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A Comparative Study on the Growth and Nutrient Uptake Characteristics of Fifteen Wetland Species in Taihu Lake Region of China

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ABSTRACT: Fifteen kinds of local wetland plants in Taihu Lake region of China were investigated on their respective growth conditions, biomass allocations and nutrient uptake capacities. The test plants were cultured in 3 L nutrient solutions for 28 days with NH_4^+-N, NO_3^--N and P concentrations of 38.5, 132.8 and 10 mg/L, respectively. Mean species total biomass ranged from 1.2-21.6 g/plant with above/below ground ratios (AG:BG) between 1.7-5.5. Mean NH_4^+-N, NO_3^--N and P uptake rates ranged from 3.7-14.3 mg/day (8.0-49.4 % of NH_4^+-N supplied), 17.8-59.4 mg/day (17.8-59.6 %) of NO_3^--N supplied and 1.71-4.61 mg /day (24.1-61.5 % of P supplied), respectively. Plant tissue N and P concentrations ranged between 28.2-606.1 mg N /plant and 4.1-53.1 mg P/plant, with AG:BG ratio between 1.7-7.0 and 1.6-4.6, respectively. The accumulation of N and P in plant tissues was significantly correlated with plant biomass and root surface area. Among the different species, C. generalis, T. latifolia, T. dealbata and L. salicaria were better than the other plants in above- and below-ground biomass, root surface area, nutrient uptake and storage rates. T. dealbata and L. salicaria were more suitable for year-round application in this area due to their tolerance of coldness.

Key words: Wetland, Plant, Nutrient, Uptake, Taihu Lake

INTRODUCTION

Constructed wetlands, which have been used for many years as part of municipal wastewater treatment, are now being applied more often to the treatment of varieties of wastewater to reduce nutrients, organic matter, solids and pathogens under a wide range of loading conditions. Plants, as an integral part of wetland systems, play a key role in pollutant removal (Brix, 1987; Reed *et al.*, 1988; Tanner, 1996). The integral role of plants are the result of turbulence reduction that encourages particle settling; facilitation of chemical and bacterial processes by changing rhizosphere properties; enhancement of nutrients removal through biomass accumulation; fixation of inorganic and organic particulates; and removal of ammonium N through the creation of an oxidized rhizosphere (Burgoon *et al.*, 1995; Brix, 1997). The selection of local plant species suitable for use in constructed wetland wastewater treatment systems could be crucial for the successful operation of a wetland as it includes general requirements such as ecological acceptability, tolerance of local conditions, tolerance of pollutants and waterlogged conditions, rapid establishment and growth, and high pollutant removal capacities (Tanner, 1996). Specific requirements will vary depending on the function of plants in the treatment systems, as well as many other factors, such as the type of wetland design employed (e.g. surface or subsurface, vertical or horizontal flow), its mode of operation (e.g. continuous, batch or intermittent flow), loading rate and wastewater characteristics. Other objectives (ecological, aesthetic, recreational and economic) and local conditions (geographical, climatic and resource) of wetland developments may also affect the species selection. Thus, random selection of local plant species or based on only one or two parameters are inadequate to yield desired result when designing wetlands.

Taihu Lake is located between Shanghai City, Jiangsu Province and Zhejiang Province of China with annual mean temperature around 15^{o}C and rainfall of 1000-1500 mm. Taihu Lake is the 3rd largest lake in China with an area of 36900 km^2. This is one of the most developed regions of China and its average GDP per person is 3.5 times that of the whole country. Taihu Lake plays important roles in supplying water for drinking, industrial and agricultural production,

