulation of nutrient discharge into surface water bodies, in an effort to reduce eutrophication (US EPA, 2005). Total nitrogen (TN) and Total Phosphorous (TP) are the two highest rated nutrients of concern in a survey of state officials directly involved in various aspects of the NPDES program (n = 51) conducted by Collins et al. (2010). Stormwater best management practices (BMPs), such as bioretention (BR) systems, are low cost alternatives for nutrient management, which can serve as a means of meeting NPDES requirements.

Planted BR systems have been proven to remove significantly more pollutants from stormwater runoff than unplanted systems (Tanner, 2001; Stottmeister et al., 2003; Fraser et al., 2004; Wiessner et al., 2006; Milandri et al., 2012). Plants, which contribute to nutrient retention through plant uptake, maintenance of soil porosity, and the influence of soil microbial communities (Read et al., 2008), are increasingly being used to address NPDES regulations.

Stormwater pollutants entering a BR system are retained in the soil media via sedimentation, filtration, and sorption on mulch and soil layers, may be biodegraded by soil microorganisms, or mobilized and sequestered in the root cells, and/or taken up into the aerial portions of plants (Davis et al., 2001). The pollutants stored in the above ground biomass can be harvested and disposed of offsite, preventing the seasonal re-release of pollutants. The literature also provides evidence that certain species are more capable of surviving the stressful flood and draught conditions of a stormwater BR system than others (Brisson and Chazarenc, 2009), and that some of these species are better accumulators of pollutants than others (Tanner 1996; do Nascimento and Xing 2006; Bratieres et al., 2008; Read et al., 2008). Most of these studies focus on plant variations in pollutant removal from the exfiltrate, and little work has been done to evaluate differences in nutrient uptake potential that exist among plant species typically planted in stormwater BR systems. Additionally, these studies assume accurate measurements for each of the water, plant and/or soil compartments, without a complete mass balance, implying, but not providing, explicit nutrient recoverability from start to end of the experiments.

This experiment used six plant species typically found in stormwater BMPs undergoing pollutant loading and hydraulic stresses typical of stormwater BR systems. The results provide stormwater BMP managers data necessary to make more informed

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choices when selecting vegetative species, and when considering BMP management options, such as plant harvesting, to optimize nutrient removal from urban runoff and prevent pollution of sensitive downstream surface water bodies. This study had three primary objectives:

1) to provide a mass balance of constituents at the end of the study to ensure the accuracy of measurements and analyses,
2) to calculate mass distribution at the beginning and end of the study to explore differences in the extent of nutrient uptake and soil sequestration, and
3) to assess nutrient retention efficiency, plant biomass production, and uptake by the six plant species.

With this information, relevant facility design and maintenance procedures can be incorporated into future stormwater management systems to optimize pollutant retention and decrease nutrient discharge into downstream surface water.

2. Materials and methods

2.1. Experimental design

This greenhouse study used a randomized block design with six plant species and three hydraulic, nutrient loading regimes in triplicate, as previously described in detail (Rycewicz-Borecki et al., 2016). The fate of the response factors (TN and TP) was measured in the exfiltrate, soil, above ground (AG), and below ground (BG) plant tissue. Fate of metals (Cu, Pb, and Zn) were also evaluated but reported elsewhere (Rycewicz-Borecki et al., 2016). The study was conducted at Utah State University's Research Greenhouse from October 2010 through June 2011. Plastic Sterilite 19 L containers (42.5 cm L × 32.4 cm W × 23.2 cm H; surface area of 0.143 m^2) were filled with a 21 kg mixture of half Kidman Sandy Loam soil (coarse-loamy, mixed, mesic Calcic Haploxeroll) and half sand, which enhanced water flow in this small-scale microcosm study. All treatments underwent consistent greenhouse temperatures and illumination, using Sunlight Supply's 1000 W high-pressure sodium bulbs using a photoperiod of 12 h per day.

Six plant species most frequently found in constructed wetland BMPs (Brisson and Chazarenc, 2009), and commonly identified in stormwater BMPs in Northern Utah (Rycewicz-Borecki and Winkler, 2009) were chosen for this study. The six plant species investigated included: Phr – *Phragmites australis* (Common Reed); Typ – *Typha latifolia* (Broadleaf Cattail); Scv – *Scirpus validus* (Soft-stem Bulrush); Sca – *Scirpus acutus* (Hard-stem Bulrush); Cap – *Carex praegracilis* (Common field sedge); Cam – *Carex microptera* (Smallwing Sedge); and an unplanted, soil only control. Six plugs, obtained from the Aquatics and Wetland Nursery, Ft. Lupton, Colorado, were planted equidistantly within each container. Plants were allowed to root and produce new growth for 6 months before synthetic stormwater application and water-sample collection began. Biomass of plugs at time of planting was considered negligible within the experiment. Nine non-vegetated containers filled only with the soil-sand mixture served as the controls.

