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American Wildcelery, *Vallisneria americana*, as a Biomonitor of Organic Contaminants in Aquatic Ecosystems

Lesley Lovett Doust, Jon Lovett Doust, and Maciej Biernacki

Biological Sciences
University of Windsor
Windsor, Ontario, N9B 3P4

ABSTRACT. *This paper assesses the value of American wildcelery,* Vallisneria americana, *as a biomonitor of organochlorine contamination. Plants provide a valuable indicator of local environmental conditions and sub-lethal effects of contaminants on growth and reproduction provide a means of assessing both acute and chronic contaminant effects. In a field survey,* Vallisneria *plants in the St. Clair and Detroit rivers were found to accumulate significant amounts of organochlorine contaminants, and the concentration increased over the season. Root tissue contained the highest concentrations on each occasion, suggesting contaminant transfer occurred from sediments to the roots. A factorial experiment was set up at two stations in the channel connecting Lakes Huron and Erie to assess the separate effects of contaminant concentrations in the sediment, water column, and source population of the plants, upon growth and reproduction of* Vallisneria *plants. Contaminant concentrations in sediment and plant tissues were also measured to correlate contaminant content and demographic effects. A clear relationship between exposure to contaminants and effect (on plant performance) was observed. Results indicated that exposure first to the water column, and secondarily to the sediments from the more contaminated site had detrimental effects on plant performance and survival. Plants at each site appeared to be locally adapted and differed in their apparent resistance to organochlorine contaminants. An "**impairment index**" (reflecting relative plant performance) was calculated and can be used to calibrate the degree of contamination of different sites relative to a "clean" reference site. This may allow prioritization of remediation of contaminated sites, and should allow field managers to track and document the restoration of environmental quality in recognized Areas of Concern in the Great Lakes.*

INDEX WORDS: *Biomonitor, macrophyte,* Vallisneria americana, *organochlorine contaminants, Great Lakes.*

INTRODUCTION

Past evaluations of water quality in contaminated natural environments have focused on direct chemical measurement of the concentration of toxic and carcinogenic substances. However, for environmental management and protection of human health, contaminant concentrations do not necessarily account for, or enable prediction of, the impairment of biota. If the objective is to monitor and improve environmental quality for the biota, and to assess potential risks of human exposure, biotic measures of contamination are sometimes more useful than measures of ambient contaminant concentrations. Furthermore, the cost of evaluation and measurement of contaminants, particularly persistent, toxic organochlorines, is substantial, and is generally impractical for routine monitoring programs. Therefore, for ecological and economic reasons, it is important to develop biological monitors of environmental quality that are useful and valuable.

The presence of indicator organisms provides a measure of cumulative exposure to contaminants over time and avoids the need for frequent sampling. Furthermore, the use of a biomonitor removes concerns about the bioavailability of contaminants that must be dealt with if only water or sediments are sampled.

Scientists model contaminant dynamics in aquatic ecosystems by measuring rates of change in contaminant concentrations in various plant and animal tissues. Plants form the basis of both the herbi-

vore and detrital food webs, so they are a likely pathway for contaminant movement between trophic levels. Nevertheless, most models of contaminant trophic transfer do not yet explore in detail the role of plants (but see Gobas *et al.*1991).

Plants are good biomonitors of environmental conditions in aquatic ecosystems. Many macrophytes are capable of extensive clonal growth; thus genotype can be held constant. To evaluate environmental conditions, this means that genetically identical individuals can be deployed at numerous sites and the effect of environmental conditions clearly evaluated. In addition, genetically identical replicates can be deployed at a single site, and harvested regularly over the period of study to measure both acute and chronic exposure to contamination. Depending on the contaminant, rates of bioaccumulation in plants may be very high. For example, PCB levels can be 3–4 times higher in plants than in sediment, and 6,000–9,000 times higher in plants than in the water around them (on a dry weight basis) (Painter 1990).

Most of the existing biomonitoring studies have involved using caged animals that are recovered after some specific period of exposure. However, in addition to the complication of genetic variation among individuals, there is always a concern that cages may create unnatural conditions, particularly for filter feeders that need to maintain their own local water currents, and for animals that normally range freely. Plants, unlike animals, do not need to be caged in order to keep them in the same area, which obviates some of the problems that arise with animal biomonitors. Indeed plants are likely to be superior biomonitors of point source impact zones (PSIZ), as described in the Revised Great Lakes Water Quality Agreement (Government of the United States and Government of Canada 1987). In the highly contaminated areas identified by the International Joint Commission (IJC) as Areas of Concern, plants can monitor cumulative exposure at a particular location.

In the field, plants are exposed to the complex array of chemicals and to the physical and biological conditions that exist at different locations. If a biomonitor experiment is to be useful, it has to discriminate between effects that are due to properties of hydrology and sediment, and the geographic location itself (which may encompass various factors, such as latitude and geology).

The present study evaluates plants as biomonitors of organochlorine contamination, and correlates plant growth and both sexual and asexual reproduction with the degree of contamination of the water column and sediments. Our objective was to use plant growth to measure the degree of contamination in different sites or treatments, and to correlate the amount of growth with the actual measured contaminant content of the plants.

MATERIALS AND METHODS

The present study involves plants growing naturally, and planted experimentally at two sites in the Detroit and St. Clair rivers, both recognized as areas of concern by the IJC (Hartig and Thomas 1988). Specifically, plant populations were examined in the Chenal Ecarte in the delta of the St. Clair River, 37 km downstream of Sarnia and the petrochemical industrial region known locally as "Chemical Valley," and the population adjacent to Turkey Island in the Detroit River.

Vallisneria americana is a dioecious, aquatic macrophyte that can propagate both through sexual reproduction and through clonal growth (Titus and Stephens 1983, Lovett Doust and Laporte 1991). It overwinters as a turion (swollen bud on the buried stolon), a storage structure that is rich in carbohydrates. The plant clones by producing connected daughter plants, "ramets," which can spread to occupy large areas (Lovett Doust and Laporte 1991). Elsewhere (Biernacki *et al.* 1994) we have described the effects of the organochlorine, trichloroethylene, on *Vallisneria americana*. That study was made on plants from the same two sites, however they were raised under controlled conditions in the greenhouse, in 40-L glass tanks.

Contaminant Distribution in Two Natural (Undisturbed) Populations of *Vallisneria americana*

In spring (May), summer (July), and fall (October) of 1991, 20 samples of plants from each site ("Turkey Island" and "Ecarte") were taken at random from the submerged macrophyte bed. The samples were kept in an iced cooler, and returned to the lab where they were stored in hexane-washed aluminum foil at –80°C until analysis for organochlorine contaminants. Each plant was divided into the following three tissue categories: 1. turion (the overwintering storage organ) plus stolon (the organ of clonal growth); 2. root; and 3. leaf. Tissues from the 20 replicates were pooled for the purposes of organochlorine analysis.

The proportion of lipid contained in each plant tissue was measured separately for each sample. Percent lipid was determined gravimetrically, i.e., it was assessed in terms of the increment in mass of the extracting solution following extraction of the

fraction of each plant sample (of known mass) that was dichloromethane (DCM)/hexane-extractable. Obviously the organization of lipid distribution in plants is rather different from that found in animal tissues. Rather than containing localized fatty deposits and having some tissues of high lipid content as in animals, plants contain relatively low and evenly distributed lipid fractions, much of it found in cellular membranes and leaf cuticle (although the cuticle is very thin in *Vallisneria* as it is a submerged plant). It is therefore very important to ensure that the extracting solution has access to, and sufficient time to penetrate, all regions where lipids are present. Since the percent lipid was known, it was possible, for each sample, to calculate lipid-corrected values for each contaminant. The average percent lipid for our plant tissues was 0.16; this is 1–2 orders of magnitude lower than the lipid content of most animal tissues.

Contaminant Distribution in Experimental Transplants and Replants in Two Populations of *Vallisneria americana*

In addition to the study of plants growing naturally at each site, further samples of *Vallisneria* were taken from the experimental tubs at Turkey Island and Ecarte (see experimental design, below). Plants were again partitioned into their respective tissues (turion, root, stolon, and leaf), and sampled separately in terms of the following eight categories: plants originating from Turkey Island placed in Turkey Island sediment at the Ecarte site; those placed in Turkey Island sediment at the Turkey Island site; in Ecarte sediment at the Ecarte site; or in Ecarte sediment at the Turkey Island site. Similarly, plants originating from the Ecarte site were taken from tubs in which they were growing in Turkey Island sediment at the Ecarte site; or in Turkey Island sediment at the Turkey Island site; in Ecarte sediment at the Ecarte site; and in Ecarte sediment at the Turkey Island site. Tubs were sampled on two occasions, in July and September 1991.

Organochlorine residues in plants from each treatment were analyzed to determine whether impairment of growth and reproduction (see below, under Design of the Reciprocal-Transplant-Replant Experiment) was associated with contaminant content.

Analytical Procedure

The procedures used here are based on those described in Gobas *et al.*, (1991). All sample extracts from the field and experimental sites were analyzed using gas chromatography and electron capture detection (GC/ECD) for the presence and concentrations of penta- and hexachlorobenzene (QCB, HCB), octachlorostyrene (OCS), trans-nonachlor, 1,1-dichloro-2,2-bis(p-chlorophenyl)-ethylene (pp'-DDE), and a number of polychlorinated biphenyls (PCBs [PCB numbering scheme from Ballschmiter and Zell 1980]). A Hewlett-Packard Model 5790A capillary column GC-ECD fitted with a 15m × 0.25 mm fused silica column containing a cross-linked DB-1 stationary phase (supplied by J & W Scientific, Rancho Cordova, CA) was used for the analysis, performed by the Great Lakes Institute, University of Windsor. A Hewlett-Packard auto-injector and a model 3390 A integrator completed the apparatus.

Each sample was extracted in a solvent mixture of DCM:hexane (1:1 by volume), then concentrated to an approximate volume of 2 mL, which was then passed to the florisil clean-up procedure, evaporated again, made up to a suitable volume with hexane, cleaned on activated copper powder (to remove sulfur-containing secondary plant substances), and analyzed by GC/ECD. Earlier macrophyte samples, in the first instance, contained two peaks that corresponded to organic sulphur-containing compounds. In the copper clean-up procedure, approximately 0.5 g of activated copper powder was added to the 5 mL volumetric flask. The solution was carefully vortexed for 1–2 min, and then stored in a refrigerator at 4°C for 24 h before GC/ECD analysis.

Two experiments were performed simultaneously to assess the recovery of separated compounds using 10 g of "clean" macrophyte samples spiked with a standard spiking "cocktail" solution. The mixture was left for 1 h to ensure the contaminants were absorbed onto the tissue, then the sample was prepared in the manner described above, for regular samples. All compounds were found to show 85–110% recovery efficiencies. The standard used for quantification of samples was a standard mixture solution containing 10 organochlorine compounds, and Arochlor mixture 1242:1254:1260 in the ratio 1:1:1, provided by the Canadian Wildlife Service (CWS) Laboratories.

