A field study to evaluate the impact of different factors on the nutrient pollutant concentrations in green roof runoff

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ABSTRACT

The objectives of this study are to investigate the impact of different factors on the nutrient pollutant concentrations in green roof runoff and to provide reference data for the engineering design of dual substrate layer green roofs. The data were collected from eight different trays under three kinds of artificial rains. The results showed that except for total phosphorus, dual substrate layer green roofs behaved as a sink for most of the nutrient pollutants (significant at $p < 0.05$), and the first-flush effect did not occur during the 27 simulated rain events. The results also revealed that the concentration of these nutrient pollutants in the runoff strongly depended on the features of the nutrient substrates used in the green roof and the depth of the adsorption substrates. Compared with the influence of the substrates, the influence of the plant density and drainage systems was small.

Key words | drainage system, green roof, nutrient pollutant, plant density, substrate

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INTRODUCTION

Fitting well with the concept of modern green cities, green roofs have become a popular choice in urban design in many countries such as the UK, Sweden, the USA, Australia, Switzerland, Japan and Singapore (Mentens *et al.* 2006; Brenneisen 2006; Berndtsson *et al.* 2008; Williams *et al.* 2010; Vijayaraghavan *et al.* 2012). Although green roofs were first invented for aesthetic appeal, research studies showed that green roofs had numerous benefits, including reducing and retaining storm water and improving the urban water balance (Bengtsson *et al.* 2005; Mentens *et al.* 2006; Palla *et al.* 2011); reducing the cost of heating, air conditioning and the urban heat island effect (Wong *et al.* 2003); decreased rooftop temperatures (Köhler *et al.* 2002); improvement of the local microclimate through evaporation; creating a wildlife habitat and biodiversity enhancement (Brenneisen 2006); and reducing air pollution (Currie & Bass 2008).

From a storm water management perspective, because of the ability to retain and detain storm water, green roofs have played an important role in modern urban drainage (Villarreal & Bengtsson 2005). Many research studies investigated green roofs' performance on controlling the storm water runoff quantity and lowering and delaying the runoff peaks, thus reducing runoff volume mechanisms. However, as Berndtsson and colleagues suggested, little was known on the actual influence of vegetated roofs on the runoff quality (Berndtsson *et al.* 2006). A few research studies showed that green roofs could act as pollution filters for some of the pollutants and as a source of contaminants for others (Vijayaraghavan *et al.* 2012). Research conducted at Augustenborg and the Canoe Club House showed that using easily dissolvable fertilizers might cause vegetated roofs to behave as a source of contaminants (Berndtsson *et al.* 2006). A recent study in Singapore showed that the concentrations of most of the chemical components in runoff were highest during the beginning of rain events and subsided in subsequent rain events. Both Hathaway's and Vijayaraghavan's research studies demonstrated the importance of green roof media selection when pollutant removal was a concern (Hathaway *et el.* 2008; Vijayaraghavan *et al.* 2012). Beck amended green roof soil with biochar and got significant improvements in both the runoff water quality and retention (Beck *et al.* 2011). The study of a lightweight aggregate-based green roof in Estonia proved that the quality of the runoff water varies depending on the character of the runoff and the pollutants accumulated on the roof (Teemusk

doi: 10.2166/wst.2013.547

& Mander 2007). Another research showed that runoff conductivity depended primarily on the soil depth and the existence or absence of vegetation (Buccola & Spolek 2011).

The fundamental studies mentioned above have pointed out some of the factors affecting green roof runoff quality and some of the methods to improve runoff quality. To enhance our knowledge on this topic, the present study was conducted to evaluate the impact of different factors on the nutrient pollutant concentrations in dual substrate layer green roof runoff. To achieve this goal, eight pilot-scale green roof trays with artificial rainfall devices were constructed on a real roof. Several simulated rain events were used to evaluate the runoff water quality on the basis of nutrient pollutants, such as the total nitrogen (TN), ammonia-nitrogen (NH_3-N), the total phosphorus (TP) and the chemical oxygen demand (COD).

