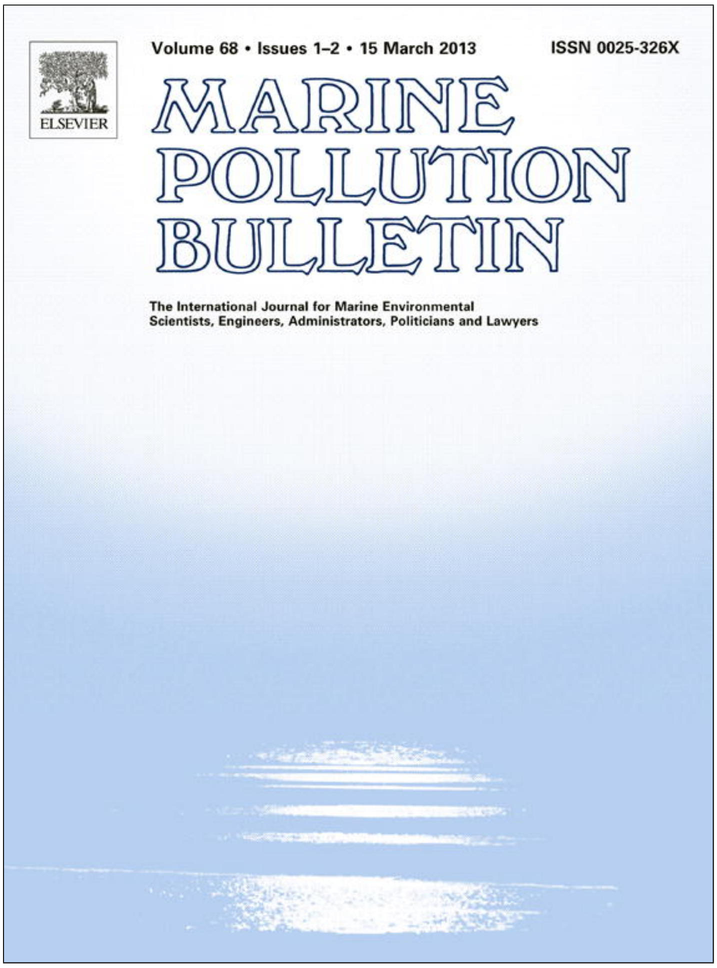
Volume 68 • Issues 1–2 • 15 March 2013
ISSN 0025-326X
ELSEVIER
MARINE POLLUTION BULLETIN
The International Journal for Marine Environmental Scientists, Engineers, Administrators, Politicians and Lawyers

Marine Pollution Bulletin 68 (2013) 147–151

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Trace metal contamination of the aquatic plant *Hydrilla verticillata* and associated sediment in a coastal Alabama creek (Gulf of Mexico – USA)

C. Lafabrie [a,b,*], K.M. Major [c], C.S. Major [c], J. Cebrián [a,b]

[a] *Dauphin Island Sea Lab, 101 Bienville Blvd., Dauphin Island, AL 36528, USA*
[b] *Department of Marine Sciences, University of South Alabama, Mobile, AL 36688, USA*
[c] *Department of Biology, University of South Alabama, Mobile, AL 26688, USA*

A R T I C L E   I N F O

Keywords:
Hydrilla verticillata
Sediment
Chemical contamination
Metal(s)/metalloid(s)
Bioaccumulation
Gulf of Mexico

A B S T R A C T

The objectives of this study were to (i) assess trace metal concentrations in *Hydrilla verticillata* and sediment from an estuarine creek in Alabama (USA), where high metal levels in biota were previously reported, and (ii) investigate the relationship between metal concentrations in *H. verticillata* and the sediment compartment. Our results indicate that sediment and *H. verticillata* exhibit moderate metal concentrations in the study area. We found that levels in plant tissues can be up to five times higher than in the sediment (e.g., Cd), suggesting that *H. verticillata* can take up and store several trace metals (Cd, Hg, Ni, and Zn) from this compartment. Together with studies focused on the uptake and accumulation of trace metals from the surrounding water, laboratory- and field-based studies are needed to better evaluate this plant's ability to acquire metals from the sediment that constitutes a contaminant sink in human-impacted coastal regions.

Human activities in coastal areas introduce significant amounts of trace metals into aquatic environments. Although some of these elements are essential for metabolic and biological processes (e.g., Cu, Fe, Mn, Ni, and Zn), all are toxic to biota above threshold levels (Haynes and Johnson, 2000). Trace metals are important environmental contaminants and their potential toxicity constitutes a problem of increasing significance with ecological, evolutionary, and nutritional implications (Nagajyoti et al., 2010).