Quantification of each compound was achieved by comparing the sample peak areas with the standard peak areas from the CWS-Standard Solution, which contained the same compounds at known concentrations. This calibration is repeated every month, and quality control verification is made in-

dependently every 3 months. The limit of detection (LOD) for these compounds was determined in a concurrent study involving clam and fish analyses. Comparisons with the baseline study indicated that if concentrations were <0.01 ng/g (0.01 μg/kg) they were below the detection limits of the procedure.

In order to verify calibration of the organochlorine analysis system at the Great Lakes Institute Analytical Laboratory (GLI) at the University of Windsor, standards provided by the Canadian Wildlife Service (CWS-Standard Solutions, see above) were run every month (in round-robin comparisons of QA/QC at Canadian government, commercial, and academic analytical laboratories, the GLI lab has ranked first for the past several years). Duplicate samples were run on every tenth sample for the present study. The variation in the results for the duplicate samples did not exceed 1% of the mean of the two values.

Design of the Reciprocal-Transplant-Replant Experiment

In the past, most studies of toxicity have been based on identification of lethal doses; the goal then was to measure how much contaminant corresponded to standardized mortality, for example the LD_{50} (lethal dose) or LC_{50} (lethal concentration), where 50% of individuals died. However, plants may:

1. Increase/decrease overall rate of growth (including clonal growth) as determined by biomass, stolon, and ramet production
2. Increase/decrease rate of production and turnover of leaves
3. Change their relative rates of sexual reproduction and clonal growth
4. Die

The present field experiment was designed to enable us to evaluate *sublethal* effects of (a) sediment type; (b) water column (i.e., living at one site or an other); (c) the site of origin of a particular plant; and (d) time since setup of the experiment, on growth, survivorship, and reproduction of *Vallisneria* using analysis of variance, and to assess the relative importance of each of the main factors (above), as well as their interactions.

In September 1990 a total of 800 *Vallisneria* plants, 400 originating from each of the two sites, was deployed. Plants were contained in plastic tubs (51 × 38 × 11 cm; 10 plants/tub). Half of the tubs were placed at each of the two sites. The first site was on the Chenal Ecarte of the St. Clair River, east of Walpole Island between Port Lambton and Wallaceburg, Ontario (42°37'N, 82°28'W). The second site was approximately 86 km downstream, on the western shore of Turkey Island (42°11'N, 83°28'W), downstream of Fighting Island in the Detroit River, and approximately 7 km upstream of Lake Erie. Tubs containing plants were set in the sediment surface.

In a factorial design, plants from each site were grown in tubs, each containing one of the two sediment types. Their leaves extended in the water column flowing at each site. Thus, at each site there were 40 tubs, 20 filled with sediment from the Turkey Island site and 20 with sediment from the Ecarte site, and each tub contained 10 plants (genetic individuals, or genets, made up, initially, of a single ramet, or rosette).

All of the tubs were permanently marked according to source of sediment and plant origin so they could be identified each time we returned. Measurements were made of plant survival, clonal growth (production of new shoots via stolons) and leaf number, regularly throughout the year, and on two occasions (22 July, and 15 September 1991) destructive harvests were made and patterns of biomass allocation and contaminant content were determined.

The replicated factorial experimental design allowed analysis of variance of all aspects of plant growth and performance, and where ANOVA indicated significant factors or interactions, follow-up tests of comparison of means (Duncan's multiple range test) were performed.

RESULTS

Contaminant Distribution in Two Natural (Undisturbed) Populations of *Vallisneria americana*

We first verified that contaminant content of plants in the field was measurable by GC/ECD scanning. It was evident that the macrophytes accumulate significant amounts of organochlorines *in situ*, and that these increase over the growing season.

In May (before leaves had been produced from the overwintering turion) most contaminants were concentrated in roots (Tables 1, 2); the levels were higher for HCB, OCS, pp'-DDE, and the Arochlor mix of PCBs in plants at Ecarte than at Turkey Island. By the end of June-early July, leaves contained measurable amounts of contaminants, but roots still contained the highest concentrations, and plants from Ecarte were more heavily contaminated. By October, when female plants were in fruit, again roots contained the highest levels of contaminants,

TABLE 1. Organochlorine contamination in* Vallisneria *collected from natural populations at Ecarte (E) and Turkey Island (T) (μg/kg; in parentheses, μg/kg of lipid). The symbol (–) indicates results which were below detection limits.

Time	Tissue	ID Site	% Lipid	QCB	HCB	OCS	Trans-Non	pp'DDE
20 May	turion	T	0.037	–	0.02	–	–	0.08
				(–)	(54)	(–)	(–)	(216)
	root	T	0.020	0.03	0.08	0.02	–	0.15
				(150)	(350)	(100)	(–)	(750)
22 May	turion	E	0.060	–	.01	–	–	–
				(.1)	(17)	(–)	(–)	(–)
	root	E	0.050	.05	.37	1.11	0.02	–
				(100)	(740)	(2,220)	(40)	(5.0)
5 July	stolon	E	0.110	–	–	–	–	–
				(–)	(–)	(–)	(–)	(–)
5 July	leaf	E	0.088	–	–	–	–	–
				(–)	(0.2)	(0.2)	(–)	(–)
5 July	root	E	0.121	0.05	0.37	1.11	0.04	0.25
				(41)	(306)	(917)	(33)	(207)
5 July	turion	E	0.070	–	–	–	–	–
				(–)	(–)	(–)	(–)	(–)
25 June	root	T	0.020	0.02	0.06	0.02	0.02	0.14
				(100)	(300)	(100)	(100)	(700)
25 June	leaf	T	0.050	–	0.02	0.01	–	0.09
				(–)	(40)	(20)	(–)	(180)
25 June	stolon	T	0.030	–	0.01	–	–	0.07
				(–)	(33)	(–)	(–)	(233)
25 June	turion	T	0.050	–	0.02	–	–	0.08
				(–)	(40)	(–)	(–)	(160)
2 October	turion	T	0.180	0.04	0.01	–	–	0.03
				(22)	(6)	(–)	(–)	(17)
2 October	turion	T	0.160	0.05	0.01	–	–	0.03
				(31)	(6)	(–)	(–)	(19)
2 October	root	T	0.090	0.13	0.26	0.03	0.04	0.23
				(144)	(289)	(33)	(44)	(256)
2 October	leaf	T	0.020	0.06	0.05	0.11	0.01	0.09
				(300)	(250)	(550)	(50)	(450)
2 October	stolon & caudex	T	0.020	0.06	0.02	–	–	0.03
				(300)	(100)	(–)	(–)	(150)
2 October	fruit	T	0.030	0.06	0.02	–	–	0.03
				(200)	(67)	(–)	(–)	(100)
4 October	turion	E	0.250	0.08	0.02	–	–	0.20
				(32)	(8)	(–)	(–)	(80)
4 October	root	E	0.190	0.26	1.02	1.75	0.05	0.42
				(137)	(537)	(921)	(26)	(221)
4 October	leaf	E	0.240	0.10	0.15	0.19	0.01	0.10
				(42)	(62)	(79)	(4)	(42)
4 October	stolon & caudex	E	0.140	0.17	0.04	0.04	–	0.14
				(121)	(29)	(29)	(–)	(100)
4 October	fruit	E	0.310	0.06	0.02	–	–	0.10
				(19)	(6)	(–)	(–)	(32)
4 October	fruit	E	0.230	0.07	0.02	–	–	0.06
				(30)	(9)	(–)	(–)	(26)

TABLE 2. PCB contamination of plants collected from the field populations at Ecarte (E) and Turkey Island (T). (μg/kg; in parenthesis μg/kg lipid). The symbol (–) indicates results which were below detection limits.

Time	Tissue	ID Site	% Lipid	Arochlor 1254:1260	PCB #28	PCB #52	PCB #66/95	PCB #101	PCB #99	PCB #87
20 May	turion	T	0.037	0.75 (2,027)	0.04 (108)	0.23 (621)	– (–)	– (–)	– (–)	– (–)
20 May	root	T	0.020	1.08 (5,400)	– (–)	0.05 (250)	– (–)	– (–)	– (–)	0.05 (250)
22 May	turion	E	0.060	0.10 (167)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)
22 May	root	E	0.050	2.01 (4,020)	0.06 (120)	0.12 (240)	0.17 (340)	0.15 (300)	0.07 (140)	– (–)
5 July	stolon	E	0.110	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	0.84 (764)
5 July	leaf	E	0.088	– (1.5)	– (0.1)	– (0.1)	– (0.1)	– (–)	– (–)	– (–)
5 July	root	E	0.121	2.49 (2,058)	0.05 (41)	0.10 (83)	0.24 (198)	0.18 (149)	0.10 (83)	0.03 (25)
5 July	turion	T	0.070	0.10 (143)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)
25 June	roots	T	0.020	1.08 (5,400)	– (–)	0.05 (250)	0.07 (350)	0.05 (250)	0.03 (150)	– (–)
25 June	leaf	T	0.050	0.49 (980)	– (–)	0.03 (60)	0.04 (80)	0.02 (40)	– (–)	– (–)
25 June	stolon	T	0.030	0.50 (1,677)	0.02 (67)	0.06 (200)	0.03 (100)	– (–)	– (–)	– (–)
25 June	turion	T	0.050	0.75 (1,500)	0.04 (80)	0.06 (120)	0.05 (100)	0.03 (60)	– (–)	– (–)
2 Oct.	turion	T	0.180	– (–)	0.04 (22)	0.04 (22)	– (–)	– (–)	– (–)	0.07 (39)
2 Oct.	turion	T	0.160	– (–)	0.02 (12)	0.04 (25)	0.02 (12)	– (–)	– (–)	– (–)
2 Oct.	root	T	0.090	1.75 (1,944)	0.05 (56)	0.09 (100)	0.22 (244)	0.13 (144)	0.05 (56)	– (–)
2 Oct.	leaf	T	0.020	0.46 (2,300)	0.02 (100)	0.11 (550)	0.06 (300)	0.07 (350)	0.03 (150)	– (–)
2 Oct.	stolon & caudex	T	0.020	– (–)	0.02 (100)	0.04 (200)	0.02 (100)	– (–)	– (–)	– (–)
2 Oct	fruit	T	0.030	– (–)	0.04 (133)	0.06 (200)	– (–)	– (–)	– (–)	0.62 (2,067)
4 Oct.	turion	E	0.25	– (–)	0.04 (16)	0.13 (52)	0.09 (36)	0.05 (20)	– (–)	– (–)
4 Oct.	root	E	0.19	2.99 (1,574)	0.09 (47)	0.52 (274)	0.35 (184)	0.35 (184)	0.20 (105)	0.13 (68)
4 Oct.	leaf	E	0.24	0.41 (171)	– (–)	0.14 (58)	0.09 (38)	0.04 (17)	0.03 (12)	0.02 (8)
4 Oct.	stolon & caudex	E	0.14	– (–)	0.06 (43)	0.11 (79)	0.06 (43)	0.05 (36)	– (–)	– (–)
4 Oct	fruit	E	0.31	0.41 (132)	0.07 (19)	0.26 (84)	0.17 (55)	0.19 (61)	– (–)	– (–)
4 Oct.	fruit	E	0.23	– (–)	0.04 (17)	0.44 (191)	0.32 (139)	– (–)	– (–)	– (–)

TABLE 2. (Continued).

