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Original Research

COD, TN and TP Removal of *Typha* Wetland Vegetation of Different Structures

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Abstract

The diversity of aquatic macrophytes plays an important role in wastewater purification. To optimize poly-culture vegetation structure, *Typha-Phragmites-Scirpus* (with *T. angustata, P. communis, S. validus* as major species) vegetation, *Typha*-main (with *T. angustata* as major species) vegetation and *Typha*-monoculture vegetation as three design treatments were planted in pilot-scale gravel-based subsurface wetlands to treat artificial sewage. The *Typha* vegetation depicted had high COD, TN and TP removal loads in wetlands when low pollution load was treated, *Typha-Phragmites-Scirpus* vegetation had COD, TP and TN removal loads of 0.517 g m^{-2} d^{-1}, 0.277 g P m^{-2} d^{-1} and 0.023 g N m^{-2} d^{-1} in autumn. A Partial Correlations Analysis showed that COD removal loads significantly and positively correlated with plant species and stem density in either pilot scale or medium-sized (430 m^2 in area) constructed wetland. The N, P amounts in the above-ground tissue are only 3.5~11.1 g N m^{-2} yr^{-1} and 1.3~13.5 g P m^{-2} yr^{-1} in medium-sized and pilot scale wetlands, because both biomass and N, P contents of wetland vegetation harvested in late autumn were low. Thus, it is important for constructed wetlands to optimize poly-culture vegetation structure to improve treatment efficiency. Generally, the poly-culture wetlands vegetation of *T. angustata*, *P. communis*, *S. validus*, *Z. latifolia*, *Acorus calamus* with stem densities of 23 stem m^{-2}, 194 stem m^{-2}, 112 stem m^{-2}, 26 stem m^{-2}, 42 stem m^{-2} could gain excellent removal efficiency.

Keywords: *Typha angustata*, poly-culture wetland vegetation, total nitrogen, total phosphorous, chemical oxygen demand

Introduction

Multipurpose constructed wetlands are being used increasingly throughout the world and their uses in aesthetic, recreational, commercial, educational aspects have received significant attention [1]. For constructed wetlands, its vegetation is essential for the improvement of treatment efficiencies and aesthetic value [2, 3]. Macrophyte species may exhibit a species-specific ability to aerate water, uptake heavy metals and nutrients by providing organic carbon and affecting plant productivity and thus, the species mixture might out-perform monoculture in treatment ability [3]. If compound wetland vegetation could substantially exhibit its removal ability, treatment wetlands could be expected to be smaller and less expensive [4].

Effective treatment capabilities and good aesthetic properties make poly-culture vegetation preferable to the monoculture community. In an experiment of 400 L plastic

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cattle trough wetlands vegetated by monocultures (15 shoots of each trough) of *Juncus effuses* L., *Scirpus validus* L., *Typha latifolia* L. and their mixture of the three species (5 shoots of each species) in the USA, the species mixture was found to have consistently greater effects on effluent quality than did either *Typha*, *Scirpus* or *Juncus* in monocultures [2]. Generally, the poly-culture systems seemed to provide the best and most consistent treatment for all wastewater parameters, while being least susceptible to seasonal variations [5]. Therefore, the U.S. Environmental Protection Agency recommends that constructed treatment wetlands should be designed to provide habitat for a diversity of native species comparable to similar wetlands in the region and maximize vegetative species, where appropriate, without increasing the proportion of weedy, non-indigenous, or invasive species at the expense of native species. Multiple plant vegetation and native plant systems were reported to be less susceptible to plant death due to parasite predation or incidence of disease, while monoculture (single plant systems) had a greater probability of weed invasion and was more susceptible to catastrophic plant death [6].

However, poly-culture vegetation also had different removal efficiencies. For example, *Schoenoplectus*-dominated wetland was more effective than the *Typha-Echinochloa*-dominated wetland in removing total nitrogen (85% vs. 61%) and ammoniacal nitrogen (91% vs. 52%) [7]. With time and without operator intervention, one of the planted species or an invader species may become the dominant species in all or part of the wetland systems [8]. Even the species optimal for water treatment replace a diversity of plant species, it in turn would decrease wetland biodiversity or removal efficiency [9]. Therefore, the aggressive nature and aesthetic drawback of *Typha* and *Phragmites* have restricted its use in wetland systems, although it was clearly superior in facilitating the treatment processes [2].

