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Effects of interspecific competition on the growth of macrophytes and nutrient removal in constructed wetlands: A comparative assessment of free water surface and horizontal subsurface flow systems

Yucong Zheng [a], Xiaochang Wang [a,*], Mawuli Dzakpasu [a,b], Yaqian Zhao [b], Huu Hao Ngo [c], Wenshan Guo [c], Yuan Ge [a], Jiaqing Xiong [a]

[a] *Key Laboratory of Northwest Water Resource, Environment and Ecology, MOE, School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China*
[b] *UCD Dooge Centre for Water Resources Research, School of Civil Engineering, Newstead Building, University College Dublin, Belfield, Dublin 4, Ireland*
[c] *School of Civil and Environmental Engineering, University of Technology Sydney, Broadway, NSW 2007, Australia*

HIGHLIGHTS

- Interspecific competition of *Phragmites* and *Typha* was investigated in two large CWs.
- *P. australis* showed higher growth performance in mixed cultured FWS and SSF wetlands.
- Interspecific competition caused different ecological responses of plant species.

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ABSTRACT

The outcome of competition between adjoining interspecific colonies of *Phragmites* and *Typha* in two large field pilot-scale free water surface (FWS) and subsurface flow (SSF) CWs is evaluated. According to findings, the effect of interspecific competition was notable for *Phragmites australis*, whereby it showed the highest growth performance in both FWS and SSF wetland. In a mixed-culture, *P. australis* demonstrates superiority in terms of competitive interactions for space between plants. Furthermore, the interspecific competition among planted species seemed to cause different ecological responses of plant species in the two CWs. For example, while relatively high density and shoot height determined the high aboveground dry weight of *P. australis* in the FWS wetland, this association was not evident in the SSF. Additionally, while plants nutrients uptake accounts for a higher proportion of the nitrogen removal in FWS, that in the SSF accounts for a higher proportion of the phosphorous removal.

1. Introduction

Constructed wetlands (CWs), as a cost-effective and eco-friendly wastewater treatment technology, have been widely applied for the treatment of various types of wastewater, as well as polluted river and lake waters due to their easy operation and maintenance (Rai et al., 2013; Svensson et al., 2015; Vymazal, 2013c; Wu et al., 2015). CWs are typically classified into free water surface flow (FWS) and subsurface flow (SSF) systems. The efficient removal of water pollutants is achieved through a number of biotic and abiotic processes, especially around the rhizosphere of macrophytes, as the wastewater flows through the CWs substrate materials (Stottmeister et al., 2003).

The macrophytes growing in CWs perform several direct and indirect roles in relation to the treatment process such as uptake and assimilation of nutrients and heavy metals, provision of substrates for the growth of attached bacteria, the release of oxygen and exudates, surface insulation, hydraulic condition regulation and wind velocity reduction (Vymazal, 2013b). In fact, CWs with plants have been proven to be more efficient compared with unplanted CWs (Boog et al., 2014). Nonetheless, recent findings indicate that bacteria richness and the performance of CWs varied greatly in relation to different plant species (Toscano et al., 2015).

Therefore, to ensure efficient performance of CWs, the macrophyte species to be planted should be considered as an integral design component by careful selection. To increase CWs

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* Corresponding author. Tel./fax: +86 29 82205841.
E-mail address: xcwang@xauat.edu.cn (X. Wang).

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performance, mixed planted systems have been considered to treat different types of wastewater. The multi-species wetlands were considered less susceptible to seasonal variation and more effective in pollutants removal than single-species wetlands (Chang et al., 2014; Liang et al., 2011). However, these CWs were mainly tested at laboratory-scale or short experimental periods. Moreover, interspecific competition for resources among planted species, such as space, light, and nutrients, is one of the important factors in determining wetland vegetation. Nevertheless, due to the high variability in this interspecific competition among planted species, the development and stability of different species in mixed planted wetlands during long-term operation remain unclear (Agami and Reddy, 1990; Amon et al., 2007). Besides, to date, no studies have directly compared the performance or evaluated the competitive interaction between plant species of the mixed culture plants in FWS and SSF wetlands under the same wastewater loading and environmental conditions at the field scale.

The common reed (*Phragmites australis*) and cattail (*Typha* spp.) are the most often used plant species in CWs (Vymazal, 2013a), because of their high flood-tolerant and reproduction abilities. However, the application of these two plants in mixed cultures in FWS and SSF wetlands is rare. *Phragmites* spp. and *Typha* spp. are both colonial macrophytes that share several morphological traits, such as tall, unbranched shoots and both rhizomes and roots as underground structures. They also share similar habitats and a large range of site conditions, including resistance to saline conditions (Miklovic and Galatowitsch, 2005). Like *Phragmites*, *Typha* often forms dense stands due to their strong vegetative propagation, and both *Typha* species and their hybrid display invasive tendencies in disturbed wetlands (Shih and Finkelstein, 2008). Consequently, the contact zone between *Phragmites* and *Typha* stands is probably characterized by intense competition for space, the outcome of which is best revealed by the spatial dynamics at that contact zone over time as one species progress to the detriment of the other. Thus, adjoining colonies of *Phragmites* and *Typha* represent an ideal model for testing hypotheses about competitive interactions between these clonal species and developing an understanding of interspecific plant competition in CWs.

