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Biofilter design for effective nitrogen removal from stormwater – influence of plant species, inflow hydrology and use of a saturated zone

Conception de biofiltres pour la rétention de l'azote des rejets urbains de temps de pluie – l'influence des espèces de plante, de la zone saturée et de l'hydrologie en entrée

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RÉSUMÉ

Il a été démontré par de nombreuses études que les systèmes de biofiltration sont une technique efficace pour le traitement des rejets urbains par temps de pluie. Les paramètres jouant un rôle important sur leurs performances comprennent le type de plantes et la présence d'une zone saturée, avec une source de carbone. Afin de mieux comprendre les mécanismes qui contribuent au traitement de l'azote, cette étude en colonnes a comparé la performance de 22 espèces de plantes différentes ainsi que différents points de sortie (une moitié des colonnes avec un point de sortie élevé afin de créer une zone saturée). La qualité de l'effluent des colonnes a été mesurée, ainsi que la croissance et la morphologie des plantes. Les concentrations des rejets des biofiltres sont présentées pendant des périodes 'sèches' et 'humides'. Toutes les espèces testées ont atteint un rendement épuratoire satisfaisant lorsque le massif était humide, mais les périodes sèches ont provoqué une forte diminution de la performance, renforçant l'importance d'une zone saturée pour maintenir la fonction d'un biofiltre. La zone saturée est également capable de retenir l'eau influente entre deux pluies, mais ce temps de rétention ne semble pas indispensable pour maintenir la performance des espèces les plus performantes. Cette étude a démontré qu'une diversité des plantes dans un biofiltre protège contre la variabilité climatique, et qu'elle contribue à une biodiversité dans la ville.

ABSTRACT

The use of biofilters to remove nitrogen and other pollutants from urban stormwater runoff has demonstrated varied success across laboratory and field studies. Design variables including plant species and use of a saturated zone and carbon source have large impacts upon performance. A laboratory column study of 22 plant species and designs with varied outlet configuration was therefore conducted to further investigate the mechanisms and influences driving biofilter nitrogen processing. Various parameters were measured across a 1.5 year period of stormwater dosing, including effluent quality, plant growth and morphology. This paper presents outflow concentrations of total nitrogen in both 'wet' and 'dry' frequency dosing periods, and results from sampling across two points in the outflow hydrograph. All plant species were effective under conditions of frequent dosing, but extended drying increased variation between species and highlighted the importance of a saturated zone in maintaining biofilter function. The saturated zone also effectively treats the volume of stormwater stored between inflow events. However, this longer retention time was not generally necessary for the concentration reductions demonstrated by the highest performing species. The study shows the importance of biodiversity in protecting against climate variability, while enhancing biodiversity values.

KEYWORDS

Biofilter, Nitrogen, plant species, Stormwater, Water dynamics

1 INTRODUCTION

As a technology for urban stormwater treatment, biofilters can effectively reduce concentrations and loads of nutrients, heavy metals, pathogens and other pollutants in runoff, whilst also providing substantial hydrological benefits to downstream waterways (Hatt et al., 2008; Hunt et al., 2008). However, in the case of some pollutants such as nitrogen, performance can vary from in the order of 70% concentration reduction to net production and leaching (Bratieres et al., 2008; Henderson et al., 2007). Nitrate, as the most mobile form of nitrogen, is particularly susceptible to leaching. Previous studies have identified the biofilter media, presence of a saturated zone, additional carbon source (to augment denitrification rates), and plant species as critical design variables for nitrogen performance (Bratieres et al., 2008; Hatt et al., 2008). Use of a loamy sand media with low organic content, the inclusion of a saturated zone with supplemented carbon source (such as mulch or bark chips) in the lower media layers and selection of plant species with extensive and fine root systems (Fletcher et al., 2007; Read et al., 2010; Zinger et al., 2007a), improve the removal of nitrate and total nitrogen from the stormwater effluent. However, greater understanding of the interaction between design variables and nitrogen processing is necessary to improve biofilter performance, and perhaps more importantly, to make it more reliable.