Apparently, the quality and quantity of wetland vegetation is of considerable importance in achieving treatment efficiency [1]. If poly-cultured with other species, the originally fast invading and dominant plant (such as *T. latifolia*) became desirable as they could provide diversity of food sources, increase diversity of aquatic organism, be advantageous for the oxygenation of sediment and form a physical habitat for the degrading micro-organisms [10]. In addition, the *Typha* poly-culture vegetations may form floristical and structural vegetation patterns with enhanced ecological, functional and aesthetic values [5]. Therefore, it was generally hypothesized that, to maintain the diversity of aquatic macrophytes in wetlands, such as sustaining or restoring a natural disturbance regime to prohibit the exclusion of less competitive species, there may be a need to sustain ecosystem functioning and promote the services of those wetlands to humans [11]. In light of this hypothesis, *Typha*-dominated compound vegetation may have greater removal effects than monocultures, but it still remains to be seen if a stable and optional species mixture can be found that will significantly exceed *Typha* monocultures in treatment ability, and this is just what this paper focuses on.

Materials and Methods

Pilot-Scale Wetland Construction

Pilot-scale wetlands consisted of two baffed polythene basins (Φ=2 m×0.5 m, round) and two troughs (2.4 m×1.15 m×0.8 m, rectangle) filled with pea gravel (47.8% porosity) of equal quality in the Beijing Glorious Land Agricultural Sightseeing Garden. Root blocks (rhizomes with little shoot) of *Typha angustata* Bory et Chaubard, *Phragmites communis* Trin., *Scirpus validus* Vahl, *Zizania latifolia* (Griseb.) Stapf, *Acoras calamus* L. and *Scirpus maritimus* L. were planted in rows perpendicularly to water flow in the polythene basins and in the troughs. Details of experimental set up conditions are shown in Fig. 1 and Table 1. To control water depth, four permanent signals were chiseled on the inner wall of each basin or trough to indicate water level after root blocks were transplanted. During the following wetland operation, each basin or

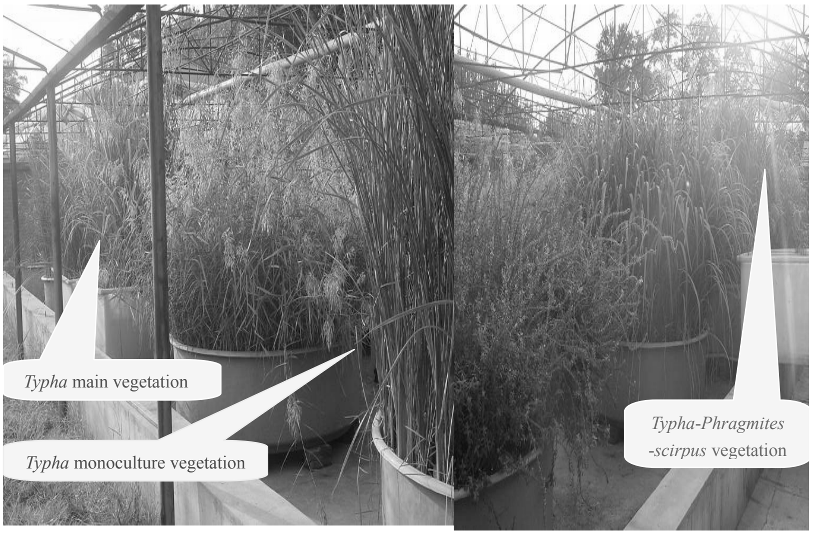

Fig. 1. *Typha* pilot subsurface wetland in the Beijing Glorious Land Agricultural Sightseeing Garden, Beijing, China.

Table 1. Pilot-scale wetlands with different vegetation.

Pilot-scale subsurface wetlands	Design treatment			
	Typha-Phragmites-Scirpus trough	*Typha*-main trough	*Typha*-monoculture basin	Control basin
Surface area (m^2)	2.76	2.76	3.14	3.14
Standing water volume (L)	356.90	284.20	274.95	195.90
Vegetation species (in row)	*P. communis*	*T. angustata*	*T. angustata*	
	T. angustata	*Z. latifalia*		
	S. validus	*T. angustata*		
	Z. latifolia	*S. validus*		
	T. angustata	*T. angustata*		
	P. communis	*S. maritimus*		
	S. validus	*T. angustata*		
	T. angustata	*A. calamus*		
	P. communis			
	A. calamus			

trough held a precise volume of water (standing water volume) if water level was controlled just at the signals when draining and refilling water (Table 1).

