

Nutrient leaching from extensive green roofs with different substrate compositions: a laboratory study

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ABSTRACT

To investigate nutrient leaching from extensive green roofs, green roof platforms were established to investigate the effluent quantity and quality during artificial rainfall. When the influent volume reached three times the empty bed volume, for which the cumulative rainfall was around 300 mm, the effluent TP and COD concentrations of green roof platforms filled with peat soil did not tend to stabilize. For a long-term operation, the substrate depths had little significant influence on TN, TP and COD concentrations of the green roof effluents. A normalized cumulative emission process method was proposed to discuss the difference in various pollutant leaching processes. Obvious differences in the leaching process of different contaminants for green roof platforms filled with various substrates were observed. For the green roof filled with modified substrates, the nitrogen and phosphorus pollutant leaching rates were relatively high in the initial stage of green roof operation and the phosphorus leaching rate was higher than that of nitrogen. The green roof is a sink for TN, but not for TP and COD in this study. The outcomes are critical for the selection of green roof substrates and also contribute to green roof maintenance.

Key words | extensive green roof, leaching, nutrient, substrate

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INTRODUCTION

Green roofs are one of most used technical practices in urban stormwater management, such as sustainable urban drainage systems (SUDS), low-impact development (LID), best management practice (BMP), water-sensitive urban design (WSUD) and other sustainable drainage systems (Fletcher *et al.* 2015), as well as the sponge cities proposed in China (Zhang & Che 2016). Green roofs may have great potential for managing urban stormwater but their effect on the quality of infiltrating water is variable. It is also a method of recovering and increasing biologically active spaces in urban areas, but the main function of green roofs is slowing down the outflow of rainwater (Getter & Rowe 2006). Intensive vegetated roofs can be designed as gardens with deep soil layers supporting bigger plants such as trees and bushes, which require maintenance (Berndtsson *et al.* 2009). The extensive green roof is another typical type of green roof with a shallower substrate layer and less planted vegetation, which has a greater potential for application as it is simple in structure and easy to implement.

The hydrological performance of green roofs has been investigated through experimental plots (Stovin 2010;

Gregoire & Clausen 2011; Stovin *et al.* 2012), field studies (Bengtsson *et al.* 2005; Ouldboukhite *et al.* 2012), and mathematical modelling (Vesuviano & Stovin 2013; Locatelli *et al.* 2014; Yang & Wang 2014). The previous researchers indicated that green roofs can effectively retain stormwater, reducing runoff peaks and decreasing the annual runoff volume. Green roofs have the function of controlling stormwater volume, but the impact of green roofs on the quality of infiltrating water can be either positive or negative (Malcolm *et al.* 2014; Harper *et al.* 2015; Vijayaraghavan 2016).

Runoff water quality from intensive and extensive vegetated roofs have been the subject of much research (Hathaway *et al.* 2008; Berndtsson *et al.* 2009; Teemusk & Mander 2011). The green roof structure has a deterministic effect on runoff quality. In addition, factors influencing the water quality of the green roof's runoff include type and composition of substrate, thickness of the substrate layer, type of vegetation cover, roof age, atmospheric deposition, bird droppings and roof maintenance (Berndtsson *et al.* 2009; Bus *et al.* 2016). For a particular area with

same climatic conditions, the substrate types and the thickness of substrate may be the two main influencing factors.