Time	Tissue	ID Site	% Lipid	PCB #110	PCB #118	PCB #153	PCB #138	PCB #182/187	PCB #180	PCB #170/190	PCB #194
20 May	turion	T	0.037	0.05	–	–	–	–	–	–	–
				(135)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
20 May	root	T	0.020	0.07	–	–	–	–	–	–	–
				(350)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
22 May	turion	E	0.060	–	–	–	–	–	–	–	
				(–)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
22 May	root	E	0.050	–	–	–	–	–	–	–	–
				(0.1)	(0.1)	(–)	(–)	(–)	(–)	(–)	(–)
5 July	stolon	E	0.110	0.20	0.01	0.07	0.18	0.11	0.04	–	–
				(182)	(9)	(64)	(164)	(100)	(36)	(–)	(–)
5 July	leaf	E	0.088	–	–	–	–	–	–	–	–
				(–)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
5 July	root	E	0.121	0.07	0.03	0.08	0.08	0.02	0.04	–	–
				(58)	(25)	(66)	(66)	(17)	(33)	(–)	(–)
5 July	turion	T	0.070	0.04	–	0.01	0.04	–	–	–	–
				(57)	(–)	(14)	(57)	(–)	(–)	(–)	(–)
25 June	roots	T	0.020	0.04	0.06	0.03	0.04	–	–	–	–
				(200)	(300)	(150)	(200)	(–)	(–)	(–)	(–)
25 June	leaf	T	0.050	0.04	–	0.02	0.06	–	–	–	–
				(80)	(–)	(40)	(120)	(–)	(–)	(–)	(–)
25 June	stolon	T	0.030	0.02	–	0.01	–	–	–	–	–
				(67)	(–)	(33)	(–)	(–)	(–)	(–)	(–)
25 June	turion	T	0.050	0.03	–	0.01	–	–	–	–	–
				(60)	(–)	(20)	(–)	(–)	(–)	(–)	(–)
2 Oct.	turion	T	0.180	0.10	0.08	0.11	0.13	0.04	0.06	–	–
				(55)	(44)	(61)	(72)	(22)	(33)	(–)	(–)
2 Oct.	turion	T	0.160	0.04	0.96	0.02	0.03	–	–	–	–
				(25)	(600)	(12)	(19)	(–)	(–)	(–)	(–)
2 Oct.	root	T	0.090	0.02	–	–	–	–	–	–	–
				(22)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
2 Oct.	leaf	T	0.020	0.03	–	–	–	–	–	–	–
				(150)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
2 Oct.	stolon & caudex	T	0.020	–	–	–	–	–	–	–	–
				(–)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
2 Oct	fruit	T	0.030	0.11	0.01	0.05	0.12	0.10	0.03	–	–
				(367)	(33)	(167)	(400)	(333)	(100)	(–)	(–)
4 Oct.	turion	E	0.25	0.09	–	0.03	–	–	–	–	–
				(36)	(–)	(12)	(–)	(–)	(–)	(–)	(–)
4 Oct.	root	E	0.19	0.25	0.17	0.21	0.32	0.09	0.05	–	–
				(132)	(90)	(111)	(168)	(47)	(26)	(–)	(–)
4 Oct.	leaf	E	0.24	0.06	0.04	0.02	0.03	–	–	–	–
				(25)	(17)	(8)	(12)	(–)	(–)	(–)	(–)
4 Oct.	stolon & caudex	E	0.14	0.05	–	–	–	–	–	–	–
				(36)	(–)	(–)	(–)	(–)	(–)	(–)	(–)
4 Oct	fruit	E	0.31	0.06	0.03	0.03	0.03	–	–	–	–
				(19)	(10)	(10)	(10)	(–)	(–)	(–)	(–)
4 Oct.	fruit	E	0.23	0.03	–	–	–	–	–	–	–
				(13)	(–)	(–)	(–)	(–)	(–)	(–)	(–)

although levels in leaves were also high, in both sites. Fruits held disproportionate amounts of PCBs 52, and 66/95 (Table 2). Roots contained most contaminant year-round (Tables 1-2). Overall, in comparing the two sites, plants at Ecarte were 3–4× more contaminated than those at Turkey Island; the levels of HCB are about 6× as high at Ecarte, OCS about 50× as high as at Turkey Island.

Lipid-corrected contaminant concentrations are shown in parentheses in Tables 1 and 2. Roots did not contain more lipid than other plant organs. However, on a lipid-corrected basis, for the Turkey Island plants, roots contained 4× as much contaminant, and for the Ecarte plants, roots had approximately 10× the concentration of contaminants found in other tissues.

Reciprocal-Transplant-Replant Experiment

Non-destructive Monitoring

Time, site, plant origin, and sediment type all had significant effects on plant growth (Table 3). Significant interactions are also shown in Table 3: clonal growth (assessed as number of ramets/genet) was most strongly affected by factors and their interactions, and therefore provides a particularly sensitive measure of relative plant vigor. The mean length of a leaf and the cumulative length of leaves on a ramet seem characteristic of a plant's site of origin and responsive to environmental conditions where plants were grown.

In general, the relatively adverse effect of having been grown at Ecarte was greatest, with sediment type and site of origin of the plant also showing statistically significant effects (Table 3). The number of ramets produced per m^2 was about 2× greater for any of the treatments at Turkey Island than at Ecarte (Figs. 1a,b). At both sites, by the end of the season, "locals" (i.e., plants originating at the site to which they were transplanted) produced more ramets than "aliens" (after controlling for sediment type). A similar pattern is evident for the number of leaves per m^2 at each site (Figs. 2a,b). The number of leaves per ramet was comparable at the two sites, being in the range of 5–7 leaves per ramet (Figs. 3a,b). Plants originating from Turkey Island had more leaves per ramet at the outset, in tubs placed at both sites, but by the end of the season Turkey Island plants in Ecarte sediment, raised at the Ecarte site, had the fewest leaves. At the Ecarte site, flowering did not occur in any plants grown in Ecarte sediment; at the Turkey Island site, flowering by plants from Ecarte was negligible, and plants from Turkey Island flowered significantly more if they were in Turkey Island than in Ecarte sediment (see Figs. 4a,b).

TABLE 3. Summary of Analyses of Variance of plant growth in the* Vallisneria *reciprocal transplant-replant (biomonitor) experiment. (= $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; NS = not significant). Only factors that were significant for some parameters are tabulated.***

Trait	Factors													
	Time (T)	Site (S)	Sediment (E)	Plant Origin (P)	T×S	T×P	T×E	S×P	S×E	P×E	T×S×E	T×P×E	S×P×E	T×S×P×E
# of ramets/m^2	***	***	***	**	***	NS	***	***	NS	NS	NS	NS	NS	NS
# of ramets/genet	***	***	***	***	***	***	***	***	***	*	*	*	NS	NS
# of leaves/genet	***	***	***	***	NS	***	***	***	***	*	NS	*	NS	*
# of leaves/ramet	***	***	***	***	**	NS	**	*	NS	*	*	*	*	NS
# of leaves/m^2	***	***	***	***	***	NS	***	***	NS	**	NS	NS	NS	NS
mean length of leaf/ramet	NS	*	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
cumulative length of leaves/ramet	NS	**	NS	***	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
cumulative length of leaves/genet	***	***	***	***	NS	**	**	***	NS	***	NS	*	*	NS
# of flowering ramets/m^2	***	**	***	***	*	**	*	**	NS	**	NS	NS	NS	NS

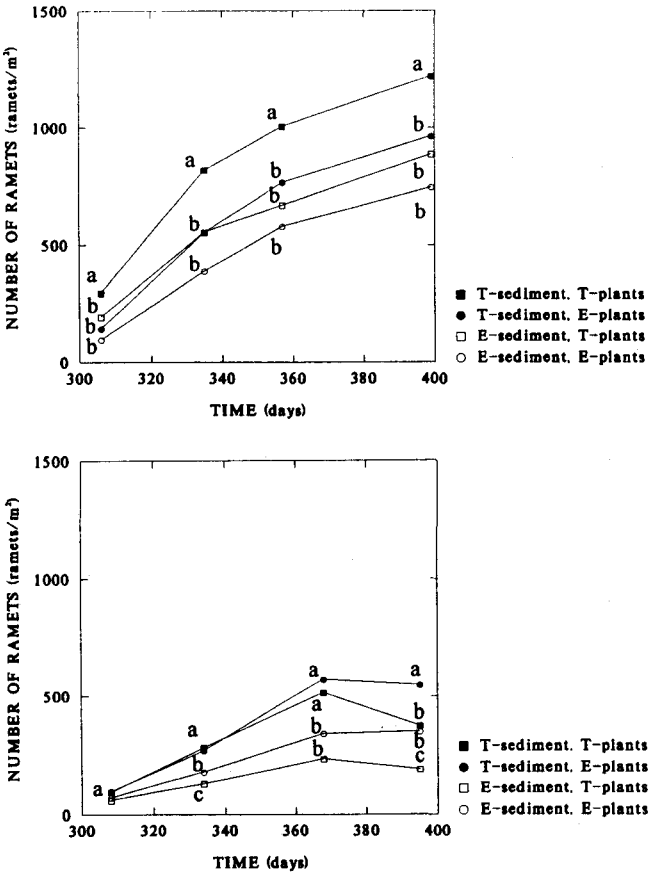

FIG. 1. Number of ramets per m² at (a) [upper] the Turkey Island site, and (b) [lower] the Ecarte site, over time (in days post-initiation of the experiment). Different letters at single points in time indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$) between mean values.

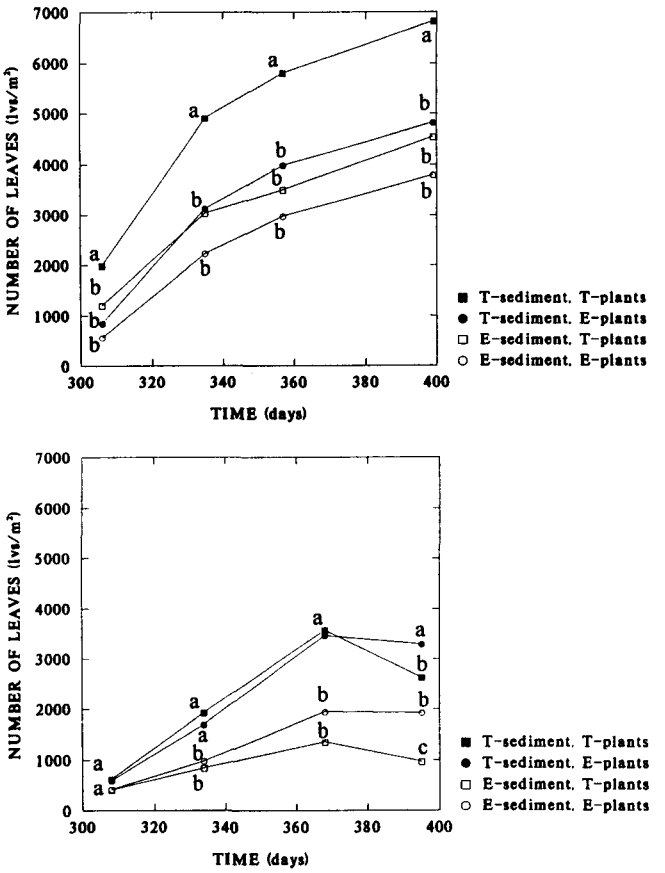

FIG. 2. Number of leaves per m² at (a) [upper] the Turkey Island site, and (b) [lower] the Ecarte site, over time (in days post-initiation of the experiment). Different letters at single points in time indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$) between mean values.

