Bioretention gardens for improved nutrient removal

Mark T. Randall and Andrea Bradford

ABSTRACT

Bioretention gardens are stormwater management practices capable of providing numerous water quantity and quality benefits. However, previous studies have reported inconsistent removal of nitrogen and phosphorus in these systems. This study used ten, vegetated, mesoscale (0.20 m^3), bioretention cells in a field setting to provide a comparison of the nutrient removal capabilities of five, alternative bioretention designs. Applying a synthetic stormwater to the bioretention cells demonstrated that a sandy soil mix can provide a 75.5 and 53.4% reduction in concentrations of total phosphorus and total nitrogen, respectively. Phosphorus removal was found to be only slightly enhanced in bioretention cells where soil was amended with alum-based drinking water treatment residuals, a commercially available oxide-coated media, or a commercially available lanthanum-modified bentonite product. However, improvements in phosphorus removal were observed in some cells when elevated phosphorus loads were applied to evaluate longer term performance. In cells incorporating a permanently saturated zone containing shredded newspaper to promote denitrification, effluent concentrations of nitrate were reduced by >99%, however total nitrogen concentrations increased.

Key words | anoxic, bioretention, low impact development, nitrogen, phosphorus, stormwater

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INTRODUCTION

The bioretention garden is a low impact development (LID) stormwater management practice capable of mitigating runoff volumes, reducing peak flows, transforming and sequestering pollutants and providing aesthetic appeal in urban areas. Numerous studies have been conducted showing high removal efficiencies of pollutants including: nutrients, metals, oil and grease, and pathogens (Davis *et al*. 2001; Hsieh & Davis 2005; Davis 2007; Hsieh *et al.* 2007a; Hathaway *et al*. 2008; Hunt *et al*. 2008). However, other studies have indicated leaching of phosphorus and/or nitrogen from bioretention systems (Dietz & Clausen 2005; Hunt *et al*. 2006; Toronto & Region Conservation Authority 2006; Denich 2009). Identifying bioretention designs which can reliably remove a high percentage of nutrients from stormwater is a necessity as eutrophication of surface waters remains a high priority water quality challenge.

Hunt & Lord (2006) specified a bioretention soil mix consisting of 85–88% sand, 8–12% fines (i.e. clay and silt) and 3–5% organics intended to provide adequate drainage, reduce pollutant levels and support plant growth. This soil specification is recommended in bioretention design guidelines including those published by the Toronto and Region Conservation Authority and Credit Valley Conservation Authority (2010) and has become commonly used in Southern Ontario. The low percentage of organic matter (OM) in this mix relative to previous mixes reduces the potential of nutrient leaching, however there is minimal data published on potential nutrient removal achieved in bioretention gardens using this mix.

In addition to testing alternative bioretention mixes, some studies have investigated bioretention soil amendments capable of improving phosphorus retention. Some of the materials tested include: steel wool (Erickson *et al.* 2007), fly ash (Zhang *et al*. 2008) and alum-based drinking water treatment residuals (Al-WTRs) (Lucas & Greenway 2010). Bachand & Heyvaert (2005) suggested that Phoslock,

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a product typically added directly to eutrophied surface waters may also be suitable as an amendment to increase phosphorus removal in stormwater practices. There are also commercially available oxide coated media such as Sorbtive Media (Imbrium Systems Inc., Toronto, ON) now available which are designed specifically to remove phosphorus from stormwater.

To improve nitrate removal, there have been attempts to promote microbial denitrification in bioretention gardens using a design where a portion of the bioretention soil remains saturated (Kim *et al*. 2003; Dietz & Clausen 2006; Hsieh *et al*. 2007b; Ergas *et al*. 2010). Soil saturation is typically achieved by the use of an elbow in the underdrain which prevents the stormwater from draining until a certain portion of the soil column is saturated. This creates anoxic conditions, allowing denitrification to occur. An organic carbon source is required to act as an electron donor to sustain the denitrification process. Of the numerous organic carbon sources tested by Kim *et al*. (2003), the best NO_3-N removal was achieved using shredded newspaper. Although shown to be an effective design for improving NO_3-N removal, the effects of an anoxic zone on other contaminants, including phosphorus, requires further investigation. Clark & Pitt (2009) found that in soils with high organic content, maintaining an aerobic environment is necessary to prevent the release of phosphorus. It is therefore crucial to investigate in greater detail the effect that an anoxic zone would have on phosphorus removal in bioretention gardens.

Laboratory column studies have been used to test the effectiveness of saturated zones on nitrate removal (Kim *et al*. 2003) and various filter media on phosphorus sorption (O'Neill & Davis 2011). More recently, mesocosms and pilot studies in outdoor settings have tested bioretention designs targeting nutrient removal (Ergas *et al*. 2010; Lucas & Greenway 2010). However, additional studies incorporating important bioretention elements such as vegetation and microbes associated with the soil and root system are needed to further refine these studies. In a review of bioretention literature, Davis *et al*. (2009) highlighted the need for research into bioretention media composition and the control of subsurface redox conditions. Roy-Poirier *et al*. (2010) suggested that a thorough investigation of bioretention modifications intended to improve nitrification, denitrification, and phosphorus sorption processes should be conducted to improve designs and identify any impacts on the removal of other pollutants. Dietz (2007) identified the export of phosphorus from vegetated practices as one of the priority research needs in the field of LID. The study described in this paper aimed to address these research needs by evaluating the nutrient removing capability of a variety of bioretention designs in a field setting.

METHODS

Mesocosm assembly

Field experiments were conducted from May through November 2010 at the Hilton Centre Nursery on the University of Guelph campus in Guelph, Canada. In these experiments, bioretention cells contained in rain barrels, referred to as mesocosms, were used to replicate full size bioretention gardens. Each of the five bioretention designs tested was constructed in duplicate, for a total of ten mesocosms. Each mesocosm was constructed from a rain barrel with the tapered top section removed. All ten mesocosms were assembled side by side on top of a 40 cm high wooden stage in order to facilitate drainage, plumbing and water sampling. A photograph of the constructed mesocosm setup is shown in Figure 1. Figures 2(a) through (e) are schematics showing design details of each mesocosm.

