Ecotoxicology (2011) 20:457–465
DOI 10.1007/s10646-011-0598-0

Adaptability of *Typha domingensis* to high pH and salinity

M. M. Mufarrege · G. A. Di Luca · H. R. Hadad · M. A. Maine

Accepted: 13 January 2011 / Published online: 2 February 2011

Abstract The aim of this work was to compare the adaptability of two different populations of *Typha domingensis* exposed to high pH and salinity. The plants were sampled from an uncontaminated natural wetland (NW) and a constructed wetland (CW) for the treatment of an industrial effluent with high pH and salinity. The plants from each population were exposed to the following combined treatments of salinity (mg l^{-1}) and pH: 8,000/10 (values found in the CW); 8,000/7; 200/10 and 200/7 (typical values found in the NW). Chlorophyll concentration, relative growth rates (RGR) and root structure parameters (cross-sectional areas of root, stele and metaxylem vessels) were measured. Images of roots and leaves by scanning electronic microscopy (SEM) were obtained, and X-ray microanalysis in different tissues was carried out. In all treatments, the RGR and chlorophyll increase were significantly lower in the plants from the NW than in the plants from the CW. However, stress was observed when the plants from the CW were exposed to treatment 200/7. In treatment 8,000/10 the tissues of the plants from the NW showed severe damages. The root structure of plants from the CW was modified by salinity, while pH did not produce changes. In plants from the CW there were no differences between Na concentration in leaves of the treatments 8,000/10 and 200/7, indicating that Na was not transported to leaves. The CW population already possesses physiological and morphological adaptations due to the extreme conditions of pH and salinity. Because of its adaptive capacity, *T. domingensis* is an efficient species to treat wastewater of high pH and salinity.

Keywords Macrophyte · Wetland · Tolerance · Phytoremediation

M. M. Mufarrege (✉) · G. A. Di Luca · H. R. Hadad · M. A. Maine
Química Analítica, Facultad de Ingeniería Química, Universidad Nacional del Litoral, Santiago del Estero 2829, 3000 Santa Fe, Argentina
e-mail: mmufarrege@fiq.unl.edu.ar

M. M. Mufarrege · G. A. Di Luca · H. R. Hadad · M. A. Maine
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santa Fe, Argentina

Introduction

Constructed wetlands (CWs) are efficient systems for the removal of solids, organic matter, nutrients and metals contained in many types of wastewaters (Hammer 1989; Kadlec et al. 2000; Kadlec and Wallace 2009; Maine et al. 2009; Vymazal et al. 1998).

The choice of macrophytes is an important issue in CWs, as they must survive the potentially toxic effects of the effluent and its variability. Regionally abundant macrophyte species are adapted to the local climatic and edaphic conditions. However, their performance under the environmental conditions imposed by the wastewater, such as salinity, pH, dissolved oxygen (DO) and contaminant concentrations are usually unknown. Effluents with high pH and high salinity are a common result from many industrial processes. Some macrophytes, such as *Salvinia herzogii* De la Sota, *Pistia stratiotes* L. and *Eichhornia crassipes* (Mart.) Solms., could be more affected by high pH and salinity than by metal or sulphide concentration (Hadad et al. 2006; Maine et al. 2009). The adaptability of macrophytes to salinity is variable and species-dependent. Hester et al. (2001) studied salinity stress in different populations of *Panicum hemitomon* Schult., *Spartina patens* (Aiton) Muhl., and *Spartina alterniflora* Loisel. These

authors found that plant morphology (size attributes) were strongly associated with salt tolerance in *P. hemitomon*, weakly associated in *S. patens*, and not associated in *S. alterniflora*. Highly salt-tolerant populations of *S. alterniflora* displayed the greatest ion selectivity (lower leaf Na^+/K^+ ratios), which was not displayed by the other two species. Populations from high salinity sites have specialized physiological and anatomical adaptations that can confer salinity stress resistance through mechanisms such as selective ion exclusion and secretion.

Studies on salinity and pH effects on the tolerance of *Typha* species are scarce. Macek and Rejmánková (2007) studied the response of emergent macrophytes to experimental nutrient and salinity additions, and found that *Typha domingensis* Pers. behaved as a typical competitor reducing only the plant height. Glenn et al. (1995) studied the effects of salinity on growth and evapotranspiration of *T. domingensis* and found that a salinity value of 7–10 ppt (7,000–10,000 mg l^{-1}) would result in the deterioration of the macrophyte stands. The effects on *Typha* species root structure and the comparison of responses among different populations to salinity and pH were not found in literature.