Green roofs leach significantly higher concentrations of the nutrients phosphorus and nitrogen than gravel roofs, but reduction in runoff volume does not similarly mitigate the nutrient load (Malcolm *et al.* 2014). Organic matter, nutrients, and contaminants in the growing medium or roof membranes can cause discharged water to be a new source of surface-water pollution (Oberndorfer *et al.* 2007). Berndtsson *et al.* investigated influence on runoff water quality from two full-scale vegetated roofs (an intensive roof in Japan and an extensive roof in Sweden), and the results indicated that both extensive and intensive vegetated roofs are a sink of nitrate nitrogen and ammonium nitrogen with similar performances (Berndtsson *et al.* 2009). Total phosphorus (TP) and PO₄-P mean concentrations in green roof runoff were higher than in precipitation but lower than in runoff from the control. The green roof was a sink for NH₃-N, Zn, and Pb, but not for TP, PO₄-P, and total Cu (Gregoire & Clausen 2011). Green roofs acting as a sink or a source of contaminants in stormwater outflows are still being investigated (Gnecco *et al.* 2013; Vijayaraghavan & Joshi 2014). Despite the fact that green roof leachate can impact runoff quality, whether they are a positive influence on urban water quality mentioned in previous research (Rowe 2011; Vijayaraghavan *et al.* 2012) can be generalized to other climatic conditions and filled with different substrates need to be further discussed.

In this study, pilot-scale green roof platforms were established to assess the nutrient leaching from extensive green roofs with different substrate compositions. The study objectives were: (1) to quantitatively assess the nutrient leaching process from extensive green roofs, and the cumulative leaching load; (2) to determine the factors influencing the nutrient leaching process from extensive green roofs.

MATERIALS AND METHODS

Experimental sites

The study period started on 30 September 2016 and lasted until 30 December 2016. The study included six pilot-scale green roof platforms having external dimensions of 13 cm wide × 42 cm long × 12 cm high. They were placed on the roof of the stormwater laboratory building at the Beijing University of Civil Engineering and Architecture, China.

Based on previous research in our group, the size is not the main influential factor. If the substrate depth and planting density are similar, the test bed size may not impact the results significantly. Small test beds are easier for implementing a batch experiment with different substrate compositions. The test platform size in this study was similar to green roof facilities in previous research (Mickovski *et al.* 2013; Wang *et al.* 2017).

The green roof platforms had a longitudinal slope of 5%, and the lower end of the device was provided with an out-flow pipe. They were built according to the Chinese engineering standard 'Technical specification for green roof (JGJ 155-2013)', a national standard to guide the design and construction of green roofs in China. The drainage layer at the bottom of the device was a concave-convex plastic drainage plate, non-woven geotextile was used as the filtration material to prevent the particulate matter in the filler from flowing out with the effluent, and the drainage layer thickness was 3 cm. *Sedum lineare* Thunb was selected as the green roof plant with a planting density of 240 plants/m².

Considering the low organic matter content of the local soil in Beijing, peat soil rich in organic matter was selected for its organic matter composition, and vermiculite and perlite were selected for its inorganic lightweight materials to reduce the effective load per unit area of green roof. Several main physical-chemical properties of the substrates are shown in Table 1.

A total of six platforms were established in this study. Platform C was filled only with local soil. Platform B was used to represent the traditional roof with no substrates. Platforms V1 and P1 were filled with 10 cm depth of different substrates. Platforms V2 and P2 were filled with the same substrates as platforms V1 and P1, but the substrate depth was 5 cm to evaluate the influence of substrate depth on water quality of green roof runoff. The composition of simulated green roof substrates is shown in Table 2.

Table 1 | Several physico-chemical properties of the substrates

Substrates	Particle density g/cm ³	Organic matter content %	Available phosphorus mg/kg	Alkali solution N mg/kg
Local soil	1.22	0.3	1.79	7.35
Peat soil	0.59	17.7	59.85	9.80
Vermiculite	0.14	0.5	–	–
Perlite	0.08	0.2	–	–

Table 2 | Composition of simulated green roof substrates

No.	Depth (cm)	Composition (volume ratio)	Organic matter content (%)	Available phosphorus (mg/kg)	Alkali solution N (mg/kg)	Particle density (kg/m ³)
C	10	Local soil 100%	0.30	1.79	7.35	1,220
V1	10	Local soil 40% + peat soil 30% + vermiculite 30%	3.98	61.27	382.2	774
P1	10	Local soil 40% + peat soil 30% + perlite 30%	2.85	56.86	394.6	711
V2	5	Local soil 40% + peat soil 30% + vermiculite 30%	3.98	61.27	382.2	774
P2	5	Local soil 40% + peat soil 30% + perlite 30%	2.85	56.86	394.6	711
B	-	-	-	-	-	-