Read et al. (2008) found wide variation in performance across plant species, and only ten species reduced concentrations of nitrate more than bare soil designs. Performance was correlated to plant morphological characteristics in a further study by Read et al. (2010). Root characteristics were strongly related to nutrient removal. In particular, deep root systems, with high total root length and mass were beneficial traits, alongside a high growth rate. Read et al's studies were relatively short-term, making it difficult to extrapolate them to long-term biofilter performance. Furthermore, there is not yet a clear understanding of how the morphological and physiological characteristics of different species interact with nitrogen cycling. This process-based understanding is necessary to expand the list of species recommended in biofilters, particularly across different biotic zones.

Nitrogen cycling occurs across both aerobic and anaerobic redox conditions. Nitrification, which converts ammonium to the mobile species nitrate, requires aerobic (oxic) conditions whereas denitrification, converting nitrate to dinitrogen gas, requires low oxygen (anaerobic) conditions. Hence, the water status across the biofilter profile, which is a primary driver of redox potential, is a critical determinant of nitrogen processing. As a biofilter dries or becomes saturated, the distribution and interaction between nitrification and denitrification shifts. Effective nitrogen removal requires both processes in close proximity, and so variation in water availability within the biofilter is necessary. Saturated zones in the lower biofilter layers have been designed to provide anaerobic conditions to promote denitrification. A supplementary carbon source is also frequently added to provide the electrons necessary to drive the heterotrophic process. However, while the use of a saturated zone and carbon source can improve nitrate removal significantly, the improvement in total nitrogen can be largely offset by poorer removal of organic nitrogen or ammonia (Hunt et al., 2006; Sharkey and Hunt, 2005; Zinger et al., 2007a). In addition, little is known about nitrogen dynamics across the wetting and drying spectrum. Extended drying greatly reduces performance (Zinger et al., 2007b), but further understanding of the shift in processes that occurs during drying, the source of nitrogen leached upon re-wetting, and the recovery time after drying will facilitate designs suitable for specific climates.

Biofilter performance may also be influenced by the magnitude of inflow events. Another key factor influencing performance across the hydrograph is the presence of a saturated zone, which also acts to provide an extended detention time for the volume of stormwater stored between inflow events. Differentiating between the performance of designs with and without a saturated zone requires greater understanding of its role and the quality difference between the initial flush of stored effluent and the recently infiltrated stormwater that follows.

A laboratory column experiment was thus conducted to investigate some of these knowledge gaps in nitrogen processes, with a focus on the role of plant species and water dynamics on biofilter N-removal performance. The project ultimately aims to expand plant selection guidelines for biofilters and enhance design towards consistent and effective nitrogen removal from stormwater.

This paper focuses on four aspects of biofilter design and operation that influence nitrogen removal performance:

- Plant species
- Wet and dry periods

- Use of a saturated zone
- Inflow event magnitude

2 METHODS

2.1 Plant selection

In total 20 native plant species from Victoria and Western Australia were selected for the experiment, in conjunction with two common lawn grasses, as listed in Table 1. The native species included grasses, sedges, rushes and small shrubs or trees. The criteria for plant selection favoured species currently used in biofilters, adapted to ephemeral wet and dry conditions and with desirable characteristics for nutrient removal, including a high root biomass, fine roots and relatively high growth rate, as identified in previous studies (Read et al. 2010). Several species previously found to be poorer performers for nitrogen removal in biofilters, such as *Dianella* species, were included to provide the greatest possible explanatory power.

Table 1 - Plant species selected

Broad plant type	Western Australia	Victoria
grasses	<i>Sporobolus virginicus</i>	<i>Poa labillardieri</i>
	<i>Austrodanthonia caespitosa</i>	<i>Poa sieberiana</i>
	<i>Poa poiformis</i>	<i>Carex appressa</i>
sedges / reeds	<i>Cyperus gymnocaulis</i>	<i>Gahnia sieberiana</i>
	<i>Juncus kraussii</i>	<i>Juncus pallidus</i>
	<i>Gahnia trifida</i>	<i>Dianella revoluta</i>
	<i>Carex tereticaulis</i>	<i>Dianella tasmanica</i>
shrubs / trees	<i>Melaleuca incana</i>	<i>Allocasurina littoralis</i>
	<i>Astartea scoparia</i>	<i>Leptospermum continentale</i>
	<i>Hypocalymma angustifolium</i>	<i>Hakea laurina</i>
lawn grass	Velvetene™	Palmetto® Soft Leaf Buffalo

2.2 Experiment design

2.2.1 Variables tested

The laboratory experiment involved 225 single-plant columns and 20 bare soil control columns. Two outlet configurations were tested; columns draining freely from the base ('non-saturated' design) and columns with an elevated outlet providing a saturated zone in the lower half of the column ('saturated' design) (Figure 1). These columns included a supplementary carbon source of sugar cane mulch and pine chips mixed into the media within the saturated zone. Five replicates of each species and outlet combination were tested. In addition, five columns planted with *Carex appressa*, a high performer for nitrogen removal (Bratieres et al., 2008) were constructed with a saturated zone but no carbon source, to investigate the role of a supplementary carbon source. However, the results from these additional columns have not been reported here.