T. domingensis is an abundant emergent macrophyte in marshes in the Middle Paraná River system (Argentina). This species is frequently used in CWs. We studied a free-water surface wetland constructed at Bahco S.A. metallurgic industry to treat the wastewater from the whole factory (sewage and industrial effluents) in Santo Tomé, Santa Fe (Argentina). The wastewater presents high pH and salinity and contains low concentrations of Cr, Ni and Zn. The wetland proved to be very efficient in metal and nutrient retention (Maine et al. 2009). At the beginning of its functioning (November 2002), different locally available floating and emergent macrophyte species (including *T. domingensis*) were transplanted into the wetland. Salinity and pH of the incoming wastewater were toxic for the floating species (Hadad et al. 2006). After 3 years of operation, *T. domingensis* displaced the other species, becoming the dominant species with a cover of 80% (Maine et al. 2009). We hypothesized that *T. domingensis* possesses morphological plasticity that allows its adaptation to extreme conditions of pH/salinity. The aim of this work was to evaluate the response of two populations of *T. domingensis* (plants from a CW and a NW) under different pH and salinity treatments.

Materials and methods

Plant material and experimental design

Similar size and healthy plants were selected from the NW and the CW. The CW is a free-water surface wetland (31°40′S; 60°47′W) that has an area of 2,000 m^2 and 0.3–0.6 m deep. The NW is located in a uncontaminated natural environment belonging to the Middle Paraná River floodplain, near to Santa Fe city, Argentina (31°32′45″S; 60°29′37″W).

Two plants were placed in plastic pots of 10 l of capacity with sediment prepared by composting from a plant nursery. The sediment composition ensured the normal growth of the plants (Organic matter: 8%; pH: 7.67; Cr: 0.015 mg g^{-1}; Ni: 0.006 mg g^{-1}; Zn: 0.13 mg g^{-1}; TP (Total phosphorus): 0.57 mg g^{-1}; Total Kjeldahl nitrogen (TKN): 1.32 mg g^{-1}). The pots were placed in a greenhouse under natural photoperiod. After acclimatization period of 10 days, they were pruned to a height of approximately 19 cm at the beginning of the experiment. Three liters of buffer solutions with the studied salinities were added. Salinity was achieved adding Na_2SO_4. This salt was chosen because Na^+ and SO_4^{2-} are major ions in the effluent treated in the CW. The treatments of salinity (mg l^{-1})/pH applied to the plants from the constructed wetland (CW) and the natural wetland (NW) were: 8,000/10 (values found in the CW); 8,000/7; 200/10 and 200/7 (characteristic values found in the NW). The experiment lasted 90 days and was carried out in triplicate.

Analytical determinations

Water

The water chemical characterization of the CW and the NW is showed in Table 1. To characterize the water from the CW and NW, conductivity was measured with an YSI 33 conductimeter and pH with an Orion pH-meter. Dissolved oxygen (DO) was measured with a Hanna Hi 9146 portable meter. Water samples were filtered through Millipore membrane filters (0.45 μm) for soluble P and N determinations. Chemical analyses were performed following APHA (1998). NO_2^- was determined by coupling diazotation followed by a colorimetric technique. NH_4^+ and NO_3^- were determined by potentiometry (Orion ion selective electrodes, sensitivity: 0.01 mg l^{-1} of N, reproducibility: ±2%). Soluble reactive phosphorous (SRP) was determined by the colorimetric molybdenum blue method. Ca^{2+} and Mg^{2+} were determined by EDTA titration. Na^+ and K^+ were determined by flame emission photometry. Alkalinity (carbonate and bicarbonate) was measured by HCl titration. Cl^- was determined by the argentometric method. SO_4^{2-} was assessed by turbidimetry. Chemical oxygen demand (COD) was determined by the open reflux method and biochemical oxygen demand (BOD) by the 5-Day BOD test. Total Fe, Cr, Ni and Zn concentrations were determined by atomic absorption spectrometry

Table 1 Chemical characterization of the natural wetland and the inlet of the constructed wetland (NW and CW, respectively)

Parameter	NW	CW (inlet)
pH	7.9	12.6
Conductivity (μmho cm^{-1})	208	5,200
Total solids (mg l^{-1})	149.2	3145.3
Alkalinity ($CaCO_3$) (mg l^{-1})	105.2	1427.2
HCO_3^- (mg l^{-1})	128.1	ND
CO_3^{2-} (mg l^{-1})	ND	483.2
Cl^- (mg l^{-1})	10.6	257.4
SO_4^{2-} (mg l^{-1})	8.2	759.2
Total hardness ($CaCO_3$) (mg l^{-1})	33.6	623.2
Ca^{2+} (mg l^{-1})	9.8	249.3
Mg^{2+}(mg l^{-1})	2.2	0.5
Na^+ (mg l^{-1})	35.1	834.2
K^+ (mg l^{-1})	11.1	18.2
Fe (mg l^{-1})	0.29	53.41
Cr (mg l^{-1})	ND (DL = 0.005)	0.062
Ni (mg l^{-1})	ND (DL = 0.005)	0.045
Zn (mg l^{-1})	ND (DL = 0.005)	0.025
SRP (mg l^{-1})	0.015	0.040
TP (mg l^{-1})	0.069	0.085
NO_2^- (mg l^{-1})	ND (DL = 0.005)	0.170
NO_3^- (mg l^{-1})	0.63	27.8
NH_4^+ (mg l^{-1})	2.16	3.97
BOD (mg l^{-1})	3.0	243.4
COD (mg l^{-1})	6.0	982.5
DO (mg l^{-1})	6.5	5.4

ND Not detected, *DL* detection limit

(by flame or electrothermal atomization, according to the sample concentration, Perkin Elmer 5000).