Hydrilla verticillata (L.f.) Royle (Hydrocharitaceae) is a submerged aquatic angiosperm that is thought to be native to the warmer regions of Asia (Langeland, 1996). Several studies have investigated its potential with respect to trace metal accumulation and its use for remediation purposes (e.g., Bunluesin et al., 2007; Dixit and Dhote, 2010; Gupta, 1999; Gupta and Chandra, 1994; Kumar et al., 2008b; Sinha and Pandey, 2003; Srivastava et al., 2007; Xue et al., 2010). However, although *H. verticillata* is a rooted plant, the majority of previous studies have focused solely on metal uptake and accumulation from the water column. To date, little information is available regarding this plant's ability to take up and accumulate metals from the sediment. Moreover, the majority of previous studies were laboratory-based. Thus, as reported by other authors (e.g., Srivastava et al., 2007), field studies are required to better estimate and accurately evaluate the ability of *H. verticillata* to accumulate trace metals from contaminated environments.

The objectives of this study were to (i) assess *in situ* trace metal concentrations in *H. verticillata* and sediments in an estuarine creek in Alabama (USA) and (ii) to determine if a relationship exists between trace metal concentrations in plants and those in sediments to improve our knowledge regarding the ability of *H. verticillata* to take up and accumulate trace metals from the sediment compartment.

The present study was conducted in Barner Branch, a spring-fed creek that flows from the east into Fish River, the principal source of freshwater inflow to the Weeks Bay estuary (Mobile Bay, USA, northern Gulf of Mexico; Fig. 1). The Fish River is cited in the Clean Water Act Section 303(d) and is listed as being impaired with respect to mercury (Hg; US EPA, 2008). As a result, a consumption advisory for *Micropterus salmoides* (largemouth bass) caught in this river was issued by the Alabama Department of Public Health (ADPH, 2008). High levels of Hg were reported in biota from the Barner Branch creek (e.g., algal community: Novoveska, 2005; and, *M. salmoides* individuals: Shelton, 2005). Three sampling sites were chosen along a linear transect (running from west to east) to detect any contamination gradient: site 1 was located at the mouth of Barner Branch and closest to the Fish River (N30°27.465′, W87°48.185′), site 2 was mid-way along the transect (N30°27.475′, W87°48.144′), and site 3 was farthest from the mouth of Barner Branch and the Fish River (N30°27.486′, W87°48.114′). The depth of all sampling sites was similar (≈1 m).

H. verticillata plants were collected ($n = 9$ per site; 27 total), washed, cleaned of sediment and periphyton, freeze-dried (6L Labconco Freeze-Dry system, Labconco Corp.), manually ground to

* Corresponding author. Present addresses: IRD - UMR 5119 ECOSYM (Montpellier, France), Faculté des Sciences de Bizerte, 7021 Zarzouna, Tunisia.
E-mail address: celine.lafabrie@ird.fr (C. Lafabrie).

