A comparative study of nutrient retention performance in vegetated and non-vegetated bioretention mesocosms

Comparaison des performances pour le traitement de l'azote d'ouvrage de biorétention végétalisés ou non.

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RESUME

Les systèmes de **biorétention** sont des ouvrages de traitement des eaux pluviales installés pour éliminer les polluants dissous et particulaires. Dans notre étude, 20 mésocosmes de biorétention (10 avec le sable glaiseux et 10 avec la terre grasse arénacée, moitié avec et moitié sans végétation) ont été employés pour étudier la conservation nutritive dissoute. La conservation moyenne de TP dans des mésocosmes végétalisés de terre grasse était de plus de 90%, comparé à 75% dans les mésocosmes non-végétalisés (stériles). La conservation de TP dans le sable était très haute (moyenne 90%), indépendamment du traitement. La conservation de TN a grimpé jusqu'à 80% dans des mésocosmes végétalisés de terre grasse et de 43% dans les mésocosmes sans terre grasse. L'augmentation du temps de conservation dans les mésocosmes de sable a augmenté la conservation de l'azote à 61%, une augmentation de 50% des capacités de rétention. Tandis que la terre grasse est moins efficaces par elle-même, la présence de la végétation améliore sensiblement la conservation de TP et de TN.

ABSTRACT

Bioretention systems are stormwater treatment devices installed to remove both dissolved and particulate pollutants. In our study, 20 bioretention mesocosms (10 with loamy sand and 10 with sandy loam, half with and half without vegetation) were used to investigate dissolved nutrient retention. Average TP retention in the vegetated loam mesocosms was over 90%, compared to 75% in non-vegetated (barren) mesocosms. TP retention in the sand was very high (average 90%), regardless of treatment. TN retention increased to 80% in the vegetated loam mesocosms from 43% in barren loam mesocosms. Increasing retention time in the sand mesocosms increased retention of nitrogen to 61%, a 50% increase in retention performance. While the loam is a less effective media by itself, the presence of vegetation substantially improves TP and TN retention.

KEYWORDS

Bioretention, Nutrient Retention.

INTRODUCTION

Bioretention systems are better management practices (BMPs) which typically consist of an excavated basin filled with porous media and planted with vegetation. The media in most bioretention systems ranges from loamy sands to sandy loams. As the stormwater passes through the bioretention system, particulates are removed by filtration. Dissolved pollutants are removed from solution by chemical adsorption/precipitation processes largely affected by the media, as well as biological processes within the media, such as vegetative and microbial biomass uptake.

Initial studies of bioretention systems documented that they offer considerable potential to retain TSS and metals, while providing encouraging results for nutrient retention (Davis et al, 2001). However, there is still a considerable amount of uncertainty about long-term nutrient retention, particularly in relation to phosphorus (P). Another issue that is 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.

In one of the first studies to explicitly investigate the effect of vegetation, Henderson et al (2006) compared retention in vegetated mesocosms to those without vegetation (barren). The setup of this study applied 5.4 mg-l^{-1} TN and 0.5 mg-l^{-1} TP 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 32.9 g-m^{-2} of TN and 3.1 g-m^{-2} of TP, or an annual loading rate 61.1 g-m^{-2}-y^{-1} of TN and 5.7 g-m^{-2} -$y^{-1}$of TP. These hydraulic and nutrient loads are typical to bioretention systems. After 12 months establishment, Ortho-phosphate (PO_4-P) removal approached 100% in the vegetated treatments and sand media; but only 75% in the loam media. The vegetated treatments also removed 77% of TN from synthetic stormwater, compared to retention of only 10% in barren sand and 25% in barren loam treatments (Henderson et al 2006).

METHODS

The experiments were conducted from May to August 2006 in Brisbane, Australia using the existing bioretention mesocosms of Henderson et al (2006). These bioretention mesocosms were constructed in June 2003 in 240L containers (105cm by 53cm by 53cm, tapering to 42cm by 42 cm) using 2 media types, a loamy sand (2% clay) and a sandy loam (3% clay and 8% silt). The media depth is approximately 80cm, with 20 cm of freeboard, and a 5cm gravel underdrain layer. The media is separated from the underdrain layer by coarse screening. For each media type, five mesocosms were planted with native vegetation, with the remaining five being non-vegetated (barren), providing 5 replicates for each treatment. For the dosing experiments, synthetic stormwater (4.8 mg-l-1 TN and 0.78 mg-l-1 TP) was applied at a uniform rate of 36 L-hr-1. Concentrations of specific nutrient species are discussed in more detail below to facilitate interpretation of the results.

