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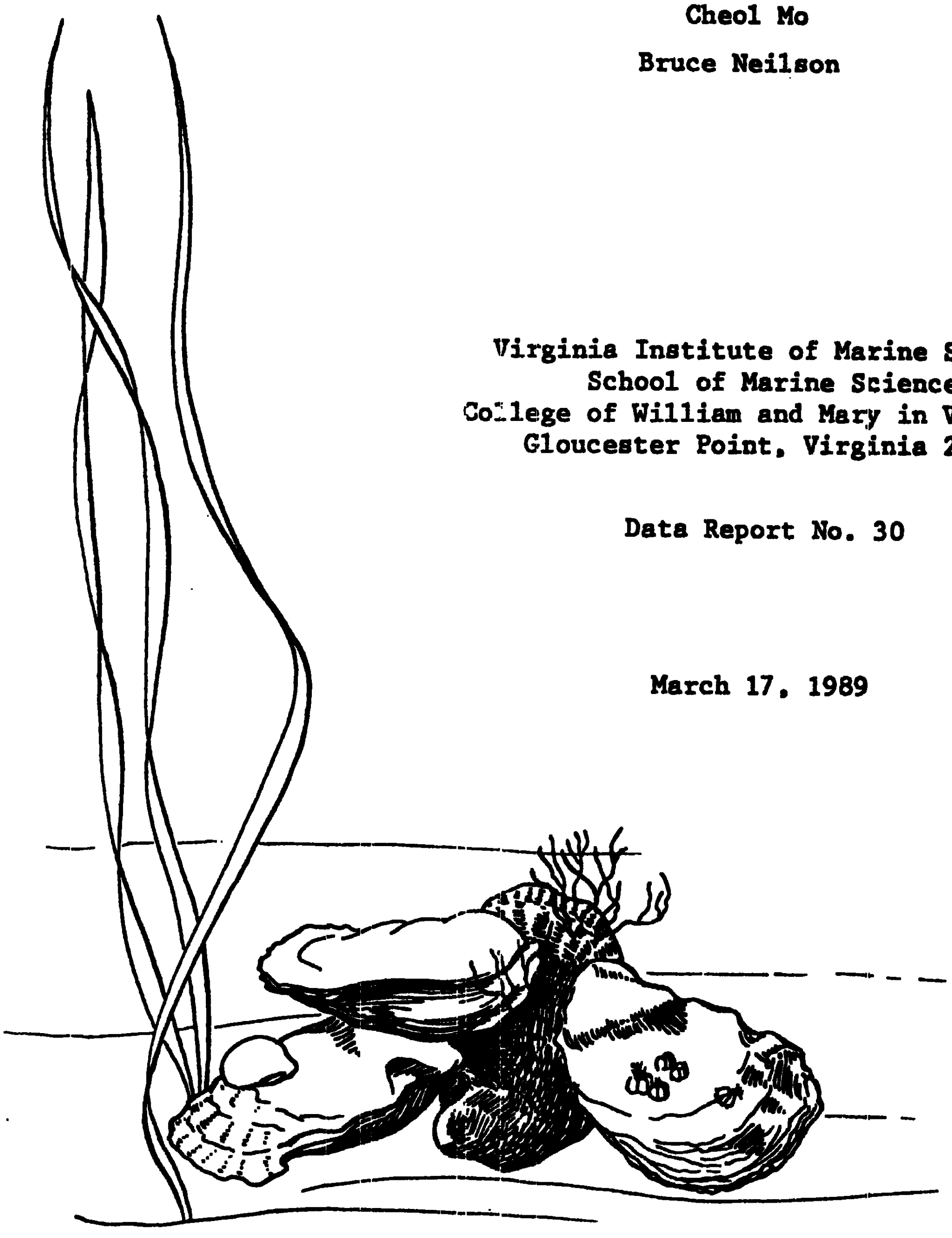
Data Report No. 30

March 17, 1989



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PREFACE

The data in this report have been obtained in order to estimate parameters in a model of heavy metal bio-accumulation by the American oyster, Crassostrea virginica Gmelin.

Related works:

(1) Experimental Studies of Zinc-65 Uptake Rates by the American Oyster, Crassostrea virginica with Regard to Salinity, Sediment Concentration, and Body Size. VIMS Data Report No. 29, August, 1988.

(2) Short Term Uptake Rate of Zinc by the American oyster, Crassostrea virginica, - Relationship Among Body Size, Salinities, and Uptake Rates. In preparation.

(3) Contribution of Extraneous Materials to Variability of Oyster Zinc Bio-concentration Measurements. In preparation.

(4) Modelling of Zinc Bio-accumulation in the American Oyster, Crassostrea virginica - Influence of Biological and Environmental Factors in Bio-accumulation." Dissertation.

The authors express appreciation for the help of Mr. J. Whitcomb in collecting the oyster and mussel samples.

DEFINITION OF TERMS

Soft tissue: organic body of oyster or mussel excluding shell, gut contents, and faecal pellets but including the exoskeleton of the crab.

Body size: a general term that may mean any one of: shell length, body weight, dry meat weight, or wet meat weight.

Body weight: dry (meat) weight or wet (meat) weight of soft tissue (grams).

Body burden: the total amount of a metal in soft tissue (micrograms). The metal in gut contents may be included in this report when the amount of the gut content is small.

Concentration: a general term that expresses the mass (of a metal) per unit mass of a material such as water or sediment (dry weight). The unit "ppm" is used interchangably for either microgram/gram of dry material or microgram/ml of solution.

Bio-concentration: concentration of metal expressed in mass of the metal per unit mass (dry weight) of soft tissue (ppm).

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ABSTRACT

Oysters and mussels of varying sizes and sediment samples were collected from oyster beds with different salinity regimes of three Virginian coastal plain rivers: Rappahannock River, James River, and Piankatank River.

Zinc concentrations of 1) soft tissues, gut contents, and shells of the oysters, 2) soft tissues of the mussels, 3) pea crabs, and 4) sediment samples were measured with a flame atomic absorption (Flame AA) spectrophotometer. Particulate organic carbon and nitrogen concentrations of the sediments were measured with a carbon-nitrogen analyzer.

