The use of trees in urban stormwater management

Abstract

Sustainable stormwater management presents unique challenges and opportunities in the urban built environment. The disposal of stormwater directly from impervious urban surfaces into surrounding waterways is detrimental to the aquatic environment. In response to this, processes such as evapotranspiration and soil and groundwater recharge are increasingly being used so that hydrological patterns of urban areas more closely mimic natural areas. Vegetation, including urban trees, affects many of these processes and is an important component of stormwater management.

An experiment was conducted in Melbourne, Australia, to assess the potential role of street trees in urban biofiltration systems. Four tree species, *Eucalyptus polyanthemos* (red box), *Lophostemon confertus* (brush box), *Callistemon salignus* (willow bottlebrush) and *Platanus orientalis* (oriental plane) were grown in three different constructed soil profiles, including one chosen for its low, and potentially growth limiting, drainage rate. The plants were irrigated with tapwater (potable) or a model stormwater solution. In general, tree growth, in all soils, was increased when the irrigation was with the model stormwater solution.

Compared to unplanted controls, the presence of trees in the biofiltration system resulted in significant reductions of the soluble nitrogen and phosphorus concentrations of the stormwater. In general, biofiltration systems effectively reduced the filterable reactive phosphorus (FRP) concentration of stormwater. The treatment of nitrate plus nitrite (NO_X) concentration of stormwater was more variable from planted systems, with reductions achieved during cooler months while NO_X was generated during warmer months.

Species selection did not appear to be an important element in terms of system success. Profiles planted with the deciduous species performed similarly in terms of nutrient removal to the systems with evergreen species, although there was some seasonal variation. Incorporating street tree plantings as stormwater treatment measures offers an exciting opportunity to create multi-functional landscapes.

Introduction

Keywords:

trees, stormwater, biofiltration

Urbanization changes many attributes of the land that is developed. One of these is a reduction in the permeability of surfaces that can lead to modified patterns of runoff and increased loads of pollutants entering downstream waterways. The degree of impervious surfaces or perhaps more importantly the nature of the pathway between where the stormwater is generated and where it flows into the receiving waters, can be important predictors of the extent of disturbance to the health of aquatic ecosystems (Hatt *et al*., 2004; Taylor *et al*., 2004; Walsh, 2004,). Approaches that are used to offset this disturbance are known by various names that include water sensitive urban design (WSUD) (Australia), sustainable urban drainage systems (SUDS) (UK) and low impact development (LID) (USA). Urban trees are an important component of these more sustainable approaches to stormwater management.

Biofiltration systems, also known as raingardens or biofilters, are one of the strategies used as part of WSUD to improve the quality and reduce the quantity of urban stormwater runoff. Biofiltration systems direct stormwater runoff into a treatment area that has plants growing in a moderately permeable soil. The runoff percolates through the system and a combination of physical, chemical and biological processes reduces the nutrient and

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sediment load of the runoff. The volume and speed of delivery of runoff directed into waterways is also reduced if stormwater is retained within the systems. Most biofilters use herbaceous species (grasses, sedges and rushes are common) but in highly urbanized locations, such as streets, trees may be more suitable vegetation. While an extensive literature exists that discusses the performance of predominantly herbaceous biofiltration systems (Davis *et al*., 2006; Blecken *et al*., 2007; Henderson *et al*., 2007, Bratieres *et al*., 2008; Read *et al*., 2008) systems using large, woody vegetation are less well documented.

This paper examines existing literature on the performance of woody plants in stormwater management systems and reports on an experiment that investigated the use of four street tree species (*Eucalyptus polyanthemos, Lophostemon confertus, Callistemon salignus* and *Platanus orientalis*) in model infiltration systems. All of these species are used as street trees in southeastern Australia.

The use of woody plants in stormwater management systems

Urban trees can contribute to stormwater management in a number of ways. Stormwater runoff can be reduced by the evaporation of rainfall intercepted by the canopy and transpiration losses, while stormwater quality can be improved by retention of pollutants in soil and plant uptake (Stovin *et al*., 2008).

Rainfall interception in canopy

The volume of runoff is reduced by the evaporation of rainfall from leaf surfaces within the tree canopy. Rainfall interception by trees in the parks and streets of a Californian city equated to 1.6% of total precipitation and a saving of $3.80 per tree on expenditure for stormwater management (Xiao and McPherson, 2002). Rainfall interception is maximized with large, evergreen tree species (Xiao and McPherson, 2002).