Plants

Chlorophyll concentration This parameter was measured initially and at the end of the experiment. The increase in chlorophyll concentration was expressed as a percentage. Chlorophyll was extracted with acetone for 48 h in cold darkness (3–5°C). Transmittances of the extracts at wavelengths of 645 and 665 nm were recorded with a spectrophotometer UV–Vis (Westlake 1974).

Scanning Electron Microscopy (SEM) X-ray microanalysis These analyses were carried out after 90 days. Samples of roots and leaves of about 1 cm were cut, and dried in an oven at 20°C for 10 days so as not to damage the tissues (Suñé et al. 2007). Samples were examined with a Scanning Electron Microscope (SEM) JEOL; model JSM-35C, equipped with an energy dispersive system EDAX. For the tissue elemental chemical analysis leaves were divided into abaxial and adaxial faces, and mesophyll. Roots were divided into epidermis, cortical parenchyma and stele. Representative portions of the samples were adhered with graphite double-sided tape. After obtaining the spectra and the digital images, the samples were adhered to the sample holder with silver paint and then covered with gold using an evaporator Veeco, model VE-300 operating at argon atmosphere. Image acquisition was carried out with the SemAfore system.

Biological analyses

Relative growth rate

The external appearance of plants was observed in order to detect senescence. Plant height was daily measured (data not shown). Relative growth rate (RGR) (cm cm^{-1} day^{-1}) was calculated in each treatment considering plant height according to:

$$\mathrm{RGR} = \frac{\ln H_2 - \ln H_1}{T_2 - T_1}$$

where H_1 and H_2 are the initial and final plant height (cm), respectively, and (T_2-T_1) is the experimental period (days).

Anatomical measurements

These measurements were carried out after 90 days at the end of the experiment. A section approximately 30 mm long was cut from the middle of the root and stored in 4% formaldehyde. After 48 h, the sections were immersed in 70% ethanol for preservation. The main roots were taken at random and cross-sectioned by hand applying the technique proposed by D'Ambrogio de Argüeso (1986). In order to distinguish cell walls from the background, the material was stained with aniline blue, which stains cellulose blue. The sections were examined by light microscopy (100× and 400×). The cross-sectional areas (CSA) of root, stele and metaxylem vessels were measured using a micrometric ocular. The formula to calculate the area of a circle was applied to obtain the values of the CSA of the whole root, stele and metaxylem vessels (Wahl et al. 2001). In addition, the number of metaxylem vessels (NV) per section was recorded.

Statistical analysis

Two-way ANOVA was carried out to determine the effects of salinity and pH on RGR and the increase in chlorophyll concentration in plants from the NW and the CW. The normality of residuals was previously tested graphically,

and the homocedasticity of variances was checked applying Bartlett's test. Duncan test was used to differentiate means where appropriate.

Since the root structure parameters (root, stele and metaxylem vessels CSAs and number of vessels) did not show a normal distribution, non-parametric tests and box and whisker plots were performed using median as central trend measure and interquartile range (25 and 75%) as its variability measure. Kruskal–Wallis analysis was applied to check the differences between the anatomical parameters measured in roots among the different treatments. When statistically significant differences were found, Wilcoxon's test was used to compare treatments among themselves. In all comparisons a level of $p < 0.05$ was used. Calculations were carried out with Statgraphics Plus 5.0.

Results

The RGR and the percentage of chlorophyll increase were significantly higher in the plants from the CW than in the plants from the NW (Fig. 1a, b). The lower RGR and chlorophyll increase observed in the plants from the NW demonstrated the toxic effects of the increased pH and/or salinity. The plants from the CW showed the highest RGR and chlorophyll increase in treatment 8,000/10 (typical conditions of the effluent treated in the CW). In the plants from the NW, the highest RGR and chlorophyll increase were observed in the treatment 200/7 probably because this treatment presented the normal values of salinity/pH of NW waters.

