ARE STREET TREES AND THEIR SOILS AN EFFECTIVE STORMWATER TREATMENT MEASURE?

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Abstract
Stormwater management is shifting from systems that rapidly collect and discharge stormwater to nearby waterways towards more sustainable methods. These newer strategies aim to reduce contaminant load and the volume of runoff by incorporating stormwater treatment into the design of urban landscapes. The re-design of street tree rootzone environments is an option for incorporating stormwater treatment measures into streetscapes, where space is limited. This article details the performance of a pilot scale street tree bioretention system in reducing nitrogen loads in urban stormwater. Three tree species (*L. confertus, E. polyanthemos* and *P.* orientalis) and three soils of different hydraulic conductivity were tested in a randomised block design. Over the course of the experiment, all tree species displayed seasonal height growth patterns with maximum growth rates occurring in late Spring and Summer. Applications of stormwater increased height growth and root density compared with tapwater. Two species had significantly higher foliage nitrogen concentrations in trees receiving stormwater than those receiving tapwater. Tree growth was similar in the three soils studied. Leached nitrogen loads were significantly reduced in systems with a tree. Whilst there were some statistically significant differences in nitrogen removal between species, the output loads were all low compared to the unplanted systems. The difference between unplanted and planted profiles was consistent for the three forms of nitrogen measured: ammonium, oxidised nitrogen and organic nitrogen. Compared to the total nitrogen input (25.2 mg), the load leached in December 2004 from the *L. confertus* profiles following a 5 hour collection period was 95% less for the low SHC (1.4 mg), 85% for the medium SHC (4.1 mg) and 82% for the high SHC soils (4.6 mg). In the unplanted profiles the low SHC soil reduced nitrogen by 36% (16.2 mg), whereas the medium (25.2 mg, 0%) and high SHC soils (27.0 mg, -7%) did not remove nitrogen. Therefore, to achieve good nitrogen removal in these systems trees are required.

Keywords
Bioretention, *Lophostemon confertus*, *Eucalyptus polyanthemos*, *Platanus orientalis,* leachate, nitrate, ammonium, total nitrogen.

INTRODUCTION

Water Sensitive Urban Design (WSUD) aims to incorporate water cycle management initiatives into the design of urban landscapes. One goal of WSUD is reducing the negative impacts of stormwater discharge on aquatic environments, in terms of both runoff quality and quantity (Victorian Stormwater Committee 1999). Elevated nutrient levels contribute to eutrophication and in coastal ecosystems nitrogen is thought to be particularly important (Howarth & Marino 2005). Reducing the amount of nitrogen discharged from urban areas to the rivers and sea is therefore important.

The incorporation of stormwater management into urban landscapes is increasingly common. However, potential treatment measures are restricted in highly urbanised areas where space is limited. The re-design of street-tree rootzones is one option for incorporating stormwater treatment into such areas. This paper provides some detail from an experiment that was conducted to evaluate the potential for using street trees as elements of a bioretention system. In this paper, tree growth responses and nitrogen behaviour are reported.

METHODS

The experimental method has been described previously (Breen *et al.* 2004). Briefly, trees were grown for 15 months in model soil profiles, which were built in above ground-containers. The species were *Eucalyptus polyanthemos*, *Lophostemon confertus*, *Platanus orientalis* and an unplanted control. Three soil treatments with different drainage rates (saturated hydraulic conductivities of 4, 95 and 170 mm/hr) were used and are referred to as, low, medium and high saturated hydraulic conductivity (SHC). Profiles were charged with tapwater (control) or a model stormwater solution weekly. The model stormwater solution, adapted from Davis *et al.* (2001), contained nitrate, organic nitrogen, phosphorus, copper and dissolved solids as sodium and magnesium chloride. No sediment was included. The total nitrogen load applied during each irrigation event was 25.2 mg, 8.4 mg N as nitrate and 16.8 mg N as glycine. In total the experiment contained 30 treatments with 8 replicates of each making a total of 240 experimental units.