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adjusting climate, preventing flooding, keeping ecological balance as well as developing tourism and trade. Due to the rapid accumulation of nutrients in Taihu Lake resulting from the fast development of economics, agricultural practices and human activities, a blue-green algae bloom occurred in 2007 and resulted in a wide degradation of the aquatic environment characterized by poor transparency and malodor of the water. The deterioration of water in the Lake cut off the provision of drinking water for over 5 million people. Investigation showed that the nutrients causing eutrophication of Taihu Lake were mainly from agricultural drainage, municipal wastewater and wastewater from aquatic culture. The advantages of constructed wetland as opposed to tradition wastewater treatment facilities is that they consume less energy; are efficient in removing nutrient and provide other ecological benefits (Li *et al.,* 2008). The selection of plant species that are used in a constructed wetland depends on the purpose or function of the wetland. For example, plant species with high removal rate of N and P, and high shoot/ root ratio are the best choices for the secondary treatment of wastewater when nutrients from the water need to be removed. For sewage treatment, the plants need a root system for O_2 translation to roots to oxidize organic matter and NH_4^+-N. For polluted river water treatment, species need to be selected that can grow well under water-logged conditions with high loading rate. Aimless selection of plants may result in low efficiency or even failure of constructed wetland that are used for wastewater treatment. Presently, the lack of information on the characteristics of aquatic plants in Taihu Lake results in random selection of species or selection based on only a few characteristics that may or may not be appropriate (Nie *et al.,* 2007) leading to low efficiency of the wetlands that are currently constructed. Total plant uptake of N and P accounted for only 2-6% of the overall nutrients in the wetland wastewater treatment systems (Li *et al.,* 2007), while plants could remove 50-80% of the N and P loaded into the system under different HRT (Wang *et al.,* 2008). Nutrient removal capacities caused by different plant species in the wetland systems varied considerably across studies(Deng *et al.,* 2007; Wang *et al.*, 2008). To clarify the role of plant species in nutrient removal as well as the variance, among species we study chose15 common wetland plant species in the Taihu Lake region for a comparative study on their growth, biomass allocation, nutrient uptake, root characteristics.

MATERIALS & METHODS

Fifteen wetland species that are representative and common for constructed wetland systems in the Tai Lake region of China were tested in this study and showed in Table 1._Two groups of seedlings were purchased from Hangzhou Nursery Garden when the seedings were 15-20 cm tall, carefully washed with tap water, and acclimated in clean water for 3 days. The plants were selected for uniformity in vigor and were transferred to 3 L plastic containers (d=20 cm, h=17 cm) filled with nutrient solution. Plants with three replicates for each species were grown in tanks and fitted by a piece of foam on polystyrene plates with four holes each plate. The composition of the nutrient solution followed Yoshida *et al.* (1975) method for rice cultivation. The concentration of NH_4^+-N and NO_3^--N were 38.5 and 132.8 mg/L respectively. Phosphorus (10 mg/L) was supplied in the form of $NaH_2PO_4 \cdot H_2O$. The culture solution was renewed every four days.

After 28 days of culture in nutrient solution, plants were harvested, carefully washed with tap water, and rinsed with deionized water before plant sample preparation. Half of the plants were prepared for root oxidizing capacity (α-naphthylamine)(Hou, 2004) and root morphological analysis (MIN MAV, STD 1600+, Epson, USA). Root analysis was carried out using WinRhizo software (MAC, STD1600+, Canada). Another half was separated into shoots and roots and heated in an oven at 105! for half hour and then dried at 70! for 48 hours. Oven-dried shoots and roots were ground, weighed and put in digestion tubes to measure N and P concentration (Lu, 1999). Before the culture solution was renewed, water samples were taken and NH_4-N, NO_3-N and TP measured. NH_4-N was determined by the Nessler method, NO_3^--N by ultraviolet spectrophotometry method, P by ascorbic acid method (Lu, 1999). The average daily uptake of nutrients by plants was calculated by the following equation:

$$U= (C_0-Cs)*3/4$$

where U is the average daily uptake of the nutrients by the plants, C_0 is the original concentration of the nutrient solution, Cs is the concentration of the nutrient solution at sampling.

RESULTS & DISCUSSION

All of the test species showed positive growth in the culture solution without obvious symptom of nutrient deficiency. After 28 days of growth, mean biomass of plants ranged between 1.2 and 21.6 g /plant with mean above/below-ground (AG:BG) ratios between 1.7 and 5.5 (Fig.1). Biomass varied widely among the 15 species. The plant above- and below-ground biomass was recorded for *C. generalis* (15.5 g

Table 1.The characteristics of the different wetland plants

Name of plants	abbreviation	characteristics
Cyperus nutans	CN	a kind of perennial wetland plant, widespread in temperate regions
Juncus effusus	JE	a common plant native in most temperate countries, usually found at water edges or ditches
Cyperus alternifolius	CA	a grass-like plant in the large sedge family, cultivated worldwide and native to Madagascar
Zizania latifolia	ZL	Manchurian wild rice, a perennial native of China
Arund donax	AD	Giant reed, a tall perennial grass growing in fresh and moderately saline waters of temperate and subtropical regions
Canna generalis	CG	a widespread horticultural species, native of America
Typha latifolia	TL	common cattail, a perennial herbaceous plant growing in marshes of temperate and tropical regions of the northern hemisphere
Scirpus triangulatus	ST	a perennial wetland species, common in the Taihu lake region
Typha orientalis	TO	Raupo, a perennial herbaceous wetland species, common in the Taihu lake region
Reineckia carnea	RC	a rare evergreen perennial plant originating from the Himalayas, and cultivated in mild climate
Iris ensata	IE	Russian Iris, a flowering species with a long hollow stem
Thalia dealbata	TD	a cultivated tropical perennial, native to America and Mexico
Alisma orientale	AO	a still water perennial species
Cladium mariscus	CM	Great-Fen sedge, widely distributed in Europe, Asia and Africa, characterized by leaves with sawtooth-like margins
Lythrum salicaria	LS	Purple-loosestrife, a flowering plant native to Europe, Asia, northwest Africa and southeast Australia

