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Pollutant removal efficiency of native versus exotic common reed (*Phragmites australis*) in North American treatment wetlands

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ABSTRACT

Growing concerns about the threat of invasive macrophyte species increasingly require the use of substitute native species in constructed wetlands for wastewater treatment. We conducted a mesocosm experiment at two loading rates to compare the removal efficiency of treatment wetlands planted with *Phragmites australis* from a lineage native to North America (*P. australis* subsp. *americanus*) versus the widely used but highly invasive European *P. australis*. Based on the plant's relative ecophysiological and morphological characteristics as reported in field studies, we hypothesized that the native *Phragmites* would show lower pollutant removal efficiency than the exotic European subspecies. *P. australis* subsp. *americanus* was found to show potential for treatment wetlands, and there was no evidence that its removal efficiency would be inferior to that of European *P. australis*. In fact, contrary to our expectations, our results suggest that the native *Phragmites* may be the preferred subspecies, due to its slightly more effective removal of phosphorus. Further pilot or full scale experiments are needed to quantitatively assess the efficiency of treatment wetlands planted with this subspecies, as well as its resistance to diseases, before its use in treatment wetlands could be definitively recommended. Also, while plant characteristics measured under field conditions may reflect a species' potential removal efficiency, growing conditions in treatment wetlands may differently affect morphological, ecological and physiological plant attributes and, consequently, pollutant removal efficiency.

1. Introduction

Selection of plant species for treatment wetlands (TWs) has always been an important design issue. Tolerance to saturated substrate and high wastewater loads, as well as biological attributes including fast growth, large biomass and a well-developed root system, have been identified as desirable traits in plants used for wastewater treatment (Tanner, 1996; Kadlec and Wallace, 2009; Vymazal, 2011; Leto et al., 2013). However, although differences in removal efficiency between plant species have been widely documented, the possible correlations with specific plant attributes have been the subject of only limited detailed analysis (Brisson and Chazarenc, 2009). One exception is Tanner (1996) pioneering comparison of pollutant removal efficiency among eight macrophyte species, showing a linear correlation between mean removal of total nitrogen and total plant biomass. A clearer understanding of the role of plant traits in treatment efficiency would allow more effective plant selection for TWs.

In addition to biological attributes, the ecological acceptability of plants selected for TWs is also important to consider, since exotic invasive species represent a threat to local biodiversity. The biological attributes considered highly desirable for plant species used in water treatment often characterize invasive plants as well. Common reed (*Phragmites australis*) is the most widely used species in subsurface flow constructed wetlands (SSFCW) (Vymazal, 2011), and it is also considered highly invasive outside its native range.

Introduced to the east coast of North America in the early 1800s, the European haplotype of common reed (referred to hereafter as "exotic *Phragmites*") has been gradually expanding its range ever since (Saltonstall, 2002; Lelong et al., 2007). It tolerates a broad range of hydrologic conditions and disturbance regimes (Brisson et al., 2010; Taddeo and de Blois, 2012). The tall, dense monospecific stands it forms displace native vegetation, reduce animal diversity and modify environmental conditions (Chambers et al., 1999; Mal and Narine, 2004). In addition to negatively impacting biodiversity, the plant may obstruct roadside and agricultural ditches, block shoreline views and pose a fire hazard

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because of its dry shoots. Since its deep and dense rhizome and root systems make it highly resistant to most control methods, managing established stands is costly (Hazelton et al., 2014).

Despite these drawbacks, the exotic *Phragmites* has been commonly planted in TWs of North America due to its availability and well-established efficiency in water treatment systems (Brisson and Vincent, 2009; Vymazal, 2011). However, there are growing concerns that these TWs may be sources of propagules and invasion loci for nearby natural wetlands. Some governmental authorities are envisioning or applying regulations to prohibit *P. australis* from TWs (Wallace and Knight, 2006; MDDEP Québec, 2009), in favor of alternative native plant species such as broadleaf cattail (*Typha latifolia*) or bulrushes (*Schoenoplectus* sp.).

