1   **Seasonal applicability of three vegetation constructed floating**
2   **treatment wetlands for nutrient removal and harvesting**
3   **strategy in urban stormwater retention ponds**

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ABSTRACT

Three floating treatment wetlands (FTWs), which consist of emergent macrophytes, were constructed and planted to investigate the influence of seasonal change on contaminant removal and harvesting strategy. The investigation was carried out by treating simulated urban stormwater runoff sewage through selected aquatic plants in Jiaxing, Yangtze River Delta, China. Samples collected from the influent and effluent water of three FTWs planted with *Canna indica*, *Thalia dealbata*, and *Lythrum salicaria*, respectively, were analyzed for contaminant concentration in different batches. Results demonstrated that *T. dealbata* outperformed *C. indica* and *L. salicaria* in nutrient removal. The FTWs of *T. dealbata* achieved average removal efficiencies (AREs) of 71.17% $\pm$ 2.01% for chemical oxygen demand (COD), 69.96% $\pm$ 2.11% for total nitrogen (TN), and 82.40% $\pm$ 2.34% for total phosphorus (TP) in nine stages. The COD and TN concentrations in effluent water were under 20 and 1.5 mg L⁻¹ for 20 weeks. Based on the analyses of accumulated nutrient removal in vegetation over time, the strategy of harvesting the aboveground tissues of *T. dealbata* and *C. indica* in late October or early November is recommended. However, *L. salicaria* aboveground tissues should be harvested in September. In Jiaxing, the constructed FTWs of *T. dealbata* exhibited the best seasonal applicability.

Keywords: Urban stormwater runoff, Floating bed, Nutrient removal, Harvesting strategy, Seasonal applicability

1. Introduction

Considerable attention has been directed toward the poor water quality and limited habitat value of China's urban rivers, because the creation of impervious surfaces has caused these modified ecosystems to transform from clear water resources into severely eutrophic water bodies as a result of the excessive transport of nutrients and other pollutants into the rivers (Streb, 2013). Urban stormwater runoff pollution, which is serious especially for earlier runoff, is one of the reasons leading to the eutrophication of urban river, lakes, and coastal waters, and eventually, algal bloom (Laber et al., 1997; Kim et al., 2007). As one of the largest uncontrolled nonpoint sources of pollution to receiving waters, urban stormwater runoff should be treated before it flows into rivers (Guido et al., 2014). Urban stormwater ponds, similar to other best management practices (BMPs) for stormwater management, provide storage and water quality treatment for urban stormwater through sedimentation (Semadeni-Davies, 2006; Wang and Sample, 2013). In Sweden, the United States, and some other developed countries, the international trend of constructing retention ponds to manage urban stormwater runoff and improve water quality has proved popular (Semadeni-Davies, 2006; Chang et al., 2013). However, urban stormwater ponds are much less effective in treating pollutants in dissolved form, such as nutrient and metals (Shilton, 2006). To enhance the performance of wet ponds in removing dissolved pollutants without the need for additional space, more floating treatment wetlands (FTWs), which are a relatively new stormwater treatment practice, should be established.

As an emerging BMP for stormwater treatment, FTWs consist of macrophytes growing on [floating beds](#), which sustain and support terrestrial macrophytes, and may be uniquely sustainable and economical as an ecologically friendly treatment practice with widespread applicability in water bodies, including urban stormwater retention ponds (Hubbard et al., 2011; Zhao et al., 2012; Shao et al., 2014). Macrophytes in FTWs, together with microorganisms in their root zone, remove nutrients through direct or indirect uptake into their tissue (Breen, 1990; Billore et al., 2008). As a promising ecotechnology, FTWs are favored by water quality management practitioners for the following advantages: [their](#) improved efficiency in eliminating the dissolved forms of N and P from water, scalable nature, relative simplicity of construction, no required land acquisition, additional esthetic values, and low installation costs, which can be further reduced if locally available (wetland) plants and materials, such as man-made plastic bottles and natural bamboo, can be recycled (Li et al., 2007; Stefani et al., 2011). [Another](#) important factor is that the damaging effects of severe water level fluctuation can be avoided because the plants grow on [floating beds](#) rather than root in sediments (Headley and Tanner, 2006).

Previous studies have shown that floating wetlands can be effective systems for removing the nutrients present in domestic and agricultural wastewaters, swine lagoons, and hyper-eutrophic lake waters (Hubbard et al., 2004; Wu et al., 2006; Yang et al., 2008; Moortel et al., 2010; Xian et al., 2010; White and Cousins, 2013). With regard to the combination of FTWs with retention ponds, the performance of existing retention ponds

may be improved and urban stormwater runoff quality may be managed effectively and economically (Headley and Tanner, 2012; Winston et al., 2013). Except for a few recently published FTW studies, actual urban stormwater runoff has not been widely tested (Tanner and Headley, 2011; Chang et al., 2012; Wang et al., 2014). In addition, the vast majority of research on FTW performance has been conducted during periods of active plant growth. From these studies, significant water quality improvement was achieved. However, knowledge on the temporal variation of nutrient distribution in FTW plant tissues and the seasonal applicability of different plant species is deficient. Further studies should focus on the plant species selection and nutrient distribution of macrophytes related to the seasonal pattern of change and nutrient reduction.