Pilot Scale Wetlands Operation

From the end of June in 2006, the pilot scale wetlands were drained and refilled with artificial sewage at different intervals to find proper wetland operation model. The artificial sewage was confected by glucose, nitrogenous fertilizer, phosphate fertilizer and water. After 2-3 months, the vegetation in the basin or trough wetland became stable and the static experiment on pilot scale wetlands of different vegetation formally commenced on Sept. 13. Since then, each basin or trough was drained completely and refilled with artificial sewage every two weeks for a period of three months.

Water Sampling and Analysis

Initial and treated water samples were collected in synchronization with wetland refilling and drainage from September to November. Samples were analyzed for COD (chemical oxygen demand), TN (total nitrogen), and TP (total phosphorous) at the Beijing Glorious Land Analytical Center using a UV-240IPC Spectrophotometer. The analytical methods referred to the standards of the Peoples' Republic of China, including water quality-determination of the chemical oxygen demand dichromate method (GB 11914-1989), water quality-determination of total nitrogen-alkaline potassium persulfate digestion UV spectrophotometric method (GB 11894-1989), water quality-determination of total phosphorus-ammonium molybdate spectrophotometric method (GB 11893-1989).

Vegetation Harvest and Sample Analysis

When plant senescence became obvious in late autumn, the entire above-ground biomass of each species in each basin or trough were harvested during Nov. 25-28. Partial or all above-ground biomass of each species was sampled and fresh plant material was dried at 105ºC for 48 h to get constant weight. The dried plant material was analyzed for total N and P contents at the Beijing Glorious Land Analytical Center, according to standards of the Peoples' Republic of China, including determination of moisture in feed (GB 6435-1996), determination of protein in foods (GB/T 5009.3-2003), and determination of phosphorus in feed-spectphotometry (GB/T 6437-2002).

Data Analysis

For each basin or trough wetland system, the treatment efficiencies on different pollutant indexes were determined using the following equations:

$$\text{Loading rate (g m}^{-2}\text{ d}^{-1}) = C_i \times V/(S \times I) \times 10^{-3} \quad (1)$$

$$\text{Removal amount (g)} = (C_i - C_e) \times V \times 10^{-3} \quad (2)$$

$$\text{Removal load (g m}^{-2}\text{ d}^{-1}) = (C_i - C_e) \times V/(S \times I) \times 10^{-3} \quad (3)$$

$$\text{N standing stock (g m}^{-2}\text{ yr}^{-1}) = (B \times C_N)/S \times 10^{3} \quad (4)$$

$$\text{P standing stock (g m}^{-2}\text{ yr}^{-1}) = (B \times C_P)/S \times 10^{3} \quad (5)$$

Where C_i was the initial water concentration (mg L^{-1}), C_e the treated water concentration (mg L^{-1}), V standing water volume (L), S basin or trough wetland surface (m^2), I the interval between water drainage and refilling (day), B the dry above-ground biomass of plant harvest (kg), C_N the N content in dry above-ground biomass (%), C_P the P content in dry above-ground biomass (%).

Table 2. Average COD_{cr}, TN and TP removal loads of pilot-scale wetlands with different vegetation (from September to November).

Item	Index	Design treatment			
		Typha-Phragmites-Scirpus vegetation	*Typha*-main vegetation	*Typha*-monoculture vegetation	Control wetland
COD					
Initial water	g COD L^{-1}	138.2±8.6	138.2±8.6	138.2±8.6	135.2±5.7
Treated water	g COD L^{-1}	32.8±11.9	26.6±16.0	39.8±15.8	32.7±15.3
Wetland	Removal amount (g)	188.1	158.5	135.3	100.4
average	[a]Removal load (g m^{-2} d^{-1})	0.974	0.820	0.616	0.457
[b]Net	Removal amount (g)	87.7	58.1	34.9	
vegetation	Removal load (g m^{-2} d^{-1})	0.517	0.363	0.159	
	[c]Ratio of Control (%)	113	79.5	34.7	
TN					
Initial water	g N L^{-1}	9.4±2.8	9.4±2.8	9.4±2.8	9.3±2.9
Treated water	g N L^{-1}	5±1.1	5±0.9	5.7±1.4	5.4±1.3
Wetland	Removal amount (g)	7.8	6.2	5.1	3.8
average	Removal load (g m^{-2} d^{-1})	0.040	0.032	0.023	0.017
Net	Removal amount (g)	4.0	2.4	1.3	
vegetation	Removal load (g m^{-2} d^{-1})	0.023	0.015	0.0062	
	Ratio of Control (%)	135	88	36	
TP					
Initial water	g P L^{-1}	63.2±21.0	63.2±21.0	63.2±21.0	63.2±21.9
Treated water	g P L^{-1}	13.0±10.6	14.2±6.0	9.2±6.1	21.4±7.5
Wetland	Removal amount (g)	89.5	69.7	74.3	40.9
average	Removal load (g m^{-2} d^{-1})	0.463	0.361	0.338	0.186
Net	Removal amount (g)	48.6	28.8	33.4	
vegetation	Removal load (g m^{-2} d^{-1})	0.277	0.175	0.152	
	Ratio of Control (%)	149	93.6	81.4	