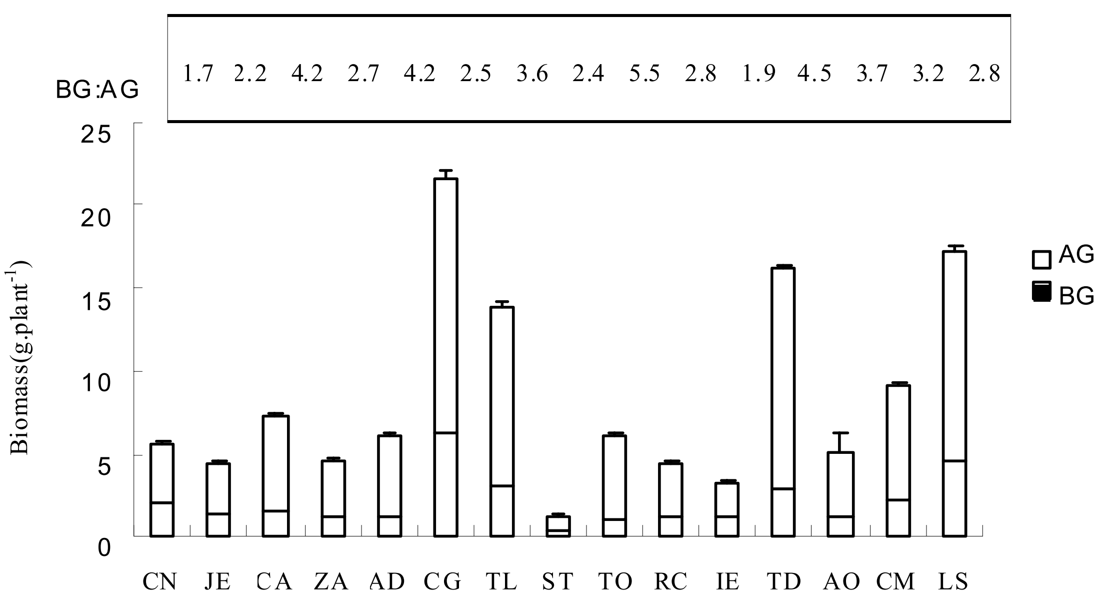

Fig. 1. Mean above-ground (AG) and below- ground (BG) biomass of the 15 wetland species after 28 days of culture

and 6.1 g), *T. latifolia* (10.8 g and 3.0 g) *T. dealbata* (13.2 g and 2.9 g) and *L. salicaria* (12.8 g and 4.6 g).

Mean root surface area ranged between 581.05 and 1683.21 cm^2, with highest root surface area records for *C.* generalis,T. dealbata and T. latifolia. Mean number of tips ranged from 6874 and 24023. Canna genralis, T. latifolia, T. orientales and L. salicaria produced more tips than the other species. Mean root oxidizing capacity ranged between 68.17 to 180.27 ug g^{-1} $hour^{-1}$ with highest oxidizing capacity reached by *C.* generalis, T. dealbata, A. orientale and L. salicaria. Canna. generalis showed higher root surface area, more tips and higher oxidizing capacity compared with the other plants, which could provide additional spaces for the precipitation and uptake of pollutants, facilitation of chemical and bacterial processes by changing rhizosphere properties through the creation of an oxidized rhizosphere (Table 2).