The contribution of extraneous materials, such as gut contents, faeces, and pea crabs, to the variability in oyster metal bioconcentration measurements is examined. The effect of salinity differences on bioconcentrations and the relationships between oyster and mussel dry meat weights and body burdens and bio-concentrations also are examined. The relationships are assumed to have the form: uptake equals the product of a constant times weight raised to the power "b" (e.g., a $\{\text{body size}\}^b$). Values for the constants a and b are determined for each case.

INTRODUCTION

It is well known that the American oyster, *Crassostrea virginica* (Gmelin), accumulates trace metals to concentrations many orders higher than those of surrounding water. Oysters, however, have not been used as biological indicators of metal pollution, at least not as extensively as the common mussel, *Mytilus edulis* (L.). This may be because there is little information in the literature concerning the relationship between bio-concentration and the various factors that influence the metal uptake rate of oysters.

Assuming first order kinetics, the movement of metals in and out of an organism is

$$\frac{dCo}{dt} = k_1Ce - k_2Co$$

where Co : concentration of metal in the organism.

Ce : concentration of metal in environment.

k_1 : uptake rate constant.

k_2 : depuration rate constant.

t : time of exposure.

When Ce is constant,

$$Co = \frac{k_1}{k_2}Ce\ (1 - e^{-k_2t})$$

In steady state, $\frac{dCo}{dt} = 0$

then,

$$\frac{Co}{Ce} = \frac{k_1}{k_2}$$

When Ce is the total concentration of metal in the water, regardless of the bio-availability, this value, $\frac{Co}{Ce}$, is the "Bio-Concentration Factor" (Hamelink 1977).

In the natural environment, it can be assumed that the time of exposure is long enough for the organism to be in steady state in terms of uptake and depuration. As with other metal pollution indicator organisms, it is often assumed that oysters do not regulate metals to any great extent (Phillips 1977). If k_1 and k_2 are constant for all sizes of oysters, then a simple linear regression, i.e., $Co = \frac{k_1}{k_2}$ Ce + random deviation, would be established for a given set of physiological and environmental conditions.

The total concentration of a metal in the environment and that in the organism, however, are not linearly related (Preston 1966; Boyden 1974, 1977) even though some laboratory uptake and depuration studies suggest that the metal bio-concentration of oysters reaches an equilibrium with ambient concentration (Romeril 1971). The exponential growth rate of the organism and the dilution effect of tissue mass growth makes this body size and body burden per unit mass of tissue relationship complex (Strong and Luoma 1981; Thomson 1982; Simkiss and Mason 1984). Moreover, it has not been understood whether the metal concentration in every cell of the body tissue of oyster changes over the life time (cf. Simkiss and Mason 1984).

The salinity effect, that is, lower trace metal bio-concentrations in higher salinity water and *vice versa*, has been noticed but the reason for the phenomenon has not been well explained. Information regarding the relationship between body size and metal bio-concentration of an organism provides clues for understanding the bioaccumulation mechanism but the relationship in oysters has not been clearly defined yet.

A major problem in studying the metal accumulation in oysters is that the measured metal body burden of oysters collected from the same site at one time shows a wide variation, which makes it difficult to interpret the data. Likely sources of variability are: (1) the use of wet weight instead of dry weight, (2) inclusion of biologically inactive metals associated with sediments in the gut of the organisms, (3) differences in size. Moreover, because of the long biological half lives of trace metals in oyster soft tissues, the metal bio-concentration reflects the cumulative effect of conditions over the life history of the organism rather than just the conditions occurring at the time of collection.

In this study, the relationships between bio-concentrations and the dry meat weights of oysters and mussels were determined. Of interest is whether the relationships change with salinity in each estuarine system. The degree to which the above mentioned extraneous variables contribute to the metal bioconcentration measurements will be examined. The effect of body size on the metal concentration of oysters is hard to evaluate using field samples because metal accumulation is a complex interactive process (cf. Boyden 1974, 1977; Norstrom et al. 1976; Widdows 1978; Strong and Luoma 1981; Phelps et al. 1985; Phillips and Muttarasin 1985); however, it is believed that the analysis of the data from this study will give insights on the bio-accumulation process because 1) oysters with wide range of weights were individually analyzed, 2) oysters were collected from different salinity regimes for each estuarine system making it possible to separate the salinity effects from the body weight effects, 3) many extraneous variabilities were eliminated by excluding gut contents and pea crabs and using dry weights, and 4) seven out of nine samplings were done in a short time span (1 week) eliminating seasonal effects.

Zinc is chosen because it is the metal most accumulated by oysters and by mussels, its bioaccumulation process by mussels has been extensively studied by many authors, its radioactive isotope zinc-65 has a relatively long half life (34.4 weeks) and contamination of the environment by the radioactive material is of concern, and it is a physiologically important element with a long biological half life (300 to 900 days) in oyster soft tissues (Wolfe 1970; Seymour and Nelson 1972, 1973). The ubiquitous use of zinc, moreover, as "the sacrificial anode" for crab pots, monitoring instruments, navigational structures, and boats will increase zinc concentrations in some areas where oysters grow and, thus, might pose some health hazards.

Zinc bio-concentration in oysters and in mussels, moreover, is one of the most simple and easy procedures to monitor because of the high concentrations in soft tissues and because zinc measurements by atomic absorption spectrophotometry are not influenced by interferance of other metals or salts in the samples. By monitoring zinc concentrations, one can detect if there is a pertubation in the environmental trace metal concentrations.

MATERIALS AND METHODS

All of the oysters and mussels, except those from Mulberry Island in the James River, were collected by a dredge (Table 1). The samplings were done concurrently with the annual spring and fall "spat fall survey" by Mr. Whitcomb of VIMS. Oysters from Mulberry Island were collected by oyster tongs. Sediments that were collected coincidentally with oysters were transferred to bottles by a plastic spoon. Oysters were brushed under running sea water to remove adhering mud. After surface water was removed by blotting with paper towels, they were placed in vinyl freezer bags marked with sampling site and date and kept in a freezer maintained at -12 C^{o}.