A 20 mm hole was drilled near the bottom of each mesocosm and fitted with plastic tubing to allow the effluent to drain by gravity through a hose and into a covered collection container below. Two of the mesocosms designed to have an anoxic zone, had an alteration of this configuration in which the drainage tube was run through a bracket located 37 cm from the bottom of the mesocosm before entering the effluent container so that the bottom half of the soil column would remain saturated between stormwater loadings (Figure 2(b)). A wooden support frame built around the setup allowed a plastic container to be mounted 40 cm above each barrel. Four 2 mm diameter drainage holes were drilled in the bottom of these containers to allow synthetic stormwater to drip evenly over the bioretention mesocosms. A 12 cm thick layer of 6 mm diameter gravel at the bottom of each mesocosm prevented the outlet at

Figure 1 | Photograph of constructed bioretention mesocosms.

the bottom from clogging with sediment. Bioretention media was placed in the barrel, on top of the gravel and compacted with a hand held tamper after each 10 cm lift of media was added, until a depth of 50 cm of media (equivalent to approximately 100 L) was reached. The diameter of each barrel was 50.2 cm, giving each of the mesocosms an exposed surface area of 0.20 m^2.

Bioretention media

The first two mesocosms constructed (designated M1 and M2) contained a sandy soil mix based on the specifications of Hunt & Lord (2006). Two different truckloads of this sandy soil mix were obtained in order to construct all the mesocosms. Although both truckloads were ordered to the same specification, it was discovered after mesocosm construction that the added OM used in each load was not identical. The soil from the first truck load contained OM consisting of mostly composted wood/bark and will be referred to as Base Mix A. The soil from the second load contained OM consisting of primarily food waste and will be referred to as Base Mix B.

The remaining four soil treatments consisted of the either Base Mix A or B and one of the amendments to be tested. The amendments included: shredded newsprint, a lanthanum-modified bentonite product designed for direct application to surface waters (i.e. Phoslock), alum-based drinking water treatment residuals (i.e. Al-WTRs), and an oxide-coated media designed for use in stormwater best management practices (i.e. Sorbtive Media). As recommended in Kim *et al*. (2003), anoxic mesocosms (designated M3 and M4) were built with a layer of soil overlying a layer of soil mixed with shredded newsprint. Newsprint was shredded into long thin strands (200 cm × 1 cm) using a paper shredder. For the Phoslock mesocosms (designated M5 and M6) and Al-WTR mesocosms (designated M7 and M8), soil and amendments were weighed out separately and then dry-blended (in the proportions shown in Figure 2) with a shovel until they were uniform in appearance. The Al-WTR used in the mesocosms was obtained from the water treatment plant in cakes approximately 20 mm thick and 100–300 mm in diameter, then broken up with a shovel into pieces <10 mm in diameter before being mixed with the sandy soil. As recommended by the manufacturer (Imbrium Systems, Toronto, ON), Sorbtive mesocosms (designated M9 and M10) consisted of a soil layer overlying a layer of the Sorbtive Media (ASTM C33 Standard Specification).

Vegetation

Vegetation is an important component of the bioretention system because it reduces stormwater effluent volumes through evapotranspiration, mitigates the effects of clogging, uptakes nutrients and facilitates biogeochemical processing. Each mesocosm was planted with locally available plants suitable for bioretention areas in Ontario. The plant species (see Table 1) were selected to meet the criteria required for northern climate bioretention gardens (i.e. plants which can tolerate well drained sandy soils, periodic inundation, cold winters and some degree of salt). All mesocosms were planted with one of each of the species, along with its potting soil (approximately 1.5 L per pot). A 3 cm layer of shredded hardwood mulch was spread on top of the

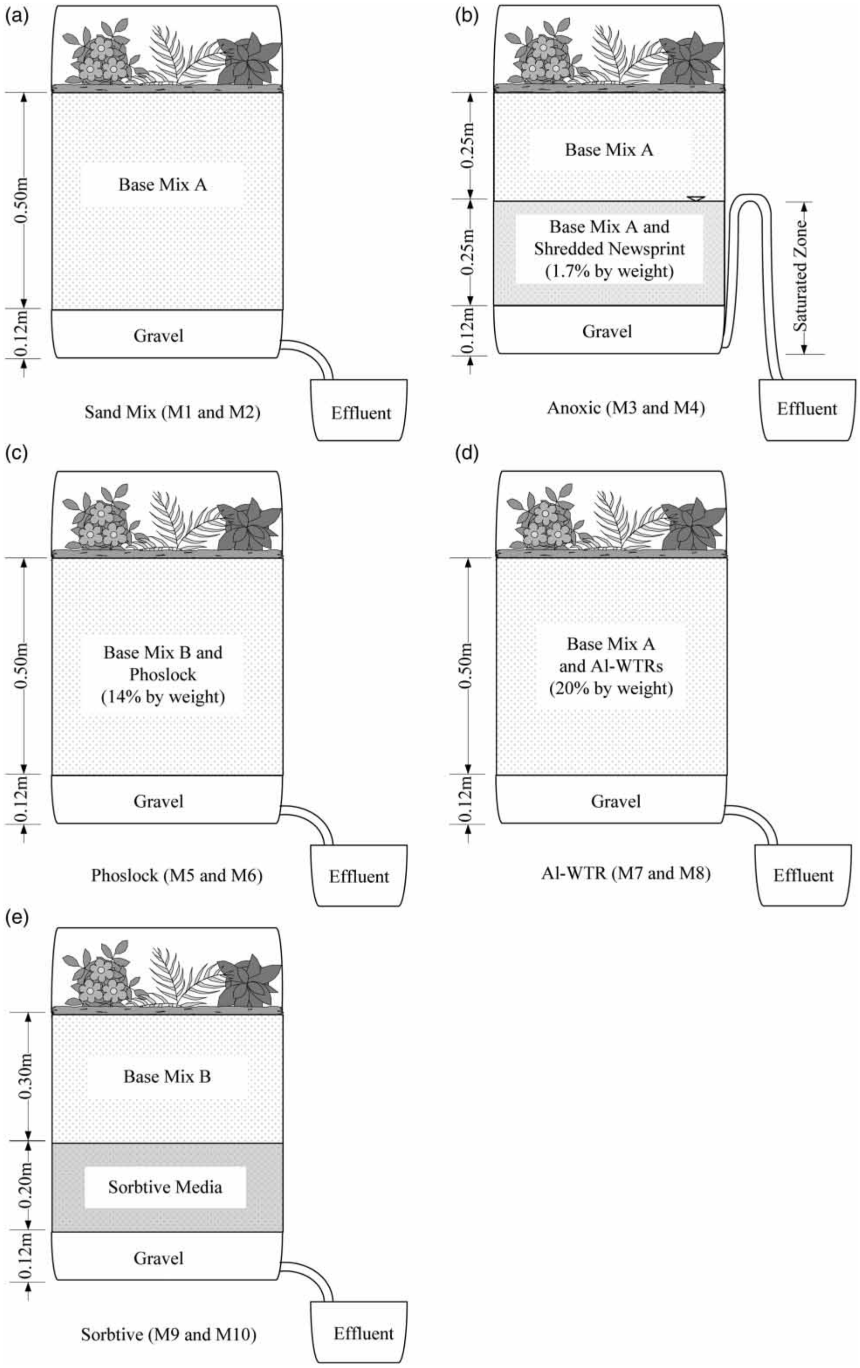

Figure 2 | Schematics of bioretention mesocosms.