METHODS

Study site and green roof design

The green roof test plot was established on the Environmental Experimental building in March 2012 on the campus of Tianjin University, Tianjin, China. The roof systems were in eight 0.5 m × 0.7 m trays (Figure 1). The dual substrate layer green roof trays (A1–A8) consisted of the following layers: a base roof, a commercial plastic wave drainage layer (8 mm/16 mm), a geotextile filter layer to prevent small particles from getting into the drainage layer or out of the system, a dual substrate layer (10–35 cm) and a vegetation layer on the top. The dual substrate layer consisted of two parts, the uppermost being a thin layer (5 cm) with a nutritional substrate for plant growth and a thick media layer (5–30 cm) for water detention and the reduction of nutrient pollutants. All trays were placed on a 3° slope to simulate common roof design. Roof runoff was collected from the lower end of the trays through sampling orifices (Figure 1). The experiments were carried out between early June and late October 2012.

Sedum is widely used in green roofs because of its ability to survive in low nutrient and drought conditions and extreme temperature (Villarreal & Bengtsson 2005). Commonly seen in China, *Sedum lineare* Thunb. was selected. To evaluate the impact of the plant density on the runoff quality, the plants were planted in A2 at a density of 36 plugs/m^2 and at a density of 64 plugs/m^2 in the other trays. After 1 month of growth, when the mature roots were about 5 cm long, the experiment was conducted.

Two kinds of nutrient substrates were used in the study. One was local grass charcoal soil (NS2), which was used in A3, and the other one was a commercial substrate called BAOLVSU (NS1), which was used in the other trays. BAOLVSU is specially made for green roofs based on inorganic material and organic and inorganic fertilizers. A perlite and vermiculite mixed (1:1) substrate (AS) was used as the adsorption substrate for nutrient adsorption and water retention. All assemblies had a nutrient substrate depth of 5 cm. However, A4, A5 and A6 had different adsorption substrate depths (5, 20, and 30 cm, respectively), and the other trays' AS depths were 10 cm. The impact of

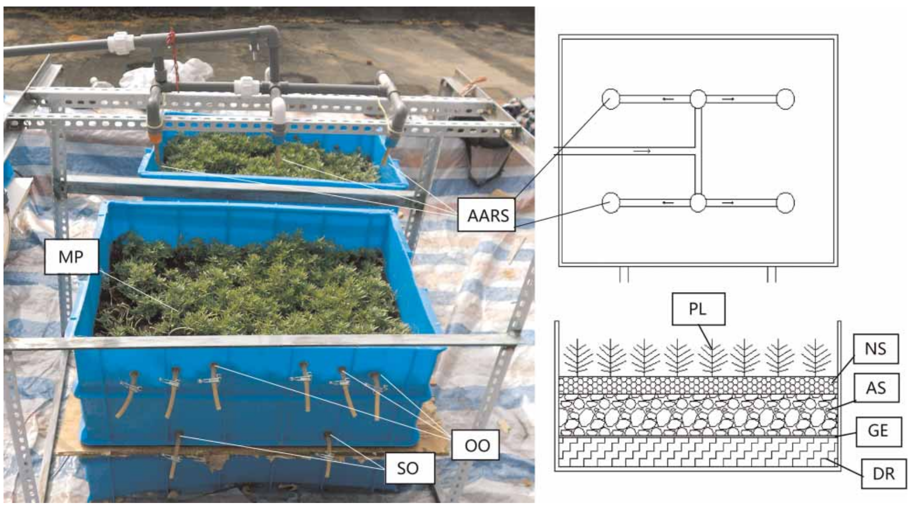

Figure 1 | Green roof trays on the rooftop in Tianjin University, China (MP: *Sedum lineare* Thunb.; AARS: adjustable artificial rainfall sprinklers; OO: overflow outlet; SO: sampling orifice; PL: plant layer; NS: nutrient substrate; AS: adsorption substrate; GE: geotextile; and DR: drainage system).

the depth ratio of the nutrition substrate and adsorption substrate on the runoff quality was of high concern in this study.

