Phosphorus Retention Performance in Vegetated and Non-Vegetated Bioretention Mesocosms using Recycled Effluent

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Abstract

Phosphate removal from stormwater and wastewater is essential to prevent eutrophication of waterways. The aim of our study was to evaluate phosphorus retention in vegetated and non-vegetated (barren) bioretention mesocosms. Existing well-established bioretention mesocosms with sandy loam, loamy sand and gravel media were irrigated with 60.9 g-m⁻² (609 kg-ha⁻¹) TP from recycled effluent between August 2006 and March 2007. Initially, P retention in the barren loam and sand media approached 100%, while gravel retention was only 20%. However, after application of this load, retention by all barren media had declined substantially. In contrast, retention by vegetated treatments remained very high, with 92% of the total mass load retained in the vegetated loam, 84% in the sand, and 55% in the vegetated gravel. These results indicate that the vegetated treatments provide far more TP retention than the barren treatments.

Over the 31 week period, the difference in retained loads was 15.4 g-m⁻² P in the vegetated loam mesocosms, 16.9 g-m⁻² P in the vegetated sand mesocosms, and 23.5 g-m⁻² P in the vegetated gravel mesocosms. These removal rates substantially exceed typical phosphorus uptake rates for plants, suggesting that other plant-soil-microbe interactions are influencing phosphorus retention in the vegetated mesocosms.

Introduction

The literature suggests that phosphorus (P) retention in bioretention systems is primarily a geochemical process largely controlled by media properties (Davis et al, 2001; Hsieh and Davis, 2005). This process involves different reactions with a variety of substrates at varying kinetics. Initial studies of bioretention systems documented that they offer considerable potential to retain TP (Davis et al, 2001). Ultimately, the extent and rate of P retention is understood to be a function of P saturation status. For instance, Hunt et al (2005) reported increased concentrations of P in effluent from field scale systems. The authors attributed the increase to high P saturation status of the media. Dietz and Clausen (2005) also reported P export in a rain garden treating roof runoff. The P losses seem to reflect the very low P concentrations originating from the roof source area (<0.019 mg-l⁻¹), which were below the equilibrium concentration of the media. Over time, there was a very clear leaching trend, with outflow concentrations decreasing from 0.14 mg-l⁻¹ to 0.04 mg-l⁻¹. These findings highlight the importance of the influent concentration and media composition in determining P retention dynamics of bioretention systems.

Another issue of substantial importance is the effect of vegetation. While the results of Davis et al (2001) were derived from vegetated systems, no comparison was made with unvegetated systems, so the effect of vegetation could not be ascertained. Henderson et al (2007) compared retention in vegetated and unvegetated (barren) mesocosms. In of this study 0.5 mg-l⁻¹ TP was applied at a volume of 43cm per fortnight, an annual rate of 11.2m. At this hydraulic loading rate, the concentrations applied over 28 weeks resulted in a nutrient mass load application of 3.1 g-m⁻² of TP, or an annual loading rate of 5.7 g-m⁻²-y⁻¹ TP. These hydraulic and nutrient loads are typical to bioretention systems for stormwater. Stormwater dosing results indicated that the presence of vegetation had a pronounced effect to promote P retention. After 12 months establishment, ortho-phosphate (PO₄-P) removal approached 100% in the vegetated treatments and sand media; but only 75% in the loam media (Henderson et al, 2007).
The preceding studies are the only published studies of which we are aware that quantitatively examine the effect of vegetation upon nutrient retention performance in bioretention systems. The results of Henderson et al (2007) need to be replicated, and subjected to long-term nutrient and hydraulic loads typical to bioretention facilities during typical design conditions. This is the focus of our study.

Methods

The experiments were conducted from August 2006 through March 2007 in Brisbane, Australia using the existing bioretention mesocosms of Henderson et al (2007). The 30 bioretention mesocosms were constructed in June 2003 in 240L containers using 3 media types, pea gravel, loamy sand (2% clay) and sandy loam (3% clay and 8% silt). The media depth is approximately 80cm, with 20 cm of freeboard, and a 5cm gravel underdrain layer. For each media type, five mesocosms have been planted with native vegetation, with the remaining five (barren), providing 5 replicates for each treatment. 20 cm of sand was added to provide a rooting medium in the vegetated gravel mesocosms. The plant species were selected to represent a mixture of grasses and shrubs. At the time of our experiments, the vegetation had been established for 3 years. Our experiments occurred after 18 months of irrigation with only rainfall and tap water.