2.2.2 Column design

Each column was 150 mm in diameter and 600 mm deep with a 200 mm ponding zone, formed with clear Perspex pipe (Figure 1). The biofilter media comprised a 300 mm layer of loamy sand filter media above 200 mm of sand, acting as a transition layer before a 100 mm gravel drainage layer. If present, the saturated zone and carbon source were restricted to the sand and gravel layers.

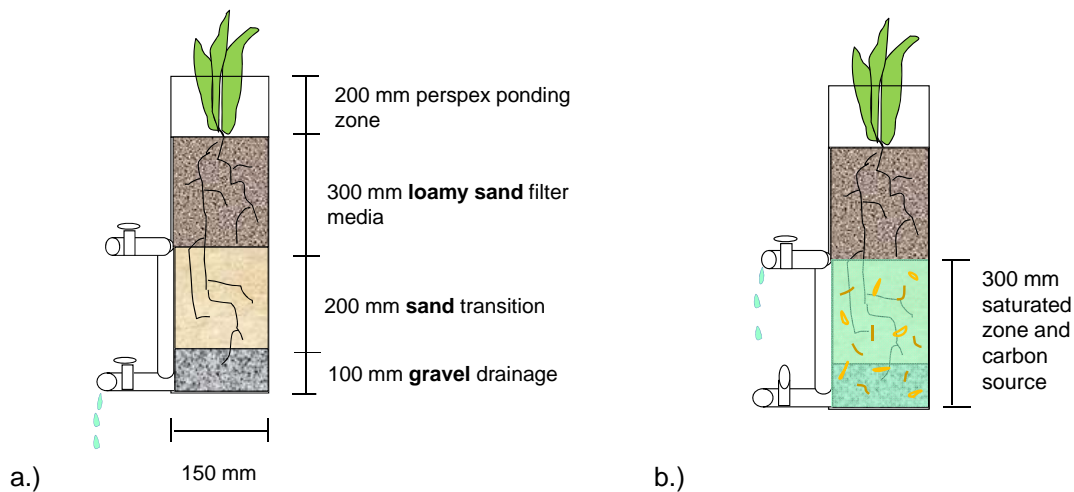


Figure 1 Design of lab-scale biofilter columns either a.) non-saturated, showing the depth and composition of layers and b.) additionally with a saturated zone and carbon source

2.2.3 Stormwater dosing

The experiment was conducted across a 1.5 year period of stormwater dosing, including a six month establishment period and a one year period of sampling from November 2010 to May 2012. Dosing was conducted twice weekly across the experiment ('wet' conditions) with the exception of four months, from November to February, when 'dry' conditions were simulated. Across this time the watering regime was varied to aim for maximum drying but minimal plant death, which resulted in approximately fortnightly dosing.

The dosing volume was calculated to reflect a biofilter sized to 2.5% of its catchment area and using the annual average effective rainfall for Perth and Melbourne across a twice-weekly frequency. As a result, the West Australian columns were dosed with 4.2 L at each watering and Victorian columns with 3.7 L.

The semi-synthetic stormwater comprised sediment from a local stormwater retention wetland, sieved to 1 mm, and mixed with tapwater and laboratory chemicals to provide the average nitrogen and phosphorus concentrations summarised in Table 2. Sodium thiosulphate pentahydrate was also added to de-chlorinate the tapwater. The concentrations were targeted to typical stormwater nutrient levels and a total suspended solids (TSS) concentration of 150 mg/L (Duncan, 1999; Taylor et al., 2005).