Two commercial drainages were used to evaluate the impact of the drainage system. They were both specially made from a pressure-moulded polyethylene plastic floor. DM1 was a storage drainage plate. DM2 was a common drain board. Single-layer DM1 was used in most trays. However, a double-layer DM1 was used in A8, and DM2 was used in A7. A summary of the contrasting factors of the green roof trays is provided in the supporting information (available online at http://www.iwaponline.com/wst/068/547.pdf).

Simulations with artificial rain

To study the impact of different rainfall densities and durations on the runoff quality, rain simulations with artificially mixed rain water were performed on A1–A8 with three different rainfall densities (Table 1) using a movable multifunctional artificial rain generator. The artificially mixed rain water was made by utility water and chemicals to simulate the chemistry of rain water according to the rainwater quality experimental data field analysis in Tianjin, China. (TN: 2 ± 0.1 mg/L; NH_3-N: 1.0 ± 0.005 mg/L; TP: 0.05 ± 0.0025 mg/L; COD: 30 ± 1.5 O_2 mg/L).

Sampling and analysis

When the runoff started to occur during a simulated rain event, a runoff sample was taken for chemical analyses every 5 or 10 min. Additionally, the ambient temperature, substrate moisture and runoff reserved volume were also recorded. All the runoff samples were immediately brought to the laboratory to analyse the COD, TN, NH_3-N and TP.

RESULTS AND DISCUSSION

All trays were exposed to dry conditions for at least 3 days, and only when the substrate moisture fell to 20% were the experiments started. As a result, runoff started to generate 6–15 min after rain events started. In total, 366 nutrient concentration tests were completed (120 tests under R1, 154 tests under R2, and 92 tests under R3), and the results are presented in Table 2. The results showed that the different types of dual substrate layer green roofs used in the present study generally behaved as a sink for most of the nutrient pollutants, such as the TN, NH_3-N, and COD (significant at $p < 0.05$), but also released phosphorus to the water, causing the TP concentration in the runoff to increase. This result is consistent with Berndtsson's study on an extensive green roof in Sweden (Berndtsson *et al.* 2009).

Table 1 | Simulated rainfall sizes

Rain pattern	R1	R2	R3
Average flow (L/s)	0.0012	0.0023	0.0036
Duration (min)	50 ± 2	35 ± 2	20 ± 2
Total volume (L)	3.6 ± 0.05	4.8 ± 0.05	4.3 ± 0.05
Effective area (m^2)	0.50 ± 0.01	0.50 ± 0.01	0.50 ± 0.01
Intensity (mm/h)	86 ± 10	168 ± 10	258 ± 10

Table 2 | Statistical results of nutrient concentrations in runoff from all eight trays (UL/LL: upper limit/lower limit within a 95% confidence interval; AC: average concentration; SD: standard deviation; and ARE: average removal efficiency)

	Rainfall pattern	UL (mg/L)	LL (mg/L)	AC (mg/L)	SD (mg/L)	ARE (%)
TN	R1	1.84	2.28	1.98	0.75	1.19
	R2	1.72	1.88	1.79	0.34	10.50
	R3	1.53	1.74	1.64	0.31	18.00
TP	R1	0.29	0.41	0.35	0.21	–
	R2	0.43	0.54	0.49	0.20	–
	R3	0.41	0.55	0.48	0.20	–
NH_3-N	R1	0.48	0.71	0.59	0.39	39.15
	R2	0.45	0.56	0.51	0.22	48.32
	R3	0.38	0.54	0.46	0.25	53.80
COD	R1	16.31	20.31	18.30	6.42	39.00
	R2	15.43	19.18	17.30	7.20	42.33
	R3	14.79	19.26	17.02	6.51	43.67