0025-326X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2012.11.045

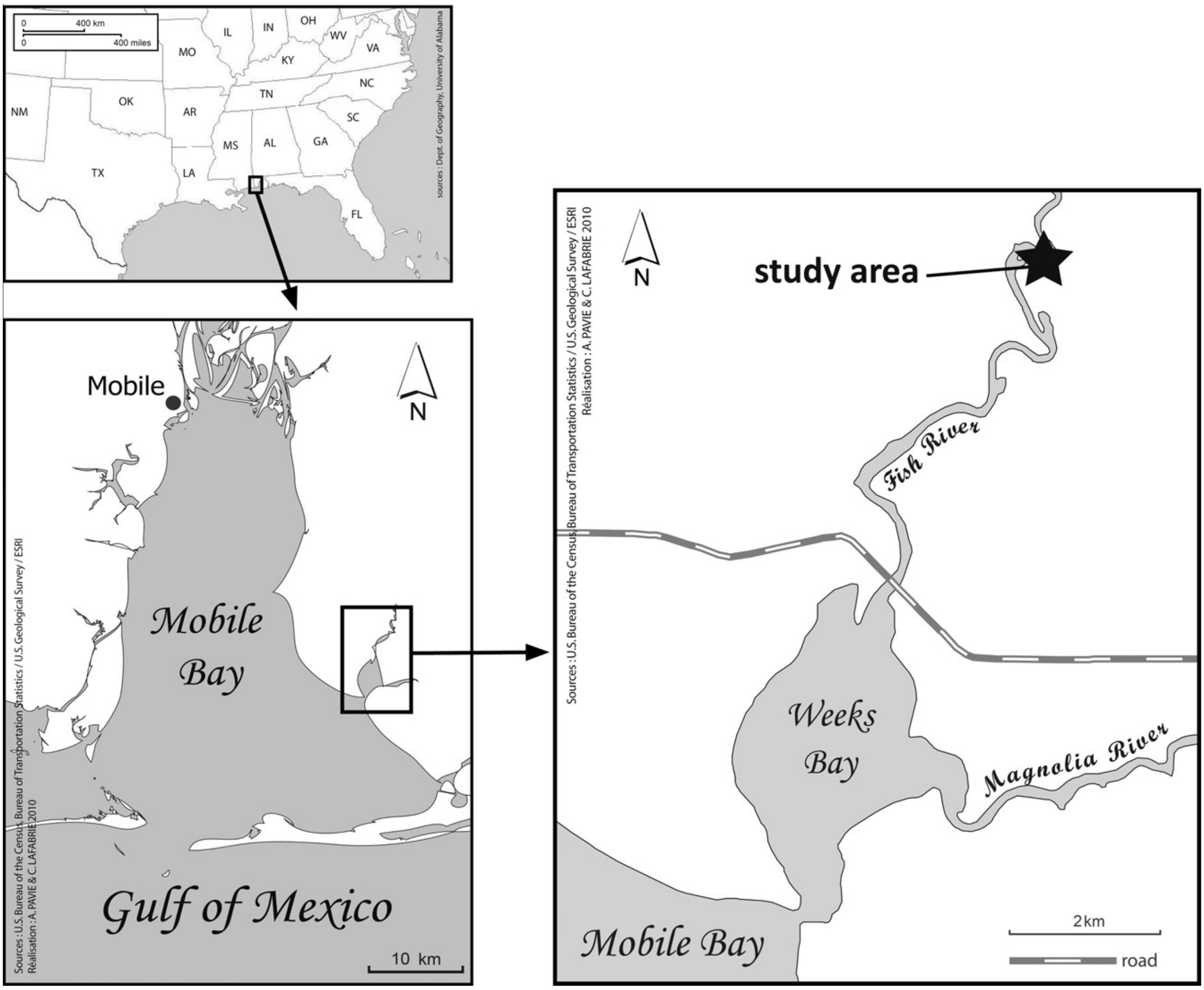

Fig. 1. The Barner Branch study area (Alabama, USA; northern Gulf of Mexico). Physicochemical parameters of the water column during the study period in the Barner Branch study area (mean values): temperature = 24.7 °C, salinity = 0.03‰, dissolved oxygen = 6.29 mg L^{-1}, pH = 6.1, hardness = 13 mg L^{-1} as $CaCO_3$.

coarse powder, and stored until trace metal analyses. Additionally, surficial sediment cores were collected within *H. verticillata* stands ($n = 3$ per site; nine total) using an acrylic plastic corer to avoid contamination (Onuf et al., 1996), cleaned of fauna and plant/wood fragments, freeze-dried (6L Labconco Freeze-Dry system, Labconco Corp.), and stored until trace metal and grain-size analyses were conducted. Trace metal analyses on plants and sediments included arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn); these eight elements are listed as priority pollutants by the US Environmental Protection Agency (US EPA, 2010). As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations were measured by inductively coupled plasma mass spectrometry (ICP-MS) after microwave-digestion of samples in HNO_3/H_2O_2 (Optima grade), with quality assurance procedures at the Trace Element Analysis Core Facility of the Dartmouth College (Hanover, NH, USA). Hg concentrations were determined by the "thermal decomposition – amalgamation – atomic absorption spectrophotometry" process as described in the US EPA Method 7473 (US EPA, 1998), using a Direct Mercury Analyzer 80 (DMA 80, Milestone Inc.) for sediment samples and a Hydra-C DMA (Teledyne Leeman Labs) for plant samples. Standard reference materials (BCR-060 *Lagarosiphon major*, SRM-1547 peach leaves, TORT-2 lobster hepatopancreas, and SRM-2711 Montana soil) were used to verify the analytical procedures and guarantee the reliability of results (mean recoveries were superior to 73%). Sediment grain-size analyses were carried out using the standard pipette and sieve method (Coventry and Fett, 1979).

Significant differences in trace metal concentrations among sites were determined using STATISTICA™'s non-parametric Kruskal–Wallis analysis of variance (ANOVA). The Student–Newman–Keuls multiple comparison test was performed where Kruskal–Wallis ANOVA revealed significant differences. Statistical tests were assessed at the $\alpha = 0.05$ level.

Trace metal concentrations measured in sediments are shown in Table 1. Among all the trace metals assayed, only Cr and Zn significantly differed across sites; site 1, the closest to Fish River, displayed higher levels of contamination than site 2 for both elements (Table 1). Although significant differences were not detected for other elements, concentrations for all trace metals were highest in sediment from site 1 relative to those from sites 2 and 3. Thus, sediment from the mouth of Barner Branch generally appeared to be more metal contaminated than sediments from areas further up the creek. Regardless, based on the guidelines proposed by Long et al. (1995), Cd, Cr, Cu, Ni, Pb, and Zn levels detected in Barner Branch sediments (Table 1) are unlikely to cause adverse biological effects. Indeed, all concentrations are below the ERL ("Effects

Table 1
Trace metal concentrations in sediments (mean ± S.E., in ng g^{-1} dry wt for Hg and μg g^{-1} dry wt for the other elements, $n = 3$).