Tree height was recorded monthly from September 2003 until January 2005. Relative height growth rate for each monthly interval (cm cm^{-1} $week^{-1}$) is presented here. Foliage collected in January 2005 was oven dried (70℃), finely ground a nd then analysed for nitrogen content by the Dumas combustion method (Carlo Erbra, NA1500 Series II). For root analysis, a 400 mm long, 16 mm diameter, core sample was taken vertically from each profile in January 2005. The core samples were divided into four 100 mm long sections which were then halved lengthwise, to allow simultaneous analysis of both tree root growth and soil nutrient status. *P. orientalis* root length was measured with WinRHIZO (Regent Instrument Inc.) software using a flat bed scanner (Epson Expression 1680). Root lengths are reported as root length densities.

Leachate from the soil columns was collected for two hours after irrigation commencement. In December 2004 collection times were extended for another 3 hours from a sub sample of profiles to quantify the percent completeness of the standard collection. Leachate samples for nutrient analysis were stored at 4℃ until analysed. Oxidis ed nitrogen (NO_x) was analysed by an automated cadmium reduction method (Clesceri *et al.* 1998) with an Alpkem (Perstorp Analytical) segmented flow autoanalyser. Ammonium (NH_3) was analysed with an automated phenate method (Clesceri *et al.* 1998) with a flow injection autoanalyser. Total nitrogen was determined as nitrate, following alkaline persulphate digestion (Clesceri *et al.* 1998). Organic nitrogen was calculated as the difference between total and mineral (NO_x + NH_3) nitrogen.

RESULTS AND DISCUSSION

Tree growth parameters

Tree height

Figure 1 shows the relative height growth rate of *E. polyanthemos, L. confertus and P. orientalis* growing in the medium SHC soil from October 2003 to January 2005. The relative height growth rates were similar for all treatments. There appears to be a response to stormwater treatment during periods of accelerated growth. The species all exhibited seasonal changes in growth patterns with maximum growth rates occurring in late Spring and Summer. *L. confertus* also continued to grow through the Autumn months (Figure 1). Absolute height growth rates were significantly greater in the stormwater treatments compared with tapwater (Figure 2). In general there were no differences between height growth in the three soils used.

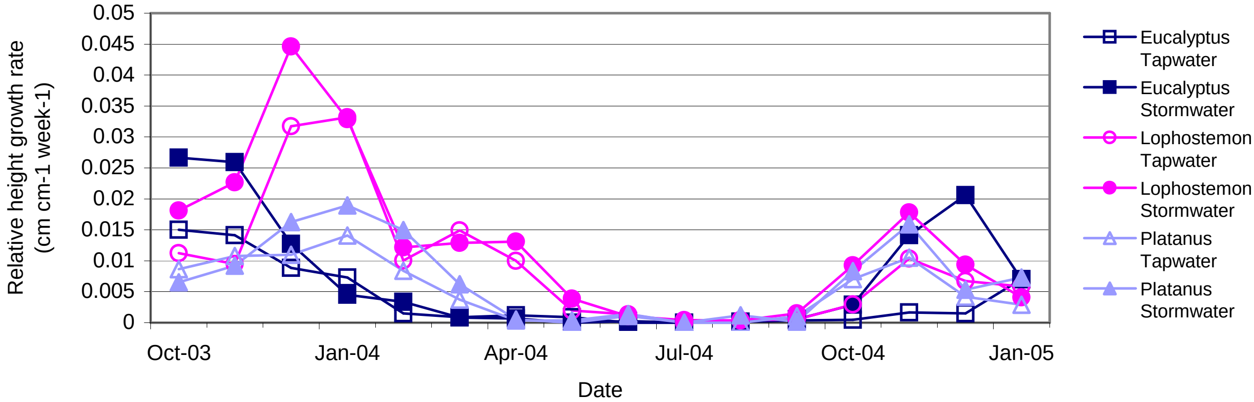

Figure 1 Relative height growth rate of *E. polyanthemos*, *L. confertus* and *P. orientalis* growing in the medium SHC soil (cm cm^{-1} week^{-1}) in response to water quality treatment