[a] total removal amount (g)/(70 d×3.14 m^2) or total removal amount (g)/(70 d×2.76 m^2);
[b] the value difference between vegetated wetland and Control wetland;
[c] the ratio between the net vegetation removal load and the Control wetland (naked substrate without vegetation).

Medium-Sized Wetland Verification Experiment

To verify the removal effect of pilot-scale wetlands, a medium-sized surface *Typha* wetland of 430 m^2 in Cuihu National Municipal Wetland Park in a western suburb of Beijing City was used to treat polluted water from Shangzhuang reservoir. The medium-sized *Typha* wetland had a soil substrate of 30 cm depth and treated water of about 50.5±5 m^3 d^{-1} from April to October. The water samples of medium-sized *Typha* wetland were analyzed as described above. To estimate the *Typha* vegetation harvest in medium-sized wetland, three plots (3 m×1 m each) were selected and the number, water, N and P contents of *Typha* plant in each plot were analyzed.

Results and Discussion

COD, TN and TP Removal of Different *Typha* Vegetation in Pilot-Scale Wetlands

By COD budget during experimental period, the COD removal loads of *Typha-Phragmites-Scirpus* vegetation wetland, *Typha*-main vegetation wetland, *Typha*-monoculture vegetation wetland and Control wetland varied with 0.373-1.021 g m^{-2} d^{-1}. Meanwhile, the net vegetation COD removal loads (the value difference between vegetated wetland and Control wetland) of *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation, and *Typha*-monoculture vegetation reached 0.517 g m^{-2} d^{-1}, 0.363 g m^{-2} d^{-1} and

Table 3. Above ground biomass, nutrient content and N, P standing stocks of different vegetation in pilot-scale wetlands.

Vegetation types treatment	Species	Stem density	Weight per stem	Dry matter yield	N content	N standing stock	P content	P standing stock
		stem m^{-2}	g	kg m^{-2}	%	g m^{-2} yr^{-1}	%	g m^{-2} yr^{-1}
Typha-Phragmites-Scirpus vegetation	*P. communis*	194	2.37	0.459	0.889	4.09	0.67	3.1
	T. angustata	23	35	0.820	0.179	1.47	0.73	5.8
	S. validus	112	1.2	0.13	0.772	1.0	0.84	1.1
	A. calamus	42	1.5	0.06	0.937	0.58	0.42	0.26
	Z. latifolia	26	21	0.549	0.317	1.74	0.46	2.5
	Tribulus terrester L.			0.01	1.980	0.2	1.60	0.2
	Other weed	10	4.1	0.040	1.240	0.51	0.97	0.4
	Sum	407		2.07		9.60		13.5
Typha-main vegetation	*T. angustata*	41	19.9	0.820	0.165	1.35	0.23	1.9
	A. calamus	4	6	0.02	1.070	0.2	0.15	0.03
	S. maritimus	66	0.4	0.03	0.868	0.3	0.15	0.04
	S. validus	42	3.2	0.14	0.878	1.2	0.67	0.91
	Z. latifolia	24	10	0.24	0.262	0.62	0.26	0.62
	P. communis	3	5	0.01	0.858	0.1	0.14	0.02
	T. terrestris			0.066	1.980	1.3	1.60	1.1
	Other weed	4	11	0.044	2.570	1.1	1.40	0.62
	Sum	183		1.37		6.20		5.18
Typha-mono vegetation	*T. angustata*	126	17.3	2.18	0.441	9.59	0.17	3.7
	P. communis	4	3	0.01	1.120	0.16	0.43	0.04
	T. terrestris			0.007	1.980	0.1	1.60	0.1
	Other weed	5	13	0.069	1.920	1.3	0.70	0.49
	Sum	135		2.26		11.1		4.3

T. terrestris was harvested at Oct. 21 to prevent seed to diffuse.

0.159 g m^{-2} d^{-1} (Table 2), accounting for 113%, 68.9% and 34.7% of that of Control wetland. Obviously, *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation, and *Typha*-monoculture vegetation could enhance COD removal to different efficiencies [12].