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Site 1	**8.17 ± 1.80**^{a}	**0.24 ± 0.03**^{a}	**21.54 ± 0.91**^{b}	**16.20 ± 3.12**^{a}	**240.9 ± 65.4**^{a}	**10.22 ± 1.83**^{a}	**22.69 ± 1.66**^{a}	**52.03 ± 11.18**^{b}
Site 2	2.68 ± 0.59^{a}	0.05 ± 0.04^{a}	10.02 ± 0.19^{a}	6.90 ± 0.62^{a}	108.3 ± 20.0^{a}	5.54 ± 0.38^{a}	17.61 ± 1.09^{a}	7.57 ± 3.45^{a}
Site 3	5.78 ± 0.47^{a}	0.11 ± 0.05^{a}	15.68 ± 1.93^{ab}	8.31 ± 1.02^{a}	103.7 ± 15.0^{a}	8.15 ± 0.69^{a}	21.37 ± 3.13^{a}	16.21 ± 4.54^{ab}
Mean	*5.55 ± 0.97*	*0.13 ± 0.04*	*15.75 ± 1.77*	*10.47 ± 1.74*	*151.0 ± 30.2*	*7.97 ± 0.89*	*20.56 ± 1.31*	*25.27 ± 7.71*

Maximum concentrations are in bold. Mean concentrations for all three sites are indicated in the *Mean* row. Concentrations sharing the same letter do not significantly differ ($p \geqslant 0.05$).

Range-Low") threshold values that represent the concentrations below which adverse effects rarely occur ($ERL_{Cd} = 1.2$, $ERL_{Cr} = 81$, $ERL_{Cu} = 34$, $ERL_{Ni} = 20.9$, $ERL_{Pb} = 46.7$, $ERL_{Zn} = 150$ μg g^{-1} dry wt; Long et al., 1995). However, As and Hg levels detected in the sediment from site 3 lie between ERL and ERM ("Effects Range-Medium") threshold values ($ERL_{As} = 8.2$ and $ERM_{As} = 70$ μg g^{-1} dry wt; $ERL_{Hg} = 150$ and $ERM_{Hg} = 710$ ng g^{-1} dry wt; Long et al., 1995), and could potentially cause adverse biological effects. Additionally, Hg sediment concentrations in Barner Branch were high when compared to those reported for neighboring areas (mean value of the present study: 151.0 ± 30.2 ng g^{-1} dry wt, Table 1; value found in Fish River in August 2008: 72.7 ± 11.6 ng g^{-1} dry wt, Lafabrie et al., 2011; range of values found across sub-estuaries of the lower Mobile Bay Delta in August 2008: 9.7 ± 1.8–47.2 ± 3.6 ng g^{-1} dry wt, Lafabrie et al., 2011). Sediment grain size did not differ among sites and were primarily comprised of fine particles (clay + silt: 66–69%).

Trace metal concentrations found in *H. verticillata* are shown in Table 2. As, Cd and Zn concentrations were significantly higher in plants collected from site 1 than site 2, with intermediate values determined for those from site 3. Pb concentrations were significantly higher in plants collected from site 1 than site 3, with intermediate values determined for those from site 2. Cu concentrations were significantly higher in plants from site 1 than plants from either sites 2 or 3. In contrast, Hg concentrations were higher in plants from sites 2 and 3 than those collected from site 1, while Ni concentrations were higher in plants from site 3 than those from sites 1 and 2. Similar to sediment data, *H. verticillata* plants from the mouth of Barner Branch generally appeared to be more metal contaminated than those from other areas further up the creek. When compared to previously published data, trace metal concentrations in *H. verticillata* plants from Barner Branch lie well within the range of published values (Table 3). For instance, our concentrations for the non-essential elements Pb and Hg fall below those found in a fly-ash contaminated area in India (National Thermal Power Corporation; Dwivedi et al., 2008), while our values for Zn are above those reported in the same study (Table 3). Although the Cd, Cu, and Zn concentrations reported for Barner Branch are lower than those found in the Kanewal Community Reserve (India; Kumar et al., 2008a), values for Ni and Pb are similar between studies (Table 3). Finally, values reported herein for Cu, Pb, and Zn are lower, while Cd and Ni are higher when compared to values measured in the Pariyej Community Reserve (India; Kumar et al., 2008b; Table 3). Such comparisons suggest that *H. verticillata* plants growing in Barner Branch contain moderate amounts of trace metals relative to other locations.

