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INFLUENCE OF BIOLOGICAL FACTORS ON THE BIOACCUMULATION OF METALS BY <u>ELLIPTIO COMPLANATA</u> AND <u>LAMPSILIS RADIATA RADIATA</u> (BIVALVIA: UNIONIDAE) FROM THE ST. LAWRENCE RIVER

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NWRI CONTRIBUTION NO. 95-50

Influence of biological factors on the bioaccumulation of metals by Elliptio complanata and Lampsilis radiata radiata (Bivalvia: Unionidae) from the St. Lawrence River.

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Management Perspective

"Mussel watch" programs, which use concentrations of contaminants in the tissues of bivalves to indicate spatial and temporal trends in pollution, have been well-established in marine and estuarine environments for many years. Freshwater mussels could perform the same function in freshwater systems, but to date they have received surprisingly little attention. Studies on marine bivalves have shown that biological factors can significantly influence the bioaccumulation of metals by these organisms, and must therefore be standardized or accounted for in the design of biomonitoring programs. This study is believed to be the first major attempt to quantify the effects of biological factors on the bioaccumulation of metals by freshwater mussels. The impetus behind the study was to provide a biomonitoring technique in support of the St. Lawrence Action Plan (covering the Québec portion of the river) and the St. Lawrence River Remedial Action Plan (covering the Cornwall-Lake St. Francis area) that would demonstrate the success of cleanup activities and track improvements in the river over time.

A wide size range of specimens of Elliptio complanata and Lampsilis radiata radiata (F. Unionidae) was collected from the metal-polluted Sorel delta area of the St. Lawrence River in June 1990, and 35 males and females of each species were weighed, measured, aged and individually analyzed for residues of 12 metals in their soft tissues. The best-fitting multiple regression models predicting metal concentrations in mussels from these variables were then determined. Such models explained a substantial proportion of the variability in the data, ranging from 17% for Se to 68% for Mn. In general, species was the most important factor, followed by age/size, growth rate and sex, although age/size explained more of the variability than species for Cd and Hg. Standardizing for these factors, or accounting for them in multiple regression models, would therefore greatly improve precision in mussel monitoring programs. E. complanata generally accumulated higher and less variable concentrations of metals; thus this species would be the better choice for most biomonitoring applications.

Sommaire à l'intention de la direction

Depuis de nombreuses années, on a recours à des programmes de «surveillance des moules» pour recueillir des données sur les concentrations de contaminants dans les tissus des bivalves et les utiliser comme indicateurs des tendances spatio-temporelles de la pollution, en milieu tant marin qu'estuarien. Les moules d'eau douce pourraient fort bien être utilisées aux mêmes fins mais, assez curieusement, très peu d'attention leur a été accordée à ce jour. Les études sur les bivalves marins ont révélé que les facteurs biologiques peuvent avoir un effet déterminant sur la bioaccumulation des métaux par ces organismes. Ces facteurs doivent donc être pris en compte ou standardisés dans la conception des programmes de biosurveillance. À notre connaissance, la présente étude constitue la première véritable tentative de quantifier les effets des facteurs biologiques sur la bioaccumulation des métaux par les moules d'eau douce. L'objectif de départ était de mettre au point une méthode de biosurveillance utilisable dans le cadre du Plan d'action Saint-Laurent (portion québécoise du Saint-Laurent) et du Plan d'assainissement du Saint-Laurent (région Cornwall-lac Saint-François) pour montrer le succès des travaux de nettoyage et suivre l'évolution temporelle de l'assainissement du Saint-Laurent.

Des spécimens de toutes tailles d'*Elliptio complanata* et de *Lampsilis radiata radiata* (Unionidae) ont été récoltés en juin 1990 dans le Saint-Laurent, dans les eaux polluées par les métaux du delta de Sorel. On a pesé et mesuré 35 mâles et femelles de chacune des espèces, déterminé leur âge et effectué une série d'analyses afin de déterminer les concentrations des résidus de 12 métaux accumulés dans leurs tissus mous. Les meilleurs modèles de régression multiple permettant de prévoir les concentrations de métaux dans les moules à partir de ces variables ont ensuite été déterminés. Ces modèles expliquaient une part importante de la variabilité des données, qui variait de 17 % pour le Se à 68 % pour le Mn. De façon générale, le facteur le plus important était l'espèce, suivi par l'âge et la taille et par le taux de croissance et le sexe. Toutefois, pour le Cd et le Hg, l'âge et la taille expliquaient un plus fort pourcentage de la variabilité que l'espèce. La standardisation de ces facteurs ou leur prise en compte dans les modèles de régression multiple permettrait donc d'accroître considérablement la précision des programmes de surveillance des moules. De façon générale, les concentrations de métaux étaient plus élevées mais moins variables chez *E. complanata*. Cette espèce s'impose donc pour la majorité des applications de biosurveillance.

Abstract

Metcalfe-Smith, J.L., R.H. Green, and L.C. Grapentine. 1994. Influence of biological factors on the bioaccumulation of metals by Elliptio complanata and Lampsilis radiata radiata (Bivalvia: Unionidae) from the St. Lawrence River. Can. J. Fish. Aquat. Sci.

Studies on marine bivalves have shown that biological factors can significantly influence the bioaccumulation of metals by these organisms, but similar studies on freshwater mussels are virtually absent. This information is needed for the proper design of mussel monitoring programs in freshwater systems. A wide size range of specimens of Elliptio complanata and Lampsilis radiata radiata was collected from a metal-polluted site on the St. Lawrence River, and 35 males and females of each species were weighed, measured, aged and individually analyzed for residues of 12 metals in their soft tissues. The best-fitting multiple regression models predicting metal concentrations in mussels from these variables were then determined. Such models explained a substantial proportion of the variability in the data, ranging from 17% for Se to 68% for Mn. In general, species was the most important factor, followed by age/size, growth rate and sex, although age/size explained more of the variability than species for Cd and Hg. E. complanata generally accumulated higher and less variable concentrations of metals; thus this species would be the better choice for most biomonitoring applications.

Résumé

Metcalfe-Smith, J.L., R.H. Green et L.C. Grapentine. 1994. Effets des facteurs biologiques sur la bioaccumulation des métaux par *Elliptio complanata* et *Lampsilis radiata radiata* (Bivalvia : Unionidae) dans le Saint-Laurent. Journal canadien des sciences halieutiques et aquatiques.

Des études sur les bivalves marins ont démontré que les facteurs biologiques peuvent avoir un effet déterminant sur la bioaccumulation des métaux par ces organismes. Très peu d'études ont été consacrées à ce phénomène chez les bivalves d'eau douce. Cette information est extrêmement utile pour concevoir les programmes de surveillance des moules dans les écosystèmes d'eau douce. Des spécimens de toutes tailles d'*Elliptio complanata* et de *Lampsilis radiata radiata* (Unionidae) ont été récoltés dans le Saint-Laurent, dans un milieu pollué par les métaux. On a pesé et mesuré 35 mâles et femelles de chacune des espèces, déterminé leur âge et effectué une série d'analyses afin de déterminer les concentrations des résidus de 12 métaux accumulés dans leurs tissus mous. Les meilleurs modèles de régression multiple permettant de prévoir les concentrations de métaux dans les moules à partir de ces variables ont ensuite été déterminés. Ces modèles expliquaient une part importante de la variabilité des données, qui variait de 17 % pour le Se à 68 % pour le Mn. De façon générale, l'espèce était le facteur le plus important, suivi par l'âge et la taille et par le taux de croissance et le sexe. Toutefois, pour le Cd et le Hg, l'âge et la taille expliquaient un plus fort pourcentage de la variabilité que l'espèce. De façon générale, les concentrations de métaux accumulés étaient plus élevées mais moins variables chez *E. complanata*. Cette espèce s'impose donc pour la majorité des applications de biosurveillance.

Introduction

"Mussel watch" programs, which use concentrations of contaminants in the tissues of bivalves to indicate spatial and temporal trends in pollution, have been well-established in marine and estuarine environments for many years. Bivalves meet most of the criteria normally used for selecting a biomonitor to evaluate the distribution and bioavailability of contaminants; an up-to-date list of these criteria is provided by Crawford and Luoma (1993). In particular, bivalves are sedentary, relatively tolerant and hardy, of reasonable size and have high bioconcentration capacities for most organic and inorganic contaminants. Perhaps the most difficult criterion to satisfy is the need for concentrations of chemicals in a biomonitor to correlate well with levels of exposure (Johnson et al. 1993). Clearly, organisms that can regulate metals will not be suitable as indicators of metal bioavailability. Bivalves are generally considered to be poor metal regulators in comparison with more highly-evolved aquatic organisms such as fish and crustaceans (Bryan 1979), thus they offer a distinct advantage as biomonitors.

Despite the extensive use of marine bivalves in biomonitoring programs, freshwater mussels have received surprisingly little attention (Phillips and Rainbow 1993). This has been attributed to a lack of species with widespread distributions, but the fact that marine shellfish are consumed by humans while freshwater species are not is surely a factor. The only group of freshwater organisms for which protocols are well established are commercial species of freshwater fish (Crawford and Luoma 1993; Phillips and Rainbow 1993), even though fish are not the ideal choice for all biomonitoring applications.

According to Thomson et al. (1984), "...metal uptake by organisms remains the only method available for estimating biologically available metal concentrations in natural systems...". Although this is the main purpose of biomonitoring, organisms also provide a time-integrated measure of contaminant levels in the environment. Phillips and Rainbow (1993) believe the latter role to be even more critical in freshwater than marine systems, as temporal fluctuations are more extreme due to variations in river flows and the magnitude of trace metal sources. Unfortunately, organisms are also inherently variable. Studies on marine bivalves have shown that biological factors such as species, sex, age, size, reproductive cycle and nutritional status can significantly influence the bioaccumulation of metals by these organisms. Although the literature on the use of freshwater mussels to monitor metal pollution appears extensive (see Metcalfe-Smith et al. 1992, Metcalfe-Smith 1994 and references therein), a closer examination reveals that most studies were limited to assessing the upstream/downstream influence of a metal-discharging industry on a local species. There have been few attempts to standardize beyond species and perhaps a limited size range, even though it has long been recognized that the considerable variation in metal residues among individual mussels "...remains an obstacle to more extensive applications" (Millington and Walker 1983).

As the demands placed on freshwater mussel biomonitoring programs move beyond the simple documentation of point source impacts and toward more complex applications such as: (a) prioritization of sites for remedial action, (b) detection of incremental change over time in response to pollution abatement initiatives and (c) supporting the wide-ranging objectives of large-scale ambient monitoring programs such as the U.S. Geological Survey's National Water-Quality Assessment Program (Crawford and Luoma 1993), it is apparent that the design of these programs will have to become more sophisticated. The principles learned from studies on marine bivalves may apply to freshwater species; however, this has not been confirmed to date (Crawford and Luoma 1993). This study is believed to be the first major attempt to quantify the effects of biological factors (species, sex, age, size and growth rate) on the bioaccumulation of metals by freshwater mussels. It therefore takes a step toward the development of protocols for the use of these organisms in biomonitoring programs, and provides a basis for comparison with the marine literature.

Materials and Methods

Study site

The Sorel delta area of the St. Lawrence River was chosen for this investigation because it is known to be heavily contaminated with metals. The study site (Fig. 1) was located several kilometres downstream of three major metal-discharging industries, namely, Tioxide Canada Inc., Aciers Inoxydables Atlas Inc. (Atlas Steel) and Q.I.T.-Fer et Titane Inc. (Québec Iron and Titanium). In 1988, Tioxide produced 52,000 t of titanium dioxide pigments, Atlas Steel manufactured 60,000 t of stainless steel, and Q.I.T. produced 1,040,000 t of titanium slag (Gonthier 1991). According to a 1976-77 survey of the 43 industries discharging into the river between Cornwall, Ontario and Sorel, Québec, these three industries alone contributed nearly half of the total metal loadings to this 200 km reach (Environnement Canada 1985). Loadings of Pb, Ni, Fe, Cr and Zn from the industries, as well as Cu and Zn from the Richelieu River, were particularly high (Table 1). The most recent data available on industrial loadings are for 1989, and these are also shown in Table 1.

Collection, measurement and ageing of mussels

In previous work (Metcalfe-Smith 1994), Lampsilis radiata radiata (Subf. Lampsilinae) and Elliptio complanata (Subf. Ambleminae) were identified as the dominant species of unionids in the St. Lawrence River. Therefore, the study focused on these two species. A wide size range of specimens of both species was collected from the study site by SCUBA divers on 27 June 1990 during the peak of the reproductive season, i.e. just prior to the release of glochidia (Clarke 1981; Trdan 1981). A total of 201 L. r. radiata and 134 E. complanata were obtained. Mussels were rinsed clean of sediment using river water, wiped dry with Kimwipes®, placed in plastic food storage bags and immediately frozen on dry ice without permitting them to clear their digestive tracts. A rationale for omitting the depuration step is provided by Metcalfe-Smith (1994). In the laboratory, all specimens of E. complanata and 125 specimens of L. r. radiata were thawed for 30 min, then opened, sexed and shucked individually into acid-washed glass jars and weighed. As the latter species is dioecious and sexually dimorphic, all 201 specimens were first separated into males and females on the basis of shell shape. Then, 59 females and 66 males representing a wide size range were processed for each sex. E. complanata cannot be sexed by external examination, and populations may include dioecious, hermaphroditic and sequentially-hermaphroditic individuals (Downing et al. 1989). In a study on Lac de l'Achigan, Québec, Downing et al. (1989) found that hermaphrodites functioned as females but with an efficiency of ova or glochidia production that was correlated with the percentage of female tissue in their gonads. In the present study, the 65 gravid specimens were considered to be females and the 69 non-gravid specimens were designated as males.

In order to obtain an equal number of specimens and a similar gradient of sizes for each species:sex combination, all specimens in each category were sorted into size-classes based on 5 g intervals of soft tissue wet weight ranging from 5-10 g to 50-65 g. Four specimens from each size-class were then arbitrarily chosen for analysis. Where fewer than four specimens were available (the under 15 g and over 50 g size-classes), all were taken. A total of 35 specimens in each category was selected and these were individually freeze-dried, weighed and ground to a fine, homogeneous powder using a Bel-Art Micro-Mill® with stainless steel blades and grinding chamber. One male L. r. radiata had been misidentified as a male E. complanata, thus the sample sizes were adjusted to n = 36 and n = 34 for these two categories, respectively.