In vegetated wetland, macrophytes are essential to efficient nitrate removal [3] and most plant species played uniquely important roles in nitrogen transformations [13]. Concretely, the pilot scale wetlands vegetated by *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation, *Typha*-monoculture vegetation had variable TN removal loads. Compared with that of Control wetland (0.017 g m^{-2} d^{-1}), the net vegetation TN removal loads of *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation and *Typha*-monoculture vegetation were 0.023 g m^{-2} d^{-1}, 0.015 g m^{-2} d^{-1} and 0.0062 g m^{-2} d^{-1} (Table 2), accounting for 135%, 88% and 36% of that of Control wetland respectively.

Undoubtedly, different vegetation types resulted in different denitrification rates [4]. In practice, N removal, highly dependent on loading rates [12], remains usually 30-50% in most cases [14] and the high N removal efficiency could have happened only if nutrient loading rates did not exceed 1,000 kg N hm^{-1} yr^{-1} [15], or 0.287 g m^{-2} d^{-1} [16]. In these pilot wetlands, TN removal would not be hindered by too much N loading because their TN loading rates ranged with 0.029-0.14 g m^{-2} d^{-1}. But the TN removal loads of subsurface wetland with *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation, *Typha*-monoculture vegetation and Control wetland ranged between 0.010-0.081 g m^{-2} d^{-1}, far below the levels of nitrate removal capacity reported in literature, such as 0.15-0.7 g N m^{-2} d^{-1} [17], 0.63-1.26 g N m^{-2} d^{-1} [3], 0.29-1.51 g N m^{-2} d^{-1} [18], and 2.8-5.0 g N m^{-2} d^{-1} [19]. Furthermore, the TN removal efficiency of pilot-scale wetland would not be limited by carbon supply because the ratio of COD loading rate (0.564: 1.422 g m^{-2} d^{-1}) and TN loading rate (0.029: 0.14 g m^{-2} d^{-1}) was above 3.5: 8 [3]. Hence, the most probable reason is that TN removal processes in pilot-scale wetlands operated by the static operation model is hindered by oxygen deficiency.

The major phosphorus removal mechanisms in horizontal subsurface wetlands are chemical adsorption, precipitation and plant uptake if wetland vegetation is harvested [20]. For the pilot scale wetlands with *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation, *Typha*-monoculture vegetation and Control wetland, their TP removal loads ranged 0.107-0.67 g m^{-2} d^{-1}. The net vegetation TP removal loads of *Typha-Phragmites-Scirpus* vegetation, *Typha*-main vegetation, and *Typha*-monoculture vegetation were 0.277 g m^{-2} d^{-1}, 0.175 g m^{-2} d^{-1}, and 0.152 g m^{-2} d^{-1}, accounting for 149%, 93.6%, and 81.4% of that of Control wetland (0.186 g m^{-2} d^{-1}), respectively (Table 2). The wetland vegetation all had notable capacity to enhance TP removal in subsurface wetland [12].

Vegetation Harvest and Nutrient Removal by Different *Typha* Vegetation in Pilot-Scale Wetlands

It was clear in Table 3 that *Typha-Phragmites-Scirpus* vegetation and *Typha*-monoculture vegetation had higher dry biomass yield (2.07 kg m^{-2} and 2.26 kg m^{-2}) compared to *Typha*-main vegetation (1.37 kg m^{-2}). Wetland efficiency would decrease over time through saturation of P sorption sites and its potential for nutrient removal was finite, unless plant shoots in wetland beds could be harvested [21]. But in vegetated wetland, the maximum removal of nutrients (N and P) by direct plant uptake and harvesting are insignificant [6, 14, 22], unless nutrient loadings are very low (27-36 kg N hm^{-}1 d^{-1}) [12]. Estimates of net annual nitrogen, phosphorus uptake by emergent wetland species were 12-120 g N m^{-2} yr^{-1}, 1.8-18 g P m^{-2} yr^{-1}, reeds (*Phragmites*) and bulrush (*Scirpus*) were at the lower end of both ranges while cattails (*Typha*) was at the higher end [14, 23]. Due to the different N and P contents of different species, *Typha*-monoculture vegetation had more annual N standing stock (11.1 g N m^{-2} yr^{-1}) while *Typha-Phragmites-Scirpus* vegetation had more annual P standing stock (13.5 g P m^{-2} yr^{-1}).