Containers were constructed at one of two time periods, 1 month apart, in response to plant availability. Significant differences in the initial soil properties and pollutant concentrations were found between containers constructed during the two time periods (Table 1). For this reason, each individual container's initial and final constituent soil concentrations were used for all subsequent calculations.

Each species was planted in triplicate containers under three hydraulic and nutrient loading regimes representing Logan, UT; Des Moines, IA; and Scranton, PA. These three inland cities are located 18° longitudinally apart, on the 41°N latitude. Rainfall frequency, intensity and duration (hydraulic loading) were calculated based on rainfall data from each city from 2005 to 2009 using the Driscoll method (Driscoll et al., 1989), rather than using the more generalized region's average values (GeoSyntec, 2002).

Synthetic runoff was applied to each container at the start of each rainfall event in a concentrated initial flush solution, simulating the storm's 'first flush.' Pollutant total mass in the synthetic stormwater, as described in greater detail in Rycewicz-Borecki et al. (2016), was based on the locations' regionally reported average pollutant event mean concentrations (EMC) in the EPA BMP Design Guide (2004). Surface area of the study containers was set to 5% of an adjacent urban area (US EPA, 2002), and the water volume for each rain event was calculated with a 50% impervious surface runoff coefficient. Table 2 presents the number of events for each region, event volumes, and total mass of constituents applied in the synthetic stormwater ($M_{inwater}$; TN, and TP), for each loading regime. The constituent mass and hydraulic loading regimes for the three cities were categorized into Low (Logan), Medium (Des Moines), and High (Scranton). Logan, UT received the lowest rainfall intensity and frequency, producing the lowest total constituent mass loads.

Logan City tap water was added to the initial flush solution and was used to represent the remainder of the storm runoff volume. Constituent concentrations in the tap water were measured as: pH = 7.6; EC = 285 μs cm^{-1}; alkalinity = 166 mg $CaCO_3$ L^{-1}; TP = 0.05 mg L^{-1}; TN = 0.40 mg L^{-1}; and 64.4, 3.2, and 67.3 μg L^{-1} for Cu, Pb, and Zn, respectively. Pollutant loading contributed by the tap water was added to the total mass input of the system. Total input constituent mass was calculated as:

$$M_{\text{in water}} = \left(\sum_{i=1}^{a} \left(C_{EMC} + C_{tap} \right) V_i \right) \qquad (1)$$

Table 1
Soil properties, and nutrient concentrations (mg kg^{-1} dry soil) in the soil-sand mixtures used to construct test BR systems.

	SOIL-SAND MIXTURE	
	Reactor Batch 1	Reactor Batch 2
pH	8.2 ± 0.03	7.3 ± 0.07
EC (μS cm^{-1})	630 ± 80	2330 ± 100
Alkalinity (mg $CaCO_3$ L^{-1})	–	–
CEC (meq 100 g^{-1})	1.3 ± 0.1	1.6 ± 0.09
Organic Matter (%)	0.3 ± 0.0	0.3 ± 0.0
Saturation (%)	25.6 ± 0.4	22.7 ± 1.1
Particle size distribution		
Sand (%)	91.7 ± 0.3	88.7 ± 0.3
Silt (%)	2.3 ± 0.3	4.7 ± 0.3
Clay (%)	6.0 ± 0.0	6.3 ± 0.3
Nutrient concentration		
TP (mg kg^{-1})	83.3 ± 5.0[a]	142 ± 24[a]
TN (mg kg^{-1})	476 ± 25[a]	690 ± 26[a]

Mean ± SE; n = 3 unless otherwise noted.
[a] Batch 1 n = 22; Batch 2 n = 7.

Table 2
Calculated rainfall events, event volume, total water, and total mass load for the Low, Medium, and High Loading Regimes.

	Low (Logan)	Medium (Des Moines)	High (Scranton)
Number of Events	32	47	63
Event Volume (L)	14.4	29.1	37.7
Tot. Water (L m^{-2})	3231	9580	16,594
Total-P (mg m^{-2})	2098	3532	5790
Total-N (mg m^{-2})	14,223	26,539	37,664

*Total applied mass m^{-2} after 27 weeks of synthetic stormwater application.