One alternative plant that does not appear to have been tested in TWs is the native subspecies of common reed – *P. australis* subsp. *americanus* (hereafter referred to as "native *Phragmites*"). This recently identified subspecies is much less abundant, and its decline in some parts of its range is often attributed to the spread of exotic *Phragmites* (Saltonstall, 2002). Due to its large size, it represents an excellent candidate for TWs, but while it is broadly similar to its exotic conspecific, some of its attributes suggest that it may not be as efficient in pollutant removal. In a review of the major ecophysiological differences between native and exotic *Phragmites*, Mozdzer et al. (2013) showed that the exotic subspecies produces more total biomass, has taller shoots and greater shoot density than the native. Exotic *Phragmites* also has superior ecophysiological attributes, including a 50% higher rate of photosynthesis, and up to 100% higher rates of stomatal conductance (Mozdzer and Zieman, 2010). When grown under increased nutrient levels, both subspecies produce more biomass, but the exotic *Phragmites* outperforms the native with a significantly greater aboveground: root biomass ratio, and is more responsive to an increase in nutrients, suggesting more efficient nutrient uptake (League et al., 2007; Saltonstall and Stevenson, 2007; Price et al., 2014).

In the context of a search for alternatives to invasive exotic *Phragmites* for use in North American TWs, the aim of this study was to compare the removal efficiency of native and exotic subspecies in a mesocosm experiment and evaluate the potential of native *Phragmites* in TWs. Based on the relative plant ecophysiological and morphological characteristics reported in field studies, we hypothesized that the native *Phragmites* would represent an acceptable species for TWs, although we expected it would exhibit lower pollutant removal efficiency than the exotic subspecies.

2. Methods

2.1. Experimental set-up

The experiment was conducted on the site of the Montreal Botanical Garden, Québec, Canada (latitude: 45°33′43.00″ N; longitude: 73°34′18.50″ W). In 2008, twenty-five sub-surface flow mesocosms (L 107 cm, W 55 cm, H 35 cm) were filled with granite river gravel (Ø = 10–15 mm) and planted with rhizomes. Ten of the mesocosms were planted with native *Phragmites* (N), ten with exotic *Phragmites* (E), and five were left unplanted (U) (Fig. 1). Permission was obtained to collect native *Phragmites* rhizomes from a large colony near Lac Saint-François (Québec, Canada: 45°02′29.92″ N, 74°27′47.35″ W), and exotic *Phragmites* rhizomes from Îles-de-Boucherville National Park (Québec, Canada: 45°35′13.19″ N, 73°29′03.33″ W). Plants were allowed to establish from spring 2008 to spring 2010. During this period, water level was maintained constant at approximately 2 cm below the surface of the substrate, and plants were fed with a 20:20:20 nutrient solution (percentage, by weight, of nitrogen–phosphorus–potassium: N–P–K) with microelements. During the winters of 2008–2009 and 2009–2010, the mesocosms were protected with insulating textile covered with mulch. The mesocosm were fully colonized with tall, flowering shoots at the end of fall 2009.

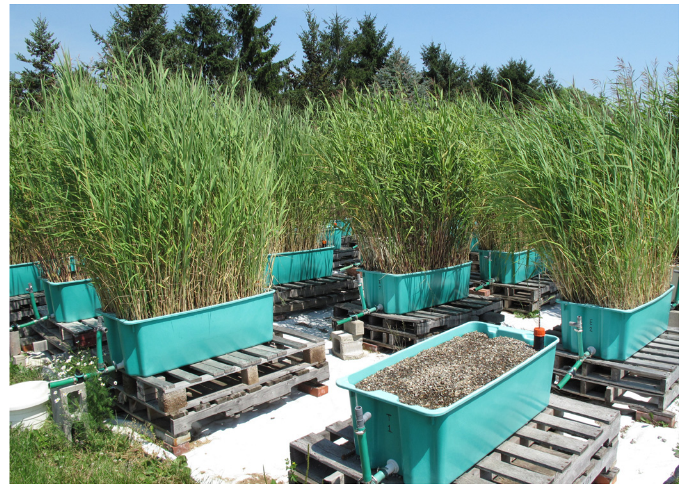

Fig. 1. Experimental site in the Montreal Botanical Garden (Québec, Canada) (photo: Jacques Brisson, July 2010).

Beginning in May 2010, mesocosms were fed with reconstituted wastewater composed of diluted fish farm sludge, urea (46%) and mono potassium phosphate (23%) (Table 1). Mesocosms were drained before batch feeding, and filled with 30 L of fresh wastewater twice per week. For 10 consecutive weeks starting in July, total outflow water was sampled weekly for water quality assessment. The outflow was collected in a bucket connected to the mesocosms by an evacuation tube and its volume was measured daily. Evapotranspiration was calculated as the difference between inflow and the total outflow volume, plus rainfall.