media and around vegetation in each mesocosm. For the first four weeks after vegetation was planted, the mesocosms were each watered every two to three days to allow the plants' root systems to become established before the stormwater application began. Previous studies have emphasized the essential role played by plants in the removal of nutrients in bioretention systems (Lucas & Greenway 2008, 2011). However, the current study focuses on the

Table 1 | Vegetation planted in bioretention mesocosms

Common name	Botanical name
Sea Thrift	*Armeria maritima* 'Splendens'
Pandora's Box Daylily	*Hemerocallis* 'Pandora's Box'
Silver Mound Wormwood	*Artemisia schmidtiana* Silver Mound

bioretention media and has assumed that the effects of the vegetation will be the same in each mesocosm.

Stormwater application

A synthetic stormwater was prepared in the field by combining a concentrated solution of chemicals and 220 L of well water in a plastic barrel. The mass of chemicals added to each batch was based on the bioretention experiments described by Davis *et al.* (2001). The resulting synthetic stormwater nutrient concentrations are summarized in Table 2. These nutrient concentrations are within the ranges reported by urban runoff characterization studies (Bannerman *et al.* 1993; Lee & Bang 2000).

The average yearly rainfall for Guelph, ON during the time period 1971 to 2000 was 923 mm, based on data from the Guelph Arboretum monitoring station (ID# 6143069) (Environment Canada 2009). Using the assumptions that 85% of precipitation becomes runoff and the ratio of urban drainage area to bioretention area is 14:1, each mesocosm (with surface area of 0.20 m^2) was required to accommodate an average of 21 cm of stormwater per week. To simulate these average loading rates, 41 L of the synthetic stormwater was added weekly to the stormwater applicator container mounted above each mesocosm. The holes in the bottom of each applicator container allowed the stormwater to drip onto the mesocosm below within a period of 2.5 hours. Every second week, 24 hours after stormwater application began, samples from the effluent collection vessel were collected in 500 mL bottles and stored at 4 °C. Phase 1 of the research involved loading the mesocosms with synthetic stormwater as described above for a period of 10 weeks.

Immediately following Phase 1, a concentrated stormwater application period of 6 weeks (i.e. Phase 2) was used to provide an indication of the long term nutrient removal potential of the mesocosms. On odd numbered weeks during Phase 2, the 41 L of stormwater added to each mesocosm was 104 times more concentrated than the previously used stormwater to simulate 2 years' worth of nutrient loading in a single application. On even numbered weeks, the mesocosms were doused with normal synthetic stormwater, as in Phase 1. Effluent water was collected and analyzed only during these even numbered weeks. During this 6-week period of concentrated loading, the mesocosms were exposed to approximately 6 years' worth of nutrient loads. Due to the time required for microbial growth and some geochemical processes to occur, a concentrated stormwater applied to a bioretention cell in a short period of time is not equivalent to a lower concentration of pollutants applied over a long period of time. However, in lieu of a long duration study, this method of concentrated loading can provide an indication of relative long term performance and has been used in previous mesocosm studies to simulate pollutant loading over many years (Lucas & Greenway 2008). In contrast with Lucas & Greenway (2008), this study did not include rinses between accelerated loadings.

Soil analysis

Grain size analysis of the bioretention base soil mixes was performed at the University of Guelph Engineering Soils Lab (Guelph, Ontario, Canada). A sample of the soil was sent to Guelph Laboratory Services (Guelph, Ontario,

Table 2 | Chemicals added to 220 L of water in mixing barrel to produce synthetic runoff

Pollutant	Compound to be added	Mass of chemical added (g)	Resulting concentration (mg/L)
Nitrate	Sodium nitrate (NaNO3)	2.67	2.91 ± 0.15
Total Kjeldahl nitrogen	Glycine (NH_2CH_2COOH)	4.72	2.82 ± 0.85
Phosphorus	Dibasic sodium phosphate (Na_2HPO_4)	0.60	0.568 ± 0.072

Canada) for testing of OM, cation exchange capacity (CEC), phosphorus (P), nitrogen (N), pH, and metals (Al, Cu, Fe, Mn, Ni, Pb). The laboratory methods and detection limits for the various soil analyses performed are summarized in Table 3. The grain size and OM content results and the chemical analysis results for the base mix soils are presented in Tables 4 and 5, respectively.

Water analysis

Temperature, pH and electrical conductivity of mesocosm influent and effluent were measured in situ at the time of sample collection using a portable Accumet meter model AP85 (Fischer Scientific, Pittsburgh, Pennsylvania), with resolution of 0.01 pH, 1 μS and 0.1 °C, respectively and accuracy of ±0.01 pH, ±1 μS and ±0.5 °C, respectively. Redox potential was measured using an Oakton (Vernon Hills, IL, USA) ORPTestr 10 portable meter with a resolution of 1 mV and an accuracy of ±2 mV. During each sampling event, one full 500 mL sample bottle from each mesocosm was taken to an accredited laboratory (Guelph Laboratory Services, Guelph ON) where water was analyzed for orthophosphate (PO_4-P), total phosphorus (TP), nitrate nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N) and total Kjeldahl nitrogen (TKN) according to standard methods as summarized in Table 6. Although no metals were added to the synthetic stormwater influent, effluent was tested for metals for one of the sampling events (August 13, 2010) to determine if there was any indication of metals leaching from the soil treatments. Results below detection limits were replaced with the detection limit for the calculation of all statistical parameters. Removal efficiencies of all nutrient species were calculated

Table 3 | Analytical methods and detection limits for soil parameters tested

Parameter	Analysis method	Detection limit (units)	
CEC	Barium chloride	1	(cmol + /kg)
OM	Walkley-Black	0.1	(% dry)
pH	Saturated paste		–
Phosphorus	Mehlich-III	0.85	(mg/kg)
Nitrogen	LECO FP 428	0.05	(% dry)
Al	ICP, E3073	2.3	(μg/g dry)
Cu	ICP, E3073	0.6	(μg/g dry)
Fe	ICP, E3073	17	(μg/g dry)
Ni	ICP, E3073	1	(μg/g dry)
Pb	ICP, E3073	2.5	(μg/g dry)