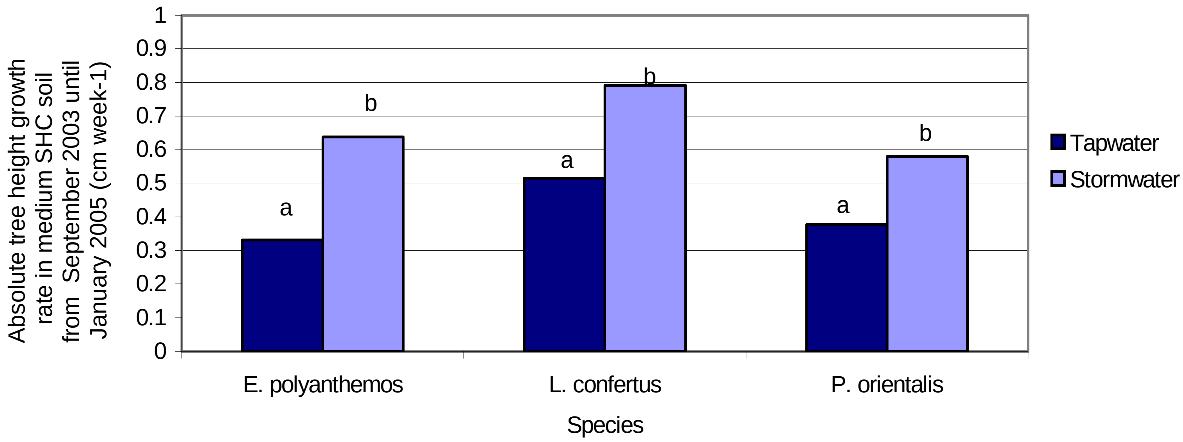

Figure 2 Absolute height growth rate (cm week^{-1}) of *E. polyanthemos*, *L. confertus* and *P. orientalis* growing in the medium SHC soil, from September 2003 to January 2005, in response to water quality treatment, within each species, means with the same letter are not significantly ($p<0.05$) different

Foliage nitrogen

The significant interaction between species and water quality application for foliage nitrogen content is shown in Table 1. *E. polyanthemos* and *P. orientalis* receiving stormwater had significantly higher concentrations of foliage nitrogen than those receiving tapwater (Table 1). Stormwater application had no effect on foliage nitrogen concentration in *L. confertus*. There was no affect of soil on foliage nitrogen content.

Comparisons with published foliage data of the same or similar species suggests that the trees in this experiment were most likely nitrogen deficient (Table 1). Boardman *et al.* (1997) suggest 11–14 mg g^{-1} as an adequate concentration of foliage nitrogen for *L. confertus*. Dell (1996) reports *Eucalyptus maculata* foliage in the range of 10-12 mg g^{-1} nitrogen as deficient, while 17-26 mg g^{-1} indicates adequate nitrogen concentrations. Although not investigating critical levels for tree growth, Wood *et al.* (1977) reported foliage nitrogen concentrations of 17 mg g^{-1} in *Platanus occidentalis* trees growing on an unfertilised terrace site. Foliage nitrogen content was significantly higher in *P. occidentalis* following the addition of nitrogen fertiliser only (22.7 mg g^{-1}) or nitrogen and phosphorus (21.8 mg g^{-1}) fertiliser (Wood *et al.* 1977). Similarly, the nitrogen content of healthy looking *Platanus* x *acerifolia* 'Bloodgood' and *Platanus occidentalis* leaves were in the range of 16.2-27.3 mg g^{-1} (Mills & Jones Jr. 1996).