The root CSA of the plants from the CW was significantly lower than that of the plants from the NW, with exception of the treatment 200/10 (Fig. 2a). The highest root CSA was registered in plants from the NW in the treatment 200/7. In the root CSA of the plants from the CW there were not registered significant differences between the treatments 8,000/10 and 8,000/7, and between the treatments 200/10 and 200/7. In the plants from the CW the stele CSA was lower in the treatments of high salinity (8,000/7 and 8,000/10) than in the other treatments (Fig. 2b). The plants from the NW showed a stele CSA significantly higher than the plants from the CW in the treatment 8,000/10 and a lower value in the treatment 200/10. The highest stele CSA in the plants from the NW was observed in the treatment 8,000/10. In treatments 8,000/7 and 200/10 the plants from CW showed higher metaxylem vessel CSA than that of the obtained in NW plants (Fig. 2c). In the plants from the CW the metaxylem vessel CSA was lower in the treatments of high salinity (8,000/7 and 8,000/10) than in the other treatments. The highest metaxylem vessel CSA in the plants from the NW was observed in the treatment 8,000/10. The highest NV

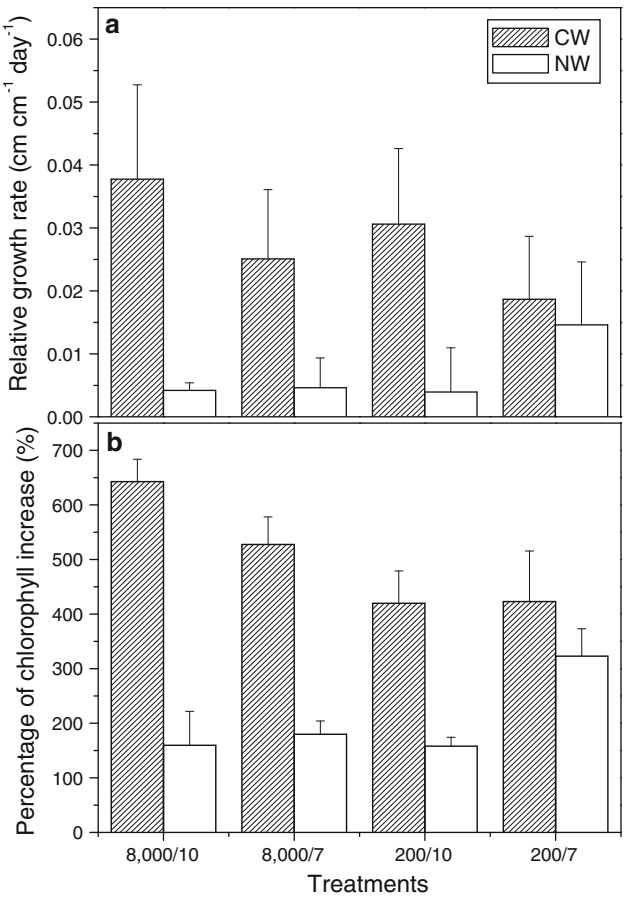

Fig. 1 Relative growth rate (cm cm^{-1} day^{-1}) (**a**) and percentage of chlorophyll increase (%) of *T. domingensis* (**b**) obtained at the different treatments in the CW and the NW (mean ± standard deviation)

was observed in the plants from the NW in the treatment 8,000/10 (Fig. 2d). In the plants from the CW, the NV were lower in the treatments of high salinity (8,000/7 and 8,000/10) than in the other treatments.

Regarding SEM analyses (Fig. 3), the tissues of the plants from the CW were in a healthy state, except in treatment 200/7, in which the leaf and root tissues were not clearly differentiated, indicating an evident damage. Contrarily, for the plants from the NW, in treatment 8,000/10 the leaf and root tissues were not clearly differentiated showing dehydration and severe damages, while the plants in treatment 200/7 were found to be under normal conditions.

According to the X-ray microanalysis, Si contents were not significantly different between plant tissues from the CW and NW. Si relative ratio in % (w/w) found in plant tissues from the CW were 2–19% and 1–3% for roots and leaves, respectively. For plant tissues from the NW the values were 1–18% and 1–4% for roots and leaves, respectively. Due to its high relative abundance that masks