We applied 108L of recycled tertiary effluent from the Loganholme Water Pollution Control Centre to each mesocosm at weekly intervals. At an average concentration of 4.3 mg-l\(^{-1}\) TP, this resulted in an accumulated load of 60.9 g-m\(^{-2}\) of TP over 31 weeks, or 102 g-m\(^{-2}\) per year. These application rates were similar to a constructed wetlands for sewage treatment in tropical Queensland (Greenway, 2005), but over an order of magnitude greater than typical agronomic TP rates of 50 kg-ha\(^{-1}\) yr\(^{-1}\). Three leaching runs with tap water and synthetic stormwater were conducted in an attempt to observe responses at stormwater concentrations.

After every fourth recycled effluent application, the entire effluent volume was collected in 150L cylindrical PVC chambers (300cm x 250mm diameter) for 24h from the sand and gravel mesocosms and for 48h from the loam mesocosms, and composite subsamples collected for analysis. This resulted in a cumulative sampled event load of 18.0 g-m\(^{-2}\) of TP. Samples were taken from all mesocosms on three runs, and from two of the five replicates for the rest of the runs. Of the latter, the single largest difference in mean values between the two selected and all five replicates was 26%, which occurred in the vegetated loam. The rest of the differences were less than 9%, confirming that the sampled replicates were representative of the treatments as a whole. Samples were refrigerated, and filtered with a 0.45µ filter, and analyzed for PO\(_4\)-P using a Lachat Quikchem 8000 Flow Injection Analyzer. Total P was measured using standard persulfate digests on unfiltered samples. The barren loam mesocosms were not sampled on two events. However, since their retention trends were consistent, the sampled mass loads applied to and retained by them were adjusted in proportion to the total loads applied to the sampled mesocosms. The data is normalized in terms of the load per square meter to facilitate comparison with other BMP studies in terms of loading rates.

Results

Given the monthly sampling protocol, the effluent loading resulted in cumulative sampled inflow loads of 18.0 g-m\(^{-2}\) of TP, nearly all of which is PO\(_4\)-P. Table 1 displays the TP retention responses. Cumulative outflow loads sampled from the barren mesocosms are shown in the upper row, while loads from the corresponding vegetated systems are shown in the line below. The difference represents the mass load reduction attributable to the presence of vegetation. The percentage of applied TP retained by each treatment is also
displayed in Table 1. Since the systems were sampled at every fourth application, this percentage was applied to the total inflow load to obtain the load retained over the period. The prorated load reduction in the vegetated mesocosms over the 31 week period is presented, and normalized on an annual basis in terms of agronomic units.

To evaluate the trends in retention as loading proceeded, Figure 1 displays outflow concentrations from the discrete sampling measurements according to the cumulative load applied at each sample date. While the initial outflow concentrations from the barren sand and loam treatments were very low, there was a clear trend for increasing outflow concentrations as the cumulative load increased. In contrast, outflow concentrations from the vegetated loam treatments remained very low until 30 g-m⁻² had been applied, but then stabilized in the range of 0.3 mg-l⁻¹. A similar trend was observed in the vegetated sand, with values stabilizing around 1.0 mg-l⁻¹. As shown in Table 1, the cumulative retention in the vegetated sand and loam treatments was very substantial, being 92% in the loam and 84% in the sand, while declining to 55% in the gravel. The retention values for loam and sand are remarkably high for long term effluent treatment studies, even though these treatments were never formulated for their TP sorption capabilities. Figure 1 displays final retention trends in the sand and loam indicating that saturation has not yet occurred in these vegetated systems.