Table 2 – Average inflow nitrogen and phosphorus concentrations (mg/L)

Total nitrogen	2.21
Nitrate/nitrite	0.99
Ammonia	0.41
Particulate organic nitrogen	0.38
Dissolved organic nitrogen	0.44
Total phosphorus	0.36
Phosphate	0.19

2.3 Parameters measured

Concentrations of total nitrogen (TN), total phosphorus (TP), total dissolved phosphorus (TDP), total dissolved nitrogen (TDN), ammonium (NH_4^+), filterable reactive phosphorus (FRP) and nitrate/nitrite (NO_x) in the effluent were determined monthly for all columns in a NATA (National Association of Testing authorities, Australia) accredited laboratory. Sampling was undertaken over a one year period.

A sub-set of columns was also dosed with a higher volume of stormwater (8 L) in order to investigate

changes in effluent concentration across the outflow hydrograph. The first 0.5 L of outflow was sampled to characterise stormwater stored between events (ie. the 'old' water). The following 4.5 L was not sampled and the final 1-3 L draining from the columns was sampled to characterise effluent from the current water, passing immediately through the column. The higher volume sampling was conducted twice at the conclusion of the 12 month sampling period, within the 'wet' dosing regime. Three replicates for 9 different species and soil only columns were tested under these conditions.

This paper presents results for total nitrogen (TN) from the October 2011 ('wet' dosing period) and December 2011 ('dry') effluent sampling, and one of the high inflow sampling events.

3 RESULTS

3.1 Effluent nitrogen concentrations

The removal of total nitrogen (TN) was consistently high across all species during the wet period (Figure 2), but became much less reliable and effective following a 15 day dry period (Figure 3).

During the wet period all plant species decrease TN concentrations on average by 79% (*Dianella tasmanica*) to 93% (*Melaleuca incana*) in saturated designs and 58% (*Hypocalymma*) to 89% (*Melaleuca incana*) in non-saturated designs. In contrast, the soil-only columns only reduce TN concentrations by an average of 34% (Victorian (Vic) controls) to 42% (West Australian (WA) controls) for columns with a saturated zone or 31% (WA) to 32% (Vic) for non-saturated designs. When averaged across replicates, saturated zones always produced a greater concentration reduction than did non-saturated designs. However, the difference between designs was smaller for the higher performing species.

Following a 15 day dry period, biofilter performance declines across all species and designs, with variation between treatments substantially increased (Figure 3). Concentrations of TN are reduced on average by 12% (*Gahnia trifida*) to 78% (Buffalo) across saturated designs. Designs without a saturated zone (non-saturated) increased nitrogen concentrations by 10% on average when *Hypocalymma angustifolium* was planted, while the other species on average reduced concentrations by 7% (*Gahnia trifida*) to 45% (Velvetene™). Soil-only controls with a saturated zone performed better than some plant species with average concentration reductions of 48% (WA) to 56% (Vic). However, soil-only designs without a saturated zone performed poorly, producing a 5% increase in TN concentrations relative to the inflow.

It is important to note these concentrations are low relative to other lab and field studies (Bratieres et al., 2008; Hunt et al., 2006; Read et al., 2008). This may partly reflect the limitations of a small column study undertaken over a relatively long time frame. For example, prolific moss growth occurred across many columns in the sheltered environment of the ponding zone, and this may have increased nitrogen uptake. Hence, further investigation is required to determine if the outflow concentrations shown in Figures 2 and 3 are achievable in field biofilters.

Across both the wet and dry periods the highest performing species include Velvetene™ and Buffalo lawn grasses, *Carex appressa*, *Juncus pallidus*, *Melaleuca incana*, *Leptospermum continentale* and *Carex tereticaulis*. The poorest performers include *Hypocalymma angustifolium*, *Astartea scoparia*, *Hakea laurina*, *Sporobolus virginicus*, *Dianella tasmanica* and *Gahnia sieberiana*.