As *H. verticillata* is a rooted aquatic plant, trace metal uptake can occur from the water column (via leaves and stems) and sediment (via roots). Roots are thought to be more important for trace metal uptake than leaves and stems (Jackson, 1998), mainly because the sediment compartment constitutes a sink for contaminants. The general view is that plants would primarily extract trace metals from the sediment with subsequent translocation to aboveground tissues (Jackson, 1998). For each trace metal, the biota-sediment accumulation factor (BSAF) was calculated using the following formula: $BSAF = C_x/C_s$, where C_x is the mean concentration in the organism (i.e., *H. verticillata*) and C_s is the mean concentration in the sediment (Szefer et al., 1999). The BSAF is an indicator of an organism's ability to take up and accumulate trace metals that are present in the sediment. In our study, BSAF values ranged from 0.1 (Cr and Pb) to 5.3 (Cd; Fig. 2). These values suggest the potential exists for *H. verticillata* to take up and accumulate Cd, Hg, Ni, and Zn from sediments (BSAF values >1). Uptake and accumulation of these elements from the surrounding water have also been reported to occur in this plant (Table 4). Concerning As, Cr, Cu, and Pb, our BSAF values (<1) suggest limited plant uptake from sediment with respect to these particular elements. It is likely that *H. verticillata* has a higher capacity to uptake and accumulate As, Cr, Cu, and Pb from the water column than from the sediment (Table 4). A recent laboratory experiment by Xue et al. (2010) showed that Cu accumulation ability of aboveground tissues was much higher than that of belowground tissues in *H. verticillata*, providing further support for an element-specific strategy with respect to uptake and accumulation of trace metals (i.e., some trace metals would be more readily taken up by aboveground organs, while others would be more likely to enter the plant via belowground structures). Furthermore, some noted differences in plant uptake and accumulation are likely attributed to the impact of sediment grain-size on contaminant bioavailability. Biogeochemical and physico-chemical processes also play important roles in the adsorption onto or release of contaminants from sediment particles and, thus, influence the availability to biota. Therefore, in addition to research investigating the uptake and accumulation capacity of trace metals by *H. verticillata* from the surrounding water, laboratory- and field-based studies are needed to better evaluate the uptake and accumulation capacity of trace metals by *H. verticillata* from the sediment compartment that is viewed as a sink of contaminants in human-impacted areas.

Table 2
Trace metal concentrations in *H. verticillata* (mean ± S.E., in ng g^{-1} dry wt for Hg and μg g^{-1} dry wt for the other elements, $n = 9$).

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Site 1	**2.28 ± 0.27**^{b}	**0.86 ± 0.05**^{b}	**0.93 ± 0.10**^{a}	**7.02 ± 0.47**^{b}	97.3 ± 4.4^{a}	8.77 ± 0.63^{a}	**1.63 ± 0.16**^{b}	**112.88 ± 6.66**^{b}
Site 2	1.17 ± 0.09^{a}	0.56 ± 0.03^{a}	0.70 ± 0.06^{a}	3.18 ± 0.12^{a}	288.4 ± 34.4^{b}	10.56 ± 0.48^{a}	1.19 ± 0.17^{ab}	88.87 ± 2.43^{a}
Site 3	1.61 ± 0.16^{ab}	0.69 ± 0.05^{ab}	0.88 ± 0.05^{a}	4.20 ± 0.21^{a}	**414.0 ± 48.0**^{b}	**18.24 ± 1.57**^{b}	0.79 ± 0.07^{a}	95.57 ± 3.88^{ab}
Mean	*1.69 ± 0.14*	*0.70 ± 0.03*	*0.84 ± 0.04*	*4.80 ± 0.36*	*266.56 ± 31.8*	*12.52 ± 0.98*	*1.21 ± 0.10*	*99.10 ± 3.26*

Maximum concentrations are in bold. Mean concentrations for all three sites are indicated in the *Mean* row. Concentrations sharing the same letter do not significantly differ ($p \geqslant 0.05$).

Table 3
Trace metal concentrations (mean, in µg g^{-1} dry wt) reported in field-based studies for *H. verticillata* plants.

As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Reference
				1.51		175	32	Dwivedi et al. (2008)[a]
	40.00		17.65		14.26	1.37	160.17	Kumar et al. (2008a)[b]
	0.15		16.32		4.84	7.16	457.68	Kumar et al. (2008b)[c]
	4.1/0.10		38.6/3.6	0.2/bdl		32.5/27.5		Mishra et al. (2008)[d]
		4.34[e]					691	Rai (2009)[e]
1.69	0.70	0.84	4.80	0.26	12.52	1.21	99.10	This work[f]

[a] Study conducted in fly-ash contaminated areas situated around the National Thermal Power Corporation, Tanda, Uttar Pradesh, India.
[b] Study conducted in Kanewal Community Reserve, Gujarat, India.
[c] Study conducted in Pariyej Community Reserve, Gujarat, India (considered as contaminated by authors).
[d] Study conducted in the anthropogenic lake of Govind Ballabh Pant Sagar (India) receiving several coal mining effluents (one of Asia's largest man-made reservoirs) – the first and second values given correspond to concentrations measured in roots and leaves, respectively (bdl: below detection limit).
[e] Study conducted in Rihand dam, in the surrounding of Govind Ballabh Pant Sagar, India (considered to be a reference site by authors).
[f] Values correspond to mean of three sites.