Between the 2010 and 2011 experimental periods, mesocosms were insulated for winter as described above. The protection was removed in April 2011 and wastewater batch feeding resumed in May 2011. The objective of the 2011 experimental phase was to test the three treatments, U, E and N, at two different inflow concentrations: a low load (L) similar to that of 2010, and a high load (H) (Table 2). Five out of the ten replicates from each planted mesocosm were randomly selected to be treated either with low or high inflow concentrations (five E and five N for each inflow load). The same procedure was followed for the unplanted mesocosms, with two mesocosms fed with low load and three with high load.

In 2011, batch feeding frequency was increased to three times per week. Once per week, for 12 consecutive weeks (June–October, 2011), water samples were collected from the total outflow for water quality assessment after two days' retention time, and the quantity of outflow was measured daily as in 2010.

2.2. Plant parameters

At the end of the experimental period, both in 2010 and 2011, stem density was counted in each mesocosm and the aboveground portions were cut, dried and weighed. A section of substrate was excavated from top to bottom (36 cm) at the center of each mesocosm using a 15–cm diameter drill. Roots and rhizomes were separated from the gravel, dried and weighed to estimate belowground biomass. Leaf and root samples were collected from each planted mesocosm and analyzed for nutrient content at the Horticulture Research Center of Laval University (Québec, Canada). For purposes of comparison with plant parameters under natural conditions, shoot density and plant

Table 1
Mean inflow load (±SE), concentration (±SE) and removal efficiency (±SE) for the sampling period between July and September, 2010. Inflow was measured 3 times a week during 10 weeks, while outflow was measured once a week in each mesocosms during the same period.

	TSS	COD	TP	TN	NH_4	NO_3
Load ($g m^{-2} d^{-1}$)	7.1 (2.2)	12.6 (3.9)	0.6 (0.08)	1.7 (0.2)	0.15 (0.05)	0.07 (0.01)
Concentration ($mg L^{-1}$)	270 (88)	479 (128)	23 (5)	65 (12)	5.7 (3.2)	2.7 (0.8)
Mean percentage removal efficiency (10-week period)						
Exotic	96 (9)	94 (7)	91 (10)	97 (4)	83 (37)	76 (23)
Native	94 (11)	90 (17)	92 (19)	97 (5)	92 (22)	79 (16)
Unplanted	75 (31)	89 (9)	61 (18)	53 (20)	−14 (50)	51 (48)

height were measured in three 1 m^2 plots randomly located at the sites where the rhizomes were collected: Lac Saint-François for the native *Phragmites*, and Îles-de-Boucherville National Park for the exotic *Phragmites*.

2.3. Data analysis

Physico-chemical analyses (TSS, COD, NT, N-NO_3, N-NH_4 and TP) were conducted according to (APHA, 2005). Based on a mass balance calculation, the amount of pollutants removed in 2010 and 2011 was compared between the three treatments (E, N, U). Results from 2010 (Table 1) generally showed the same patterns as the low treatment in 2011. Therefore, data analysis emphasizes mainly the 2011 phase of the experiment, to further explore the differences between plant species under the two different loads.

Repeated ANOVA measurements revealed that the effect of plants on pollutant removal efficiency changed over time throughout the sampling period, both in 2010 and 2011. Therefore, for the 2011 data, a two-factor ANOVA, with three treatments (E, N, U) and two loads (L, H inflow), was performed for each sampling week ($n = 5$ for EL, EH, NL, NH; $n = 3$ for UH and $n = 2$ for UL). A two-factor ANOVA for the overall mean removal efficiency of the entire season (12 weeks) was performed as well (see bar graphs in Fig. 2 and supplementary material). Plant parameters were also analyzed by a two-factor ANOVA, with two treatments (E, N) and two loads (L, H inflow) ($n = 5$ for EL, EH, NL and NH). In case of interaction between factors, a one-way ANOVA was performed individually for each factor (see supplementary material). Assessments of normality and homoscedasticity were verified and further differences between treatments were established with the post-hoc Tukey test at $p < 0.05$. Statistical analyses were performed using JMP software (JMP®, Version 6 for Mac. SAS Institute Inc.), except for the repeated measurements ANOVA, which was performed using SAS Software (SAS Software®, Version 9.2 for Windows XP, SAS Institute Inc.).