Oysters and mussels were taken out of the freezer and placed in a refrigerator for 6 to 12 hours until the soft tissues were partially thawed. Oyster shells were opened with a stainless steel oyster shucking knife. Mussel shells were opened with a stainless steel paring knife. Soft tissues were separated from the shells with a stainless steel dissecting knife. The shells were marked and kept for later references. When it was judged that an oyster had enough particulate materials to be of concern, the thinned end of a pipette was inserted into the anal opening of the oyster and gut contents were removed by flushing with deionized water. Gut contents and any sedimentary material (mostly faecal pellets and pseudofaeces) inside of the cavity of the oyster shells were collected in a vial. Oysters were examined to find any female pea crabs and, when one was found, the pea crab was put into a separate vial. Thin (approximately 3 mm) strips of oyster shell were cut along the length.

All of the oyster and mussel soft body tissue samples, the oyster gut content samples, the oyster shells (prepared strips or whole shell when small enough to go into vials), and pea crabs were put into pre-weighed plastic "liquid scintillation counter (LSC) vials" and dried at 105 C^{o} until there were no weight changes. After determining the dry weights, 2 ml of concentrated nitric acid (HNO_3) were added to each vial (cf. APHA, Standard Methods, 1985).

ZINC STANDARDS: Ten milliliters of "Certified atomic absorption standard - zinc reference solution 1000 ppm ± 1%" from Fisher Scientific Co., which was zinc oxide in dilute nitric acid solution (1 ml = 1 mg Zn), and 150 ml of concentrated nitric acid were put in a 1000 ml volumetric flask and deionized water was added to make a final volume of 1000 ml. This 10 ppm stock standard was diluted with deionized water to make 0.01, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 5.0, and 10.0 ppm zinc standards.

QUALITY ASSURANCE MEASUREMENTS: All glass vials were made of borosilicate glass. Pipettes were of TFE. Plastic vials and tubes were of either polypropylene or linear polyethylene with polyethylene caps (cf. Robertson 1965; Struempler 1973; Batley and Gardner, 1977). All non-metal instruments and containers were soaked in 2N HCl and rinsed with deionized water. Prior to use, they were soaked with 2N HNO_3 and rinsed with distilled-deionized water three times. All metal instruments were rinsed with deionized water before and during the use; moreover, the contact of those instruments with samples was kept to a minimum.

For standards and samples, blanks were made following the same procedures as for the standard or the samples but without the metal or the sample. The measurements of the blanks were subtracted from those of the samples. All acids were Fisher "ACS" grade and had no detectable amount of zinc in them. There was no detectable contamination during sample treatments for the atomic absorption spectrophotometer (see Table 2).

SAMPLE DIGESTION: Each sample was transferred into a 150 ml "fleaker". The vial in which the sample was kept was rinsed with 5 ml of concentrated HNO_3 three times and the 15 ml of the acid was added to the fleaker. The fleaker was covered with a watch glass and heated to boiling. Deionized water was added to the 50 ml mark and the fleaker was heated to boiling again. The content of the fleaker was transferred to a 100 ml volumetric cylinder. Fifteen milliliters of deionized water was added to the empty fleaker and the water was poured into the cylinder after rinsing the fleaker. This procedure was repeated three times. Deionized water was added to the cylinder to make the final volume 100 ml. The cylinder was shaken vigorously and then an aliquot was transferred to a volumetric flask to make a final dilution with an estimated concentration of around 0.5 ppm zinc. The final diluents were put into acid-cleaned new LSC vials and centrifuged. These samples were used for the atomic absorption spectrophotometer zinc analyses.

ZINC MEASUREMENTS: Samples, prepared blanks, and 0.01, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 5.0, and 10.0 ppm zinc standards were measured by a flame atomic absorption (Flame A.A.) spectrophotometry (Instrumentation Laboratory aa/ae spectrophotometer model "video 12") (wave length 213.9 nm; flame gases air-acetylene; detection limit 0.005 mg/L; sensitivity 0.02 mg/L; optimum concentration range 0.05 to 2 mg/L). A standard blank and 0.5 ppm and 1.0 ppm standards were measured. After 10 samples were measured, the blank and the standards were measured again. When there were differences in absorbances of the blank and standards, the instrument was checked until the values were in agreement with previous ones and the 10 samples were measured again. These steps were repeated until all of the samples were measured. The analysis of absorbance values showed that the absorbance increased linearly up to 0.5 ppm concentration but it became non-linear at higher values (Fig. 1). The absorbance curve became too non-linear to be used as a concentration measurements above 2 ppm.

CALCULATION OF ZINC CONCENTRATIONS: The absorbance values up to 0.208 (0.5 ppm) were converted into ppm values assuming linearity. The absorbance values of standards were fit into a non-linear equation $Y = a\ (1 - e^{-b\ X})$ using "SAS NREG" procedure (SAS Inc., 1985), yielding

$$\text{Absorbance} = 1.671473886\ (1 - e^{-0.266595963\ \text{PPM}}).$$

The equation

PPM = (LOG(1.0-ABSORB/1.671473886))/(-0.266595963)

was used to convert absorbance values from 0.208 to 0.7 (from 0.5 ppm to approximately 2 ppm) to concentration values.

For each sample, the absorbance value was converted to concentration and then multiplied by the final volume of the sample after dilutions to calculate the total amount of zinc ($\frac{g}{ml}$ x ml = g-zinc) in the sample. The resulting body burden was divided by the dry weight of the organism to get the zinc bio-concentration ($\frac{\text{g-zinc}}{\text{g-dryweight}}$).

SEDIMENT NUTRIENT ANALYSIS: Sediment samples were mixed with deionized water and sieved using a stainless steel frame and cloth sieve (No. 230, 63 micrometer opening) to remove large particles. The samples were homogenized and 20 ml aliquots were dried in LSC vials. Particulate nitrogen and carbon contents were measured with a Carlo-Erba "CN Analyzer."

