An Investigation into Bioretention Systems for Management of Urban Runoff and Wastewater

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Aims of Study

BACKGROUND

- Most controlled research on bioretention systems has been restricted to studies of media alone, typically using columns.
- Only limited studies have investigated the effect of the vegetation.
- Of these, most research reports on immature systems (6-18 months).
- Such systems have poorly developed plant/microbial community.
- Even more important, these systems do not even approach media saturation.

AIMS

1. To investigate the effect of bioretention media and vegetation on nutrient retention responses,
2. To investigate the effect of media saturation on nutrient retention,
3. To develop relationships between media composition and vegetation type on nutrient retention.
240 L mesocosm study of well-established systems in Brisbane.
Study design used 6 treatments, with 5 replicates of each.
Systems loaded weekly with treated sewage effluent to accelerate nutrient loading.
Every 6 months, loaded with synthetic stormwater over four weeks to observe nutrient retention at stormwater concentrations.
Study completed, media exhausted with respect to phosphorus retention.

240 L mesocosm study of new systems in Brisbane
Study design used 9 treatments, and 3 replicates of each.
Study in progress, media still effective.
Mesocosms are 240 liter “wheelie bins” with 3 different media treatments:

- 20cm Loamy Sand and 60cm Gravel (or all Gravel)
- 80cm Loamy Sand (4% clay)
- 80cm Sandy Loam (8% clay)

Half of the mesocosms are vegetated with a mix of shrubs and grasses. Other half are barren (all gravel).

Influent is a mix of dissolved inorganic and organic nutrients.

Inflow distributed by a manifold system and regulated by irrigation drippers.

Outflows collected in 3m long chambers of 250mm pipes.
Chambers placed on scales to record flows.

Thanks to Vinidex for the chambers!
Effluent loading: irrigated weekly with ~45cm secondary effluent (=24 m-yr⁻¹).

At concentrations of 4.8 mg-l⁻¹ TP, annual load of 1090 kg-ha⁻¹ represents over ten times typical annual bioretention load of TP.

To account for plant uptake, open inflow column represents inflow net of uptake.

Compared to TP inflow average, gravel rapidly saturated, and sand now saturated, while barren loam still partially effective.

No difference between vegetated and barren in the gravel and sand by the end.

In contrast, vegetated loam provided 91% TP retention at high effluent concentration.

Cumulative effect of vegetation over a year substantially exceeds projected uptake.
Barren sand as good as vegetated in beginning, but then rapidly saturates.
Vegetated sand shows over twice the capacity at saturation.
Stormwater runs “rinsed” sand, increasing capacity in both barren and vegetated.
Barren loam never as good as vegetated loam, capacity less than vegetated sand.
Vegetated loam has twice the capacity of other systems.
Vegetated loam still effective at stormwater concentrations well after other systems are saturated.
After application of 1,090 kg-ha\(^{-1}\) TP in 52 weeks, cumulative retention in the barren media is much less than in the vegetated systems.

The presence of vegetation reduces losses from 317 to 387 kg-ha\(^{-1}\)-yr\(^{-1}\).

These retention values Far exceed terrestrial plant uptake capacity of 63 kg-ha\(^{-1}\)-yr\(^{-1}\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Media Type</th>
<th>Barren Retention</th>
<th>Vegetated Retention</th>
<th>Difference Mass</th>
<th>Difference Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Phosphorus</td>
<td>Uptake</td>
<td>0</td>
<td>63</td>
<td>63</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>160</td>
<td>476</td>
<td>316</td>
<td>29%</td>
</tr>
<tr>
<td>Annual Load</td>
<td>Sand</td>
<td>415</td>
<td>725</td>
<td>311</td>
<td>29%</td>
</tr>
<tr>
<td>1,090</td>
<td>Loam</td>
<td>614</td>
<td>1,000</td>
<td>387</td>
<td>35%</td>
</tr>
</tbody>
</table>
Total phosphorus shows response to media type, with loam initially being worse. Note further reduction in vegetated loam systems.

Halfway through loading runs, gravel and sand exhausted, but retention in vegetated sand still greater than uptake. Surprisingly, vegetated load was less effective.

By end of loading runs, all media saturated and vegetation makes little difference at stormwater concentrations.
NO$_x$ retention in barren systems is negative, nor does it improve as they mature. This is typical behavior in most studies.

However, NO$_x$ retention in vegetated systems greater, especially in the loam. Note that much of this retention seems to be due to uptake.

Retention in the vegetated loam systems gets better as they mature.