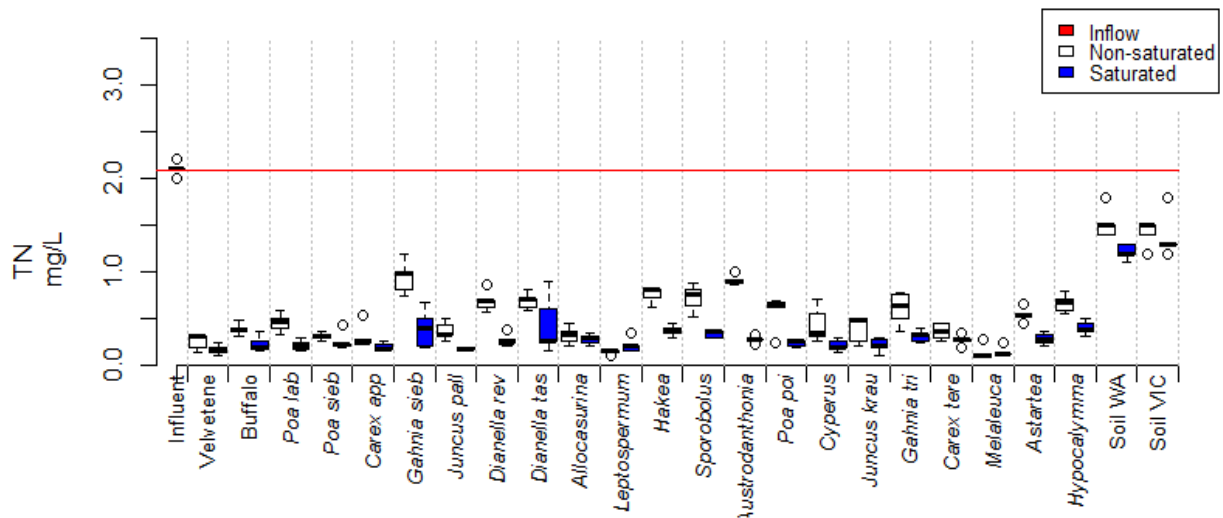


Figure 2 Boxplots of outflow TN concentrations (mg/L) across the plant species in October 2011 during the wet dosing period (twice weekly)

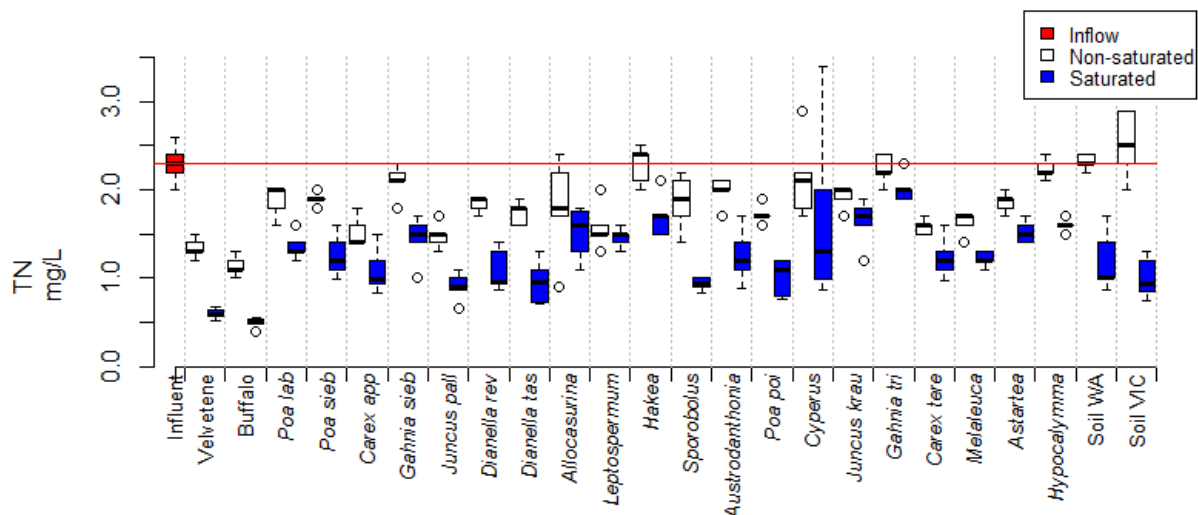


Figure 3 Boxplots of outflow TN concentrations (mg/L) across the plant species in December 2011 when dosing is undertaken after 15 days of drying

3.2 Influence of dosing volume

The variation in outflow quality across the event hydrograph is illustrated for designs without a saturated zone (non-saturated) in Figure 4 and designs with a saturated zone in Figure 5. Concentrations of TN in the initial outflow are shown on the x-axis and represent the quality of water stored in the biofilter between inflow events (or 'old' water). The quality of effluent later in the event hydrograph, which has immediately passed through the biofilter (or 'new' water), is shown on the y-axis.