Obviously, macrophytes nutrient uptake capacity in wetland was limited [14]. First of all, the low nutrient standing stocks of pilot-scale wetland vegetation were decided by low above-ground vegetation biomasses. For vegetation in subsurface gravel-beds such as *Phragmites* vegetation, the maximum biomass usually occurred after 3-4 growing seasons [12, 24] and could reach 5.07 kg m^{-2} [24]. But the dry biomass yields of different *Typha* vegetation similarly rooted in gravel-bed subsurface pilot scale wetlands, were only 1.37-2.26 kg m^{-2} at the end of the first growing season after transplanting (Table 3). Moreover, most vascular plants could provide measurable enhancement of nutrient removal by nutrient uptake and sequestration in accumulating organic matter during spring emergence and summer growth [12]. But a significant portion of the plant-sequestered nutrients will be released back into water if plants are not harvested before autumn senescence [6, 14], indicating that nutrient transportation may be from shoots to roots-rhizomes in autumn [25]. For example, in *Phragmites* biomass harvested at the end of August or beginning of September, P concentrations in aboveground biomass varied 2.0-2.44 mg g^{-1} dry biomass and would decrease to 1.0 mg g^{-1} dry mass in February [20]. Therefore, *Phragmites* stand is usually harvested in September-October under the eutrophic conditions prevailing in treatment wetlands [15]. Vegetation in

Table 4. COD removal effect of medium-sized *Typha* wetland (430 m^2 in area).

Sampling date	Influent	Effluent
	mg L^{-1}	
6th April	23.0	24.3
13th April	31.2	24.3
20th April	48.4	43.9
27th April	29.3	30.8
8th May	36.4	35.2
19th May	34.7	29.3
26th May	34.4	29.8
7th June	41.6	37.0
10th June	47.5	40.8
16th June	31.9	33.8
22th June	55.5	38.2
2th July	29.2	25.1
7th July	42.8	39.4
14th July	35.3	36.9
21th July	32.6	33.0
27th July	23.3	21.0
23th August	44.6	35.0
31th August	43.9	38.3
7th September	32.4	35.6
14th September	34.4	33.3
22th September	37.8	38.0
12th October	38.7	35.4
19th October	30.6	29.8
27th October	26.6	24.7
Average	36.1±8.1	33.0±6.0

The influent water was pumped directly from nearby Shangzhuang reservoir and its quality was unstable. The influent water would stay about 2.5 days (430 m^2×30 cm/50.5 m^3 d^{-1}) in medium-sized surface wetland and thus the effluent sometimes had more COD pollutant than the influent of that day when the influent of last day had too-high COD content.

Table 5. *Typha* vegetation sampling and analysis of medium-sized wetland.

Plot number	Sampling *Typha* cluster			Each plot				
	Water content	N content	P content	Plant number	Fresh weight	Dry matter	Stem density cluster	Weight Per stem
	%	%	%	cluster	kg	kg	m^{-2}	g
1	6.92	0.276	0.21	100	2.37	2.17	33	21.7
2	9.66	0.744	0.19	106	1.58	1.44	35	13.6
3	9.31	0.661	0.23	108	2.28	2.08	36	21.1
Average	8.63	0.560	0.21		2.08	1.90	35	18.8

Table 6. COD removal of wetland with *Typha* vegetation of different components.

Wetland vegetation	Plant species*	Dry biomass	Stem density stem	Weight per stem**	COD removal load
		kg m^{-2}	m^{-2}	g	g m^{-2} d^{-1}
Typha-Phragmites-Scirpus vegetation	7	1.07	407	35	0.974
Typha main vegetation	8	1.37	183	19.9	0.820
Typha monoculture vegetation	4	2.26	135	17.3	0.616
Typha medium-sized wetland vegetation	1	0.36	35	18.8	0.36

*included the unwanted species like *T. terrestris* and gramineous weed,
**aboveground dry weight of individual *Typha* cluster.