Table 4 | Grain size and OM analysis of soil mixes

	Mass (%)		
Parameter	Base mix A	Base mix B	Hunt & Lord (2006) specification
Gravel, retained on No. 4 Sieve	0.7	4.7	0
Sand, retained on No. 200 Sieve	87.0	84.1	85–88
Fines, retained in pan	4.7	3.9	8–12
OM	4.7	5.2	3–5

Table 5 | Chemical analysis of soil mixes

Parameter	Units	Base mix A	Base mix B
CEC	cmol + /kg	23.8	22.5
pH	pH	7.7	7.5
P	mg/kg	49.9	79.6
N	mg/kg	2.8	2.9
Al	g/kg	9.9	12
Cu	mg/kg	13	21
Fe	g/kg	14	18
Ni	mg/kg	20	29
Pb	mg/kg	9.2	14

Table 6 | Analytical methods and detection limits for water parameters tested

Parameter	Analysis method	Detection limit	
NH_4-N	4500-NH3F	0.007	mg/L
NO_3-N	4500-NO_3F	0.002	mg/L
NO_2-N	4500-NO2B	0.001	mg/L
TKN	Sulphuric digest, read colorimetrically	1.0	mg/L
TP	Sulphuric digest, read colorimetrically	0.05	mg/L
PO_4-P	Total Reactive, 4500-P	0.05	mg/L
Al	3120B	0.02	μg/L
Cu	3120B	0.001	μg/L
Fe	3120B	0.004	μg/L
Ni	3120B	0.01	μg/L
Pb	3120B	0.04	μg/L
Zn	3120B	0.002	μg/L

for each sampling period using the influent and effluent sample concentrations for that period with the following equation:

$$R = \frac{C_i - C_e}{C_i} \times 100\% \quad (1)$$

where R is the removal efficiency, C_i is the influent concentration and C_e is the effluent concentration. This method of calculating a concentration-based removal efficiency has been used in previous studies (Davis *et al.* 2001, 2006; Hunt *et al.* 2006). However, other studies (Dietz & Clausen 2005; Hunt *et al.* 2006; Hsieh *et al.* 2007a) have reported mass-based removal efficiencies. In this study, concentration-based removal efficiencies will always be smaller than mass-based removal efficiencies due to some influent volume being lost to evapotranspiration. The concentration-based removal efficiency and effluent concentrations are reported in this paper. Approximately 30–35 L of the 41 L applied was recovered in the effluent collection vessels after each 24-hour period, depending on the antecedent conditions of the soil. Rainfall was not measured, however each of the adjacently positioned mesocosms would have received the same rainfall volume. It should be noted that the removal efficiencies reported in this study may only be applicable to situations where the incoming stormwater has nutrient concentrations similar to those in the synthetic stormwater used in this study, as recent research suggests that removal efficiencies may vary greatly depending on influent concentrations (McNett *et al.* 2011).

RESULTS AND DISCUSSION

Hydraulic performance

The Anoxic and Phoslock mesocosms often required the full 24 hours to drain the majority of applied stormwater, whereas all other mesocosm treatments typically drained within one hour after stormwater application was complete. The Anoxic and Phoslock mesocosms were not sampled during one scheduled sampling event during Phase 1 because the majority of applied stormwater had not yet drained even after 24 hours. In Phase 2, one Anoxic and one Phoslock sample were missed, again due to incomplete drainage. Although evaluation of hydraulic performance was not a focus of this study, it is worth noting that these two configurations may have relatively poor hydraulic performance if constructed as described in this study. The Anoxic and Phoslock mesocosms frequently had several centimeters of water ponded on their surfaces hours after the other mesocosm treatments had drained. Poor hydraulic performance can cause much of the runoff to bypass the bioretention system, leading to poor water treatment performance.

Phase 1

Redox potential and pH

Mean mesocosm effluent pH and Eh are presented in Table 7. Mean influent pH and Eh were 7.30 ± 0.19 and 64.0 ± 20.5 mV, respectively. The pH remained near a neutral value of 7 in all influent and effluent throughout the monitoring period. Mean Eh measured for the Sand Mix, Al-WTR and Sorbtive mesocosms ranged from 84.4 to 97.8 mV. The Phoslock mesocosm effluent had a much lower mean (−42.8 mV) and higher standard deviation (±70.9 mV) compared with the effluent from all other mesocosms.

Leaching of metals

Metal oxides associated with some amendments (i.e. Sorbtive Media and Al-WTRs), as well as potential effects of a saturated anoxic zone on metal mobilization prompted the analysis of metal concentrations during one of the sampling events. Results from this sampling event are shown in Table 8. Except for Fe and Mn which were always higher in effluent than in influent, none of the metals showed signs of leaching, at the detection limits used. The

Table 7 | Summary of mean mesocosm effluent pH and Eh

Bioretention treatment	*n*	pH	Eh (mV)
Sand Mix	10	7.18 ± 0.18	84.4 ± 21.7
Anoxic	8	7.12 ± 0.22	52.0 ± 31.4
Phoslock	10	7.03 ± 0.21	-42.8 ± 70.9
Al-WTR	10	7.32 ± 0.19	85.8 ± 21.2
Sorbtive	10	7.01 ± 0.21	97.8 ± 23.7

Table 8 | Summary of mean metal concentrations in effluent

		Mean mesocosm effluent concentration (mg/L)				
Metal	**Influent (mg/L)**	**Sand mix**	**Anoxic**	**Phoslock**	**AL-WTR**	**Sorbtive**
Al	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020
Cu	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Fe	0.028	0.275	10.3	11.2	0.037	0.049
Mn	0.000	0.505	2.9	6.0	0.006	0.335
Ni	< 0.010	< 0.010	< 0.010	0.010	< 0.010	< 0.010
Pb	< 0.040	< 0.040	< 0.040	< 0.040	< 0.040	< 0.040
Zn	0.110	0.006	0.006	0.008	0.008	0.004

Note: ' < ' = indicates concentration was below detection limits.

mesocosms which were frequently saturated and had relatively low redox potentials (i.e. Anoxic and Phoslock) showed the greatest indication of Mn and Fe mobilization. Effluent concentrations of both Fe and Mn were found to be at least five times higher in the Anoxic and Phoslock mesocosms compared to any of the other mesocosms.