Destructive Harvests

It should be noted that the biomass samples of 1991 represent the contents of a single tub from each treatment on each occasion, therefore plants, rather than tubs, are replicated. The results are therefore descriptive, and provide no assessment of between-tub variance.

In absolute terms, greatest biomass per m^2 was found in Turkey Island plants growing at Turkey Island, whether they were grown in Ecarte sediment or sediment from Turkey Island (Fig. 5a). By September, this differential had increased; greater biomass per unit area was recorded for Turkey Island plants at their native site, with those in their natural sediment producing more biomass than those in Ecarte sediment (Fig. 5b). In terms of the biomass of individual ramets in each treatment, a similar pattern was seen (Figs. 6a,b); Ramets from the Turkey Island population were of greater biomass, and by September were bigger in the Turkey Island site, and in Turkey Island sediment.

In July, all plants (from each source or sediment type) at Turkey Island had proportionately more leaf tissue and less root and stolon tissue than was the case for the corresponding treatment at Ecarte (Figs. 7a,b). By September, for each treatment, the plants growing at Turkey Island had proportionately *less* biomass in leaves and roots, and more in stolons (Figure 8a,b).

Number of leaves per genet was also greatest for Turkey Island plants growing at Turkey Island in July (Fig. 9a); by September the Turkey Island plants in their natural sediment, but growing at

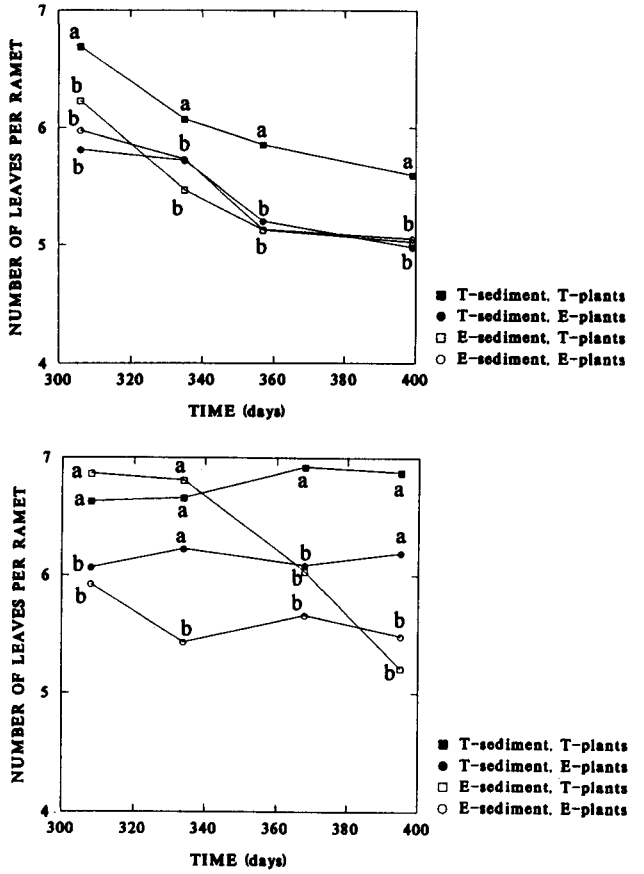

FIG. 3. Number of leaves per ramet at (a) [upper] the Turkey Island site, and (b) [lower] the Ecarte site, over time (in days post-initiation of the experiment). Different letters at single points in time indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$) between mean values.

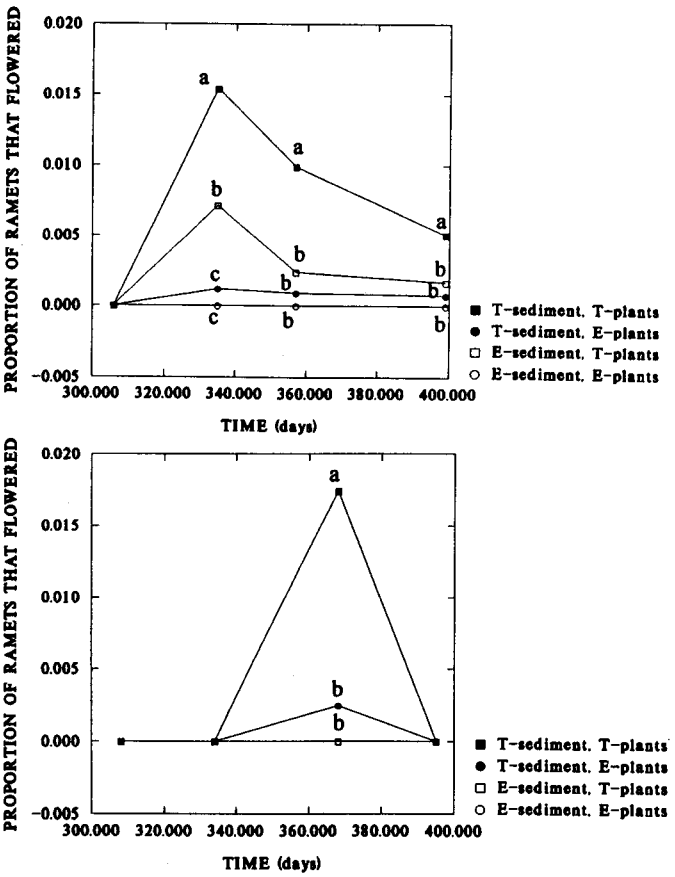

FIG. 4. Proportion of ramets that flowered at (a) [upper] the Turkey Island site, and (b) [lower] the Ecarte site, over time (in days post-initiation of the experiment). Different letters at single points in time indicate statistically significant differences according to Duncan's multiple range test ($p<0.05$) between mean values.

Ecarte, had almost as many leaves (Fig. 9b). In natural populations, plants from Turkey Island typically have longer leaves (personal observations). By September it was apparent that Ecarte leaves did not become longer at Turkey Island, whereas the length of Turkey Island leaves was reduced when Turkey Island plants were grown in Ecarte sediment, or at the Ecarte site (Figs. 10a,b).

The effects of treatments by July 1991 and September 1991, respectively (i.e., 10 and 12 months after the experiment was set up) are shown in Tables 4 and 5. Exposure to both water and sediment from the Ecarte site had the greatest depressant effect on plant growth, whatever the original source of the plants. The cumulative length of leaves per genet reflects both the size and number of leaves and ramets. By September (Table 5), cumulative leaf length at the Ecarte site was greatest for the plants in Turkey Island sediment. At the Turkey Island site greater cumulative leaf length per genet was noted in plants originating from Turkey Island, whichever sediment they were in. The number of ramets per genet at Ecarte was greater in Turkey sediment, but at Turkey Island, plants originating from Turkey Island had produced more ramets. Cumulative length of leaves per ramet was greater for plants from Turkey Island at both sites, and again was greatest for plants from Turkey Island growing at Turkey Island in Turkey Island sediment.

At both sites the number of ramets per m^2 was greater for plants grown in sediment from Turkey Island, overall ramet production was greatest at the Turkey Island site. In both sites, flowering was

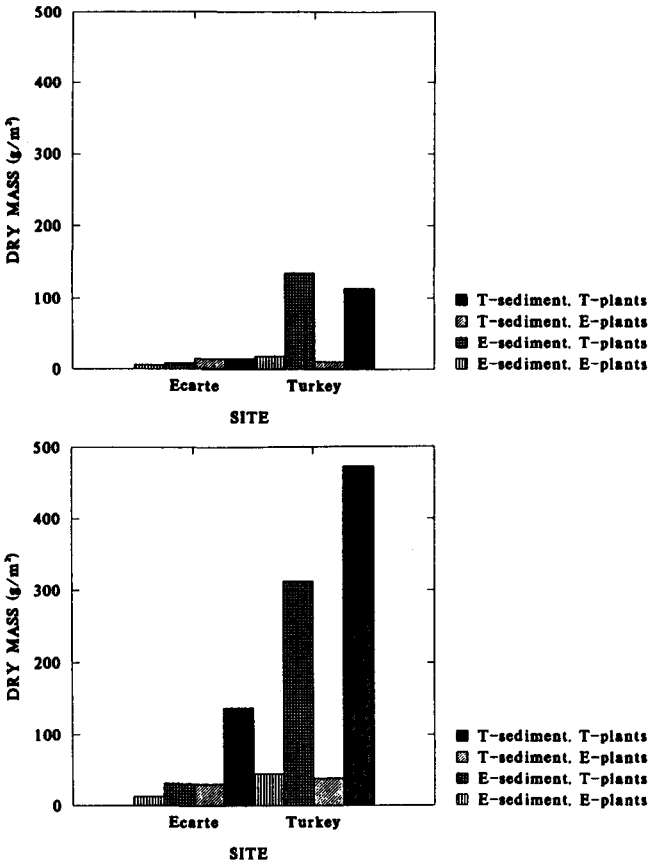

FIG. 5. Dry mass of plants per m² at the Turkey Island site, and the Ecarte site, (a) [upper] in July 1991, and (b) [lower] in September 1991.

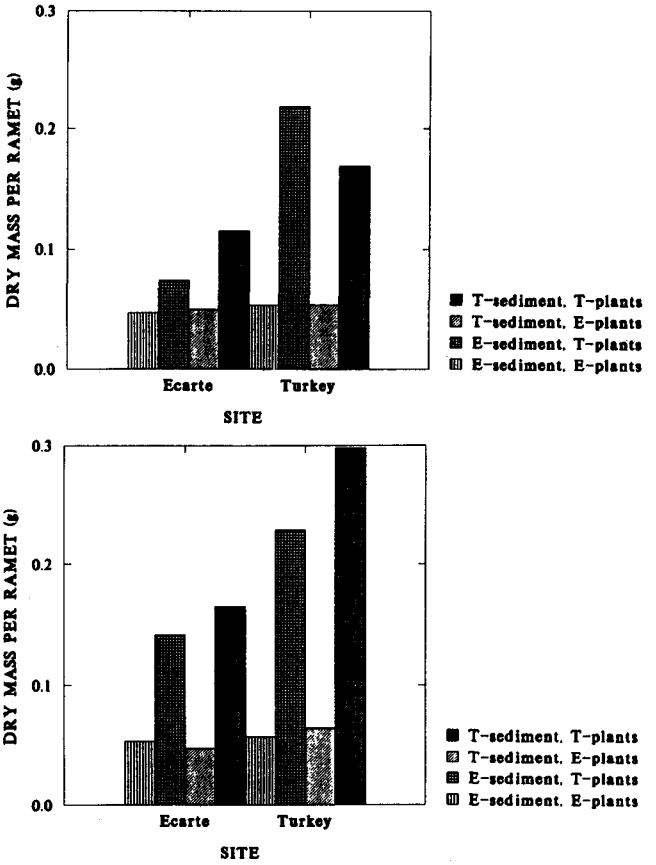

FIG. 6. Dry mass per ramet at the Turkey Island site, and the Ecarte site, (a) [upper] in July 1991, and (b) [lower] in September 1991.

more frequent for plants from Turkey Island growing in sediment from Turkey Island (see Fig. 4).