Nitrogen uptake differed among species and time. At the beginning of the experiment, NH_4^+-N uptake ranged from 0.64 to 7.24 mg /day. As time passed, the uptake of NH_4^+-N increased and reached an uptake peak of 4.29-22.06 mg /day during the 20-24th day of culture. After that, a slight decrease was noticed for most of the plants during the 24th-28th day (Fig.2). All of the plants showed a gradual increase of NO_3^--N uptake at 4.65-32.75 mg /day on day 4 to 21.31-67.04 mg /day on day 12 -16 of the experiment. After that, most of the plants showed a decline in the uptake of NO_3^--N, while others like *C.* generalis and R. carnea continued to increase in NO_3^--N uptake until the 24th day of culture. The initial uptake rate of P ranged from 0.34-1.96 mg / day on the 4th day of culture and gradually increased to 4.30-7.31 mg /day on the 20th day of culture for most of the plants except *L. salicaria.*

Differences among the plant species in N and P uptake became more obvious with time. Mean NH_4^+-N uptake was highest for *C. generalis* (14.3 mg /day), *T. latifolia* (12.2 mg /day), *T. dealbata* (13.6 mg /day) and *L. salicaria* (10.0 mg /day). Mean NO_3^--N uptake rates were highest for *C. generalis* (59.4 mg /day) and *C. mariscus* (57.6 mg /day). Mean P uptake rates were highest for *C. generalis* (4.61 mg /day), *T. latifolia* (3.17 mg /day), *T. dealbata* (3.38 mg /day) and *C. mariscus* (3.62 mg /day). Mean plant uptake accounted for 8.0-49.4 % of NH_4^+-N, 17.8-59.6 % of NO_3^--N and 24.1-61.5 % of P supplied to the culture solution.

Plant tissue N and P concentrations ranged between 28.2-606.1 mg N/plant and 4.1-53.1 mg P/plant (Fig. 3). The above-ground levels of N and P storage

Table 2. The root morphological characteristics of the different plant species

	Surface Area (cm2)	ROC (ug/g.hour)	Number of Tips
CN	824.03 ef	83.48 de	8449.37 e
JE	581.05 g	71.39 e	6874.24 ef
CA	934.68 de	76.74 e	7772.08 ef
ZA	985.238 cd	107.93 cde	7514.05 ef
AD	800.44 ef	80.72 e	6353.77 f
CG	1683.21 a	151.01 ab	17866.35 b
TL	1439.83 b	98.62 cde	23873.41 a
ST	716.84 fg	68.17 e	7416.98 ef
TO	1111.86 c	130.88 bc	24023.51 a
RC	807.34 ef	72.85 e	7199.33 ef
IE	715.43 fg	79.95 e	7827.09 ef
TD	1488.49 b	148.63 ab	12083.45 d
AO	878.54 de	180.27 a	13884.36 c
MC	1133.956 c	123.58 bcd	11435.28 d
LS	1104.28 c	175.93 a	17204.52 b