The shells of all 140 specimens selected for analysis were air-dried, then maximum length, height and width were measured to the nearest 0.01 mm using vernier callipers (dimensions are illustrated in Figure 2 of Green and Hinch 1986) and both valves were weighed together. Estimates of age for E. complanata and L. r. radiata were generally obtained by counting macroscopically visible external growth rings on the shells, which were assumed to be annual (Tevesz and Carter 1980). Shells were cleaned of sediment and attached algae, then examined using reflected and transmitted light from an incandescent lamp. The dark, annual growth rings were counted from the umbo outwards. During previous examinations of shells in this laboratory, the first visible growth ring tended to be 10 to 20 mm in length. This agrees with other estimates of length at one year (Lampsilis: McCuaig and Green 1983, Day 1984; Elliptio: Strayer et al. 1981). Thus, for shells in which a growth ring less than 20 mm in length was not visible due to erosion of the umbo region, the first visible ring (in all cases > 25 mm) was assumed to be the second year's growth ring. All specimens estimated to be less than 13 years old (49 of the 69 E. complanata and 60 of the 71 L. r. radiata) could be aged using external rings.

For approximately half of the 31 specimens aged 13 years and older (12 E. complanata and 3 L. r. radiata), counts of external growth rings were considered unreliable as estimates of age because rings were either (a) irregular or unusually close in their spacing (especially at the outer edges), or (b) weakly differentiated by their colour and physical relief from the adjacent periostracum. In these cases, cross sections or "thin sections" of the shells (Clark 1980; Day 1984) were prepared. Valves were cut along the longest axis from the umbo to the posterior edge using a low speed saw with a diamond blade. Cut surfaces were polished with emery and lapidary papers, and epoxy-glued to microscope slides. Shells were cut a second time to leave 0.5 to 1.0 mm sections, which were polished and coated with clear nail polish. Under light microscope (dissecting and/or compound), the dark lines extending through both the nacre and the prismatic layer were counted as annual growth bands (Day 1984).

Shell ageing is somewhat subjective; therefore, all estimates were made by the same experienced person (L.C. Grapentine). Table 2 provides a guide to the precision of age estimates based on the best judgement of the estimator. Nearly 95% of the mussels in this study could be aged to within a range of two years. Ages of the study specimens were 3 to 40 years for E. complanata and 2 to 17 years for L. r. radiata.

Analysis of mussels for metal residues in soft tissues

Mussels were analyzed individually for metal residues in their soft tissues by Environment Canada's National Laboratory for Environmental Testing (NLET), Burlington, Ontario, using standard procedures described in their Analytical Methods Manual (NLET 1992). Briefly, the analytical methods and associated detections limits (DLs) on a $\mu g.g^{-1}$ dry weight basis for the tested elements were: Hg - cold vapour atomic absorption (AA) spectroscopy, DL = 0.03; As and Se - atomic emission spectroscopy using an inductively coupled argon plasma (ICAP) system, DL = 0.50 for both elements; Al, Cr, Cu, Fe, Mn, Ni and Zn - direct aspiration AA spectroscopy, DLs = 0.50 (Ni), 2.0 (Cr, Cu, Zn), 10.0 (Fe, Mn) and 50.0 (Al); Cd and Pb - graphite furnace AA spectroscopy, DLs = 0.01 (Cd) and 0.20 (Pb). Samples were analyzed in accordance with the routine quality assurance (QA) procedures of the NLET, which include duplicate analyses to determine sample homogeneity, analysis of three reference materials to determine accuracy, spike-recovery tests to assess interference, and analysis of blanks to determine contamination due to laboratory procedures. Samples which do not meet the QA objectives are reanalyzed, and those which still do not meet the standards are rejected. No samples from this study were rejected. However, due to insufficient material one sample could not be analyzed for As, Se, Cd or Pb and two others could not be analyzed for Cd or Pb. Quality control reports are available from the authors. Raw data are attached as Appendix I.

Statistical methods

Measures of eight biological parameters (species, sex, age, dry weight of soft tissues, and shell length, width, height and weight) and twelve chemical parameters (concentrations of Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se and Zn as $\mu g.g^{-1}$ dry weight in the soft tissues) on 140 individual mussels from the study site constituted the dataset. Linear statistical models, i.e. multivariate and univariate analysis of covariance (MANCOVA, ANCOVA), were applied to the dataset in order to develop multiple regression models that best predicted metal concentrations in mussel tissues from biological factors. In such models relationships between variables should be linear. Therefore, the data were transformed to maximize linearity. Because interpretation of results is simpler if predictor variables are not highly correlated, principal components analysis (PCA) was used to reduce the biological parameters, which were expected to contain redundant information, to independent components prior to applying the models.

Correlation-based PCA was first performed on seven of the biological variables: species, sex, the four measures of shell size and dry tissue weight, with the latter five variables log-transformed for allometry. The first principal component (PC1) accounted for 61% of the variability and was strongly and similarly related to all five measures of size, but unrelated to sex or species. Therefore, it was defined as "PC size". PC2 accounted for 19% of the variability and represented species, with some loading on shell shape that would be species-related. PC3 explained 14% of the variability and loaded entirely on sex. Because age was significantly correlated with all size variables in both species ($r = 0.48$ to 0.67 in E. complanata and 0.56 to 0.72 in L. r. radiata, $p < 0.01$), it could not be used as an independent variable in the prediction models. A further PCA was thus performed on the variables PC size and age, using the transformation ln (age - 1.5) to achieve maximum linearity. PC1 accounted for 89% of the variability and had equal same-sign loadings on both variables. PC1 thus represented the main axis of the age-size relationship, distinguishing large/old from small/young mussels. PC2 accounted for the remainder of the variability (11%) and had equal opposite-sign loadings on the two variables. PC2 thus represented deviation from the main age-size relationship, distinguishing fast-growing from slow-growing mussels (Fig. 2).

After reducing the eight biological parameters to four independent components, namely species (species 1 = E. complanata, species 2 = L. r. radiata), sex (sex 1 = female; sex 2 = male), age/size (PC1 of the PC size vs. transformed age PCA) and growth rate (PC2 of the PC size vs. transformed age PCA), linear models were generated using these components as the predictors and metal concentrations (ln-transformed) as the dependent variables. Covariates were the age/size and growth rate components. Initially, MANCOVAs on the full dataset were used to assess significance of the four predictors across all dependent variables. These were followed by a series of ANCOVAs, one for each dependent variable, to examine the influences of biological factors on the accumulation of individual metals.

Results

Based on a MANCOVA test performed on the full dataset, all biological factors were significant predictors of metal concentrations in mussel tissues (Table 3). Significance of the species x sex interaction term indicated that the influence of sex was primarily species-dependent. MANCOVAs were also run separately for each species, and the results were similar in both cases (Table 3). Age/size was the most significant predictor, followed by growth rate, with sex being the least important factor influencing metal concentrations. Relationships appeared to be a bit stronger for E. complanata.

To determine the importance of the various biological factors as predictors of individual metals in mussels, univariate ANCOVAs were performed on the full dataset for each of the 12 metals. The models explained a substantial proportion of the variability in tissue residues for most metals, ranging from 17% for Se to 68% for Mn (Table 4). Species was a highly significant predictor for every metal except Se, and explained more of the variability than any other predictor for all remaining metals except Cd and Hg. Age/size was a significant predictor for all metals except Cr, Pb and Se, and concentrations of Cd and Hg were much more dependent on the age/size of a mussel than its species. Growth rate was also a significant predictor for half of the metals, accounting for 2-12% of the total variability. The effect of sex was significant for only three metals (Cd, Hg and Zn), but the species x sex interaction was significant for Cu and Se. This indicates that concentrations of Cd, Hg and Zn were higher in the same sex in both species, while concentrations of Cu and Se were higher in males of one species and females of the other. In any case, sex never explained more than 3% of the variability in the data.

Concentrations of Ni, Cr, Al, Cu, Pb, Hg and Fe were significantly higher in E. complanata, whereas those of Zn, As, Mn and Cd were significantly higher in L. r. radiata. Mean concentrations are compared in Table 5. To determine whether higher concentrations were accumulated by male vs. female, old vs. young or fast-growing vs. slow-growing mussels, separate ANCOVAs were performed for each species and the signs of the regression coefficients (positive or negative) were used to indicate the direction of each biological effect (Table 6). Concentrations of As, Cd, Mn, Zn, Hg and Fe were higher in older/larger individuals of both species, although the effect was not statistically significant for Fe in L. r. radiata. Concentrations of Cu, Al, Ni, Cr, and Se were higher in younger/smaller specimens of L. r. radiata, but only Cu showed this trend in E. complanata. Concentrations of Pb were not affected by age/size in either species. Growth rate was a significant predictor of Mn and Fe residues in both species and also of Cd, Hg, Se and Pb in E. complanata. In all cases, concentrations were higher in slower-growing mussels. For the three metals that had shown a significant sex effect in the full dataset (Cd, Zn and Hg), concentrations were higher in males of both species, but not significantly so. For the two metals that had shown a significant interaction between species and sex in the full dataset, Cu was higher in female E. complanata and Se was higher in male L. r. radiata.

In general, the prediction models accounted for more of the total variability in tissue metal concentrations for E. complanata than L. r. radiata (Table 6). For example, the largest proportion of variability explained for a metal in L. r. radiata was 29% for Cd, whereas 46-73% was explained for Cd, Fe, Hg, Mn and Zn in E. complanata. The notable exception was Al, for which age/size accounted for a significant proportion of the variability in L. r. radiata but none of the biological factors had predictive value for E. complanata. Table 5 compares the coefficients of variation (CV) for each metal between the two species. Concentrations of Ni, Cr, Al, Zn and As were much more variable in L. r. radiata, whereas concentrations of Mn, Cd and Se were slightly more variable in E. complanata and there were no differences between species for Cu, Pb, Hg and Fe. Thus, for most metals E. complanata displayed less variability among individuals, and more of this variability could be explained.

Although it is appropriate to use techniques such as PCA and log-transformation of the data to quantify relationships between biological factors and metal concentrations in mussels, it is useful to return to the raw data for confirmation. Four metals selected to illustrate the various relationships are presented in Fig. 3, where concentrations of Cr, Zn, Cd and Cu in mussel tissues are plotted against true age for each species:sex combination. Species accounted for 41% of total variability in the data for Cr, where concentrations were higher in E. complanata than L. r. radiata; none of the other biological factors were significant predictors of this metal (Fig. 3a). Species accounted for 39% of the total variability for Zn and concentrations were higher in L. r. radiata than E. complanata (Fig. 3b). Concentrations were also significantly higher in older specimens and in males of both species, however, age/size explained much more of the total variability (17%) than sex (2%). Similar to Zn, levels of Cd were significantly higher in L. r. radiata than E. complanata and in older specimens and males of both species (Fig. 3c). However, interspecific differences accounted for only 5% of the total variability for this metal, whereas age/size accounted for 36% and growth rate (higher concentrations in slower-growing mussels) an additional 6%. Copper (Fig. 3d) was the only metal for which concentrations were significantly higher in younger/smaller specimens of both species. The significant species x sex interaction for this metal was driven by higher concentrations in female E. complanata.

Discussion

Use of linear models to predict metal concentrations in bivalves from biological factors

Metal concentrations in the tissues of unionids from the Sorel delta area of the St. Lawrence River were significantly influenced by biological factors. In general, species was the most important determinant, followed by age/size, growth rate and sex. Several other studies have used similar models to show that biological factors account for much of the variability in the metal burdens of freshwater and marine bivalves. Hinch and Stephenson (1987) analyzed the gills and bodies of E. complanata from two relatively uncontaminated Ontario lakes for Cd, Cu, Mn and Zn, and found that age and shell length were frequently as important as, or even more important than, the lake of origin as sources of variability. Jones and Walker (1979) calculated multiple linear regressions of Cd, Fe, Mn and Zn concentration against shell volume (a measure of the amount of shell material produced and thus an indicator of age) and dry body weight for the freshwater mussel Velesunio ambiguus from the River Murray in South Australia. Their models explained a significant proportion of the variability for all metals except Cd. Popham and D'Auria (1983) collected 20 size groups of the blue mussel, Mytilus edulis, from a clean and a polluted site in Burrard Inlet, British Columbia over a period of 13 months, and determined the effects of both mussel size (dry weight) and season on concentrations of various elements in the tissues. Their models explained a significant amount of the variation for Cu, Fe, Mn, Pb, Zn, Br and Sr. Both factors were significant determinants for most elements, although the influence of season was mainly due to seasonal changes in weight. Popham and D'Auria (1983) found that the way in which concentrations of elements were influenced by size and season differed between the two sites, and concluded that regression equations derived for one location cannot necessarily be applied to another location with a different pollution status. Strong and Luoma (1981) came to similar conclusions in their study of four populations of Macoma balthica in San Francisco Bay.

Lobel et al. (1989) collected M. edulis from a subtidal site in Newfoundland and determined the contribution of biological factors to the total variability in tissue residues for 25 elements. Predictors included all of those considered in the present study except age, plus condition index, various growth ratios (e.g. shell width:height), and an "insolubility index" that measured the contribution of gut contents and was only significant for Al. They included many redundant variables in their models and the predictive values of individual parameters were difficult to separate. However, sex was significant for the largest number of elements, followed by soft tissue dry weight and condition factor, followed by width:height ratio, which is an indicator of relative age. The importance of sex was clearly greater for M. edulis than for E. complanata or L. r. radiata in the present study. Lobel et al. (1989) accounted for significant proportions of the variability in their data for Al, As, Cd, Cu, Mn, Pb, Se and Zn (Cr, Fe, Hg and Ni were not tested). In a later paper, which appears to have examined a subset of these mussels, Lobel et al. (1991) reported that chronological age was not a significant predictor of any element in specimens aged 3 to 14 yrs. They concluded that "...age is better dealt with in physiological terms by factors such as size, condition and growth rate...". In contrast, chronological age (in combination with size) had more influence than growth rate on metal concentrations in unionids from the St. Lawrence River.

Influence of species on metal accumulation

Intuitively, one would expect species to be the most important biological factor influencing the metal concentrations accumulated by mussels. With the notable exceptions of Cd and Hg, species was the most significant predictor of metal levels in the current study. Interspecific differences observed were consistent with those reported in previous studies on the St. Lawrence and Ottawa Rivers (Metcalfe-Smith 1994 and Metcalfe-Smith et al. 1992, respectively; Table 7). In most cases, these differences were so dominant that they emerged even when the samples were not controlled for other biological factors. For some elements, increasing the sample size or standardizing for biological parameters noticeably enhanced the differences between species. Absolute concentrations in tissues varied between species by factors ranging from 1.2 to 2.5 X in both this study (calculated from mean values given in Table 5) and the earlier St. Lawrence River studies, and by 1.5 to 2.5 X in the Ottawa River study. Metcalfe-Smith et al. (1992) reviewed the literature comparing metal accumulation among various species of unionids, and found that maximum factors of 2 to 3 X were most commonly observed. Reasons for the differential uptake of metals by E. complanata vs. L. r. radiata are not understood at present. Both species are filter-feeders and they coexist in mixed colonies, suggesting that their exposure regimes should be similar. However, they are members of different subfamilies of the F. Unionidae and have different reproductive strategies, growth rates and lifespans. There are also indications that L. r. radiata may be more capable of regulating metals (Metcalfe-Smith 1994).