Table 1 Foliage nitrogen content (mg g^{-1}) for the interaction between species and water quality

Species	Water quality [y]LSD = 0.9	
	Tapwater	Stormwater
E. polyanthemos	6.0 ab	8.3 c
L. confertus	5.4 a	6.3 ab
P. orientalis	9.9 d	11.7 e

[y] means followed by the same letter are not significantly ($p<0.05$) different

Root growth

Root length density of only *P. orientalis* is presented here. Root length measurements of *E. polyanthemos* and *L. confertus,* were not possible due to the presence of an apparent fungal association on the root samples (see Figure 3). The scanning equipment used to quantify root length was unable to distinguish between the roots and fungal mass. Dry weight will be used to estimate root growth for future reporting.

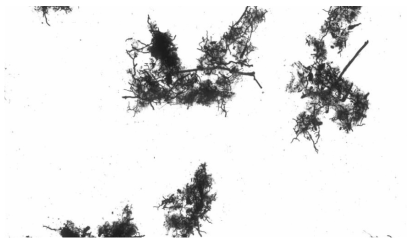

Figure 3 Fungal presence on *E. polyanthemos* root sample

Analysis of *P. orientalis* root length density showed that the application of nutrients in the stormwater resulted in greater root growth. Interactions between depth/water quality and depth/soil were significant resulting in the pattern of root distribution down the profile varying between the water quality treatments. Root density peaked in the 100-200 mm zone for the control trees and then reduced significantly, to values similar to the surface, in the lower two zones (Table 2). In contrast, when stormwater was applied root density at the lowest two zones (200-300 and 300-400 mm) was similar to the 100-200 mm zone.

Table 2 *P. orientalis* root length density (cm cm^{-3}): water quality and depth interaction

Water quality	Sample depth from surface (mm) [y]LSD=1.99			
	0-100	100-200	200-300	300-400
Tapwater	7.5 a	10.5 c	7.2 a	8.2 ab
Stormwater	10.0 bc	17.4 de	15.9 d	18.6 e

[y] means followed by the same letter are not significantly ($p<0.05$) different

Table 3 *P. orientalis* root length density (cm cm^{-3}): soil and depth interaction

Soil	Sample depth from surface (mm) [y]LSD=2.43			
	0-100	100-200	200-300	300-400
Low SHC	10.5 bcd	15.2 g	13.6 efg	13.1 efg
Medium SHC	7.1 a	13.7 fg	11.3 cde	14.6 fg
High SHC	8.6 ab	12.9 efg	9.7 bc	12.5 def

[y] means followed by the same letter are not significantly ($p<0.05$) different

In all three soils, root length density was lowest in the surface zone (0-100mm), significantly so except for one instance (High 200-300 mm). In the low SHC soil, root density was similar in the three lower zones (Table 3). The pattern differed in the medium and high SHC soils where root length density was significantly lower in the third zone, compared to the second and forth.

These tree height and root density results demonstrate that under the relatively high frequency of recharge events used in this experiment the trees were able to establish and grow successfully and there was an apparent response to the nutrients carried in the stormwater. *P. orientalis*, root growth was affected by the treatments in as much as roots were distributed through the profile in patterns that conform to expected behaviour. Especially encouraging was the uniform penetration of roots in the low SHC soil where it had been anticipated that low aeration would result in limited growth. *Platanus* has a reputation for tolerating poor soil aeration (Smith *et al.* 2001) and so this observation is perhaps not unexpected. The different distributions of roots in the medium and high SHC soils may be due to leaching of nutrients to lower parts of the profile in these more freely drained soils. Soil nutrient analysis will be used to validate this assumption. These data prove the concept in terms of plant success.

Nitrogen behaviour

NO_x loads are presented for unplanted and planted (3 species averaged) for January, June and December 2004. Analysis of leachate volumes for these months is also provided to allow some assessment of the relationship between NO_x load and concentration. Ammonium, NO_x and Organic N loads leached from the planted profiles in December 2004 are also presented.