Sampling and laboratory testing

To assess the ability of the green roofs to attenuate and retain rainwater, rainfall simulation tests were performed. The rainfall simulation tests were performed by peristaltic pumps to control the simulated rainfall intensity, and the water was sprayed onto the surface of the devices to simulate the actual rainfall process. The design rainfall depth, corresponding to 80% rainwater volume control rate in Beijing, is 25 mm. Hence, the rainfall intensity was 12.5 mm/h for 2 hours' rainfall duration. It was assumed that rainfall intensity was uniform, and that there may be some differences with the actual rainfall. Because the average antecedent dry period (ADP) is 7.3 days during June to September (rainy season) in Beijing, the ADP in this study was determined as 7. The average rainfall events are around 15 for the rainy season in Beijing, and the rainy season is normally 3 to 4 months. Hence, the experiment period was determined as 3 months (12 rainfall events over about 3 months). Moreover, before a rainfall simulation test, each tray was exposed to a dry period of 7 days. A total of 12 rainfall simulation tests were performed in this study and the total rainfall depth was approximately 300 mm.

A drain hole with polyvinyl chloride piping was installed at the low end of each test plot to collect runoff from individual platforms. The runoff was sampled manually with a fixed time interval. Runoff samples were tested for turbidity (with results given in nephelometric turbidity units, NTU),

chemical oxygen demand (COD), total nitrogen (TN) and TP using standard methods (APHA 2012). Tap water was usually used to simulate rain events in similar research (Bus *et al.* 2016; Kuoppamäki & Lehvavirta 2016). The local tap water was used to simulate rain water, and the characteristics of tap water are shown in Table 3.

RESULTS AND DISCUSSION

Nitrogen leaching

The concentration and leaching process of nitrogen substances for 12 rainfall simulation tests is illustrated in Figure 1. In the third simulation test, the concentration peak of TN appears for green roof platforms V1 and P1. With the increase of the simulation tests times, the TN concentration of the effluent for six platforms decreased with a slight fluctuation, and basically stabilized. For the green roof platforms with a high organic matter composition (peat soil), including platforms V1, P1, V2 and P2, the TN concentrations of the effluent were much higher than the corresponding concentration of platform C which was filled with only local soil (Figure 1(a)). This is because the alkali solution N of green roof substrates in platforms V1, P1, V2 and P2 was much higher than in platform C (Table 2). The high alkali solution N in substrates may result in the TN leaching at the beginning of the green

Table 3 | Characteristics of tap water used in this study

Pollutant	TN (mg/L)	NO ₃ ⁻ -N (mg/L)	NH ₄ ⁺ -N (mg/L)	TP (mg/L)	PO ₄ ⁻ -P (mg/L)	COD (mg/L)	Turbidity (NTU)
Concentration	2.78	1.79	0.04	0.01	0.01	6.0	0.23