3. Results

3.1. Pollutant removal efficiency

3.1.1. Experimental period – 2010

During the first sampling period in 2010, both native and exotic *Phragmites* showed excellent pollutant removal efficiency (Table 1). One-way ANOVA analysis with three levels (E, N, U) per week showed that planted mesocosms significantly outperformed unplanted ones in terms of TSS, COD, TN, NH_4 and NO_3 removal efficiency. Few exceptions were observed, i.e., only for three out of ten sampling weeks, where removal efficiency of COD and was similar for all treatments (see supplementary material SM 1). There was very little difference in removal efficiency between the *Phragmites* for most pollutants. Significant differences in performance between mesocosms planted with exotic or native *Phragmites* occurred during only one week for COD, and two weeks for TSS removal efficiency, each time to the advantage of the exotic *Phragmites* (SM1). On the other hand, TP removal was not only significantly different between planted and unplanted mesocosms, with 61 and 91% average removal efficiency respectively (Table 1), but also between native and exotic *Phragmites*. Although the average efficiency of both subspecies was comparable, a Tukey post-hoc test performed per week showed a significant difference in five out of ten sampling weeks (SM 1). In all cases, native *Phragmites* outperformed exotic *Phragmites*, a pattern consistent with the results of 2011 (see below).

3.1.2. Experimental period – 2011

As in 2010, results for 2011 showed excellent removal efficiency for all treatments, under both low and high loads, for all parameters measured (TSS, COD, TN, TP) (Fig. 2). Repeated measurements ANOVA results showed a significant effect of load (L, H) and plant treatment (E, N, U), influenced by the effect of time, for all parameters. A two-factor ANOVA analysis per sampling week confirmed the significant effect of load and plant treatment on pollutant removal (in $g m^{-2} d^{-1}$) for all parameters throughout the sampling season (SM 2). Absolute pollutant removal evolved in a very similar way under low and high inflow concentrations throughout the sampling period, with higher loads resulting in higher pollutant removal (Fig. 2). Percentage removal efficiency, on the other hand, was not affected by load, and was very high under both loading rates. As a general trend, more differences were found between treatments later in the season (Fig. 2). TSS removal, for example, was significantly higher on planted versus unplanted mesocosms only after the fourth sampling week and until the end of the experiment. COD removal was also very high in all treatments; however, planted mesocosms were significantly more efficient than unplanted ones in 9 out of 12 sampling weeks (Fig. 2). No differences for TSS and COD removal were detected between

Table 2
Mean inflow load (±SE) and concentration (±SE) for the 12-week sampling period between June and September, 2011. Inflow was measured 3 times a week during 12 weeks.

	TSS	COD	TP	TN	NH_4	NO_3
Average inflow load in $g m^{-2} d^{-1}$						
Low load	5.2 (2.1)	11.1 (1.9)	0.2 (0.1)	1.1 (0.3)	0.4 (0.1)	0.05 (0.01)
High load	18.1 (3.2)	22.6 (2.8)	0.6 (0.1)	2.5 (0.4)	0.8 (0.2)	0.07 (0.02)
Average inflow concentration in $mg L^{-1}$						
Low load	198 (94)	422 (165)	7.6 (3.2)	41 (13)	15 (8)	2.1 (0.9)
High load	687 (156)	859 (215)	22.8 (4.6)	95 (21)	39 (19)	2.9 (1.6)