NO_x Load: January, June and December 2004

The NO_x leached from unplanted profiles was substantially greater than from planted systems in all three months (Figure 4). In the unplanted profiles all stormwater systems leached more NO_x than tapwater systems. With the exception of the low SHC systems, this pattern was similar for the planted systems but much less pronounced. There was no difference between the loads leached from the low SHC for tapwater and stormwater. This suggests that low SHC can significantly influence nutrient retention. Some seasonal patterns seem evident, but are not considered to be significant in a practical sense.

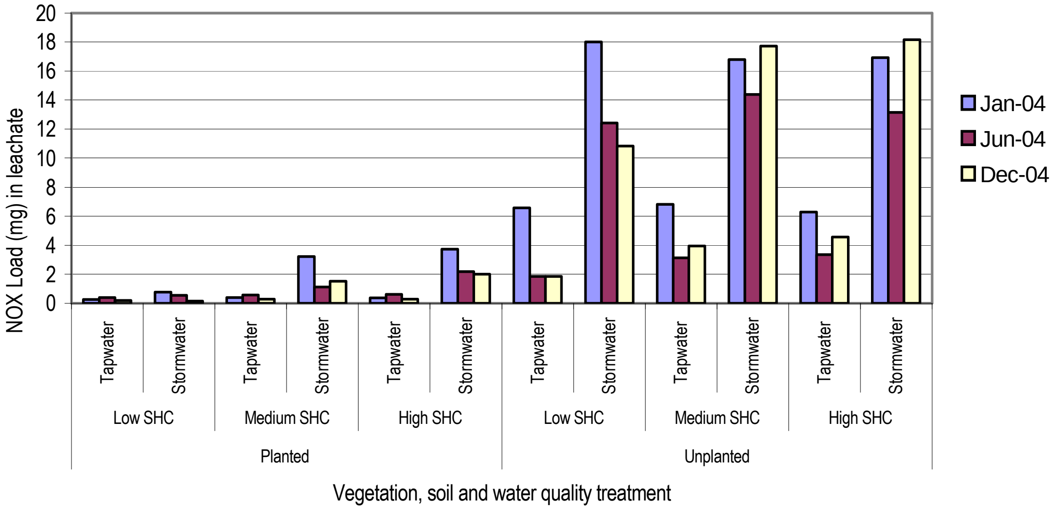

Figure 4 NO_x load (mg) in the leachate from planted (*E. polyanthemos, L. confertus* and *P. orientalis* averaged*)* compared with the unplanted systems in January, June and December 2004

Leachate volumes: January, June and December 2004.

In January, June and December 2004 leachate volumes from all systems were significantly affected by soil treatments (Table 4). In January and June the leachate volumes were statistically different with low SHC<medium SHC<high SHC (Table 3). In December, the leachate volumes were again significantly lower in the low SHC soil, but similar in the medium and high SHC soils.

Table 4 Leachate volumes (mL) in January, June and December 2004 in response to soil treatment

Soil	Month of leachate collection		
	[y]January 2004 (LSD = 137.6)	[y]June 2004 (LSD = 172.8)	[y]December 2004 (LSD = 203.9)
Low SHC	1367 a	1950 a	979 a
Medium SHC	1805 b	2830 b	1463 b
High SHC	1981 c	3060 c	1565 b

[y] means followed by the same letter down the column are not significantly ($p<0.05$) different.

Table 5 Leachate volumes (mL) from all systems in January, June and December 2004: vegetation treatment and water quality interaction

Vegetation treatment	Water quality	Month of leachate collection		
		[y]January 2004 (LSD = 251.2)	June 2004	[y]December 2004 (LSD = 263.2)
E. polyanthemos	Tapwater	1378 ab	2559	1120 b
	Stormwater	1291 ab	2515	469 a
L. confertus	Tapwater	1806 c	2513	1714 c
	Stormwater	1179 a	2340	722 a
P. orientalis	Tapwater	1478 b	2897	991 b
	Stormwater	1316 ab	2758	516 a
Unplanted	Tapwater	2675 d	2586	2602 d
	Stormwater	2795 d	2711	2655 d

[y] means followed by the same letter down the column are not significantly ($p<0.05$) different. Main effect (species) rather than interaction is significant in June.