The impact of each factor on the nutrient concentration in green roof runoff

Plant density

Table 3 shows that, except for TP, A1 performed as a sink for nutrient pollutants with all rain events, while A2 performed as a source of nutrient pollutants with R1. The results also showed that, during R1, the nutrient concentrations in the A2 runoff were much higher than that in A1, but there were little differences between R2 and R3. The possible cause was that the high density of plants reduced the rainfall erosion on the surface nutrient substrate to some extent, but when the rainfall intensity increased to a certain extent, this reduction was no longer evident. The first 5 minutes of runoff quality was much better than the final and the average quality. Unlike Berndtsson's research in Sweden, the first-flush effect was not observed in the present study

Table 3 | Nutrient pollutant concentrations in the runoff at different artificial rain events from A1 and A2 (FFC: nutrient concentrations in the first 5 minutes of runoff; FC: nutrient concentrations in the final runoff; AC: average concentrations; and ARE: average removal efficiency)

	Rain event	No.	FFC (mg/L)	FC (mg/L)	AC (mg/L)	ARE (%)
TN	R1	A1	1.90 ± 0.05	1.86	1.98	1
		A2	2.65 ± 0.50	4.94	4.48	–
	R2	A1	1.62 ± 0.04	1.90	1.79	10.5
		A2	1.64 ± 0.07	1.91	1.82	9
	R3	A1	1.49 ± 0.06	1.52	1.49	22.5
		A2	1.40 ± 0.09	1.76	1.64	18
NH_3-N	R1	A1	0.07 ± 0.02	0.46	0.23	77
		A2	0.61 ± 0.23	1.94	1.29	–
	R2	A1	0.11 ± 0.01	0.38	0.34	66
		A2	0.47 ± 0.02	0.76	0.6	40
	R3	A1	0.16 ± 0.02	0.13	0.17	83
		A2	0.20 ± 0.02	0.33	0.29	81
TP	R1	A1	0.46 ± 0.01	0.64	0.5	–
		A2	0.53 ± 0.02	0.84	0.74	–
	R2	A1	0.43 ± 0.04	0.6	0.52	–
		A2	0.58 ± 0.08	0.72	0.63	–
	R3	A1	0.35 ± 0.04	0.48	0.43	–
		A2	0.44 ± 0.01	0.5	0.51	–
COD	R1	A1	14 ± 1	25	21	30
		A2	21 ± 1	34	27	10
	R2	A1	4 ± 1	14	8	73.3
		A2	5 ± 1	17	11	63.3
	R3	A1	12 ± 2	19	17	43.3
		A2	14 ± 1	23	20.4	32

(Berndtsson *et al.* 2008). This was probably because the existence of the unique adsorption substrate layer strengthened the adsorption of the contaminants. This also indicated that substrate adsorption was one of the main factors in removing nutrients.

The plant density also influenced the concentration of nutrient in the water at the end of the rain events. During the same growth period and conditions, a higher density of green plants consumed more nutrients in the substrate, resulting in a relatively smaller release of nutrients from the surface nutrient substrate and thus, in the process of rainfall, reduced the pollutant load of the adsorption substrate layer. Therefore, A1's final runoff nutrient concentrations were lower than A2's (Table 3).

Nutrient substrate materials

Figure 2(a) shows that A1's runoff quality was much better than A3's, especially for TP and COD. Because the composition of NS2 was mainly humus and inorganic fertilizers, as Emilsson suggested, conventional fertilizers or nutrient-rich material can lead to serious nutrient leaching (Emilsson *et al.* 2007). In contrast to NS2, the commercial substrate NS1 was mainly composed of inorganic materials and had the ability to control nutrients so that they were released slowly and efficiently; so it had relatively less adverse effects on the runoff quality.