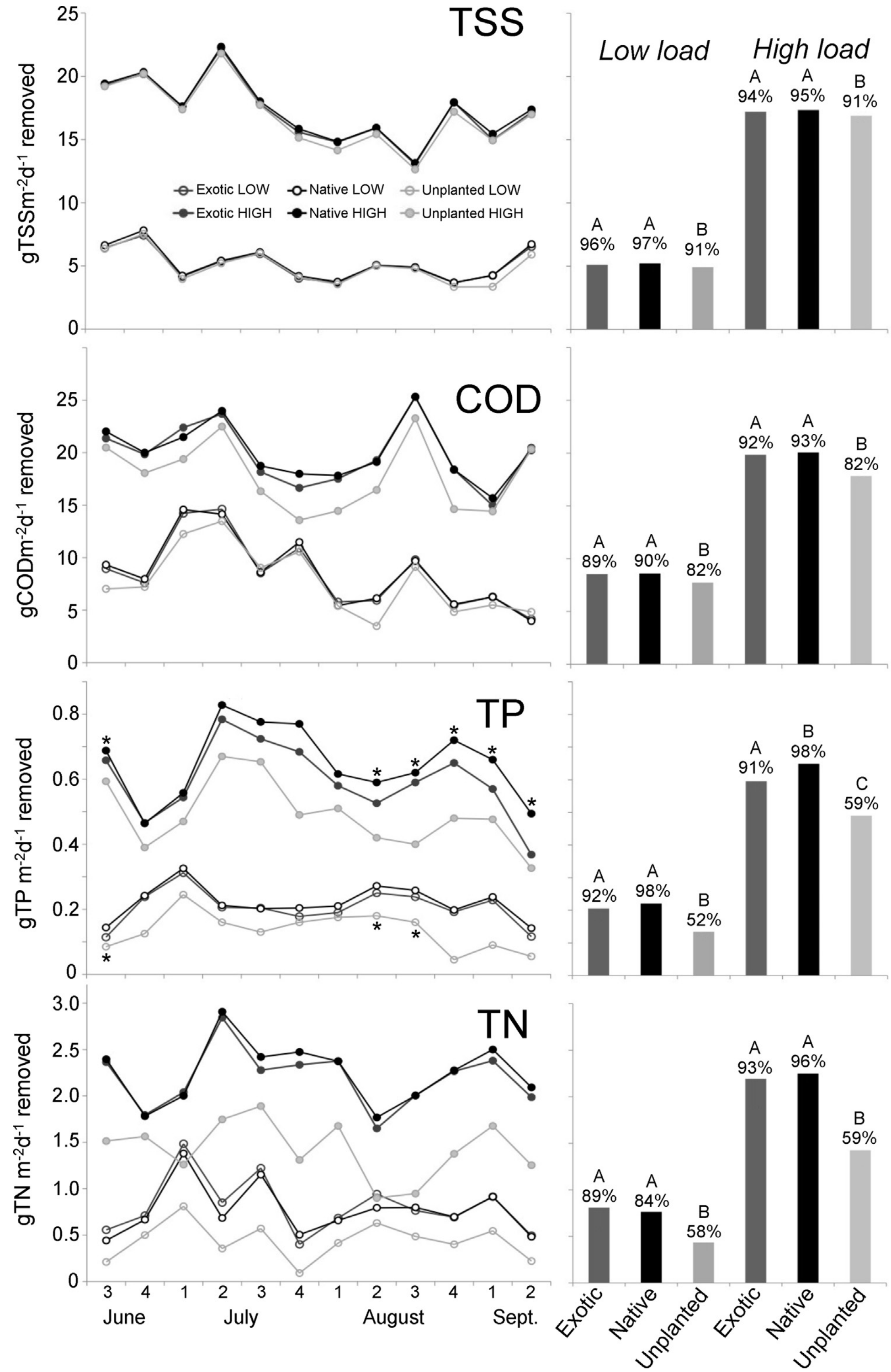

Fig. 2. Pollutant removal in $gm^{-2}d^{-1}$ during the 2011 sampling period. Bar graphs show the overall mean of the 12 sampling weeks per treatment and the respective percentage removal efficiency. Different letters indicate a significant difference between treatments (Tukey post hoc test $p < 0.05$). Time lines show means per treatment per week; line colors, black/dark grey/light grey, indicate native/exotic/unplanted respectively. Empty/full circles specify low/high loads respectively. * denotes weeks in which significant differences between native and exotic *Phragmites* were detected (Tukey post hoc test $p < 0.05$).

native and exotic *Phragmites*; both subspecies showed very high removal efficiency, ranging on average from 94% to 97% for TSS and from 89% to 93% for COD.