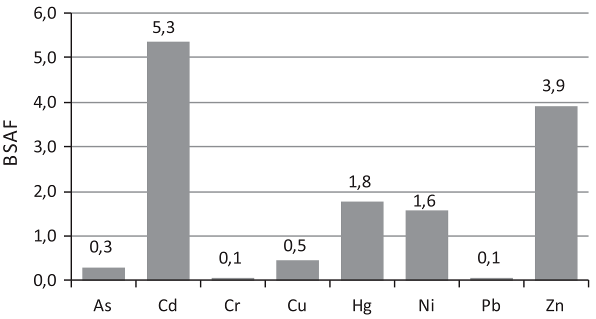

Fig. 2. Biota-sediment accumulation factor (BSAF = C_x/C_s, where C_x = mean concentration in the organism, i.e., *H. verticillata*, $n = 27$; C_s = mean concentration in the sediment, $n = 9$).

Table 4
Laboratory experiments that report uptake and accumulation of trace metals by *H. verticillata* from surrounding water.

As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Reference
	X							Bunluesin et al. (2004)
	X							Bunluesin et al. (2007)
		X				X	X	Dixit and Dhote (2010)
						X		Gallardo-Williams et al. (2002)
						X		Gupta and Chandra (1994)
				X				Gupta and Chandra (1996)
			X					Gupta et al. (1996)
				X				Gupta et al. (1998)
				X		X		Gupta (1999)
			X			X	X	Nesterov et al. (2009)
	X	X						Rai et al. (1995)
		X						Sinha et al. (1993)
					X			Sinha and Pandey (2003)
			X					Srivastava et al. (2006)
X								Srivastava et al. (2007)
							X	Srivastava et al. (2009)
X								Srivastava et al. (2010)
			X					Xue et al. (2010)

In conclusion, this study contributes to our knowledge of the nature and magnitude of trace metal uptake and accumulation in the aquatic plant, *H. verticillata*. Our study is novel in that it simultaneously examines the concentrations of eight trace metals in plant tissues and associated sediment in the field, across an apparent gradient of metal contamination. Our results show that *H. verticillata* has the ability to take up and store a number of trace elements from the sediment: Cd, Hg, Ni, and Zn. In many areas (including the state of Alabama, USA), *H. verticillata* is considered to be an invasive, noxious weed. It forms dense stands that can be both economically and ecologically costly by affecting water quality and flow, displacing native aquatic plant species, and adversely impacting aquatic foodweb dynamics (AL ANS Management Plan, 2007; Langeland, 1996; Simberloff et al., 1997). Thus, *H. verticillata* could be an attractive candidate for bioremediation projects in polluted environments where it is considered to be a pest. Indeed, harvesting *H. verticillata* would likely result in (i) the improvement of water quality, (ii) limited transfer of heavy metals (e.g., via the detrital food web and deposit feeders) to higher trophic levels, and (iii) the ultimate removal of an invasive pest. Furthermore, *Hydrilla* is an important model for the investigation of the role that pollution tolerance plays in invasive plant success. Future studies should consider translocation phenomena (flux of contaminants among different parts of the plant, i.e., roots, stem, leaves) and how they relate to contaminant scavenging and detoxification mechanisms in *Hydrilla* and other stress-tolerant taxa as we strive to better understand and characterize the biology and ecology of invasive plants.

Acknowledgements

This research was supported by a Grant from the Alabama Center for Estuarine Studies (**R83-0651), a Center supported by the U.S. Environmental Protection Agency (USA), and a grant from the "Collectivité Territoriale de Corse" (France). The authors thank Drs. D. Haywick and E. Cioffi, from the University of South Alabama, for their assistance with sediment analyses and access to analytical instruments, respectively; Dr. D.W. Evans, from NOAA, for his help with some metal analyses; and Dr. S. Phipps and E. Brunden, from the Weeks Bay NERR, for their assistance in the field. Additionally, we wish to thank S. Glenos, M. Mintz-Miller, K. VanDeven, B. Christiaen, J. Goff, L. Marino, L. Moore, and A. McDonald for their assistance in the field and/or laboratory. We also thank the anonymous reviewers for their helpful comments and suggestions that improved this manuscript.