It is likely that Mn and Fe were being reduced and mobilized via anoxic respiration, whereas other metals were not. When oxygen supply is diminished specialized microorganisms in the soil have the capacity to use other oxidants for respiration. Electron acceptors which can be used for respiration will generally be favored by soil microbes in the following order: oxygen > nitrate > manganese > iron (Reddy & DeLaune 2008). Based on effluent concentrations from the Phoslock and Anoxic mesocosms, most subsurface nitrate was removed via denitrification. With the preferred electron acceptors (i.e. oxygen and nitrate) depleted, Mn and Fe oxides would have been the next to be used by microbial respirators. When Mn and Fe oxides are used in microbial respiration they are reduced from insoluble Mn^{4+} and Fe^{3+} to soluble Mn^{2+} and Fe^{2+}, very mobile ions which could easily leach from the soil column (Baldwin & Mitchell 2000). Although the more frequently saturated mesocosms monitored in this study were sources of Mn and Fe after initial construction, longer-term studies would be needed to determine if this would continue.

Phase 1 phosphorus removal

The effluent concentrations and removal efficiencies of TP (total phosphorus) and PO_4-P (orthophosphate) during Phase 1 are summarized in Table 9. Mean removal efficiencies were calculated by taking the average of the removal efficiencies calculated for each individual sample. Influent concentrations (± standard deviation) of TP and PO_4-P were 0.568 ± 0.072 mg/L and 0.534 ± 0.069 mg/L, respectively. The relative magnitude of the TP removal efficiencies were in the following order: Sorbtive > Al-WTR > Sand Mix > Anoxic > Phoslock. The relative magnitude of the PO_4-P removal efficiencies were in the following order: Anoxic > Sorbtive > Phoslock > Al-WTR > Sand Mix.

The Anoxic and Phoslock mesocosms which had the poorest hydraulic performance and most frequently saturated conditions also had the highest mean TP effluent concentrations of 0.257 and 0.365 mg/L, respectively. There are several processes associated with the saturation of soils which may explain the higher total phosphorus concentrations in the effluent of these mesocosms. Much of the immobilized phosphorus in soils may be incorporated into Fe-PO_4 compounds or sorbed onto iron oxides (Baldwin & Mitchell 2000). As discussed above, the more reducing conditions in these mesocosms could cause these iron compounds to dissolve, preventing additional phosphorus from sorbing onto or becoming incorporated into these compounds.

The decomposition rate and quantity of OM in the bioretention soil may also explain the relatively high total phosphorus concentrations observed in the effluent from the Anoxic and Phoslock mesocosms. As OM in soil decomposes, phosphorus can be released into soil pore water (Kadlec & Knight 1996). The Anoxic mesocosms contained an additional source of decomposing OM (i.e. the shredded

Table 9 | Phase 1 mean phosphorus and nitrogen effluent concentrations and removal efficiencies

		TP		PO_4-P	
Bioretention treatment	***n***	**Effluent concentration (mg/L)**	**Removal efficiency (%)**	**Effluent concentration (mg/L)**	**Removal efficiency (%)**
Sand Mix	10	0.137 ± 0.044	75.5 ± 8.8	0.080 ± 0.031	84.8 ± 6.6
Anoxic	8	0.257 ± 0.072	54.1 ± 8.7	0.053 ± 0.005	89.8 ± 1.5
Phoslock	10	0.365 ± 0.149	33.9 ± 31.1	0.077 ± 0.049	85.4 ± 9.5
AL-WTR	10	0.120 ± 0.044	78.4 ± 9.0	0.076 ± 0.041	85.3 ± 9.0
Sorbtive	10	0.113 ± 0.045	79.3 ± 10.1	0.055 ± 0.008	89.6 ± 2.2
		NO_3-N		TKN	
Bioretention treatment	***n***	**Effluent concentration (mg/L)**	**Removal efficiency (%)**	**Effluent concentration (mg/L)**	**Removal efficiency (%)**
Sand Mix	10	1.08 ± 0.529	62.7 ± 18.8	1.72 ± 0.50	33.4% ± 29.0%
Anoxic	8	0.020 ± 0.017	99.3 ± 0.55	5.53 ± 3.58	−75.3% ± 91.2%
Phoslock	10	0.057 ± 0.042	98.0 ± 1.44	18.96 ± 7.38	−626.4% ± 304.8%
AL-WTR	10	2.20 ± 0.40	24.5 ± 13.6	2.18 ± 0.50	18.6% ± 22.3%
Sorbtive	10	6.37 ± 1.76	−118 ± 55.6	3.47 ± 5.15	− 9.9% ± 133.2%
		TN			
Bioretention treatment	***n***	**Effluent concentration (mg/L)**	**Removal efficiency (%)**		
Sand Mix	10	2.63 ± 0.67	53.4 ± 13.2		
Anoxic	8	5.55 ± 3.59	8.79 ± 53.9		
Phoslock	10	19.0 ± 7.40	−235 ± 118		
AL-WTR	10	4.38 ± 0.80	23.1 ± 12.7		
Sorbtive	10	9.84 ± 6.14	−67.3 ± 84.0		

newspaper), which may have released phosphorus as it decomposed. Although the Phoslock mesocosms did not necessarily contain more OM, they were constructed using the Base Mix B soil containing the food scrap-based mulch which likely had a faster rate of decomposition compared to the wood/bark-based mulch. In addition, the phosphorus content of Base Mix B was 79.6 mg/kg, considerably more than the 49.9 mg/kg in Base Mix A. Although the Sorbtive mesocosms were also constructed with Base Mix B, the mean TP concentrations in the effluent from the Sorbtive mesocosms were the lowest. This may be partially attributed to its layered configuration (i.e. a 20 cm layer of Sorbtive on the bottom), as well as its rapid drainage.

The Anoxic and Phoslock mesocosms did not lower effluent phosphorus concentrations as much as the other mesocosms because of the reasons mentioned above. However, no mesocosms had higher effluent than influent concentrations of TP or PO_4-P as some previous studies have reported (Dietz & Clausen 2005; Hunt *et al.* 2006; Toronto and Region Conservation Authority 2006; Denich 2009). The TP removal of 75.5% demonstrated by the sand mix mesocosms in this study was comparable to removals reported in some other studies where a basic sandy soil mix was used. Hsieh *et al.* (2007a) used an influent concentration of 3 mg/L of TP and removals ranging from 63 to 85% in columns containing sandy soil with phosphorus contents between 75 and 120 mg/kg. Davis *et al.* (2001) observed a mean TP removal of 81% when stormwater containing 0.44 mg/L TP was applied to a 55 cm deep column of sandy loam.