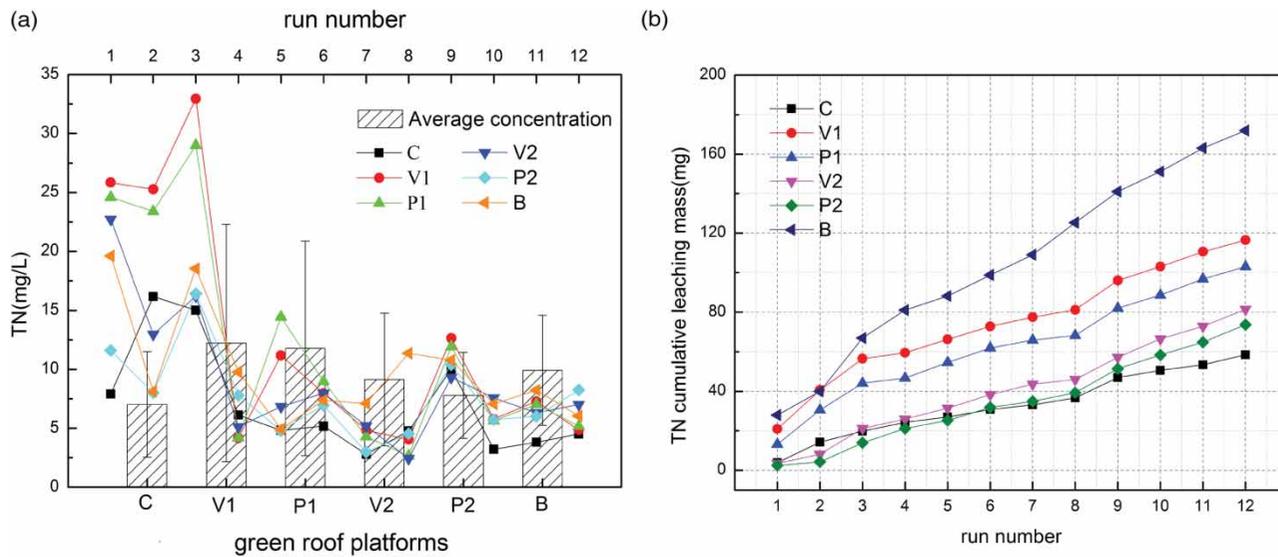


Figure 1 | Concentration and leaching process of nitrogen substances. (a) TN. (b) TN cumulative leaching mass.

roof operation, and it is similar to previous research (Emilsson *et al.* 2007; Beecham & Razzaghamanesh 2015).

In order to assess the influence of substrate depth on the effluent water quality, green roof platforms filled with same substrates, but different depths were established in this study. The green roof platforms V1 and P1 were 10 cm, and V2 and P2 were 5 cm. In the first three simulation tests, the effluent TN concentration of platforms V1 and P1 were obviously higher than platforms V2 and P2. It is indicated that the higher the substrate depth, the more TN is leached at the initial stage of the green roof's operation, and the result in this study is similar to previous research (Seidl *et al.* 2013). However, from the fourth simulation test, the TN concentrations of platforms V1, P1, V2 and P2 tend to be stable. There was no significant difference in the effluent TN concentrations between green roof platforms with 10 cm substrate depth (V1, P1) and green roof platforms with 5 cm substrate depth (V2, P2) for the last eight simulation test ($P > 0.05$).

Based on results in this study, at the initial stage of green roof operation (when the influent was within one empty bed volume, around 100 mm), the larger the substrate depth, the greater the amount of nitrogen that may leach. However, the substrate depth had little effect on the effluent TN concentrations for a long-term operation.

As shown in Figure 1(b), TN cumulative leaching mass of green roof platforms C, V1, P1, V2 and P2 were obviously lower than the corresponding discharge mass from platform B, which represents a typical traditional roof. It is indicated that a green roof could retain nitrogen

pollutants whichever substrates were used relative to the traditional roof.

Phosphorus leaching

The concentration and leaching process of phosphorus substances for 12 rainfall simulation tests is shown in Figure 2. As the available phosphorus in the substrate of green roof platforms V1, P1, V2 and P2 were much higher than platform C, the effluent TP concentrations remained at a higher level in the first five simulation tests. This is because of phosphorus leaching in peat soil within the simulation tests. When the influent volume reaches three times the empty bed volume, for which the cumulative rainfall is around 300 mm, the effluent TP concentrations of green roof platforms filled with peat soil (V1, P1, V2 and P2) did not tend to stabilize.