For the non-saturated columns both the highest (*Carex appressa*, *Melaleuca incana*, *Poa sieberiana* and *Juncus kraussii*) and poorest performing species (*Gahnia sieberiana*) lie close to the 1:1 line, indicating little difference between the resident ('old') and immediately treated ('new') effluent. However, in the middle range of performance (e.g. for Buffalo and *Sporobolus virginicus*) the quality of the two samples diverges away from this line and the 'old' resident water has higher quality than the newly infiltrated effluent. Despite this, the concentrations remain relatively low. The soil-only columns display the opposite, with slightly improved quality of effluent immediately passing through the column relative to effluent stored between events.

Saturated columns also show little difference between the 'old' and 'new' water for the highest performing species (such as *Carex appressa*, *Melaleuca incana* and *Leptospermum continentale*). Other species display high quality 'old' water, but increasingly poor treatment of the 'new' water across Buffalo, *Juncus kraussii*, *Sporobolus virginicus*, *Dianella revoluta* and *Gahnia sieberiana*. The quality of the 'new' water tends to approach the performance of the non-saturated columns. The poorest performance is demonstrated by the soil-only controls, but the quality of resident 'old' water is marginally higher than the newly infiltrated stormwater.

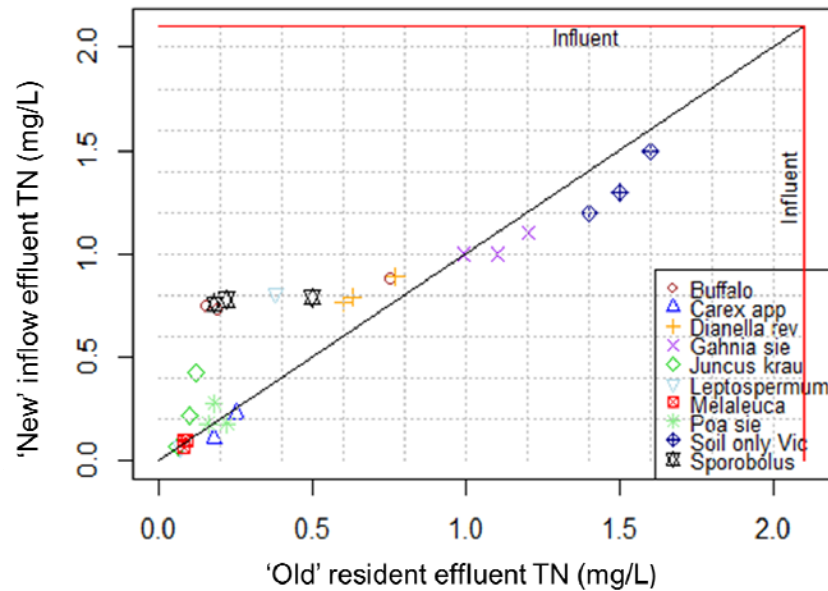


Figure 4 Outflow concentrations of TN (mg/L) across the event hydrograph for non-saturated columns

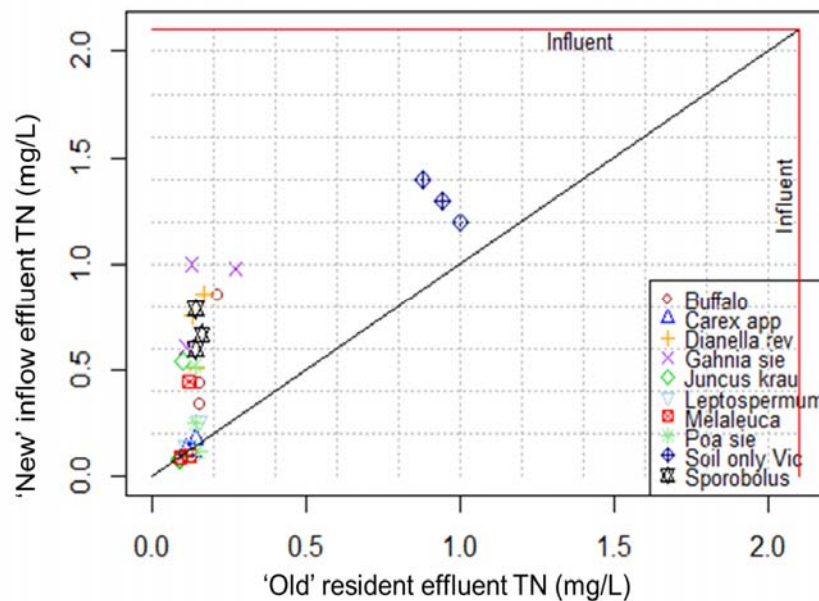


Figure 5 Outflow concentrations of TN (mg/L) across the event hydrograph for columns with a saturated zone

