Journal of Environmental Management 166 (2016) 267–275

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Bioaccumulation of copper, lead, and zinc in six macrophyte species grown in simulated stormwater bioretention systems

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A R T I C L E I N F O

Article history:
Received 21 May 2015
Received in revised form
2 October 2015
Accepted 11 October 2015
Available online xxx

Keywords:
Stormwater BMP
Bioretention
Vegetation
Metal bioaccumulation
Greenhouse

A B S T R A C T

Stormwater bioretention (BR) systems collect runoff containing heavy metals, which can concentrate in soil environments and potentially leach into groundwater. This greenhouse experiment evaluated differences among six plant species undergoing three varying hydraulic and pollutant loads in their bioaccumulation potential when subjected to continual application of low metal concentrations as a means of preventing copper, lead, and zinc accumulation in the BR soil. Results show that >92% of metal mass applied to the treatments via synthetic stormwater was removed from the exfiltrate within 27 cm of soil depth. Compacted soil conditions of unplanted controls retained significantly more Cu, Pb, and Zn than *Carex praegracilis*, and *Carex microptera* treatments. Differences in above and below ground plant tissue concentrations differed among species, resulting in significant differences in mass accumulation. In the above ground tissue, from highest to lowest, *Phragmites australis* accumulated 8 times more Cu than *Scirpus acutus*, and *C. microptera* accumulated 18 times more Pb, and 6 times more Zn than *Scirpus validus*. These results, and differences among species in mass distribution of the metals recovered at the end of the study, reveal various metal accumulation mechanisms.

1. Introduction

Trace metals such as copper, lead, and zinc (Cu, Pb, and Zn) accumulate in stormwater runoff where they concentrate in soil environments, and potentially leach into the groundwater once the soil sorption capacity is reached. Bioretention (BR) systems are a type of stormwater best management practice (BMP) that utilize soil and plants to treat stormwater runoff from commercial, residential, and industrial areas by allowing stormwater to collect and infiltrate into the underlying soils (U.S. EPA, 1999).

It is well documented that BR systems remove significant quantities of nutrients and metals from stormwater runoff (Tanner, 1996; Fraser et al., 2004; Davis et al., 2006; Read et al., 2008; Trowsdale and Simcock, 2011; Fassman, 2012; Li et al., 2014). The efficiency of pollutant removal is often defined as the difference in pollutant concentrations, or mass, between the influent and exfiltrate water. This implies that metals are retained in the soil or plant components of these systems. Previous investigations indicate that more than 80% of the metal pollutants retained in BR systems accumulate in the soil (Sun and Davis, 2007; Marchand et al., 2010). The sorption capacity of soils is finite, and continuous application of metals may increase the risk of toxic metal buildup and subsequent leaching to groundwater. Davis et al. (2003) estimated that in the BR system they studied, Pb and Zn accumulation from runoff would reach or exceed regulatory limits for biosolids application (U.S. EPA, 1993) after 16 years of continuous use, and concluded that long-term accumulation of metals is an unintended consequence of treating stormwater in BRs.

BR systems are stressful environments for plant growth due to periods of flooding and pollutant loading, followed by long dry periods. Certain plant species are more capable of thriving in these hydraulic and pollutant loading extremes than others. Additionally, certain species contribute to higher levels of metal removal efficiencies under similar conditions (Read et al., 2008). Bioaccumulation potential for these plants is based on their ability to absorb and transport potentially toxic compounds, such as trace metals, from the soil to the aerial parts of a plant, allowing for the harvest and removal of the plant biomass which contains these toxic compounds. The effectiveness of metal uptake is contingent upon plant biomass yield and metal concentrations in the harvestable plant parts (Meers et al., 2008; Sheoran et al., 2011). Processes that influence accumulation include: 1) mobilization

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http://dx.doi.org/10.1016/j.jenvman.2015.10.019
0301-4797/

from soil, 2) uptake and sequestration in the roots, 3) efficiency of xylem transport, and 4) transport and storage into the aerial tissue (Clemens et al., 2002).

Most bioaccumulation studies focus on the remediation of highly contaminated soils at mining and industrial sites, with high soil metal concentrations (Stottmeister et al., 2003; Wiessner et al., 2006; Marchand et al., 2010; Yadavet al. 2011; Narhi et al., 2012; Ladislas et al., 2013). Liu et al. (2007) found that among 19 species, capacity for Cd, Pb, and Zn accumulation in aerial tissue differed by 47, 60, and 121 fold, respectively, and asserts that species selection in constructed wetlands significantly influences metal uptake (bioaccumulation) potential. However, these studies do not consider the bioaccumulation potential of plants grown in soils with continual application of low metal concentrations, nor do they assess bioaccumulation as a means of *slowing* that rate of metal accumulation in BMP soils. Research focusing on the bioaccumulation potential of plants in lower-level contamination conditions is vital to understand how to reduce, slow, and potentially prevent metal accumulation and the resulting formation of hazardous sites at BMPs.