Influence of size and age on metal accumulation

Since the early work of Boyden (1977) identified a strong link between organism size and metal uptake in shellfish, the influence of size and, to a lesser extent, age on metal accumulation by marine and freshwater bivalves has been a topic of considerable research. The magnitude and direction of these effects have been shown to vary greatly among and within metals, species and studies (Brix and Lyngby 1985; Hinch and Stephenson 1987; Elder and Collins 1991). As a result, few generalizations have been made. While some differences among metals and species might be expected, differences among studies on the same metals or species are more difficult to explain. Much of the confusion may be due to the great variety of conditions under which these relationships have been tested. Factors such as sample size, the biological response variables measured and their ranges (Boyden 1977; Bryan and Uysal 1978), sampling season (Strong and Luoma 1981; Lobel et al. 1991) and the pollution status of the study site (Manly and George 1977; Popham and D'Auria 1983) have considerable influence on the relationships between size or age and metal concentrations in bivalves.

Twenty-five papers on the influence of size or age on metal uptake by bivalves, including eight on freshwater mussels and 17 on marine bivalves, were reviewed for comparison with the present study. Only studies on natural populations were considered, i.e. laboratory experiments and caged mussel studies were not included. All studies considered size, and five also considered age. Results for size are summarized in Table 8 (a detailed compilation of the data is presented in Appendix II). Data on freshwater mussels are presented separately from those on marine mussels, because they are directly relevant to the present investigation. The 25 studies examined 18 different species from 65 locations of varying pollution status. Sample sizes used to determine relationships between size and metal residues ranged from 5 to 126 specimens analyzed individually or in composites. Metal concentrations in whole soft tissues, or in a few cases individual organs, were related to either dry weight (most studies), wet weight or shell length of the organism. Ranges of values tested varied from 3 to 430 X for dry weight, 2 to 25 X for wet weight and 2 to 3 X for shell length. Season or reproductive condition were reported only sporadically. It is apparent from the variety of experimental conditions and their potential for confounding the results that few studies can be directly compared. However, the body of information can be examined for prevailing trends and compared with the results of the present study. Because age and size were significantly correlated in E. complanata and L. r. radiata populations from the Sorel delta, it was assumed that the effect of age/size in this study would be comparable to the effect of size in other studies. In fact, separate linear regressions of metal concentrations against age and size yielded the same trends. The influence of age will be specifically addressed later.

Unfortunately, there have been very few studies to date on freshwater mussels and most were conducted at uncontaminated sites. Furthermore, Merlini et al. (1965), Renzoni and Bacci (1976) and Hinch and Stephenson (1987) used concentrations in organs, rather than whole soft tissues, to determine relationships. Nevertheless, some general trends emerge from Table 8a. Relationships between size and metal concentrations in mussels were more often significant at polluted sites (57% of 21 tests) than clean sites (37% of 71 tests). Where significant relationships occurred, they were usually negative at clean sites (54% of significant tests) and positive at polluted sites (58%). However, this dataset is very small and the findings are inconclusive. Trends for individual metals were unclear except that concentrations of Cu tended to be higher in smaller specimens.

The data on marine bivalves are more extensive (Table 8b), but it is not known how readily they can be applied to freshwater mussels. For example, many of the species tested were deposit feeders that might be expected to behave differently than filter-feeders. Similar to the results for freshwater mussels, however, relationships were more often significant at polluted sites (72% of 72 tests) than clean sites (61% of 88 tests). In general, significant relationships were more common among marine than freshwater studies. Where significant relationships occurred, they were usually negative at both clean (85% of significant tests) and polluted sites (60%). However, the incidence of positive relationships was obviously much greater at polluted sites. This suggests that at relatively uncontaminated sites, bivalves are able to regulate at least some metals such that body burdens do not accumulate over time. However, at polluted sites these mechanisms fail and body burdens increase with size and age. Trends were examined on a metal-by-metal basis and were in several cases similar to those observed for freshwater mussels. Concentrations of Cu in marine and freshwater bivalves, including E. complanata and L. r. radiata, were consistently higher in smaller animals. Copper is an essential nutrient that may be well-regulated by many species, thus preventing it from accumulating over time. Zinc demonstrated the same trend as Cu in marine bivalves from clean sites, but the reverse trend at polluted sites. Levels of Zn were also higher in older/larger unionids from the Sorel delta area, which is known to be highly contaminated with Zn. This suggests that the regulatory capabilities of bivalves for Zn, which is also an essential nutrient, may be more limited than those for Cu. Concentrations of Ni were usually higher in smaller marine bivalves, and this was also observed for unionids. Iron and Mn were higher in smaller marine bivalves at all sites where significant relationships were observed. In contrast, Fe and Mn were higher in larger E. complanata and L. r. radiata in the present study. Seah and Hobden (1969) and Hobden (1970) found that Mn and Fe were actively accumulated by E. complanata and stored in an insoluble form that was not depleted after 6 months of starvation. In earlier work, they had found that concentrations of Fe in M. edulis, which were initially one-third of those in E. complanata, decreased steadily under conditions of starvation until a stable level of permanently stored Fe was reached. It would appear that unionids have a greater capacity for storing Fe and Mn, which would accumulate over time and hence be higher in larger animals. Trends for Pb and Cd were variable, with negative, positive and insignificant effects observed in marine bivalves from both clean and polluted sites. Age/size did not influence Pb concentrations in either E. complanata or L. r. radiata, but Cd levels were higher in older/larger specimens of both species. Data on Al, As, Cr, Hg and Se were insufficient to draw any general conclusions from the marine data, although the two studies on Hg reported, as we did, higher concentrations in larger animals.

For the six metals showing an increase in concentration with increasing age/size in E. complanata and L. r. radiata, this effect explained a considerable proportion of the variability in the data for all metals except As. For the five metals showing an increase in concentration with decreasing age/size in one or both species, the proportion of the variability accounted for was much lower. According to Strong and Luoma (1981), smaller individuals of many bivalve species accumulate higher concentrations than larger individuals due to their more rapid uptake rates. For metals that do not accumulate over time, i.e. those that can be regulated, a negative correlation may occur when young animals have been included in the sample. For slow-exchanging metals such as Cd and Hg that have been shown to accumulate with age (Strong and Luoma 1981), the negative influence of younger animals may be offset and an overall positive correlation for the metal would result. Negative correlations between age/size and metal levels were significant for Cu, Al, Ni, Cr and Se in L. r. radiata, but only for Cu in E. complanata. Metcalfe-Smith (1994) found that L. r. radiata displayed a narrower range of tissue concentrations for all metals except Mn and Zn than sympatric E. complanata from 11 sites of varying pollution status on the St. Lawrence River, and concluded that L. r. radiata may be more capable of regulating metals. This would be consistent with the greater number of negative correlations observed for this species in the present study.

Bivalves tend to become larger as they age, hence one would expect age and size to be directly related and the influence of both factors on the accumulation of metals to be the same. Many studies on unionids have demonstrated significant positive correlations between age and various measures of organism size (for a review, see Metcalfe-Smith and Green 1992). Others, however, have found age and size to be poorly related (e.g. Hinch and Stephenson 1987; Hanson et al. 1988). Age and size are not simple parameters; rather, they represent multiple biological processes. Size, for example, may reflect factors such as growth rate and surface-to-volume ratio, whereas age may reflect sexual maturation and duration of exposure (Newman and Heagler 1991). It therefore seems plausible that the effects of age and size on metal bioaccumulation might differ. Williamson (1980) reported that age and size (body weight) had opposite and independent effects on Cd concentrations in a land snail, and recommended that the two factors be controlled separately in biomonitoring programs. Actually, he found that concentrations of Cd increased with both age and size over the entire population, because age and size were correlated. However, within a given year-class concentrations were higher in smaller individuals. Williamson (1980) felt that this was due to higher metabolic rates, and hence greater uptake, in animals that were small for their age. Whereas rapid uptake might explain the high concentrations sometimes observed in very young mussels, it would not explain differences among members of a cohort. Within a specific year-class, it is more likely that animals that are small for their age would be slower-growing and thus have slower metabolic rates. It follows that they may also have slower uptake rates, but the effect could be offset by less dilution of body residues. Williamson's (1980) study is often quoted as an example of the opposite effects of age and size on metal uptake, but this is somewhat misleading. In fact, his findings point out the importance of growth rate as a determining factor.

As previously mentioned, only five investigators considered the influence of both size and age on the accumulation of metals by bivalves. Of these, only two aged their specimens, as we did, by counting annual growth bands in the shells (Hinch and Stephenson 1987 for E. complanata and Lobel et al. 1991 for M. edulis). Langston (1980) inferred ages of Scrobicularia plana from shell length using the Walford Plot method, while Jones and Walker (1979) and Millington and Walker (1983) used shell volume as a surrogate for age in their studies on V. ambiguus. One might expect that where age and size were correlated, both factors would have the same effect on metal uptake. Conversely, where age and size were not correlated, opposite effects might occur. This was generally true, although there were exceptions. Langston (1980) found that age and size of S. plana were correlated in three different populations, and that the effects of both parameters on As concentration were the same, i.e., effects of both age and size were negative in an uncontaminated estuary, positive in a polluted estuary and insignificant at an intermediate site. Jones and Walker (1979) reported that age and size were not correlated in V. ambiguus from a site on the River Murray, and that concentrations of Fe, Mn and Zn increased with age but decreased with dry weight. Millington and Walker (1983) sampled the same site in the same year and confirmed the result for Fe, but reported strong correlations between age and size for this population. Hinch and Stephenson (1987) determined that age and size were not correlated in populations of E. complanata from Beech and Tock Lakes in Ontario, but observed only one statistically significant opposite effect among 16 age-size comparisons involving five metals and two components of the soft tissues (gills and bodies). Interestingly, Campbell and Evans (1991) collected a similar number of E. complanata of the same size range from Beech Lake a year later and found that age and size were highly correlated. They observed a significant positive correlation between size and Cd concentration in whole soft tissues, as did Hinch and Stevenson (1987) for gills and bodies. Finally, Lobel et al. (1991) examined the effects of age and size on concentrations of 24 elements in M. edulis. The effect of size (dry weight) was significant for 14 elements and negative for all except potassium. Chronological age was not a significant predictor of any element. However, width to height ratio (W:H), which is an indicator of relative age, was significant for seven elements and always positive. Lobel et al. (1991) did not state whether age and size were correlated in their study population, but it appears that they were not. The use of W:H as an indicator of age deserves comment. Animals age at rates that are individually determined by genetic and environmental factors. A parameter such as W:H, which represents the physiological age of an individual, should therefore be a more sensitive indicator of the ageing process than a categorical parameter such as chronological age. This might explain why significant relationships were observed for W:H but not for years of age in Lobel et al.'s (1991) study. Concentrations of As, Cd, Fe, Hg, Mn and Zn in E. complanata and L. r. radiata from the St. Lawrence River were found to be higher in older specimens. The same relationship was also observed for these metals in several other studies, e.g. Fe, Mn and Zn in V. ambiguus (Jones and Walker 1979; Millington and Walker 1983), As and Cd in M. edulis (Lobel et al. 1991) and As in S. plana from a contaminated site (Langston 1980).

Influence of growth rate on metal accumulation

By using PCA, we were able to extract a growth rate component from the dataset and to evaluate its influence on metal concentrations separately from age and size per se. The effect of growth rate was significant for Cd, Fe, Hg, Mn, Pb and Se in E. complanata, but only for Fe and Mn in L. r. radiata. In all cases, concentrations were higher in slower-growing mussels. The effect may have been more pronounced in E. complanata due to the wider range of ages and thus growth rates among the tested specimens, or because this species had a slower growth rate in general. Over the full range of specimens examined, the average yearly increment in soft tissue dry weight was 0.09 g for E. complanata vs. 0.23 g for L. r. radiata. These values are not directly comparable, because all L. r. radiata were 17 years old or younger, whereas nine E. complanata were between the ages of 18 and 40. However, when growth rates of specimens aged three to 17 years were compared, the average yearly increment was still 20% lower for E. complanata (0.20 g) than L. r. radiata (0.24 g).

Other investigators have consistently reported higher concentrations of metals in slower-growing bivalves whenever the effect of growth rate was significant. Davies and Pirie (1978) examined trends for Hg in separate size classes of M. edulis from the Firth of Forth, Scotland, and in the population as a whole. They found that concentrations of Hg increased with increasing wet tissue weight at the population level, but within each size class the correlation tended to be negative. This is very similar to the findings of Williamson (1980) for Cd in land snails. Langston (1980) found that the growth rate (increase in dry soft tissue weight with age) of S. plana slowed with age in a contaminated estuary in Wales and accelerated with age in a clean estuary. In both locations, concentrations of As were higher in slower-growing clams, thus levels increased with age at the contaminated site and decreased with age at the clean site. Lobel and Wright (1982) determined the influence of various biological factors on levels of Zn in M. edulis from the Tyne

Estuary, UK, and used the ratio of soft tissue dry weight to shell dry weight as an indicator of flesh condition (FC). Although not strictly comparable to the growth rate parameter used in the present study, both variables provide a measure of the degree of dilution by soft tissue. Lobel and Wright (1982) found that FC was negatively correlated with Zn concentration, suggesting that levels were higher in animals that were "less meaty". In later studies on M. edulis from Newfoundland, Lobel et al. (1991) replaced FC with CI (condition index = soft tissue dry weight: shell length x width x height), because they felt it was a more reliable indicator of condition. They concluded that CI was the most important variable influencing element concentrations in mussels, because it was highly significant for all chemical classes. For 14 of the 24 elements tested, including Cd, Cu, Mn and Pb, concentrations were higher in specimens with a low flesh weight for the size of their shell. Concentrations of Al, As, Se and Zn were unaffected.

Influence of sex on metal accumulation

Sex was the least important factor influencing metal concentrations in unionids, accounting for at most 3% of the overall variability in the data. Concentrations of Cd, Hg and Zn were higher in males of both species, but the effect appeared to be weak since it only reached statistical significance when all 140 specimens were considered. The effect of sex on levels of As, Cu, Mn and Se was species-dependent, i.e., concentrations differed between the sexes for one species but not the other. In a related study that was conducted concurrently, Metcalfe-Smith (1994) compared metal concentrations in males and females of these species among six sites on the St. Lawrence River. Samples were analyzed as composites, and differences between the sexes were determined over all sites using a paired-difference test. The Sorel study site was included in the investigation. Concentrations of Cu were found to be higher in female than male E. complanata, while concentrations of Cd, Fe, Se and Zn were higher in male than female L. r. radiata. The results of the two studies taken together suggest that Cu and As tend to be higher in female mussels, while Cd, Fe, Hg, Mn, Se and Zn tend to be higher in males. There were no apparent differences between the sexes for Al, Cr, Ni or Pb.