In June 2004, the leachate volumes for the planted profiles were similar to the unplanted (Table 5). In this winter month, the leachate volumes were greatest from the *P. orientalis* profiles, and the difference between the *P. orientalis* profiles and the other two planted profiles was significant. In December 2004, the volume of leachate from the planted systems was significantly lower in stormwater treatments compared to tapwater. In contrast, the leachate volumes from the unplanted tapwater and stormwater treatments were similar. In January 2004, there was no difference between the water quality treatments for *P. orientalis*, *E. polyanthemos* and the unplanted, but as was the case for December the tapwater volumes were higher for *L. confertus*.

Leachate volumes were affected by the development of the trees (January > December 2004 and December tapwater > December stormwater), by season (June > December and January) and to some extent by species. In winter when *P. orientalis* had no leaves and therefore transpirational drying was reduced, the leachate volumes were significantly higher from this species.

Nitrogen in December 2004 leachate

Ammonium, NO_x and Organic N loads were markedly lower in planted compared to unplanted systems. For both NO_x and Organic N the loads from planted profiles receiving stormwater were not statistically greater than the unplanted tapwater controls when comparing the same soil treatment. As evidenced by increased tree height and root growth, the trees and potentially the soil microbes were clearly utilizing some of the nitrogen within the systems. The following sections detail the behaviour of NH_3, NO_x and Organic N in planted profiles only.

Ammonium

Analysis of the ammonium leachate load for *L. confertus*, *E. polyanthemos* and *P. orientalis* showed that the Species/Soil (Table 6) and Soil/Water Quality (Table 7) interactions were significant. In terms of species differences, in the low SHC soil significantly higher ammonium loads were leached from the *L. confertus* planted profiles as compared to the *E. polyanthemos* and *P. orientalis*. Although statistically significant, the differences are small in practical terms. In the medium and high SHC soils no statistically significant differences in ammonium leaching were found between the three species. The ammonium loads leached from the low, medium and high

SHC soil profiles with tapwater were not statistically different. However, when stormwater charges were used the differences in ammonium leachate load between the three soils were significant with low < medium <high SHC (Table 7).

Table 6 Species and soil interaction for NH_3-N load (mg) in December 2004 leachate, planted profiles

Species	[y]Soil		
	Low SHC[z]	Medium SHC	High SHC
E. polyanthemos	0.005 a	0.036 bc	0.065 bc
L. confertus	0.030 b	0.045 bc	0.054 bc
P. orientalis	0.006 a	0.036 bc	0.076 c

[y] means followed by the same letter are not significantly (p<0.05) different. Means are log back transformed.
[z]zero leachate volumes were measured for some of the *E. polyanthemos* and *P. orientalis* systems.

Table 7 Water quality and soil interaction for NH_3-N load (mg) in December 2004 leachate, planted profiles

Water quality	[y]Soil		
	Low SHC	Medium SHC	High SHC
Tapwater	0.014 ab	0.024 b	0.019 b
Stormwater	0.007 a	0.061 c	0.216 d

[y] means followed by the same letter are not significantly (p<0.05) different. Means are log back transformed.

Oxidised Nitrogen (NO_x)
There was a significant species effect on NO_x leaching (Table 8) and as with ammonium, the interaction between Soil and Water quality was also significant (Figure 5). In the medium and high SHC soils the NO_x load from the stormwater treatments was significantly greater than from the tapwater (Figure 5). This was due to higher NO_x concentrations in the stormwater charged leachate. In the low SHC soil, NO_x load from the tapwater charged soil was higher than from stormwater, however the difference is not large in practical terms.