The objectives of this paper are as follows: (i) to compare the potentials of three aquatic macrophytes for treating urban stormwater runoff using FTWs, (ii) to determine the best seasonal applicability of vegetation-constructed FTWs, and (iii) to investigate the harvesting strategy for the best macrophytes.

2. Materials and methods

2.1. Experimental site

This experiment was carried out in a greenhouse. The experimental tanks simulated an urban wet pond. The tanks were located in the Jiaxing City, Zhejiang Province at a Jiaxing University site (30°44'N, 120°43'E). The area of the characteristics of urban stormwater runoff consisted of 4.50 km² of Jiaxing Middle Ring South Road adjoining Jiaxing University with 100% impervious surfaces. During the experiment period

(April–December 2015), the monthly mean air temperature ranged from 8.7 °C to 28.1 °C.

2.2. Design of the experiment

The FTW experiments were conducted from April 6 to December 14, 2015 and were divided into nine stages. One stage (28 days) consisted of four batches, and one batch comprised seven days. In the early investigation in 2014, 12 effective waters of earlier urban stormwater runoff were collected at Middle Ring South Road adjacent to Jiaxing University. Then, the characteristics and pollutants in the water were analyzed. The simulated (experimental) water was simulated urban stormwater runoff, which was collected from local river water after it was used to wash the Middle Ring South Road. The concentrations of COD, TN, and TP of the simulated water were modified in a large reservoir with glucose, carbamide, KH_2PO_4 , and freshwater according to the mean concentrations of major pollutants in urban stormwater runoff within 60 min in the early investigation, such as chemical oxygen demand (COD) ($129.84 \pm 8.52 \text{ mg L}^{-1}$), total nitrogen (TN) ($5.15 \pm 0.33 \text{ mg L}^{-1}$), and total phosphorus (TP) ($0.26 \pm 0.01 \text{ mg L}^{-1}$). In this study, the mean physicochemical characteristics of the simulated water were pH (6.98) and dissolved oxygen (DO) (8.93 mg L^{-1}). The mean concentrations of pollutants during the nine stages are described in Table 1. The reservoir ($6 \times 5 \times 2.0 \text{ m}$, $L \times W \times D$) was built to reserve the simulated water before it was injected into the tanks. Twelve tanks ($3.3 \times 1.5 \times 1.0 \text{ m}$, $L \times W \times D$) were installed in a greenhouse to facilitate the photosynthesis of macrophytes and exclude the influence of bird droppings, falling leaves, and rainfall

(Fig.1). The 12 floating beds (3.0×1.2 m, L×W) were made from polyvinyl chloride pipes, plastic mesh, and pot holders (Fig.1). The plants, including *C. indica*, *T. dealbata* and *L. salicaria*, were purchased from the Perennial Root Flowers and Plants in Nanjing Botanical Garden, Nanjing, China. After flushing with tap water, the selected plants (15–20 cm in height) were collected and transported into hydroponic pots and fixed by coir fibers with an initial density of 10 plant m⁻² in the floating beds (Table 2). In this study, following a completely randomized block design, three treatments with three replicates were designed to test the effects of the three plant species (Table 2). The other plants in the three reserved FTWs were reserved to replace the samples.

[Insert Fig. 1, Tables 1 and 2 here]

2.3. Operation of the experiment

Under batch operational mode, the simulated water in tanks was completely replaced by a volume of 3 m³ fresh simulated water in the reservoir every seven days when the tanks were completely emptied, except for the FTWs. In this operation, the flow was slow and smooth to avoid disturbing the biofilm and microorganism in the root system of the vegetation. A total of 500 mL water samples of influent water were collected from the reservoir at the start (9:00 AM in the first day) of each batch, and the same volume of effluent water was extracted in each tank at the end (8:30 AM in the seventh day). Water samples were filtered with a 0.45 µm glass microfiber filter (GF/C, Whatman, USA) to evaluate the effect of the FTWs on simulated water during each batch by determining soluble COD, soluble TN, and soluble TP. The pH was measured before filtration. The

TN (Persulfate Digestion UV Spectrophotometry), TP (Potassium Persulfate Digestion Mo-Sb Anti-Spectrophotometry), and COD (Closed Refluxing Titrimetric Method) concentrations of water samples were analyzed following Standard Methods for the Examination of Water and Wastes (APHA, 2005). The pH was recorded on a portable pH meter equipped with microprobes (HACH, LA-pH10, USA). DO was measured by a portable hand-held dissolved oxygen meter (YSI550A, USA). One experimental plant was taken out for analysis in each tank after 28 days (four batches or one stage) and was replaced by reserved plants from reserved FTWs at the end of each stage. The harvested whole plants were taken back to the laboratory and were blotted with absorbent paper after gentle washing with deionized water.

