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Research paper

Interactions between design, plant growth and the treatment performance of stormwater biofilters

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ABSTRACT

Plants play a critical role in the nutrient removal performance of stormwater biofilters. However, the influence of biofilter design on plant growth and subsequent implications for treatment performance are not well understood. A 12 month, laboratory-scale biofilter column experiment was conducted to investigate the response of *Carex appressa* to variations in biofilter design and implications for nutrient removal performance. Plant growth in Skye sand, a natural iron-coated sand with a strong capacity to immobilize phosphorus, was evaluated against a typical loamy sand filter media in biofilters with and without a saturated zone. Plant biomass correlated strongly with nutrient removal and was significantly greater in biofilters with a saturated zone, suggesting that inclusion of a saturated zone facilitates nutrient uptake. In the presence of a saturated zone, plants grown in Skye sand had a significantly higher specific root length, surface area and volume than plants grown in loamy sand, illustrating *C. appressa*'s ability to adapt root morphology to maintain growth under nutrient limited conditions. These root traits also correlated strongly with nutrient removal, suggesting that use of Skye sand in biofilters rather than loamy sand would be advantageous for nutrient removal. However, root adaptations, in particular increased etiolation, can make plants vulnerable to stressful environments (e.g. prolonged drying). Therefore, it is critical that a saturated zone be included in stormwater biofilters to increase growth and protect against drying.

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1. Introduction

Stormwater biofilters provide passive treatment of urban runoff by harnessing the natural bioremediation properties of plant-soil systems (Fletcher et al., 2006; PGC, 2002). Extensive research in laboratory- and field-scale settings has demonstrated that plants play a critical role in facilitating stormwater treatment, particularly nutrient removal (Bratieres et al., 2008; Davis et al., 2006; Lucas and Greenway, 2008; Payne et al., 2014a; Read et al., 2008). Nevertheless, achieving co-optimised nitrogen and phosphorus (P) removal (particularly phosphate) remains a challenge for biofilters, as does meeting nutrient removal objectives for ecosystem protection (Davis et al., 2006; Glaister et al., 2014). Whilst nitrogen removal relies predominately on biological processes, which has been shown to improve with the inclusion of an internal water storage or 'saturated zone' (Zinger et al., 2013), the predominant mechanism by which phosphate is removed in plant-soil systems is through sorption to filter media (Erickson et al., 2007; Reddy et al., 1999).

The endeavour to improve the effectiveness of P removal in biofilters, among other stormwater and wastewater treatment systems, has led to many alternate filter media types being investigated (Bachand, 2003; Ballantine and Tanner, 2010; Lucas and Greenway, 2011; Vohla et al., 2011). The affinity of iron-rich soils and sediments for P sorption (Goldberg and Sposito, 1985) has motivated numerous researchers to test how augmenting the filter media of stormwater and wastewater treatment systems with iron-rich materials affects the P removal performance and retention capacity (Arias et al., 2006; Ayoub et al., 2001; Boujelben et al., 2008; Dobbie et al., 2009; Erickson et al., 2012). Recent research has shown that using 'Skye sand', a natural iron-coated filter media with a strong affinity for phosphorus (Glaister et al. unpublished data), in conjunction with a saturated zone, can improve N and P removal and enable biofilters to achieve ecosystem protection

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Table 1
Biofilter column configurations.

Configuration ID	Filter Medium	Saturated Zone (Y/N)
Loamy sand (S)	Loamy Sand	Y
Skye sand (S)	Skye Sand	Y
Skye sand (NS)	Skye Sand	N

objectives (Glaister et al., 2014). However, while success in ameliorating N and P removal has been demonstrated, the influence of Skye sand on plant growth in biofilters has not been specifically tested. As such, further research is needed to understand how Skye sand filter media influences plant growth and nutrient removal in biofilters.

Iron-rich soils are typically associated with limited nutrient availability (Handreck, 1997; Lambers et al., 2008; White and Hammond, 2008; Wild, 1950). The ability of plants to respond to such conditions is fundamentally important to environmental adaptation. Root development responses to nutrient limited conditions can have a profound effect on root system architecture and nutrient acquisition (Lambers et al., 2008; López-Bucio et al., 2003; Schmidt and Schikora 2001). Such responses include: elongation of primary roots; formation of lateral roots, to increase the exploratory capacity of the root system; and the formation of root hairs, which increase the total surface area of primary and lateral roots and allow roots to exploit a considerably larger cylinder of soil (López-Bucio et al., 2003).

Previous studies investigating plant traits that enhance nutrient removal in biofilters have found that plant biomass and root traits, such as root length, surface area and fineness, are strongly correlated with nutrient removal, particularly dissolved N and P species (Payne et al., 2014b; Read et al., 2010, 2008). As such, nutrient limited conditions may present advantageous conditions for the development of plant traits which correlate with enhanced nutrient removal. This may explain in part why the use of Skye sand filter media has been shown to be beneficial for nutrient removal.