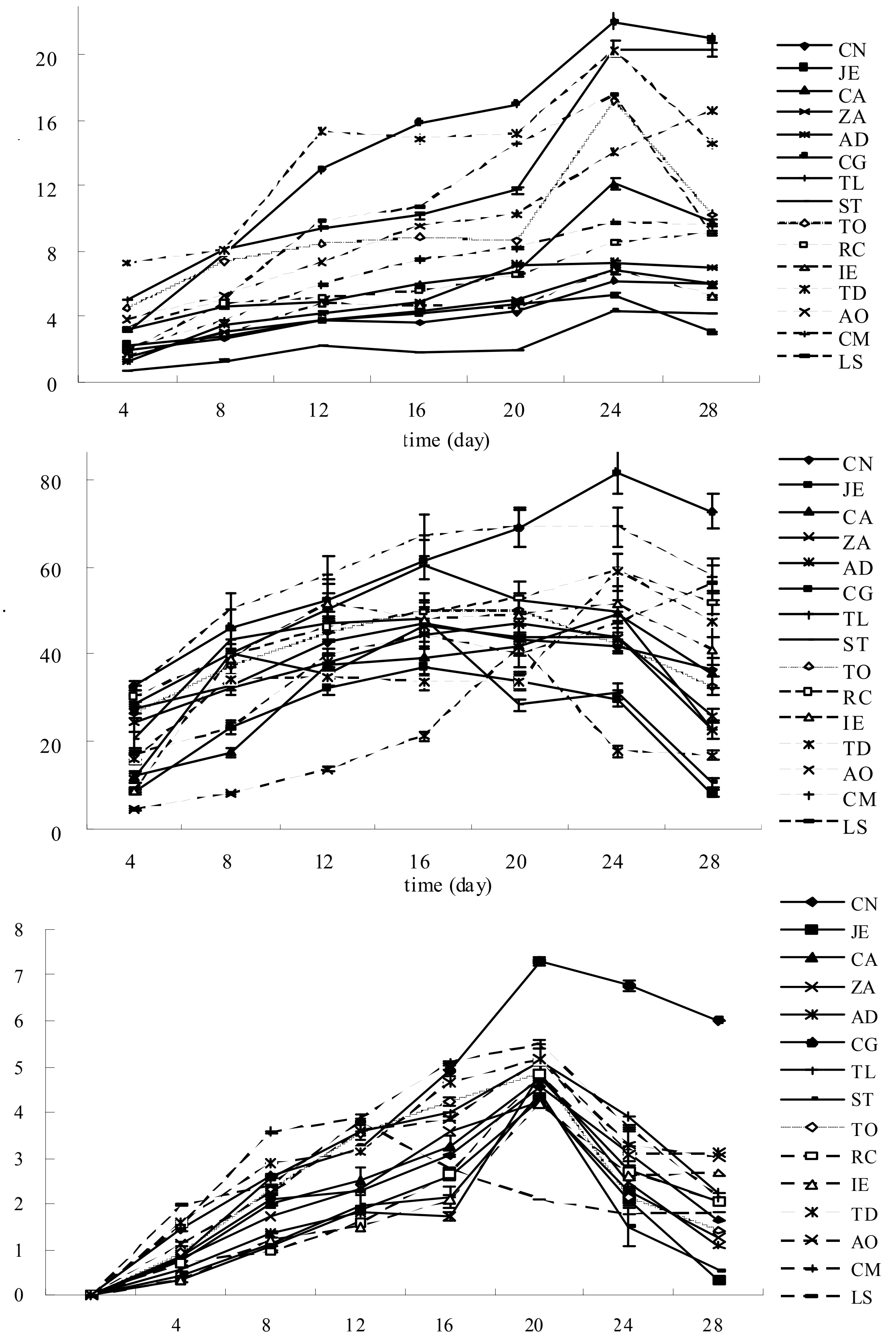

Fig. 2. Mean daily NH_4^+-N, NO_3^--N and P uptake rates by the 15 kinds of wetland plants during the 28-days of culture period