To determine the plant dry weight (DW), each plant sample was separated into belowground (roots and rhizomes) and aboveground (leaves and stems) sections. Roots and rhizomes were washed first with tap water, and then with distilled water to remove any adhering foreign material. Each sample was cut into small pieces, well mixed, and dried in a vacuum oven (BOXUN, Model: DZF-6050MBE) at 80 °C for 48 h to be stabilized (Plank, 1992). The dried plant tissues of each plant were weighed. Next, the powder of the aboveground tissue was passed through a 35-mesh (0.5 mm) screen after it was ground in an equivalent high-speed grinder Wiley Mill (Thomas Scientific, Model: 3379-K38). The plant N content in the aboveground tissue was analyzed by combusting 30 mg finely ground samples after the CHNOS Elemental Analyzer (Thermo Fisher Scientific Inc., Model: EA 1112, Flash 2000) was prepared according to the

manufacturer's operating manual. The plant P content in the aboveground tissue was determined following the methods described above for water quality samples after the finely ground sample (50 mg each) was digested first in concentrated nitric acid, followed by perchloric acid digestion at incrementally higher temperatures, which ended at 210 °C.

2.4. Calculation and statistical analysis

The removal efficiency (E, %) of each treatment in each batch (seven days) was calculated based on Eq. (1):

$$E = \frac{(C_i - C_f)}{C_i} \times 100\% \quad (1)$$

where $C_{i/f}$ (mg L⁻¹) is a constituent concentration of the influent water/effluent water in each batch.

Plant relative growth rate (RG) was estimated according to the DW changes of the plant. Hunt (1978) reported that the RG parameter represents the new material production efficiency of the plant. The RG is calculated as shown below:

$$RG_{i,j,\delta} = \frac{\ln DW_{i,j,\delta,t_2} - \ln DW_{i,j,\delta,t_1}}{t_2 - t_1} \quad (2)$$

$RG_{i,j,\delta}$ is the average relative growth rate of stage i , group j , and tissue type δ (mg g⁻¹ day⁻¹);

DW dry weight (g);

t_1 initial time of stage i (0 days);

t_2 final time of stage i (28 days);

δ tissue type: whole plant, above-ground tissue, or below-ground tissue.

In this study, each sample was tested in triplicate. The average values were expressed as means $\pm$ standard deviation values. The statistical analysis was conducted with one-way analysis of variance at $P < 0.05$.

3. Results and discussion

3.1. Effects of different FTWs on aqueous nutrient removal

Table 1 shows the significant difference in TN mean removal efficiencies (REs) between the *C. indica* and *T. dealbata* FTWs over the study period ($P < 0.05$). However, no significant differences of the COD and TP mean REs were found between those FTWs ($P > 0.05$). The contaminant average REs and mean concentrations of COD, TN, and TP of the effluent water in the *L. salicaria* FTWs were lower than those in the *C. indica* and *T. dealbata* FTWs in the 36 batches (Table 1). Different efficiencies were obtained by the studied FTWs, indicating that plant species have a significant impact on the REs of COD, TN, and TP. The results illustrate that the *T. dealbata* FTWs achieved a higher efficiency of TN removal compared with other FTWs. Thus, *T. dealbata* FTWs can play an important role in nutrient removal for urban stormwater runoff. The data of 36 batches in Fig. 2 show that the COD concentrations of effluent water in the *C. indica*, *T. dealbata*, and *L. salicaria* FTWs were under 30 mg L^{-1} (Class IV Environmental Quality Standards for Surface Water, GB3838-2002, China.) for 15, 20, and 3 weeks, respectively. By contrast, in *T. dealbata* FTWs only, the COD concentration of the effluent water was under 20 mg L^{-1} (Class III) for 12 weeks. The maximum COD REs of the *C. indica*, *T. dealbata*, and *L. salicaria* FTWs were $83.21\% \pm 2.14\%$, $89.15\% \pm 2.22\%$, and $75.55\% \pm$

2.18%, respectively (Fig. 2). The data in Fig. 3 reveal that the TN concentrations of the effluent water in the *C. indica* and *T. dealbata* FTWs were under 1.5 mg L^{-1} (Class IV) for 16 and 20 weeks. However, the same concentrations in *L. salicaria* FTW could not meet Class IV. The TN concentrations of the effluent water in the *C. indica* and *T. dealbata* FTWs were under 1.0 mg L^{-1} (Class III) for 5 and 16 weeks, including 5 weeks under 0.5 mg L^{-1} (Class II). The *C. indica*, *T. dealbata*, and *L. salicaria* FTWs achieved maximum TN REs of $82.37\% \pm 2.22\%$, $92.35\% \pm 2.13\%$, and $68.54\% \pm 2.25\%$, respectively. The data in Fig. 4 indicated that the TP concentration of the effluent water in the *C. indica*, *T. dealbata*, and *L. salicaria* FTWs met Class II (0.1 mg L^{-1}) for 34, 34, and 26 weeks over the study period. These results indicated that the performance of *T. dealbata* FTW is better in COD, TN, and TP removal compared with the *C. indica* and *L. salicaria* FTWs.