The "relative impairment" of plants is an index that can be calculated to represent performance at one site compared to another. Ideally, in applying the biomonitor approach used here, the standard of comparison should be the comparatively "cleanest" site, where plants grow optimally. Relative impairment should be calculated from that baseline. In the present study, at the Turkey Island site plants from both locations produced more ramets per genet and more plants flowered, so it was chosen as the baseline for this preliminary study.

Relative Impairment (RI) =

$$\frac{\text{performance at Turkey Island–performance at Ecarte}}{\text{performance at Turkey Island}}$$

Relative impairments are shown in Table 6. Exposure to the Ecarte water column was the most damaging factor for plants from both populations. The Ecarte sediment was the next most detrimental factor. In Table 7, coefficients of selection are presented. These measure the probable degree of adaptation of plants to their native site, and are calculated as:

Selection coefficient (s) =

$$1-\frac{\text{performance of alien plants}}{\text{performance of native plants}}$$

Contaminant Distribution in Experimental Transplants and Replants in Two Populations of *Vallisneria americana* (Biomonitor Experiment)

Analyses by GC/ECD confirmed that plants grown at Ecarte had become more contaminated over the year of the experiment, whatever their original source (Tables 8, 9). Organic contaminant

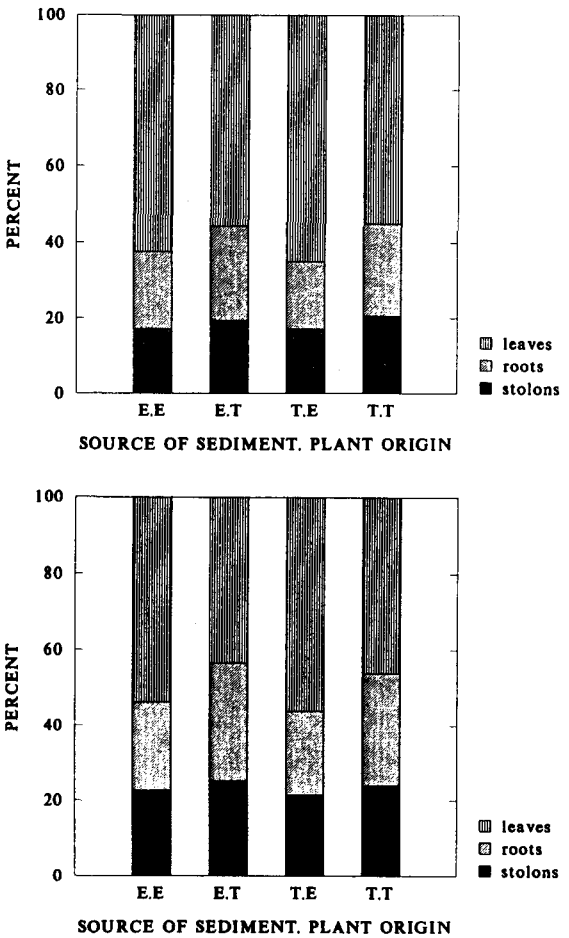

FIG. 7. Proportionate contribution of leaves, roots and stolons to dry mass at (a) [upper] the Turkey Island site, and (b) [lower] the Ecarte site in July 1991. Each bar represents a particular combination of plant source and sediment type as indicated.

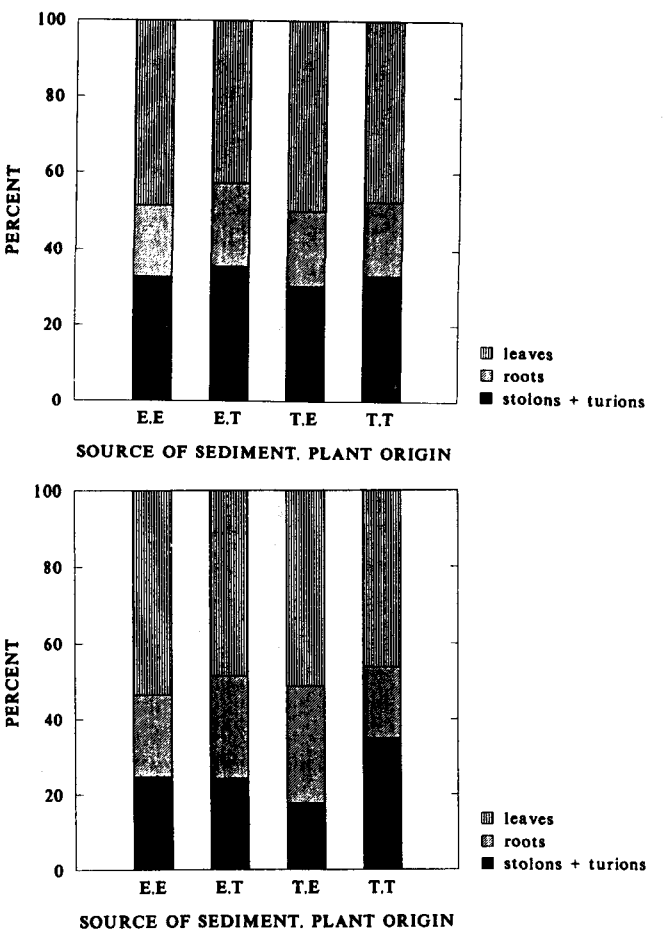

FIG. 8. Proportionate contribution of leaves, roots and stolons to dry mass at (a) [upper] the Turkey Island site, and (b) [lower] the Ecarte site in September 1991. Each bar represents a particular combination of plant source and sediment type as indicated.

TABLE 4. Performance of plants in the reciprocal transplant experiment (July) (E = Ecarte; T = Turkey Island).

Site	Ecarte				Turkey Island			
Sediment	E		T		E		T	
Plants	E	T	E	T	E	T	E	T
Total length of leaves (per genet)	79.2	81.1	167.5	132.6	263.3	775.6	194.0	1,090.2
Ramets per genet	2.2	2.4	4.3	2.2	4.8	8.8	3.5	9.7
Total length of leaves (per ramet)	35.2	33.4	39.0	58.9	54.9	88.1	55.4	112.4
# of ramets per m^2	71.0	60.0	97.2	94.5	96.6	194.5	137.9	297.2

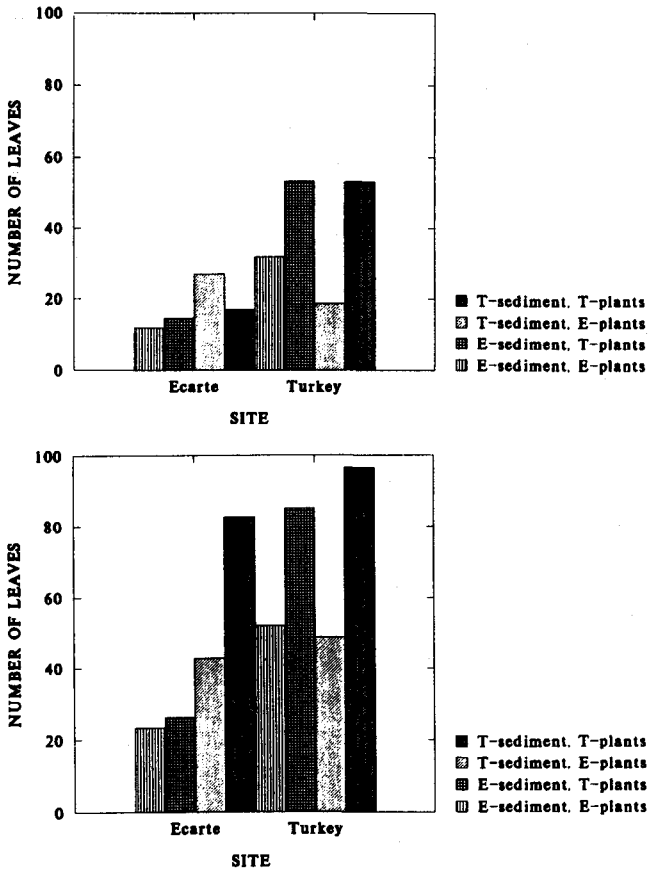

FIG. 9. Number of leaves per genet in plants in each treatment, at each site in (a) [upper] July 1991, and (b) [lower] September 1991.

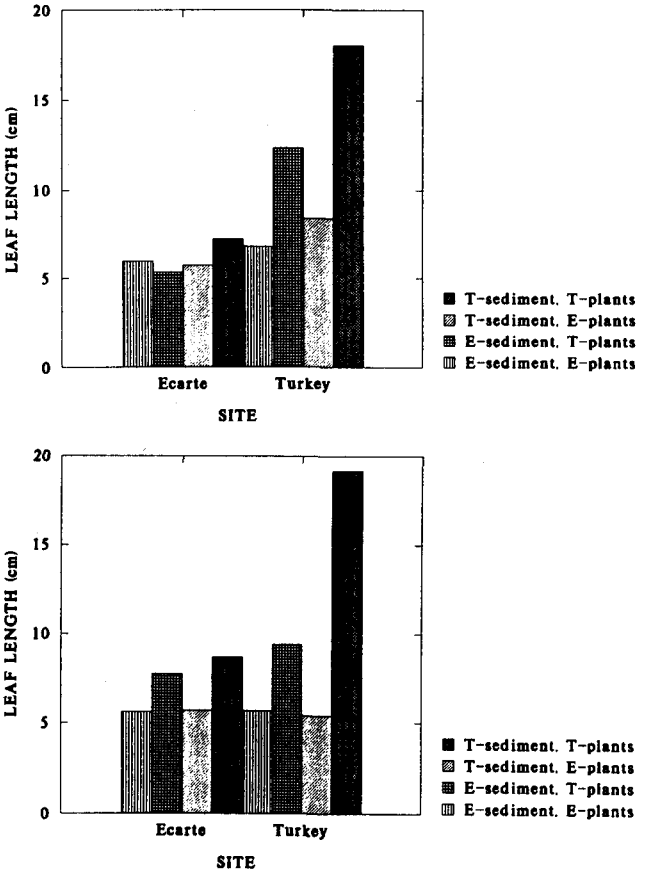

FIG. 10. Mean length of a leaf in plants in each treatment, at each site in (a) [upper] July 1991, and (b) [lower] September 1991.