Studies on marine mussels have shown that concentrations of metals in both males and females are highest immediately prior to spawning, and that differences between the sexes are at a minimum during this period (for a review, see Metcalfe-Smith 1994). In this study, unionids were collected just before releasing their glochidia. Thus, it is possible that sex may be a more important source of variability at other times of the year. Only one other study on a freshwater mussel was available for comparison. Jones and Walker (1979) found no differences in the accumulation of Cd, Fe, Mn or Zn by male vs. female V. ambiguus, but did not describe the reproductive status of the specimens. The literature on marine bivalves generally showed that sex was an important predictor of metal residues and, in contrast to the results for unionids, that levels were usually higher in females. The results of five studies (Watling and Watling 1976 for Choromytilus meridionalis, no season given; Orren et al. 1980 for post-spawn C. meridionalis; Klumpp and Burdon-Jones 1982 for pre-spawn Trichomya hirsuta; Latouche and Mix 1982 for M. edulis, no season given; Lobel et al. 1989 for post-spawn M. edulis) were remarkably consistent. They indicated that Cu, Fe, Mn, Zn and probably also As and Se were higher in female mussels, Pb was higher in males, and there were no differences between the sexes for Cd, Ni and probably also Al and Cr. Lobel et al. (1991) determined that sex explained most of the variability in their data for As, Cu, Mn, Se and Zn in M. edulis.

Conclusion

In conclusion, biological factors accounted for a substantial proportion of the variability in tissue metal concentrations among individual freshwater mussels from a metal-contaminated site on the St. Lawrence River. Standardizing for these factors, or accounting for them in multiple regression models, would therefore greatly improve precision in biomonitoring programs that use mussels to determine spatial and temporal trends in metal pollution. Species, size, age and probably growth rate should all be considered when designing a mussel monitoring program, but sex could be ignored at little cost. The influences of biological factors sometimes differed greatly among metals; however, relationships for a given metal were often similar in both species. E. complanata would be the superior choice for biomonitoring for the following reasons: (a) it exhibited less individual variation in metal levels than L. r. radiata, and more of this variability could be explained; (b) it accumulated higher concentrations of most metals; and (c) it was shown in earlier work (Metcalfe-Smith 1994) to have a greater capacity for discriminating among sites of differing pollution status, probably because of a general inability to regulate metals. Comparisons between this study and the marine literature revealed many inconsistencies with respect to the relative importance of various biological factors as predictors for certain metals and the magnitude and direction of their effects on tissue concentrations. For example, sex seemed to be more important and age less important in marine bivalves, and the influence of size was usually significant regardless of the pollution status of the study site. There may be fundamental differences in the mechanisms of bioaccumulation between marine and freshwater mussels or in the behaviour of metals in marine vs. freshwater systems. However, more studies must be conducted in freshwater systems before it can be determined if marine "mussel watch" protocols are applicable to freshwater mussel monitoring programs, or if new protocols must be developed.

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TABLE 1. Combined loadings of metals (kg·d^{-1}) to the Sorel delta area of the St. Lawrence River from industrial point sources (Québec Iron and Titanium, Atlas Steel and Tioxide Canada Inc.) in 1976-77 and 1989, and loadings from the Richelieu River in 1976-77. Data for 1976-77 from Environnement Canada (1985); 1989 data on Q.I.T. and Atlas Steel from Danielle Joly, Environmental Protection Service, Montréal (pers. comm.); 1989 data on Tioxide from Centre Saint-Laurent (1992). NA = data not available.

	Loadings of metals (kg·d^{-1})		
Metal	Industries, 1976-77	Industries, 1989	Richelieu River, 1976-77
Al	NA	1764	NA
Cd	0.60 (3.5%)*	19	NA
Cr	570 (61%)	513	NA
Cu	148 (34%)	311	1135
Fe	29101 (67%)	98734	18
Hg	0.18 (19%)	0.11	NA
Ni	225 (80%)	217	NA
Pb	942 (97%)	44	109
Zn	923 (55%)	325	1587

* % of total loadings from the 43 industries discharging to the river between Cornwall, Ontario and Sorel, Québec.

TABLE 2. Precision of age estimates for E. complanata and L. r. radiata based on counts of annual growth increments (external rings or internal bands) in the shells.

Precision of age estimate (± # years)	E. complanata External rings (n = 57)	E. complanata Internal bands (n = 12)	L. r. radiata External rings (n = 68)	L. r. radiata Internal bands (n = 3)
	Number of specimens in each precision category			
0	21	0	28	0
0.5[a]	18	0	28	0
1	17	5	12	2
1.5[b]	1	0	0	0
2	0	2	0	0
3	0	3	0	1
5-10	0	1	0	0
10-15	0	1	0	0

[a]range of 1 year, e.g. 6-7; [b]range of 3 years, e.g. 6-9.

TABLE 3. Significance of biological factors as predictors of metal concentrations in mussels (results of MANCOVA tests where x = biological factors, y = ln-transformed concentrations of all 12 metals, n = 137 for species combined, n = 69 for E. complanata, and n = 68 for L. r. radiata).

Species combined		Species separate		
Predictor	Probability value	Predictor	E. complanata Probability value	L. r. radiata Probability value
Species	0.0001 **	Sex	0.0487 *	0.0679
Sex	0.0947	Age/size	0.0001 **	0.0001 **
Species x Sex	0.0024 **	Growth rate	0.0013 **	0.0398 *
Age/size	0.0001 **			
Growth rate	0.0001 **			

** significant @ $p < 0.01$; * significant @ $p < 0.05$.

TABLE 4. Significance of biological factors as predictors of metal concentrations in mussels (results of ANCOVA tests where x = biological factors, y = ln-transformed concentrations of individual metals, n = 137 for Cd and Pb, n = 139 for As and Se, and n = 140 for all other metals).

	Percent of total variability in the data explained by the model and by individual predictors					
Metal	Model	Species	Age/size	Growth rate	Sex	Species x Sex
Mn	68% **	38% **	27% **	2% **	-	-
Zn	59% **	39% **	17% **	-	2% *	-
Fe	55% **	35% **	14% **	6% **	-	-
Ni	51% **	48% **	2% *	-	-	-
As	49% **	38% **	7% **	-	-	-
Cd	49% **	5% **	36% **	6% **	2% *	-
Cr	42% **	41% **	-	-	-	-
Pb	42% **	38% **	-	3% *	-	-
Hg	40% **	9% **	25% **	3% *	2% *	-
Al	31% **	23% **	6% **	-	-	-
Cu	28% **	17% **	8% **	-	-	3% *
Se	17% **	-	-	12% **	-	3% *

** significant @ $p < 0.01$; * significant @ $p < 0.05$; - not significant.

TABLE 5. Mean concentrations of metals ($\mu g.g^{-1}$ dry weight) in E. complanata (n = 69) and L. r. radiata (n = 68 for Cd and Pb, n = 70 for As and Se, and n = 71 for all other metals), and coefficients of variation (CV = SD/mean X 100%).

	E. complanata		L. r. radiata	
Metal	Mean conc'n	CV	Mean conc'n	CV
Ni	7.81 **	32%	3.10	88%
Cr	25.8 **	34%	12.2	74%
Al	718 **	56%	300	79%
Cu	14.3 **	25%	11.3	28%
Pb	10.81 **	34%	6.07	36%
Hg	0.12 **	42%	0.10	40%
Fe	8783 **	36%	5167	37%
Zn	223	30%	448 **	58%
As	3.43	22%	5.43 **	36%
Mn	1592	48%	2954 **	38%
Cd	0.40	70%	0.51 **	59%
Se	2.65	16%	2.58	10%

** concentration significantly higher in this species @ $p < 0.01$.

TABLE 6. Significance of biological factors as predictors of metal concentrations in E. complanata and L. r. radiata, the direction of each effect, and percent of total variability in the data explained by the models. (a "+" sign indicates higher concentrations in male, older/larger and faster-growing mussels; a "–" sign indicates higher concentrations in female, younger/smaller and slower-growing mussels).

	E. complanata				L. r. radiata			
	Predictor and direction of its effect				Predictor and direction of its effect			
Metal	Sex	Age/size	Growth rate	Percent variability explained by model	Sex	Age/size	Growth rate	Percent variability explained by model
As	– *	+ **	–	27% **	+	+ **	–	13% *
Cd	+	+ **	– **	63% **	+	+ **	–	29% **
Mn	+ *	+ **	– *	73% **	–	+ **	– *	21% **
Zn	+	+ **	–	57% **	+	+ **	–	25% **
Hg	+	+ **	– **	46% **	+	+ **	–	23% **
Fe	+	+ **	– **	65% **	+	+	– **	14% *
Cu	– *	– *	+	12% *	+	– **	+	14% *
Al	–	–	+	6%	+	– **	+	17% **
Ni	–	–	+	5%	+	– *	+	8%
Cr	–	+	–	3%	+	– *	+	9%
Se	–	+	– **	23% **	+ *	– *	–	15% *
Pb	+	+	– **	15% *	–	–	–	6%

** significant @ $p < 0.01$; * significant @ p 0.05.

TABLE 7. Differences in the bioaccumulation of metals by E. complanata vs. L. r. radiata compared among several studies on the St. Lawrence and Ottawa Rivers. The species with the higher concentration (E or L) and level of significance are presented. Where differences observed were not statistically significant, the species that tended to have the higher concentration is indicated in brackets.

Metal	This study	St. Lawrence R., 1989[1] 11 sites tested together[a]; composites of 3 males and 2 females/site	St. Lawrence R., 1990[1] 6 sites tested together[a]; composites of 5 specimens/sex/site Males	Females	Ottawa R., 1985-86[2] 3 sites tested separately; 4-13 individuals/site; sex not determined	
Cr	E **	E **	E *	(E)	E **	(2 of 3 sites)[b]
Ni	E **	E **	E **	E *	E *	(1 of 3 sites)
Fe	E **	E **	(E)	E *	NA	
Hg	E **	E **	E **	E **	E **	(1 of 3 sites)
Al	E **	E **	E *	(E)	NA	
Se	(E)	(E)	(E)	E *	E *	(2 of 3 sites)
Pb	E **	(E)	(E)	(E)	NA	
Zn	L **	L **	L **	L *	L **	(3 of 3 sites)
Cu	E **	L **	(L)	(E)	L *	(2 of 3 sites)
Mn	L **	L **	(L)	L **	NA	
As	L **	L *	L *	(L)	L *	(1 of 3 sites)
Cd	L **	(L)	L **	(L)	L *	(1 of 3 sites)

** significant @ $p < 0.01$; * significant @ $p < 0.05$; NA = not analyzed.
[a]paired-difference test used to determine mean difference between species over all sites.
[b]no difference between species at the remaining site(s).
[1]Metcalfe-Smith (1994); [2]Metcalfe-Smith et al. (1992).

TABLE 8. Summary of the literature on relationships between organism size and concentrations of metals in the soft tissues of freshwater mussels and marine bivalves from clean and metal-polluted sites. Size parameters tested included dry weight (15 studies), wet weight (3 studies) and shell length (7 studies).

8a. Freshwater mussels

Numbers of clean and polluted sites at which negative, insignificant and positive correlations observed

	Clean sites			Polluted sites				
Metal	Negative	Insignificant	Positive	Negative	Insignificant	Positive	# species tested	References
Cd	8	18	2	-	-	3	3	5,10,21,24.
Cu	2[a]	4	1[a]	3	1	-	3	5,21,22.
Cr	-	-	1	-	-	-	1	22.
Fe	2	2	1	-	-	-	2	10,18,22.
Mn	1	2[b]	3[b]	-	-	-	3	1,10,21,22.
Ni	-	4	-	-	3	-	1	5.
Pb	-	4	-	-	-	3	1	5.
Zn	1	8[c]	4[c]	-	3	-	4	5,10,18,21,22.
Hg	-	3	-	2	2	1	2	2,5.
Totals	14	45	12	5	9	7	4	

[a]at one site, gills showed a negative correlation and bodies a positive correlation.
[b]at one site, gills showed no relationship and bodies showed a positive correlation.
[c]at two sites, gills showed no relationship and bodies showed a positive correlation.

TABLE 8 (continued).

8b. Marine bivalves

Numbers of clean and polluted sites at which negative, insignificant and positive correlations observed

Metal	Clean sites: Negative	Clean sites: Insignificant	Clean sites: Positive	Polluted sites: Negative	Polluted sites: Insignificant	Polluted sites: Positive	# species tested	References
Cd	3	5	2	3	4	4	10	3,4,6,7,9,11, 14,15,17,20,25.
Cu	9[d]	4	3[d]	10[e]	2	3[e]	12	3,4,6,7,9,11,13, 14,15,17,19,20,25.
Cr	2	1	-	-	1	1	3	3,6,7,20.
Fe	12	2	-	5	3	-	10	3,4,6,7,9,11,19,23.
Mn	5	4	-	5	2	-	7	3,4,6,7,9,11,15,25.
Ni	3	2	1	4	2	2	8	3,4,6,7,11,14,15.
Pb	3	5	1	3	2	4	11	3,4,6,7,9,14, 17,19,20,25.
Zn	7	9	1	1	3	4	11	3,4,6,7,9,11,14,15, 16,17,19,20,25.
Hg	-	-	-	-	-	2	1	8,20.
Al	1	-	-	-	-	-	1	25.
As	1	1	-	-	1	1	2	12,25.
Se	-	1	-	-	-	-	1	25.
Totals	46	34	8	31	20	21	14	

[d]at two sites, correlations changed from negative to positive depending on season.
[e]at one site, correlations changed from negative to positive depending on season.

TABLE 8 (continued).