In this study, local *Phragmites australis* and *Typha orientalis* were equally planted in monospecific colonies in pilot-scale FWS and SSF wetlands to treat highly polluted river water over two years. The pollutants treatment performance and the roles of plants were evaluated in a side-by-side comparison of the FWS and SSF wetlands. The specific objectives were to: (1) evaluate pollutant removal in pilot-scale FWS and SSF wetlands over two full years of operation; (2) assess the effects of interspecific competition between *P. australis* and *T. orientalis* in terms of growth characteristics, species range extension and nutrients accumulation abilities under mixed culture conditions; and (3) analyze the different interspecific competition characteristics of *P. australis* and *T. orientalis* in FWS and SSF wetlands.

2. Methods

2.1. Description of the pilot wetlands

The pilot-scale FWS and SSF wetlands were constructed on the eastern bank of the Zaohe River in Xi'an, northwestern China (34°22′54″N, 108°51′05″E). The area has a sub-humid continental monsoon climate, which is cold and lacks rainfall during the winter. The FWS CW was designed with a length of 45 m, width of 20 m and height of 0.6 m, and was filled with sand (0.06–10 mm, initial porosity about 30%) to a depth of 0.35 m. The water depth was controlled at 0.4 m. The SSF wetland was designed with a length of 34 m, width of 20 m and height of 0.8 m, and was filled with gravel (1–70 mm, initial porosity about 50%) to a depth of 0.6 m. The water depth was controlled at 0.55 m. Both wetlands were lined with high-density polyethylene to prevent the seepage of polluted water to the underlying groundwater. The bottom slope of all the CWs was 0.5%. The chemical characteristics of the gravel and sand substrates are shown in Table 1. Water from the Zaohe River is pumped into an elevated feeding tank for sedimentation and subsequent distribution to the CWs continuously. The inflow rate to the FWS and SSF was 90 m^3/d and 68 m^3/d, respectively, both of which correspond to a surface loading of 0.1 m/d. Local *P. australis* and *T. orientalis* with similar size obtained from the field near the riverbank were selected and washed with tap water. They were then planted in equal proportions in the CWs at a density of 9 shoots/m^2 and a height of about 20 cm in September. Plants harvesting was carried out in November, for the two successive years, when the plants began to wither. Each year is defined here as November to October. The pilot wetlands were commissioned in November 2010.

2.2. Water sampling and analysis

During the two-year experimental period, water samples were collected weekly from the influent and effluent of the two CWs. All of the water samples were transported to the laboratory for chemical analyses within 24 h. The parameters measured include SS, COD, BOD_5, NH_3-N, TN and TP. Standard methods (MEPC and WWMAA, 2002) were followed for all the chemical analyses. Water temperature and dissolved oxygen (DO) were measured on site by using a portable meter (HQ30d53LED™, HACH, USA). The removal efficiencies for each wetland were calculated from the difference in concentration between the influent and effluent of the CWs. Significant differences were determined at $\alpha = 0.05$ by paired samples *t*-tests and one-way analysis of variance (ANOVA).

2.3. Plant sampling and analysis

During the experimental period, the plant heights in the two CWs were measured monthly in three randomly selected quadrats of 0.25 m^2. The number, weight and coverage of *P. australis* and *T. orientalis* in the two CWs were measured before the harvesting in November. The selected harvested plants were separated into stems, leaves and flowers and washed with distilled water to remove the adhering water and sediments. Plant parts were then oven-dried at 80 °C to a constant weight, and their dry biomass were determined. All dried plant samples were ground separately to pass through a 0.25 mm mesh screen, digested and analyzed for total N and P according to the routine analysis method for soil agro-chemistry (Bao, 2000). The average nutrients concentration in the aboveground biomass was calculated as follows:

$$C_{\text{total}} = \frac{(\text{DM}_{\text{leaves}} \times C_{\text{leaves}}) + (\text{DM}_{\text{stems}} \times C_{\text{stems}}) + (\text{DM}_{\text{flowers}} \times C_{\text{flowers}})}{(\text{DM}_{\text{leaves}} + \text{DM}_{\text{stems}} + \text{DM}_{\text{flowers}})} \tag{1}$$

where DM = dry matter of a particular shoot part (g), *C* = concentration of nutrients in the respective plant parts (% DM).

The amount of nutrients uptake by the aboveground biomass was calculated according to the following equation:

$$N_{\text{total}} = (\text{DM}_{\text{leaves}} \times C_{\text{leaves}}) + (\text{DM}_{\text{stems}} \times C_{\text{stems}}) + (\text{DM}_{\text{flowers}} \times C_{\text{flowers}}) \tag{2}$$

where DM values represent the total biomass of leaves, stems and flowers, and *C* represents the average concentrations of N and P in these respective plant parts. *N* values represent the amount of nutrients uptake by the aboveground biomass of plants.

Table 1
Chemical properties of the substrates.

Substrate	pH	Chemical composition mass percentage (%)											
		C	N	P	O	Na	Mg	Al	Si	K	Ca	Ti	Fe
Gravel	8.76	–	–	–	51.61	1.11	1.01	8.79	27.58	4.05	0.73	–	5.12
Sand	7.14	–	–	–	56.82	2.99	0.23	7.67	26.25	3.55	0.87	–	1.62

The relative importance value (I.V.) (Hong et al., 2014) of each species was calculated as a sum of the relative density and relative coverage in each CW, to represent a plant-sociological result, after the interspecific competition among the planted species. The competitive value (C.V.) of each species was used to compare their growth responses to interspecific competition. The C.V. (Eq. (3)) provides a means to determine interactions among plant groups (Hong et al., 2014).

$$C.V. = 100(X_2 - X_1)/X_2 \tag{3}$$

where X_1 is the dry weight of a particular species grown alone, and X_2 is the dry weight of a particular species grown with neighbours.