TABLE 5. Performance of plants in the reciprocal transplant experiment (September) (E = Ecarte; T = Turkey Island).

Site	Ecarte				Turkey Island			
Sediment	E		T		E		T	
Plants	E	T	E	T	E	T	E	T
Total length of leaves (per genet)	143.0	206.0	249.9	752.8	319.0	976.2	311.0	1,930.0
Ramets per genet	4.4	4.0	9.2	12.0	12.2	19.8	12.3	23.0
Total length of leaves (per ramet)	32.7	51.5	27.2	62.7	26.1	49.3	25.3	83.9
# of ramets per m^2	343.5	236.6	573.1	515.9	579.3	673.8	771.0	1,006.2
# of ramets flowering per m^2	0.0	0.0	1.38	9.66	0.0	2.28	0.62	8.97

TABLE 6. Relative impairment (RI) of plants.

$$RI = \frac{(\text{Performance at Turkey Site}) - (\text{Performance at Ecarte Site})}{(\text{Performance at Turkey Site})} \times 100\%$$

Trait	Impairment due to Ecarte Water Column	Impairment due to Ecarte Sediment
Plants Originating from Turkey Island		
# of ramets per genet	62.6	32.0
# of ramets per m^2	55.2	40.2
# of lvs per ramet	−18.0	12.7
# of lvs per m^2	47.0	48.1
Mean length of leaf per ramet	42.6	38.4
# of flowering ramets per m^2	14.3	87.7
Plants Originating from Ecarte Site		
# of ramets per genet	44.6	22.7
# of ramets per m^2	32.1	31.4
# of lvs per ramet	−13.7	4.4
# of lvs per m^2	22.3	34.0
Mean length of leaf per ramet	−2.1	−1.7
# of flowering ramets per m^2	−120.5	−100.0

TABLE 7. Coefficient of selection at Ecarte and Turkey Island sites.

$$\text{Selection coefficient} = 1 - \frac{\text{Performance of alien plants}}{\text{Performance of native plants}}$$

Trait	Ecarte Site	Turkey Island Site
# of ramets per genet	−0.179	0.427
# of ramets per m^2	0.179	0.196
# of lvs per ramet	−0.103	0.060
# of lvs per m^2	0.089	0.252
Mean length of leaf	−0.451	0.612
# of flowering ramets per m^2	−5.997	0.944

concentrations in sediment, water, and in plant tissues matched the relative impairment of growth that we observed under each set of circumstances. For most contaminants, particularly the PCBs, OCS, and HCB, the Ecarte sediment was more contaminated, and roots, in particular, bioaccumulated these materials most strongly.

Table 8 shows the concentration in μg/kg of each of the organochlorine contaminants that was tracked in the experimental plant tissues, water, and sediment. The level of HCB was greatest in roots (up to 125 μg/kg), when plants were raised in Ecarte sediment, both at the Turkey Island site and the Ecarte site. Similar patterns of contaminant distribution are seen for OCS and for PCBs (Table 9). Lipid-corrected values for the concentration of contaminants are shown in parentheses (Tables 8, 9).

DISCUSSION

Submersed aquatic plants are well known to sequester metals, and nutrients from both the sediments and the water in which they grow (Franzin and McFarlane 1980, Harding and Whitton 1978, Schierup and Larson 1981, Forstner and Wittmann 1979, Hutchinson 1975, Lovett Doust *et al.* 1994). However, very few workers have studied the presence of organic contaminants in plants. Stewart *et al.* (1992) showed that the macrophyte *Potamogeton foliosus* and filamentous algae from a settling basin containing contaminated sediment became enriched with PCBs (as well as heavy metals). In the present study plants responded to different levels of organochlorine contamination in terms of leaf production, rates of clonal growth, sexual reproduction (flowering), and plant survival. Our growth measurements are more sensitive, and are more likely to reflect the subtle and gradual damage done by persistent low-level exposure to contaminants than simple observations of mortality.

Pugsley *et al.* (1985, 1988) measured contaminant levels (PCBs, OCS, lead, and cadmium) simultaneously in a unionid clam (*Lampsilis radiata siliquoidea*) and surrounding sediments from 102 sites in Lake St. Clair and the Canadian shoreline of the St. Clair and Detroit rivers (including the areas studied in the present study). Clams are long-lived filter-feeders that move little (Imlay 1982) and so are to a degree comparable to plants in their utility as a biomonitor (though the analysis of the separate roles of sediment and water column in contaminating the organism are not so tractable for the clams).

Our measurements of contaminants in naturally growing plants at each site suggest that the two populations of *Vallisneria* differ in their exposure to, and uptake of, the suite of organochlorine contaminants examined. The pattern of greater contaminant concentration in roots, but with progressive accumulation in all tissues over the growing season, suggests an important role for uptake of these organochlorine contaminants via the sediment to *roots*, rather than to leaves via the water column. It also shows that plant tissues are not in equilibrium with each other or with contaminant concentrations in the surrounding water column. Furthermore, since lipid-corrected values do not show equilibrium between tissues it appears that

TABLE 8. Organochlorine contamination in experimental* Vallisneria americana *("Biomonitor experiment") (μg/kg: in parentheses, μg/kg of lipid).

Sample Number	Time	Identity (Site/Plant/ Sediment)	% Lipid	QCB	HCB	OCS	Trans-non	pp'DDE
(21)	July	T/T/T	0.131	—	0.03	0.04	0.02	0.14
				(—)	(23)	(31)	(15)	(107)
(22)	July	T/T/T	0.069	—	0.02	—	—	0.09
				(—)	(29)	(—)	(—)	(130)
(23)	July	T/T/T	0.050	0.03	0.08	—	0.05	0.30
				(60)	(160)	(—)	(100)	(600)
(24)	July	T/E/T	0.256	0.02	0.09	0.07	0.06	0.36
				(8)	(35)	(27)	(23)	(141)
(25)	July	T/E/T	0.314	—	—	—	—	0.72
				(—)	(—)	(—)	(—)	(229)
(26)	July	T/E/T	0.329	—	0.13	—	0.15	0.72
				(—)	(40)	(—)	(46)	(219)
(27)	July	T/T/E	0.131	0.04	0.09	0.06	0.03	0.15
				(31)	(69)	(46)	(23)	(115)
(28)	July	T/T/E	0.093	0.03	0.04	0.11	0.02	0.19
				(32)	(43)	(118)	(22)	(204)
(29)	July	T/T/E	0.031	0.03	0.11	0.02	0.02	0.14
				(97)	(355)	(65)	(65)	(452)
(30)	July	T/E/E	0.188	0.04	0.11	0.13	0.04	0.22
				(21)	(58)	(69)	(21)	(117)
(31)	July	T/E/E	0.136	—	0.15	0.45	—	0.44
				(—)	(110)	(331)	(—)	(324)
(32)	July	T/E/E	0.031	0.08	0.21	1.65	0.11	0.46
				(258)	(677)	(5,323)	(355)	(1,484)
(38)	July	E/E/T	0.240	0.06	0.25	0.74	0.03	0.14
				(25)	(104)	(308)	(12)	(58)
(39)	July	E/E/T	0.190	—	0.29	0.19	—	0.35
				(—)	(153)	(100)	(—)	(184)
(40)	July	E/E/T	0.180	—	0.16	0.25	—	0.23
				(—)	(89)	(139)	(—)	(128)
(41)	July	E/E/E	0.300	0.09	0.47	0.55	—	0.38
				(30)	(157)	(183)	(—)	(127)
(42)	July	E/E/E	0.530	—	0.85	1.06	—	0.91
				(—)	(160)	(200)	(—)	(172)
(43)	July	E/E/E	0.360	0.56	1.78	3.06	—	—
				(156)	(494)	(850)	(—)	(—)
(44)	July	E/T/T	0.252	0.05	0.32	0.27	0.04	0.14
				(20)	(127)	(107)	(16)	(56)
(45)	July	E/T/T	0.234	—	0.14	0.10	—	0.09
				(—)	(60)	(43)	(—)	(38)
(46)	July	E/T/T	0.383	—	0.26	0.21	—	0.28
				(—)	(68)	(55)	(—)	(73)
(47)	July	E/T/E	0.453	0.72	0.36	0.41	—	0.15
				(159)	(80)	(90)	(—)	(33)
(48)	July	E/T/E	0.410	—	0.71	1.11	—	—
				(—)	(173)	(271)	(—)	(—)
(49)	July	E/T/E	0.510	—	0.44	2.15	—	—
				(—)	(86)	(422)	(—)	(—)

TABLE 8. Continued

Sample Number	Time	Identity (Site/Plant/ Sediment)	% Lipid	QCB	HCB	OCS	Trans-non	pp'DDE
(50)	Sept.	E/T/T	0.190	0.04	0.27	0.16	0.04	0.13
				(21)	(142)	(84)	(21)	(68)
(51)	Sept.	E/T/T	0.110	—	0.10	0.02	—	0.06
				(—)	(91)	(18)	(—)	(54)
(52)	Sept.	E/T/T	0.100	0.04	124.84	0.12	0.03	0.17
				(40)	(124,840)	(120)	(30)	(170)
(53)	Sept.	E/E/T	0.103	0.03	0.15	0.15	0.04	0.29
				(29)	(146)	(146)	(39)	(282)
(54)	Sept.	E/E/T	0.100	—	0.03	0.12	—	0.23
				(—)	(30)	(120)	(—)	(230)
(55)	Sept.	E/E/T	0.040	0.09	0.62	0.28	0.14	0.31
				(225)	(1,550)	(700)	(350)	(775)
(56)	Sept.	E/T/E	0.171	0.15	0.59	0.89	0.05	0.13
				(88)	(345)	(520)	(29)	(76)
(57)	Sept.	E/T/E	0.146	0.12	0.20	0.33	—	0.24
				(82)	(137)	(226)	(—)	(164)
(58)	Sept.	E/T/E	0.188	0.13	0.54	2.46	—	0.42
				(69)	(287)	(1,308)	(—)	(223)
(59)	Sept.	E/E/E	0.159	—	0.35	0.93	—	0.25
				(—)	(220)	(585)	(—)	(157)
(60)	Sept.	E/E/E	0.172	0.16	0.24	0.26	—	0.49
				(93)	(140)	(151)	(—)	(285)
(61)	Sept.	E/E/E	0.570	3.38	70.00	12.35	0.54	2.04
				(593)	(12,281)	(2,167)	(95)	(358)
(62)	Sept.	T/E/T	0.040	—	0.05	0.03	0.02	0.14
				(—)	(125)	(75)	(50)	(350)
(63)	Sept.	T/E/T	0.060	—	0.04	—	—	0.15
				(—)	(67)	(—)	(—)	(250)
(64)	Sept.	T/E/T	0.060	—	0.16	—	—	0.25
				(—)	(267)	(—)	(—)	(417)
(65)	Sept.	T/E/T	0.120	0.04	0.11	0.39	0.02	0.24
				(34)	(92)	(325)	(17)	(200)
(66)	Sept.	T/E/E	0.040	0.04	0.09	0.20	0.02	0.25
				(100)	(225)	(500)	(50)	(625)
(67)	Sept.	T/E/E	0.040	0.08	0.36	6.83	—	0.19
				(200)	(900)	(17,075)	(—)	(475)
(68)	Sept.	T/T/T	0.100	—	0.04	0.03	—	0.10
				(—)	(40)	(30)	(—)	(100)
(69)	Sept.	T/T/T	0.100	—	0.03	—	—	0.06
				(—)	(30)	(—)	(—)	(60)
(70)	Sept.	T/T/T	0.500	0.03	0.11	—	0.02	0.16
				(6)	(22)	(—)	(4)	(32)
(71)	Sept.	T/T/E	0.180	—	0.05	0.16	—	0.10
				(—)	(28)	(89)	(—)	(56)
(72)	Sept.	T/T/E	0.170	0.07	0.30	1.68	0.04	0.11
				(41)	(176)	(988)	(24)	(65)
(73)	Sept.	T/T/E	0.090	0.03	0.11	0.17	—	0.20
				(33)	(122)	(189)	(—)	(222)

contaminant content in different plant tissues is not simply a function of relative solubility in aqueous and lipid phases, but rather demonstrates dynamic, and possibly regulated, gradients between sediment, root, turion/stem, and leaves.