Mean removal efficiencies of TP and PO_4-P were 78.4 and 85.3% for Al-WTR and 79.3 and 89.6% for the Sorbtive Media mesocosms, respectively, which were very similar to the removal efficiencies of the sand mix (75.5% for TP and 84.8% for PO_4-P). The authors are not aware of any other studies published on the use of Sorbtive Media or Phoslock as bioretention soil amendments for comparison; however one mesocosm study has documented the use of Al-WTRs in bioretention mesocosms. Lucas & Greenway (2010) reported a mass removal of 95 to 99% of PO_4-P during an 80-week period of applying 3.3 mg/L of PO_4-P to mesocosms containing sandy soil and Al-WTRs (20% by weight). The Al-WTR mesocosms in the current study provided a mean concentration reduction of 85.3%, using an influent PO_4-P concentration of 0.534 mg/L.

Phase 1 nitrogen removal

The Phase 1 mean effluent concentrations and removal efficiencies for nitrogen species are summarized in Table 9. The Sand Mix, Anoxic, and Al-WTR mesocosms had less total nitrogen (TN) in the effluent than the influent. However, the Phoslock and Sorbtive Media mesocosms had more TN in the effluent, indicating nitrogen was leaching from these mesocosms. The influent concentrations (± standard deviation) for NO_3-N, TKN, and TN were 2.91 ± 0.15, 2.82 ± 0.85 and 5.64 ± 1.71 mg/L, respectively. In Figure 3, the shaded section of a bar represents the mean concentration of the nitrogen species indicated in the legend, while the total height of each bar represents the mean total nitrogen concentration. Note that the components of TKN (i.e. organic nitrogen and NH_4-N) are shown as separate bars in Figure 3. However, the proportions of organic nitrogen and NH_4-N are

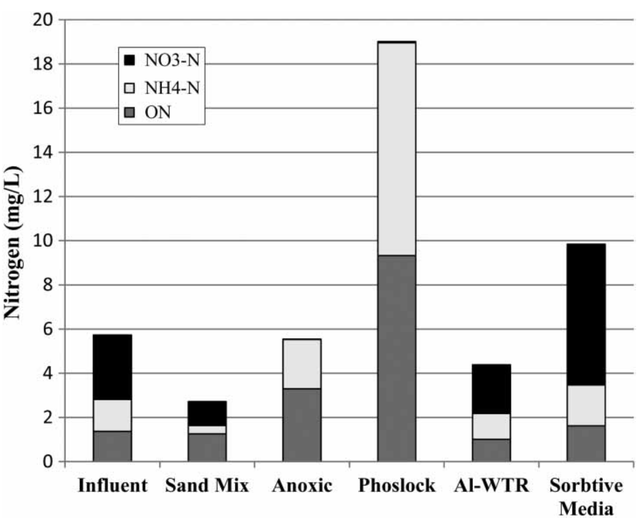

Figure 3 | Mean nitrogen concentrations in mesocosm influent and effluent.

highly variable due to the rapid mineralization and ammonification of glycine.

The Anoxic and Phoslock mesocosms provided the most NO_3-N treatment with removal efficiencies of 99.3 ± 0.5% and 98.0 ± 1.4%, respectively. The high NO_3-N removal efficiencies observed in these mesocosms were likely due to low nitrification rates and high denitrification rates. Nitrification, the transformation of NH_4-N to NO_3-N occurs only in environments with sufficient oxygen present. The more frequently saturated conditions of the Anoxic and Phoslock mesocosms likely suppressed the production of NO_3-N via the process of nitrification. However, denitrification, the transformation of NO_3-N to N_2 gas, occurs most readily in anoxic environments where there is a carbon source present to act as an electron donor. Anoxic and Phoslock bioretention treatments were therefore able to remove a relatively high percentage of the applied NO_3-N due to their frequently saturated, anoxic conditions. The NO_3-N mean removal efficiency of 99.3% observed in the Anoxic mesocosms was somewhat higher than observed in comparable setups. Dietz & Clausen (2006) and Kim *et al.* (2003) reported removals of 87% and 70–80%, respectively, from systems using a similar saturated zone design. The NO_3-N removal efficiency of 62.7 ± 18.8% observed in the Sand Mix mesocosms was also higher than those observed in other bioretentions constructed using a comparable sandy soil. Dietz & Clausen (2005) reported a NO_3-N removal efficiency of 35.4% in a bioretention garden constructed using a native loamy sand. In laboratory bioretention cells, Hsieh & Davis (2005) and Davis *et al.* (2001) reported NO_3-N removal efficiencies of 9–20% and 24%, respectively.

The lowest NO_3-N removal efficiency of −118.0 ± 55.6% was observed in the Sorbtive mesocosms. It is likely that nitrate was leaching from these mesocosms due to subsurface environments which promoted relatively high rates of nitrification and low rates of denitrification. Sorbtive Medium is a coarse sand-based medium which promotes rapid drainage, and contains no OM to help retain water or act as a carbon source. These characteristics of the Sorbtive Media allow for a well oxygenated environment ideal for the transformation of influent NH_4-N to NO_3-N (via nitrification), while the lack of long term saturated pore storage and low organic carbon content are not conducive to the removal of NO_3-N (via denitrification). The result of this high rate of nitrification and low rate of denitrification is effluent with NO_3-N concentrations that are much greater than the influent concentrations.

The TN concentrations in effluent from the Phoslock and Sorbtive mesocosms were higher than the influent concentrations, indicating that more TN was leaving these mesocosms than was entering. The more rapidly decomposing food-scrap-based OM in Base Mix B may have released nitrogen at a faster rate, explaining why both of the mesocosms constructed with this mix had much higher total nitrogen concentrations in their effluent.

The Phoslock mesocosms had the highest mean TKN effluent concentration of 18.96 ± 7.39 mg/L. The frequently saturated, oxygen deprived conditions in these mesocosms did not allow for nitrification (the transformation of NH_4-N to NO_3-N) to occur in the soil column. This result is consistent with the findings of Phillips (1999), who found that NH_4-N concentrations in pore water increased under waterlogged conditions in most soils tested. The other frequently saturated mesocosms (i.e. Anoxic) had the second highest TKN mean effluent concentration of 5.53 ± 3.59 mg/L.

Of all the mesocosm configurations, the Sand Mix had the highest TN removal efficiency. The best option to remove TN may therefore be a plain sandy soil mix with no amendments added and no saturated zone as this design seems to promote the best balance of ammonification, nitrification and denitrification processes. The results from Phase 1 have shown that incorporating a saturated anoxic zone and a carbon source would greatly reduce effluent NO_3-N concentrations, however the TN effluent concentration from such a bioretention design may be higher due to the decomposition of the OM added as a carbon source.