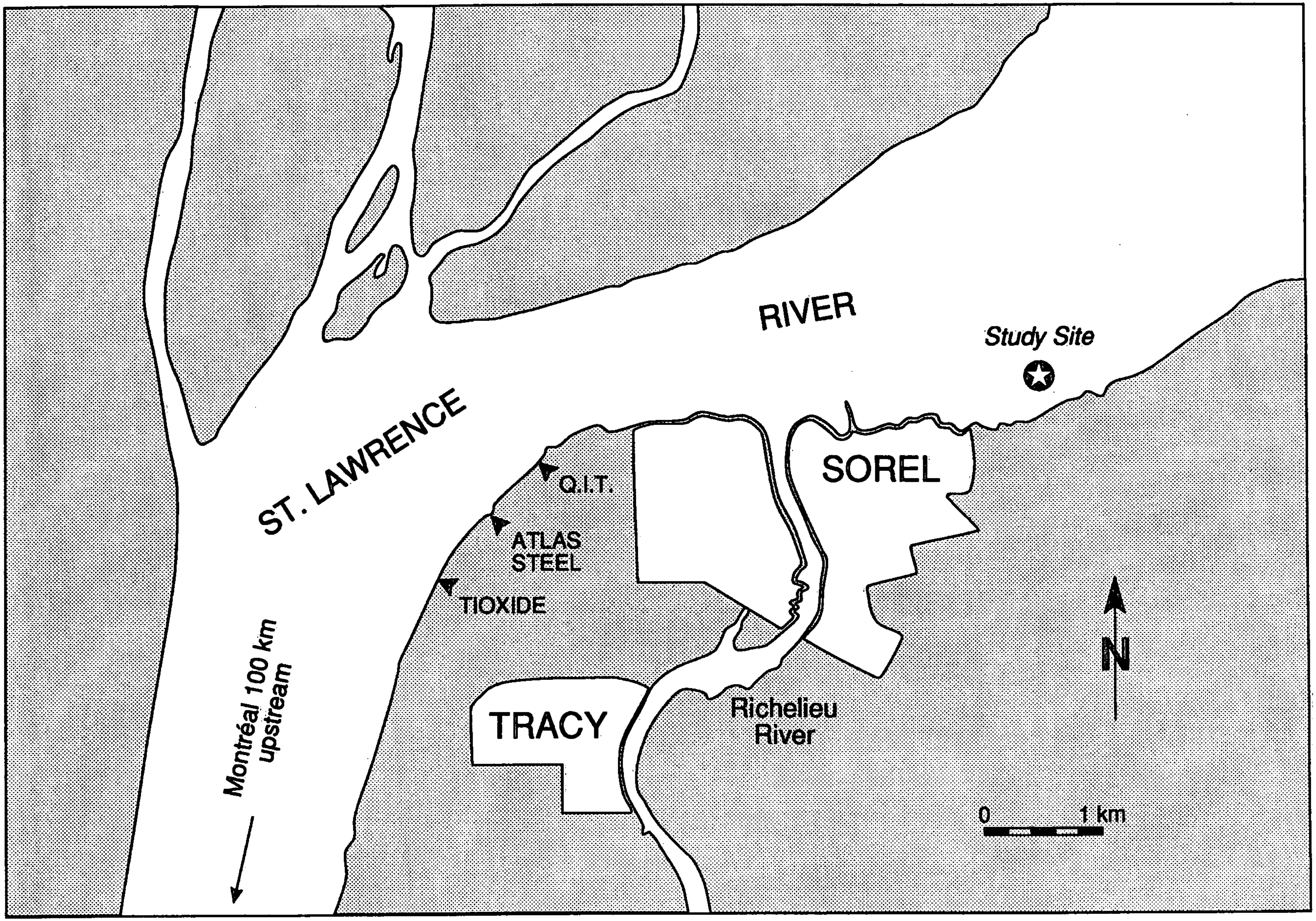
References: [1]Merlini et al. 1965; [2]Renzoni and Bacci 1976; [3]Watling and Watling 1976; [4]Boyden 1977; [5]Manly and George 1977; [6]Bryan and Hummerstone 1978; [7]Bryan and Uysal 1978; [8]Davies and Pirie 1978; [9]Harris et al. 1979; [10]Jones and Walker 1979; [11]Cossa et al. 1980; [12]Langston 1980; [13]Strong and Luoma 1981; [14]Klumpp and Burdon-Jones 1982; [15]Latouche and Mix 1982; [16]Lobel and Wright 1982; [17]Ritz et al. 1982; [18]Millington and Walker 1983; [19]Popham and D'Auria 1983; [20]Brix and Lyngby 1985; [21]Hinch and Stephenson 1987; [22]Baudo and Galanti 1988; [23]Brown and Kumar 1990; [24]Campbell and Evans 1991; [25]Lobel et al. 1991.

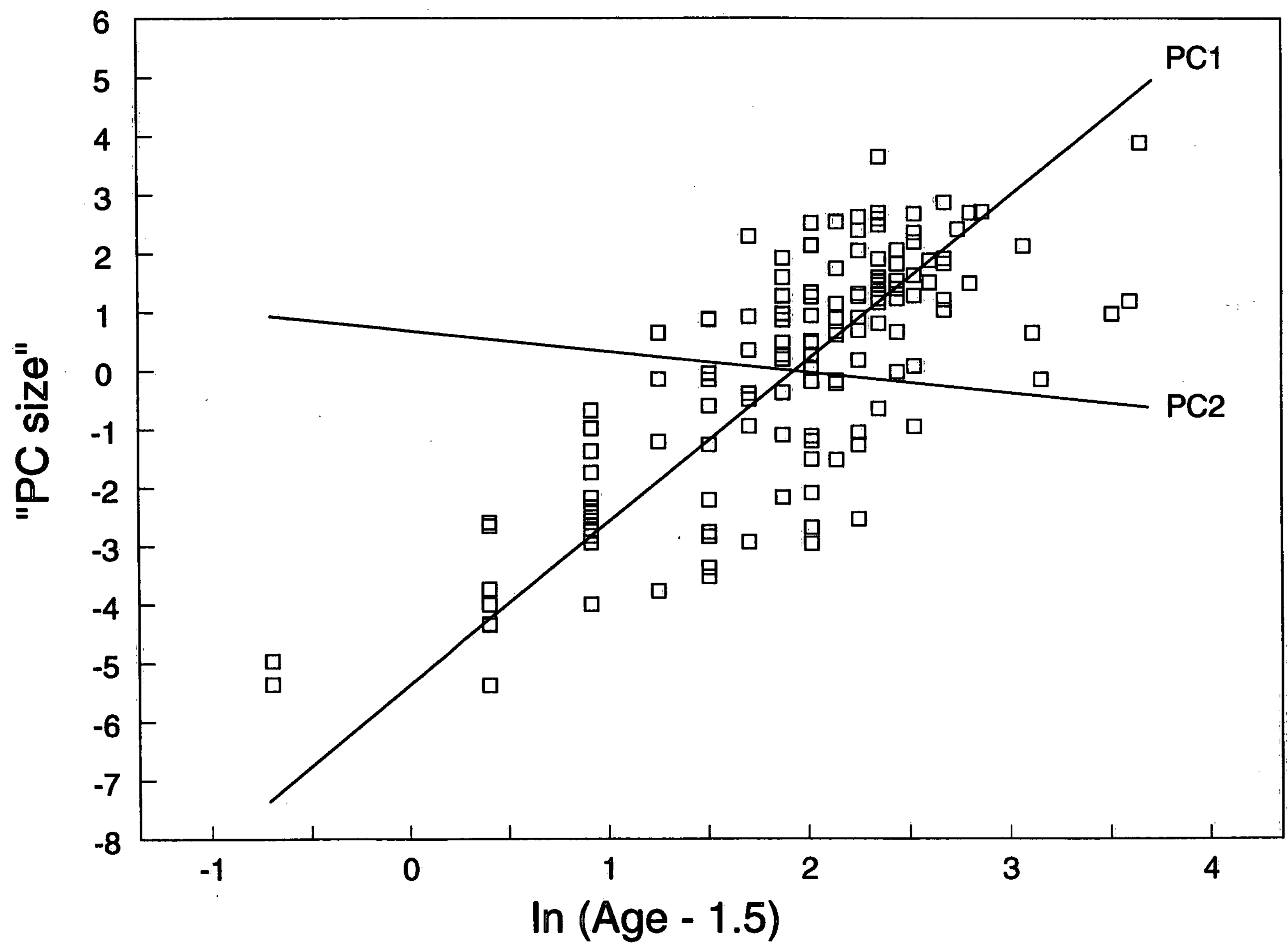
Figure captions

FIG. 1. Location of the study site on the St. Lawrence River, downstream of three major metal-discharging industries (Québec Iron and Titanium, Atlas Steel and Tioxide Canada, Inc.).

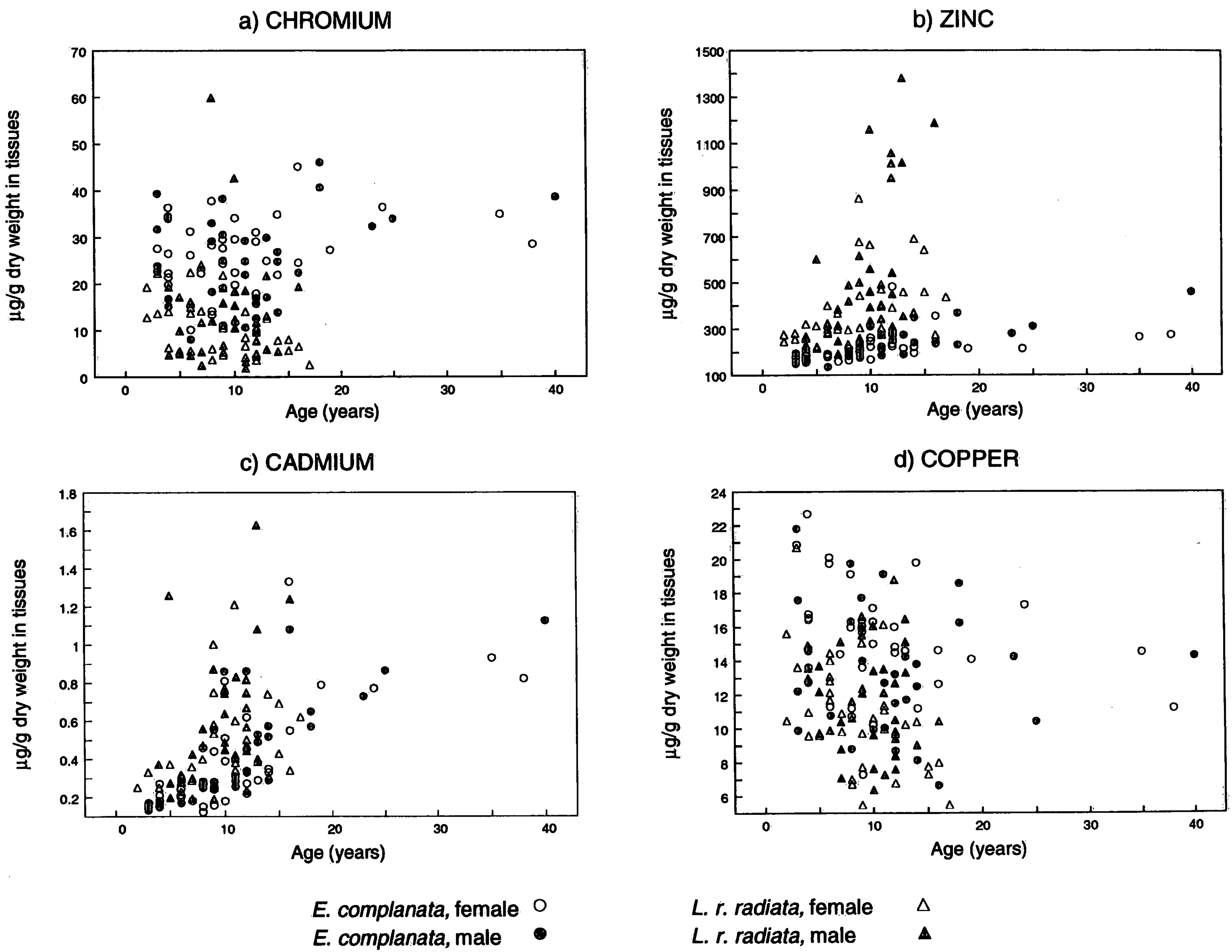
FIG. 2. Relationship between size and age of mussels, where "PC size" represents all five measures of size (shell length, width, height, weight and soft tissue dry weight) and age is ln-transformed to achieve maximum linearity with PC size. PC1 distinguishes large-old from small-young mussels and PC2 distinguishes fast-growing from slow-growing mussels.

FIG. 3. Relationships between concentrations of metals in the soft tissues and years of age for each species and sex tested. Four representative metals are illustrated.


RIVER
Study Site
ST. LAWRENCE
SOREL
Q.I.T.
ATLAS
STEEL
TIOXIDE
Montréal 100 km
upstream
N
TRACY
Richelieu
River
0
1 km



"PC size"
ln (Age - 1.5)
PC1
PC2
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-1
0
1
2
3
4


a) CHROMIUM
b) ZINC
c) CADMIUM
d) COPPER
µg/g dry weight in tissues
Age (years)
E. complanata, female
E. complanata, male
L. r. radiata, female
L. r. radiata, male

APPENDIX I.

Appendix I. Concentrations of metals in individual mussels collected from Sorel, Quebec, in 1990 as ug/g dry weight.
(data sorted in ascending order by species, sex and age.)

MUSSEL #	SPECIES	SEX	DRY WGT (g)	SHELL LGTH (mm)	SHELL WDTH (mm)	SHELL HGHT (mm)	SHELL WGT (g)	AGE (yrs)	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
203	1	1	0.99	72.12	19.43	35.96	13.72	3	1130	3.53	0.17	27.5	20.8	5950	0.08	777	8.44	10.2	2.96	177
225	1	1	1.65	75.91	19.67	42.16	19.03	4	763	3.26	0.21	19.8	16.5	3640	0.08	716	6.25	9.26	2.56	155
212	1	1	1	70.66	16.53	37.02	14.23	4	982	3.86	0.18	22.2	16.4	4710	0.08	655	7.25	7.39	3.08	159
204	1	1	1.35	80.09	20.21	41.37	17.51	4	1410	3.55	0.17	36.4	22.7	7150	0.08	929	10	11.1	2.5	181
197	1	1	1.61	80.17	22.51	43.37	23.67	4	985	2.29	0.27	26.5	16.8	5370	0.1	930	8.1	11.2	2.23	186
196	1	1	1.24	73.98	18.11	42.56	16.89	4	794	2.94	0.17	21.4	13.6	4460	0.11	593	5.79	8.56	2.6	164
198	1	1	1.3	77.1	20.19	43.37	24.39	6	147	2.88	0.2	10.1	11.3	3940	0.1	1000	6.56	7.54	2.29	183
209	1	1	1.1	69.21	19.61	36.58	16.73	6	1590	3.59	0.24	31.2	19.7	8700	0.09	893	9.78	13.5	2.52	175
205	1	1	1.1	65.35	23.52	39.35	24.09	6	1310	3.73	0.21	26.2	20.1	7280	0.08	1020	8.58	11	2.8	189
323	1	1	1.94	89.37	25.41	48.63	34.68	7	581	3.62	0.18	22.3	14.4	6050	0.11	1130	9.77	8.31	2.99	158
254	1	1	3.04	102.8	23.99	55.22	53.38	8	297	2.9	0.12	13.4	10.7	7130	0.08	1370	5.35	5.28	2.68	202
313	1	1	1.55	82.11	26.88	48.49	49.66	8	1560	3.22	0.46	37.6	19.1	9080	0.1	888	12.2	11.7	2.75	181
304	1	1	2.27	94.48	25.99	51.53	38.86	8	409	3.95	0.15	14.1	11.2	5560	0.09	1050	4.97	7.23	2.47	163
237	1	1	4.46	103.3	28.39	59.53	57.49	8	888	3.66	0.27	28.3	16	8530	0.11	1640	9.14	7.93	2.58	215
263	1	1	2.33	95.09	23.97	48.96	34.75	9	1010	3.65	0.28	29.5	15.7	8130	0.08	1270	13.1	11.9	2.42	199
220	1	1	1.15	80.7	18.66	47.25	24.19	9	441	3.15	0.44	24.4	13.6	11300	0.08	1740	8.33	14.7	3.17	214
242	1	1	3.52	109.67	29.46	60	68.69	9	493	2.67	0.16	19.1	16.4	7260	0.1	1250	10.8	8.5	2.18	237
301	1	1	2.59	94.22	25.31	50.43	42.57	9	143	2.86	0.28	11	7.3	6180	0.11	1720	2.22	5.15	2.07	196
295	1	1	3.36	102.77	26.42	57.03	48.51	9	735	3.28	0.24	27.6	16	8190	0.09	1430	7.36	14	2.5	205
229	1	1	5.9	115.02	30.55	58.16	60.14	10	552	4.75	0.51	22.5	17.1	7470	0.1	1990	7.47	11.4	2.76	246
271	1	1	2.56	96.9	29.29	54.2	61.1	10	609	2.97	0.81	34.2	15	11700	0.13	2040	9.19	13.8	2.75	259
310	1	1	2.72	85.39	26.48	46.49	39.87	10	900	3.84	0.18	29.5	16.3	7500	0.11	823	10	7.15	2.6	167
303	1	1	3.31	96.43	30.31	52.84	49.22	10	387	3.23	0.39	19.8	10.2	8500	0.1	1410	4.51	8.3	2.51	221
234	1	1	2.38	103.74	27.73	60.37	59.88	12	678	5.22	0.62	31	16	16500	0.2	3050	5.66	14.2	2.89	483
62	1	1	3.53	106.5	26.15	54.4	48.47	12	769	3.12	0.27	29.2	14.8	7780	0.11	1560	10.5	7.65	2.29	236
230	1	1	4.55	111.86	26.5	60.21	48.83	12	608	3.5	0.22	17.9	14.5	8050	0.16	1330	7.89	8.95	2.36	226
318	1	1	2.04	88.6	25.57	49.47	48.45	13	517	3.57	0.29	24.9	14.6	8260	0.09	1600	8.27	12.1	2.35	216
316	1	1	2.43	86.54	26.84	50.86	39.94	14	1140	3.46	0.33	34.8	19.8	11100	0.09	1420	10.9	16.7	2.51	219
221	1	1	2.21	83.13	23.1	46	30.08	14	404	3.23	0.35	21.9	11.2	8970	0.09	1250	9.64	12.3	2.79	193

APPENDIX I. (cont'd)

MUSSEL #	SPECIES	SEX	DRY WGT (g)	SHELL LGTH (mm)	SHELL WDTH (mm)	SHELL HGHT (mm)	SHELL WGT (g)	AGE (yrs)	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
65	1	1	4.59	102.95	31.05	55.35	58.68	16	151	3.39	1.33	24.5	12.6	10800	0.32	3510	10.9	7.53	4.43	350
252	1	1	3.16	101.85	33.24	54.77	67.7	16	832	5.56	0.55	45.1	14.6	14900	0.19	2100	10.1	9.59	3.47	241
240	1	1	3.15	102.47	36.89	59.42	109.85	19	646	4.82	0.79	27.1	14.1	11700	0.12	1920	4.98	14.8	3.1	214
284	1	1	2.36	82.67	31.57	49.74	66.68	24	847	4.21	0.77	36.5	17.3	11400	0.13	1430	10.9	13.4	2.81	214
258	1	1	3.3	98.71	28.55	50.81	49.84	35	835	4.5	0.93	35	14.5	16200	0.21	2660	8.07	18.6	3.23	265
288	1	1	3.47	90.9	31.78	49.25	67.49	38	346	4.52	0.82	28.6	11.2	9770	0.24	2230	6.42	9.56	3.13	274
222	1	2	0.65	69.81	17.13	36.43	13.04	3	387	2.37	0.15	23.8	9.9	3900	0.09	793	11.3	10.1	3.16	159
211	1	2	0.66	62.66	14.76	33.52	9.95	3	1760	4.01	0.16	39.5	21.8	6550	0.11	660	11.3	11.5	2.66	148
216	1	2	0.89	75.34	15.36	38.52	12.07	3	1070	3.12	0.18	31.7	17.6	5590	0.1	787	11	7.68	2.84	197
218	1	2	0.77	72.34	15.71	36.91	11.58	3	528	2.45	0.13	22.5	12.2	4300	0.11	727	6.8	12.3	2.48	156
213	1	2	1.15	77.88	17.93	41.55	19.78	4	597	2.72	0.17	15.3	14.6	4790	0.07	948	6.96	7.02	2.35	167
267	1	2	1.77	83.82	21.12	44.76	27.27	4	1070	3.09	0.15	34.4	14.8	5860	0.09	686	11.3	10.4	2.56	153
277	1	2	1.99	86.62	22.15	47.21	25.68	4	579	2.12	0.15	16.7	12.8	4130	0.09	804	6.62	6.92	1.99	155
195	1	2	1.24	77.65	19.34	39.68	19.06	4	927	2.15	0.17	33.9	12.7	5370	0.07	812	7.98	8.45	2.01	175
199	1	2	0.78	77.47	18.13	44.05	20.52	6	65.8	2.69	0.17	8.1	10.8	4070	0.15	817	2.19	7.01	2.96	136
239	1	2	3.77	104.78	28.85	53.44	55.65	8	1140	3.66	0.25	29.1	16.3	7920	0.1	1430	9.5	11	1.85	203
292	1	2	2.14	94.65	24.21	52.4	44.8	8	510	2.88	0.28	18.3	8.8	9570	0.11	1840	6.64	10.9	2.66	202
206	1	2	1.79	76.91	24.75	43.82	35.45	8	1670	3.22	0.25	33	19.7	8350	0.09	1070	9.64	12.4	2.31	188
255	1	2	2.26	98.57	23.21	55.93	42.88	9	1070	3.21	0.56	38.3	17.7	12900	0.12	2160	8.09	16.9	2.71	216
300	1	2	2.38	97.58	23.63	48.59	39.49	9	1120	3.3	0.28	30.5	14	9000	0.1	1800	8.97	14.6	2.23	177
278	1	2	2.17	97.8	26.45	52.46	40.6	9	677	3.82	0.25	24.9	15.9	8070	0.1	1310	8.31	10.1	2.92	189
280	1	2	1.4	86.4	26.69	50.3	44.69	10	82.8	3.46	0.86	11.8	9.9	10700	0.11	1980	5.89	18.4	2.84	311
275	1	2	3.07	92.23	30.7	54.23	55.2	11	772	3.1	0.25	24.8	12.7	7190	0.09	1510	9.45	9.52	2.33	221
232	1	2	4.64	107.8	31.91	59.07	77.4	11	679	4.04	0.28	22	11.3	8820	0.1	1770	6.43	8.81	2.06	273
202	1	2	0.69	75.71	20.8	44.06	25.02	11	72.7	2.68	0.39	10.6	10	9760	0.12	2020	2.91	9.44	2.95	216
226	1	2	1.78	81.95	23.07	45.39	25.14	11	1030	2.75	0.31	29.2	19.1	8190	0.1	1330	9.46	12.8	3.03	186
238	1	2	3.25	105.77	27.24	56.33	55.25	12	367	3.73	0.33	16.8	11.5	12500	0.12	1640	3.23	7.21	2.65	284
247	1	2	2.68	101.94	26.52	51.99	44.3	12	139	2.88	0.86	15.8	13.2	9010	0.15	2020	4.59	6.88	2.71	275
64	1	2	4.05	114.45	29.6	62.7	76.55	12	63.5	2.69	0.34	12.6	8.7	8510	0.12	2070	4.1	3.08	2.6	252
241	1	2	3.51	101.8	28.06	53.9	53.58	13	607	3.82	0.49	29.8	11.7	10100	0.17	1100	9.18	6.53	2.81	191
233	1	2	2.92	106.23	28.73	55.54	55.49	13	458	3.22	0.53	17	14.2	13600	0.12	2680	4.12	23	2.4	273

APPENDIX I. (cont'd)

MUSSEL #	SPECIES	SEX	DRY WGT (g)	SHELL LGTH (mm)	SHELL WDTH (mm)	SHELL HGHT (mm)	SHELL WGT (g)	AGE (yrs)	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
244	1	2	3.73	107.81	30.02	60.54	72.65	14	818	1.99	0.57	26.8	13.8	10500	0.11	2170	6.6	8.14	2.16	349
293	1	2	3.49	92.98	30.53	56.73	62.84	14	276	3.55	0.29	14	8.11	8520	0.11	1400	5.26	11	2.12	243
251	1	2	3.73	109.46	30.87	56.37	69.51	14	649	2.62	0.52	24.8	12.5	9580	0.14	1650	7.26	10	2.08	245
324	1	2	2.23	85.01	32.34	53.59	66.03	16	18.8	3.71	1.08	22.4	6.67	11600	0.16	2740	5.48	9.61	2.65	238
235	1	2	4.92	102.99	32.59	59.96	81.16	18	885	5.45	0.65	40.7	18.6	13600	0.2	3640	9.37	15	2.56	366
256	1	2	2.72	98.78	29.17	54.42	73.03	18	1220	4.27	0.57	45.9	16.2	14900	0.21	2620	9.93	16.4	2.98	231
298	1	2	3.19	96.22	33.03	57.99	84.38	23	852	3.7	0.73	32.3	14.2	14100	0.15	2730	7.57	15.3	2.92	281
266	1	2	2.21	91.46	24.65	46.85	41.56	25	655	3.89	0.87	34	10.4	13800	0.28	3510	5.09	18.8	3.02	312
243	1	2	6.45	122.11	33.62	67.06	96.21	40	823	3.51	1.12	38.7	14.3	11500	0.23	3300	6.97	8.32	3.22	459
106	2	1	1.81	56.49	17.03	31.66	8	2	357	5.07	0.25	12.8	10.5	5820	0.09	2680	2.2	6.4	2.21	272
68	2	1	1.75	53.58	17.26	31.76	5.8	2	685	4.15	0.25	19	15.6	4960	0.07	1400	4.2	6.3	2.61	244
77	2	1	1.23	62.07	24.08	41.78	20.75	3	837	3.91	0.33	22.1	20.7	4840	0.09	2090	5.5	13.2	3.01	282
89	2	1	1.39	64.26	24.04	40.54	19.98	3	413	4.04	0.17	13.6	13.6	2790	0.08	1860	4.4	7.26	2.69	254
93	2	1	1.66	65.86	22.83	37.79	17.59	4	221	4.33	0.17	6.2	9.6	2050	0.07	1330	1.8	4.49	2.79	221
79	2	1	1.33	64.08	24.88	41.88	23.28	4	489	3.64	0.2	13.9	12.9	3970	0.08	2400	3.1	7.2	2.54	258
138	2	1	2.39	81	24.3	48.51	29.01	4	605	3.67	0.25	13.9	11	3790	0.08	1620	3.8	8.96	2.8	315
88	2	1	0.86	56.89	22.51	38.49	16.16	5	125	3.96	0.37	5.4	9.5	4790	0.07	2940	1.1	4.45	2.51	313
148	2	1	2.38	77.85	26.02	48.71	30.3	6	553	5.05	0.23	15.8	14.4	4280	0.07	2210	5.1	6.02	2.71	281
155	2	1	3.33	85.38	30.99	53.59	44.45	6	271	4.34	0.32	5.5	11.7	4080	0.08	1780	2	6.44	2.57	280
146	2	1	2.58	72.47	31.8	48.7	36.13	6	516	4.52	0.28	13.6	12.8	5040	0.09	3140	3.7	7.71	2.66	318
141	2	1	2.03	81.29	28.07	52.27	37.96	6	735	2.69	0.307	16.1	14	4600	0.07	2860	5.5	5.51	2.41	315
153	2	1	3.15	88.45	30.51	54.29	41.1	6	458	4.62	0.3	14.9	12.1	4420	0.08	2680	4.4	7.3	2.62	400
91	2	1	2.26	70.86	26.45	44.97	24.89	6	804	4.09	0.28	22.5	13	6020	0.07	2570	6.6	7.41	2.29	315
83	2	1	1.93	70.52	28.82	45.36	33.33	7	620	3.99	0.29	23.6	10.9	6630	0.07	3760	6.6	8.05	2.47	297
128	2	1	5.02	98.96	34.2	57.86	61.04	7	326	4.53	0.36	14.1	9.8	3830	0.09	2720	2.9	5.4	2.21	363
81	2	1	1.1	66.46	26.84	42.8	23.32	8	74	6.69	0.4	5.9	7	6040	0.11	3140	4.3	4.9	2.75	295
163	2	1	3.52	85.55	30.68	54.02	40.51	8	50	5.48	0.28	3.3	6.7	2970	0.07	2190	1.2	1.56	2.68	229
123	2	1	6.61	95.54	34.36	59.51	60.52	9	287	8.42	0.75	11	9.7	4720	0.1	3200	2.4	5	2.53	440
149	2	1	1.6	77.77	25.94	48.03	25.36	9	50	5.36	0.53	5	5.5	5080	0.07	3270	1.2	5.91	2.53	305
151	2	1	2.95	89.77	31.29	55.78	38.61	9	52	5.21	0.58	10.6	7.7	5610	0.09	5410	3.5	9.68	2.41	864
69	2	1	1.48	62.58	23.87	41.17	17.82	9	736	7.87	1	21.9	15	10500	0.12	5130	4	10.3	2.87	675

APPENDIX I. (cont'd)

MUSSEL #	SPECIES	SEX	DRY WGT (g)	SHELL LGTH (mm)	SHELL WDTH (mm)	SHELL HGHT (mm)	SHELL WGT (g)	AGE (yrs)	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
140	2	1	2.33	80.99	33.24	54.61	41.43	10	517	5.41	0.767	12.3	10.6	6350	0.09	5040	3.6	8.75	2.63	663
147	2	1	2.43	72.04	25.63	47.65	24.72	11	252	5.35	0.34	8.3	10	3590	0.08	2090	2	8.11	2.53	271
143	2	1	2.08	85.44	33.1	52.75	49.4	11	81.5	7.8	1.21	6.7	11.3	7850	0.08	4690	2.1	9.84	2.91	468
125	2	1	3.4	94.13	31.69	54.63	47.42	11	58	5.01	0.6	4.1	16.1	4470	0.31	2880	0.6	5.37	2.53	402
144	2	1	3.28	79	30	48.98	37.09	11	503	5.2	0.381	14.1	11.1	7050	0.09	2620	3.2	4.88	2.5	302
136	2	1	7.96	109.32	36.76	62.5	91.55	12	56.7	6.65	0.5	4.9	6.8	3380	0.09	2490	0.9	4.19	2.67	278
70	2	1	2.66	70.4	29.35	46.66	30.45	12	50	5.1	0.47	3.6	9.7	4990	0.08	3270	1	3.02	2.2	389
158	2	1	4.51	83.91	35.31	59.51	52.66	13	427	4.78	0.4	12.6	10.2	4180	0.09	3450	3.4	6	2.06	459
159	2	1	3.58	89.44	32.47	54.55	48.2	14	233	5.44	0.74	7.8	10.4	7050	0.13	4310	1.8	6.67	2.82	687
114	2	1	3.62	91.5	31.85	56.05	55.04	15	50	7.85	0.43	5.5	7.3	5680	0.11	3170	1.9	6.38	2.38	459
129	2	1	4	94.33	33.71	55.92	62.19	15	50	6.19	0.69	7.8	7.7	5920	0.1	2770	0.6	8.05	2.35	641
130	2	1	6.4	93.94	37.78	60.72	73.67	16	73.1	4.01	0.34	6.5	8	3300	0.11	2200	1.8	2.89	1.94	273
135	2	1	5.24	93.93	37.25	56.98	67.53	17	50	5.51	0.62	2.6	5.5	2910	0.1	2520	0.5	2.83	2.18	434
67	2	2	0.58	71.24	24.48	42.74	28.83	4	179	NSSMP	NSSMP	4.7	14.9	2670	0.07	1530	1.3	NSSMP	NSSMP	217
104	2	2	2.25	71.88	20.72	41.83	17.13	4	716	3.79	0.37	19.4	13.6	5450	0.07	2100	4.5	8.13	2.7	265
185	2	2	3.61	86.32	28.87	50.18	40.81	5	174	4.43	0.2	10	9.7	2990	0.08	1400	3.9	5.83	2.64	222
96	2	2	1.91	74.79	26.51	44.4	24.54	5	563	3.6	0.27	17.3	13.7	5010	0.09	1740	3.8	5.66	2.5	213
174	2	2	2.03	84.34	29.47	48.54	31.5	5	120	7.59	1.26	5.1	12.2	5020	0.09	4540	1	3.67	2.66	603
95	2	2	1.04	62.7	22.57	40.59	11.86	6	50	3.38	0.28	4.8	9.9	4440	0.06	2710	0.7	4.53	3.11	298
166	2	2	2.91	83.17	29.88	51.23	33.52	7	50	4.29	0.3	5.4	8.8	3020	0.07	2010	1.8	2.01	2.53	247
94	2	2	2.63	73.32	29.29	45.98	31.21	7	388	4.01	0.19	11.8	10.4	3970	0.07	1390	2.4	4.26	2.84	196
165	2	2	2.5	88.26	30.82	53.87	49.1	7	50	3.4	0.42	2.7	7.1	2840	0.07	2750	1	5.56	2.26	387
100	2	2	0.68	66.16	24.06	41.75	19.56	7	901	4.57	NSSMP	23.8	15.1	4190	0.1	1410	5.3	NSSMP	3.03	319
171	2	2	2.95	89.75	32.39	53.03	56.77	8	307	4.51	0.47	12.1	10.6	4830	0.1	3510	3.8	7.55	2.42	487
177	2	2	3.31	82.04	28.82	52.06	36.89	8	112	8.1	0.56	60	11.6	4570	0.1	2660	19.9	8.36	2.74	421
85	2	2	1.8	71.71	26.79	44.74	28.12	9	388	4.5	NSSMP	16.1	15.5	7200	0.09	3570	2.3	NSSMP	2.82	501
102	2	2	1.5	71.81	26.16	44.95	24	9	56	3.74	0.19	5.4	12.4	2040	0.07	1630	1.1	5.63	2.45	238
99	2	2	1.97	64.13	20.4	38.81	14.89	9	637	4.32	0.25	19.2	12.1	5410	0.08	2130	4.2	6.89	2.73	260
168	2	2	3.02	88.14	33.26	54.27	54.26	9	83.4	8.64	0.87	6.9	16.6	5720	0.11	4250	1	7.06	2.63	617
73	2	2	1.5	72.73	24.01	45.61	26.63	10	233	10.35	0.76	15.3	7.6	9020	0.12	3070	2	3.45	2.88	558
180	2	2	2.96	79.73	32.95	52.07	40.81	10	406	9.66	0.74	18.5	13.4	8370	0.13	4280	4.8	4.94	2.56	1160

APPENDIX I. (cont'd)

MUSSEL #	SPECIES	SEX	DRY WGT (g)	SHELL LGTH (mm)	SHELL WDTH (mm)	SHELL HGHT (mm)	SHELL WGT (g)	AGE (yrs)	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
178	2	2	3.25	90.63	29.74	53.15	39.18	10	415	3.54	0.49	42.7	16.1	4930	0.09	2000	11	6.23	2.68	462
124	2	2	2.93	95.14	34.5	55.16	61.57	10	275	3.77	0.45	10.5	6.4	5430	0.1	3040	2.6	4.85	2.5	394
139	2	2	2.97	81.22	31.26	51.05	43.4	10	392	4.6	0.64	10.5	9.6	6460	0.09	3210	2.4	5.04	2.26	331
167	2	2	3.88	82.47	30.88	52.29	43.59	11	50	4.98	0.4	3.4	12.1	4050	0.12	2330	1	4.87	2.74	344
111	2	2	3.86	101.85	30.73	58.01	61.15	11	565	4.9	0.83	18.5	13.5	6970	0.09	2920	3.3	7.8	2.46	492
132	2	2	5.3	97.95	33.42	60	55.78	11	50	3.21	0.42	2	7.3	3540	0.09	2450	0.49	3.63	2.36	400
126	2	2	3.33	88.75	34.56	55.59	50.56	12	252	8.25	0.82	10	18.8	7170	0.18	4610	2	3.42	3.03	954
122	2	2	4.25	93.57	31.06	54.9	50.03	12	245	5.12	0.75	10.3	10.5	5550	0.14	2270	2.8	4.45	2.71	547
109	2	2	4.35	104.66	34.84	59.75	70.93	12	116	12.53	0.67	7.8	12.7	4770	0.12	4530	2	3.37	2.87	1020
160	2	2	3.59	91.02	31.41	55.95	45.74	12	155	6.83	0.47	10.5	7.6	4770	0.11	2670	2.5	5.92	2.95	451
115	2	2	5.11	99.16	34.18	58.59	71.92	12	217	4.76	0.23	9.8	8.4	3590	0.09	1600	2.5	5.25	2.31	295
170	2	2	2.77	91.13	31.95	54.46	47.13	12	50	9	0.57	4.7	9.4	5550	0.25	4120	1	7.29	2.6	1060
133	2	2	5.22	93.82	35.47	58.39	68.66	12	323	3.93	0.45	11.6	9.8	4820	0.11	2510	2.9	5.35	2.45	303
172	2	2	1.6	89.58	32.06	56.68	39.44	13	326	8.64	1.63	21.8	15.1	11700	0.14	6030	3.6	8.55	2.94	1380
173	2	2	1.98	98.67	31.54	58.2	44.6	13	380	3.75	0.39	13	13.3	7110	0.11	3910	4	6.97	2.36	356
112	2	2	3.54	98.59	33.26	58.21	60.2	13	65	7.18	1.08	6	16.4	5510	0.14	4600	1	9.17	2.59	1020
120	2	2	6.48	90.86	39.24	56.91	66.13	14	50	3.93	0.31	5.6	9	3660	0.1	3030	0.9	1.93	2.03	371
306	2	2	2.5	90.2	33.26	53.94	53.5	16	277	8.31	1.24	19.3	10.4	11000	0.13	5370	6.07	8.97	2.86	1190

NOTES: species 1 = Elliptio complanata; species 2 = Lampsilis radiata radiata
sex 1 = female; sex 2 = male
NSSMP = insufficient material for analysis

APPENDIX II.

APPENDIX II. Summary of the literature on relationships between size or age and soft tissue metal concentrations in marine and freshwater bivalves. Species are identified as F (freshwater) or M (marine); # samples is qualified as i (individual organisms) or c (composites), and # organisms per composite is shown in brackets; pollution status is indicated as C (clean) or P (polluted with metals), # sites tested is given in brackets if more than one, and gradients of pollution and/or response are indicated by arrows; na = information not available. A positive sign "+" indicates a positive correlation between metal concentration and size or age, a negative sign "−" indicates a negative correlation, an "o" indicates no relationship, and where relationships are weak the signs are in brackets.

Metal	Species	Effect of Size Parameter	Effect of Size Range	Effect of Size Effect	Effect of Age Parameter	Effect of Age Range	Effect of Age Effect	Number of samples	Pollution Status	Reference
Al	*M. edulis* (M)	dry weight	14 X	−	W:H & <CI[a]	2 X	o & o	69i	C	Lobel et al. 1991
As	*Scrobicularia plana* (M)	dry weight	10-35X	−→o→+	years	6-9 X	−→o→+	5-8i	C → P (3)	Langston 1980
As	*M. edulis* (M)	dry weight	14 X	o	W:H & <CI[a]	2 X	+ & o	69i	C	Lobel et al. 1991
Cd	*Elliptio complanata* (F)	shell length	2 X	o, $+_{gill}$	years	7 X	o_{gill}	50i	C (2)	Hinch & Stephenson 1987
Cd	*Elliptio complanata* (F)	shell length	2 X	o, $+_{body}$	years	7 X	o_{body}	50i	C (2)	Hinch & Stephenson 1987
Cd	*Elliptio complanata* (F)	dry weight	2 X[c]	−,o,+				12-30i	C (21)	Campbell and Evans 1991
Cd	*Velesunio ambiguus* (F)	dry weight	5 X	o	shell volume	na	o	11-23i[b]	C	Jones & Walker 1979
Cd	*Anodonta anatina* (F)	dry weight	50 X	o → +				14-16i	C → P (7)	Manly & George 1977
Cd	*Mytilus edulis planulatus* (M)	shell length	3 X	+				5-8c (3-5)	P	Harris et al. 1979
Cd	*M. edulis* (M)	wet weight	3 X[c]	o				25i	C	Brix & Lyngby 1985
Cd	*M.e. planulatus* (M)	shell length	2 X	+				2c (10)	C	Ritz et al. 1982
Cd	*M. edulis* (M)	dry weight	14 X	o	W:H & <CI[a]	2 X	+ & +	69i	C	Lobel et al. 1991
Cd	*M. edulis* (M)	shell length	1.5 X	+				6c (10)	C	Latouche & Mix 1982
Cd	*Ostrea edulis* (M)	dry weight	13 X	o				38i	C	Boyden 1977
Cd	*Crassostrea gigas* (M)	dry weight	430 X	−				39i	C	Boyden 1977
Cd	*Crassostrea gigas* (M)	dry weight	200 X	−				22i	P	Boyden 1977
Cd	*M. edulis* (M)	dry weight	6-14 X	o				17-22i	P (4)	Boyden 1977
Cd	*Mercenaria mercenaria* (M)	dry weight	401 X	−				35i	C	Boyden 1977
Cd	*Venerupis decussata* (M)	dry weight	16 X	−				30i	P	Boyden 1977
Cd	*Chlamys opercularis* (M)	dry weight	19 X	o				20i	C	Boyden 1977

APPENDIX II. (cont'd)

Metal	Species	Effect of Size Parameter	Range	Effect	Effect of Age Parameter	Range	Effect	Number of samples	Pollution Status	Reference
Cd	*M. edulis* (M)	dry weight	230 X	−				126i	P (3)[d]	Cossa et al. 1980
Cd	*Trichomya hirsuta* (M)	shell length	3 X	+				78i	P (3)[d]	Klumpp & Burdon-Jones 1982
Cd	*S. plana* (M)	dry weight	20 X	+				10c (5)	P	Bryan & Uysal 1978
Cd	*S. plana* (M)	dry weight	7 X	+				5c (5)	P	Bryan & Hummerstone 1978
Cd	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Cd	*Choromytilus meriodionalis* (M)	dry weight	4 X	−				78i	C	Watling & Watling 1976
Cu	*Unio elongatus* (F)	wet weight	10 X[c]	−				11c (na)	C	Baudo & Galanti 1988
Cu	*Elliptio complanata* (F)	shell length	2 X	$-, o_{gill}$	years	7 X	$o, +_{gill}$	50i	C (2)	Hinch & Stephenson 1987
Cu	*Elliptio complanata* (F)	shell length	2 X	$+, o_{body}$	years	7 X	o, o_{body}	50i	C (2)	Hinch & Stephenson 1987
Cu	*Anodonta anatina* (F)	dry weight	50 X	o → −				14-16i	C → P (7)	Manly & George 1977
Cu	*Mytilus edulis planulatus* (M)	shell length	3 X	o				5-8c (3-5)	P	Harris et al. 1979
Cu	*Macoma balthica* (M)	dry weight	5-15	−, o, +				20-30i[e]	C → P (4)	Strong & Luoma 1981
Cu	*M. edulis* (M)	wet weight	3 X[c]	o				25i	C	Brix & Lyngby 1985
Cu	*M. edulis* (M)	dry weight	50 X	−				20c (2-20)	C→P (2)	Popham & D'Auria 1983
Cu	*M.e. planulatus* (M)	shell length	2 X	−				2c (10)	C	Ritz et al. 1982
Cu	*M. edulis* (M)	dry weight	14 X	−	W:H & <CI[a]	2 X	o & +	69i	C	Lobel et al. 1991
Cu	*M. edulis* (M)	shell length	1.5 X	+				6c (10)	C	Latouche & Mix 1982
Cu	*Ostrea edulis* (M)	dry weight	13 X	o				38i	C	Boyden 1977
Cu	*Crassostrea gigas* (M)	dry weight	430 X	−				39i	C	Boyden 1977
Cu	*Crassostrea gigas* (M)	dry weight	200 X	−				22i	P	Boyden 1977
Cu	*M. edulis* (M)	dry weight	6-14 X	−				17-22i	P (4)	Boyden 1977
Cu	*Mercenaria mercenaria* (M)	dry weight	401 X	−				35i	C	Boyden 1977
Cu	*Venerupis decussata* (M)	dry weight	16 X	−				30i	P	Boyden 1977
Cu	*Chlamys opercularis* (M)	dry weight	19 X	o				20i	C	Boyden 1977
Cu	*Pecten maximus* (M)	dry weight	52 X	−				37i	C	Boyden 1977
Cu	*M. edulis* (M)	dry weight	230 X	−				119i	P (3)[d]	Cossa et al. 1980
Cu	*Trichomya hirsuta* (M)	shell length	3 X	o				78i	P (3)[d]	Klumpp & Burdon-Jones 1982

APPENDIX II. (cont'd)

Metal	Species	Effect of Size Parameter	Range	Effect	Effect of Age Parameter	Range	Effect	Number of samples	Pollution Status	Reference
Cu	*S. plana* (M)	dry weight	20 X	−				10c (5)	P	Bryan & Uysal 1978
Cu	*S. plana* (M)	dry weight	7 X	+				5c (5)	P	Bryan & Hummerstone 1978
Cu	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Cu	*Choromytilus meriodionalis* (M)	dry weight	4 X	−				78i	C	Watling & Watling 1976
Cr	*Unio elongatus* (F)	wet weight	10 X[c]	+				11c (na)	C	Baudo & Galanti 1988
Cr	*M. edulis* (M)	wet weight	3 X[c]	−				25i	C	Brix & Lyngby 1985
Cr	*S. plana* (M)	dry weight	20 X	+				10c (5)	P	Bryan & Uysal 1978
Cr	*S. plana* (M)	dry weight	7 X	o				5c (5)	P	Bryan & Hummerstone 1978
Cr	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Cr	*Choromytilus meriodionalis* (M)	dry weight	4 X	−				78i	C	Watling & Watling 1976
Fe	*Unio elongatus* (F)	wet weight	10 X[c]	+				11c (na)	C	Baudo & Galanti 1988
Fe	*Velesunio ambiguus* (F)	dry weight	5 X	−	shell volume	na	+	11-23i[b]	C	Jones & Walker 1979
Fe	*Velesunio ambiguus* (F)	dry weight	3 X	(−)	shell volume	na	(+)	25i	C (LAX)	Millington & Walker 1983
Fe	*Velesunio ambiguus* (F)	dry weight	5 X	−	shell volume	na	+	25i	C (OCR)	Millington & Walker 1983
Fe	*Velesunio ambiguus* (F)	dry weight	15 X	(−)	shell volume	na	(−)	12i	C (RGL)	Millington & Walker 1983
Fe	*Mytilus edulis planulatus* (M)	shell length	3 X	−				5-8c (3-5)	P	Harris et al. 1979
Fe	*M. edulis* (M)	dry weight	50 X	−,o				20c (2-20)	C (2)	Popham & D'Auria 1983
Fe	*Saccostrea cucullata* (M)	dry weight	10 X	−				30i	C→P(3)	Brown & Kumar 1990
Fe	*Isognomon isognomon* (M)	dry weight	12 X	−				30i	C→P(3)	Brown & Kumar 1990
Fe	*Ostrea edulis* (M)	dry weight	13 X	−				38i	C	Boyden 1977
Fe	*Crassostrea gigas* (M)	dry weight	430 X	−				39i	C	Boyden 1977
Fe	*Crassostrea gigas* (M)	dry weight	200 X	−				22i	P	Boyden 1977
Fe	*M. edulis* (M)	dry weight	6-14 X	−				20-22i	P (3)	Boyden 1977
Fe	*Mercenaria mercenaria* (M)	dry weight	401 X	−				35i	C	Boyden 1977
Fe	*Venerupis decussata* (M)	dry weight	16 X	o				30i	P	Boyden 1977
Fe	*M. edulis* (M)	dry weight	230 X	−				122i	P (3)[d]	Cossa et al. 1980

APPENDIX II. (cont'd)

Metal	Species	Effect of Size Parameter	Range	Effect	Effect of Age Parameter	Range	Effect	Number of samples	Pollution Status	Reference
Fe	*S. plana* (M)	dry weight	20 X	o				10c (5)	P	Bryan & Uysal 1978
Fe	*S. plana* (M)	dry weight	7 X	o				5c (5)	P	Bryan & Hummerstone 1978
Fe	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Fe	*Choromytilus meriodionalis* (M)	dry weight	4 X	–				78i	C	Watling & Watling 1976
Hg	*Anodonta anatina* (F)	dry weight	50 X	o → –				14-16i	C → P (7)	Manly & George 1977
Hg	*Unio elongatus* (F)	shell length	2 X	+				59i	P	Renzoni & Bacci 1976
Hg	*M. edulis* (M)	wet weight	3 X[c]	+				25i	P	Brix & Lyngby 1985
Hg	*M. edulis* (M)	wet weight	25 X	+				66i	P	Davies & Pirie 1978
Mn	*Unio elongatus* (F)	wet weight	10 X[c]	+				11c (na)	C	Baudo & Galanti 1988
Mn	*Elliptio complanata* (F)	shell length	2 X	o, o_{gill}	years	7 X	$o, -_{gill}$	50i	C (2)	Hinch & Stephenson 1987
Mn	*Elliptio complanata* (F)	shell length	2 X	$o, +_{body}$	years	7 X	$-, o_{body}$	50i	C (2)	Hinch & Stephenson 1987
Mn	*Velesunio ambiguus* (F)	dry weight	5 X	–	shell volume	na	+	11-23i[b]	C	Jones & Walker 1979
Mn	*Unio elongatus* (F)	shell length	2 X	+				na	C	Merlini et al. 1965
Mn	*Velesunio ambiguus* (F)	dry weight	3 X	+	shell volume	na	(+)	25i	C (LAX)	Millington & Walker 1983
Mn	*Velesunio ambiguus* (F)	dry weight	5 X	(–)	shell volume	na	(+)	25i	C (OCR)	Millington & Walker 1983
Mn	*Velesunio ambiguus* (F)	dry weight	15 X	(–)	shell volume	na	(+)	12i	C (RGL)	Millington & Walker 1983
Mn	*Mytilus edulis planulatus* (M)	shell length	3 X	–				5-8c (3-5)	P	Harris et al. 1979
Mn	*M. edulis* (M)	dry weight	50 X	–				20c (2-20)	C (2)	Popham & D'Auria 1983
Mn	*M. edulis* (M)	dry weight	14 X	–	W:H & <CI[a]	2 X	o & +	69i	C	Lobel et al. 1991
Mn	*M. edulis* (M)	shell length	1.5 X	–				6c (10)	C	Latouche & Mix 1982
Mn	*Ostrea edulis* (M)	dry weight	13 X	o				38i	C	Boyden 1977
Mn	*Crassostrea gigas* (M)	dry weight	430 X	o				39i	C	Boyden 1977
Mn	*Crassostrea gigas* (M)	dry weight	200 X	o				22i	P	Boyden 1977
Mn	*M. edulis* (M)	dry weight	7-14 X	–				17-22i	P (2)	Boyden 1977
Mn	*Pecten maximus* (M)	dry weight	52 X	o				37i	C	Boyden 1977
Mn	*M. edulis* (M)	dry weight	230 X	–				119i	P (3)[d]	Cossa et al. 1980

APPENDIX II. (cont'd)

		Effect of Size			Effect of Age			Number of	Pollution	
Metal	Species	Parameter	Range	Effect	Parameter	Range	Effect	samples	Status	Reference
Mn	*S. plana* (M)	dry weight	20 X	–				10c (5)	P	Bryan & Uysal 1978
Mn	*S. plana* (M)	dry weight	7 X	o				5c (5)	P	Bryan & Hummerstone 1978
Mn	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Mn	*Choromytilus meriodionalis* (M)	dry weight	4 X	–				78i	C	Watling & Watling 1976
Ni	*Anodonta anatina* (F)	dry weight	50 X	o				14-16i	C → P (7)	Manly & George 1977
Ni	*M. edulis* (M)	shell length	1.5 X	+				6c (10)	C	Latouche & Mix 1982
Ni	*Ostrea edulis* (M)	dry weight	13 X	–				38i	C	Boyden 1977
Ni	*M. edulis* (M)	dry weight	7-14 X	–				17-22i	P (3)	Boyden 1977
Ni	*Mercenaria mercenaria* (M)	dry weight	401 X	o				35i	C	Boyden 1977
Ni	*Venerupis decussata* (M)	dry weight	16 X	o				30i	P	Boyden 1977
Ni	*Chlamys opercularis* (M)	dry weight	19 X	–				20i	C	Boyden 1977
Ni	*M. edulis* (M)	dry weight	230 X	–				118i	P (3)[d]	Cossa et al. 1980
Ni	*Trichomya hirsuta* (M)	shell length	3 X	+				78i	P (3)[d]	Klumpp & Burdon-Jones 1982
Ni	*S. plana* (M)	dry weight	20 X	+				10c (5)	P	Bryan & Uysal 1978
Ni	*S. plana* (M)	dry weight	7 X	o				5c (5)	P	Bryan & Hummerstone 1978
Ni	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Ni	*Choromytilus meriodionalis* (M)	dry weight	4 X	–				78i	C	Watling & Watling 1976
Pb	*Anodonta anatina* (F)	dry weight	50 X	o → +				14-16i	C → P (7)	Manly & George 1977
Pb	*Mytilus edulis planulatus* (M)	shell length	3 X	o				5-8c (3-5)	P	Harris et al. 1979
Pb	*M. edulis* (M)	wet weight	3 X[c]	+				25i	P	Brix & Lyngby 1985
Pb	*M. edulis* (M)	dry weight	50 X	o→+				20c (2-20)	C→P (2)	Popham & D'Auria 1983
Pb	*M.e. planulatus* (M)	shell length	2 X	+				2c (10)	C	Ritz et al. 1982
Pb	*M. edulis* (M)	dry weight	14 X	o	W:H & <CI[a]	2 X	o & +	69i	C	Lobel et al. 1991
Pb	*Ostrea edulis* (M)	dry weight	13 X	–				38i	C	Boyden 1977
Pb	*Crassostrea gigas* (M)	dry weight	200 X	–				22i	P	Boyden 1977
Pb	*M. edulis* (M)	dry weight	14 X	–				22i	P	Boyden 1977

APPENDIX II. (cont'd)

Metal	Species	Effect of Size Parameter	Range	Effect	Effect of Age Parameter	Range	Effect	Number of samples	Pollution Status	Reference
Pb	*Mercenaria mercenaria* (M)	dry weight	401 X	o				35i	C	Boyden 1977
Pb	*Venerupis decussata* (M)	dry weight	16 X	−				30i	P	Boyden 1977
Pb	*Chlamys opercularis* (M)	dry weight	19 X	o				20i	C	Boyden 1977
Pb	*Pecten maximus* (M)	dry weight	52 X	−				37i	C	Boyden 1977
Pb	*Trichomya hirsuta* (M)	shell length	3 X	o				78i	P (3)[d]	Klumpp & Burdon-Jones 1982
Pb	*S. plana* (M)	dry weight	20 X	+				10c (5)	P	Bryan & Uysal 1978
Pb	*S. plana* (M)	dry weight	7 X	+				5c (5)	P	Bryan & Hummerstone 1978
Pb	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Pb	*Choromytilus meriodionalis* (M)	dry weight	4 X	−				78i	C	Watling & Watling 1976
Se	*M. edulis* (M)	dry weight	14 X	o	W:H & <CI[a]	2 X	o & o	69i	C	Lobel et al. 1991
Zn	*Unio elongatus* (F)	wet weight	10 X[c]	+				11c (na)	C	Baudo & Galanti 1988
Zn	*Elliptio complanata* (F)	shell length	2 X	o,o_{gill}	years	7 X	−,o_{gill}	50i	C (2)	Hinch & Stephenson 1987
Zn	*Elliptio complanata* (F)	shell length	2 X	+,$+_{body}$	years	7 X	o,$+_{body}$	50i	C (2)	Hinch & Stephenson 1987
Zn	*Velesunio ambiguus* (F)	dry weight	5 X	−	shell volume	na	+	11-23i[b]	C	Jones & Walker 1979
Zn	*Anodonta anatina* (F)	dry weight	50 X	o				14-16i	C → P (7)	Manly & George 1977
Zn	*Velesunio ambiguus* (F)	dry weight	3 X	+	shell volume	na	+	25i	C (LAX)	Millington & Walker 1983
Zn	*Velesunio ambiguus* (F)	dry weight	5 X	(−)	shell volume	na	+	25i	C (OCR)	Millington & Walker 1983
Zn	*Velesunio ambiguus* (F)	dry weight	15 X	(−)	shell volume	na	(−)	12i	C (RGL)	Millington & Walker 1983
Zn	*Mytilus edulis planulatus* (M)	shell length	3 X	+				5-8c (3-5)	P	Harris et al. 1979
Zn	*M. edulis* (M)	wet weight	3 X[c]	o				25i	C	Brix & Lyngby 1985
Zn	*M. edulis* (M)	dry weight	50 X	o→+				20c (2-20)	C→P (2)	Popham & D'Auria 1983
Zn	*M. edulis* (M)	various[f]	3-10X	+	various[g]	3-10X	+	98i	C	Lobel & Wright 1982
Zn	*M.e. planulatus* (M)	shell length	2 X	o				2c (10)	C	Ritz et al. 1982
Zn	*M. edulis* (M)	dry weight	14 X	−	W:H & <CI[a]	2 X	o & o	69i	C	Lobel et al. 1991
Zn	*M. edulis* (M)	shell length	1.5 X	o				6c (10)	C	Latouche & Mix 1982
Zn	*Ostrea edulis* (M)	dry weight	13 X	o				38i	C	Boyden 1977

APPENDIX II. (cont'd)

Metal	Species	Effect of Size Parameter	Range	Effect	Effect of Age Parameter	Range	Effect	Number of samples	Pollution Status	Reference
Zn	*Crassostrea gigas* (M)	dry weight	430 X	o				39i	C	Boyden 1977
Zn	*Crassostrea gigas* (M)	dry weight	200 X	o				22i	P	Boyden 1977
Zn	*M. edulis* (M)	dry weight	6-14 X	–				17-22i	P (4)	Boyden 1977
Zn	*Mercenaria mercenaria* (M)	dry weight	401 X	o				35i	C	Boyden 1977
Zn	*Venerupis decussata* (M)	dry weight	16 X	o				30i	P	Boyden 1977
Zn	*Chlamys opercularis* (M)	dry weight	19 X	o				20i	C	Boyden 1977
Zn	*Pecten maximus* (M)	dry weight	52 X	–				37i	C	Boyden 1977
Zn	*M. edulis* (M)	dry weight	230 X	–				119i	P (3)[d]	Cossa et al. 1980
Zn	*Trichomya hirsuta* (M)	shell length	3 X	o				78i	P (3)[d]	Klumpp & Burdon-Jones 1982
Zn	*S. plana* (M)	dry weight	20 X	+				10c (5)	P	Bryan & Uysal 1978
Zn	*S. plana* (M)	dry weight	7 X	+				5c (5)	P	Bryan & Hummerstone 1978
Zn	*S. plana* (M)	dry weight	9 X	o				5c (5)	C	Bryan & Hummerstone 1978
Zn	*Choromytilus meriodionalis* (M)	dry weight	4 X	–				78i	C	Watling & Watling 1976

[a]width to height ratio (W:H) increases and condition index (CI) decreases with age
[b]samples collected during three seasons
[c]range given was for shell length
[d]results are for three polluted sites combined
[e]samples collected about once monthly over a 20 month period
[f]measures of size included tissue weight and shell length (L), width (W) and height (H)
[g]measures of relative age included condition, and ratios of W:L and W:H

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