Plants perform phytoremediation in various processes, such as metabolism, volatilization, and sequestration followed by harvesting (Zou et al., 2013). In FTWs, vegetation plays a significant role in removing pollutants because it takes up nutrients from wastewater and substrates, as well as provides a large surface area and other favorable growing conditions for microbial growth (Brix, 1997; Tanner, 2001b; Zhou and Hosomi, 2008). In the current study, the different performance of removal contaminants in three FTWs may be related to the ability of direct nutrient uptake by the three plants and the degradation by microorganisms in their extensive root system. The rhizosphere is an ecosystem of intense microbial activity (Bowen and Rovira, 1999; Zou et al., 2013).

The direct nutrient uptake by *C. indica*, *T. dealbata*, and *L. salicaria* in the aboveground tissues were discussed in Section 3.3. The extensive root system can be qualitatively described with the root biomass on the basis of the root DW. The root DW of the three plants can be calculated according to the data in Table 3 and Fig. 5. The results showed that the ranking of root DW in nine stages was $T. dealbata > C. indica > L. salicaria$. The larger root biomass in *T. dealbata* FTWs implied a more extensive root system, wherein plant roots interact with wastewater and microbes. Hence, the activities and abundance of microbes were significantly enhanced, which was one reason for the higher contaminant removal efficiency compared with other FTWs. This inference was in agreement with other findings. Wang et al. (2012) reported that plant roots that replace the conventional matrix become the main carrier of microbial species. In addition, more root biomass can provide more surface area for microorganism growth, larger effective space, higher chance of attachment for microorganisms and nutrients, and a more significant microorganism microenvironment, all of which are beneficial to the processes of degradation.

In stages 7 and 8, the performance of simultaneous COD and nutrient removal in *T. dealbata* FTWs was comparable with those in some enhanced floating beds, hybrid constructed wetlands, and other bioreactor systems. Sun et al. (2009) reported that an enhanced floating bed of canna can improve the efficiency of pollutant removal. Their research also achieved COD RE of 94.6% and TN RE of 72.1%. Guo et al. (2014) found that a vertical flow constructed wetland, which was planted with *T. dealbata*, combined

with a sequencing batch biofilm reactor could remove COD 97.0%, TN 91.5%, and TP 88.5% at concentrations of 200.22, 48.11, and 6.11 mg L⁻¹, respectively. The research of Falahti-Marvast and Karimi-Jashni (2015) in a pilot-scale membrane bioreactor system showed that the maximum efficiencies of COD, TN, and TP removal were 95%, 86.2%, and 55.9%, respectively.

In week 36, COD and TN REs, which were calculated according to the data in Figs. 2-4, still exceeded 30%, whereas TP REs were above 50% in the three FTWs. The result may be partly attributed to gravity sedimentation, physical adsorption, and the metabolism of microorganisms, such as aerobic and anaerobic bacteria, nitrobacterium, denitrifying bacteria, and polyphosphate-accumulating bacteria. Additionally, the underground tanks, vegetation filling the tanks, and coir fibers may also play a role in keeping the microorganisms warm.

On the basis of all the above results and discussion, the *T. dealbata* and *C. indica* FTWs enhanced nutrient removal more effectively in urban stormwater runoff than the *L. salicaria* FTWs. However, when the major pollutants (COD, TN) were in urban stormwater runoff at Jiaxing, *T. dealbata* FTWs might be the optimum option.