For green roof platforms filled with different substrates, there was little difference in the effluent TP concentration, and the trend of change is basically consistent. There was no significant difference in the effluent TP concentrations between green roof platforms with 10 cm substrate depth (V1, P1) and green roof platforms with 5 cm substrate depth (V2, P2) ($P > 0.05$). The substrate depth had little effect on the effluent TP concentrations for a long-term operation.

As shown in Figure 2(b), TP cumulative leaching mass of green roof platforms V1, P1, V2 and P2 were obviously higher than the corresponding discharge mass from platform B (representing a typical traditional roof) and

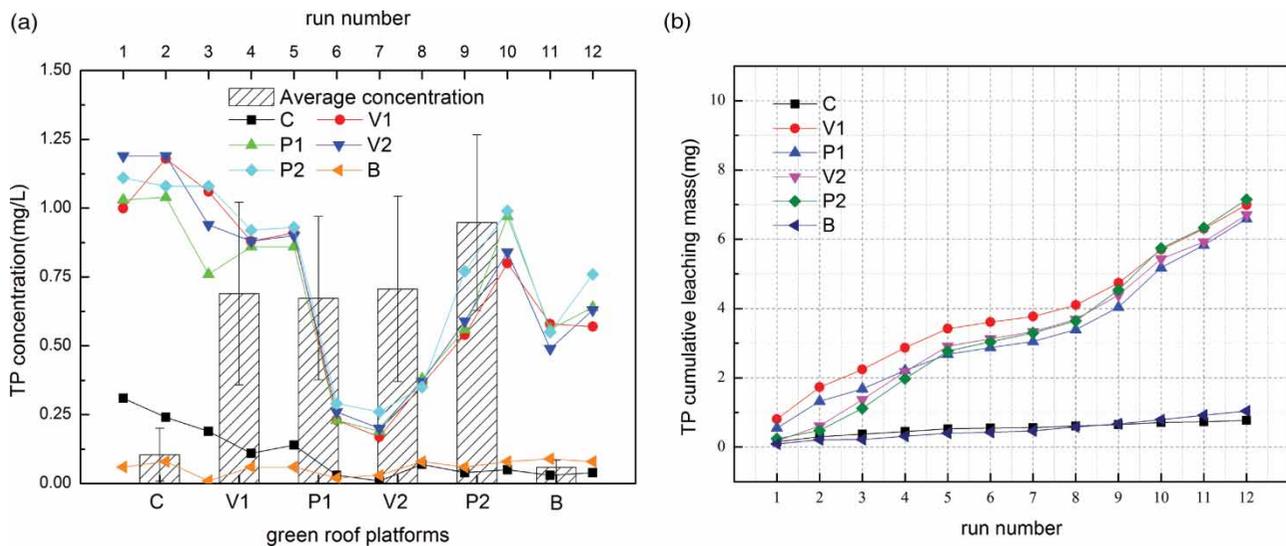


Figure 2 | Average concentration and leaching process of phosphorus substances. (a) TP. (b) TP cumulative leaching mass.

platform C (representing a typical green roof without modified substrates). It is indicated that the green roof could be regarded as a source of phosphorus substances relative to the traditional roof, especially for green roofs with modified substrates, such as peat soil etc. Although peat soil is a commonly used substrate for green roofs (Berndtsson *et al.* 2009; Vijayaraghavan *et al.* 2012; Zhang *et al.* 2015), there is still a risk of phosphorus leaching in the initial stage of the green roof's operation.

COD leaching

The concentration and leaching process of COD and turbidity for 12 rainfall simulation tests is illustrated in Figure 3. The effluent COD concentration for six platforms shows a large fluctuation, and there was no obvious trend when the cumulative rainfall reached 300 mm. This may be caused by the gradual release of organic matter in peat soil.

In the first six simulation tests, the effluent COD concentrations of green roof platforms V1, P1, V2 and P2 was much higher than the corresponding concentration of green roof platform C. This is because the organic matter content of green roof substrates in platforms V1, P1, V2 and P2 was much higher than in platform C (Table 2).