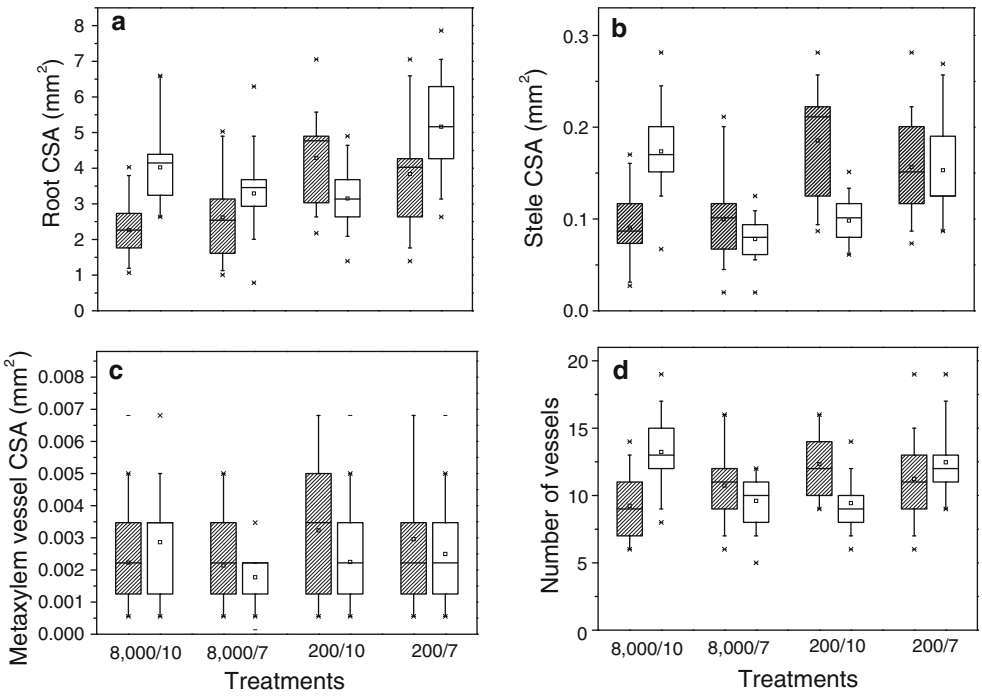

Fig. 2 *Box* and *whisker* plots of cross-sectional areas (CSA) of root (**a**), stele (**b**) and metaxylem vessels (**c**) and *box* and *whisker* plots of the number of metaxylem vessels (**d**) of *T. domingensis* plants from the CW (*square with upper left to lower right fill*) and NW (*open square*)

studied element content, it was excluded and the percentages of the other elements were recalculated (Table 2).

In all treatments, Na, S, Cl, K and Ca presented the highest proportions in plant tissues. Cl was significantly higher in leaves than in roots in all cases. In the leaves of the plants from the CW, Ca was substituted for K when salinity increased. In roots, Na replaced K, and S replaced Cl. In the leaves and roots of the plants from NW, Ca was substituted for Na in treatment 8,000/10. Our interest focused on Na and S in tissues, since they were the major elements of the studied solution of high salinity (treatment 8,000/10). Na in leaves of plants from CW was significantly lower than that of the values obtained in the plants from NW. In the plants from CW, Na accumulated in epidermis and parenchyma roots, while a low accumulation was observed in the stele. In comparison with the plant roots from CW, a higher Na value was observed in the stele of the plant roots from NW. The leaves of the plants from the CW showed higher S values than that of the obtained in the leaves of the plants from the NW. Although S accumulated in roots of plants from the CW and NW, S contents in roots of the plants from NW were the highest values.

In treatments 8,000/7 and 8,000/10 dehydration and the presence of salts adhered on leaf epidermis was observed in plants from the NW (Fig. 4). This was not observed in the plants from the CW.

Discussion

In comparison with the plants from the NW, the higher RGR and percentage of chlorophyll increase observed in the plants from the CW, demonstrated that these plants had modified its physiology and morphology in order to tolerate the conditions of the industrial effluent to which they are permanently exposed. Therefore, they already possess adaptations to tolerate the extreme conditions of pH and salinity studied in this work.

The effects of salinity and pH on the plants from the NW were in agreement with Nilratnisakorn et al. (2007) who observed that the growth rate of *T. angustifolia* was affected by a synthetic reactive dye caustic wastewater of high salinity. They found that the inhibition of photosynthesis was due to the precipitation of Na salt crystals in leaves and roots that caused the obstruction of the solute transportation. Macek and Rejmánková (2007) found that the vertical and horizontal growth of *T. domingensis* was limitied by high salinity. Glenn et al. (1995) observed that at a concentration of 9 ppt of NaCl, the height and the number of new shoots of *T. domingensis* presented a significant decrease. Munns et al. (1993) suggested that growth under salinity is inhibited through two phases. Initially (phase 1), growth is affected because of cellular responses to the osmotic effects. In the subsequent phase (phase 2), growth is reduced due to the toxic effects of accumulated salts.