3. Results and discussion

3.1. Overall performance of the FWS and SSF wetlands

Fig. 1 shows the variation in the concentrations of COD, BOD_5, TN, NH_3-N, TP, and PO_4^{3-}-P in the river water, the average of which were 303.6 ± 10.3, 98.3 ± 4.6, 39.6 ± 0.7, 29.1 ± 0.8, 3.6 ± 0.1, and 1.6 ± 0.1 mg/L, respectively (Table 2). These concentrations indicated that the river water was highly polluted and was similar to that of domestic wastewater. This high level of pollution was to be expected as currently the main function of the Zaohe River is an urban drainage channel to receive effluents from several domestic wastewater treatment plants, urban runoff, and untreated industrial wastewater. Moreover, the treatment performance of two CW types is also shown in Fig. 1 and Table 2. While both wetland types achieved significantly high levels of organic matter removal, the levels of nutrients removal were moderate. Nonetheless, the COD removal in the SSF wetland was significantly higher than that in the FWS ($p < 0.05$, Fig. 1a), whereas the BOD_5 concentration of the effluents in the two wetlands were similar and below 10 mg/L ($p > 0.05$, Fig. 1b and Table 2). Furthermore, the microbial population in the SSF wetland (10^6 cfu/ml) was nearly one order of magnitude higher than that of the FWS wetland (10^5 cfu/ml) during the experimental period. However, the DO concentration in the SSF wetland (about 0.48 mg/L) was lower than that of FWS

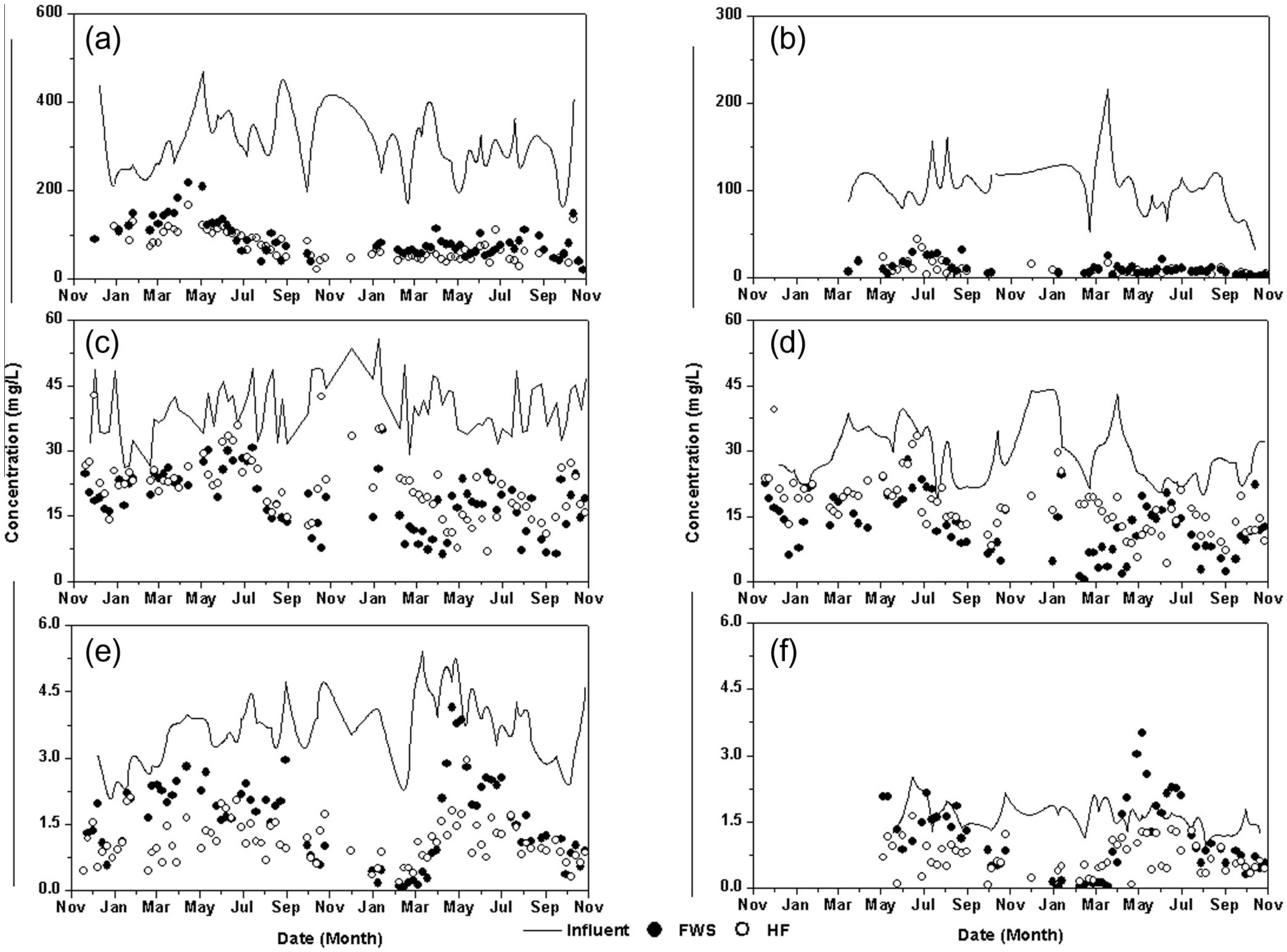

Fig. 1. Variations in (a) COD, (b) BOD_5, (c) TN, (d) NH_3-N, (e) TP, (f) PO_4^{3-}-P concentrations in the pilot FWS and SSF wetlands during the operation period ($n = 77$; for BOD_5 and PO_4^{3-}-P, $n = 62$).