Figure 4 summarizes the findings of Phase 1 of this study. The Sand Mix, Al-WTR and Sorbtive mesocosms behaved like the mesocosm shown in Figure 4(a) (i.e. no permanently saturated anoxic zone was present). In these mesocosms, the processes of ammonification and denitrification allowed for the removal of organic nitrogen and NH_4-N, but the lack of a saturated zone and minimal denitrification did not allow for significant NO_3-N removal. The Anoxic mesocosms behaved like Figure 4(b) (i.e. a permanently saturated anoxic zone was present). In these mesocosms, the anoxic zone allowed nearly all of the NO_3-N to denitrify, however there was not as much capacity for ammonification and nitrification. Although the Phoslock mesocosms were not designed to function as a bioretention with an anoxic saturated zone, very slow drainage caused them to maintain saturated areas much of the time and behave more like Figure 4(b) than Figure 4(a).

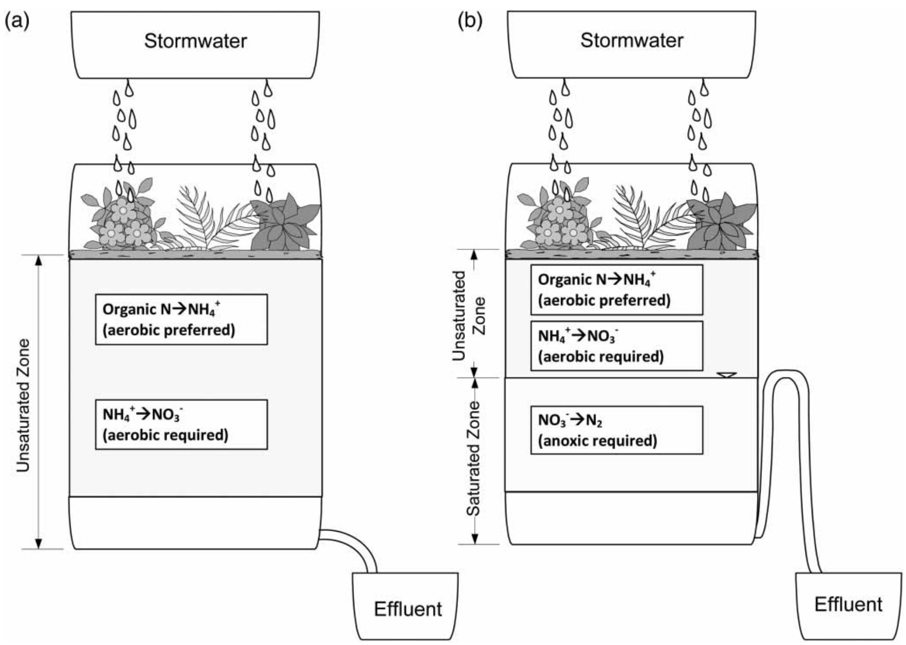

Figure 4 | Schematic of nitrogen transformations in mesocosms.

Phase 2

The results of Phase 2's 6-week-long concentrated loading period are shown in Figures 5(a) through (e) for tested phosphorus and nitrogen species. In these figures, the data points plotted for each soil treatment at 0 years equivalent are averages of the results obtained during Phase 1. The data points plotted at 2, 4, and 6 years equivalent are the effluent concentrations from weeks 2, 4 and 6 of Phase 2.

Phase 2 phosphorus removal

The results from Phase 2 presented in Figures 5(a) and (b) show that the TP and PO_4-P effluent concentrations from the Sand Mix, Anoxic and Al-WTR mesocosms increased after each concentrated loading, while the Sorbtive and Phoslock mesocosms maintained nearly the same effluent concentrations throughout the concentrated loading period. Sorbtive Media and Phoslock amended mesocosms maintained concentrations below or barely above the detection limit of 0.05 mg/L of TP and PO_4-P throughout Phase 2.

The TP and PO_4-P effluent concentrations of the Sand Mix, Anoxic and Al-WTR mesocosms increased over time during Phase 2. During the long term nutrient loading simulation, the Al-WTR amended mesocosms did not consistently outperform the Sand Mix mesocosm in terms of phosphorus removal despite the high sorption capacity as reported in previous studies such as Dayton & Basta (2005). One possible explanation for the performance of the Al-WTR mesocosms is that the Al-WTRs used in the bioretention mesocosms were not broken into sufficiently small grains. Dayton & Basta (2005) demonstrated that the grain size (and therefore exposed surface area) of the Al-WTRs greatly influences the potential P-sorption capacity.

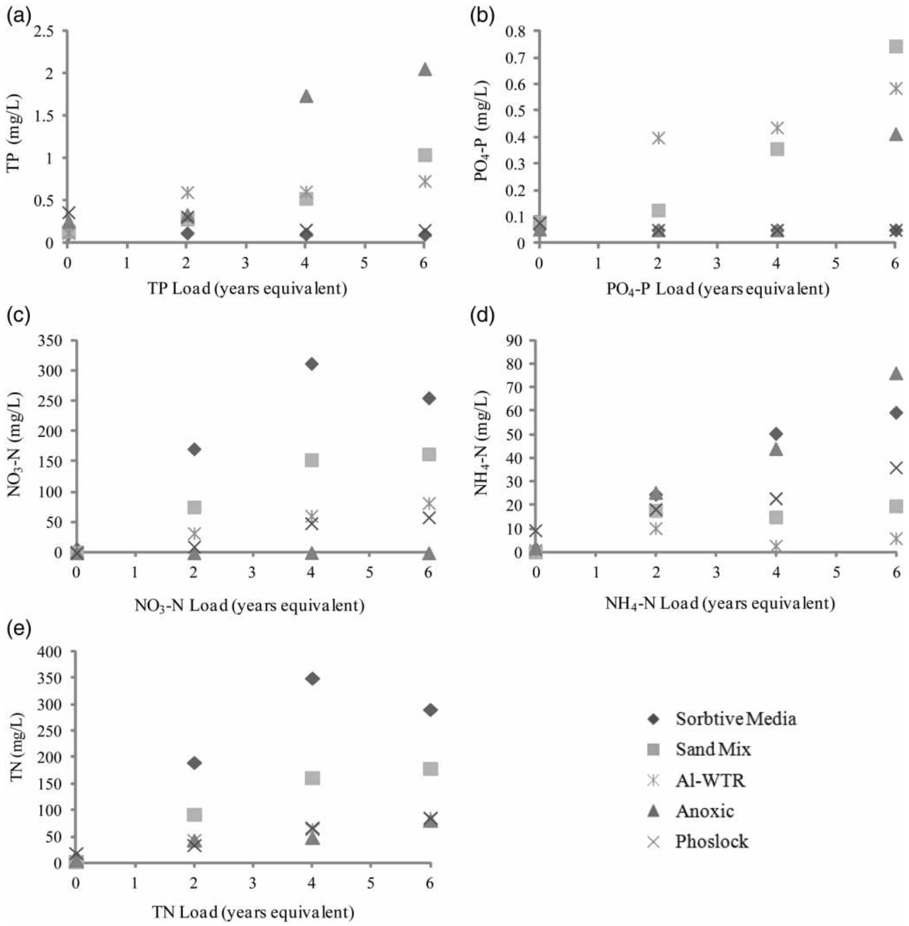

Figure 5 | Mean mesocosm effluent concentrations during Phase 2.