The soil permeability and porosity and the nitrifying bacteria content of the nutrient substrate or soil also had a great impact on the green roof's ammonia nitrogen removal efficiency (Dietz & Clausen 2006). The void ratio of NS2 was 20% higher than that of NS1, and the microbial content of the garden soil was richer. Furthermore, NH_4^+ can be stored in soil and is not easy to leach, so the ammonia concentration is much smaller than the nitrate. Therefore, A3's average ammonia concentration was higher than A1's by approximately 0.1 to 0.25 mg/L and was only about 60% of the average ammonia concentration of the precipitation. The organic nitrogen content of conventional soil like NS2 generally accounted for 90 to 92% of the total soil nitrogen, but the content of organic nitrogen in its soil solution was relatively low, generally less than 2 mg/L. So the average TN concentration of the A3 runoff was higher than the A1 runoff by only 0.20–0.30 mg/L in different rain events (Figure 2(a)).

For the two substrates tested in our research, NS1 had a better performance on the removal of nutrient pollutants and a longer fertilization cycle than NS2, but it also had disadvantages such as higher costs, a larger bulk density and a lower field capacity. The winter green roof experiment showed that NS1 had a poor winter heat preservation, and about a quarter of the plants were dead and needed to be replaced in the spring, whereas almost all plants in NS2 survived the winter (0 to −15 °C). In specific engineering applications, the ability to detain and retain runoff, heat preservation, bulk density, cost, fertilization and maintenance of the substrate are all important factors when choosing a substrate (Berndtsson 2010).

Substrate depth

The experimental results of A1, A4, A5 and A6 (Figure 2(b)) revealed that the thicker the media depth was, the lower the runoff nutritional pollutant concentrations were. The average TP concentration of A6, whose adsorption substrate depth was 30 cm, was only about 50–60% of A1 or A4. When the volume ratio of adsorption substrate and nutrient substrate (VR) was 2:1, the green roofs started to act as a sink