Increased infiltration of rainfall and soil water storage

Trees can increase the rate or amount of soil water infiltration and subsequently increase soil and groundwater recharge. A proportion of the rainfall temporarily held on the canopy will flow down the stem and trunk (Xiao *et al*., 2000). In highly impervious areas this trunk flow increases the likelihood that rainfall is directed into soil at the base of the tree rather than onto surrounding impervious surfaces.

Tree pits can be designed to maximize water storage. The use of structural soil under pavement areas such as car parks and footpaths to retain stormwater is an example of this. By providing increased rooting volumes through the use of structural soils, these systems should support larger-sized trees and will further mitigate stormwater by rainfall interception and retention within the soil (Day *et al*., 2008). *Fraxinus pennsylvanica* (green ash) and *Quercus bicolor* (swamp white oak) grew successfully in structural soil planting pits that were designed to retain stormwater (Bartens *et al*., 2009).

The percolation of stormwater through compacted soil layers can also be increased by tree root growth. The saturated hydraulic conductivity (SHC) of a compacted subsoil layer under structural soil was 0.79 mm h^{-1} (27-fold higher) with *Fraxinus pennsylvanica* (green ash) than in unplanted systems (Bartens *et al*., 2008). *Acer rubrum* (red maple) and *Quercus velutina* (black oak) increased the saturated hydraulic conductivity of compacted clay soil in less than 12 weeks after planting (Bartens *et al*., 2008).

Pollutant removal

In addition to reducing the quantity of urban runoff, vegetation and its associated soil can play an important role in removing nutrients and heavy metals from stormwater (Davis *et al*., 2001, Henderson *et al*., 2007, Read *et al*., 2008). To date there has been limited research on the performance of individual plant species in biofiltration systems, with two notable exceptions: Bratieres *et al*. (2008) and Read *et al*. (2008). These two studies investigated a range of plant species, varying in size from rushes to large shrubs or small trees, indigenous to southeastern Australia.

Research programme

The seasonal performance of street tree species in biofiltration systems is largely unknown. A study was designed to assess the combined performance of street trees and tree soils as part of an integrated urban stormwater treatment system. The proposed treatment system could be retrofitted into most urban streets, either at the time of tree replacement, or to amend an existing planting. Stormwater from the road and footpath is directed along the gutter and into the biofiltration system. The soil surface is set at a designed depth below the surrounding surfaces, referred to as the extended detention depth, allowing stormwater to fill this space during rain events. The systems are designed so that if the detention depth is filled, additional stormwater is bypassed into the conventional stormwater management systems to avoid flooding.

Materials and methods

The experiment was designed to evaluate both tree growth responses and also the efficacy of nutrient removal of these biofiltration systems. Trees were grown outdoors in experimental biofiltration systems, constructed with 240 mm diameter columns, cut into 600 mm lengths. The constructed soil profiles were 500 mm deep with 10% (v:v) composted green waste added to the surface 200 mm. The three soils used were sands with saturated hydraulic conductivities (SHC) of 4, 95 and 170 mm h^{-1} and the soils are referred to as low, medium and high SHC soil respectively. The hydraulic conductivity of the slowest draining soil was below the range (20–1000 mm h^{-1}) stipulated in the Australian Standard AS 4419 'Soils for landscaping and garden use' (Standards Australia, 2003).

The four species selected are common in urban landscapes in southern Australia (Frank *et al*., 2006) and three are Australian species. The tree species chosen come from a range of climates and environments and were chosen in part to investigate innate differences in response to the regular inundation that would be expected in biofiltration systems. The evergreen trees were planted in late March to early April 2003 and the deciduous trees in June 2003. The application of simulated runoff commenced in September of the same year.

The trees were irrigated using tapwater or a model stormwater solution and compared to unplanted, control profiles. The profiles received weekly applications of approximately 100 mm depth of either tapwater or stormwater. The chemical composition of the simulated stormwater was adapted from one devised by Davis *et al*. (2001) and included 2 mg L^{-1} NO_3^--N, 4 mg L^{-1} organic-N and 0.6 mg L^{-1} phosphate-P as well as a heavy metal (copper) and dissolved solids (sodium chloride and magnesium chloride). As suspended solids were not included in the synthetic stormwater the implications of surface clogging and changes in hydraulic performance over time were not investigated.

The model soil profiles were raised off the ground, allowing collection of leachate following simulated runoff events. An irrigation system was used to deliver the simulated runoff events. All profiles received a volume of tapwater via a microspray within a 500 mL plastic food container, and the addition of stormwater concentrate in this container prior to the system running created the simulated stormwater solution.