The entire effluent volume was collected in 150L cylindrical PVC chambers. After collecting the entire effluent volume, subsamples were then refrigerated. Influent and effluent samples were all filtered with a 0.45μ filter, and analyzed for NH_4, NO_x and PO_4-P using a Lachat Quikchem 8000 Flow Injection Analyzer. Total N and P were measured using standard persulfate digests on unfiltered samples. The difference between the inorganic nutrient fraction and the total was allocated as the dissolved organic nutrient fraction. Two dosing runs were made at the end of July, 2006, separated by an interval of a week. Controllable outlets were placed in the sand mesocosms to restrict outflows ion the second run, thus increasing retention time.

RESULTS

Retention percentages in the following discussion are expressed in terms of subtracting the ratio of mean effluent to mean influent concentration of each run from 100%. The nutrient retention response of the media and vegetation treatments are presented in Figures 1 through 5. Both runs are shown to compare the previous run to the later run. Comparisons between treatments are shown on the first runs, while comparisons between runs within treatments are shown on the second run. Significant changes ($p \leq 0.008$) are shown with one asterisk, with very significant changes (≤0.0001) shown with two asterisks.

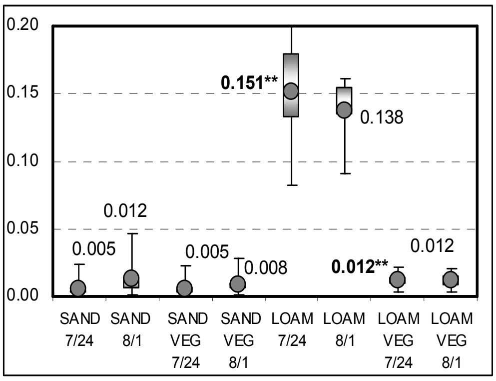

Figure 1:
PO_4-P in effluent of mesocosms (mg-l^{-1})

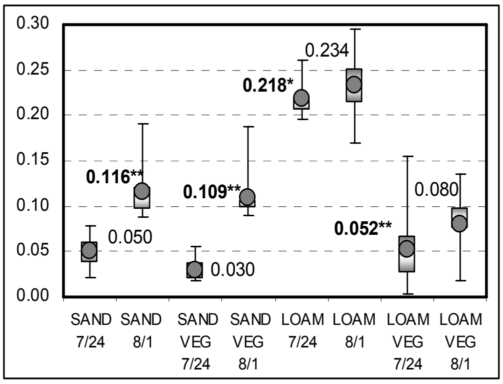

Figure 2:
Total-P in effluent of mesocosms (mg-l^{-1})

Given an average influent PO_4-P concentration of 0.56 mg-l^{-1}, the response for PO_4-P displays several unusual aspects, as shown in Figure 1. Note how the sand has very high nutrient retention, with or without vegetation. Retention was 99% in the first run, and only declined marginally in the second run. In contrast, the loam performed less effectively, with retention of 73% to 77% without vegetation. However, with vegetation, the retention in the loam mesocosms was as effective as in the sand. These results replicate the findings of Henderson et al (1996). There was no significant effect of the second run on any treatments.

Figure 2 displays a similar trend between treatments in the case of total phosphorus. In this case, there was an increase in effluent levels in all treatments in the second run. The average influent concentration was 0.78 mg-l^{-1}, of which the sand mesocosms retained 93% in the first run, decreasing to 86% in the second run. A similar decline in the vegetated sand mesocosms from 93% to 87% retention was also significant. Retention in the loam mesocosms was significantly improved by the presence of vegetation, increasing from 71% to 93% in the first run. In contrast to the sand mesocosms, the decline to 90% retention in the second run in the vegetated loam mesocosms was not significant (p = 0.08).