Differences between planted and unplanted wetlands were more pronounced regarding nutrient (TN, TP) removal. Total P removal efficiency in unplanted mesocosms was on average 60%, while planted wetlands showed around 90% efficiency (Fig. 2). Total N removal efficiency was significantly higher in planted systems under both low and high loads (86–95% respectively) than in unplanted mesocosms (58%), except in one sampling week (SM 2). The difference between planted and unplanted removal efficiency was greater under high N load (Fig. 2). High ammonium (NH_4-N) outflow concentrations were detected in unplanted mesocosms, while planted mesocosms

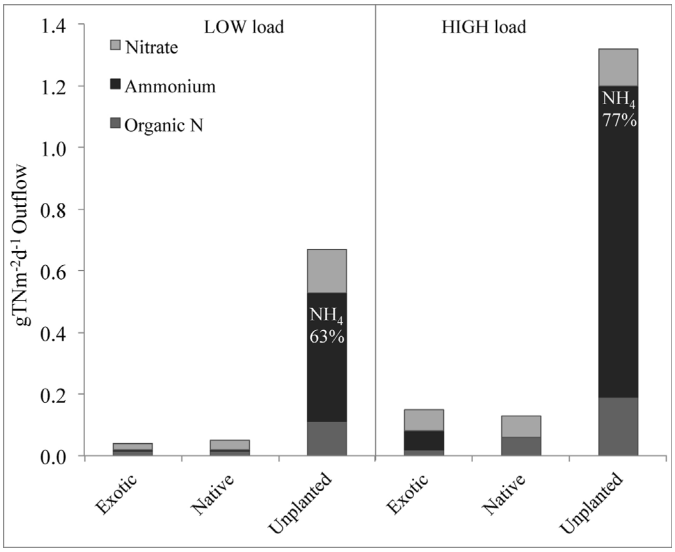

Fig. 3. Overall average TN outflow charge (12 weeks) and proportions of the different N forms between treatments.

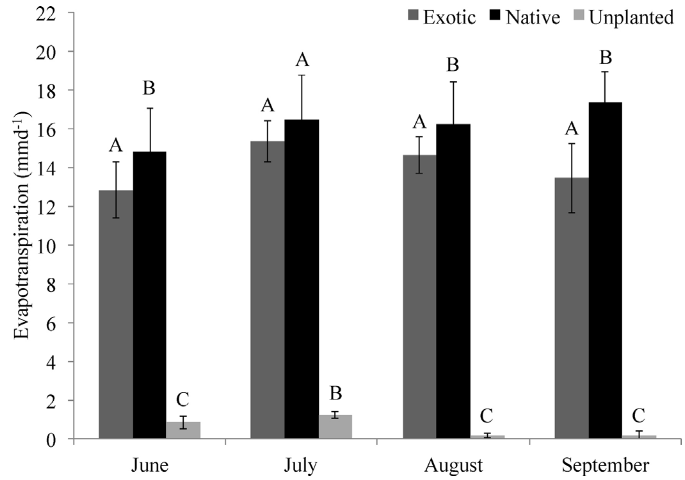

Fig. 4. Mean evapotranspiration rate per month based on weekly measurements (±SE) in each mesocosm. Evapotranspiration was calculated as the difference between inflow and outflow volume, plus rainfall. Different letters indicate

had very low outflow concentrations of both organic and inorganic N forms (Fig. 3). Nitrate (NO_3-N) concentrations were very low for all treatments, meaning that in planted mesocosms, nitrogen was not accumulated in the form of NH_4-N or NO_3-N (Fig. 3).

In terms of nutrient removal, both *Phragmites* subspecies showed excellent results. No significant differences were found between the subspecies for N removal. The most notable difference between native and exotic *Phragmites* was in terms of P removal, which was very high for both subspecies, but significantly higher for the native *Phragmites*. Load concentration also played a role, since differences between subspecies were found more frequently in mesocosms under high load (6 out of 12 sampling weeks) (SM 2 and Fig. 2).

3.2. Plant morphology and foliar content

Phragmites shoot density measured in the field ranged from 55 to 117 stems per m^2 respectively for native and exotic *Phragmites*. Plant stem height was around 3 m and stem diameter around 1 cm for both subspecies. These results contrast with those obtained in the mesocosm experiment, where average shoot density was approximately 20 times higher, ranging from 789 to 1366 stems per m^2. Shoots were also significantly shorter (1.8 m) and thinner (0.6 cm) compared to field measurements (Table 3).

Morphological differences were also found between plant subspecies in the mesocosms. Although shoot density of both subspecies was considerably higher in the mesocosms than in the field, exotic *Phragmites* shoot density was significantly higher than native *Phragmites*, particularly under high input load. However, as native *Phragmites* stems were more robust, aboveground biomass was similar for both subspecies (Table 3). Native *Phragmites* had significantly greater belowground biomass than the exotic, and this difference was greater under low inflow load. Root biomass was greater under low load for both subspecies.