Plants in the transplant experiment had only been exposed to experimental conditions for 1 year, and there may be some "home site" carry-over effects. Most of the plants that were originally set up remain in place for subsequent harvest in the experiment. Future analyses should show the difference between this relatively short-term study and the effects of longer (chronic) exposure to a particular sediment and water column.

Overall, the contrasts are clear; growth at the Ecarte site is less than growth at Turkey Island. In general, growth of plants at either site but in sediment from the Ecarte site was less than that of plants growing in sediment from Turkey Island. However, plants from Turkey Island grew more vigorously than plants from Ecarte at both sites.

According to the destructive harvest, clonal growth was reduced at Ecarte, and the presence of Ecarte sediment was detrimental to both Ecarte and Turkey Island plants. At Turkey Island, the negative effect of Ecarte sediment was less severe; plants that originated from Turkey Island still produced almost 50% more ramets than the alien Ecarte plants (which were, nevertheless, producing more ramets than they did at their native site).

In comparisons between ecotypes at "clean" environments, we found almost invariably that locals grew better than alien plants (see also Lovett Doust 1981). Plants from the Turkey Island site were better adapted to the Turkey Island site than were the Ecarte plants. At the Ecarte site, the generally superior growth of plants from the Turkey site shows up in per capita measures such as leaves per plant, biomass per ramet, etc. However, it is important to note that, at the Ecarte site, the *survival* of plants from Turkey Island is significantly lower than it is for plants from Ecarte, despite the fact that clonal growth is typically higher for plants from the Turkey Island population (ramets per m^2 are greater for Ecarte natives, see Table 5). There are therefore more intrinsically resistant individuals at the Ecarte site, and it is possible that this greater resistance has a genetic basis.

Since plants can reflect the relative pollution of different areas, tracking their *relative* growth can provide an inexpensive indicator of exposure to contaminants. When we examined this in terms of "relative impairment" (Table 6) or selection coefficients (Table 7), we can describe the degree of impairment using a single number, which makes it relatively simple to compare between sites. This could be of considerable assistance in prioritizing remedial actions in order to clean up polluted areas and to demonstrate successful remediation of polluted sites. We therefore recommend calculation of these simple indices of plant performance as one metric of local (and comparative) site conditions. Sufficient tub replicates remain in our experiment that the present biomonitor study will be conducted for a further 3 years in order to evaluate chronic effects of exposure (to the experimental treatments) on plant growth, reproduction, and survival.

Some of the possible selection pressures that may explain differential growth and reproduction at the two sites are:

1. the shorter growing season at Ecarte (plants there are approximately 2 to 3 weeks behind those at Turkey Island in terms of phenology)
2. different sediment properties at the two sites,
3. colder water at Ecarte, and
4. higher organochlorine contamination at Ecarte.

Several factors may be responsible for the greater mortality of plants from the Turkey Island site when they were grown at Ecarte. However, on the basis of the factorial transplant experiment, we believe that the most important factors are contamination of water followed by the effects of sediment, because detrimental effects on growth are qualitatively and quantitatively correlated with contaminant concentration in the plant tissues. This macrophyte is an abundant member of the plant community, and provides important food resources for diving ducks and turtles as well as forming beds of vegetation that are used by fish as nursery areas. Although the leaves are not the most contaminated of the *Vallisneria* tissues, they may, as Manny and Kenaga (1991) and Manny *et al.* (1991) have pointed out, enter the drift and may transport contaminants downstream. In addition uprooted turions and their attached roots may also convey contaminants downstream, concentrating contaminants in sediments when they establish and eventually decay, or transferring contaminants to other compartments of the food web when they are consumed by herbivores and detritivores.

It may be debated whether uptake by plants is best referred to as "bioaccumulation" or "bioconcentration." Here we use the term "bioaccumulation" because bioconcentration simply refers to the uptake of pollutant from *water*, whereas bioaccumulation indicates there is uptake from food as well as water. Macrophytes are in contact with two media: sediment

TABLE 9. PCB contaminants in experimental **Vallisneria americana** *("biomonitor experiment") (μg/kg; in parentheses, μg/kg of lipid).*

Sample Number	Time	Identity (Site/Plant/ Sediment)	% Lipid	Arochlor 1254:1260	PCB #28	PCB #52	PCB #66/95	PCB #101	PCB #99
(21)	July	T/T/T	0.131	1.37	0.02	0.92	0.35	0.14	0.08
				(1046)	(15)	(702)	(267)	(107)	(61)
(22)	July	T/T/T	0.069	1.48	0.03	0.12	0.10	0.08	0.04
				(2145)	(44)	(174)	(145)	(116)	(58)
(23)	July	T/T/T	0.050	1.76	—	0.16	0.33	0.12	0.09
				(3520)	(—)	(320)	(660)	(240)	(180)
(24)	July	T/E/T	0.256	1.88	0.07	0.21	0.53	0.30	0.23
				(734)	(27)	(82)	(207)	(117)	(90)
(25)	July	T/E/T	0.314	4.70	—	0.60	0.43	0.34	—
				(1516)	(—)	(194)	(139)	(110)	(—)
(26)	July	T/E/T	0.329	11.91	0.52	1.79	1.48	0.47	0.24
				(3620)	(158)	(544)	(450)	(143)	(73)
(27)	July	T/T/E	0.131	1.48	0.05	0.11	0.15	0.17	0.07
				(1130)	(38)	(84)	(114)	(130)	(53)
(28)	July	T/T/E	0.093	0.97	0.07	0.22	0.19	0.14	0.10
				(1043)	(75)	(237)	(204)	(150)	(108)
(29)	July	T/T/E	0.031	1.30	0.04	0.11	0.10	0.07	0.04
				(4193)	(129)	(355)	(323)	(226)	(129)
(30)	July	T/E/E	0.188	3.33	0.08	0.20	0.22	0.23	0.10
				(1771)	(43)	(106)	(117)	(122)	(53)
(31)	July	T/E/E	0.136	3.17	0.22	0.39	0.31	0.30	—
				(2331)	(162)	(287)	(228)	(221)	(—)
(32)	July	T/E/E	0.031	4.65	0.20	0.59	0.44	0.30	0.23
				(15000)	(645)	(1903)	(1419)	(968)	(742)
(38)	July	E/E/T	0.240	2.18	0.12	0.14	1.22	0.21	0.72
				(908)	(50)	(58)	(508)	(88)	(300)
(39)	July	E/E/T	0.190	4.90	0.25	0.50	0.34	0.19	—
				(2579)	(132)	(263)	(179)	(100)	(—)
(40)	July	E/E/T	0.180	4.43	0.20	0.68	0.17	—	—
				(2461)	(111)	(378)	(94)	(—)	(—)
(41)	July	E/E/E	0.300	3.98	0.21	0.22	0.26	0.11	—
				(1327)	(70)	(73)	(87)	(37)	(—)
(42)	July	E/E/E	0.530	22.81	0.42	0.45	0.47	—	—
				(4304)	(79)	(85)	(89)	(—)	(—)
(43)	July	E/E/E	0.360	33.36	0.62	1.18	1.82	—	—
				(9267)	(172)	(328)	(506)	(—)	(—)
(44)	July	E/T/T	0.252	1.66	0.11	0.15	0.18	0.11	0.06
				(659)	(44)	(60)	(71)	(44)	(24)
(45)	July	E/T/T	0.234	2.91	0.13	0.17	0.16	—	—
				(1244)	(56)	(73)	(68)	(—)	(—)
(46)	July	E/T/T	0.383	8.76	0.28	0.44	0.30	—	—
				(2287)	(73)	(115)	(78)	(—)	(—)
(47)	July	E/T/E	0.453	2.92	0.10	0.21	0.25	0.16	0.11
				(645)	(22)	(46)	(55)	(35)	(24)
(48)	July	E/T/E	0.410	6.60	0.14	0.40	0.52	—	—
				(1610)	(34)	(98)	(127)	(—)	(—)
(49)	July	E/T/E	0.510	7.77	0.22	0.85	0.40	—	—
				(1524)	(43)	(167)	(78)	(—)	(—)