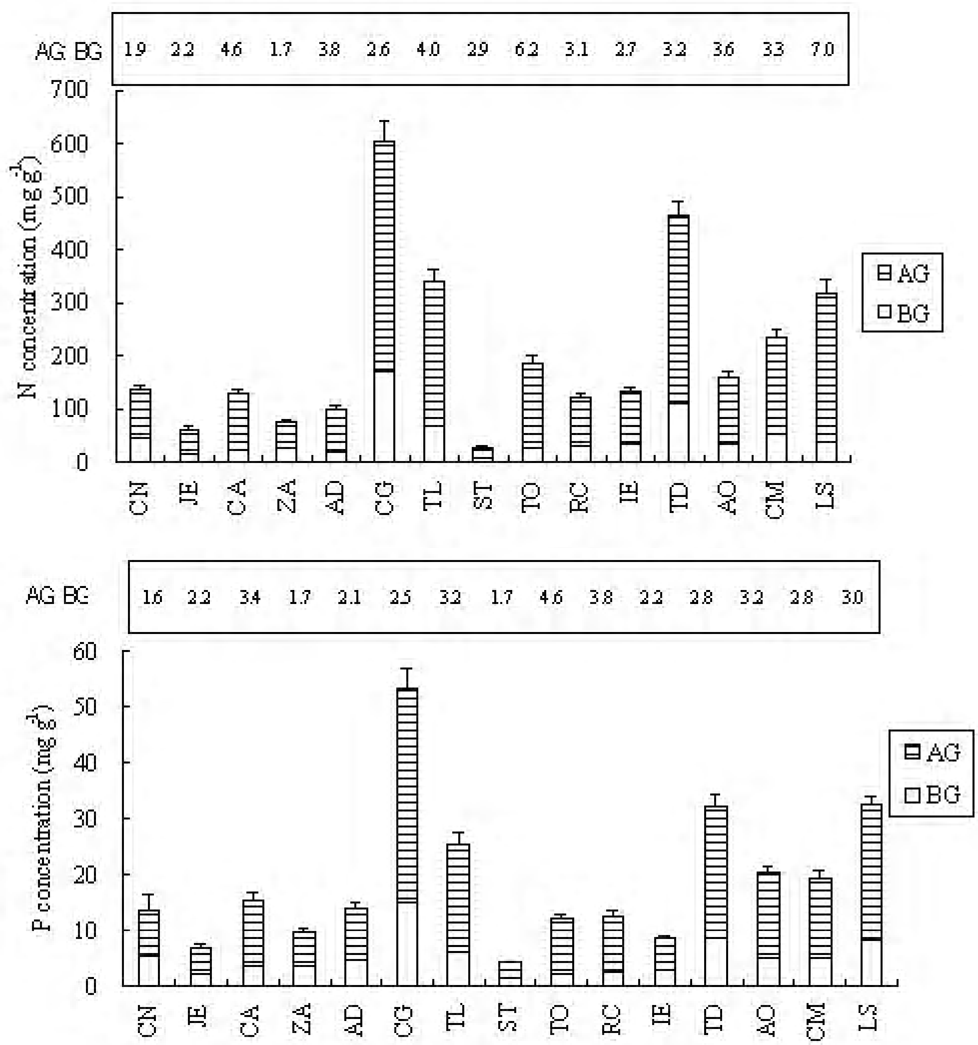

Fig. 3. N and P concentration in the plant above-ground(AG) and below-ground (BG) tissues after 28 days culture

were 21.0-354.6 mg N /plant and 2.6-38.0 mg P/plant, respectively. The below-ground levels of N and P were lower, 7.3-169.8 mg N/plant and 1.5-15.1 mg P/plant respectively, and the relative levels and allocation of nutrients showed wide variation between species. Highest storage of N and P was recorded by *C. generalis,* 606 mg N (28.9 % of total N uptake) and 53 mg P (41.1 % of total P uptake), respectively, followed by *T. dealbata, L. salicaria* and *T. latifolia.* The lowest N and P storage was recorded by *S. triangulates*, 28.2 mg N (2.9 % of total N uptake) and 4.1 mg P (8.4 % of total P uptake), respectively. The AG:BG ratio for P storage in the plant tissue ranged from 1.7-7.0 and that for N storage ranged from 1.6-4.6.

Accumulation of N and P in above- and below-ground tissues largely reflected patterns of biomass allocation. N and P accumulation in the plant tissues were correlated with plant biomass (r= 0.9501 and r= 0.9552, p<0.01, respectively; Fig. 4), root surface area (r= 0.9311 and r^2= 0.8654, p<0.01, respectively), and root oxidizing capacity (r=0.6225 and r= 0.6806, p<0.05, respectively).

The variation in the above- and below-ground biomass among the plant species is likely to derive in part from their relative differences in initial propagule vigor, as well as to intrinsic species and possible ecotype growth characteristics. The selection of wetland plants is important for wetland performance, as plants with high biomass could uptake and store more nutrients in their tissue. Among the 15 test plants, *C. generalis, T. latifolia, T. dealbata* and *L. salicaria* produced higher above- and below-ground biomass than the other species, which suggested these four species are more suitable for wetland application owing