References

ADPH, 2008. Alabama Fish Consumption Advisories. Alabama Department of Public Health, <http://www.adph.org/tox/assets/2008_FishAdvisory.pdf> (12.20.10).
AL ANS Management Plan, 2007. Alabama division of wildlife and freshwater fisheries. Alabama Aquatic Nuisance Species Management Plan. Developed by the Alabama Aquatic Nuisance Species Task Force.
Bunluesin, S., Kruatrachue, M., Pokethitiyook, P., Lanza, G.R., Upatham, E.S., Soonthornsarathool, V., 2004. Plant screening and comparison of Ceratophyllum demersum and Hydrilla verticillata for cadmium accumulation. Bull. Environ. Contam. Toxicol. 73, 591–598.
Bunluesin, S., Kruatrachue, M., Pokethitiyook, P., Upatham, S., Lanza, G.R., 2007. Batch and continuous packed column studies of cadmium biosorption by *Hydrilla verticillata* biomass. J. Biosci. Bioeng. 103, 509–513.
Coventry, R.J., Fett, D.E.R., 1979. A Pipette and Sieve Method of Particle Size Analysis and Some Observations on its Efficiency, 38 ed. Commonwealth Scientific Industrial Research Organisation Division of Soils Report.

Dixit, S., Dhote, S., 2010. Evaluation of uptake rate of heavy metals by *Eichhornia crassipes* and *Hydrilla verticillata*. Environ. Monit. Assess. 169, 367–374.

Dwivedi, S., Srivastava, S., Mishra, S., Dixit, B., Kumar, A., Tripathi, R.D., 2008. Screening of native plants and algae growing on fly-ash affected areas near National Thermal Power Corporation, Tanda, Uttar Pradesh, India for accumulation of toxic heavy metals. J. Hazard. Mater. 158, 359–365.

Gallardo-Williams, M.T., Whalen, V.A., Benson, R.F., Martin, D.F., 2002. Accumulation and retention of lead by cattail (*Typha domingensis*), hydrilla (*Hydrilla verticillata*), and duckweed (*Lemna obscura*). J. Environ. Sci. Health., Part A 37, 1399–1408.

Gupta, M., 1999. Effect of lead and mercury on changes in protein profile in the aquatic macrophytes *Hydrilla verticillata* (lf) Royle and *Vallisneria spiralis* L. J. Environ. Sci. Health., Part A 34, 1093–1104.

Gupta, M., Chandra, P., 1994. Lead accumulation and toxicity in *Vallisneria spiralis* (L) and *Hydrilla verticillata* (Lf) Royle. J. Environ. Sci. Health., Part A 29, 503–516.

Gupta, M., Chandra, P., 1996. Bioaccumulation and physiological changes in *Hydrilla verticillata* (Lf) royle in response to mercury. Bull. Environ. Contam. Toxicol. 56, 319–326.

Gupta, M., Sinha, S., Chandra, P., 1996. Copper-induced toxicity in aquatic macrophyte, *Hydrilla verticillata*: effect of pH. Ecotoxicology 5, 23–33.

Gupta, M., Tripathi, R.D., Rai, U.N., Chandra, P., 1998. Role of glutathione and phytochelatin in *Hydrilla verticillata* (lf) Royle and *Vallisneria spiralis* L. under mercury stress. Chemosphere 37, 785–800.

Haynes, D., Johnson, J.E., 2000. Organochlorine, heavy metal and polyaromatic hydrocarbon pollutant concentrations in the Great Barrier Reef (Australia) environment: a review. Mar. Pollut. Bull. 41, 267–278.

Jackson, L.J., 1998. Paradigms of metal accumulation in rooted aquatic vascular plants. Sci. Total Environ. 219, 223–231.

Kumar, J.I.N., Soni, H., Kumar, R.N., 2008a. Evaluation of biomonitoring approach to study lake contamination by accumulation of trace elements in selected aquatic macrophytes: a case study of Kanewal Community Reserve, Gujarat, India. Appl. Ecol. Environ. Res. 6, 65–76.

Kumar, J.I.N., Soni, H., Kumar, R.N., Bhatt, I., 2008b. Macrophytes in phytoremediation of heavy metal contaminated water and sediments in Pariyej Community Reserve, Gujarat, India. Turk. J. Fish. Aquat. Sci. 8, 193–200.

Lafabrie, C., Major, K., Major, C.S., Cebrián, J., 2011. Arsenic and mercury bioaccumulation in the aquatic plant, *Vallisneria neotropicalis*. Chemosphere 82, 1393–1400.

Langeland, K.A., 1996. *Hydrilla verticillata* (L.F.) Royle (Hydrocharitaceae), "The Perfect aquatic Weed". Castanea 61, 293–304.

Long, E.R., Macdonald, D.D., Smith, S.L., Calder, F.D., 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environ. Manage. 19, 81–97.