Table 7. Partial Correlations analysis of COD removal and *Typha* vegetation factors.

Variable	Vegetation factors	Plant species	Dry Biomass	Stem density	Weight per stem
Removal	Pearson Correlation	0.933	0.292	0.925	0.733
load	Sig. (2-tailed)	0.067	0.708	0.075	0.267

pilot-scale wetlands were harvested at the end of November, the N, P contents of *T. angustata* varied only between 0.165-0.882%, 0.17-0.73% in different *Typha* vegetation, while N, P contents of *P. communis* varied with 0.858-1.372% and 0.14-0.67% respectively. Undoubtedly, N, P removal efficiencies could be increased by vegetation harvesting in October, rather than in November or December [15].

COD Removal, Vegetation Harvest and Nutrient Removal of Medium-sized Wetlands

Medium-sized *Tyhpa* wetland had only a little COD removal effect (from 36.1 mg L^{-1} in influent to 33.0 mg L^{-1} in effluent) under COD loading of 2.70-6.52 g m^{-2} d^{-1} (Table 4). Correspondingly, its COD removal load could only reach 0.36 g m^{-2} d^{-1} when its average daily influent water volume reached 50.5±5 m^3 d^{-1}.

In winter, the whole above-ground vegetation biomass of one *Typha* cluster in each plot was collected to analyze its water, N and P contents. The whole *Typha* vegetation biomass in medium-sized wetland and its annual N and P standing stocks were estimated to be 274 kg, 3.55 g N m^{-2} yr^{-1}, 1.3 g P m^{-2} yr^{-1} (Table 5). Undoubtedly, N and P standing stocks of the *Typha* vegetation in surface medium-sized wetland were much lower than the estimated values for Cattails (120 g N m^{-2} yr^{-1}, 18 g P m^{-2} yr^{-1}) owing to its stem density of only 35 stem m^{-2}, although its N and P contents averaged to be 0.560% and 0.21% (Table 5). By comparison of pilot and medium-sized *Typha* wetland (Table 6), it was noted that the COD removal load was obviously improved with the increased number of plant species and their stem densities in *Typha*-dominated wetland vegetation.

Partial Correlations Analysis of COD Removal and Wetland Vegetation Harvest

To find out the main factors affecting wetland removal effect, Partial Corrections Program (in SPSS 10.0) was used to analyze the effect of plant species, dry above-ground biomass, stem density and weight per stem of different *Typha* vegetation on COD removal loads of pilot-scale wetlands and medium-sized wetland (Table 6). It was clearly revealed in Table 7 that plant species and stem density had significant (Sig.<0.1) and positive effects on wetland COD removal loads and their Pearson Correction Values reached 0.933 and 0.925, respectively.

Conclusions

The *Typha* vegetation in different systems had different COD, TN and TP removal loads, COD, TN and TP removal could be enhanced in subsurface wetlands when low pollution load was treated. For example, the *Typha-Phragmites-Scirpus* vegetation had COD, TP and TN removal loads of 0.517 g m^{-2} d^{-1}, 0.277 g P m^{-2} d^{-1} and 0.023 g N m^{-2} d^{-1}, accounting for 113%, 135% and 149% of that of Control wetland. As far as TN removal was concerned, the TN removal in subsurface wetland operated by static operation model was hindered by oxygen deficiency. Moreover, the N, P amounts in above-ground tissue were only 3.5-11.1 g N m^{-2} yr^{-1} and 1.3-13.5 g P m^{-2} yr^{-1} in medium-sized and pilot-scale wetland. By Partial Correlations Analysis, the COD removal loads significantly and positively correlated with plant species and stem density in either pilot scale or medium-sized constructed wetland.