The available phosphorus and alkali solution N of local soil is much lower than in modified substrates, and the nutrients may be not sufficient for the plants' growth needs. The nitrogen and phosphorus leaching process of green roof platform C also confirms this (Figures 1 and 2). In this study, the plants in green platform C are not lush enough during this experiment period. From the fourth test, as the ambient

temperature decreased, some of the stems and leaves in green platform C gradually withered and decayed. This may have been the main reason for the increase of COD concentration in the effluent of platform C during the sixth to ninth simulation tests.

As illustrated in Figure 3(b), obvious trends were observed in the turbidity effluent for the green roof platforms. The turbidity in the effluent decreased significantly in the first three simulation tests. After a slight fluctuation, the overall performance tended to be stable once the cumulative rainfall reached 100 mm. With the increase of influent volume, the filling of the device gradually stabilized and the loss of particulate matter decreased.

As shown in Figure 3(c), the COD cumulative leaching mass of green roof platforms V1, P1, V2 and P2 was obviously higher than the corresponding discharge mass from platform B (representing a typical traditional roof) and platform C (representing a typical green roof without modified substrates). It is indicated that the green roof could be regarded as a source of COD relative to the traditional roof. There is also a risk of COD leaching when peat soil and other modified substrates are used.

Nutrient leaching characteristics

As mentioned above, there were different leaching characteristics for nitrogen, phosphorus and COD in these 12 simulation tests. In order to discuss the differences in the leaching processes of the various pollutants, their normalized cumulative emission mass versus normalized