Data collected during the experiment included final above-ground plant biomass as well as soluble nitrogen and phosphorus concentration of the leachate over time. For above-ground biomass measurements all trees were harvested at the completion of the experiment, oven dried (70ºC for 48 hours) and weighed. Sampling of leachate from the constructed profiles for nutrient analysis was undertaken from December 2003 until December 2004. On 10 occasions during the 13-month period the leachate was collected from the base of the systems for two hours after a simulated runoff event. Filtered (0.45 µm) samples were analysed for NO_x and FRP using colorimetric methods and an Alpkem (Perstorp Analytical) segmented flow autoanalyser. In some instances, typically in higher evaporative demand months towards the end of the experiment, all of the applied water was retained within the soil and no leachate drained from the profiles. The concentration was recorded as a missing value.

Analysis of variance (ANOVA) was used to make overall comparison between treatment means and differences were recorded as significant at the 5% level ($p<0.05$). Paired comparisons were made using the least significant difference (LSD). For the vegetation growth data n=8 and for the nutrient concentration of leachate from the biofiltration systems data n=3.

Results

Tree growth

All four tree species grew well in all three soils, including one chosen for its low, and potentially growth limiting, drainage rate. Above-ground growth of *C. salignus*, *L. confertus* and *P. orientalis* was increased when the irrigation was with the model stormwater solution rather than tapwater (Table 1). *E. polyanthemos* growth was similar with tapwater and stormwater applications in the low and high SHC soils.

Table 1 Above-ground dry weight (g): species, soil and water quality interaction.

Species	^{yz}Soil and water quality											
	Low SHC				Medium SHC				High SHC			
	Tapwater		Stormwater		Tapwater		Stormwater		Tapwater		Stormwater	
C. salignus	136	b	265	fg	168	cd	266	fg	133	b	233	fg
E. polyanthemos	174	cd	177	cd	149	bcd	243	fg	131	b	159	bcd
L. confertus	147	bcd	273	g	155	bcd	255	fg	129	b	219	ef
P. orientalis	86	a	182	de	85	a	150	bcd	89	a	143	bc

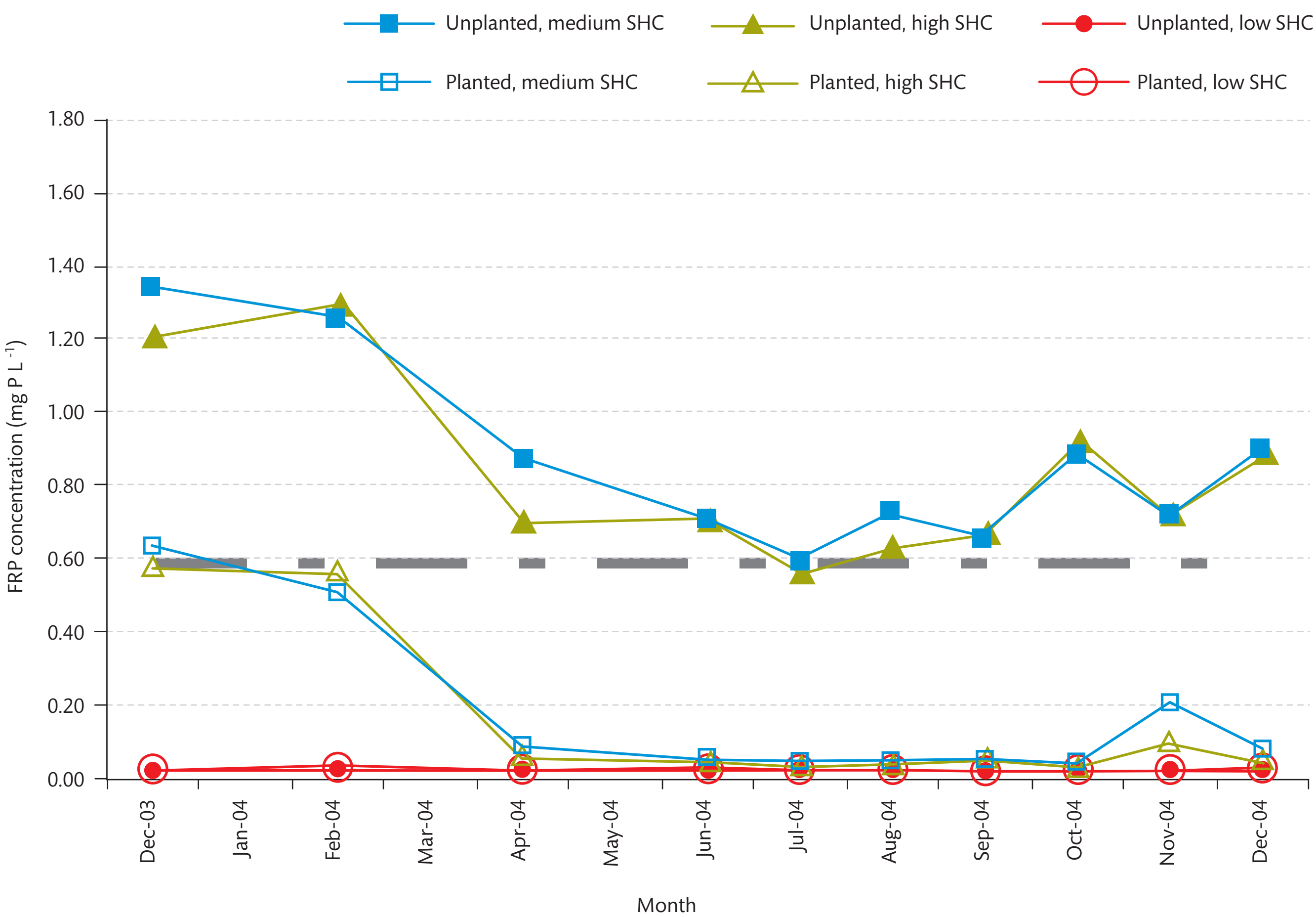
[y] Means followed by the same letter down the column and across the row are not significantly ($p<0.05$) different
[z] Means are back $\log_e$ transformed