### Table 1: Loading Results, Computed Retention, and Effect of Vegetation

<table>
<thead>
<tr>
<th>Media</th>
<th>20cm Sand</th>
<th>80cm Sand</th>
<th>80cm Loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outflow Load (g-m⁻²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barren</td>
<td>15.1</td>
<td>7.9</td>
<td>6.0</td>
</tr>
<tr>
<td>Vegetated</td>
<td>8.1</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Difference</td>
<td>7.0</td>
<td>5.0</td>
<td>4.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percent Retention</th>
<th>Barren</th>
<th>Vegetated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17%*</td>
<td>55%*</td>
</tr>
<tr>
<td></td>
<td>56%</td>
<td>84%</td>
</tr>
<tr>
<td></td>
<td>67%</td>
<td>92%</td>
</tr>
</tbody>
</table>

*Vegetated has 20cm sand, barren has none

In contrast, the barren loam and sand mesocosms retained 67% and 56%TP, respectively, while the barren gravel mesocosms retained an average of only 17% of TP applied. However, the decline in retention in all barren systems suggests that the near-

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**Figure 1:** Cumulative Sampled TP results. Trends in outflow as function of inflow.
term results in table 1 do not reflect long-term performance. TP was leached from all barren systems during the leaching runs, indicating that the barren media had become saturated at stormwater concentrations. On the other hand, in comparing the final results to those obtained just before the leaching runs, the barren sand and loam treatments seem to have recovered some retention after leaching, even though only ~1.0 g-m$^{-2}$ TP was actually leached from these systems.

Comparing the vegetated to the barren systems, the effect of vegetation was substantial, particularly in the gravel. Normalized on an annual basis, the increase in retention in the vegetated treatments was at least 250 kg-ha$^{-1}$. Part of the 394 kg-ha$^{-1}$ difference in the gravel seems attributable to the difference in media composition. These findings emphasize the effect that the presence of vegetation has upon bioretention performance. This response of TP is what would be expected from typical adsorption/precipitation processes, in that output approaches an irreducible (equilibrium) concentration, regardless of input concentration. This means that there is relatively more retention at higher input concentrations, while low input concentrations result in leaching of accumulated P.

**Discussion**

**Biological Retention Mechanisms**

Vegetation is the most conspicuous biological component of bioretention systems. In addition to vegetation, many other biological processes occur in bioretention systems. Macroinvertebrate ingestion and excretion activities transform more labile nutrient forms into increasingly refractory forms (Atlas and Bartha, 1998). There is also a large pool of soil microbial biomass which is involved in extensive nutrient uptake and transformation of carbon and nutrients into immobile forms (Brady, 1990; Atlas and Bartha, 1998). By providing aeration which improves habitat for micro-organisms, plant roots promote biological retention of nutrients (Davis et al, 2001). Carbon and nutrient exudates leaching from roots promote the growth of these soil microbes. As a result, microbial biomass density is two orders of magnitude higher in the vicinity of plant roots compared to barren soils (Atlas and Bartha, 1998).

Mycorrhizal fungi associated with plant roots are also very active in taking up nutrients from the soil solution, as well as phosphorus adsorbed to soil fractions. With mycorrhizal fungi, the resulting effective rooting surface area can be ten times that of bare roots, and they extend considerably farther into the soil (Brady, 1990). Crops inoculated with mycorrhizal fungi obtain twice the level of tissue P in nutrient poor situations. Vegetation also has considerable effects upon iron complexes in the media. Reduced ferrous iron in the media is oxidized to ferric iron, which has a substantial capacity for P-sorption. It is thought that even relatively inaccessible iron compounds are mobilized by this process (Mendelssohn et al, 1995), furthering P retention performance of the media.

Soil microbial biomass can take up substantial amounts of P. In highly reactive tropical clay soils, Olander and Vitousek (2004, 2005) report that microbial uptake of applied P was very rapid, and substantially out-competed the soil adsorption kinetics. This suggests that microbial uptake of P was very rapid under the nutrient deficient setting of the experiment. However, microbial P uptake did not persist at this high rate in the surface profile under nutrient enriched circumstances after TP had been applied at 10 g-P-m$^{-2}$-y$^{-1}$ for 15 years (Olander and Vitousek, 2004). Therefore, whether such microbial reactivity would persist under the long term high nutrient loads of bioretention systems seems unlikely.