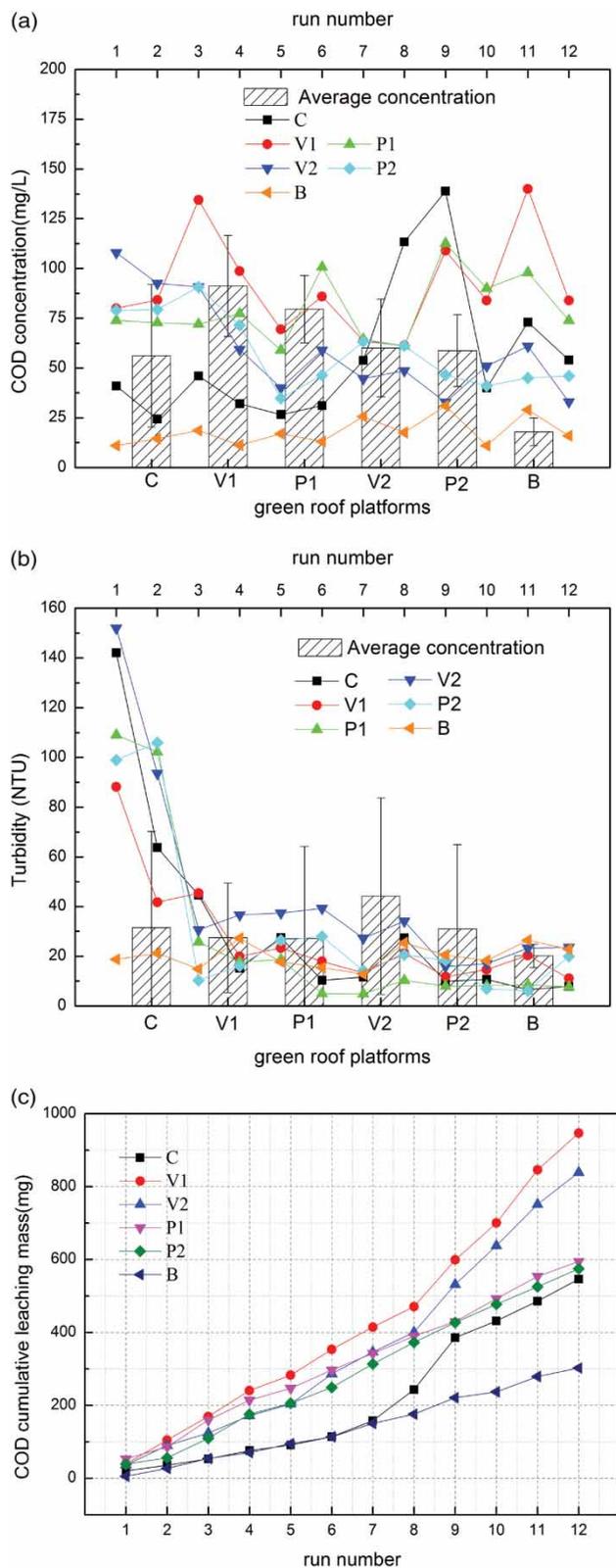


Figure 3 | Concentration and leaching process of COD and turbidity. (a) COD. (b) Turbidity. (c) COD cumulative leaching mass.

cumulative emission volume for the 12 simulation tests were plotted as shown in Figure 4.

Platform B represented the typical traditional roof. As illustrated in Figure 4(d), the leaching processes of TN, TP and COD were close to each other, although TN leaching was slightly faster than TP and COD. This is because the conditions of the 12 simulation tests were almost the same. The TN emission of the traditional roof is mainly related to atmospheric nitrogen deposition. The nitrogen deposition rate at the initial stage of the experiment was relatively high. Thus, TN leaching was slightly faster in the initial few simulation tests.

For the green roofs filled with modified substrates (V1 and P1), the nitrogen and phosphorus pollutant leaching rate was relative high in the initial stage of green roof operation, and the leaching rate of phosphorus was higher than that of nitrogen (Figure 4(b) and 4(c)). This is similar to the typical first flush in urban runoff pollution (Lee & Bang 2000; Sansalone & Cristina 2004). Meanwhile, the COD leaching process was close to a uniform discharge process, which means that the COD leaching rate changed little during the experiment.

However, for the green roof filled with only local soil, the leaching rate of phosphorus was lower than that of nitrogen (Figure 4(a)). This was because the alkali solution N of the substrate was low. Meanwhile, as COD leaching was lead by the stems and leaves gradually withering and decaying, the COD pollutants leaching rate was relative high in the middle and late phases of green roof operation.

For green roofs filled with modified substrates, especially for substrates rich in nitrogen and phosphorus as peat soil, more attention should be paid to the nitrogen and phosphorus leaching in the initial stages of the green roof operation.

CONCLUSION

The nutrient leaching process from extensive green roofs were quantitatively assessed by six pilot-scale green roof platforms in this study.

At the initial stage of green roof operation (when the influent was within one empty bed volume, around 100 mm), the larger the substrate depth, the greater the amount of nitrogen that may leach. However, the green roof could retain the nitrogen pollutant whichever substrates were used relative to the traditional roof. When