This suggests that the stabilized values for NO$_x$ retention can be in the range of 80%.
Nitrogen Response - Effluent

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Media Type</th>
<th>Barren Retention</th>
<th>Vegetated Retention</th>
<th>Difference Mass</th>
<th>Difference Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Oxides</td>
<td>Uptake</td>
<td>0</td>
<td>300</td>
<td>300</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>-79</td>
<td>201</td>
<td>280</td>
<td>46%</td>
</tr>
<tr>
<td>Annual Load 609</td>
<td>Sand</td>
<td>-159</td>
<td>253</td>
<td>412</td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td>Loam</td>
<td>-134</td>
<td>453</td>
<td>587</td>
<td>96%</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>Uptake</td>
<td>0</td>
<td>375</td>
<td>375</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>83</td>
<td>459</td>
<td>377</td>
<td>34%</td>
</tr>
<tr>
<td>Annual Load 1,093</td>
<td>Sand</td>
<td>132</td>
<td>577</td>
<td>444</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>Loam</td>
<td>226</td>
<td>864</td>
<td>638</td>
<td>58%</td>
</tr>
</tbody>
</table>

After application of 1,093 kg-ha\(^{-1}\) TN in 52 weeks, cumulative retention in the barren media is also much less than in the vegetated systems.

With vegetation present, NO\(_x\) losses reduced by 280 to 587 kg-ha\(^{-1}\)-yr\(^{-1}\).

Retention in sand and loam exceeds terrestrial plant NO\(_x\) uptake capacity.

The presence of vegetation reduces TN losses from 375 to 638 kg-ha\(^{-1}\)-yr\(^{-1}\).

Retention in sand and loam exceeds terrestrial plant uptake capacity.
Nitrogen Response—Stormwater

Note substantial reductions in nitrogen oxides (NO\textsubscript{x}) in all vegetated systems compared to barren systems.

NO\textsubscript{x} went down in vegetated systems, even though it increased in the media.

Total N response also shows effect of vegetation.

However, note that uptake in last run could account for all reductions in NO\textsubscript{x} and TN.
Old Mesocosm Findings

- Infiltration/percolation in loam confounded by clogging of underdrain, while remaining high in sand and gravel.
- High percolation rates in sand and gravel reduce retention time needed for processes other than uptake.
- Therefore, N retention in rapidly draining systems is reduced compared to more slowly draining systems.
- N retention in vegetated systems is quite good, especially in the loam systems, and improves over time as the biomass accumulates.
- At stormwater concentrations, barren media become saturated with P within months in the gravel, ~1 year in the sand, and ~2 years in the loam.
- Leaching temporarily restores P retention in barren media.
- However, vegetated media still retain most P, at least until the media is completely saturated.
- At stormwater concentrations, vegetated media become saturated with P within months in the gravel, ~4 years in the sand, and ~6 years in the loam.
Mesocosms are 240 liter “wheelie bins” with 9 different treatments.

- 4 Krasnozem (iron-rich) soil, 2 Red Mud (Bauxite byproduct), and 3 Water Treatment Residual (WTR) replicates. Systems have restricted outlets.
- Systems have 20cm Underdrain, 60cm Media, and 20cm ponding depth.
- One Krasnozem system barren, one WTR system unrestricted.
3 Krasnozem systems: 30% Krasnozems (K30), 10% over 30% Krasnozems (K10-30), and 20% Krasnozems (K20). Latter has barren controls (K20 nv).

K10-30 and K30 systems show more capacity than loam, exceeding 1 mg/l at over 23 g sorbed. (Compare to less than 18 g for loam.)

Since concentrations over 1 mg-l⁻¹ by 23g, second stormwater run “rinsed” systems.

Systems still effective at stormwater concentrations at over 27g. (Compare to no retention in loam at less than 18 g.)
Phosphorus Response

K20 at over 27 g still well under 1.0 mg/l. Barren Krasnozems as good as vegetated in beginning, but saturating faster. Both still better than K10-30 or K30. (?) Stormwater run “rinsed” systems, increasing capacity in barren (but not vegetated). Vegetated K20 effective at stormwater concentrations after barren K20 is saturated.
Red Mud shows opposite trend from saturation. Concentrations decrease as systems mature! Note that 10% Red Mud (RM10) worse than RM6 in beginning, so less sorbed by final stormwater run. Interesting trend.

Even after 26 g sorbed, very low concentrations at stormwater concentrations.

In contrast, WTR systems are very effective throughout so far, with no indication of saturation. Systems are 6 months newer, so not as much applied yet.

WTR systems even more effective at stormwater concentrations. Outflows in range of 0.05 mg·l⁻¹, which is supportive of sensitive ecosystems.
Bioretention Vegetation

- Note how deep the roots extend in all systems.
- Systems increased soil OM from 0.3% to 1.0 to 2.4% depending upon depth and type of system.
The role of plant and microbial biomass seems to be:

1. Temporarily retain ortho-phosphorus within the profile so that media sorption processes can occur over a longer time frame.
2. Provide a carbon source for denitrification to occur throughout the profile in even ostensibly “aerobic” conditions.
Sand systems to continue for clogging experiments.

New mesocosms constructed in January 2007 with media formulated to retain P show excellent P retention.

As vegetation establishes, the N retention performance improving. Now 70%

Systems have very high infiltration/percolation rates. Rates now constricted by elevated outlets, which reduce head.

Washington State University developing experimental setup to replicate aspects of the media and vegetation with pilot scale study.

Study involves 5-6 foot diameter systems, 10 treatments, 4 replicates.

Setup funded and under design.
Acknowledgement:
My sincere thanks to Dr. Margaret Greenway