Table 2
Pollutant concentrations and loadings at the influent and effluent of the two CWs during the experimental period.

Items	Unit	COD		BOD_5		TN		NH_3-N		TP		PO_4^{3-}-P	
		Mean	SD[a]	Mean	SD[a]	Mean	SD[a]	Mean	SD[a]	Mean	SD[a]	Mean	SD[a]
Influent	mg/L	303.6	10.3	98.3	4.6	39.6	0.7	29.1	0.8	3.6	0.1	1.6	0.1
PLR[b]	g/m^2 year	10,489	356	3396	159	1368	24	1005	28	124.4	3.5	55.3	3.5
FWS effluent	mg/L	89.9	4.4	9.6	1.0	18.5	0.7	12.9	0.7	1.6	0.1	1.1	0.1
FWS RR[c]	g/m^2 year	7385	280	3063	170	728	18	560	15	70.6	1.6	17.6	1.1
SSF effluent	mg/L	71.9	3.4	8.6	1.0	21.7	0.8	17.0	0.7	1.1	0.1	0.7	0.05
SSF RR[c]	g/m^2 year	8006	244	3097	176	619	16	416	14	87.0	2.0	32.1	1.3

[a] Standard deviation.
[b] Pollutant loading rate.
[c] Removal rate.

wetland (about 1.53 mg/L). As the biodegradation of organics proceeds more rapidly under aerobic conditions (Li et al., 2014), the FWS wetland was expected to show higher BOD_5 removal. However, the organics removal in CWs has also been shown to be accomplished by the physical processes of sedimentation, filtration, and interception (Wang et al., 2015), which resulted in both wetlands achieving similar BOD_5 removal. Nevertheless, the COD removal efficiency in the SSF wetland was higher.

The TN and NH_3-N concentrations in the FWS wetland effluent (18.5 and 12.9 mg/L) were significantly lower than that in the SSF (21.7 and 17.0 mg/L) ($p < 0.05$, Fig. 1c–d and Table 2). The removal of NH_3-N in the FWS wetland was higher, because the DO concentration was higher, which benefited nitrification (Li et al., 2014). Moreover, the removal of TN in the FWS wetland was also higher than that of the SSF wetland. The minimal concentrations of nitrified nitrogen in the effluent of the two wetlands indicated that simultaneous nitrification and denitrification occurred in the wetlands. On the other hand, the TP and PO_4^{3-}-P concentrations in the FWS wetland (1.6 and 1.1 mg/L) was significantly higher than that in the SSF (1.1 and 0.7 mg/L) ($p < 0.05$, Table 2). The effluent concentrations of P in the FWS wetland was observed to increase slight above that of the influent during the spring season (Fig. 1e and f). This increase in effluent P concentration could be attributed to the desorption of P by the substrate. Overall, the higher P-sorption capacity of the gravel (0.8 mg/g) compared with sand (0.1 mg/g) and the flow conditions of the SSF wetland resulted in a higher phosphorus removal in the SSF wetland. Nonetheless, plants uptake also plays important roles in nutrients removal in CWs (Vymazal, 2013b). Additionally, the microbial population and communities diversity around the rhizosphere and roots of plants are reported to be higher than the other regions in the wetlands (Berendsen et al., 2012; Hallin et al., 2015). Based on this consideration, the roles and evolution of the mixed-planted macrophytes in the two wetlands were further examined.

3.2. Comparative analysis of plant growth

During the experimental period, the average air temperature in the wetland area was about 18.0 °C. The average temperatures in summer and winter were 28.9 °C and 2.2 °C, respectively. Although the average water temperature in the two wetlands were similar, the heights of plants in the FWS wetland were about 20 cm higher than that in SSF wetland. The heights of *T. orientalis* were higher than *P. australis* in both wetland types.

Before the harvesting in autumn, the average plant density in the FWS wetland was 119 shoots/m^2 in the first year, which increased to 160 shoots/m^2 in the second year (Fig. 2a). In the SSF wetland, shoot densities increased from 99 shoots/m^2 to 111 shoots/m^2 (Fig. 2a). The initial planted density in the two wetlands were 9 shoots/m^2 each. Therefore, the observed increase in the plant density mainly occurred during the first year when there was much more space available for the plants to grow into. However, the slightly higher plant density in the second year resulted in little space available for new plants to grow, which consequently increased interspecific competition among the plants (Agami and Reddy, 1990). Furthermore, the density of plants in the FWS was higher than that in the SSF wetland (Kadlec and Wallace, 2008). This difference further increased in the second year (Fig. 2b), which indicated that the FWS wetland provided much more suitable conditions for the macrophytes to grow. Although the heights of