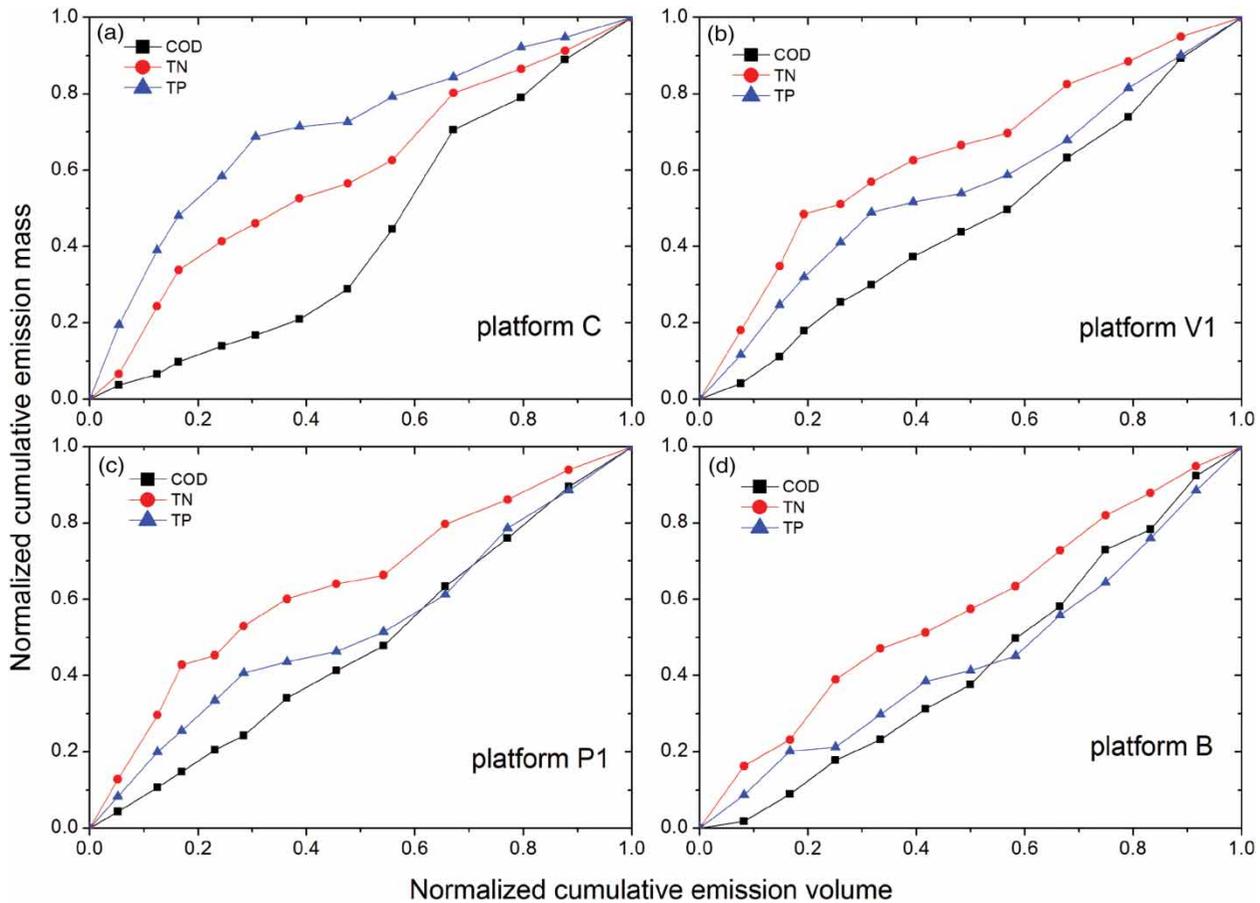


Figure 4 | Pollutant cumulative emission process.

the influent volume reached three times the empty bed volume (300 mm cumulative rainfall depth), the effluent TP concentrations of green roof platforms filled with peat soil did not tend to stabilize. The green roof could be regarded as a source of phosphorus substances relative to the traditional roof, especially for green roofs with modified substrates, such as peat soil etc. The COD concentration of the effluent for the six platforms showed a large fluctuation, and there was no obvious trend when the cumulative rainfall reached 300 mm. The turbidity in the effluent decreased significantly in the first three simulation tests, and it tended to be stable once the cumulative rainfall reached 100 mm cumulative rainfall depth.

A normalized cumulative emission process method was proposed and used to discuss the difference in the various pollutant leaching processes. Obvious differences in the leaching process of different contaminants for green roof platforms filled with various substrates were observed. For green roofs filled with modified substrates, especially for substrates as rich in nitrogen and phosphorus as peat soil,

more attention should be paid to the nitrogen and phosphorus leaching in the initial stages of the green roof operation.

The outcomes of this study are critical for the selection of green roof substrates, and also contribute to green roof maintenance. The green roof is a sink for TN, but not for TP and COD in this study, and the mechanism of nitrogen and phosphorus leaching from green roofs with different substrates should be further investigated.

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