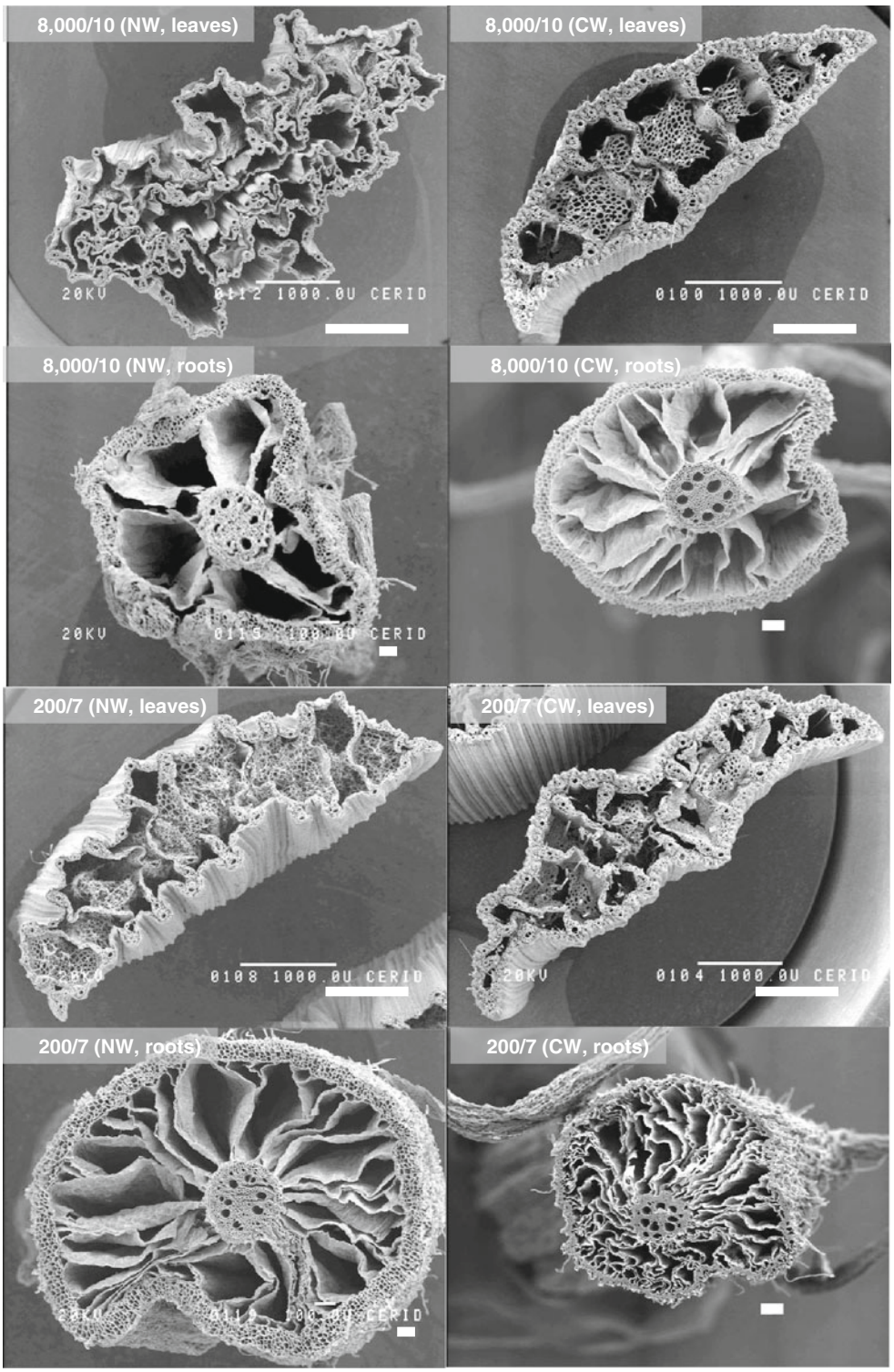

Fig. 3 Cross-sectional images of leaves and roots of plants from the CW and NW obtained in each treatment under SEM-EDX with energy of 20 kV

The root structure of plants from the CW was modified by the salinity, while pH did not produce changes in these parameters. On the other hand, pH and salinity produced changes in the root structure of the plants from the NW. Dyhr-Jensen and Brix (1996) found that at pH 3.5 *T. latifolia* showed a relative growth rate significantly lower than that obtained at pH values of 5.0, 6.5 and 8.0. Extremely low pH values are toxic for the growth of *Typha* species

Table 2 Relative ratio in % (w/w) of the leaves and roots X-ray microanalysis in the different treatments of salinity (mg l^{-1}) and pH (<1 represents values under the detection limit)