While successful tree growth has been confirmed, the systems must also treat stormwater to successfully function in terms of biofiltration. This study focused on nutrient removal, a component of stormwater treatment.

Nutrient removal

Compared to unplanted controls, the presence of trees resulted in significant reductions of soluble nitrogen and phosphorus concentration of leachate. The pattern of FRP concentration of leachate over time was similar between the unplanted and planted profiles (Figure 1). The leachate concentration of FRP was higher during the warmer months and in particular early in the experiment. The unplanted low SHC soil profiles were very effective in reducing the FRP concentration of stormwater. Conversely, FRP seemed to be generated within the unplanted, medium and high SHC soil profiles with higher concentrations of the leachate than the input stormwater during most events (Figure 1).

Figure 1 FRP concentration (mg P L^{-1}) of leachate over time from planted and unplanted profiles receiving stormwater. The dashed, horizontal line indicates the stormwater input concentration.



The effectiveness of planted profiles at reducing the FRP concentration of stormwater was variable. The low SHC soil planted profiles greatly reduced the FRP concentration of stormwater input for all events (Figure 1). The medium and high SHC soil planted profiles had little effect at the start of the experiment, with leachate FRP concentrations similar to the input stormwater. However, following the first summer, good reductions of FRP concentrations were achieved from profiles with these two soils (Figure 1).

During the first few months of the experiment the leachate FRP concentration was high from systems planted with all four species (Figure 2). During winter (June to August) the FRP concentration of leachate from the profiles with the deciduous species was relatively similar to the leachate from those planted with evergreen species. The spike of FRP in late spring (November 2004, Figure 1) was due to high concentrations in leachate from *P. orientalis* profiles (Figure 2).

The pattern of NO_x concentration of leachate over time was generally similar in both the unplanted and planted profiles (Figure 3). The leachate concentration of NO_x was typically higher during the warmer months. The spike observed in July is most likely an artefact of soil core sampling undertaken prior to leachate sampling.

The NO_x concentration of leachate from the planted profiles was less than from unplanted profiles (Figure 3). NO_x was consistently generated in the unplanted profiles with the leachate having higher concentrations than the stormwater input during all events. The effectiveness of planted profiles in reducing the NO_x concentration of stormwater was variable. On all occasions, the planted, low SHC soil profiles had lower concentrations of NO_x in leachate than the stormwater input. The performance of the planted, medium and high SHC soil profiles was less consistent, with NO_x being produced during late spring and summer (Figure 3). During the cooler months the concentration of NO_x in stormwater was reduced by biofiltration through the planted, medium and high SHC soil systems.

The effect of species on the NO_X concentration of leachate during the experiment was not significant (Figure 4, high SHC soil profiles shown).

Figure 2 The effect of species on FRP concentration (mg P L^{-1}) of leachate from medium SHC soil profiles receiving stormwater. The horizontal dashed line represents the stormwater input concentration.