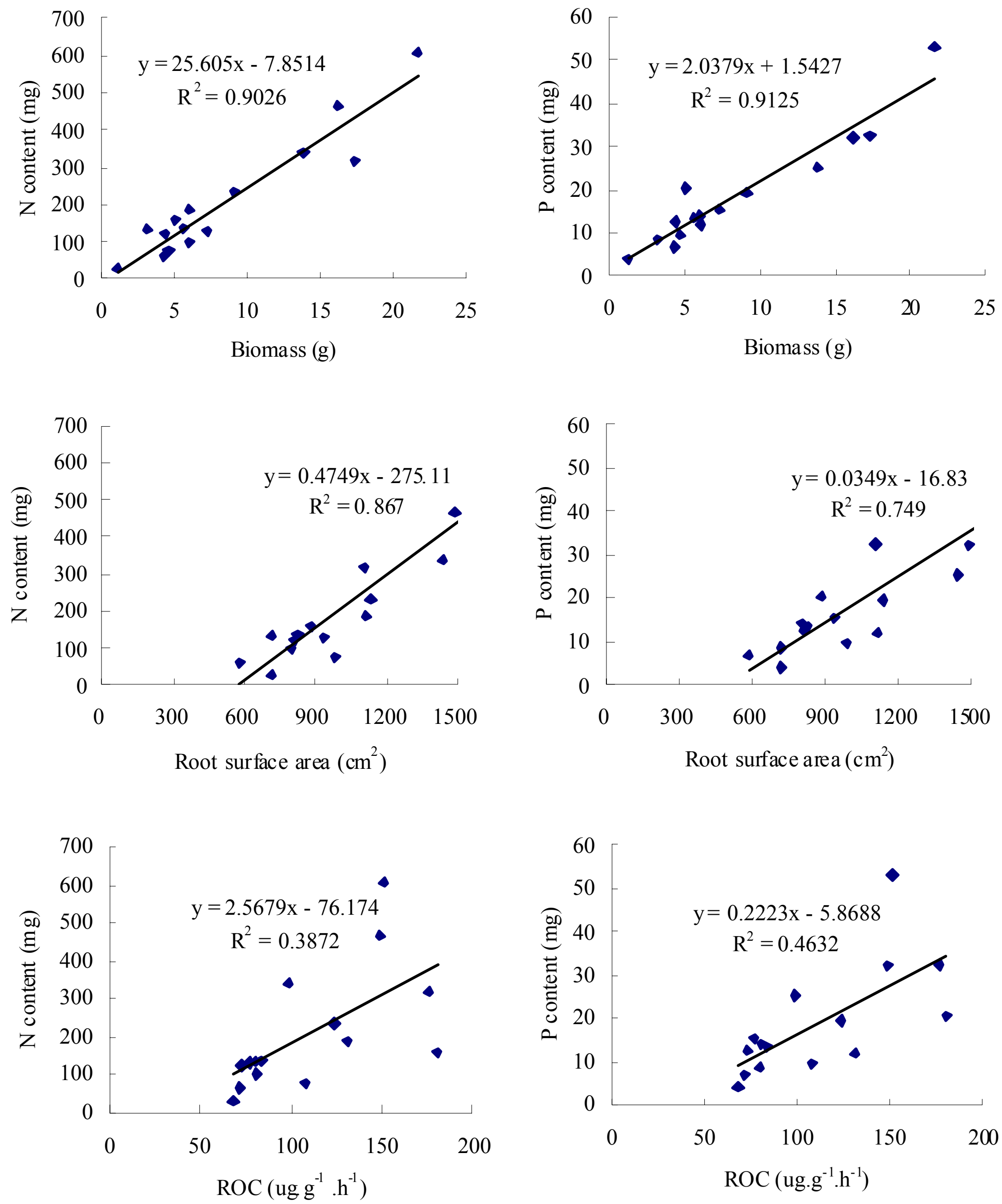

Fig. 4. The correlation between P and N concentrations in the plant tissue and biomass, root surface area and root oxidizing capacity (ROC)

to the characteristics such as fast growth and establishment and high pollutant removal capacities.

Among the 15 species, C. generalis produced a higher root surface area, more tips and higher oxidizing capacity than other plants. Higher root surface area provides more surface and spaces that facilitate the precipitation and uptake of potentially pollute nutrient. More tips and higher oxidizing capacity could influence the rhizosphere environment by increasing oxygen concentration, releasing exudates like carbohydrates and amino acids and enhancing the growth and proliferation of microorganism (Brix, 1997). Kyambadde *et al.* (2004) reported that in a comparative study of wetlands using Ceperus papyrus and Miscanthidium violaceum, the former species decreased N by 69.5 % and P by 88.8 % .reduction, while the latter species decreased N by15.8 % and P by 30.7 %. These difference were contributed to difference in their root surface area (208.6 vs 72.2cm^2) respectively.

Among the 4 species that had produced the highest biomass , C. generalis is one of the most common wetland plants that has been successfully used in constructed wetlands for wastewater treatment in middle and south China (Chen *et al.,* 2007; Lu *et al.,* 2007). This species grows well in highly polluted wastewater and have higher N and P removal capacities than other wetland species, thus it should be more suitable for wastewater such as municipal or livestock wastewater treatment. Moreover, due to its various kinds of colors, this species is aesthetically appealing. However, *C. generalis* is a tropical p species and grows well only in fertile sandy loamy soils. *Typha latifolia* also develops a fibril root system simulate to *C. generalis.* This species grows well in water-logged soil with high organic matter content. It is also a good accumulator of heavy metals such as Pb, Zn, Cu, Cd (Ye *et al.,* 1997; Deng *et al.,* 2004). Thus, it could be used to treat wastewater with high heavy metal contaminations such as effluent from Pb/Zn mines. The weakness of this species is that *T. latifolia* can not produce much biomass under high nutrient levels. High nutrient levels appears to stunt and even kill the plants. It also has a short root lifespan and begins to yellow after 2.5 months. *Typha latifolia* was the first species to die off at the end of the season in a research by Gersburg *et al.* (1986). Of the 4 high biomass productcy, *Thalia dealbata* was the only species that produces a rhizomatic root system, with higher root/shoot ratio and longer root lifespan. This species grows well on alkaline medium in warm area, thus it could be used to treat eutrophic water bodies with high pH value, such as small lakes and rivers in the Taihu Lake regions. *Lythrum Salicaria* grows well in the cold winter climate of the study region. It also develops a fibril root system that allows the species to grow well under water-logged conditions. Thus, it could be used to treat lightly polluted wastewater at a high loading rate, such as polluted water from small ponds or rivers.