Mishra, V.K., Upadhyay, A.R., Pandey, S.K., Tripathi, B.D., 2008. Concentrations of heavy metals and aquatic macrophytes of Govind Ballabh Pant Sagar an anthropogenic lake affected by coal mining effluent. Environ. Monit. Assess. 141, 49–58.

Nagajyoti, P.C., Lee, K.D., Sreekanth, T.V.M., 2010. Heavy metals, occurrence and toxicity for plants: a review. Environ. Chem. Lett. 8, 199–216.

Nesterov, V.N., Rozentsvet, O.A., Murzaeva, S.V., 2009. Changes in lipid composition in the tissues of fresh-water plant *Hydrilla verticillata* induced by accumulation and elimination of heavy metals. Russ. J. Plant. Physiol. 56, 85–93.

Novoveska, L., 2005. Benthic algal community structure and bioaccumulation of mercury in a coastal watershed. Thesis/Dissertation, Master of Science, Eastern Illinois University Charleston, Illinois (USA).

Onuf, C.P., Chapman, D.C., Rizzo, W.M., 1996. Inexpensive, easy-to-construct suction goring devices usable from small boats. J. Sediment. Res. 66, 1031–1032.

Rai, P.K., 2009. Heavy metals in water, sediments and wetland plants in an aquatic ecosystem of tropical industrial region, India. Environ. Monit. Assess. 158, 433–457.

Rai, U.N., Tripathi, R.D., Sinha, S., Chandra, P., 1995. Chromium and cadmium bioaccumulation and toxicity in *Hydrilla verticillata* (Lf) Royle and Chara corallina Wildenow. J. Environ. Sci. Health., Part A 30, 537–551.

Shelton, M., 2005. Mercury monitoring in largemouth bass tissue in the Weeks Bay watershed – Mobile Bay National Estuary Program report. Weeks Bay Reserve, Alabama Department of Conservation and Natural Resources, State Lands Division, Coastal Section.

Simberloff, D., Schmitz, D.C., Brown, T.C., 1997. Strangers in Paradise: Impacts and Management of Nonindigenous Species in Florida. Island Press.

Sinha, S., Pandey, K., 2003. Nickel induced toxic effects and bioaccumulation in the submerged plant, *Hydrilla verticillata* (L.F.) Royle under repeated metal exposure. Bull. Environ. Contam. Toxicol. 71, 1175–1183.

Sinha, S., Rai, U.N., Tripathi, R.D., Chandra, P., 1993. Chromium and manganese uptake by *Hydrilla verticillata* (If) Royle – amelioration of chromium toxicity by manganese. J. Environ. Sci. Health., Part A 28, 1545–1552.

Srivastava, S., Mishra, S., Tripathi, R.D., Dwivedi, S., Gupta, D.K., 2006. Copper-induced oxidative stress and responses of antioxidants and phytochelatins in *Hydrilla verticillata* (L.f.) Royle. Aquat. Toxicol. 80, 405–415.

Srivastava, S., Mishra, S., Tripathi, R.D., Dwivedi, S., Trivedi, P.K., Tandon, P.K., 2007. Phytochelatins and antioxidant systems respond differentially during arsenite and arsenate stress in *Hydrilla verticillata* (L.f) Royle. Environ. Sci. Technol. 41, 2930–2936.

Srivastava, S., Mishra, S., Dwivedi, S., Tripathi, R.D., Tandon, P.K., Gupta, D.K., 2009. Evaluation of zinc accumulation potential of *Hydrilla verticillata*. Biol. Plant. 53, 789–792.

Srivastava, S., Mishra, S., Dwivedi, S., Tripathi, R.D., 2010. Role of thiol metabolism in arsenic detoxification in *Hydrilla verticillata* (L.f.) Royle. Water, Air, Soil Pollut. 212, 155–165.

Szefer, P., Ali, A.A., Ba-Haroon, A.A., Rajeh, A.A., Geldon, J., Nabrzyski, M., 1999. Distribution and relationships of selected trace metals in molluscs and associated sediments from the Gulf of Aden. Yemen. Environ. Pollut. 106, 299–314.

US EPA, 1998. Method 7473 – Mercury in solids and solutions by thermal decomposition, amalgamation, and atomic absorption spectrophotometry. United States Environmental Protection Agency.

US EPA, 2008. Alabama 2008 Water Quality Assessment Report. United States Environmental Protection Agency, <http://iaspub.epa.gov/waters10/attains_index.control?p_area=AL> (20.12.10).

US EPA, 2010. Priority pollutants. United States Environmental Protection Agency, <http://water.epa.gov/scitech/swguidance/methods/pollutants.cfm> (31.12.10.).

Xue, P.Y., Li, G.X., Liu, W.J., Yan, C.Z., 2010. Copper uptake and translocation in a submerged aquatic plant *Hydrilla verticillata* (L.f.) Royle. Chemosphere 81, 1098–1103.