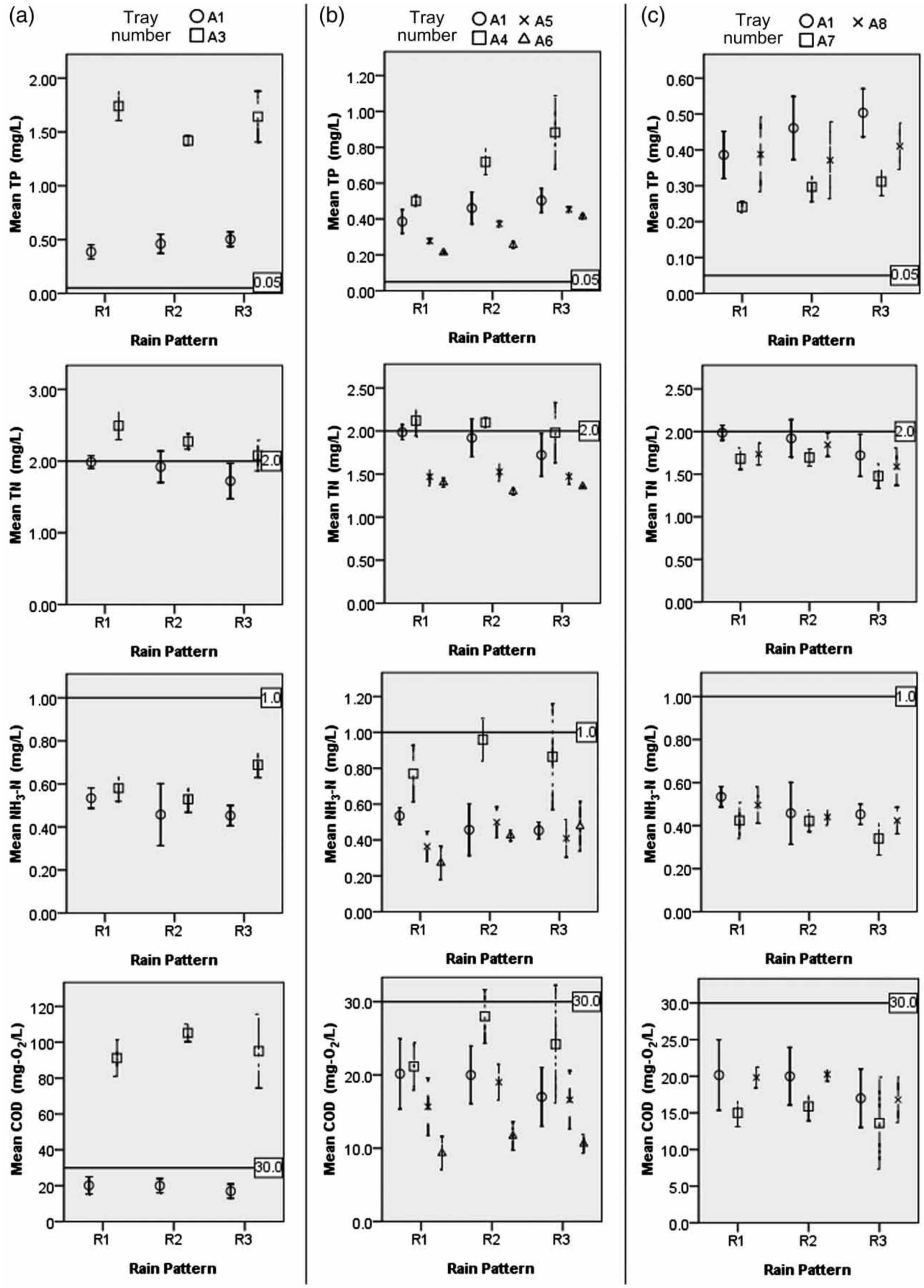

Figure 2 | Nutrient pollutant concentrations in the runoff at different artificial rain events from different trays. (As the type of extensive green roof that tray A1 represented is the most commonly used in China and its unit cost per area is relatively low, A1 was selected as the benchmark for other trays.)

for TN. When the VR increased to 4:1 (A6), the removal efficiency of the TN was increased by 12.7–20%. To further increase the volume ratio to 6:1, the removal efficiency of the TN only improved by 3–5% (Figure 2(b) – TN). Unlike the TN, when the VR increased from 1:1 to 1:2, the concentration of NH_3-N decreased by 40%. Based on this result, when the volume ratio was further increased, the improvement of the removal efficiency was not obvious, only about 5% (Figure 2(b) – NH_3-N). The tendency of the COD concentration to decrease as the VR increased was obvious in all tested pollutants. When the VR was doubled, the removal efficiency increased about 15%. Under a VR of 6:1, the removal efficiency of the COD could reach 67%. These results showed that the marginal revenue of increasing the adsorption substrate decreased for most of the pollutants, so a very large VR was unfavourable and uneconomical. Figure 2(b) also shows that a bigger volume ratio had a higher buffer capacity to the rainfall density.

Drainage system

Berndtsson suggested that the drainage material might be one of the factors that potentially influence the green roof runoff quality (Berndtsson 2010). The test results of A1, A7 and A8 showed that the influence of the drainage system on the four pollutants was quite similar (Figure 2(c)). A8's average removal efficiencies were better than A1's by 2–8%. The results confirmed that increasing the drainage layer depth led to a slight improvement of the runoff quality.

A7's average runoff nutrient pollutant concentrations were also lower than A1's or A8's. However, the hydraulic experiment results showed that A7 produced runoff 12–13 minutes earlier than A1 and decreased the water storage capacity by 2.5 ± 0.1 L as a result of using a drainage board with no water retention ability. Therefore, A1's and A7's removal efficiencies of the total amount of pollutants were almost the same.