Treatment	Zone	Na	Mg	Al	P	S	Cl	K	Ca	Mn	Fe	Ti
Leaves												
CW (8,000/pH10)	Adaxial	3	1	1	<1	18	20	37	19	<1	<1	<1
	Mesophyll	3	2	<1	1	14	25	33	21	<1	<1	<1
	Abaxial	2	1	1	1	20	14	36	21	1	1	<1
NW (8,000/pH10)	Adaxial	11	2	2	7	6	32	25	8	<1	<1	<1
	Mesophyll	12	1	1	6	4	37	25	13	<1	<1	<1
	Abaxial	13	2	3	5	6	32	16	10	<1	1	<1
CW (200/pH7)	Adaxial	2	3	1	3	15	26	19	28	<1	<1	<1
	Mesophyll	6	8	9	1	7	33	17	17	<1	<1	<1
	Abaxial	1	4	1	2	14	27	18	29	<1	1	<1
NW (200/pH7)	Adaxial	<1	3	<1	3	10	11	51	20	1	<1	<1
	Mesophyll	<1	2	<1	4	5	23	57	7	2	<1	<1
	Abaxial	1	5	1	5	5	15	43	20	2	1	<1
Roots												
CW (8,000/pH10)	Epidermis	14	3	3	2	18	2	8	29	<1	9	1
	Parenchyma	27	9	6	2	15	5	8	8	<1	5	2
	Stele	1	<1	<1	<1	33	9	22	25	<1	5	<1
NW (8,000/pH10)	Epidermis	16	2	2	3	32	3	19	14	<1	1	<1
	Parenchyma	20	2	1	2	37	3	19	14	<1	<1	<1
	Stele	22	2	<1	7	37	6	4	20	1	<1	<1
CW (200/pH7)	Epidermis	9	2	10	1	3	3	31	8	<1	3	1
	Parenchyma	15	2	<1	2	2	3	56	18	<1	<1	<1
	Stele	2	2	<1	4	2	5	54	21	<1	<1	<1
NW (200/pH7)	Epidermis	<1	3	2	6	2	<1	42	31	<1	9	<1
	Parenchyma	<1	4	5	5	1	1	47	21	<1	2	<1
	Stele	<1	3	1	5	3	<1	63	15	<1	1	<1

because an increased passive influx of H^+ would decrease the electrochemical gradient across the plasma membrane and thus the uptake of cations. In the case of free-floating macrophytes, Hadad et al. (2006) found that pH values of 10 and 11 were toxic for the growth of *S. herzogii*, *P. stratiotes* and *E. crassipes*. Also, these authors found a negative growth rate in *E. crassipes* at a conductivity of 4,000 μmho cm^{-1}. The values of pH were the same as those used in our experiment and salinity was lower, indicating a higher tolerance of *T. domingensis* than the studied floating macrophytes. Emergent plants tolerate salinity and pH better than free-floating macrophytes. Sediment acts as a barrier and equilibrates the system ionically, enhancing the tolerance of emergent species.

After 90 days, the tissues of the plants from the CW presented a healthy state as was seen in SEM images. The leaves of the plants from the CW were narrower in elevated salinity treatments, suggesting that the loss of structural support in narrower leaves might contribute to a lesser height growth. These observations confirm the adaptation acquired by the plants from the CW. Nilratnisakorn et al. (2007) observed in SEM images that *T. angustifolia* roots were damaged after the treatment with dye wastewater, and sodium crystalline was deposited in the root cells causing a decrease in evaporation and transpiration.

In plants from the CW there were no significant differences between the Na in leaves of the treatments 8,000/10 and 200/7, indicating that Na was not transported to leaves. The low concentration of Na in stele indicates its low mobility in the plants from the NW. This is due to the fact that the metaxilematic vessels, responsible of substance transport to the aerial parts, are located in the stele. The high S value found in the stele indicates its transport. The accumulation of Na in plant roots from the CW indicates an avoidance mechanism to protect the stem from sodium salts and to balance the water potential osmotic pressure (Amarante et al. 2006; Munns and Greenway 1980; Parida and Das 2005; Thomson 1975). In plants from the NW the stele presented a high value of Na indicating its transport from roots to leaves. In agreement with our results,

Fig. 4 Salt accumulated on leaves of plants from the NW in the treatment 8,000 mg l^{-1}/pH 10

Nilratnisakorn et al. (2007) found that the accumulation of Na in leaves causes obstruction of the solute transportation which leads to the inhibition of photosynthesis.

Salt excretion is a very efficient way of preventing excessive concentrations of salts building up in photosynthetic tissues. This mechanism is typical of species that have developed special features, mostly localized at the leaf epidermis, known as salt glands and salt hairs (bladders). One of the most obvious signs of salt excretion is the salt crust on leaves and shoots of those species with salt glands or salt hairs (Popp 1995). However, *T. domingensis* does not possess neither salt glands nor salt hairs, so the salt observed on the leaf surface (Fig. 4) was probably due to salt precipitation when the water level in the aquaria decreased by evapotranspiration. Munns (2002) proposed that salt tolerance is due to two main mechanisms: one of them is to minimize the entry of salt into the plant (or at least its accumulation in photosynthetic tissues), and the other is to minimize the salt concentration in the cytoplasm. Generally the salt exclusion in some plant species is a very efficient but complex way of preventing massive ion uptake in the root zone, enabling a lower uptake and accumulation of salts in the upper parts of the plant, especially in the transpiring organs. Salt exclusion is based upon lower root permeability for ions even in the presence of high external salinity.

Conclusion

The plants from the CW have physiological and morphological adaptations to tolerate high pH and salinity. Contrarily, they showed stress when they were exposed to the conditions of pH and salinity that are generally found in the NW water (treatment 200/7). The adaptations of the plants from the CW were demonstrated by a higher relative growth rate and chlorophyll increase in comparison with those obtained in the plants from the NW.