[Insert Figs. 2–4 here]

3.2. Temporal variation of nutrient removal and plant growth performance

The temporal variation of COD and the nutrient mass concentration reduction data in Figs. 2, 3, and 4 showed that the COD, TN, and TP concentrations in the tests exhibited a continuous decrease to a minimum value before it gradually increased until the end of the

experiment. This variation tendency was closely related to the temporal variation of the three whole plant DW values, which rose sharply in the middle stages after gradually increasing in the previous stages, and decreased in the later stages (Fig. 5). The finding indicated that plant growth played a major role in COD, TN, and TP removal because the sharp increase in the whole plant DW corresponded with the higher REs of COD, TN, and TP, which can be calculated by the data in Figs. 2, 3, and 4. For instance, the whole plant DW of *T. dealbata* increased sharply in stages 5–7 (August, September, and October). In these stages, the AREs of COD, TN, and TP were $85.91\% \pm 4.52\%$, $89.24\% \pm 4.99\%$, and $88.31\% \pm 4.53\%$, respectively, after gradually increasing from stage 1 (April) to 4 (July). The AREs of COD, TN, and TP in these stages were $70.33\% \pm 3.26\%$, $63.12\% \pm 2.86\%$, and $77.89\% \pm 3.90\%$, respectively. Finally, the values declined in stages 8 and 9, in which the AREs of COD, TN and TP were $68.79\% \pm 3.55\%$, $69.51\% \pm 3.85\%$ and $82.55\% \pm 4.32\%$, respectively. In this study, the whole plant DWs of *T. dealbata*, *C. indica*, and *L. salicaria* after stage 5 (Fig. 5), which were ranked in descending order, implied that the increased biomass may contribute to the ranking of the COD and TN AREs in the nine stages, which showed $T. dealbata > C. indica > L. salicaria$ in Table 1.

The plant biomass increased rapidly from August to October owing to the high temperature and started to decay because the air temperature decreased at the end of the tests (Fig. 5). These results were caused by the seasonal pattern of change, which was in agreement with other findings (Stein and Hook, 2005; Wu et al., 2011). Thus, seasonal

286 pattern of change has a direct effect on nutrient removal and plant growth performance.

287 In warmer season, the nutrients and COD removal had a **significant** increasing trend

288 described above as a result of the nutrient uptake by plants, which had more increased

289 biomass and biodegradation by **microorganisms** in the more extensive rhizosphere,

290 wherein the activities and abundance of microbes were significantly enhanced. However,

291 during colder season, the plant growth (Fig. 5) or action of microorganisms was inhibited

292 by the lower temperature, especially in the last stage (December). The plants also no

293 longer assimilated nutrients when they entered the mature and senescence phases **because**

294 **of** their slow metabolism, especially in the enzyme activity of plants. Zhao et al. (2011)

295 also found that the seasonal pattern of change had significant effects on the removal rates

296 of COD, TN, TP, and TOC in their constructed wetland systems. In addition, the removal

297 rates of nutrients declined in winter. The COD and TN data variations in Figs. 2 and 3 are

298 more drastic than the TP data variations in Fig. 4 **owing to** the initial concentrations of

299 COD, TN, and TP in the influent water. The data in Table 1 showed that the mean initial

300 values of COD, TN, and TP concentration of the influent water were 122.27 ± 7.21 , 5.23

301 ± 0.31 , and $0.24 \pm 0.01 \text{ mg L}^{-1}$, respectively. The low TP concentration in the influent

302 water was the result of the sharp decline of TP concentration in stage 1 (the first 4 weeks)

303 before it fluctuated **gradually** at the end. This condition was attributed to the limited TP

304 mass, which **was** assimilated and degraded rapidly up to stabilization by the vegetation

305 and microbes in the FTWs. Seasonal change had a non-significant effect on the P uptake

306 of *C. indica*, *T. dealbata*, and *L. salicaria* in this study. The decline of COD and TN

removal by the three FTWs in November and December, as shown by the data in Figs. 2 and 3, was caused by the seasonal pattern of change and plant senescence inferred from the plant growth data in this investigation (Figs. 5 and 6). In other findings, Wang et al. (2012) reported that the nutrient removal rate had a significantly increasing trend in warmer seasons, but a decreasing trend in colder seasons, indicating that temperature had an important effect on the nutrient removal. These results are also in line with other reports (Reddy et al., 2001; Poach et al., 2004).

As shown in Fig. 6, the relative growth rate (RGR) of whole aboveground and belowground plant parts of *C. indica*, *T. dealbata*, and *L. salicaria* exhibited similar variations through the nine stages. The RGR values of *C. indica* and *T. dealbata* increased in stages 4 and 5 after they continuously declined from stages 1 to 3 and stages 1 to 4 respectively. Then in later stages, the RGR values decreased, and finally became negative in stages 8 and 9. In stages 4 and 5, the increase in growth rate coincided with the removal of TN in those stages (Fig. 3 and Table 3). *C. indica* and *T. dealbata* also adapted to hot weather in summer, and the adaptation of *T. dealbata* was better than that of *C. indica*. The RGR values of *L. salicaria* gradually decreased after the peak in stage 1 and became negative in stages 8 and 9. Previous studies indicated that the influence of the FTW environment condition on the three aquatic macrophyte growths were not considered as a major cause because plants grew at natural habitats, which exhibited similar seasonal patterns of RGR change (Heisey and Damman, 1982). Haraguchi (1992) reported that the evaluation of the FTW performance was facilitated by the plants'

seasonal pattern of change. Aboveground RGR may be a better indicator of the performance of the *C. indica* and *T. dealbata* FTWs with regard to COD and TN removal. As the aboveground RGR approached zero in October, the COD and TN removal in FTWs planted with *C. indica* and *T. dealbata* also reached their maximum values on October 19 and October 26. For example, the COD and TN maximum REs were $89.15\% \pm 2.22\%$ and $92.35\% \pm 2.13\%$ when the above-ground RGR approached zero on October 26 in the FTWs planted with *T. dealbata* (Figs. 2, 3, and 6b). As shown in Figs. 5 and 6, the senescence of the three plants (November) resulted in the decrease of the COD and nutrient REs in stages 8 and 9.