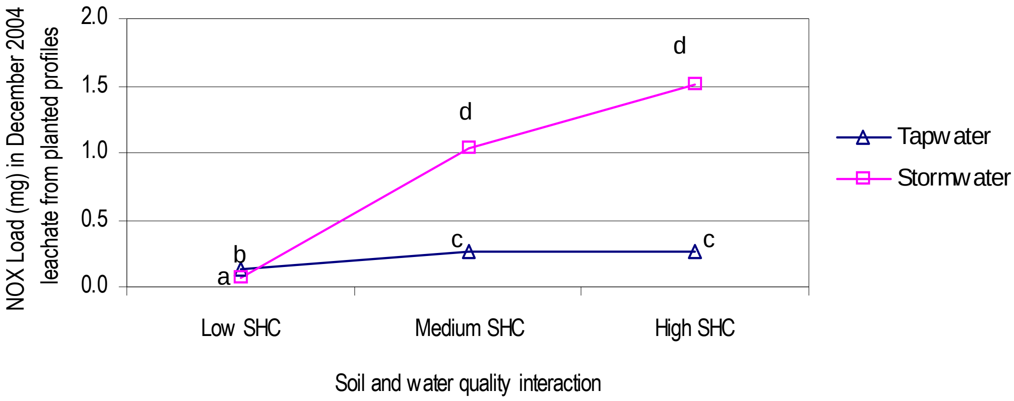

Figure 5 Soil and water quality interaction for the NO_x load (mg) in December 2004 leachate from the planted profiles, means with the same letter are not significant different (p<0.05), means are back log transformed

In terms of the species treatment effect, the NO_x load leached from the *L. confertus* profiles was statistically greater than from the *P. orientalis* and *E. polyanthemos* profiles (Table 8). In comparison to the simulated stormwater input load (8.4 mg), these species differences in NO_x load are small.

Table 8 NO_x load (mg) leached from *E. polyanthemos, L. confertus* and *P. orientalis* systems in December 2004

Species	[y]NO_x load (mg)
E. polyanthemos	0.27 a
L. confertus	0.42 b
P. orientalis	0.29 a

[y] means followed by the same letter are not significantly ($p<0.05$) different. Means are log back transformed.

Organic Nitrogen

Organic nitrogen in leachate was determined by the calculation (TN - (NO_x + NH_3)). There was a significant species effect on organic N leaching load and the interaction between Soil and Water quality was also significant. As with NO_x load, the Organic N load was higher in the *L. confertus* leachate than in the leachate from the *P. orientalis* and *E. polyanthemos* profiles (Table 9).

Table 9 Organic N load (mg) leached from planted systems in December 2004

Species	[y]Organic Nitrogen load (mg)
E. polyanthemos	0.94 a
L. confertus	1.46 b
P. orientalis	1.03 a

[y] means followed by the same letter are not significantly ($p<0.05$) different. Means are log back transformed.

There was a significant interaction between the Soil and Water quality treatments in terms of Organic N load (Figure 6). There was no difference between tapwater and stormwater treatments for the medium and high SHC soil. In the low SHC soil, the Organic N load leached from the stormwater treatments was significantly less than from the tapwater.