4 DISCUSSION

4.1 Are all plants the same?

The variation in performance across plant species in the wet dosing period was less than differences noted in previous studies (Bratieres et al., 2008; Fletcher et al., 2007; Read et al., 2008). This may reflect the influence of filter media, with this study using loamy sand with a lower content of organic material than in these previous studies. However, as noted in Section 3.1, the very low outflow concentrations found in the current study should be interpreted with caution as they may in part reflect

experimental limitations, which included the growth of moss in the columns (generally absent from field biofilters).

The results suggest that plant species selection is of limited importance under wet conditions, and many species can be expected to perform better than soil only columns. However, following extended drying there is greater difference between species. The lawn grasses perform better than the native species, possibly due to lower water loss through evapotranspiration which conserves moisture for biotic function. Of the native species, some of the highest performers continue to perform relatively well across both wet and dry, including *Carex appressa* and *Juncus pallidus*. However, there is some change in the relative performance of other species between the wet and dry conditions. For example, *Leptospermum continentale* and *Cyperus gymnocaulis* are relatively high performers under wet conditions, but compared to other species perform poorly in the dry. This may reflect varied drought tolerance and strategies of species. Plant strategies that may effectively remove nitrogen under wet conditions, such as a high growth rate and uptake, may disadvantage the plant for survival and function across dry periods, such as by exacerbating drying due to a high transpiration rate. Interestingly, *Allocasurina littoralis* is a nitrogen-fixing tree species but despite this characteristic it is not the poorest performing species, but middle of the range. The results indicate that plant species selection remains critical when conditions differ from ideal, and that a diversity of plant types and traits is the best strategy for building climate-resilient biofilters.

4.2 Effect of wet and dry periods

The frequency of inflows has a large impact upon biofilter performance. Design differences, such as plant species or use of a saturated zone, have less impact during wet periods than after extended drying. Even though biofilter inflows are characteristically stochastic, few studies have considered the impacts of various wet and dry periods on performance.

Zinger et al. (2007b) found a 7 week dry period reduced total nitrogen removal of columns with a saturated zone from 50% reduction to approximately 30% production. A 2 week dry period, similar to the length in the current experiment, had no negative impact on performance on the first re-wetting (reductions of approximately 60-70%) but on the second watering reduced performance to approximately 45%. This compares with a concentration reduction averaging 87% (across all species) for saturated columns during the wet, which reduces to an average of 45% after a 15 day dry period in the current experiment. The more extreme results for a 2 week period demonstrated in this experiment likely reflects a greater severity of drying, largely due to a smaller column diameter (150 mm relative to 375 mm used by Zinger et al. (2007b)), and possibly the prevailing climatic conditions. This suggests the findings of the current experiment would in reality reflect the performance of field biofilters after a much longer period of drying.

There are multiple design variables that can influence the rate of biofilter drying, including media depth, plant species, biofilter size and use of a saturated zone. Hence, further understanding of the impact of different length dry periods on the key processes has great scope to improve designs. In addition, designs should account for local climate conditions, such as the frequency and duration of dry periods.

4.3 Role of the saturated zone

Previous studies observed an increase from 70% TN concentration reduction without a saturated configuration to a 74% reduction with a saturated zone (Zinger et al., 2007a). The current study used the same dosing regime (twice weekly) during the 'wet' period and found vegetated columns varied from average reductions of 87% with a saturated zone to 75% without a saturated zone. The difference may partly relate to optimisation of the carbon source, as relatively high ammonium levels in saturated designs were attributed by Zinger et al. (2007a) to be due to the use of pea straw, with a low C:N ratio.

During frequent dosing the difference between concentration reductions achieved by saturated and non-saturated designs varied from only 0.4% (*Allocasurina littoralis*) to 28% (*Austrodanthonia caespitosa*) during frequent dosing. The most effective plant species tended to demonstrate less difference between saturated and non-saturated designs than the poorly performing species. This may reflect rapid rates of nitrogen processing, possibly plant uptake, in columns with high performing species, such that processes occur before drying between events (which is minimal during frequent

dosing) differentiates between the non-saturated and saturated designs.

