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Plant growth, community structure, and nutrient removal in monoculture and mixed constructed wetlands

Ming-Qiu Liang [1], Cheng-Feng Zhang [1], Chang-Lian Peng, Zeng-Long Lai, Da-Feng Chen, Zhang-He Chen *

Key Laboratory of Ecology and Environmental Science in Guangdong Higher Education, Guangdong Provincial Key Lab of Biotechnology for Plant Development, College of Life Science, South China Normal University, Guangzhou 510631, PR China

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ABSTRACT

The aim of this study was to compare the growth, community structure, and nutrient removal rates between monoculture and mixed wetlands, based on the hypothesis that it depends on the plant species used in the wetlands as to whether monoculture or mixed wetland is superior in plant growth and nutrient removal. Pilot-scale monoculture and mixed constructed wetlands were studied over 4 years. The monoculture wetland had a community height similar to the mixed wetland during the early years but a significantly lower height than the mixed wetland ($P < 0.05$) during the last year. The mixed wetland also displayed a higher plant density than the monoculture wetland ($P < 0.05$). The leaf area index in the monoculture wetland was significantly higher in the first year ($P < 0.05$) and significantly lower in the later years ($P < 0.05$) than that in the mixed wetland. The monoculture wetland had a similar vertical distribution of below-ground biomass over 4 years, while the mixed wetland showed a significant change in vertical distribution of below-ground biomass in the last 2 years. The monoculture wetland had a larger ($P < 0.05$) above-ground biomass and a similar leaf biomass in the first year, and a smaller above-ground biomass ($P < 0.05$) and a smaller leaf biomass ($P < 0.05$) than the mixed wetland during the latter 2 years. The amount of standing dead mass was smaller in the mixed wetland than in the monoculture wetland ($P < 0.05$). The mixed wetland exhibited a significantly lower NH_4–N removal rate in the first year ($P < 0.05$), and significantly higher NH_4–N removal rate in the last year, when compared to the monoculture wetland ($P < 0.05$). The study indicated that species competition and stubble growth resulted in significant differences between monoculture and mixed constructed wetlands in plant growth, community structure, and nutrient removal rates.

1. Introduction

Plants are considered to play an important role in nutrient removal from constructed wetlands (Koottatep and Polprasert, 1997; Kivaisi, 2001; Clarke and Baldwin, 2002; Kyambadde et al., 2004; Greenway, 2007; Vymazal and Kröpfelová, 2009). Research has shown that a large difference in effluent improvement exists between different plant wetlands (Tanner, 1996; Karathanasis et al., 2003; Iamchaturapatr et al., 2007; Maine et al., 2007). Improvements in plant selection and cultivation may facilitate nutrient removal from wastewater (Zhang et al., 2007a; Brisson and Chazarenc, 2009). Most constructed wetlands in the world are low in plant diversity or even monocultures, and one attempt to improve the role of plants in constructed wetlands is to increase the plant diversity and to construct mixed wetlands. Scientists have long been interested in the relationship between species diversity and system functioning (Fisher et al., 2009). It has been reported that system functioning benefits from higher plant diversity (Engelhardt and Ritchie, 2001; Tews et al., 2004). Hence, there is a question as to whether mixed wetlands are superior to the monocultures in nutrient removal. However, documented comparisons in nutrient removal between monoculture and mixed constructed wetlands are actually limited (Coleman et al., 2001), and what has been documented has shown inconsistent results (Bachand and Horne, 2000; Coleman et al., 2001; Karathanasis et al., 2003; Fraser et al., 2004; Picard et al., 2005; Zhang et al., 2007b). It is still unclear whether it is more effective to maintain monoculture or to construct mixed wetlands (Zhang et al., 2007b). Clearly, further research is essential in order to understand the differences between monoculture and mixed wetlands, as well as the mechanisms of the differences (Coleman et al., 2001; Picard et al., 2005; Brisson and Chazarenc, 2009).

Research has indicated that different wetland plants have different nutrient preferences. Although most wetland plants prefer absorbing NH_4–N in anoxic wetland substrates (Sasakawa and

* Corresponding author. Tel.: +86 020 85212758; fax: +86 020 85215535.
E-mail address: chenzhh@scnu.edu.cn (Z.-H. Chen).
[1] These authors contributed equally to this work.

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Yamamoto, 1978), some wetland plants prefer absorbing NO_3–N (Kronzucher et al., 2000; Zhang et al., 2009). Moreover, different wetland plants have different growth speed, growth rhythm, root morphology and distribution; hence, it could be deduced that mixed wetlands may have better removal rates because of the temporal and spatial compensation in plant growth, root distribution, and nutrient preference. It has been reported that mixed wetlands were more effective in root distribution, less susceptible to seasonal variations, and had more diverse microbial populations than monoculture wetlands (Karathanasis et al., 2003; Amon et al., 2007). This may increase nutrient removal in mixed wetlands. Research has also indicated that plant biomass production and microbial biomass carbon and nitrogen strongly correlated with plant species richness in full-scale constructed wetlands (Zhang et al., 2010).