Additionally, it is difficult to make definitive conclusions about the processes and mechanisms that affect BR system metal removal performance. Reasons for this include a lack of consistency in experimental methods, a wide variation in the reporting of results (load reduction versus concentration change), and a lack of explicit analysis of the fate of constituents in the plant, soil and water phases. Only two known studies investigated the fate of pollutants in plant, soil and water phases of BR systems (Sun and Davis, 2007; Borin and Salvato, 2012). Davis et al. (2009) concluded that despite the numerous studies being done regarding pollutant removal, many BMP design questions persist, such as which vegetative species provide the greatest metal bioaccumulation potential. Barrett et al. (2013) noted that it is important that any new research is conducted under controlled conditions and that detailed information be developed on the properties of the medium being tested.

A comprehensive exploration of Cu, Pb, and Zn bioaccumulation potential in this study investigates differences among six plant species undergoing three varying stormwater hydraulic and pollutant loading rates. The specific objectives of the study were to: 1) quantify differences in metal retention within simulated BR systems among six species undergoing hydraulic and metal loading typical of stormwater BR systems; 2) identify differences among species in the retention of Cu, Pb, and Zn within the plant above-ground (AG) and below-ground (BG) tissue based on biomass concentration and total harvested biomass measurements; and 3) evaluate differences in metal accumulation mechanisms used by these species in response to these hydraulic and pollutant loading conditions.

2. Materials and methods

2.1. Experimental design

This study, conducted at Utah State University's Research Greenhouse from October 2010 through June 2011, used a randomized block design with six plant species and synthetic stormwater to represent three hydraulic, nutrient and metal loading regimes, in triplicate. The concentrations of the response factors (Cu, Pb, and Zn) were measured in the exfiltrate, soil, and above ground (AG) and below ground (BG) plant tissue.

Treatment containers were built in Sterilite® polypropylene and polyethylene 19 L containers (surface area of 0.143 m^2). Each container was filled with 21 kg of soil consisting of 50% Kidman Sandy Loam (coarse-loamy, mixed, mesic Calcic Haploxeroll) and 50% sand, which enhanced water flow in this small-scale mesocosm study.

The 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 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); and Cam – *Carex microptera* (smallwing sedge). Six plugs, obtained from Aquatics and Wetland Nursery, Ft. Lupton, Colorado, were planted equidistantly within each container. Due to the availability of plants from the nursery, treatment containers were constructed at two different time periods, 1 month apart. The controls for the study were non-vegetated containers filled only with the soil-sand mixture. Sunlight Supply's 1000 W high-pressure sodium bulbs illuminated the greenhouse using a photoperiod of 12 h per day.

Soil in each container was weighed prior to planting. Initial soil samples were collected from each container and analyzed for nutrient and metal concentrations during the establishment period, prior to synthetic stormwater application. Significant differences in background nutrient and metal concentrations were found between containers constructed during the two time periods (Table 1). As a result, each container's individual initial and final constituent soil concentrations were used for all subsequent calculations. Plants were allowed to grow in the sand-soil mixture to establishment (rooted and producing new growth) for 6 months before synthetic stormwater was applied, and water sample collection began.

Each species was planted in triplicate containers under three hydraulic and metal loading regimes representing Logan, UT; Des Moines, IA; and Scranton, PA. These three cities are located along the 41°N latitude and are 18° longitudinally apart. Thus, the total number of containers monitored was 63 ($6 \times 3 \times 3 + 9 = 63$). Rainfall frequency, intensity and duration (hydraulic loading) were calculated from rainfall data from each city from 2005 to 2009 using the Driscoll method (Driscoll et al., 1989). This method is used in the EPA Stormwater Best Management Practice (BMP) Design Guide (U.S. EPA, 2004) to generate typical values of individual storm event statistics for 15 climate zones in the United States. The

Table 1
Soil properties, and nutrient and metal concentrations (mg kg^{-1} dry soil) in the soil-sand mixtures used to construct test BR systems, along with selected properties of City of Logan tap water used in the study.

	Soil-Sand mixture		Tap water
	Reactor batch 1	Reactor batch 2	
pH	8.2 ± 0.03	7.3 ± 0.07	7.6
EC (μS cm^{-1})	630 ± 80	2330 ± 100	285
Alkalinity (mg $CaCO_3$ L^{-1})	–	–	166
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]	0.05 mg L^{-1}
TN (mg kg^{-1})	476 ± 25[a]	690 ± 26[a]	0.40 mg L^{-1}
TMetal concentration			
Cu (mg kg^{-1})	1.1 ± 0.1[a]	2.3 ± 0.13[a]	64.4 μg L^{-1}
Pb (mg kg^{-1})	0.9 ± 0.1[a]	2.1 ± 0.1[a]	3.2 μg L^{-1}
Zn (mg kg^{-1})	6.2 ± 0.3[a]	7.3 ± 0.3[a]	67.3 μg L^{-1}

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