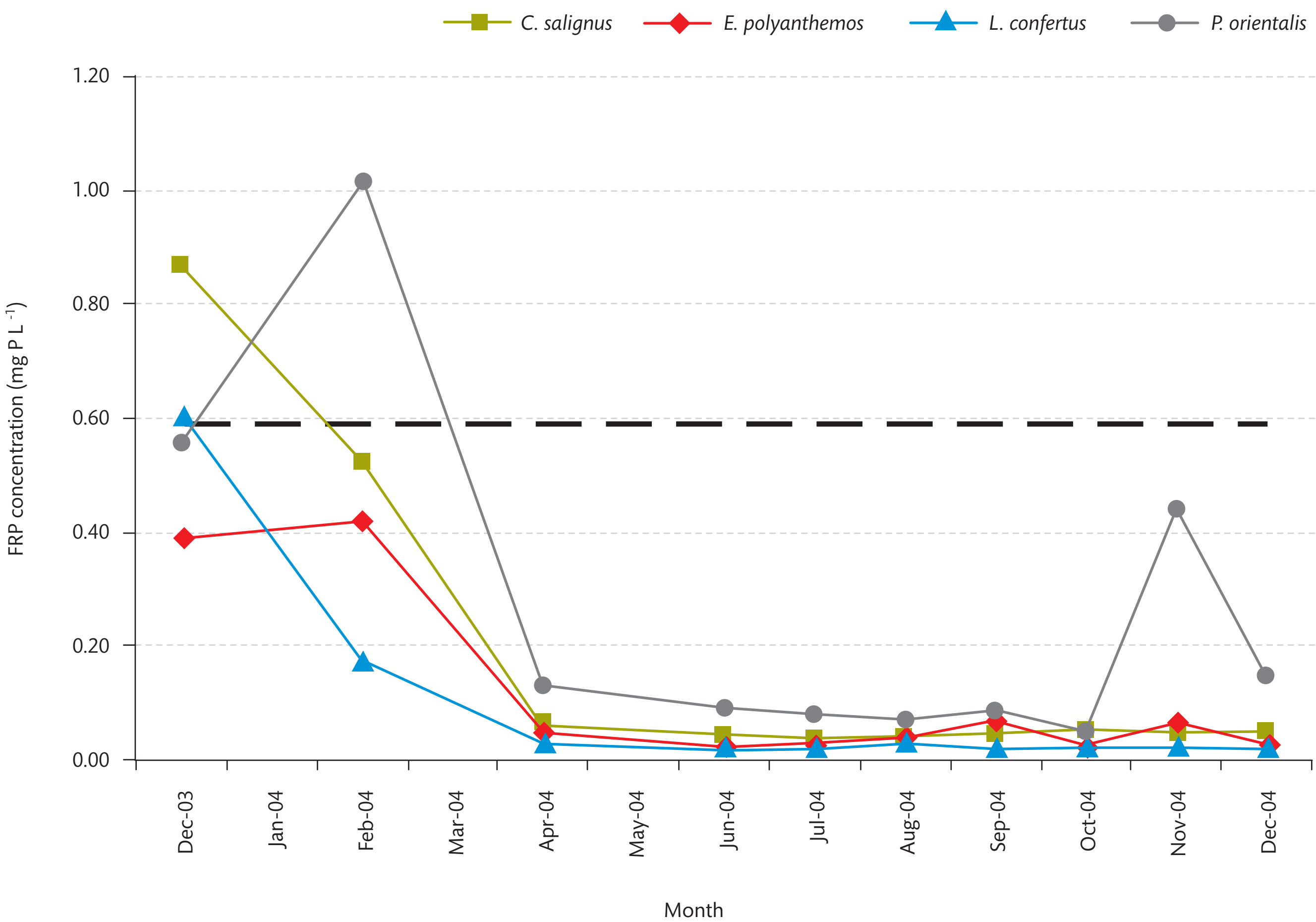


Figure 3 NOx-N concentration (mg N L-1) of output leachate over time from profiles receiving stormwater. The dashed horizontal line represents the stormwater input concentration.