ANALYSIS OF DATA: The relationships between body size (dry meat weight) and zinc concentration were examined by fitting the logarithmic transformed data into linear equations. If we assume that the body burden (Y) of the individual is related to body weight (X) as a power function (Boyden 1974; Widdows 1978):

$$Y = aX^{b} \qquad \text{-----------------------------------} \quad (1)$$

$$\text{then } \log Y = \log a + b \log X \qquad \text{----------------} \quad (2)$$

Y', the bio-concentration, or weight specific concentration, is related to body weight as follows:

$$Y' = \frac{Y}{X} = \frac{aX^{b}}{X} = aX^{(b-1)} \qquad \text{----------------------------} \quad (3)$$

that is,

$$\log Y' = \log a + (b-1) \log X \qquad \text{-----------------} \quad (4)$$

The significance of each regression coefficient was tested. The significance of the differences among the regression lines was also tested. The correlations of variables among the pea crab zinc concentration data were examined. All of the statistical analyses were performed using "SPSSX" packages (SPSS Inc., 1986).

All of the datum points in the figures (Figs. 2 to 9) are presented in the tables (Tables 3 to 19). Uniformity of presentation will make comparisons within a species easier to make. All figures of oyster body burdens and bio-concentrations have the same scale; another scale was used for mussels.

RESULTS AND DISCUSSIONS

Oyster Body Burdens and Factors Affecting Bio-Concnetrations

The dry meat weights, zinc body burdens, and zinc bio-concentrations are presented in Tables 3 to 11 for oysters and Tables 17 to 19 for mussels. The mean values of zinc bio-concentrations of oysters show that in both the James and the Rappahannock Rivers the organisms which live in higher salinity waters have lower soft tissue zinc concentrations than those in lower salinity regime and vice versa (Table 12). This result agrees with that found in previous similar studies. For the same salinity, the zinc bioconcentrations were greatest in the James River and varied as follows: James>Piankatank>Rappahannock River. There were no James River mussels; however, the mean values of bioconcentrations of these organisms showed the same salinity effect in the Rappahannock River. For the same salinity, Piankatank mussels had a higher mean bio-concentration than those of Rappahannock River (Table 20).

Some of the differences in mean concentrations, however, are believed to be caused by the weight differences among samples. It has been reported by some investigators that there is no size (i.e. weight) effect on zinc bio-concentrations in oysters (eg. Huggett 1975), but it has been shown in a short term experiment that smaller oysters take up radioactive zinc-65 faster than larger ones in an unit time (Mo and Neilson, in preparation). In the present study, the field data also indicate that there is a size effect on zinc bio-concentration.

The body burdens of zinc in oyster soft tissues observed in this study suggest that the body burden increases throughout the life of the organism. The increases were not linear with the dry weight of the organism (Fig. 2, 4, and 6) and that resulted in bio-concentration increase with dry weight (Fig. 3, 5, and 7).

The rate of increase for each group of oysters was determined by regression analyses assuming that eq. 2 and 4 applied. Once the coefficients a and b were estimated for each data set, the mean behaviour for that group could be plotted (eq. 1 in Figs. 2, 4, 6 and eq. 3 in Figs. 3, 5, 7). The values of a and b determined using eq. 2 and those determined using eq. 4 were nearly identical.

Examination of the coefficient b may provide insights on the bio-accumulation process (cf. Boyden 1977; Phelps et al. 1985; Strong and Luoma 1981; Thompson 1982). Values of b (Table 13) were bigger than 1 for all of the 7 site populations suggesting that a net uptake of the metal is occurring throughout the life of the organism (Williamson 1980; Strong and Luoma 1981). In short term laboratory exposure experiments of zinc-65 by oysters (Mo and Neilson, 1988), it was shown that there is a size dependent difference in uptake rate. Metal uptake per unit biomass by smaller individuals of many species is more rapid than that by larger individuals (Strong and Luoma 1981). It is concluded that 1) the zinc bio-concentration of an oyster keeps increasing during its life time, 2) the rate of the increase is reduced as the oyster grows, 3) in a given time period, the increase of bio-concentration is larger than the dilution effect of the tissue growth in any size oysters (Table 14).

The rate of increase in both body burden and bio-concentration was lower in oysters from a higher salinity regime than in oysters from a lower salinity regime in the James River (Fig. 2 and 3). This supports the suggestion that the uptake rates of oysters of higher salinity regime decrease more rapidly with size than those of oysters in lower salinity (Mo and Neilson, in preparation). This may contribute to the differences in trace metal concentrations at different salinities (lower concentration in higher salinity and vice versa). The salinity effect on body burdens and bio-concentrations were less obvious in the Rappahannock River oysters. The increases of body burden and bio-concentration with body weight were James>Piankatank>Rappahannock and this would partly contribute to the James>Piankatank>Rappahannock concentration differences at the same salinity regimes.

Additionally, oysters in the Rappahannock River grow faster than those in the James River and oysters in high salinity regime faster than those in lower salinity regime (Haven, personal communications). This would make all of the above discussed differences in concentrations and body burdens more pronounced.

It is suggested that, in addition to the free ion activity differences (higher in lower salinity), uptake rate and growth rate differences in different salinity regimes and different estuarine systems contribute to the salinity effects and to the differences in different systems.

Pea Crabs and Other Factors

A pea crab, the commensal Pinnotheres ostreum Say, had been found in an oyster in the previous experiments of the authors (Mo and Neilson, 1988). Its dry weight (0.059 gram) would have comprised 11 % of the combined dry weight of the oyster and the pea crab (0.4867 gram). The radioactivity of the crab after the exposure (t=4.5 days) was only 0.2050 microcurie/gram dry-weight while that of the oyster was 2.5615 microcurie/gram dry-weight. If the crab was included as part of the oyster tissue, the radioactivity concentration value would drop by 10%. If the crab is a much better regulator of zinc, this reduction would become much more pronounced as the exposure time increases. In this survey, it was found that the percentage of oysters infested with the pea crabs was highly variable from site to site (Table 22). Zinc concentrations of the crabs were roughly an order of magnitude lower than those of their host oysters and dried weights of the crabs were relatively large (Table 23); thus inclusion of the pea crabs would introduce significant individual and site concentration variability (Table 25). Interestingly, the zinc concentration of an host oyster had no correlation with that of its pea crab and the zinc concentration of a pea crab was primarily dependent on the size (dry weight) of the crab.