P uptake in crops varies from 0.9 to 2.23 g-P-m$^{-2}$-y$^{-1}$ (Flaten et al, 2003), and P accumulation rates in enriched US mid-Atlantic forests are 1.11 g-m$^{-2}$-y$^{-1}$ (Fail et al, 1986).
Plant uptake of P in tropical surface flow treatment wetlands is as high as 14 g-m\(^{-2}\)-y\(^{-1}\) but still only accounts for about 50% removal of the input nutrient load (Greenway and Wolley, 2001). Annual P biomass production rates for emergent species were as high as 15.2 g-m\(^{-2}\)-y\(^{-1}\). In subtropical Queensland, annual P biomass production rates in subsurface wetlands receiving high nutrient loads were 9.0 g-m\(^{-2}\)-y\(^{-1}\) (Greenway, 2005). However, this latter value is an order of magnitude less than the rates applied in this experiment. Given this background, the load reductions shown in Table 1 for the vegetated treatments are at least several times greater than plant uptake capabilities.

**Geochemical Retention Mechanisms**

The preceding suggests that plant uptake and microbial immobilization processes account for only a portion of the P retained in our experiments. Therefore, it falls to geochemical processes such as adsorption and/or precipitation of PO\(_4\)-P (and organic P to a lesser extent) as the primary mechanism by which P is retained in bioretention systems. While there is a fairly extensive literature on P-sorption properties of media used in constructed wetlands (see review by Johannsson-Westholm, 2006), there are only a few studies on P-sorption by bioretention media (e.g., DeBusk et al, 1999; Erickson et al, 2006).

The adsorption process involves several mechanisms. There is a rapid (within minutes) electrostatic ion-exchange reaction with outer sphere hydroxyl complexes which is highly reversible. In addition to ion exchange reactions in the outer-sphere, there is a less rapid specific adsorption by mono- and divalent chemical bonds with inner-sphere complexes. It should be noted that there is a continuous transition between inner and outer sphere complexes (Stumm and Morgan, 1996). While the monovalent bonding is relatively exchangeable, the divalent bond is much less reversible. The monovalent reaction is considered to be bioavailable, while the latter reaction is considered sequestered. In addition, there is a slow irreversible reaction that takes place over months (Sparks and Hunger, 2002). In addition to adsorption, precipitation is a process by which cation-P complexes are directly precipitated out of solution. In acidic conditions, Fe- and Al- precipitation reactions dominate, while a series of more irreversible reactions occur with Ca- in alkaline conditions. The kinetics of precipitation reactions are slower than the adsorption reactions (Sovik and Klove, 2005), so retention times in the range of at least several hours are necessary for them to occur. The preceding suggests that the “fast-reversible” adsorption reactions will predominate when flows through the media occur during runoff events, with the “slow-irreversible” adsorption/precipitations reactions then occurring between events. In this discussion, the term sorption is applied to both processes.

For best sorption responses, these dynamics suggest that retention time in the media needs to be longer than provided by the flow rate of 15 cm-hr\(^{-1}\) typical for a loamy sand media. This finding is supported by the column studies of Molle et al, (2003) where at least 5 hours of contact time is needed to approach peak sorption, and also by Brooks et al (2000), in which at least 8 to 10 hours was needed to reach peak sorption. P removal performance in constructed wetlands under field conditions has also been related to retention time (Sakadevan and Bavor, 1998).

**Experimental Results**

Given the nutrient deficiency at the beginning of our experiment, previously adsorbed P would have been sequestered by irreversible reactions, freeing up outer sphere binding sites for additional dosing. Indeed, as shown in Figure 1, initial TP retention was very high in the sand and loam, regardless of the presence of vegetation. This suggests
that outer sphere geochemical adsorption processes can operate rapidly enough (within only a few hours) to account for the observed retention seen in Henderson et al (2007).

The applied phosphorus load in these systems was 60.9 g-m\(^{-2}\) over a period of only 31 weeks, equivalent to over 102 g-m\(^{-2}\)-yr\(^{-1}\), or 1020 kg-ha-yr\(^{-1}\). In terms of urban runoff, at an event P load of 0.50 mg-l\(^{-1}\) applied to a 20m annual hydraulic load, bioretention facilities would receive 10.0 g-P-m\(^{-2}\)-y\(^{-1}\). The load applied here is thus equivalent to at least 6 years of runoff loads under typical urban concentrations and hydraulic loading rates. Our results are thus perhaps more applicable to wastewater treatment BMPs than they are to stormwater.