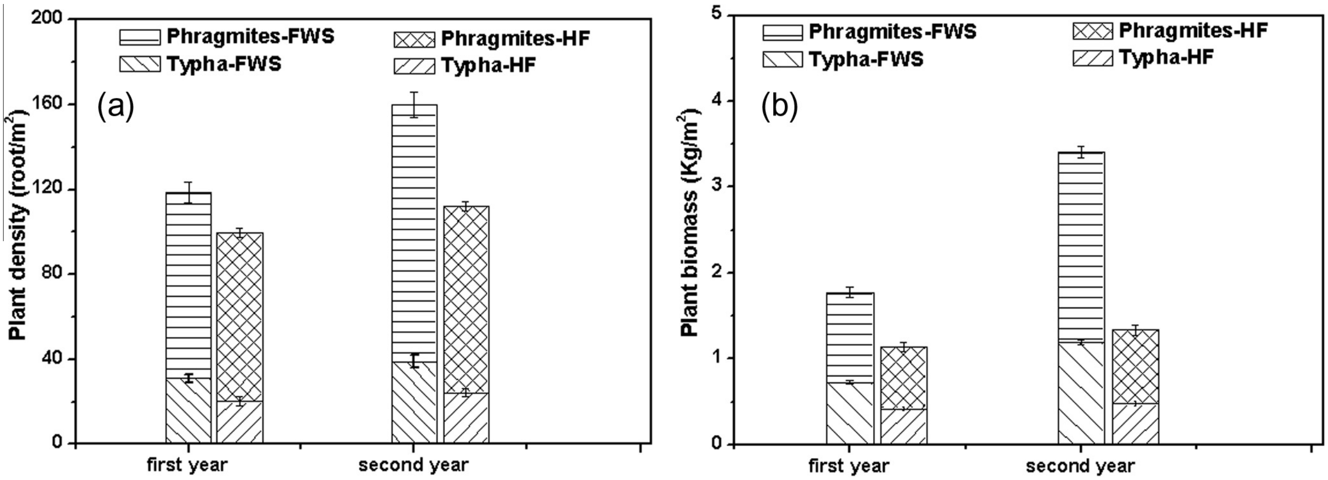

Fig. 2. Average plant densities in FWS and SSF wetlands (a) and total mean aboveground dry weights in FWS and SSF wetlands (b) at the end of the growing season during the experimental period.

T. orientalis were higher, the densities of *P. australis* in both wetlands were about three times higher than that of *T. orientalis*. In addition, the *P. australis*/*T. orientalis* ratio increased in the second year, especially in the SSF wetland (3.2–3.5). This increase indicated that *P. australis* had better reproductive and adaptive capabilities than *T. orientalis* under the mixed culture conditions, especially in the SSF wetland. However, the opposite results were reported by Kercher and Zedler (2004).

As the plants were cut about 20–30 cm above the ground, the amount of plants biomass at harvesting can be regarded as the net increase. The average biomass production of plants in the FWS CW was 1.8 kg/m^2 in the first year, which increased to 3.4 kg/m^2 in the second year. In the SSF CW biomass production increased from 1.1 kg/m^2 to 1.4 kg/m^2 (Fig. 2b). As with the plant density, the plants biomass production in the FWS was 1.6–2.4 times higher than that in the SSF wetland in the first and second year. This difference indicated that the plants in the FWS CW were denser than those in the SSF CW (Vymazal, 2013a; Leto et al., 2013). As indicated above, the plant density in the two wetlands increased slightly in the second year. Nevertheless, compared with the plant density, the biomass of plants in the two wetlands types increased significantly, especially in the FWS CW (Fig. 2), demonstrating that the plants became heavier in the second year (Leto et al., 2013).

Furthermore, the dry weights of *P. australis* in both wetlands were about 1–2 times higher than that of *T. orientalis* during the whole experimental period. The higher density of the *P. australis* resulted in the higher dry weight. The higher aboveground biomass of *P. australis* indicated a higher pollutants uptake capacity, as well as a higher belowground biomass and microbial population (Peng et al., 2014). Additionally, the densities and dry weights of the plants in these two CWs were found to be higher than those reported in the literature (Leto et al., 2013; Liang et al., 2011).

3.3. Nutrients contents in plant tissues and plant uptake

The nutrients concentrations in the aboveground tissues of plants in the two wetlands were similar, which both increased slightly in the second year of the experimental period (Fig. 3a and b). In the second year, the nutrients content of *P. australis* and *T. orientalis* tissues were 36.0 mg N/g and 3.3 mg P/g, and 31.6 mg N/g and 3.6 mg P/g, respectively, in the FWS CW. In the SSF CW, nutrient contents were 34.1 mg N/g and 3.4 mg P/g (*P. australis*), and 29.8 mg N/g and 3.5 mg P/g (*T. orientalis)* (Fig.3a and b). Overall, the nitrogen concentration in the *T. orientalis* was lower than that in *P. australis* in the two CW types (Fig. 3a and b). The opposite was found for phosphorus. However, this difference was not significant. Moreover, the nutrients concentrations in the