Gut contents and other sedimentary materials such as faeces inside of shell cavities showed a considerable dry weight and zinc concentration (Table 16). Care should be taken not to include these materials in the samples.

The zinc concentrations in oyster shells were extremely small compared to those of oyster soft tissues (Table 15) suggesting that the depuration of zinc through its shell formation is of minor importance.

Mussels

Zinc body burdens of mussels from the low salinity region of the Rappahannock River were almost linear with the dry weights of the organisms (Fig. 8), i.e., the value of b is about 1 and the metal concentration per unit body weight is independent of body size (Fig. 9). This suggests that equilibration of concentrations of the metal occurs in the tissues of the organism (Bryan 1976; Williamson 1980; Strong and Luoma 1981). Zinc body burdens of mussels in high salinity Rappahannock River showed the value b was smaller than 1 (Fig. 8), which means (b-1) is negative (Table 21), indicating that bio-concentration decreases with size (Fig. 9).

Table 1. Oyster sampling sites and dates

The James River oyster beds:

ID	SITE	CODE*1	LATITUDE	LONGITUDE	D*2	S*3	Date*4
J	Wreck Shoal	(J)WS.15(.SPRING)	37°03.2'N	76°34.6'W	30	15	6/15/87
G	Wreck Shoal	(J)WS.15(.FALL)	37°03.2'N	76°34.6'W	30	15	10/7/87
D	Nansemond Ridge	(J)NR.20(.FALL)	37°55.5'N	76°27.2'W	12	20	10/6/87
E	Horse Head Rock	(J)HH.10(.FALL)	37°06.3'N	76°37.9'W	38	10	10/7/87
C	Mulberry Island	(J)MI.14.(WINTER)	37°05' N	76°36' W	35	14	1/19/88

The Rappahannock River oyster beds:

ID	SITE	CODE*1	LATITUDE	LONGITUDE	D*2	S*3	Date*4
K	Broad Creek	(R)BC.18(.FALL)	37°34.3'N	76°18.6'W	2	18	10/9/87
H	Parrot Rock	(R)PR.15(.FALL)	37°36.4'N	76°25.2'W	20	15	10/9/87
F	Morattico Bar	(R)MB.12(.FALL)	37°46.5'N	76°39.3'W	60	12	10/2/87

The Piankatank River oyster bed:

ID	SITE	CODE*1	LATITUDE	LONGITUDE	D*2	S*3	Date*4
N	Ginney Point	(P)GP.15(.FALL)	37°32.0'N	76°24.2'W	14	15	10/12/87

*1: The code represents "(river)site.salinity(.season of collection)". In tables and illustrations, the parts of the code in parentheses are omitted except where the omission may cause a confusion.

*2: distance from the river mouth in km

*3: approximate annual average salinity

*4: month/day/year

Table 2. Zinc in digestion blanks and digestion standards

ID	AMOUNT (ml)	CONC.*1 (ppm)	ABSORB.	PPM*2	DILUT.	CONCENTRATION*3 (ppm)
BKD	10	000	0.000	0.0000	10000	0
BKD	10	000	0.001	0.0024	10000	2
BKD	10	000	0.000	0.0000	10000	0
BKD	10	000	0.001	0.0024	10000	2
BKD	10	500	0.211	0.5062	10000	506
BKD	10	500	0.210	0.5036	10000	504
BKD	10	500	0.210	0.5036	10000	504
BKD	10	500	0.219	0.5268	10000	527
BKD	10	1000	0.448	1.1704	10000	1170
BKD	10	1000	0.438	1.1398	10000	1140

*1: actual concentration

*2: measured concentration of diluted sample

*3: measured concentration of undiluted sample

Table 3. Zinc in oysters from Wreck Shoal-James River (Spring-6/15/88)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
J07	0.8297	0.141	0.3380	10000	3380	4074
J12	0.8636	0.123	0.2948	10000	2948	3414
J22	1.0251	0.146	0.3500	10000	3500	3414
J02	1.0731	0.175	0.4195	10000	4195	3909
J09	1.1062	0.356	0.8984	10000	8984	8121
J06	1.1940	0.482	1.2761	10000	12761	10687
J13	1.3292	0.130	0.3116	25000	7790	5861
J11	1.4839	0.139	0.3332	20000	6664	4491
J21	1.5877	0.360	0.9098	10000	9098	5730
J23	1.5930	0.533	1.4404	10000	14404	9042
J19	1.9463	0.279	0.6842	20000	13685	7031
J17	2.5906	0.230	0.5550	20000	11100	4285

Table 4. Zinc in oysters from Wreck Shoal-James River (Fall-10/7/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
G02	0.1866	0.051	0.1222	6000	733	3931
G09	0.3022	0.237	0.5736	5000	2868	9490
G13	0.3172	0.060	0.1438	5000	719	2267
G08	0.3235	0.170	0.4075	5000	2037	6298
G03	0.4295	0.161	0.3859	6000	2316	5391
G24	0.4445	0.093	0.2229	5000	1115	2507
G21	0.4974	0.045	0.1079	10000	1079	2169
G15	0.5562	0.083	0.1990	10000	1990	3577
G19	0.7714	0.288	0.7093	10000	7093	9196
G18	1.1999	0.350	0.8813	10500	9254	7712