Figure 3 displays the response for nitrogen oxides (NO_x) to an average influent NO_x concentration of 0.89 mg-l^{-1}. Without vegetation, retention of nitrogen oxides also showed a considerable decline from the first to the second runs. It can be seen that the sand and loam without vegetation had minimal or negative retention in the first run, with a substantial export of NO_x in the second run. With vegetation, there

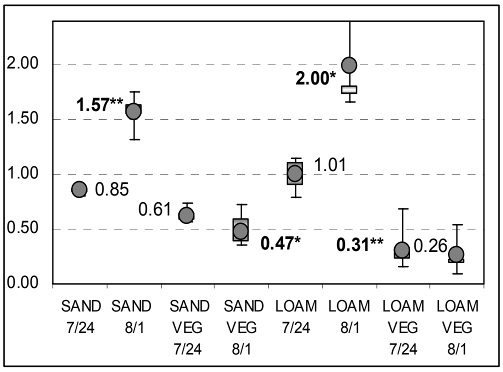

Figure 3:
NO_x in effluent of mesocosms (mg-l^{-1})

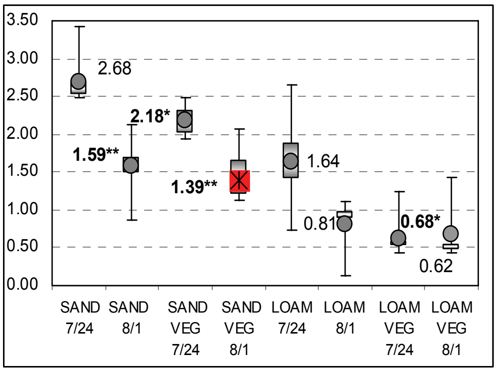

Figure 4:
Organic N in effluent of mesocosms (mg-l^{-1})

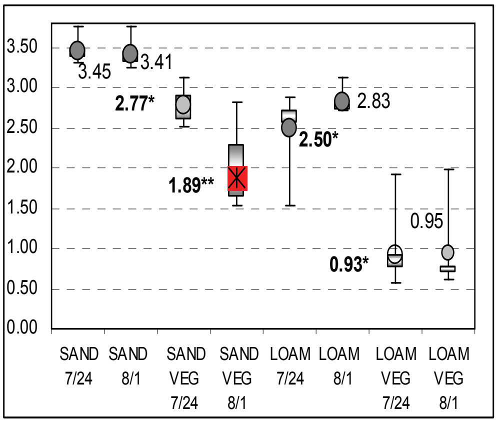

Figure 5:
Total N in effluent of mesocosms (mg-l^{-1})

was a 28% retention in the sand and a significant 64% retention in the loam in first run. In contrast to the decrease in retention seen in the second runs without vegetation, there was a respective increase to 49% and 71% retention in mesocosms with vegetation in the second run, of which only the decline in the vegetated sand was significant ($p < 0.001$). Results for ammonia are not presented since the effluent levels were quite low (0.02 to 0.09 mg-l^{-1}) in all treatments, and thus represent a only a small proportion of total N. Ammonia retention varied from 78% to 94%, and followed the trend for PO_4-P retention, as in the case of leaching.

In the case of dissolved organic nitrogen (ON), the influent average was 3.62 mg-l^{-1}. As shown in Figure 4, initial retention was 28% and 56% in the barren sand and loam mesocosms, respectively. The presence of vegetation increased retention to 41% and 83%, but the decreases were not highly significant ($p \approx 0.0025$). In contrast to TP and NO_x, the second runs generally showed an increase in retention, with the barren sand increasing to 55% and the barren loam increasing to 77% retention. The presence of vegetation increased retention in the sand to 61% in the second run, while there was no substantive change in the vegetated loam mesocosms. The increased retention in the second run for both sand mesocosm treatments was significant ($p < 0.0001$).

Figure 5 displays the retention performance for total N, which had an average influent concentration of 4.77 mg-l^{-1}. In this case, barren sand provided only 26% to 30% effective retention, with no apparent change in the second run. Vegetation improved retention in the sand to 41% in the first run, which increased substantially to 61% in the second run. Loam performed better than sand, with 47% retention declining to 42% in the second run. Vegetation substantially improved total N retention in the loam, providing for retention of 80% of the total nitrogen applied.

DISCUSSION

Vegetation is only the most conspicuous biological component of bioretention systems. In addition to vegetation, there are many other biological processes that occur in bioretention systems. There is 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). 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 mycorhizzal 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), thus extending the rhizosphere. As a result, crops inoculated with mycorhizzal fungi have twice the level of tissue P in nutrient poor situations. Macroinvertebrate ingestion and excretion activities typically transform more labile nutrient forms into increasingly refractory forms (Atlas and Bartha, 1998). By providing aeration which improves habitat for microorganisms, plant roots promote biological retention of nutrients (Davis et al., 2001). Vegetation also has considerable effects upon iron complexes in the media.