In this study, the growing period of *T. dealbata* lasted longer than that of *C. indica* and *L. salicaria* because the zero RGR of *T. dealbata* (Fig. 6b) occurred after those of *C. indica* and *L. salicaria* (Figs. 6a and 6c) from stages 7 to 8. This finding suggests that the seasonal applicability of *T. dealbata* was better than those of *C. indica* and *L. salicaria*.

In contrast to the COD and TN removal, the TP removal performance by the three aquatic plants was better. The influence of seasonal pattern of change on TP removal was not significant (Figs. 2-4.). However, the TP REs also decreased in November and December. Data in Fig. 4 showed that the ranking of the TP removal ability was *C. indica* > *T. dealbata* > *L. salicaria*. In these tests, TP concentrations in the influent water were all under 1.5 mg L^{-1} , which reached the standard of Class III Environmental Quality Standards for Surface Water, GB3838-2002, China.

[Insert Figs. 5 and 6 here]

3.3. Nutrient removal through vegetation aboveground tissue harvest

Data described in Table 3 show that nutrient removal by harvesting the aerial parts of the plants could be optimized with the knowledge on the temporal variations of N and P mass in the harvestable parts and on the temporal variations of COD, TN, and TP concentrations of the effluent water in three FTWs (Figs. 2–4). Before the aboveground tissue DW declined in the later stages (Table 3), the maximum DW of *C. indica* and *T. dealbata* reached up to 1504.678 ± 75.243 and 1989.429 ± 99.485 g on October 19 after DW continually increased in the previous stages. The maximum N mass accumulated by the aboveground tissue of *C. indica* and *T. dealbata* achieved 4.915 ± 0.236 and 5.472 ± 0.278 g/plant on October 19 before it decreased slightly in later stages. As shown in Table 3, P mass accumulated by the aboveground tissue of *C. indica* and *T. dealbata* also exhibited similar variation through the nine stages. Understanding temporal nutrient distribution changes in plants is especially important to optimizing the benefits of partial plant harvest (White and Cousins, 2013). Ruiz and Velasco (2010) indicated that the stored nutrients are relocated from aboveground to belowground tissue caused by external environment changes, such as change in seasons. At the end of the growing season, the release of nutrients stored in the aboveground parts in stages 8 and 9 was consistent with the findings of other constructed wetland studies. For instance, Wang et al. (2014) reported that the *Pontederia cordata* L. translocated most resources to the belowground storage organs in the fall, resulting in less nutrient mass in the aboveground tissue compared with the case in summer (vegetative stage). Tanner (2001a) investigated

the growth characteristics and nutritional status of *Schoenoplectus tabernaemontani* in constructed treatment wetlands, and found that negative nutrient flux (leaching) normally begins as above-ground senescence occurs. The DW of *L. salicaria* increased slowly in stages 4 and 5, which may be due to plant diseases and insect pests. The maximum DW of *L. salicaria* and N mass accumulation were recorded on September 18 (stage 6). The maximum accumulated P mass was recorded on October 19 (stage 7). Based on the data in Table 3 and plant density shown in Table 1, harvested P and N per unit FTW area could be calculated through aboveground tissue in different stages.

A management strategy using the harvest of either the aboveground or whole plant tissues should be developed based on the following factors in this study at Jiaying City: i) Nutrient content in harvestable tissue (Table 3). ii) Removal efficiency of nutrients in the experimental water by FTWs (Figs. 2–4). iii) Overwintering ability of plant. iv) Operational complexity of plant harvesting and cost-effective operation. For example, harvesting the aboveground tissues of *T. dealbata* should be conducted in late October or early November because of the following reasons: i) N mass in the aboveground tissue accounts for more than 60% of that in the whole plant at this time according to the data in Fig. 3, Tables 1, 2, and 3. ii) COD, TN, and TP REs reached up to the highest values (Figs. 2–4). iii) Lastly, under normal climate conditions, *T. dealbata* can overwinter. Thus, the rhizomes and roots of *T. dealbata* should be reserved in the FTWs for plant reproduction for the following year. However, *C. indica* and *L. salicaria* cannot overwinter.