Table 5. Zinc in oysters from Mulberry Island-James River (Winter-1/19/88)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
C16	0.0160	0.034	0.0815	1000	81	5093
C24	0.0316	0.145	0.3476	500	174	5499
C26	0.0750	0.060	0.1438	1000	144	1918
C22	0.1310	0.052	0.1246	5000	623	4757
C23	0.1470	0.276	0.6769	1000	677	4605
C39	0.1625	0.033	0.0791	12500	989	6085
C38	0.1868	0.036	0.0863	12500	1079	5774
C33	0.3285	0.081	0.1942	12500	2427	7388
C35	0.3421	0.054	0.1294	12500	1618	4730
C03	0.3688	0.090	0.2157	12500	2697	7312
C17	0.3812	0.133	0.3188	12500	3985	10454
C34	0.4053	0.056	0.1342	12500	1678	4140
C27	0.4217	0.137	0.3284	12500	4105	9734
C32	0.4377	0.082	0.1966	12500	2457	5613
C15	0.4655	0.111	0.2661	12500	3326	7145
C12	0.5890	0.042	0.1007	12500	1258	2137
C29	0.7234	0.223	0.5371	12500	6714	9281
C04	0.7407	0.199	0.4770	12500	5963	8050
C01	0.8337	0.276	0.6769	10000	6769	8120
C09	0.8705	0.139	0.3332	12500	4165	4784
C13	0.9412	0.240	0.5814	12500	7268	7722

Table 6. Zinc in oysters from Nansemond Ridge-James River (Fall-10/7/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
D33	0.0086	0.268	0.6555	50	32	3810
D13	0.0263	0.074	0.1774	500	88	3372
D11	0.0890	0.095	0.2277	1000	227	2559
D04	0.1263	0.138	0.3308	1000	330	2619
D35	0.2354	0.553	1.5069	500	753	3201
D26	0.2750	0.323	0.8055	1000	805	2929
D30	0.2779	0.241	0.5840	1000	584	2102
D20	0.4947	0.040	0.0959	12500	1198	2423
D16	0.5990	0.072	0.1726	12500	2157	3602
D27	0.6121	0.041	0.0983	12500	1228	2007
D10	0.7580	0.141	0.3380	12500	4224	5574
D22	0.7764	0.199	0.4770	12500	5962	7680
D29	1.0411	0.136	0.3260	12500	4074	3914
D25	1.0985	0.074	0.1774	12500	2217	2018
D05	1.1254	0.157	0.3763	10000	3763	3344
D06	1.2807	0.128	0.3068	12500	3835	2995

Table 7. Zinc in oysters from Horse Head Rock-James River (Fall-10/7/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
E14	0.0021	0.037	0.0887	50	4	2112
E08	0.2234	0.056	0.1342	12500	1677	7511
E19	0.2556	0.178	0.4267	5000	2133	8346
E23	0.2608	0.110	0.2637	5000	1318	5055
E30	0.3490	0.145	0.3476	5000	1737	4979
E10	0.3881	0.107	0.2565	12500	3206	8261
E22	0.4205	0.250	0.6077	5000	3038	7226
E16	0.4241	0.102	0.2445	12500	3056	7206
E35	0.4685	0.109	0.2613	10000	2612	5577
E33	0.5173	0.364	0.9213	5000	4606	8905
E03	0.5649	0.267	0.6528	12500	8160	14446
E31	0.6267	0.266	0.6502	10000	6501	10374
E32	0.7199	0.327	0.8166	10000	8166	11343
E25	0.7251	0.295	0.7284	11000	8012	11050
E17	0.7367	0.354	0.8927	10000	8926	12118
E18	0.7601	0.312	0.7750	10000	7749	10196
E28	0.8162	0.263	0.6422	10000	6421	7868
E06	0.8356	0.426	1.1035	12500	13793	16508
E04	0.8791	0.351	0.8842	12500	11052	12572
E29	0.9637	0.370	0.9385	10000	9385	9739
E27	0.9674	0.332	0.8306	10000	8305	8586
E07	0.9755	0.179	0.4291	12500	5363	5498
E05	1.0127	0.275	0.6743	12500	8428	8323
E01	1.2225	0.288	0.7085	20000	14169	11591

Table 8. Zinc in oysters from Morattico Bar-Rappahannock River (Fall-10/2/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
F05	0.3133	0.050	0.1199	5000	599	1913
F09	1.0906	0.109	0.2613	10000	2612	2396
F16	1.1102	0.137	0.3284	10000	3283	2958
F14	1.1235	0.098	0.2349	10000	2349	2091
F01	1.1346	0.088	0.2109	10000	2109	1859
F11	1.1875	0.157	0.3763	10000	3763	3169
F03	1.3914	0.085	0.2037	10000	2037	1464
F02	1.6947	0.170	0.4025	20000	8050	4750
F07	1.7480	0.152	0.3643	10000	3643	2084

Table 9. Zinc in oysters of Parrot Rock-Rappahannock River (Fall-10/9/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
H19	0.0250	0.042	0.1007	500	50	2014
H22	0.0258	0.028	0.0671	500	33	1301
H27	0.0266	0.041	0.0983	500	49	1847
H29	0.0329	0.049	0.1175	500	58	1785
H21	0.0566	0.082	0.1966	500	98	1736
H24	0.1105	0.017	0.0407	5000	203	1844
H13	0.1258	0.014	0.0336	5000	167	1334
H08	0.1293	0.013	0.0312	5000	155	1205
H07	0.1877	0.032	0.0767	5000	383	2043
H17	0.2443	0.045	0.1079	5000	539	2208
H23	0.3802	0.023	0.0551	11000	606	1595
H26	0.3861	0.031	0.0743	10000	743	1925
H03	0.3962	0.070	0.1678	5000	838	2118
H14	0.4263	0.065	0.1558	10000	1558	3655
H10	0.8646	0.117	0.2805	10000	2804	3244
H12	1.2764	0.199	0.4770	10000	4770	3737
H09	1.5068	0.124	0.2972	10000	2972	1976

Table 10. Zinc in oysters from Broad Creek-Rappahannock River (Fall-10/9/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
K14	0.0162	0.180	0.4315	50	21.5731	1332
K03	0.0279	0.023	0.0551	500	27.5656	988
K08	0.0884	0.007	0.0168	5000	83.8954	949
K15	0.1052	0.010	0.0240	5000	119.8506	1139
K02	0.1439	0.023	0.0551	5000	275.6563	1916
K17	0.1736	0.024	0.0575	5000	287.6414	1657
K24	0.1750	0.011	0.0264	5000	131.8356	753
K25	0.1822	0.025	0.0599	5000	299.6265	1644
K22	0.1887	0.017	0.0407	5000	203.7460	1080
K23	0.2075	0.023	0.0551	5000	275.6563	1328
K04	0.2695	0.021	0.0503	10000	503.3725	1868
K12	0.3042	0.015	0.0360	10000	359.5518	1182
K07	0.3903	0.036	0.0863	10000	862.9242	2211
K11	0.4372	0.039	0.0935	10000	934.8346	2138
K01	0.5479	0.030	0.0719	10000	719.1036	1312
K19	0.6488	0.022	0.0527	10000	527.3425	813
K10	0.6496	0.033	0.0791	10000	791.0139	1218
K06	0.9328	0.121	0.2900	10000	2900.3843	3109
K20	1.7274	0.263	0.6422	10000	6421.6700	4123