Drying exacerbated the differences between designs with an average 45% concentration reduction by vegetated columns with a saturated zone compared to a 20% concentration reduction without a saturated zone. Across species, the difference in concentration reductions between designs with and without a saturated zone varied by 5% (*Gahnia trifida*) to 46% (*Sporobolus virginicus*). Hence, the presence of a saturated zone is particularly important to maintain biofilter functioning across extended dry periods. A saturated zone will maintain higher soil moisture, possibly even within the lower part of the upper unsaturated layer, to support plant nitrogen uptake and microbial processing between inflow events (Hatt et al., 2007), even across up to 7 weeks of drying (Zinger et al., 2007b). Without this plant roots will limit transpiration, and thereby nitrogen uptake, roots and microbial cells will die and leach nitrogen, anaerobic processing will cease, and if drying continues all biotic processes will decline and eventually cease (Baldwin and Mitchell, 2000).

4.4 Influence of event magnitude

Similarly to previous studies (Henderson et al., 2007; Hsieh et al., 2007), effluent quality did vary across the outflow hydrograph. The results have implications on the role of the saturated zone – does it enhance treatment across the entire outflow or only facilitate treatment of the retained volume stored between events?

There was little difference between the 'old' and 'new' water for the highest performers in both non-saturated and saturated designs, which indicates in these cases the key treatment processes are relatively rapid. This suggests biotic uptake is an important mechanism and a longer retention time provides little further benefit. In other cases for both unsaturated and saturated designs the quality of retained 'old' water was greater than water passing more rapidly and immediately through the column ('new') water. This indicates continued processing between events, possibly reflecting a slower rate of biotic uptake or microbial processing. Hsieh et al. (2007) suggested slower processes become important during the inter-event period. Due to a larger storage volume, this benefit of a longer retention time is evident across more species in designs with a saturated zone. The results illustrate that given long enough residence time, the saturated zone provides effective removal irrespective of plant species. Given enough time, rates of biotic uptake or microbial processing, which differ between species, appear to have time to reach a general background concentration.

For soil-only columns the quality of water retained in non-saturated designs was poorer than rapidly treated water, indicating nitrification between events. However, a saturated zone in soil-only columns contributed positively to performance, potentially through augmentation of evapotranspiration and a smaller aerobic volume of soil to promote nitrification.

The results illustrate that a saturated zone enhances the quality of retained stormwater but may provide little benefit to the immediate processing of influent. In the case of the highest performing species, this is irrelevant as removal processes appear to be rapid. However, in the case of poorer performing species a saturated zone is essential to achieve good nitrogen removal. This beneficial effect will be of greatest significance to small-scale inflow events when a large portion of inflow is retained in the saturated zone. However, excluding dry periods, as the inflow volume increases the treatment difference between designs with and without a saturated zone may be expected to diminish. To further determine the benefits of a saturated zone, quantification of denitrification and biofilter gas fluxes is necessary, including the potential for release of potent greenhouse gases methane and nitrous oxide from microbial processes.

5 CONCLUSION

Plants play an important role in biofilter processing of nitrogen. Under conditions of frequent inflows plant selection is not critical as all species reduced TN concentrations effectively relative to soil-only designs. Similarly, the use of a saturated zone only marginally improves performance under wet conditions, particularly for the highest performing plant species. However, differentiation between plant species and designs is exacerbated following an extended dry period when performance reduces across all designs. The highest performing species include Velvetene™ and Buffalo, both common lawn grasses, *Carex appressa*, *Juncus pallidus* and *Melaleuca incana*.

The inclusion of a saturated zone improves TN removal on average across all species and both wet and dry periods. The results illustrate the key role a saturated zone plays to maintain biofilter function

across dry periods and enhance the quality of stormwater retained between inflow events, particularly when poorer performing plant species are used. This capability of the saturated zone will contribute substantially to the treatment of small and possibly also medium-sized, inflow events by biofilters. Overall, the results demonstrate the capability and flexibility of biofilters across a range of climates. We conclude that selection of plants should consider diversity, to ensure resilience against varying climatic conditions.

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