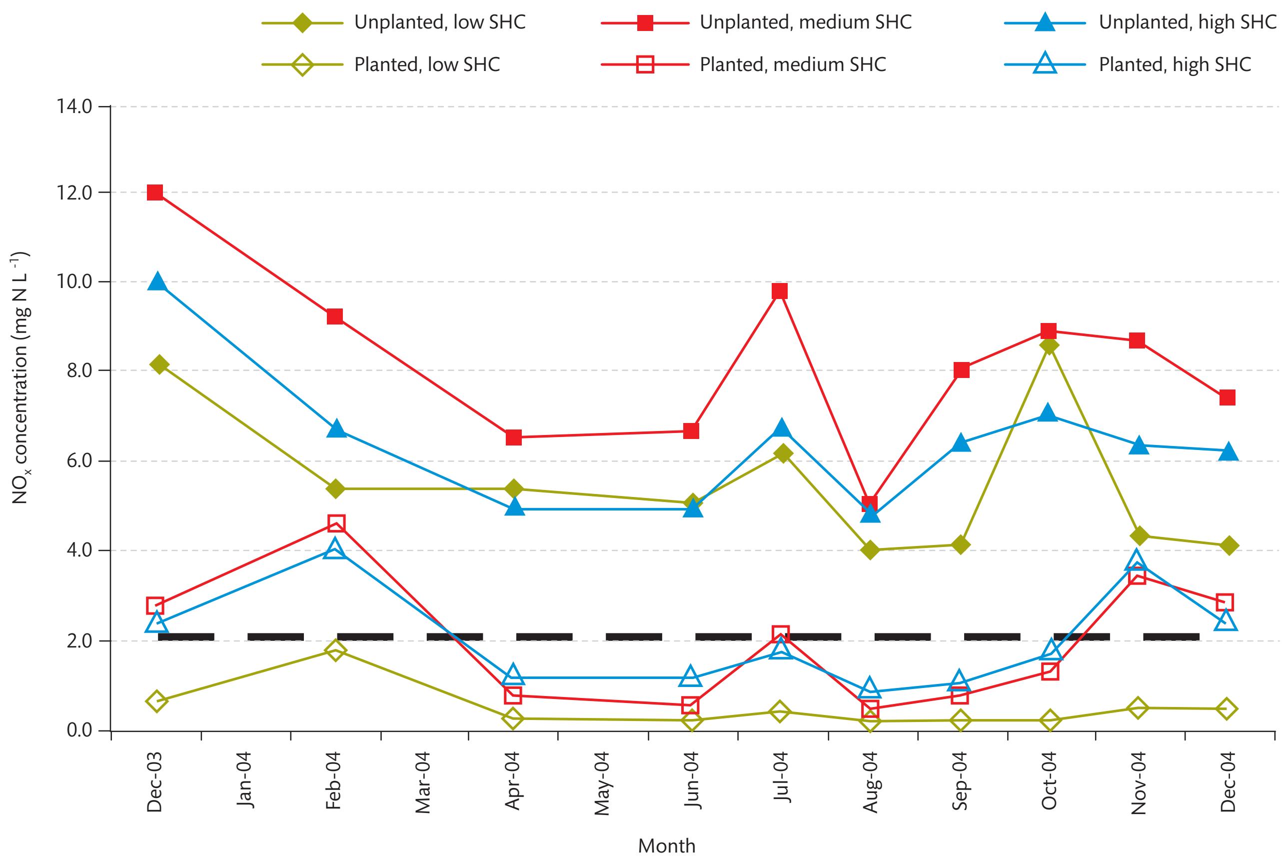
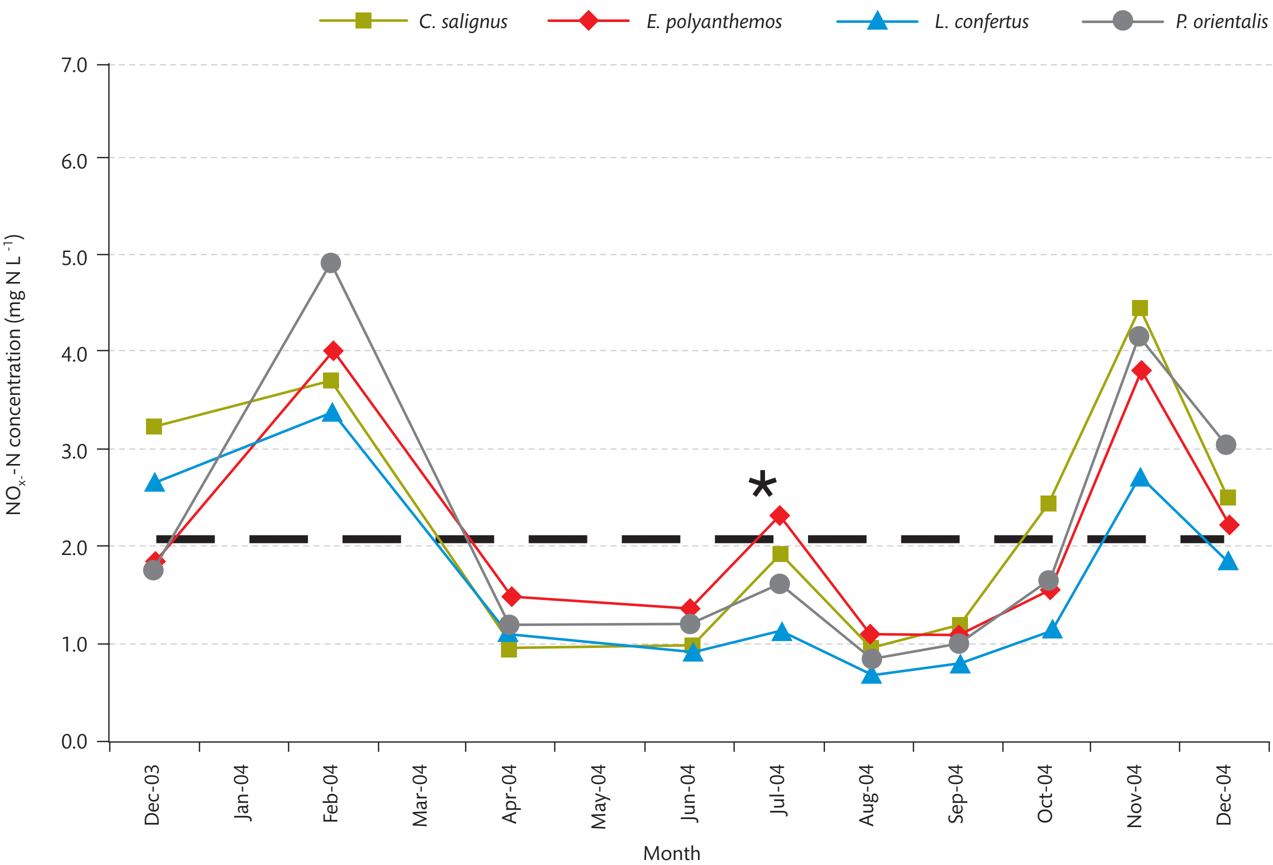