Table 11. Zinc in oysters from Ginney Point-Piankatank River (Fall-10/12/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
N18	0.0624	0.064	0.1534	1000	153	2458
N19	0.0844	0.073	0.1750	1000	174	2073
N08	0.0938	0.077	0.1846	1000	184	1968
N12	0.1229	0.008	0.0192	10000	191	1560
N13	0.1841	0.026	0.0623	5000	311	1693
N09	0.1854	0.031	0.0743	5000	371	2004
N14	0.2079	0.016	0.0384	5000	191	922
N03	0.2110	0.021	0.0503	5000	251	1193
N17	0.2414	0.036	0.0863	10000	862	3575
N07	0.2651	0.020	0.0479	5000	239	904
N25	0.2876	0.039	0.0935	10000	934	3250
N05	0.3403	0.137	0.3284	5000	1641	4825
N02	0.4974	0.063	0.1510	10000	1510	3036
N04	0.5032	0.027	0.0647	10000	647	1286
N23	0.5068	0.035	0.0839	10000	838	1655
N01	0.6312	0.047	0.1127	10000	1126	1785
N29	0.6395	0.063	0.1510	10000	1510	2361
N10	0.6486	0.125	0.2996	10000	2996	4620
N11	1.0172	0.136	0.3260	10000	3259	3205

Table 12. Summary statistics of oyster data

The James River

SAMPLE ID: J JAMES.WS.15.SPRING n: 12

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	1.275	.331	.8297	1.9463
Body burden (μg)	7530	4312	2946	14404
Bio-Conc. (ppm)	5673	2568	2333	10660

SAMPLE ID: G JAMES.WS.15.FALL n: 20

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.503	.286	.1866	1.1999
Body burden (μg)	2920	2825	719	9253
Bio-Conc. (ppm)	5254	2737	2169	9490

SAMPLE ID: C JAMES.MI.14.WINTER n: 18

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.411	0.307	0.0160	0.9412
Body burden (μg)	2690	2471	81	7267
Bio-Conc. (ppm)	5889	1979	1918	9281

SAMPLE ID: E JAMES.HH.10.FALL n: 21

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.641	0.288	0.2234	1.2225
Body burden (μg)	6077	3556	1318	14169
Bio-Conc. (ppm)	8995	2629	4979	14446

Table 12 (continued). Summary statistics of oyster data

SAMPLE ID: D JAMES.NR.20.FALL n: 16

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.588	0.414	0.0263	1.2807
Body burden (μg)	2096	1835	88	5962
Bio-Conc. (ppm)	3355	1501	2007	7680

The Rappahannock River

SAMPLE ID: F RAPP.MO.12.FALL n: 9

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	1.199	.418	.3133	1.7480
Body burden (μg)	3160	2073	599	8050
Bio-Conc. (ppm)	2520	993	1464	4750

SAMPLE ID: H RAPP.PA.15.FALL n: 17

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.386	.450	.0258	1.5068
Body burden (μg)	998	1368	34	4770
Bio-Conc. (ppm)	2097	779	1205	3737

SAMPLE ID: K RAPP.BC.18.FALL n: 17

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.322	.247	.0279	.9328
Body burden (μg)	547	668	28	2900
Bio-Conc. (ppm)	1489	612	753	3109

Table 12 (continued). Summary statistics of oyster data

The Piankatank River

SAMPLE ID: N PIANK.GP.15.FALL n: 19

Variable	Mean	Std.Dev.	Minimum	Maximum
Dry weight (g)	0.351	.255	.0624	1.0172
Body burden (µg)	927	918	153	3260
Bio-Conc. (ppm)	2426	1094	904	4825

Table 13. Results of regression analyses of oyster zinc body burden on body weight. Dependent variable is $\log_{10}$(Body Burden) and independent variable is $\log_{10}$(Dry Meat Weight). 'a' is a constant and 'b' is the coefficient of the independent variable (i.e., Y = a + bX).

The James River

SAMPLE ID: J JAMES.WS.15.SPRING

Multiple R	.74225	-------- Analysis of Variance -------			
R Square	.55094		DF	Sum of Squares	Mean Square
Adjusted R Square	.50603	Regression	1	.43060	.43060
Standard Error	.18734	Residual	10	.35098	.03510
		F =	12.26861	Signif F =	.0057

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.770731	.505539	.742252	3.503	.0057
a	3.641869	.071415		50.996	.0000

SAMPLE ID: G JAMES.WS.15.FALL

Multiple R	.77998	-------- Analysis of Variance -------			
R Square	.60837		DF	Sum of Squares	Mean Square
Adjusted R Square	.58662	Regression	1	1.57799	1.57799
Standard Error	.23756	Residual	18	1.01579	.05643
		F =	27.96214	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.301167	.246064	.779983	5.288	.0000
a	3.766645	.102202		36.855	.0000

Table 13 (continued).