Building upon existing studies of the influence of plant traits on nutrient removal (Payne et al., 2014b; Read et al., 2010), the present study aims to investigate how using Skye sand as a filter medium affects the growth and morphology of plants in biofilters and the implications for nutrient removal performance. Investigating plant responses to Skye sand in conjunction with a saturated zone is a key focus of this study and an essential part of the research needed to develop a better understanding of how co-optimisation of N and P removal in biofilters can be achieved.

2. Materials and methods

2.1. Experimental design

Three biofilter column configurations were designed to compare nutrient removal performance and plant growth characteristics of loamy sand and Skye sand biofilters with a saturated zone and Skye sand biofilters with and without a saturated zone (Table 1). A saturated zone inclusive biofilter with loamy sand filter media was not included because nutrient removal performance and plant growth characteristics of this configuration have been thoroughly investigated by a number of preceding studies, using the same experimental apparatus and testing facility (Bratieres et al., 2008; Payne et al., 2014b). Five replicate columns were constructed for each configuration. The columns were made of PVC (600 mm x 150 mm diameter) with a 200 mm acrylic collar attached to create a ponding zone. The configurations without a saturated zone drained freely from the base, while a riser pipe was attached to the outlet of the saturated zone inclusive systems to maintain a 300 mm pool of water in the lower half of the column. The biofilters contained four layers of media (from top to bottom): (1) loamy sand or Skye sand filter media (300 mm); (2) coarse, washed sand transition layer (200 mm); (3) pea gravel drainage layer (70 mm); (4) gravel drainage layer (30 mm). A cross section of the columns is shown in Fig. 1a.

The biofilter columns were each planted with a single *C. appressa* plant. *C. appressa* is an Australian tall sedge that is relatively drought tolerant and has been found to provide effective nutrient removal in biofilters (Bratieres et al., 2009; Read et al., 2008). Prior to transplanting into the columns, the plants were established for 12 weeks in small pots containing either loamy sand or Skye sand, depending on their destination biofilters. The pots were housed in a greenhouse maintained at 25 °C and watered twice weekly with tap water. The biofilter columns were constructed in July and placed in an open-air shade house (Fig. 1b). After an initial flush with tap water to settle the filter media, stormwater dosing commenced in early August.

Because of the uncertainty and inconsistency associated with the use of real stormwater, a semi-synthetic stormwater was prepared using methods described by previous biofilter column studies (e.g. Bratieres et al., 2008; Hatt et al., 2007). This approach utilises natural sediment collected from a stormwater retention pond and laboratory-grade chemicals to produce a semi-synthetic stormwater of a quality consistent with typical stormwater pollutant concentrations (Duncan, 1999; Taylor et al., 2005). The frequency and volume of dosings were designed to simulate typical Melbourne rainfall patterns. During 'wet' periods (August-November and April-July) the columns were dosed twice weekly with stormwater. Throughout the intervening 'dry' months (December-March) the dosing schedule varied, with up to 18 antecedent dry days occurring between events. Dosing volumes remained constant at 3.7L per event, which is equivalent to the rainfall received by a biofilter sized to 2.5% of its catchment area in Melbourne (540 mm effective annual rainfall, Bureau of Meteorology, 2013). Water quality was monitored by collecting bulk effluent samples from each column every five weeks for twelve months and analysing for total phosphorus (TP), total nitrogen (TN), ammonium (NH_4^+), nitrate/nitrite (NO_x), dissolved organic nitrogen (DON), particulate organic nitrogen (PON) and filterable reactive phosphorus (FRP) using standard methods and quality controls (APHA/AWWA/WPCF, 2001).

2.2. Column deconstruction and plant harvesting

In order to quantify the effect of biofilter design on plant growth and morphology, the plants were harvested from the vegetated columns (15 plants; 5 replicates per configuration) at the end of the experimental period. A longitudinal quarter segment of each column casing (the PVC pipe) was removed to allow visual examination of the filter media layers and plant roots (Fig. 2). Filter media samples were collected before the plants were removed from the columns by carefully washing away the filter media. After washing, the clean plants were stored for a few days (maximum of 14) in 10L buckets filled with tap water until growth and morphological analysis commenced.

2.3. Plant growth and morphological analysis

Plant morphology was characterised using several techniques (Table 2). The longest root and shoot length of each plant was measured, along with the bulk root length (the length to which approximately 95% of roots grew to) and bulk shoot length (length of ~95% of shoots). Each plant was then separated into roots, shoots (i.e. leaves), and stems. Roots were cut into 2–4 cm segments and placed in 10L buckets filled with water. This allowed the roots to separate and mix well. Approximately 10 g wet weight

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