Although N foliar content was not affected by plant subspecies, a two-factor ANOVA showed a significant influence of load on foliar N content; under high load inflow, plant foliar N increased (Table 3, SM 3). Native *Phragmites* P foliar content was higher, under both low and high input load (Table 3, SM 3). Root P content was also significantly higher in native *Phragmites*, irrespective of load concentration. Evapotranspiration was significantly higher in native *Phragmites* mesocosms and was not influenced by load inflow (Fig. 4).

4. Discussion

4.1. Pollutant removal efficiency

Results of our experiment suggest that *P. australis* subsp. *americanus* is indeed appropriate for use in TWs, with a level of pollutant removal efficiency comparable to that of the European subspecies.

The native *Phragmites*' efficacy in TWs is best illustrated by a comparison of our findings for planted versus unplanted

Table 3
Plant parameters (±SE) measured at the experimental site ($n = 5$) and in the fields where plants were collected: Îles-de-Boucherville National Park (Québec, Canada) and Lac Saint-François (Québec, Canada) ($n = 3$).

		Experimental set-up				Îles-de-Boucherville	Lac Saint-François
		High load		Low load			
Parameter	Unit	Exotic	Native	Exotic	Native	Exotic	Native
Stem density	stems m^{-2}	1366 (143)	789 (109)	1050 (142)	906 (167)	117 (13)	55 (4)
Stem length	m	1.8 (0.1)	1.9 (0.1)	1.6 (0.1)	1.9 (0.1)	3.3 (0.1)	2.6 (0.3)
Aboveground dry biomass	kg m^{-2}	4.1 (1.3)	3.2 (0.8)	4.0 (1.0)	4.1 (1.1)		
Belowground dry biomass	kg m^{-2}	2.3 (0.2)	2.7 (0.5)	2.8 (0.1)	3.6 (0.7)		
Nitrogen foliar content	%	2.1 (0.6)	2.1 (0.3)	1.6 (0.7)	1.4 (0.1)		
Nitrogen root content	%	0.9 (0.2)	0.9 (0.3)	0.9 (0.2)	0.8 (0.3)		
Phosphorus foliar content	%	0.12 (0.04)	0.36 (0.09)	0.10 (0.05)	0.41 (0.08)		
Phosphorus root content	%	0.25 (0.05)	0.35 (0.04)	0.27 (0.08)	0.29 (0.05)		

mesocosms. During both phases of our experiment, the mesocosms planted with native (or exotic) *Phragmites* outperformed the unplanted mesocosms in pollutant removal, and this advantage increased under high load. Planted mesocosms were slightly more efficient at COD removal and performed significantly better for TN and TP removal. Only for suspended solids removal, which involves mainly abiotic processes, was there almost no difference in treatment efficiency between planted and unplanted mesocosms.

We attribute the greater efficiency of the planted mesocosms to several factors. The presence of plants, such as native *Phragmites*, enhances the microbial community in the rhizosphere by offering a huge attachment surface area. Plants also provide a micro-aerobic environment through root oxygen release and a source of carbon through root exudates, which can improve aerobic degradation and nitrification (Brix, 1997; Gagnon et al., 2007; Vymazal, 2011; Zhai et al., 2013). In addition, a high evapotranspiration rate affects retention time and treatment efficiency by increasing the concentration of pollutants in TWs (Chazarenc et al., 2003; Shelef et al., 2013). High evapotranspiration rates may also influence the adsorption of phosphates to organic particles in the media, increasing the redox potential of the system. In our experiment, native *Phragmites* tolerated TW conditions very well, showing high growth and biomass, allowing the plants to achieve their potential to improve TW efficacy.

Contrary to our hypothesis based on the ecophysiological superiority of the exotic *Phragmites* (Mozdzer and Zieman, 2010), we found no evidence that the native *Phragmites* was less efficient than its European counterpart in TWs. The two subspecies were compared under the same experimental conditions, under two different pollutant concentrations, and showed no important differences in performance. Since exotic *Phragmites* has been shown to transfer oxygen more efficiently to roots and rhizomes than the native (Tulbure et al., 2012), we expected that this would translate into higher COD and TN removal efficiency. In fact, the only noticeable difference we found between the two subspecies in terms of removal was for phosphorus, for which the native *Phragmites* seemed to be more – not less – efficient than the exotic. The differences in TP removal were revealed during the two consecutive summer samplings, under both low and high loads for the second summer. Native *Phragmites* had a higher P content in leaves and roots compared to the exotic, which could partly explain its higher removal efficiency.