CONCLUSIONS

The present study investigated the impact of different factors on nutrient pollutant concentrations in green roof runoff with eight trays and simulated rains. The results showed that dual substrate layer green roofs acted as a sink for TN, NH_3-N and COD but a source for TP. Compared to substrate materials and depths, the influence of the plant densities and drainage systems on the runoff quality was relatively small. A suitable nutrient substrate like NS1 and a large volume ratio should be selected when runoff quality is a concern. The paper also provided unique data on dual substrate layer green roofs for engineering design.

REFERENCES

Beck, D. A., Johnson, G. R. & Spolek, G. A. 2011 Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution* **159** (8), 2111–2118.

Bengtsson, L., Grahn, L. & Olsson, J. 2005 Hydrological function of a thin extensive green roof in southern Sweden. *Nordic Hydrology* **36** (3), 259–268.

Berndtsson, J. C. 2010 Green roof performance towards management of runoff water quantity and quality: a review. *Ecological Engineering* **36** (4), 351–360.

Berndtsson, J. C., Emilsson, T. & Bengtsson, L. 2006 The influence of extensive vegetated roofs on runoff water quality. *Science of the Total Environment* **355** (1), 48–63.

Berndtsson, J. C., Bengtsson, L. & Jinno, K. 2008 First flush effect from vegetated roofs during simulated rain events. *Hydrology Research* **39** (3), 171–179.

Berndtsson, J. C., Bengtsson, L. & Jinno, K. 2009 Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering* **35** (3), 369–380.

Brenneisen, S. 2006 Space for urban wildlife: designing green roofs as habitats in Switzerland. *Urban Habitats* **4** (1), 27–36.

Buccola, N. & Spolek, G. 2011 A pilot-scale evaluation of greenroof runoff retention, detention, and quality. *Water, Air, & Soil Pollution* **216** (1–4), 83–92.

Currie, B. A. & Bass, B. 2008 Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems* **11** (4), 409–422.

Dietz, M. E. & Clausen, J. C. 2006 Saturation to improve pollutant retention in a rain garden. *Environmental Science & Technology* **40** (4), 1335–1340.

Emilsson, T., Berndtsson, J. C., Mattsson, J. E. & Rolf, K. 2007 Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. *Ecological Engineering* **29** (3), 260–271.

Hathaway, A. M., Hunt, W. F. & Jennings, G. D. 2008 A field study of green roof hydrologic and water quality performance. *Transactions of the ASABE* **51** (1), 37–44.

Köhler, M., Schmidt, M., Grimme, F. W., Laar, M., de Assunção Paiva, V. L. & Tavares, S. 2002 Green roofs in temperate climates and in the hot-humid tropics–far beyond the aesthetics. *Environmental Management and Health* **13** (4), 382–391.

Mentens, J., Raes, D. & Hermy, M. 2006 Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning* **77** (3), 217–226.

Palla, A., Sansalone, J. J., Gnecco, I. & Lanza, L. G. 2011 Storm water infiltration in a monitored green roof for hydrologic restoration. *Water Science and Technology* **64** (3), 766–773.

Teemusk, A. & Mander, Ü. 2007 Rainwater runoff quantity and quality performance from a greenroof: The effects of short-term events. *Ecological Engineering* **30** (3), 271–277.

Vijayaraghavan, K., Joshi, U. M. & Balasubramanian, R. 2012 A field study to evaluate runoff quality from green roofs. *Water Research* **46** (4), 1337–1345.

Villarreal, E. L. & Bengtsson, L. 2005 Response of a *Sedum* green-roof to individual rain events. *Ecological Engineering* **25** (1), 1–7.

Williams, N. S., Rayner, J. P. & Raynor, K. J. 2010 Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. *Urban Forestry & Urban Greening* **9** (3), 245–251.

Wong, N. H., Chen, Y., Ong, C. L. & Sia, A. 2003 Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment* **38** (2), 261–270.

First received 2 July 2013; accepted in revised form 9 September 2013. Available online 25 October 2013