Breaking the Al-WTR cakes apart with a shovel may be insufficient and mechanical crushing to a much smaller grain size could be required to fully utilize the potential sorption capacity of Al-WTRs. It is also possible that over time the Al-WTR pieces may weather and slake apart, exposing more surface area and creating more phosphorus sorption capacity (Dayton & Basta 2005). The creation of additional sorption capacity over time may explain why the Al-WTR mesocosms only began to have lower effluent concentrations than the Sand Mix mesocosms towards the end of the concentrated loading period.

The results from Phase 2 demonstrated that the phosphorus removal provided by incorporating media amendments into bioretention design may only become apparent after the bioretention has been exposed to several years of phosphorus loads and sorption capacity of a basic sandy soil mix becomes exhausted (Erickson *et al.* 2007; Hsieh *et al.* 2007a; Lucas & Greenway 2008).

Phase 2 nitrogen removal

The results from Phase 2 presented in Figures 5(c), (d) and (e) show the effluent concentrations of nitrogen species tested. The relative magnitude of the TN and NO_3-N effluent concentrations throughout Phase 2 were in the following order: Anoxic < Phoslock < Al-WTR < Sand Mix < Sorbtive. The relative magnitude of the NH_4-N effluent concentrations were in the following order: Al-WTR < Sand Mix < Phoslock < Sorbtive < Anoxic.

The results of Phase 2 showed many of the same patterns in nitrogen treatment capabilities as were observed in Phase 1. For example, throughout both Phase 1 and Phase 2, the Sorbtive mesocosms had the highest NO_3-N effluent concentrations while the Phoslock and Anoxic mesocosms had the lowest NO_3-N concentrations. As in Phase 1, the Sand Mix and the Al-WTR mesocosms had intermediate NO_3-N effluent concentrations.

The Al-WTR mesocosms produced effluent with the lowest concentrations of NH_4-N throughout the concentrated loading period, possibly due to NH^{4+} ions in the stormwater becoming adsorbed onto the OM within the Al-WTR. The Anoxic mesocosms had relatively high NH_4-N effluent concentrations during Phase 2, likely due to their low oxygen environment which did not allow for the transformation of NH_4-N to NO_3-N via nitrification. It was unexpected that the Sorbtive mesocosms would also have higher NH_4-N effluent concentrations than most other mesocosms as the subsurface in these mesocosms was believed to have sufficient oxygen to promote nitrification (i.e. the conversion of NH_4-N to NO_3-N). Total nitrogen concentrations of all mesocosm effluent most closely resembled the trends seen in the nitrate results, due to the fact that NO_3-N made up the largest percentage of influent nitrogen.

Nitrogen removal in bioretention systems is provided by a combination of microbially mediated immobilization and turnover, plant uptake, and nitrification/denitrification processes. It is unlikely that the long term removal provided by these processes can be projected by simply increasing applied concentrations. However, the results presented may provide an indication of which bioretention configurations will provide the best relative nitrogen removal in the long term or which are capable of treating higher than typical nitrogen concentrations. For more a comprehensive description of the mechanisms for N retention in bioretention systems and the time scales at which they operate, see Lucas & Greenway (2011).

CONCLUSIONS

The results of this study indicate that bioretention gardens constructed with a sandy soil mix are capable of achieving consistent removal of both nitrogen and phosphorus even when newly established. A 50 cm deep vegetated bioretention garden constructed using a sandy soil, mixed to the specifications given by Hunt & Lord (2006), was found to be capable of reducing concentrations of TN and TP in urban runoff by approximately 54 and 75%, respectively. Designs incorporating various soil amendments were capable of achieving greater nitrogen or phosphorus removal than the basic sandy soil mix. The greatest TP concentration reduction of 79.3% was provided by a bioretention mesocosm containing a layer of Sorbtive Media. The benefits of adding Sorbtive Media may only become apparent after a number of years when the phosphorus sorption capacity of a regular sand mix would become exhausted. Al-WTR provided only modest improvements to phosphorus removal in both the long and short term compared with the Sand Mix; however, better results might be achieved with mechanical crushing of the Al-WTR cakes into smaller particles with a larger surface area for sorption. The Phoslock mesocosms maintained relatively low concentrations of ~0.05 mg/L TP throughout the period of concentrated phosphorus loading, however if this product is to be successfully used as a soil amendment it would need to be used in much smaller quantities than used in this study (i.e. 14% by weight) in order to avoid drainage problems.

Although mesocosms constructed using Phoslock or shredded newspaper demonstrated an ability to remove a large percentage (>98%) of applied nitrate, these materials may not be suitable for use in bioretention gardens as they have the potential to greatly decrease the hydraulic performance of the system. The poor drainage of the Anoxic and Phoslock mesocosms caused prolonged periods of inundation and the reduction and mobilization of oxide forming metals (i.e. Fe and Mn). In terms of total nitrogen removal, the best design was shown to be a basic sandy soil mix with no saturated zone (i.e. the Sand Mix mesocosm). This design seems to provide the best balance of ammonification, nitrification and denitrification processes. A design with a saturated zone may perform better in a system with greater depth, such that a larger aerobic zone can also be maintained.

Results also suggested that the type of OM in a bioretention garden is an important factor in achieving nutrient removal. A rapidly decomposing OM such as one containing food waste may hinder the ability of bioretention media to remove nitrogen and/or phosphorus. More research should be done to identify an ideal OM type and the results incorporated into bioretention soil specifications.

This study has allowed for a relative comparison of the nutrient removal capabilities of five bioretention garden configurations. However, additional research including longer term field studies and pilot systems should be performed to thoroughly evaluate the long term performance of these systems.

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