The whole plant harvesting could neglect the reproductive problems and the nutrient distribution in the vegetation (Chua et al., 2012). This harvesting strategy is a more aggressive and less sustainable approach than aboveground tissue harvesting method for removing nutrients from water bodies because the storage organs become tangled with growth media and cannot be harvested easily (Hoffmann et al., 2012). In conclusion, the plant DW data also revealed that the maximum amount of harvestable aerial plant part biomass (DW) is equated with the highest removable COD, TN and TP mass.

Finally, the aboveground tissues of *T. dealbata* and *C. indica* should be harvested in stage 8 (late October or early November) to achieve maximum nutrient removal. The harvesting strategy of the aboveground tissue of *L. salicaria* in September is recommended. The ranking of nutrient accumulation capacity of the three aquatic plants was *T. dealbata* > *C. indica* > *L. salicaria*.

[Insert Table 3 here]

4. Conclusions

In this investigation, three aquatic plant FTWs, especially *T. dealbata* FTWs, played important roles on the degradation of pollutants in urban storm water runoff wastewater. The influence of seasonal change on the performance of FTWs is significant. The seasonal applicability of *T. dealbata* FTWs is superior to those of others. Nutrient removal and harvesting strategy should be reasonably optimized to control the urban storm water runoff pollution. However, further research is recommended to investigate the impact of root oxygen release and exudates on the microbial community structure in

the rhizosphere, and the multiple harvesting of aboveground tissues at different growth stages in a single year.

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Figure captions

Fig. 1 Schematic representation of the experimental system: (a) a tank and (b) a constructed floating bed unit.

Fig. 2 Vegetation effects on the COD removal in three experiment tanks (mean, n=3). Each tank contained one FTW with 36 plants. The weekly COD concentrations of effluent water in the *C. indica*, *T. dealbata*, and *L. salicaria* FTWs and of the influent water-simulated water in each batch were monitored to estimate the performance of the three FTWs.

Fig. 3 Vegetation effects on the TN removal in three experiment tanks (mean, n=3). Each tank contained one FTW with 36 plants. The weekly TN concentrations of effluent water in the *C. indica*, *T. dealbata*, and *L. salicaria* FTWs and the influent water-simulated water in each batch were monitored to estimate the performance of the three FTWs.

Fig. 4 Vegetation effects on the TP removal in three experiment tanks (mean, n=3). Each tank contained one FTW with 36 plants. The weekly TP concentrations of effluent water in the *C. indica*, *T. dealbata*, and *L. salicaria* FTWs and of the influent water-simulated water in each batch were monitored to estimate the performance of the three FTWs.

Fig. 5 Variations of the DW of the tested vegetation with time were consistent with the variations of temperature in the nine stages.

Fig. 6 Vegetation biomass (DW) relative growth rate (mean $\pm$ SD) of whole plant, above-ground (stem+leaf), and below-ground (rhizome+root+ sprout) tissue. (a) *C. indica*, (b) *T. dealbata*, (c) *L. salicaria*. n=3 for the current study.

580 Table 1 Mean concentration of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) (mean $\pm$ SD, n = 3) of
581 the influent water and effluent water in the three FTWs, and mean removal efficiencies in 36 batches.

Wetland types	Influent water			Effluent water			Removal efficiency		
	COD (mg l ⁻¹)	TN (mg l ⁻¹)	TP (mg l ⁻¹)	COD (mg l ⁻¹)	TN (mg l ⁻¹)	TP (mg l ⁻¹)	COD (%)	TN (%)	TP (%)
<i>Canna indica</i>	122.27 $\pm$ 7.21	5.23 $\pm$ 0.31	0.24 $\pm$ 0.01	37.68 $\pm$ 1.91	1.93 $\pm$ 0.10	0.03 $\pm$ 0.001	69.07 ^a $\pm$ 2.21	62.99 ^b $\pm$ 2.32	86.29 ^a $\pm$ 2.54
<i>Thalia dealbata</i>	122.27 $\pm$ 7.21	5.23 $\pm$ 0.31	0.24 $\pm$ 0.01	35.13 $\pm$ 1.78	1.57 $\pm$ 0.08	0.04 $\pm$ 0.002	71.17 ^a $\pm$ 2.01	69.96 ^a $\pm$ 2.11	82.40 ^a $\pm$ 2.34
<i>Lythrum salicaria</i>	122.27 $\pm$ 7.21	5.23 $\pm$ 0.31	0.24 $\pm$ 0.01	45.24 $\pm$ 2.71	2.80 $\pm$ 0.15	0.08 $\pm$ 0.005	62.27 ^b $\pm$ 2.15	46.50 ^c $\pm$ 2.30	65.35 ^b $\pm$ 2.27

582 Values with different superscript letters in the same column for the three treatments indicate a significant difference at P < 0.05
583 according to Duncan's multiple range test.

