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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

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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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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:

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

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:

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

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.