TABLE 9. Continued

PCB #87	PCB #110	PCB #118	PCB #153	PCB #138	PCB #182/187	PCB #180	PCB #170/190	PCB #194
0.06	0.11	0.12	0.26	0.10	—	0.02	—	0.02
(46)	(84)	(92)	(198)	(76)	(—)	(15)	(—)	(15)
0.04	0.09	0.04	0.05	0.11	—	—	—	—
(58)	(130)	(58)	(72)	(159)	(—)	(—)	(—)	(—)
0.42	0.13	0.07	0.11	0.13	0.05	0.05	—	—
(840)	(260)	(140)	(220)	(260)	(100)	(100)	(—)	(—)
0.09	0.16	0.27	0.13	0.14	—	0.04	—	
(35)	(63)	(105)	(51)	(55)	(—)	(16)	(—)	(—)
—	0.30	—	0.30	0.35	—	—	—	—
(—)	(97)	(—)	(97)	(113)	(—)	(—)	(—)	(—)
0.33	0.43	0.25	0.50	0.87	—	0.19	—	—
(100)	(131)	(76)	(152)	(264)	(—)	(58)	(—)	(—)
0.05	0.11	0.07	0.10	0.11	—	0.03	0.03	—
(38)	(84)	(53)	(76)	(84)	(—)	(23)	(23)	(—)
0.06	0.11	0.04	0.05	0.07	0.04	—	—	—
(65)	(118)	(43)	(54)	(75)	(43)	(—)	(—)	(—)
0.07	0.11	0.05	0.09	0.10	0.02	0.02	—	—
(226)	(355)	(161)	(290)	(323)	(65)	(65)	(—)	(—)
0.08	0.16	0.09	0.10	0.17	—	0.05	0.04	—
(43)	(85)	(48)	(53)	(90)	(—)	(27)	(21)	(—)
—	0.26	0.06	0.20	0.23	—	—	—	—
(—)	(191)	(44)	(147)	(169)	(—)	(—)	(—)	(—)
0.20	0.33	0.22	0.29	0.34	0.14	0.06	—	—
(645)	(1065)	(710)	(935)	(1097)	(452)	(194)	(—)	(—)
0.06	0.14	0.07	0.06	0.16	—	0.03	—	—
(25)	(58)	(29)	(25)	(67)	(—)	(12)	(—)	(—)
—	0.15	—	0.14	0.36	—	—	—	—
(—)	(79)	(—)	(74)	(190)	(—)	(—)	(—)	(—)
—	0.14	—	—	0.33	—	—	—	—
(—)	(78)	(—)	(—)	(183)	(—)	(—)	(—)	(—)
—	0.27	—	0.10	0.29	—	—	—	(—)
(—)	(90.6)	(—)	(34.3)	(97.2)	(—)	(—)	(—)	(—)
—	0.41	—	—	1.67	—	—	—	—
(—)	(77.9)	(—)	(—)	(315.2)	(—)	(—)	(—)	(—)
—	3.13	—	—	2.44	—	—	—	—
(—)	(869)	(—)	(—)	(678)	(—)	(—)	(—)	(—)
0.05	0.15	0.07	0.04	0.12	—	—	—	
(20)	(60)	(28)	(16)	(48)	(—)	(—)	(—)	(—)
—	—	—	—	0.21	—	—	—	—
(—)	(—)	(—)	(—)	(90)	(—)	(—)	(—)	(—)
—	0.24	—	0.23	0.64	—	—	—	—
(—)	(63)	(—)	(60)	(167)	(—)	(—)	(—)	(—)
—	0.23	—	0.13	0.22	—	—	—	—
(—)	(51)	(—)	(29)	(49)	(—)	(—)	(—)	(—)
—	0.31	—	—	0.48	—	—	—	—
(—)	(76)	(—)	(—)	(117)	(—)	(—)	(—)	(—)
—	0.31	—	0.35	0.57	—	—	—	—
(—)	(61)	(—)	(69)	(112)	(—)	(—)	(—)	(—)

TABLE 9. (continued) PCB contaminants in experimental **Vallisneria americana** *("biomonitor experiment") (μg/kg; in parentheses, μg/kg of lipid).*

Sample Number	Time	Identity (Site/Plant/ Sediment)	% Lipid	Arochlor 1254:1260	PCB #28	PCB #52	PCB #66/95	PCB #101	PCB #99
(50)	Sept.	E/T/E	0.190	1.65	—	0.10	0.53	0.11	0.07
				(868)	(—)	(53)	(279)	(58)	(37)
(51)	Sept.	E/T/T	0.110	2.05	0.05	0.09	0.09	0.04	—
				(1864)	(45)	(82)	(82)	(36)	(—)
(52)	Sept.	E/T/T	0.010	2.06	0.07	0.88	0.79	0.07	0.04
				(20600)	(700)	(8800)	(7900)	(700)	(400)
(53)	Sept.	E/T/T	0.103	1.82	0.09	0.26	0.33	0.11	0.06
				(1767)	(87)	(252)	(320)	(107)	(58)
(54)	Sept.	E/E/T	0.100	2.75	0.12	0.30	0.29	0.12	—
				(2750)	(120)	(300)	(290)	(120)	(—)
(55)	Sept.	E/E/T	0.040	1.71	0.08	0.10	0.40	0.26	0.29
				(4275)	(200)	(250)	(1000)	(650)	(725)
(56)	Sept.	E/T/E	0.171	2.41	0.20	0.20	0.20	0.18	0.12
				(1409)	(117)	(117)	(117)	(105)	(70)
(57)	Sept.	E/T/E	0.146	5.99	0.26	0.28	0.13	—	—
				(4103)	(178)	(192)	(89)	(—)	(—)
(58)	Sept.	E/T/E	0.188	11.63	0.40	0.73	0.31	0.20	—
				(6186)	(213)	(388)	(165)	(106)	(—)
(59)	Sept.	E/E/E	0.159	3.45	0.21	0.13	0.26	0.09	—
				(2170)	(132)	(82)	(164)	(57)	(—)
(60)	Sept.	E/E/E	0.172	11.78	0.56	0.26	0.19	—	—
				(6849)	(326)	(151)	(110)	(—)	(—)
(61)	Sept.	E/E/E	0.570	31.11	1.17	2.01	3.49	1.31	0.94
				(5458)	(205)	(353)	(612)	(230)	(165)
(62)	Sept.	T/E/T	0.040	0.89	0.14	0.09	0.47	0.08	0.05
				(2225)	(350)	(225)	(1175)	(200)	(125)
(63)	Sept.	T/E/T	0.060	0.44	0.05	0.13	0.06	0.08	0.04
				(733)	(83)	(217)	(100)	(133)	(67)
(64)	Sept.	T/E/T	0.060	1.05	0.25	0.27	0.17	0.08	0.08
				(1750)	(417)	(450)	(283)	(133)	(133)
(65)	Sept.	T/E/T	0.120	1.32	0.03	0.13	0.95	0.09	0.08
				(1100)	(25)	(108)	(792)	(75)	(67)
(66)	Sept.	T/E/E	0.040	0.51	0.03	0.18	0.12	0.06	0.06
				(1275)	(75)	(450)	(300)	(150)	(150)
(67)	Sept.	T/E/E	0.040	2.52	0.14	0.41	0.26	0.20	0.12
				(6300)	(350)	(1025)	(650)	(500)	(300)
(68)	Sept.	T/T/T	0.100	0.43	0.04	0.06	0.05	0.05	—
				(430)	(40)	(60)	(50)	(50)	(—)
(69)	Sept.	T/T/T	0.100	—	0.03	0.09	0.05	0.03	—
				(—)	(30)	(90)	(50)	(30)	(—)
(70)	Sept.	T/T/T	0.050	0.99	0.05	0.13	0.10	0.07	0.04
				(1980)	(100)	(260)	(200)	(140)	(80)
(71)	Sept.	T/T/E	0.180	—	0.05	0.08	0.05	0.02	—
				(—)	(28)	(44)	(28)	(11)	(—)
(72)	Sept.	T/T/E	0.170	2.00	0.07	0.34	0.24	0.16	0.08
				(1176)	(41)	(200)	(141)	(94)	(47)
(73)	Sept.	T/T/E	0.090	3.58	0.03	0.11	0.09	0.09	0.05
				(3978)	(33)	(122)	(100)	(100)	(56)

TABLE 9. Continued

PCB #87	PCB #110	PCB #118	PCB #153	PCB #138	PCB #182/187	PCB #180	PCB #170/190	PCB #194
0.06	0.29	0.12	0.05	0.12	—	—	—	—
(32)	(153)	(63)	(26)	(63)	(—)	(—)	(—)	(—)
—	0.12	0.03	—	0.15	—	—	—	—
(—)	(109)	(27)	(—)	(136)	(—)	(—)	(—)	(—)
0.05	0.07	0.04	0.09	0.15	0.06	—	—	—
(500)	(700)	(400)	(900)	(1500)	(600)	(—)	(—)	(—)
0.05	0.18	0.08	0.05	0.13	—	0.02	—	—
(49)	(175)	(78)	(49)	(126)	(—)	(19)	(—)	(—)
0.12	0.18	0.12	0.10	0.20	—	—	—	—
(120)	(180)	(120)	(100)	(200)	(—)	(—)	(—)	(—)
0.10	0.32	0.10	0.15	0.13	—	0.06	—	—
(250)	(800)	(250)	(375)	(325)	(—)	(150)	(—)	(—)
0.07	0.15	0.11	0.10	0.18	—	0.13	—	—
(41)	(88)	(64)	(58)	(105)	(—)	(76)	(—)	(—)
—	0.14	0.09	0.11	0.85	—	—	—	—
(—)	(96)	(62)	(75)	(587)	(—)	(—)	(—)	(—)
—	0.25	0.30	0.11	0.25	—	—	—	—
(—)	(133)	(160)	(59)	(133)	(—)	(—)	(—)	(—)
—	0.16	—	—	0.86	—	—	—	—
(—)	(101)	(—)	(—)	(541)	(—)	(—)	(—)	(—)
—	0.22	—	—	0.86	—	—	—	—
(—)	(128)	(—)	(—)	(500)	(—)	(—)	(—)	(—)
1.07	1.78	1.11	0.54	2.28	0.30	—	—	—
(188)	(312)	(195)	(95)	(400)	(53)	(—)	(—)	(—)
—	0.05	0.06	0.05	0.07	—	—	—	0.08
(—)	(125)	(150)	(125)	(175)	(—)	(—)	(—)	(200)
0.04	0.06	0.02	0.03	0.03	—	—	—	—
(67)	(100)	(33)	(50)	(50)	(—)	(—)	(—)	(—)
—	0.08	—	0.04	0.08	—	—	—	—
(—)	(133)	(—)	(67)	(133)	(—)	(—)	(—)	(—)
0.06	0.07	0.17	0.08	0.10	—	0.03	—	—
(50)	(58)	(142)	(67)	(83)	(—)	(25)	(—)	(—)
0.07	0.07	0.11	0.05	0.04	—	0.03	—	—
(175)	(175)	(275)	(125)	(100)	(—)	(75)	(—)	(—)
0.10	0.19	0.43	0.09	0.19	0.12	—	—	0.80
(250)	(475)	(1075)	(225)	(475)	(300)	(—)	(—)	(2000)
—	0.04	—	0.03	0.03	—	—	—	—
(—)	(40)	(—)	(30)	(30)	(—)	(—)	(—)	(—)
—	0.05	0.03	—	—	—	—	—	—
(—)	(50)	(30)	(—)	(—)	(—)	(—)	(—)	(—)
0.04	0.07	0.05	0.05	0.07	0.04	0.06	—	0.02
(80)	(140)	(100)	(100)	(140)	(80)	(120)	(—)	(40)
—	0.04	0.04	—	—	—	—	—	—
(—)	(22)	(22)	(—)	(—)	(—)	(—)	(—)	(—)
0.09	0.19	0.13	0.10	0.15	0.06	0.06	—	—
(53)	(112)	(76)	(58)	(88)	(35)	(35)	(—)	(—)
0.10	0.09	0.16	0.39	0.26	0.86	1.68	0.59	0.64
(111)	(100)	(178)	(433)	(289)	(956)	(1867)	(656)	(711)

and the water column. They absorb nutrients by active transport through roots (from sediment, but via pore water), and to some extent across the surface of leaves and other tissues. They also may absorb complex organic substances from their surroundings. We have therefore concluded that simple bioconcentration is an inadequate description of contaminant dynamics between plants, sediment, and water.

In conclusion, we recommend the use of the macrophyte, *Vallisneria americana,* as a biomonitor in the Great Lakes, specifically measuring relative growth to provide impairment indices or selection coefficients as metrics of contamination at different Areas of Concern, and to track the effects of remedial actions undertaken through RAPs (remedial action plans) by tracking conditions at one site, over time.

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