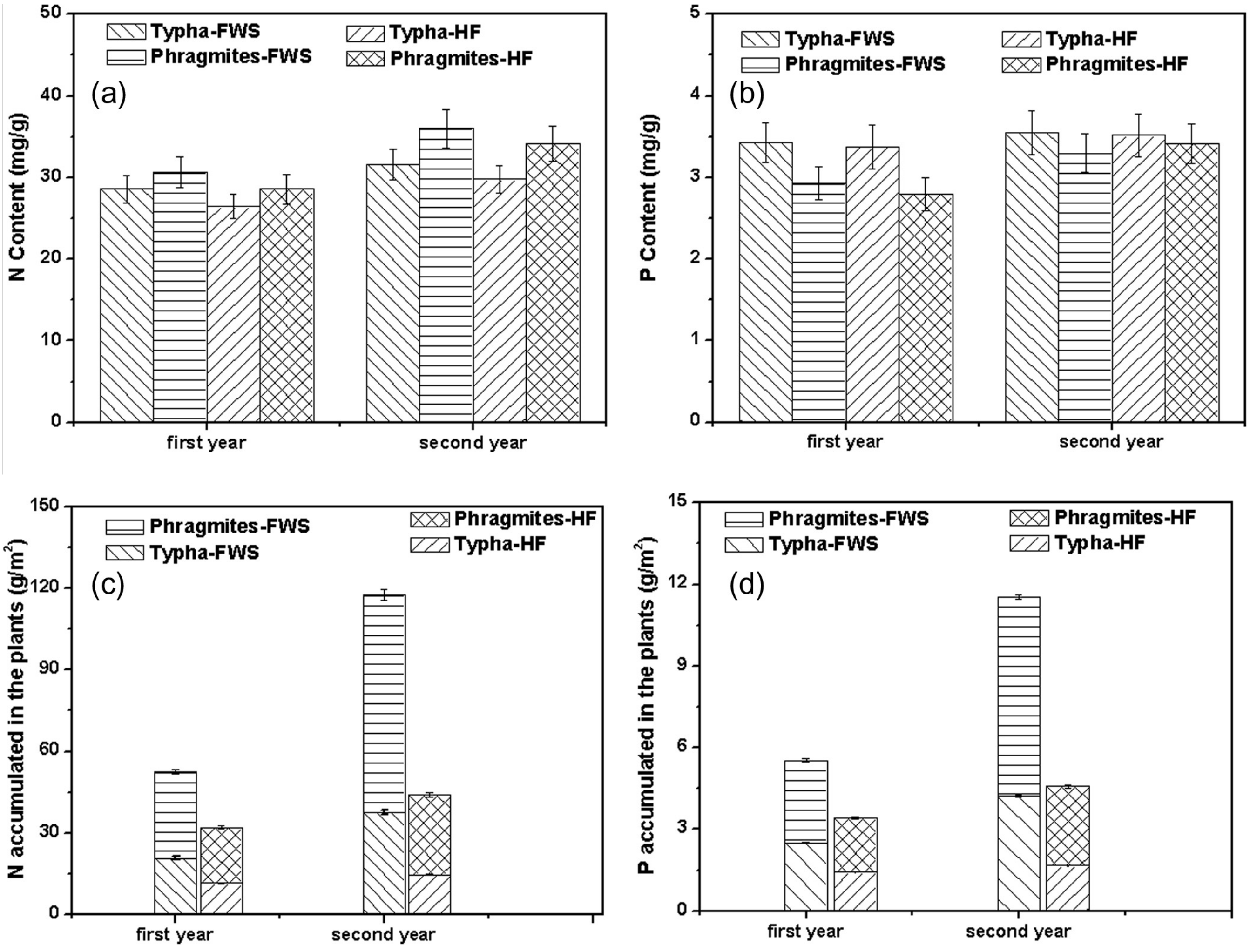

Fig. 3. Average nutrients content (a, b) and nutrients uptake by the aboveground biomass of *P. australis* and *T. orientalis* in the two wetland types (c, d) at the end of the growing season during the experimental period.

aboveground tissues of plants were within the range of values reported in other previous studies (Kadlec and Wallace, 2008).

As shown in Fig. 3c, the nitrogen uptake by the aboveground parts of *P. australis* and *T. orientalis* in the FWS were 31.7 g N/m^2 and 20.8 g N/m^2, respectively, in the first year, which increased to 80.0 g N/m^2 and 37.6 g N/m^2, respectively in the second year. The phosphorus uptake rates increased from 3.0 g P/m^2 and 2.5 g P/m^2, respectively, in the first year to 7.3 g P/m^2 and 4.2 g P/m^2, respectively, in the second year (Fig. 3d). In the SSF wetland, nitrogen uptake by the aboveground parts of *P. australis* and *T. orientalis* increased from 20.4 g N/m^2 and 11.1 g N/m^2, respectively in the first year, to 29.2 g N/m^2 and 14.2 g N/m^2, respectively in the second year (Fig. 3c). Similarly, the phosphorus uptake increased from 2.0 g P/m^2 and 1.4 g P/m^2, respectively in the first year, to 2.9 g P/m^2 and 1.7 g P/m^2, respectively in the second year (Fig. 3d). As the amount of nutrients uptake by plants were calculated by the nutrients content in the plants tissues and the dry weight of the plants (Kadlec and Wallace, 2008), the significant difference in the plants' dry weights resulted in the plants in the FWS CW showing much higher nutrients uptake ability than those in the SSF CW, especially in the second year. Moreover, the nutrients uptake by *P. australis* in both wetlands were about 1–2 times higher than that of *T. orientalis* during the whole experimental period. Therefore, in order to improve the nutrients uptake ability of plants and consequently, the performance of the wetlands, the plant species with high adaptation and reproduction ability should be selected. Additionally, despite the interspecific competition among the plant species in these two CWs, the nutrients uptake by *P. australis* and *T. orientalis* were found to fall within the range of values reported in other previous studies (Leto et al., 2013; Liang et al., 2011).