Figure 4 The effect of species on NOx-N concentration (mg N L-1) of output leachate from high SHC soil profiles receiving stormwater. The dashed horizontal line represents the stormwater concentration. * the spike observed in July is most likely due to an experimental artefact (soil cores were taken prior to leachate sampling for root and soil analysis).



Discussion

Tree growth

The trees grew well in this experiment and soil selection was not critical for plant growth with regular exposure to small-sized runoff events. The low saturated hydraulic conductivity of the low SHC soil used in the experiment would not meet AS 4419–2003 guidelines and these soils may have been expected to have poor aeration. The trees grown in the low SHC soil performed well. However, further field evaluation is required to confirm that such soils would be suitable for tree growth. The rate of water infiltration into and percolation through the constructed profiles was variable and not necessarily reflective of the different saturated hydraulic conductivity of the three experimental soils (data not shown). The low SHC soil profiles did drain more slowly than the medium and high SHC soil profiles.

As a growing medium for trees, the coarse-textured soils used in biofiltration systems inherently have low levels of available nutrients and water. The addition of organic matter to similar sandy soils is common practice in constructing designed tree soils. Greater growth of the trees that received stormwater than tapwater confirms that the systems studied had low levels of nutrition.

NO_X concentration of leachate

The NO_x concentration of leachate from planted systems was higher in warmer months. A positive correlation between NO_x concentration of leachate from biofiltration systems and temperature has been reported (Blecken *et al*., 2010). Averaged over time, the experimental street tree biofiltration systems reduced the NO_x concentration of stormwater by 2 to 78% for the various filtration media. Street trees grown in the two faster-draining soils were not effective at reducing N concentration; however, load removal was adequate (data not shown). This reduction in NO_x concentration is within reported ranges (Davis *et al*., 2006; Henderson *et al*., 2007; Bratieres *et al*., 2008; Read *et al*., 2008). Permanently saturated zones designed at the base of biofiltration systems can promote denitrification and increase nitrogen removal performance (Kim *et al*., 2003).

FRP concentration of leachate

The FRP concentration of stormwater was reduced by an average of 70 to 96% following biofiltration through street tree systems with various filtration media. These reductions are similar to those reported in the literature (Bratieres *et al*., 2008, Read *et al*., 2008).