In the case of P retention mechanisms, plant uptake of P in tropical treatment wetlands is generally only a portion of the input nutrient load (Greenway and Wolley, 2001). Given an event P load of 0.50 mg-l^{-1} applied to a 20m annual hydraulic load, bioretention facilities receive approximately 10.0 g-P-m^{-2}-y^{-1}. However, P uptake in crops varies from 0.9 to 2.23 g-P-m^{-2}-y^{-1} (Flaten et al, 2003) a value an order of magnitude less than bioretention loading rates.

P uptake by soil microbes can be substantial. In highly reactive tropical clay soils, Olander and Vitousek (2004) 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, this high proportion of microbial P uptake did not persist 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).

The preceding thus suggests that plant uptake and microbial immobilization processes account for only a fraction of the retention of P observed in our experiments. Therefore, it falls to geochemical processes such as adsorption and/or precipitation of PO_4-P 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 (eg. 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).

In addition to adsorption, precipitation occurs as cation-P complexes are directly precipitated out of solution. Since many precipitation reactions are largely irreversible, they represent a permanent sink for PO_4. The kinetics of precipitation reactions are slower than the adsorption reactions, so retention times in the range of at least several hours are necessary for them to occur.

Our observation that barren sand performs better than barren loam contradicts the expectation that higher P-sorption would be found for the loam. The sand has a fairly high iron content (1.6%) so outer sphere reactions would occur effectively, at least until the outer sphere binding sites become saturated. On the other hand, it is likely that the loam media is already phosphorus enriched, thereby having a relatively poor retention performance by itself.

However, while PO_4-P retention remained high in the second run from the sand mesocosms, there was a notable increase in effluent concentrations of total P. Assuming the difference between total P and PO_4-P is mostly organic P, it is likely that this component is less subject to sorption processes, and more subject to uptake and immobilization, factors which would be less effective in the sand in the second run, once the initial nutrient deficiency was satisfied. Indeed, there was no significant trend of P saturation in the second run in the loam media (see Figure 2); suggesting biological activity in the loam mesocosms, whether vegetated or not, is high enough to retain organic P. The loam mesocosms had substantially more organic matter content in the profile than sand mesocosms (Henderson, pers. comm.).

In contrast to its effects on organic P, the effect of vegetation on PO_4-P retention is very substantial in the loam mesocosms, with vegetated mesocosms retaining an order of magnitude more PO_4-P than the barren mesocosms (Figure 1). Our dosing runs on the same mesocosms thus replicate the results of Henderson et al (2006) showing that the presence of vegetation has a pronounced effect to promote PO_4-P retention under typical bioretention nutrient loads. Since the retention effect of vegetation is less obvious on the organic P component, total P retention in vegetated loam mesocosms is three to four times that of barren mesocosms (Figure 2).

It is clear that biological retention processes cannot account for the magnitude of P retention, where loading rates far exceed uptake/immobilization rates. This is seen in the case of the second run, where P-retention remained substantial at loading rates of 20 $g\text{-}P\text{-}m^{-2}\text{-}y^{-1}$. Somehow vegetative systems provide a remarkable ability to temporarily retain applied PO_4-P for eventual sequestration in the geochemical pool. The mechanisms by which plants improve the initial sorption of and long-term retention of P by bioretention media are of critical importance. By obtaining a better understanding of the processes occurring within the media, it is hoped that theses mechanisms of long-term P retention can be better elucidated.

In the case of N, nitrate N is essentially unaffected by media adsorption and passes through the soil profile without attenuation (Davis et al 2001). On the other hand, ammonium can be bound to outer sphere complexes, where much it is unavailable (Brady, 1990). Organic N is found in both particulate and dissolved fractions. Labile particulate organic N can be mineralized into ammonium between storm events. Concurrently, some of the ammonium is volatilized, some is adsorbed, and the rest is nitrified. The resulting nitrate is then rapidly taken up by the plants. As such, these forms of N interact in complex ways within bioretention systems.