584 Table 2 Growing state of the tested plants (mean $\pm$ SD, n = 3) in current study.

Plant species	Survival rate(%)	Initial density (plant m ⁻²)	Tiller number per plant (plant/plant)	Replicates (tank)
<i>Canna indica</i>	96.56 $\pm$ 4.31	10	66 $\pm$ 3	3
<i>Thalia dealbata</i>	98.35 $\pm$ 3.58	10	81 $\pm$ 2	3
<i>Lythrum salicaria</i>	91.63 $\pm$ 5.56	10	43 $\pm$ 2	3

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586

587 Table 3 Biomass and nutrient mass (mean $\pm$ SD, n = 3) in FTWs, single plant above ground tissues.

stage	Date	Phosphorus (g-P/plant)			Nitrogen (g-N/plant)			Dry weight (g/plant)		
		<i>Canna indica</i>	<i>Thalia dealbata</i>	<i>Lythrum salicaria</i>	<i>Canna indica</i>	<i>Thalia dealbata</i>	<i>Lythrum salicaria</i>	<i>Canna indica</i>	<i>Thalia dealbata</i>	<i>Lythrum salicaria</i>
0(initial)	4/6	0.007 $\pm$ 0.002	0.004 $\pm$ 0.001	0.006 $\pm$ 0.001	0.072 $\pm$ 0.002	0.069 $\pm$ 0.002	0.181 $\pm$ 0.004	2.872 $\pm$ 0.144	2.515 $\pm$ 0.136	6.714 $\pm$ 0.346
1	5/4	0.035 $\pm$ 0.002	0.027 $\pm$ 0.001	0.020 $\pm$ 0.001	0.402 $\pm$ 0.021	0.377 $\pm$ 0.021	0.188 $\pm$ 0.010	31.454 $\pm$ 1.672	35.245 $\pm$ 1.861	82.352 $\pm$ 4.125
2	6/1	0.076 $\pm$ 0.004	0.066 $\pm$ 0.003	0.048 $\pm$ 0.003	0.915 $\pm$ 0.048	0.936 $\pm$ 0.052	0.448 $\pm$ 0.025	119.571 $\pm$ 6.034	202.451 $\pm$ 10.155	175.850 $\pm$ 8.967
3	6/29	0.144 $\pm$ 0.007	0.102 $\pm$ 0.006	0.071 $\pm$ 0.005	1.523 $\pm$ 0.079	1.619 $\pm$ 0.079	0.908 $\pm$ 0.049	234.283 $\pm$ 11.974	347.377 $\pm$ 17.486	264.716 $\pm$ 14.215
4	7/30	0.159 $\pm$ 0.008	0.145 $\pm$ 0.008	0.101 $\pm$ 0.007	2.298 $\pm$ 0.125	2.494 $\pm$ 0.131	1.524 $\pm$ 0.080	589.227 $\pm$ 30.461	418.816 $\pm$ 21.091	308.348 $\pm$ 16.997
5	8/24	0.203 $\pm$ 0.013	0.194 $\pm$ 0.012	0.138 $\pm$ 0.009	3.163 $\pm$ 0.160	3.475 $\pm$ 0.185	2.154 $\pm$ 0.116	1009.011 $\pm$ 51.505	931.761 $\pm$ 48.502	369.151 $\pm$ 23.545
6	9/21	0.269 $\pm$ 0.016	0.249 $\pm$ 0.017	0.195 $\pm$ 0.013	4.051 $\pm$ 0.213	4.478 $\pm$ 0.226	2.772 $\pm$ 0.192	1469.556 $\pm$ 70.477	1835.055 $\pm$ 90.973	566.683 $\pm$ 28.344
7	10/19	0.329 $\pm$ 0.020	0.277 $\pm$ 0.014	0.211 $\pm$ 0.016	4.915 $\pm$ 0.236	5.803 $\pm$ 0.278	2.612 $\pm$ 0.165	1504.678 $\pm$ 75.243	1989.429 $\pm$ 99.485	553.192 $\pm$ 29.051
8	11/16	0.332 $\pm$ 0.021	0.275 $\pm$ 0.015	0.207 $\pm$ 0.011	4.897 $\pm$ 0.287	5.755 $\pm$ 0.332	2.536 $\pm$ 0.176	1335.929 $\pm$ 66.795	1866.333 $\pm$ 93.465	549.534 $\pm$ 28.142
9	12/14	0.325 $\pm$ 0.023	0.266 $\pm$ 0.014	0.203 $\pm$ 0.012	4.645 $\pm$ 0.347	5.585 $\pm$ 0.355	2.503 $\pm$ 0.171	1006.312 $\pm$ 50.515	1747.018 $\pm$ 87.359	492.245 $\pm$ 24.688

588

589

Fig.1

Fig.2

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Fig.6