Seasonal patterns of nutrient concentration of leachate

Seasonal patterns of nutrient uptake capacity have been reported for some trees, with maximum rates typically coinciding with active growth periods (Roy and Gardner, 1945, Weinbaum *et al*., 1978; Muñoz *et al*., 1993). It was therefore anticipated that nutrient removal performance would be low during winter while the trees were dormant or growing slowly. The peaks in nutrient concentration of leachate from planted profiles occurred during summer and often corresponded to periods when higher water volumes were retained in the biofiltration systems (data not shown), suggesting that the soil was dry. This seasonal pattern of NO_x and FRP concentration was also observed in the unplanted profiles with considerable leaching of nutrients during summer. This suggests that the soil may be behaving as a larger source of nutrients during these times. That is, the mineralization of organic matter is higher during the summer in response to higher temperatures (Gessler *et al*., 1998) or possibly increased soil drying and wetting.

Organic amendment of biofiltration media

Substantial leaching of nitrogen and phosphorus from unplanted soil profiles was found for the duration of this experiment. Despite the potential increase in cation exchange capacity, caution is required if biofiltration media are to be amended with organic matter. In response to high levels of nutrient leaching from organic matter amended soils, Bratieres *et al*. (2008) recommended that biofiltration soils are not amended. Further field testing is required to ascertain the impact of this recommendation on the long-term growth of street trees and stormwater treatment performance.

Species selection for biofiltration systems

Four street tree species with different waterlogging tolerances were evaluated in this study to determine differences in nutrient removal performance. Species selection was not essential to maximize nutrient removal performance of biofiltration systems. The evergreen and deciduous species performed similarly during winter, when the latter had lost leaves. This raises interesting questions about root function and nutrient uptake in dormant trees. *P. orientalis* was less effective at reducing the phosphorus concentration of leachate during the final months of the experiment, although phosphorus load reduction was adequate (data not shown). This reduced performance is possibly related to stresses caused by more severe drying of soil columns in late spring and summer. Further field evaluation is required to investigate the effect of water stress on stormwater treatment performance and the likelihood of it occurring in practice. The ability of trees to withstand drought may be an important selection criterion which requires further evaluation.

Biodiversity of vegetation within our cities is important and street tree selection should not be based on a single criterion. Therefore it is a positive finding that under these experimental conditions the differences in nutrient removal performance between the four species were not large and the planting of any one particular species is not recommended. However, it is acknowledged that the lack of differences reported in this study may reflect the regime of simulated runoff events applied in this study, which may not have been sufficiently large to impose significant deoxygenation stress on the trees.

While the tree species studied behaved similarly, it is important to reiterate that for removing nutrients from stormwater vegetation is a critical component of these systems. Newly planted biofiltration systems will initially behave largely as unvegetated systems, until the root systems have developed sufficiently to colonize large proportions of the filtration medium. Nitrogen and phosphorus leaching, in terms of concentration, was still occurring in the experimental systems nine months after planting and so these systems will take some time to perform effectively. Good post-planting practices are important to ensure rapid tree establishment in these systems. As with traditional street tree planting, irrigation is most likely the most critical aspect of post-planting maintenance. To avoid water deficit stress, additional irrigation may be required until the tree root systems have established. To optimize tree establishment, the scheduling of irrigation should be proactive rather than reactive (Harris, 1998). The frequency of irrigation post-planting is more important than the volume applied (Gilman *et al*., 1998) due to the small root ball volume and the low water holding capacity of fast-draining biofiltration media. To minimize any nutrient leaching from these newly established systems, care must be taken to apply irrigation volumes which can be fully retained within the soil profile.

Conclusions

Trees in urban built areas can contribute in many ways to sustainable stormwater management. The novel use of structural soils to form a stormwater reservoir for urban tree plantings shows promise (Bartens *et al*., 2009). In the model biofiltration systems used in this research, four common street tree species grew well. Species selection did not appear to be an important element in terms of system success. The one deciduous species behaved similarly to evergreen species, in terms of soluble nitrogen and phosphorus removal, during their dormant period. After the initial summer, the biofiltration systems were successful in reducing FRP concentration. The performance of the systems in reducing NO_X concentration was more variable, and during the warmer months NO_X was generated in the medium and high SHC soil profiles. This work shows that street trees have the potential to be effective elements in urban biofiltration systems and that field-level evaluation of these systems is required to further elucidate the role of such systems in urban stormwater treatment. Design modifications may be required, however, if consistent reductions in NO_x concentration are required.

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