But why were lower removal abilities found in mixed wetlands when compared to monoculture wetlands in some studies? Zhang et al. (2007b) considered that competition between component plants in a mixed wetland resulted in lower nutrient removal. Other studies have also indicated that species competition may affect nutrient removal and vegetation stability in constructed wetlands (Agami and Reddy, 1990). In constructed wetlands competition may be more severe than in other plant communities because of the same or similar growth forms, similar individual size, and similar light demand (few are shade-tolerant) amongst the plants used in constructed wetlands. Fierce competition in constructed wetlands may result in an unstable plant community (Agami and Reddy, 1990; Engelhardt and Ritchie, 2001; Katharina et al., 2002; Zhang et al., 2007a).

We have previously demonstrated that wetland plant growth and biomass varied greatly amongst different species, and that these differences were correlated with effluent improvement (Cheng et al., 2009a,b). We also noticed that wetland plants exhibited great differences in stubble growth (plant growth in successive years in the same constructed wetland). However, it is not clear how these stubble growth attributes affect overall plant growth, competition, and effluent improvement in monoculture and mixed wetlands. We hypothesized that mixed wetlands can be superior to or inferior to monocultures, depending on the plant species (growth speed, biomass, competition ability, and stubble growth attributes) used in both wetlands, and on whether the mixed community can maintain a relatively stable state. The aim of this study was to investigate this supposition by comparing the growth, community structure, and nutrient removal rates between monoculture and mixed wetlands, paying particular attention to the annual variation in growth and effluent improvement in stubble wetlands.

2. Materials and methods

The experiment was conducted in the Biological Garden of South China Normal University, Guangzhou, China. Guangzhou (23°8′23″N, 113°20′58″E) has a subtropical climate, with an annual average air temperature of 21–22 °C. The average air temperatures of the coldest month (January) and the hottest month (July) were 12–14 °C and 28–29 °C, respectively. Annual precipitation was about 1700–1900 mm, with the wet season from April to September, and the dry season from October to March. Surface-flow constructed wetlands of 16 m^2 (4.0 m × 4.0 m × 0.7 m, length × width × depth) were used for the study. The wetlands were filled with soil to a depth of 0.6 m. The following five wetland species were selected in the study: *Canna indica* Linn., *Cyperus flabelliformis* Rottb., *Phragmites australis* Trin. ex Steud., *Pennistum purpureum* Schum., and *Hymenocallis littoralis* (Jacq.) Salisb. They are commonly used or have potential use prospects in constructed wetlands in China. In each monoculture wetland, 100 *C. indica* plantlets (about 20 cm in height) were planted equidistantly. *C. indica* was used as the monoculture species in consideration that it is a fast-growth species, and one of the most commonly used wetland plants in China. In each mixed wetland, 20 plantlets (about 20 cm in height) of each of the five species were planted equidistantly at random. Both the monoculture and mixed wetlands had two replications. Two weeks after planting, 1.0 m^3 of wastewater was irrigated into each wetland in a week base. The wastewater was collected from a student dormitory, and deposited in a large tank (8.0 m × 2.0 m × 1.0 m, $L \times W \times D$) before use. The influent had an average concentration (monthly measurement over 48 months, mg L^{-1}) of 146.60 ± 34.50 of chemical oxygen demand (COD), 3.27 ± 0.94 of total phosphorus (TP), 2.20 ± 0.91 of soluble reactive phosphorus (SRP), 34.79 ± 9.52 of total nitrogen (TN), 23.12 ± 5.79 of ammonium nitrogen (NH_4–N), and 0.75 ± 0.37 of nitrate nitrogen (NO_3–N).

The height and shoot numbers of 10 initial individuals from each species in each wetland were measured monthly (all individuals were measured in the case of some species having less than 10 individuals in the mixed wetlands). The height and shoot numbers of each species was calculated as the average of the measured individual plants. Community height was considered as the average height of the canopy, and community density was calculated from the average shoot numbers of the component species. Leaf area index (LAI) was determined monthly around noon on sunny days using a LAI-2000 (LI-COR) portable leaf area meter. Sixteen randomly chosen locations of each wetland were measured with the probe positioned 25 cm above the wetland surface. Root biomass was measured quarterly with a soil drill. Soil medium was randomly sampled in 16 spots in each wetland, and collected separately for depth ranges of 0–5 cm, 5–15 cm, 15–30 cm, and 30–50 cm respectively. The soil samples were washed in running water over a sieve to isolate the roots, which were then cleaned, measured for both fresh weight and dry weight (after 48 h in 80 °C). Above-ground biomass was measured at the end of the growth season (January). The vegetation was cut commencing from the canopy to 10 cm above the soil at height intervals of 40 cm. Leaf, stem, flower and fruit were separated and weighed for fresh weight and dry weight. Nutrient removal rates were measured monthly with influent concentrations as the base. Water was sampled at 5 randomly chosen locations in each wetland after a 48 h retention period, and nutrient concentration was measured with three replicates according to the standard method (The Environment Bureau of the State, 2002).

The mean and standard deviation of the parameters were calculated using Microsoft Excel 2003. The software SPSS17.0 was used for statistical analysis. Statistically significant differences apparent in the study were tested using the two-tailed *t*-test.

3. Results and analyses

3.1. Community structure

The monoculture of *C. indica* exhibited a similar community height as the mixed wetland during the initial 2 years of the experiment, and a significantly lower community height than the mixed wetland ($P < 0.05$) in the concluding year (Fig. 1). During the first year, the community height of *C. indica* wetland reached a maximum of 180 cm in the late season, and showed vigorous growth. During the following years, the community height of *C. indica* wetland decreased to about 150 cm due to its diminished size of