3.4. Significance of plant for nutrients removal

As plants play important roles in nutrients removal in CWs, it is important to comprehend the different roles of plants planted in different CW types for nutrients removal. Table 3 shows the nutrients mass balance components for each CW during the experimental period. Overall, as the plant and other components of the two CWs were much mature in the second year, the amount of nutrients removed was to increase in both wetlands. The amount of nitrogen removed in the FWS wetland was higher than that of the SSF wetland. In contrast, the SSF wetland showed higher phosphorous removal than FWS wetland (Table 3). However, while the plants nutrients uptake accounted for a greater proportion of the phosphorus removal in FWS wetland than the nitrogen, the opposite was found in the SSF wetland (Table 3). Thus, the impact of plant uptake, microorganisms degradation, and substrates adsorption were quite different for the removal of nutrients in FWS and SSF wetlands (Kadlec and Wallace, 2008).

Although the amount of nutrients uptake by plants in the two wetlands both increased in the second year, the proportion attributable to plants for nutrients removal in the FWS and SSF wetlands were significantly different (Table 3). For the FWS wetland, the proportion attributable to plants for both TN and TP removal increased from 8.6% and 9.9% in the first year, to 13.9% and 13.9% in the second year. This increase highlighted the important roles that the plants in the FWS wetland played in nutrients removal. More particularly, as the biomass of plants increased, the microbial activities in the FWS wetlands would be further stimulated, resulting in a higher nutrients removal (Korboulewsky et al., 2012). However, for the SSF wetland, the proportion attributable to plants for TN removal was decreased from 6.2% to 5.8%, while the proportion attributable to plants for TP removal was increased from 4.6% to 4.8%. This possibly occurred because as the reproduction of plants in SSF wetland enhanced the nitrification-denitrification process around the rhizosphere of the plants, and the P-sorption capacity of the gravel was decreased with the long-term operation (Berendsen et al., 2012; Hallin et al., 2015; Kadlec and Wallace, 2008; Stottmeister et al., 2003). Additionally, *P. australis* contributed much more to the TN and TP removal than *T. orientalis* in both FWS and SSF CWs. Therefore, considering the important direct and indirect roles of plants in nutrient removal in the FWS wetland, the selected plant species should possess the ability to regenerate and grow vigorously. However, in the SSF wetland, as the direct impacts of plants were minimal, the planted species should possess the ability to improve the diversity and activity of the microorganisms.

Moreover, due to the importance of plants in CWs especially in the FWS wetlands, several studies have suggested that the overall nutrients removal would be higher if a multiple or earlier harvesting scheme is adopted (Batty and Younger, 2004; Kadlec and Wallace, 2008). However, multiple or earlier harvesting can be detrimental to the plants because they would not have sufficient opportunity to withdraw nutrients and nonstructural carbohydrates from the shoots to belowground plant parts (Van der Linden, 1980, 1986). Besides, frequent aboveground harvesting can slow growth and biomass development. Therefore, the annual harvesting of the plants should be based on the consideration of the economic, climatic and wetland operation conditions. According to Zheng et al. (2015), long term nutrient removal by annual harvesting of plants stands in autumn season can be considered as a good plant management approach in the prevailing conditions of northwestern China. This is because harvesting at the end of the growing season in autumn does not only promote the new plants' uptake of more nutrients. It also increases the belowground biomass and stimulates the microbial activities in the wetlands, both of which enhances CWs performance.

3.5. Plant-sociological results after interspecific competition

The importance values (I.V.) of 132.3 and 145.3 for *P. australis* in the FWS and SSF wetlands, respectively, and 67.7 and 54.7 for *T. orientalis*, respectively, indicated that after two growing seasons (2010–2012), *P. australis* was the predominant species in the two wetlands. The competitive values (C.V.) of the plant species, which were in the following order: *P. australis* in FWS (64.7), *P. australis* in

Table 3
Nutrient mass removal and uptake by plants in the two CWs at the end of the growing seasons during the experimental period.

Period	Wetland	Parameter	Influent (g/m^2)	Effluent (g/m^2)	*P. australis* (g/m^2)	*T. orientalis* (g/m^2)	Total plant uptake (g/m^2)	Plant uptake (%)
First year	FWS	TN	1335.1	723.5	31.7	20.8	52.5	8.6
		TP	116.2	60.4	3.0	2.5	5.5	9.9
	SSF	TN	1335.1	831.2	20.4	11.1	31.5	6.2
		TP	116.2	42.2	2.0	1.4	3.4	4.6
Second year	FWS	TN	1401.9	556.3	80.0	37.6	117.6	13.9
		TP	132.5	49.6	7.3	4.2	11.5	13.9
	SSF	TN	1401.9	662.5	29.2	14.2	43.4	5.8
		TP	132.5	36.1	2.9	1.7	4.6	4.8

Table 4
Relative importance and competitive values of plant species in the two constructed wetland.

Plant-sociological value	FWS wetland		SSF wetland	
	P. australis	*T. orientalis*	*P. australis*	*T. orientalis*
I.V.[1]	132.3	67.7	145.3	54.7
C.V.[2]	64.7	35.3	64.3	35.7

[1] Species importance value.
[2] Species competitive value. Lower values indicate low competitiveness under an interspecific competitive condition.