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References

1. BENYAMINE M., BACKSTROM M., SANDEN P. Multi-objective environmental management in constructed wetlands. Environ. Monit. Assess., **90**, 171, **2004**.
2. COLEMAN J., HENCH K., GARBUTT K., SEXSTONE A., BISSONNELTE G., SKOUSEN J. Treatment of domestic wastewater by three plant species in constructed wetlands. Water Air Soil Poll., **128**, 283, **2001**.
3. LIN Y., JING S., WANG T., LEE D. Effects of macrophytes and external carbon sources on nitrate removal from groundwater in constructed wetlands. Environ Poll., **119**, 413, **2002**.
4. BACHAND P.A.M., HORNE A.J. Denitrification in constructed free-water surface wetlands: II Effects of vegetation and temperature. Ecol. Eng., **14**, 17, **1999**.
5. KARATHANASIS A.D., POTTER C.L., COYNE M.S. Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. Ecol. Eng., **20**, 157, **2003**.
6. UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. Constructed wetlands treatment of municipal wastewaters. EPA Manual. Cincinnati, OH, EPA/625/R-99/010, **2000**.
7. POACH M.E., HUNT P.G., VANOTTI M.B., STONE K.C., MATHENY T.A., JOHNSON M.H., SADLER E.J. Improved nitrogen treatment by constructed wetlands receiving partially nitrified liquid swine manure. Ecol. Eng., **20**, 183, **2003**.
8. YOUNG T.C., COLLINS A.G., THEIS T.L. Subsurface flow wetland for wastewater treatment at Minoa, NY. Report to NYSERDA and USEPA. Clarkson University, NY, **2000**.
9. CREIGHTON J.H., SAYLER R.D., TABOR J.E., MONDA M.J. Effects of wetland excavation on avian communities in Eastern Washington. Wetlands, **17**, 216, **1997**.
10. MAELUEM T. Treatment of landfill leachate in on-site lagoons and constructed wetlands. Water Sci. Technol., **32**, 129, **1995**.
11. ENGELHARDT K.A.M., RITCHIE M.E. Effect of macrophyte species richness on wetland ecosystem functioning and services. Nature, **411**, 687, **2001**.
12. TANNER C.C. Plants as ecosystem engineers in subsurface-flow treatment wetlands. Water Sci. Technol., **44**, 9, **2001**.
13. THULLEN J.S., SARTORIS J.J., NELSON S.M. Managing vegetation in surface-flow wastewater-treatment wetlands for optimal treatment performance. Ecol. Eng., **25**, 583, **2005**.
14. BRIX H. Functions of macrophytes in constructed wetlands. Water Sci. Technol., **29**, 71, **1994**.
15. MEULEMAN A.F.M., BEEKMAN J.P.H., VERHOEVEN J.T.A. Nutrient retention and nutrient-use efficiency in *Phragmites australis* stands after wastewater application. Wetlands, **22**, 712, **2002**.
16. KOOTTATEP T., POLPRASERT C. Role of plant uptake on nitrogen removal in constructed wetlands located in the tropics. Water Sci. Technol., **36**, 1, **1997**.
17. KUSCHK P., WIEBER A., KAPPELMEYER U., WERBRODT E., KASTNER M., STOTTMEISTER U. Annual cycle of nitrogen removal by a pilot-scale subsurface horizontal flow in a constructed wetland under moderate climate. Water Res., **37**, 4236, **2003**.
18. XUE Y., KOVACIC D.A., DAVID M.B., GENTRY L.E., MULVANEY R.L., LINDAU C.W. In situ measurements of denitrification in constructed wetlands. J. Environ. Qual., **28**, 263, **1999**.
19. INGERSOLL T.L., BAKER L.A. Nitrate removal in wetland microcosms. Water Res., **32**, 677, **1998**.
20. VYMAZAL J. Removal of phosphorus in constructed wetlands with horizontal sub-surface flow in Czech republic. Water Air Soil Poll., **4**, 657, **2004**.
21. WATHUGULA A.G., SUZUKI T., KURIHARA Y. Removal of nitrogen, phosphorus and COD from waste water using sand filtration system with *Phragmites australis*. Water Res., **21**, 1217, **1987**.
22. MAYO A.W., BIGAMBO T. Nitrogen transformation in horizontal subsurface flow constructed wetlands I: Model development. Phys. Chem. Earth., **30**, 658, **2005**.
23. REDDY K.R., DEBUSK W.F. Nutrient removal potential of selected aquatic macrophytes. J. Environ. Qual., **14**, 459, **1985**.
24. VYMAZAL J., KROPFELOVA L. Growth of *Phragmites australis* and *Phalaris arundinacea* in constructed wetlands for wastewater treatment. In: Book of abstracts 7th INTECOL international wetlands conference. Utrecht, the Netherlands, **2004**.
25. HEADLEY T.R. Removal of nutrients and plant pathogens from plant nursery runoff using horizontal subsurface flow constructed wetlands. PhD thesis, Southern Cross University, Australia, **2004**.