On the other hand, the plants from the NW showed stress when they were exposed to the conditions of high pH and salinity, normally found in the CW. These results denote that a suitable acclimation is necessary to favour the adaptability of *T. domingensis* to tolerate effluent conditions and survive in the wetland.

Although *T. domingensis* is not a halophyte species and does not possess anatomical structures to tolerate and excrete salts, it is capable of modifying its morphology in order to adapt to extreme conditions, such as the exposition to an industrial effluent. Because of its adaptive capacity, *T. domingensis* is a good choice to treat wastewater of high pH and salinity, common characteristics of many industrial effluents.

Acknowledgments The authors thank Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and Universidad Nacional del Litoral (UNL), CAI+D Project for providing funds for this work.

References

Amarante L, Lima JD, Sodek L (2006) Grow and stress conditions cause similar changes in xilem amino acids for different legume species. J Exp Bot 58:123–129

APHA (1998) Standard methods for the examination of water and wastewater. American Public Health Association, New York

D'Ambrogio de Argüeso A (1986) Manual de técnicas en histología vegetal. Hemisfero Sur S.A, Buenos Aires

Dyhr-Jensen K, Brix H (1996) Effects of pH on ammonium uptake by *Typha latifolia* L. Plant Cell Environ 19:1431–1436

Glenn E, Thompson LT, Frye R, Riley J, Baumgartner D (1995) Effects of salinity on growth and evapotranspiration of *Typha domingensis* Pers. Aquat Bot 52:75–91

Hadad HR, Maine MA, Bonetto C (2006) Macrophyte growth in a pilot-scale constructed wetland for industrial wastewater treatment. Chemosphere 63(10):1744–1753

Hammer DA (1989) Constructed wetlands for wastewater treatment. Lewis, Chelsea

Hester WM, Mendessohn IA, McKee KL (2001) Species and population variation to salinity stress in *Panicum hemitomon, Spartina* patens, and *Spartina alterniflora*: morphological and physiological contraints. Environ Exp Bot 46:277–297

Kadlec RH, Wallace SD (2009) Treatment wetlands, 2nd edn. CRC Press, Boca Raton

Kadlec RH, Knight RL, Vymazal J, Brix H, Cooper P, Haberl R (2000) Constructed wetlands for pollution control: processes, performance, design and operation. IWA specialist group on use

of macrophytes in water pollution control. International Water Association

Macek P, Rejmánková E (2007) Response of emergent macrophytes to experimental nutrient and salinity additions. Funct Ecol 21:478–488

Maine MA, Suñé N, Hadad RH, Sánchez GC, Bonetto C (2009) Influence of vegetation on the removal of heavy metals and nutrients in a constructed wetland. J Environ Manag 90:355–363

Munns R (2002) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–250

Munns R, Greenway H (1980) Mechanisms of salt tolerance in non-halophytes. Annu Rev Plant Physiol 31:149–190

Munns R, Greenway H, Kirst GO (1993) Halotolerant eukaryotes. In: Lange OL, Nobel PS, Osmond CB, Ziegler HH (eds) Encyclopedia of Plant Physiology (New Series, Vol. 12C). Springer Verlag, Berlin, pp 59–135

Nilratnisakorn S, Thiravetyan P, Nakbanpote W (2007) Synthetic reactive dye wastewater treatment by narrow-leaved cattails (*Typha angustifolia* Linn.): effects of dye, salinity and metals. Sci Total Environ 384:67–76

Parida AK, Das AB (2005) Salt tolerance and salinity effects on plants: a review. Ecotoxicol Environ Saf 60:324–349

Popp M (1995) Salt resistance in herbaceous halophytes and mangroves. Prog Bot 56:415–429

Suñé N, Sánchez G, Caffaratti S, Maine MA (2007) Cadmium and chromium removal kinetics from solution by two aquatic macrophytes. Environ Poll 145(2):467–473

Thomson WW (1975) The structure and function of salt glands. In: Pojkoff Mayber A, Gale J (eds) Biotechnology in agriculture and foresty. Medical and aromatic plant II. Springer, Berlin, pp 118–148

Vymazal J, Brix H, Cooper PF, Green MB, Haberl R (1998) Constructed wetlands for wastewater treatment in Europe. Backhuys, Leiden

Wahl S, Ryser P, Edwards PJ (2001) Phenotypic plasticity of grass root anatomy in response to light intensity and nutrient supply. Ann Bot 88:1071–1078

Westlake DF (1974) Macrophytes. In: Vollenweider RA (ed) A manual on methods for measuring primary production in aquatic environments. IBP Handbook No 12, 2nd edn. International Biological Programme, Blackwell Scientific Publications, Oxford, pp 32–42