4.2. Plant morphology

The vast differences in growing conditions in subsurface TWs compared to natural wetlands may affect morphological, ecological and physiological plant attributes. In TWs, the substrate, usually composed of coarse sand or gravel, is loose, which maximizes hydraulic conductivity, thereby offering little resistance to root growth compared to more compact wetland soils. Soil fertility and nutrient supply is much higher than under most natural conditions, affecting plant growth as well as competition and density. Small systems such as microcosms or mesocosms are subject to strong edge effects, additional evapotranspiration loss and other sources of bias that may modify growing conditions (Dalling et al., 2013; Poorter et al., 2012). This was the case in our mesocosms, in which average stem density was approximately 20 times higher than in the field. This difference may be due to the younger age of the stands in our mesocosm: a stem count decrease over time but an increase in shoot size has been previously observed in *Phragmites* in constructed wetlands during the period of operation (Vymazal and Kropfelova, 2005). Edge effect, canopy overhang and the confined, highly concentrated nutrient environment may also explain the high density values obtained in our mesocosms.

We also identified relative morphological differences in *Phragmites* responses that were not predictable based on field observations. Under natural conditions, the exotic *Phragmites* was taller and had greater stem density than the native, a pattern widely reported for other locations (Mozdzer et al., 2013). In contrast, in the mesocosms, native *Phragmites* shoots were taller than the exotic. The exotic *Phragmites* had higher shoot density than the native, but the difference was much less under low pollutant load. Also, biomass production of native and exotic *Phragmites* was comparable in our mesocosms, while a review by Mozdzer et al. (2013) reported that the exotic produced on average between 151% and 250% more total biomass than the native.

As expected, belowground biomass was affected by load, with both native and exotic *Phragmites* investing more in root biomass under a low load rate. However, native *Phragmites* had higher root biomass than the exotic, under both low and high inflow load, a pattern that once again contrasts with the results reported by Mozdzer et al. (2013).

While it can be reasonably assumed that plant characteristics measured under field conditions may reflect potential removal efficiency in TWs, our study shows that results are not easily transposed. Different responses by the American and European lineages of *P. australis* to TW growing conditions leveled out the differences observed in the field, so that both subspecies appeared equally efficient under our experimental conditions. In fact, contrary to our expectations, our results suggest that the native *Phragmites* may be the preferred subspecies due to its slightly more effective removal of phosphorus.

While our mesocosm experiment suggests that native *Phragmites* have high removal efficiency, these experimental conditions resulted in an overestimation of quantitative values, and further evaluation under full-size TW conditions would be necessary. The very high evapotranspiration rate measured in the mesocosms also contributed to the high removal efficiency for all pollutants. Mesocosms have a high "edge – interior ratio", which amplifies evapotranspiration through advection, or the so called "oasis effect" (Kadlec and Wallace, 2009; Headly et al., 2012), which would be less pronounced in full-sized TWs.

5. Conclusion

Concerns about the threat posed by invasive macrophyte species require the use of native species in treatment wetlands. The results of this comparative assessment of removal efficiency between native and exotic *Phragmites* subspecies suggest that native *Phragmites* could be an effective alternative to the exotic subspecies in North American TWs. However, while removal efficiency is the most important factor in plant selection for TWs, other characteristics should also be evaluated. Resistance to diseases and pests is particularly important, since native plants are assumed to be more susceptible (have more "local enemies") than exotic species (Keane and Crawley, 2002), a process that has been suggested to contribute to the success of the exotic *Phragmites* in North America (Blossey, 2003). During our experiment, a fungicide treatment had to be applied to fight an infestation by *Deightionella*, a pathogenic fungus that affected both subspecies, but the native far more severely.

Finally, while most native *Phragmites* in North America have been grouped under the subspecies *P. australis* subsp. *americanus*, several different haplotypes have been recognized, as has another possible species (the so-called "Gulf Coast lineage") in the southern United States (Saltonstall, 2002; Saltonstall et al., 2004; Lambertini et al., 2012). There may also be differences in removal efficiency between genotypes, as has been demonstrated for *P. australis* in Japan (Tomimatsu et al., 2014). Thus, our results may not apply to all other North American haplotypes of *P. australis* subsp. *americanus*.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.11.005.

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