In this light, subsequent loading runs demonstrate a substantial decline in rapid media sorption under high nutrient loads. By the time the accumulated P loads reached 40 g-m\(^{-2}\), the retention performance of the barren gravel was exhausted, and the barren sand and loam were only marginally effective. Notwithstanding this trend of media saturation in barren treatments, after leaching losses in the range of only 1.0 g-m\(^{-2}\), there seems to be a partial recovery of retention capabilities in the barren sand and loam treatments, as shown in the last sampling.

Our findings on the same mesocosms support the findings of Henderson et al (2007) showing that the presence of vegetation has a pronounced effect to promote TP retention. This finding has now been extended to apply to recycled effluent. Even though the loading rates are an order of magnitude greater than biological uptake/immobilization capacities, P retention in vegetated mesocosms is very high. Representing a difference in retention of at least 258 kg-ha-yr\(^{-1}\), it is apparent that biological sequestration cannot account for the difference. Even in the 20cm sand media, which would have only a limited P sorption capacity, the presence of vegetation provided for retention of 55% of applied P, but there was a substantial declining trend. However, the overall retention of 84% in sand mesocosms and 92% retention in the loam mesocosms still persists at this point of the experiment. This suggests that that the beneficial effect of vegetation under high loading rates is enhanced by the provision of more sorption capacity in the media. Note that this retention response was found in media that was not formulated to have extensive P-retention capabilities. Experiments are now being conducted on mesocosms comprised of media with considerably greater potential to retain P.

Since our loading rates exceed uptake/immobilization rates, it is clear that biological retention processes cannot account for the magnitude of retention. However, the mechanism by which this high level of P retention is mediated by vegetation is unknown. Somehow, vegetative systems provide a remarkable ability to temporarily retain applied PO\(_4\)-P for eventual sequestration in the geochemical pool. It seems as if there is a mechanism by which excess P is rapidly accumulated in the biological pool under intermittent nutrient pulses, and then released back into the media geochemical pool during inter-event periods, where the slower irreversible reactions then take place to sequester P permanently. Even though the media may be apparently saturated in terms of rapid sorption capacity, as reflected in a high equilibrium P concentration at the short contact time in bioretention systems, it remains unsaturated in terms of total sorption capacity, and can thus still retain P. The higher retention in deeper sand mesocosms suggests that the more sorption sites available, the better overall retention performance will be, and the longer it will persist. The even higher retention of applied TP in the loam mesocosms suggests that the beneficial effect of vegetation is most important in the loam which has the greatest overall sorption capacity.
Conclusions

These experiments highlight the importance of plants and media composition in P retention processes. They also suggest complex biogeochemical interactions are involved in P retention. Once the media cannot effectively adsorb P through rapid reactions, the mechanisms by which plants improve the retention of P by bioretention media at both low concentrations of urban runoff and high concentrations of wastewater become of critical importance. Achieving a better understanding of the complex interactions involved between plants, microbes, and the media will enable the science to be optimally combined with the engineering design to improve bioretention technologies. Although there has recently been research into quantifying some of the plant-microbe-soil interactions in constructed wetland systems (Stottmeister et al, 2003; Larsen and Greenway, 2004; Tietz et al, 2007), there have been no similar investigations into stormwater bioretention systems.

The original intent of this experiment was to determine the stormwater retention performance of bioretention systems after long-term stormwater nutrient loads. However, the results we have obtained for nutrient retention in secondary effluent extend the utility of bioretention systems far beyond just stormwater applications. Even with media not designed for phosphorus retention, the performance of vegetated bioretention systems surpasses the TP retention performance of constructed wetland systems for wastewater treatment. Media specifically formulated for P retention will likely perform even better. The implications for wastewater treatment are thus very widespread. As a relatively inexpensive BMP, bioretention has capabilities that can be applied to concentrated animal feeding operations, decentralized treatment systems, as well as nutrient removal in treatment plant effluent.

As water resources become ever scarcer throughout Australia, it is imperative that methods to recycle wastewater be applied as widely as possible. Disinfected secondary effluent may be appropriate for irrigation purposes; however, for environmental flows and drinking water supplies, it is necessary that nutrients be removed to avoid eutrophication of waterways and reservoirs. On a treated volume basis, the cost of bioretention systems compares quite favorably to constructed wetlands, and very favorably to structural nutrient removal methods. Given the impending large scale effort to transfer wastewater to reservoirs in southeast Queensland, this potential of bioretention systems has imminent implications.

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References:


