EXPLORING RELATIONSHIPS IN A SEDIMENT-TISSUE BIOACCUMULATION DATABASE

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ABSTRACT

Testing of sediments proposed for dredging and open water disposal often involves the use of 28-day bioaccumulation tests. Results from these tests are then used on a project-specific basis in the assessment of the potential for adverse environmental effects. However, we believe that these data, when assembled into a data set with results from other dredging projects, can be useful in a broader context. This may include the development of a better understanding of benthic species-specific responses to a range of sediment concentrations on a regional basis. This information could then be used for proposing changes to existing testing approaches or for modifications in the selection of test species.

We have assembled a database of 11 projects comprising a diverse geographic representation within New England, including Boston, Providence, Bridgeport, and Norwalk Harbors. Most of these projects examined the bioaccumulation of a range of both metal and organic contaminants in the polychaete worm, *Nereis virens*, and the bivalve clam, *Macoma nasuta*. Most contaminants in the database were represented by 25-45 paired sediment/tissue sets where the measured tissue value and the measured sediment value were both known. While we recognize that this is a modest data set, we believe that examining the trends within the data will help lead to productive scientific discussions on the application of bioaccumulation testing on both a regional and national level. Statistical analyses were undertaken to examine trends in the data, consisting of correlation and regression analyses to determine the mathematical form of the relationship between sediment chemistry and bioaccumulation, with adjustments for background tissue levels, where known.

Keywords:. Dredged material, *Macoma nasuta*, *Nereis virens*, correlation analysis, New England

INTRODUCTION

The national approaches for evaluating sediments for aquatic disposal includes assessment of the potential for aquatic organisms to bioaccumulate sediment-associated contaminants (USEPA and USACE 1991, 1998). In the existing regulatory approach, 28-day bioaccumulation test data generated on individual projects are used on a case-by-case basis to evaluate the specific project at hand. However, as the number of projects on which such tests have been conducted grows, the compilation of data from multiple projects has the potential to inform our understanding of relationships between sediments and organism responses on a localized or regional basis. Insights gained from this analysis may then provide a technical basis to allow regulators to increase, reduce, or otherwise modify the requirements for tests on future projects.

Recently, in response to discussions in the New England regional dredging team, we have begun an assessment of the existing regional bioaccumulation data that have been developed. The initial goals of this assessment were to determine (1) whether, based on a limited data set, there was evidence of data trends that would support the investment of greater time and effort on a more comprehensive investigation and (2) whether there were any data analyses that could be used to support immediate changes in how tests are conducted.

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Literature Background

The presence of relationships between sediment contaminant concentrations and the concentrations that can be found in resident organisms has been studied by many investigators and more formally developed as biota-sediment accumulation factors (BSAFs) (e.g., see Washington State Department of Ecology 1998, California State Water Resources Control Board 1998). However, BSAFs are influenced by factors such as the amount of organic carbon in a sediment, regional sediment geochemistry, the amount of lipid in an organism, the organism's feeding mode, the organism's mobility, and other factors that all contribute to a level of uncertainty in the predictive ability of BSAFs (e.g., Model Evaluation Workgroup 1999). As a consequence, BSAFs have not been widely accepted in the national regulatory approach in lieu of direct exposure of test organisms to the specific sediment being evaluated.

Despite the uncertainties inherent in BSAFs, they undeniably can provide a first order estimate of bioaccumulation potential. Therefore, if the factors that introduce variability can be constrained or accounted for, the predictive capability should increase. This paper presents findings from a pilot study using a number of dredging projects in the New England region where we examined the mathematical and statistical relationships between the test sediments and the associated organism tissue concentrations. In this pilot study, we chose to focus on data produced by a single contract laboratory, Battelle, for proposed Federal dredging projects in order to minimize potential variability that may be inherent in data from multiple laboratories. This also reduced complexities with data formats when data from multiple laboratories are used.

METHODS

Twelve projects have been conducted by Battelle since 1997 that involved the evaluation of sediment chemistry, toxicity, and bioaccumulation. Table 1 summarizes the projects included in this report. Figure 1 shows the locations of each of these projects, including the dredging site sample locations and the associated reference site sample locations. For each of these projects, the sediment chemistry data that were collected included grain size, total organic carbon, metals, PCBs, chlorinated pesticides, PAHs, metals, and dioxin/furans for select projects. Tissue chemistry data were obtained for two species – *Macoma nasuta* and *Nereis virens* – from 28-day bioaccumulation studies. Toxicity results (% survival and toxicity) were also obtained from 10-days solid phase acute tests for *Ampelisca abdita* and *Americamysis bahia*). Data from these separate studies were combined into a single database that included study identifiers, matrix and laboratory methods, and laboratory codes

Table 1. Summary of projects used in database.

Project	Year Sampled
Providence River, RI	1997
Guilford, CT	2000
Norwalk, CT	2000/2001
New Haven Harbor, CT	2000
Weymouth-Fore River, MA	2000
Boston Harbor, MA	2001
Bridgeport Harbor, CT	2001
Clinton Harbor, CT *	2001
North Cove, CT *	2001
Plymouth Harbor, MA	2001
Westport Harbor, CT	2004
Boston Harbor, MA	2004

* These projects were compared to the same reference sample.

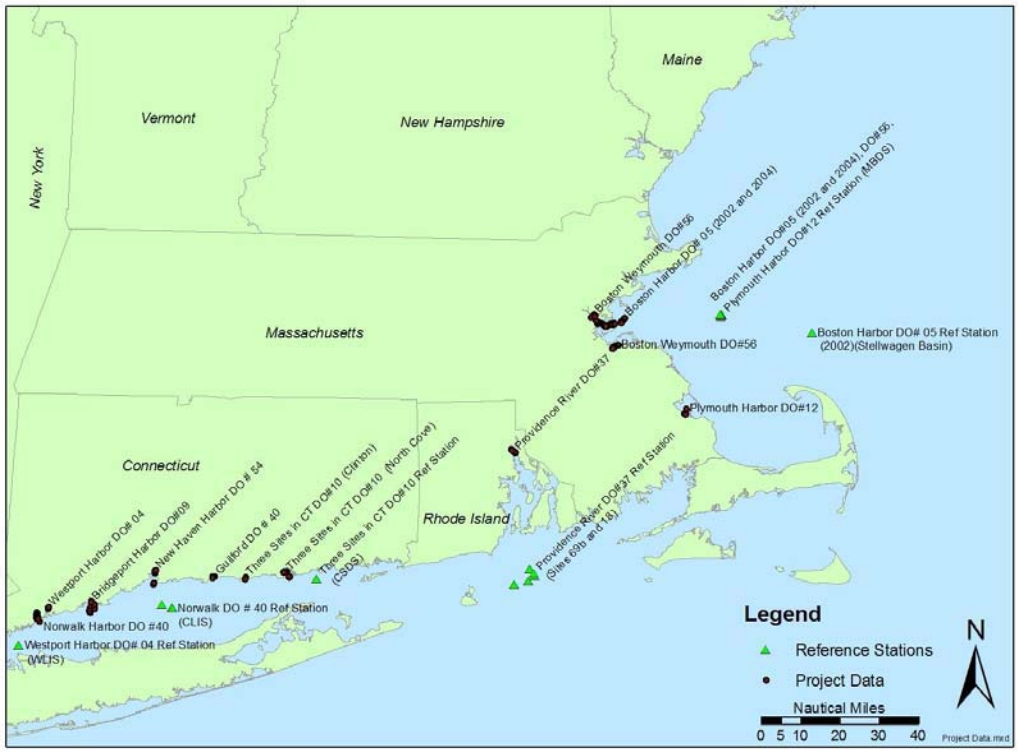

Figure 1. Map of project locations and reference site locations.

Statistical Methods

Statistical analyses of the data from the various bioaccumulation studies were undertaken to determine whether a mathematical/statistical relationship exists between chemical concentrations in sediment samples and chemical concentrations in tissue samples. These statistical analyses included several steps to evaluate and select the appropriate data for the relationship analyses, to assess data properties to determine the appropriate statistical models, to assess the specific relationship between the two measurements, and to determine predicted limits on future values of tissue concentrations associated with specific levels of sediment concentration. The specific statistical methods included:

- Scatterplots of tissue and sediment concentrations to determine the mathematical relationship between the two variables and to evaluate the strength of relationship;
- Correlation analysis between tissue and sediment concentrations to evaluate the mathematical relationship and its strength;
- Correlation analysis between tissue concentrations of the two species to determine the extent to which the bioaccumulation results were consistent between species;
- Paired t-tests between *Macoma* and *Nereis* tissue concentrations to determine whether there was significantly different bioaccumulation between the species;
- Regression analysis to determine the specific parameters of the mathematical relationship between tissue and sediment concentrations;
- Regression diagnostic analyses to determine whether the assumptions underlying the regression analyses were met; and

- Calculation of upper prediction limits for future tissue concentrations given specific values of sediment concentration.

All statistical analyses were performed using SAS® software. For more information about the statistical methods, the reader is referred to Neter, *et al.* (1996).

RESULTS

Prior to performing the statistical analyses outlined above, the data were evaluated to determine whether there were observations that should be excluded from the analysis. The evaluation looked for three specific issues:

1. censored values;
2. potential outliers; and
3. specific types of data that produced inconsistent results.

Censored values, specifically non-detected concentrations in either tissue or sediment samples, were identified from laboratory codes provided in the study databases. All non-detects were excluded from the analysis because of the likelihood that they would produce biased results; because they generally lie at one extreme end of the data distribution, non-detects have a propensity to unduly affect the fit of the regression line by misrepresenting the true relationship at their end of the data distribution. Potential outliers were identified from scatterplots of the data as observations that lay outside the general scatter of plotted points. Any identified outliers were subjected to data reviews to determine whether there were explainable causes for the inconsistent value that would lead to their removal. One sample location from one study (Station A of Norwalk) was identified in several of the plots for individual PAH measurements where the observation appeared unreasonable. This observation was removed because the MDL in the specific analysis was replaced with a higher reporting limit in defining non-detects, leading to the elimination of several replicate samples with low detected concentrations that, had they been included, may have kept the observation from being identified as an outlier.

Scatterplots using different symbols for different data characteristics were used to determine whether the results were consistent for different data characteristics. For example, the laboratory analysis methods were examined to determine whether they yielded inconsistent results. This analysis also examined background samples to determine whether their results were consistent with other study results. Of particular interest was an examination of data that were estimated during laboratory analysis (i.e., "J"-flagged data). They were plotted along with the remainder of the data to determine whether the use of laboratory estimating techniques produced inconsistent results. Examination of the plots showed that the relationship between tissue and sediment concentrations for the estimated data, which generally appeared on the lower end of the scale of both tissue and sediment concentrations, did not generally differ from the relationship for the unflagged data. As a result, the analyses continued with the estimated data included.

Upon completion of the initial data evaluation, an assessment of data sufficiency was undertaken. While relationships can be examined with only a relatively few number of observations, for this study, we chose to eliminate any chemicals for which both species had fewer than 10 observations (matching tissue with sediment). Upon completion of this operation, there were 56 chemicals remaining. These chemicals are listed in Table 2, as well as the number of observations for *Macoma* and *Nereis* that were present in the final data.

Initial evaluation of the relationships between tissue and sediment chemical concentrations included evaluation of scatterplots of the data (once unusable data had been removed) and the calculation of correlation coefficients between the sediment concentrations and the tissue concentrations. Because Pearson correlations indicate the strength of linear correlations and it was thought that the concentrations might exhibit non-linear relationships, Kendall's Tau correlation coefficient was calculated. This correlation coefficient is associated with the likelihood that for a pair of observations consisting of tissue and sediment concentrations, the higher sediment and tissue concentrations occur for the same observation. For any monotonically increasing relationship (e.g., linear or log-linear), the Tau correlation should be large. Table 2 shows the Tau correlation coefficients. Those that are statistically significantly different than zero at the 0.01 significance level (i.e., strongly correlated) are indicated in boldface. It should be noted that a high Tau correlation can be associated with a setting where a change in either the tissue or sediment concentration increase is small but consistent. Thus, an apparent "flat-line" relationship

Table 2. Summary of relationships between tissue and sediment and between species.

Chemical	*Macoma*		*Nereis*		*Macoma/Nereis*			
	No. of Obs	Tau	No. of Obs	Tau	No. of Obs	Tau	Diff	p-value
Arsenic	31	.240	31	.145	31	**.616**	3.548	<.0001
Cadmium	36	**.404**	36	.166	36	**.411**	0.077	<.0001
Chromium	16	-.230	16	.183	16	.417	1.936	0.0003
Copper	16	.383	16	.167	16	.350	2.587	<.0001
Lead	14	**.582**	14	.165	14	.011	0.770	<.0001
Mercury	51	**.325**	41	.121	41	**.369**	1.519	<.0001
Nickel	29	**-.35**	29	-.34	29	**.559**	0.568	0.0009
Zinc	16	.150	16	.050	16	.333	-1.1201	0.5947
4,4`-DDD	9	**.944**	10	**.911**	9	**1.000**	0.752	0.2036
1-Methylnaphthalene	27	**.534**	27	.108	27	.129	0.085	0.0740
1-Methylphenanthrene	27	**.645**	27	**.616**	27	**.686**	4.367	<.0001
2,6-Dimethylnaphthalene	27	**.774**	27	.254	27	.343	1.131	0.0012
2-Methylnaphthalene	31	**.554**	31	-.03	31	.095	0.419	<.0001
Acenaphthene	31	**.530**	31	**.474**	31	**.573**	0.289	0.0052
Acenaphthylene	31	.250	30	.097	30	**.493**	0.354	<.0001
Anthracene	33	**.616**	30	.345	30	**.479**	6.05	<.0001
Benzo(a)anthracene	38	**.649**	30	**.437**	30	**.793**	29.75	<.0001
Benzo(a)pyrene	38	**.663**	29	.318	29	**.585**	17.67	<.0001
Benzo(b)fluoranthene	38	**.720**	31	**.465**	31	**.741**	21.13	<.0001
Benzo(e)pyrene	33	**.730**	28	**.554**	28	**.682**	19.81	<.0001
Benzo(g,h,i)perylene	35	**.666**	30	**.428**	30	**.535**	7.326	<.0001
Benzo(k)fluoranthene	38	**.746**	31	**.534**	31	**.720**	17.94	<.0001
Biphenyl	30	.129	30	-.03	30	.065	0.118	0.7376
Chrysene	38	**.632**	35	**.521**	35	**.835**	43.0	<.0001
Dibenz(a,h)anthracene	31	**.577**	14	.265	14	.378	1.125	<.0001
Fluoranthene	38	**.709**	38	**.652**	38	**.818**	79.12	<.0001
Fluorene	31	**.676**	31	**.517**	31	**.556**	1.455	<.0001
Indeno(1,2,3-cd)pyrene	34	**.642**	23	.301	23	.365	5.612	<.0001
Naphthalene	31	.245	31	.155	31	.289	0.707	0.0449
Perylene	33	**.635**	27	.302	27	**.354**	6.826	0.0018
Phenanthrene	35	**.656**	32	.313	32	**.378**	10.93	<.0001
Pyrene	38	**.655**	38	**.663**	38	**.838**	84.27	<.0001
Total HMW PAH	47	**.685**	47	**.635**	47	**.828**	325.7	<.0001
Total LMW PAH	44	**.589**	41	.214	41	.199	17.08	<.0001
Total PAH	47	**.666**	47	**.642**	47	**.813**	343.3	<.0001
PCB 8	23	.369	11	**-.690**	11	-.54	-0.4532	0.1768
PCB 18	24	**.393**	23	.290	23	**.498**	0.06	0.7743
PCB 28	30	**.772**	30	**.689**	30	**.713**	1.376	<.0001
PCB 44	28	**.752**	29	**.680**	28	**.761**	0.151	0.1273
PCB 49	28	**.419**	29	**.474**	28	**.665**	0.832	<.0001
PCB 52	29	**.716**	29	**.706**	29	**.723**	0.839	0.0009
PCB 66	29	**.598**	29	**.741**	29	**.569**	1.416	<.0001
PCB 87	28	**.775**	28	**.743**	28	**.840**	1.099	<.0001
PCB 101	29	**.765**	30	**.749**	29	**.787**	0.829	0.0008

Table 2. Summary of relationships between tissue and sediment and between species (continued).

Chemical	*Macoma*		*Nereis*		*Macoma/Nereis*			
	No. of Obs	Tau	No. of Obs	Tau	No. of Obs	Tau	Diff	p-value
PCB 105	27	**.689**	28	**.775**	27	**.731**	0.048	0.5344
PCB 118	31	**.744**	31	**.782**	31	**.737**	0.800	<.0001
PCB 128	27	**.700**	26	**.670**	26	**.752**	-0.0367	0.3796
PCB 138	31	**.705**	31	**.709**	31	**.754**	-0.8537	<.0001
PCB 153	31	**.739**	32	**.667**	31	**.715**	-0.4634	0.0063
PCB 170	23	**.774**	29	**.714**	23	**.751**	-0.3329	<.0001
PCB 180	28	**.706**	29	**.686**	28	**.782**	-0.6972	<.0001
PCB 183	21	**.396**	26	**.666**	21	**.598**	-0.2317	<.0001
PCB 187	29	**.746**	29	**.711**	29	**.678**	-0.4683	<.0001
PCB 206	11	.073	13	.168	11	**.778**	-0.1532	<.0001
PCB 209	10	.467	12	-.27	10	.056	-0.1149	0.0001
Total PCB	43	**.771**	42	**.790**	42	**.816**	3.184	0.0117

(e.g., Arsenic in *Nereis*) may have a significantly high Tau value. A comparison of the correlation results for *Macoma* and *Nereis* show that the correlations between tissue and sediment are generally stronger in *Macoma* than in *Nereis*.

The correlation analysis was repeated with the estimated data (i.e., "J"-flagged data) removed to determine whether their inclusion may adversely affect the relationship between tissue and sediment concentrations. For many of the chemicals, the correlation coefficient decreased when the estimated data were excluded. In no cases did the correlation coefficient increase significantly with the exclusion of the estimated data. As a result, the estimated data were included in the remaining analyses.

Table 2 also includes a summary of the relationship between tissue concentrations in the two species. Kendall's Tau correlation was calculated between *Macoma* and *Nereis* tissue samples to determine the degree of consistency in bioaccumulation between species. In addition, paired t-tests were conducted to compare actual tissue concentrations between the two species. Table 2 shows that the correlations between species are generally large, indicating similar patterns of bioaccumulation between the two species. The "Diff" column of Table 2 shows the difference between average concentrations in *Macoma* and *Nereis*. In most cases, the difference is positive, indicating that *Macoma* concentrations are higher than those of *Nereis*. In many of the cases where *Nereis* concentrations were found to be higher, the difference is not statistically significant. There were a few PCB congeners where average tissue concentrations were higher for *Nereis* than *Macoma*, although total PCBs were higher for *Macoma* than *Nereis*.

Regression models were fitted to the data for each chemical and each species. Prior to fitting each model, scatterplots of the tissue chemistry versus sediment chemistry were examined to determine which of four models appeared to best represent the relationship shown in the plots:

$$T = \alpha + \beta * S \quad (1)$$
$$T = \alpha + \beta * \ln(S) \quad (2)$$
$$\ln(T) = \alpha + \beta * S \quad (3)$$
$$\ln(T) = \alpha + \beta * \ln(S) \quad (4)$$

where T is the tissue concentration and S is the sediment concentration. All four models were fitted to the tissue and sediment data, and the results of the best-fitting model are displayed in Table 3. These results include the information about the model that was fitted (in terms of the identifying number of the model from above), the R^2 from the regression, and the p-value for the test of whether the trend parameter (i.e., slope) was statistically significantly different than zero. The regression residuals were also examined to determine whether the regression assumption of normally-distributed, independent errors was met. While there were a few cases where formal tests of normality of the residuals indicated that the underlying errors may not be normally-distributed, examination of the probability plots indicated that any deviations from the normal distribution were minor.

Table 3. Summary of tissue-sediment regression.

Chemical	*Macoma*			*Nereis*		
	Model	R^2	p-value	Model	R^2	p-value
Lead	(1)	0.759	<.0001*			
4,4`-DDD				(1)	0.944	<.0001*
1-Methylnaphthalene	(1)	0.596	<.0001*			
1-Methylphenanthrene	(4)	0.777	<.0001*	(3)	0.613	<.0001*
2,6-Dimethylnaphthalene	(4)	0.799	<.0001*			
2-Methylnaphthalene	(4)	0.580	<.0001*			
Acenaphthene	(1)	0.383	<.0001*	(4)	0.519	<.0001*
Acenaphthylene	(4)	0.223	0.0074*			
Anthracene	(4)	0.823	<.0001*	(4)	0.202	0.0126*
Anthracene	(4)	0.823	<.0001*	(1)	0.045	0.2630
Benzo(a)anthracene	(4)	0.871	<.0001*	(4)	0.534	<.0001*
Benzo(a)pyrene	(4)	0.881	<.0001*	(4)	0.303	0.0020*
Benzo(b)fluoranthene	(4)	0.888	<.0001*	(4)	0.577	<.0001*
Benzo(e)pyrene	(4)	0.891	<.0001*	(4)	0.694	<.0001*
Benzo(e)pyrene	(4)	0.891	<.0001*	(1)	0.871	<.0001*
Benzo(g,h,i)perylene	(4)	0.865	<.0001*	(4)	0.304	0.0016*
Benzo(k)fluoranthene	(4)	0.908	<.0001*	(4)	0.640	<.0001*
Chrysene	(4)	0.851	<.0001*	(4)	0.734	<.0001*
Dibenz(a,h)anthracene	(4)	0.746	<.0001*			
Fluoranthene	(4)	0.873	<.0001*	(1)	0.901	<.0001*
Fluorene	(1)	0.546	<.0001*	(4)	0.371	0.0003*
Indeno(1,2,3-cd)pyrene	(4)	0.801	<.0001*	(3)	0.212	0.0271*
Perylene	(4)	0.808	<.0001*	(3)	0.225	0.0125*
Phenanthrene	(4)	0.769	<.0001*	(4)	0.157	0.0249*
Pyrene	(4)	0.857	<.0001*	(4)	0.845	<.0001*
Total HMW PAH	(1)	0.782	<.0001*	(1)	0.812	<.0001*
Total LMW PAH	(1)	0.321	<.0001*	(3)	0.040	0.2087
Total PAH	(1)	0.774	<.0001*	(1)	0.797	<.0001*
PCB 8	(4)	0.305	0.0063*			
PCB 18	(4)	0.398	0.0009*			
PCB 28	(4)	0.923	<.0001*	(1)	0.667	<.0001*
PCB 44	(4)	0.672	<.0001*	(1)	0.432	0.0001*
PCB 49	(4)	0.620	<.0001*	(1)	0.364	0.0005*
PCB 52	(4)	0.895	<.0001*	(1)	0.786	<.0001*
PCB 66	(4)	0.842	<.0001*	(1)	0.738	<.0001*
PCB 101	(4)	0.824	<.0001*	(1)	0.785	<.0001*
PCB 105	(4)	0.931	<.0001*	(1)	0.920	<.0001*
PCB 118	(4)	0.928	<.0001*	(1)	0.879	<.0001*
PCB 128	(4)	0.814	<.0001*	(1)	0.782	<.0001*
PCB 138	(4)	0.855	<.0001*	(1)	0.859	<.0001*
PCB 153	(4)	0.840	<.0001*	(1)	0.698	<.0001*
PCB 170	4	0.843	<.0001*	(1)	0.827	<.0001*

Table 3. Summary of tissue-sediment regression (continued).

Chemical	*Macoma*			*Nereis*		
	Model	R^2	p-value	Model	R^2	p-value
PCB 180	(4)	0.751	<.0001*	(1)	0.754	<.0001*
PCB 183	(4)	0.661	<.0001*	(1)	0.731	<.0001*
PCB 187	(4)	0.775	<.0001*	(1)	0.818	<.0001*
PCB 209	(4)	0.222	0.1691			
PCB 87	(4)	0.910	<.0001*	(1)	0.837	<.0001*
Total PCB	(4)	0.765	<.0001*	(1)	0.860	<.0001*

The fitted models were used to obtain 95% upper prediction limits for tissue concentrations as a function of sediment concentration. The prediction limit represents an upper bound that will be exceeded only about 5% of the time in future observed values of tissue concentration in a 28-day bioaccumulation study with a specified sediment concentration. The upper prediction limits were calculated for a series of values and plotted along with the regression line over scatterplots of the tissue concentrations versus sediment concentrations.

An examination of the scatterplots of tissue versus sediment concentrations showed that for many of the chemicals (and both species) there were influential observations. These observations were identified as those that had undue influence on the slope or the fitted regression line or those that significantly contributed to a large error variance for the regression model fit. While influential observations may have caused inaccurate representations of the relationship between tissue and sediment concentrations (slope influence) or unreasonably large prediction limits (variance influence), they were not removed from the analysis. Figure 2 shows an example of a chemical with both types of influential points. The point with the largest sediment value strongly influences the fit of the regression line, while the four points with sediment concentrations between 300 and 800 ppm affected the regression model variability so that the prediction limit line (red dashed) lies fairly high above the regression line (solid blue).

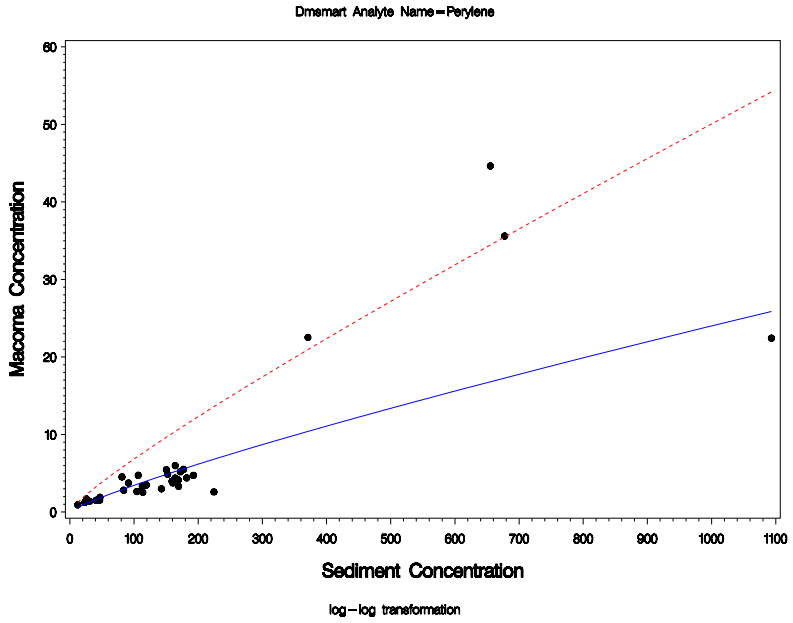

Figure 2. Example of influential observations.

Figures 3 and 4 provide six examples each of the prediction-interval graphs for selected chemicals in *Macoma* and *Nereis*, respectively. For *Macoma*, the six plotted chemicals are (a) lead, (b) cadmium, (c) 1-methylnaphthalene, (d) dibenz(a,h)anthracene, (e) total PAH, and (f) total PCB. Lead in *Macoma* is the only case where a metal exhibited a relationship between tissue and sediment concentrations. Cadmium exhibits the type of relationship found for most of the remaining metals for both *Macoma* and *Nereis* where tissue levels are only slightly elevated, if

at all, in response to increasing sediment concentration. The plots for 1-methylnaphthalene and Total PAHs show a linear relationship (Equation 1) between tissue and sediment concentrations. Other chemicals with similar relationships included acenaphthene, fluorene, total low-molecular-weight and total high-molecular weight PAHs. For the remaining individual PAHs and all the PCBs there was a log-log relationship (Equation 4) between tissue and sediment concentrations. In fact, the plots for individual PCBs all appeared generally similar to each other and to the plot for total PCBs.

For *Nereis*, the six plotted chemicals are (a) 4-4' DDE, (b), perylene, (c) fluorene, (d) benzo(k)fluoranthene, (e) total PAH, and (f) total PCB. Tissue and sediment concentrations were unrelated for all metals. Individual and total PCB concentrations in *Nereis* were linearly related (Equation 1) between tissue and sediment. Other chemicals exhibiting linear relationships included DDD, anthracene, benzo(e)pyrene, fluoranthene, high-molecular-weight PAHs, and total PAHs (as shown in Figure 4). Chemicals exhibiting log-linear relationships (Equation 3) included perylene, 1-methylphenanthrene, indeno(1,2,3-cd)pyrene, and total low-molecular-weight PAHs. The remaining chemicals exhibited log-log relationships (Equation 4) like that of fluorene.

DISCUSSION

With few exceptions (excluding most metals), plots of the data indicated that higher tissue concentrations were associated with higher sediment concentrations. Table 3 shows that for *Macoma*, the relationship was usually linear after taking logarithms of both tissue and sediment concentrations. When plotted back on the original data scale, the estimated relationship often looks like a logarithmic function (see Figure 4(c)). This could indicate that bioaccumulation decreases as the sediment concentration increases. For *Nereis*, the linear and log-log models were selected equally often. Yet, even for those chemicals for which the linear model was chosen, the plots indicate that the bioaccumulation may decrease proportionately at higher concentration levels (see Figure 4(f) and Figure 3(c)). For the chemicals where the log-linear model provided the best fit to the data (e.g., perylene in *Nereis* – see Figure 4(b)), it was often the case that no model fitted the data well (i.e., the R^2 values were generally less than 0.25), so no relationship between tissue and sediment concentrations were apparent.

It was not surprising that there were few apparent relationships between tissue and sediment concentrations for metals. Luomo and Rainbow (2005) noted this in their paper and attributed the lack of relationship to the complexity of the cycling of metals in aquatic ecosystems.

The models that were fitted here are the most basic models relating tissue concentrations to sediment concentrations. Bioaccumulation is affected by the bioavailability of the chemicals. Bioavailability is affected by physical, biological, and chemical factors in aquatic environment. The Washington State Department of Ecology (1998) suggests that total organic carbon (TOC) is one factor that can influence bioavailability and, as a result, bioaccumulation. Other studies have suggested that grain size can affect bioavailability. These factors were not incorporated in the model for tissue concentration. Further examination of the data that includes these factors may, at minimum, improve the model fit to the data, and could significantly reduce the variability in the model and, as a result, the magnitude of the prediction limit for future tissue concentrations.

There is a natural extension to the prediction limit approach to examining the relationship between tissue and sediment chemistry. This approach provides an upper limit to a future observation of tissue concentration for a fixed (specified) sediment concentration. This prediction limit method could, with further analysis, be used to find corresponding sediment concentrations that could potentially be used in risk assessment models for projects. This approach may have the most utility on the lower part of the sediment range where the prediction limits are closer to the regression line.

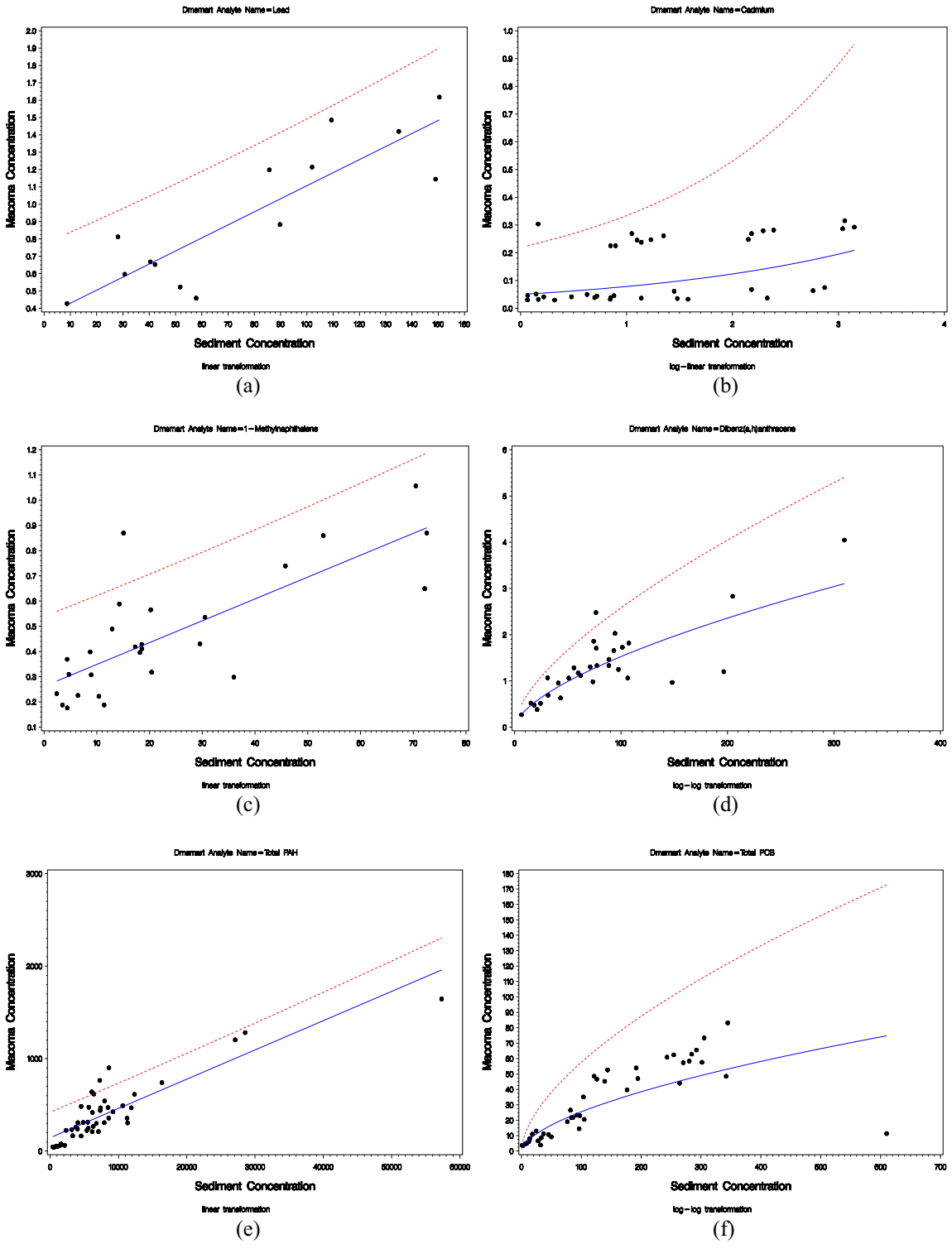

Figure 3. Examples of *Macoma* prediction limit plots.