Plant adsorption accounts partially for the removal of pollutants such as N and P. In this study, plant uptake of N and P ranged from 21-57 % and 24-62 % of the supply in the culture solution, respectively. Iamchaturapatr *et al.* (2007) reported that about 80-99 % of N could be removed by planted treatments while only 34-46 % of N could be removed by an unplanted treatment. Plant uptake, microbial assimilation and denitrification are the primary process that N removed from wastewater (Kadlec and Knight, 1996; Mitsch and Gosselink, 2000). Some studies show no difference in P removal by a planted treatment and an unplanted treatment because P is stored in the substrate (Fraser *et al.,* 2004; Huett *et al.* 2005). Other studies show considerable differences in P removal between constructed wetland with plants and without plants although plant adsorption accounts only for a small part of the total P removed (Iamchaturapatr *et al.* 2007). Vascular plants, algal and microorganisms all utilize P as an essential nutrient and contain P in their tissues though the portion of tissue P is very small compared with C and N (Brix, 1994; Silvan *et al.*, 2004).

Canna. Generalis, T. latifolia, T. dealbata and *L.* salicaria showed maximum NH_4^+-N uptake rates although the latter two species were not the best for NO_3^--N uptake. C. generalis, T. latifolia and T. dealbata also had higher P uptake rates in comparison with the other wetland species. In our study, both N and P uptake rates by the species were correlated with biomass, which suggests that the choice of plant species in wetland is important for N and P removal. This is contrary to previous studies that report P removal is not correlated with plant species or biomass but N removal is. (Tanner, 1996). This might be due to the difference in treatment conditions, since P removal was mainly removed through substrate instead of by plants in most of the constructed wetlands. Since *C. generalis* is much superior to other plants in N and P removal, it is more suitable for wastewater treatment with high concentration of N and P. However, as this species can not grow well in water-logged conditions, *T. dealbata* should be considered when a large amount of wastewater at high loading rate needs to be treated such as water from eutrophic rivers or lakes.

Most of the plants have AG:BG ratios >1 for N and P storage, which means that the above-ground plant tissues stored more N and P than the below-ground tissues and this could facilitate the eventual removal of N and P out of wetland system by harvesting. Among the four species that stored the most N and P in above-ground and below-ground tissues, *C. generalis and T. dealbata* absorbed and stored more N and P than *L. salicaria* and *T. latifolia.* But, the latter two species were higher in AG:BG ratio for N and P storage.

As the accumulation of N and P in the plant tissues was closely correlated to plant biomass and root surface area, the biomass-based N and P removal rates can be used to select plants for wetlands. However, in the design of wetlands, the choice of plant species or the combination of different plant species are very important as they should be suitable for water quality, loading rate and treatment target. Canna. generalis, T. dealbata, L. salicaria and T. latifolia are superior to other species in this study in the uptake and storage of pollutants such as N and P. However, Canna. generalis, T. dealbata produce dense root system and root tuber, causes logged systems.Stored pollutants in the roots might be released later to worsen the water quality (Lu *et al.,* 2007). As *L. salicaria* has a much higher AG:BG ratio and tolerance of cold climate, a mixture of plants could be considered as it might provide benefits over monocultures such as enhanced tolerance to abiotic stress or enhanced treatment efficiency of toxins or nutrients (Coleman *et al.*, 2001).

CONCLUSION

Plant species demonstrated significantly different nutrient uptake and storage rates under the same culture conditions. In this study, *C.* generalis, *T.* latifolia, T. dealbata and L. *salicaria* were better than the other local wetland species in above- and below-ground biomass production, root surface area, nutrient uptake and storage rates. *Canna. generalis* showed the highest N and P removal capacities, however, it senesces over the winter period and could not provide continued root-zone aeration in temperate regions like the Taihu Lake region. The root life span of *T. latifolia* is short and its above-ground part will die off during the winter period, with rhizomes and roots remaining under ground. *Thalia. dealbata* has the advantages of maintaining year-round vegetation in a temperate climate, without pulsed seasonal die-back. *Lythrum. salicaria* is a more stress tolerant species and likely to be ideal plants for wetland systems in temperate regions due to its extensive root systems, relatively high potential for root-zone aeration and competitive ability in spite of its comparatively low P uptake rates. In the practical design of ecologically suitable wetland systems, more information on plants such as structural development, recruitment rates of roots and general growth rate is crucial as this will influence plant-microorganism-wastewater interactions by providing microbial attachment sites, sufficient water residence times and trapping and settlement of suspended components.

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