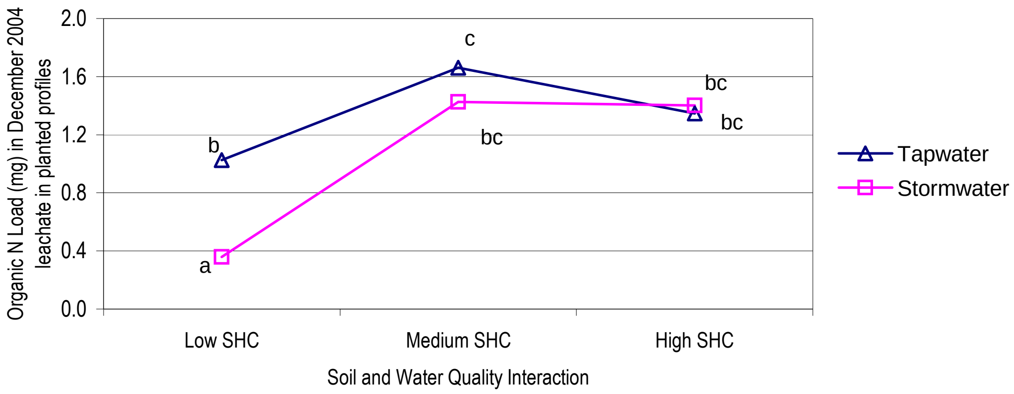

Figure 6 Soil and water quality interaction for Organic N Load in December 2004 leachate from planted profiles, means with the same letter are not significant different ($p<0.05$), means are back log transformed

In the planted profiles, the two forms of mineral nitrogen measured in leachate tended to behave in a similar manner. Higher NH_3 and NO_x loads were lost from the stormwater medium and high SHC soils compared to the tapwater controls. In the low SHC soils loads were less in the stormwater than the tapwater treatments, significantly so in the case of NO_x. Organic nitrogen behaved in a similar manner to NO_x in the low SHC soil. In contrast to the inorganic nitrogen forms, the organic N leachate loads from tapwater and stormwater treatments in the medium and high SHC soils were similar. This indicates that the organic N applied in the stormwater was not being leached through the system. Mineralisation of the glycine added may be occurring between irrigation events, leading to higher discharges of ammonium in the stormwater treatments. The difference in ammonium leachate (low<medium<high SHC) presumably reflects less cation exchange (White 1997) or reduced reaction times in the sandier, faster draining soils.

Good reductions in nitrogen load were achieved in the planted profiles. Compared to the total nitrogen input (25.2 mg), the load leached after 5 hours from the *L. confertus* profiles was 95% less for the low SHC (1.4 mg), 85% for the medium SHC (4.1 mg) and 82% for the high SHC soils (4.6 mg). In the unplanted profiles the low SHC soil achieved a 36% (16.2 mg) reduction in the output load compared to the input. The unplanted medium (25.2 mg) and high SHC (27.0 mg) soils did not reduce nitrogen leaching. Trees are therefore a necessity in these proposed systems to reduce nitrogen loads, particularly if sandy, fast draining soils are used.

CONCLUSION

The trees were able to establish successfully and growth was enhanced by stormwater applications. Relative tree height growth rates were in practical terms similar for all treatments. Absolute height growth rates were greater for stormwater than tapwater treatments. *P. orientalis* and *E. polyanthemos* receiving stormwater had significantly greater nitrogen contents in their foliage than trees receiving tapwater. This water quality response was not seen in *L. confertus.* Foliage analysis suggests that nitrogen was limiting tree growth in the system. *P. orientalis* root length density was greater in response to stormwater and the differences were most pronounced in the lower half of the profiles. The leachate volumes in December 2004 were significantly less from trees receiving stormwater than tapwater, presumably due to these differences in tree growth. The presence of a tree resulted in significantly less nitrogen being leached from the systems. NO_x and Organic N loads from the *L. confertus* systems were statistically higher than the other two species, although all these loads from planted systems were low compared to the nitrogen input. The species differences in loads were due to reduced leachate volumes in the Summer month rather than nitrogen concentrations and therefore suggest differences in transpiration rates rather than uptake efficiencies. The low SHC soil was more effective in reducing nitrogen losses, particularly the inorganic forms. However, the two faster draining soils would enable infiltration of larger volumes of stormwater in practice. Compared to the total nitrogen input (25.2 mg) the leachate loads in December 2004 following a 5 hour collection period were 82-95% reduced for the *L. confertus* profiles. However, the loads leached from the unplanted profiles ranged from a 36% reduction to a 7% increase in nitrogen output. The results suggest that street trees and their root zone soils can be successfully used as bioretention systems for nitrogen removal.

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