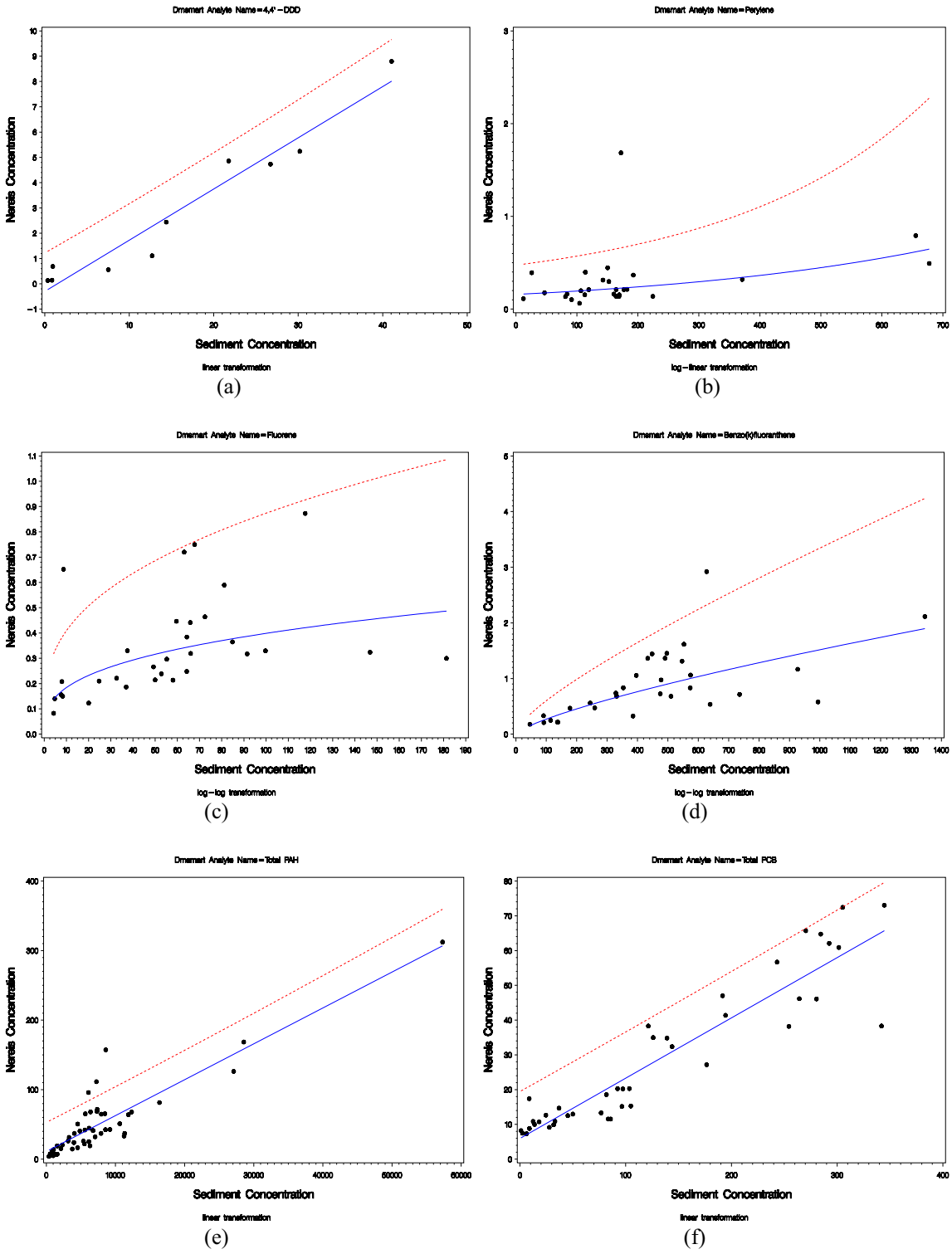

Figure 4. Examples of *Nereis* prediction limit plots.

The data that were used in this analysis all were generated using sediment collected in New England. Thus, these results should be considered regional rather than national. However, it is reasonable to expect that similar trends would be found in other coastal areas if the same species were used in the bioaccumulation tests.

CONCLUSIONS

Three initial conclusions emerge from our analysis of this data set of recent sediment bioaccumulation data. First, for any given sediment, *Macoma* usually accumulates similar or much greater tissue levels than *Nereis* over a 28-day laboratory exposure with the exception of a few PCB congeners. Secondly, metal concentrations in sediments are poorly correlated with tissue concentrations (with the exception of lead in *Macoma*). Thirdly, most measured PAHs, PCBs, and pesticides show moderate to strong correlation between sediment concentrations and tissue levels. Each of these observations has potential implications in a regulatory context.

Our analysis suggests that given the New England regional risk-based approach to evaluating bioaccumulation, *Nereis* should be considered for elimination or replacement. Although the original rationale for using two species was to provide phylogenetic diversity, the results of the risk model are driven by the species with the higher accumulation levels. *Nereis,* in that context, provides minimal added value for the additional effort and expense. Selection of a different species to replace *Nereis* should be further evaluated with a goal of selecting a species that may better complement the results obtained from *Macoma*.

In the case of metals, the results suggest that it may be appropriate to reconsider the scope of testing for such contaminants with respect to their bioaccumulation. It may be reasonable to eliminate most metals from the testing or use the existing data to establish thresholds for when these contaminants are included in bioaccumulation tests.

For the organic contaminants discussed, we recommend further evaluation of the predictive regressions with the possible development of regional thresholds for when these contaminants are required in bioaccumulation tests and when predictions can be used. Certainly on the lower end of the sediment range the predictive regressions should be very reliable and close to the regression line. The further evaluation could be done by considering a phased approach where a one-year evaluation phase is established where both the predictive approach and the laboratory approach are used in tandem. At the end of the year the performance of the predictive approach could then be judged for its use in a regional regulatory context.

Additional refinements to the analyses we've conducted could be achieved by normalizing the contaminant data to total organic carbon or grain size. It may also be possible to conduct additional data mining from projects conducted by other analytical laboratories to increase the robustness of the data base. These approaches may result in stronger regression relationships and increase the predictive value of the models. We believe that our results demonstrate that individual bioaccumulation test results should be evaluated in a broader context to assess regional trends that may be useful in refining the regulatory testing approach.

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