To examine these N responses, comparison of loading and uptake rates in a typical bioretention facility at 3.5 $mg\text{-}l^{-1}$ suggests a loading rate of 70.0 $g\text{-}N\text{-}m^{-2}\text{-}y^{-1}$. Treatment wetland plants have been reported to take up from 51 $g\text{-}N\text{-}m^{-2}\text{-}y^{-1}$ (Kadlec and Knight, 1996), to as high as 61 $g\text{-}N\text{-}m^{-2}\text{-}y^{-1}$ in tropical wetlands under tertiary effluent loads (Greenway and Wooley, 2001). However, such uptake rates are not likely in intermittently loaded bioretention systems in temperate or subtropical climates. Therefore, as in the case of phosphorus, plant uptake alone does not seem responsible for the observed N-retention.

N-retention also occurs as microbial immobilization in the soil profile. A 100-year simulation projects sequestration rates in which soil organic N (ON) doubles in the first 30 years under N loads approaching that applied to bioretention systems (Qian et al, 2003), with initial soil N sequestration rate of 6.6 $g\text{-}N\text{-}m^{-2}\text{-}y^{-1}$. However, even when taken together, microbial immobilization and plant uptake still do not seem to account for the N retention that has been observed in our experiments.

Our experiments confirm the findings reported for NO_x retention by Henderson et al (2006) for barren mesocosms, in which there was negative NO_x retention (−154 to −291%). These results follow the trends in nitrate retention reported in Davis et al (2001). NO_x retention in barren mesocosms is either very low or negative (Figure 3). The increased export in the second run could be due to several factors. On one hand, the initial nutrient deficient status in the first run would favour relatively high uptake rates compared to the second run, while inter-event nitrification of organic N left over from the first run would increase nitrate concentrations in the second run.

Without plants, the accumulated nitrate is then flushed out in the next event. However, with vegetation present, retention of NO_x is considerably greater. While there was no significant effect in retention by sand due to vegetation in the first run, there was a significant increase in retention in the loam to 64%. While not as high as the 93% retention of NO_x reported for vegetated loam mesocosms in Henderson et al (2006), this is a similar trend. Although there was a significant decrease in retention in the sand and loam without vegetation in the second run, there was a significant increase in retention in the vegetated sand. This may be partially due to the increased retention time provided by the constricted outlets.

The results for organic N are almost the inverse of that seen for NO_x, supporting the concept that residual organic N is nitrified to NO_x between events. There was a beneficial effect of vegetation, but it was not highly significant. However, as in the case of NO_x, there was a significant increase in retention for the vegetated sand in the second run. Since there was no corresponding change between runs in the vegetated loam, this suggests that this improved retention in the sand may also be due to the increased retention time provided by the constricted outlets.

Given the preceding, it is not surprising that total N retention was substantially affected by vegetation and retention time. There was no change in retention between runs in the sand alone (average 28%), while there was a significant increase in retention in the vegetated sand in the second run, increasing from 41% to 61% when retention time was increased by constricting the outlets. Loam by itself was more effective than sand (45% average retention), but vegetation increased retention to 80% in loam mesocosms. This finding is similar to Henderson et al (2006) where vegetated loam mesocosms provided 77% retention. However, our experiments did not show as high retention in the vegetated sand mesocosms, nor was there as low retention in barren loam mesocosms.

Our experiments indicate that considerable total N retention can be provided by bioretention systems. The typical literature value for TN retention is in the range of 40%, while our experiments suggest TN retention can be substantially higher, and furthermore, that longer retention times will improve TN retention in rapidly draining media. These values substantially exceed N uptake and immobilization rates. As such, this suggests that other pathways for N loss, primarily denitrification, are also likely to be involved.

The denitrification literature documents that reduced conditions suitable for denitrification occur in many ostensibly aerobic conditions. Even though overall saturation status is often low, intermittent saturation results in a temporary low redox potential. Reduced conditions favorable for denitrification occur in localized areas with high respiration (high oxygen demand), even when overall saturated conditions do not occur. This is due to the fact that anoxic zones are formed by microbial activity in the soil aggregates (Parkin, 1987) The denitrification activity is most pronounced in the drying phase of wetting and drying cycles (Groffman and Tiedje, 1988). Given the presence of available carbon sources due to plants found throughout the profile (Henderson, pers. comm.), and a plentiful source of nitrate, it is thus likely that substantial denitrification seems to occur in bioretention systems. Between direct uptake, rhizosphere development, and the provision of carbon, these factors appear to be the main reason why bioretention systems with plants have much higher nitrate retention than systems without plants.

This discussion highlights the importance of plants in N and P retention. 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 stormwater bioretention technologies.

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