SSF (64.3), *T. orientalis* in SSF (35.7), and *T. orientalis* in FWS (35.3), indicate that *P. australis* grew better than *T. orientalis* under interspecific competition in both FWS and SSF wetlands (Table 4).

From the plant-sociological results of I.V. and C.V., *P. australis* showed the overall highest growth performance in the two CWs. This high growth performance of *P. australis* coupled with its high aboveground dry weight value resulted in the species expanding its coverage in both the FWS and SSF wetlands (Fig. 4). This finding is particularly interesting for the FWS wetland because the continuously inundated condition during the growing season would be expected to confer competitiveness on *Typha* spp., rather than *Phragmites* spp., which prefer well-drained or intermittently inundated conditions. According to Asaeda et al. (2005), the growth of *Typha* spp. seedlings is usually facilitated in a continuously flooded condition, and decreases in a well-drained condition. Kercher and Zedler (2004) also reported that the growth of *Typha* spp. is not negatively influenced by an inundated condition, and could result in a competitive advantage to *Typha* spp. over *Phragmites* spp.

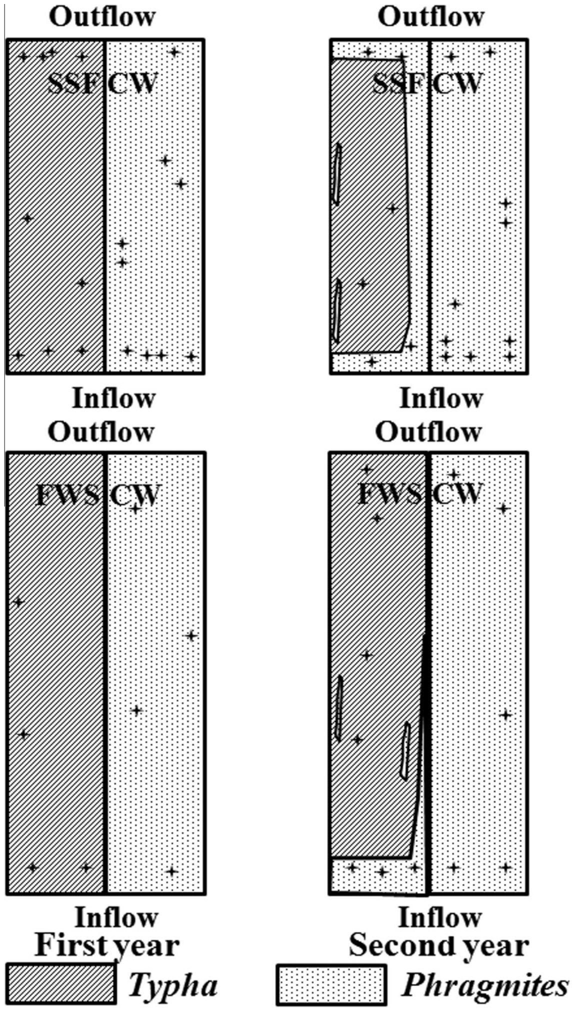

Fig. 4. Changes in the growth patterns of *P. australis* and *T. orientalis* in FWS and SSF CWs during the time of operation.

Nonetheless, despite the relatively high growth performance in both wetlands, interspecific competition of *P. australis* showed different ecological characteristics, in terms of the correlation between growth parameters, such as shoot height, density, and dry weight. For example, while relatively high plant density and shoot height determined the high aboveground dry weight of *P. australis* in the FWS wetland ($p < 0.01$), this association was not evident in the SSF wetland. This finding suggests that competition likely leads to different ecological responses among plant species in different wetland systems. Consequently, such different responses could affect the competitive status and vegetation composition in constructed wetlands (i.e., competitive effect of competitive ability) (Goldberg and Landa, 1991; Keddy et al., 1994). This differential response is further demonstrated in Fig. 4, whereby the encroachment of *P. australis* into the *T. orientalis* stands was exhibited differently in the two wetland systems. In the FWS wetland, the encroachment started in the inflow zone, which later spread to the outflow zone. In the SSF wetland, however, *P. australis* started to encroach simultaneously at the inflow, outflow and plant border zones.

Furthermore, the speed of encroachment was different in the FWS and SSF wetlands. The expansion of *P. australis* into *T. orientalis* stands in the SSF wetland was much more rapid than that in the FWS wetland (Fig. 4). This phenomenon could be explained by the fact that *P. australis* has a much stronger growing capability, resource utilization capacity, competitive potential and higher potential leaf photosynthesis capacity than *T. orientalis* (Fu et al., 2011). These advantages were more evident in the SSF wetland, where there were no conducive conditions for the growth of plants. Therefore, it becomes difficult to maintain single plant colonies within the mixed culture of wetlands due to the progressive dominance of the most aggressive species. Thus, wetland plants should be carefully selected during the planning stage when mixed culture is to be used in a particular CW.

4. Conclusions

The effect of interspecific competition was notable for *P. australis*; it showed the highest growth performance in both FWS and SSF wetlands. In mixed-culture, *P. australis* demonstrates superiority in terms of competitive interactions for space between plants. Furthermore, the interspecific competition caused different ecological responses of plant species in the two CWs. Additionally, while plants nutrients uptake accounted for a higher proportion of the nitrogen removal in FWS, that in the SSF accounted for a higher proportion of the phosphorous removal. Special management effort is, thus, required to maintain habitat characteristics and the design macrophyte diversity in mixed culture CWs.

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