SAMPLE ID: C JAMES.MI.14.WINTER

Multiple R	.95666	-------- Analysis of Variance -------			
R Square	.91521		DF	Sum of Squares	Mean Square
Adjusted R Square	.90991	Regression	1	5.47862	5.47862
Standard Error	.17811	Residual	16	.50759	.03172
		F =	172.69507	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.123115	.085464	.956665	13.141	.0000
a	3.810384	.064792		58.809	.0000

SAMPLE ID: E JAMES.HH.10.FALL

Multiple R	.92455	-------- Analysis of Variance -------			
R Square	.85479		DF	Sum of Squares	Mean Square
Adjusted R Square	.84715	Regression	1	1.59148	1.59148
Standard Error	.11929	Residual	19	.27036	.01423
		F =	111.84492	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.304121	.123313	.924548	10.576	.0000
a	4.008342	.039455		101.594	.0000

SAMPLE ID: D JAMES.NR.20

Multiple R	.95519	-------- Analysis of Variance -------			
R Square	.91239		DF	Sum of Squares	Mean Square
Adjusted R Square	.90565	Regression	1	3.63351	3.63351
Standard Error	.16383	Residual	13	.34892	.02684
		F =	135.37719	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.059964	.091100	.955189	11.635	.0000
a	3.518876	.055946		62.897	.0000

Table 13 (continued).

The Rappahannock River

SAMPLE ID: F RAPP.MO.12

Multiple R	.87486	-------- Analysis of Variance -------			
R Square	.76538		DF	Sum of Squares	Mean Square
Adjusted R Square	.73186	Regression	1	.55570	.55570
Standard Error	.15600	Residual	7	.17034	.02433
		F =	22.83555	Signif F =	.0020

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.201399	.251409	.874860	4.779	.0020
a	3.367623	.053039		63.494	.0000

SAMPLE ID: H RAPP.PA.15.FALL

Multiple R	.98490	-------- Analysis of Variance -------			
R Square	.97003		DF	Sum of Squares	Mean Square
Adjusted R Square	.96789	Regression	1	6.45349	6.45349
Standard Error	.11934	Residual	14	.19938	.01424
		F =	453.14071	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.159550	.054472	.984901	21.287	.0000
a	3.410332	.048851		69.810	.0000

Table 13 (continued).

SAMPLE ID: K RAPP.BC.18.FALL

		-------- Analysis of Variance -------			
Multiple R	.94513		DF	Sum of Squares	Mean Square
R Square	.89328	Regression	1	3.15741	3.15741
Adjusted R Square	.88616	Residual	15	.37722	.02515
Standard Error	.15858	F =	125.55339	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.176272	.104977	.945134	11.205	.0000
a	3.251504	.075988		42.789	.0000

The Piankatank River

SAMPLE ID: N PIANK.GP.15

		-------- Analysis of Variance -------			
Multiple R	.89516		DF	Sum of Squares	Mean Square
R Square	.80131	Regression	1	2.64119	2.64119
Adjusted R Square	.78962	Residual	17	.65490	.03852
Standard Error	.19627	F =	68.56083	Signif F =	.0000

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	1.123040	.135630	.895160	8.280	.0000
a	3.414074	.089529		38.134	.0000

Table 14. Results of regression analyses of oyster zinc bio-concentration on body weight. Dependent variable is $\log_{10}$(Bio-Concentration) and independent variable b is $\log_{10}$(Dry Meat Weight). 'a' is a constant and 'b' is the coefficient of the independent variable (i.e., Y = a + bX).

The James River

SAMPLE ID: J JAMES.WS.15.SPRING

Multiple R	.43423	-------- Analysis of Variance -------			
R Square	.18856		DF	Sum of Squares	Mean Square
Adjusted R Square	.10742	Regression	1	.08156	.08156
Standard Error	.18734	Residual	10	.35097	.03510
		F =	2.32376	Signif F =	.1584

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.770632	.505535	.434234	1.524	.1584
a	3.641874	.071414		50.996	.0000

SAMPLE ID: G JAMES.WS.15.FALL

Multiple R	.27717	-------- Analysis of Variance -------			
R Square	.07682		DF	Sum of Squares	Mean Square
Adjusted R Square	.02554	Regression	1	.08453	.08453
Standard Error	.23756	Residual	18	1.01582	.05643
		F =	1.49788	Signif F =	.2368

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.301156	.246067	.277169	1.224	.2368
a	3.766641	.102203		36.854	.0000

Table 14 (continued).

SAMPLE ID: C JAMES.MI.15.FALL

Multiple R	.33893	-------- Analysis of Variance -------			
R Square	.11488		DF	Sum of Squares	Mean Square
Adjusted R Square	.05956	Regression	1	.06586	.06586
Standard Error	.17808	Residual	16	.50743	.03171
		F =	2.07658	Signif F =	.1689

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.123137	.085451	.338935	1.441	.1689
a	3.810400	.064782		58.819	.0000

SAMPLE ID: E JAMES.HH.10

Multiple R	.49246	-------- Analysis of Variance -------			
R Square	.24252		DF	Sum of Squares	Mean Square
Adjusted R Square	.20265	Regression	1	.08656	.08656
Standard Error	.11929	Residual	19	.27037	.01423
		F =	6.08316	Signif F =	.0233

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.304147	.123316	.492463	2.466	.0233
a	4.008350	.039455		101.592	.0000

SAMPLE ID: D JAMES.NR.20

Multiple R	.17958	-------- Analysis of Variance -------			
R Square	.03225		DF	Sum of Squares	Mean Square
Adjusted R Square	-.04219	Regression	1	.01163	.01163
Standard Error	.16383	Residual	13	.34893	.02684
		F =	.43320	Signif F =	.5219

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.059962	.091102	.179579	.658	.5219
a	3.518894	.055947		62.896	.0000

Table 14 (continued).

The Rappahannock River

SAMPLE ID: F RAPP.MO.12

Multiple R	.28953	-------- Analysis of Variance -------			
R Square	.08382		DF	Sum of Squares	Mean Square
Adjusted R Square	-.04706	Regression	1	.01559	.01559
Standard Error	.15602	Residual	7	.17040	.02434
		F =	.64046	Signif F =	.4498

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.201232	.251449	.289525	.800	.4498
a	3.367622	.053047		63.484	.0000

SAMPLE ID: H RAPP.PA.15

Multiple R	.61704	-------- Analysis of Variance -------			
R Square	.38073		DF	Sum of Squares	Mean Square
Adjusted R Square	.33650	Regression	1	.12242	.12242
Standard Error	.11926	Residual	14	.19912	.01422
		F =	8.60741	Signif F =	.0109

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.159708	.054436	.617037	2.934	.0109
a	3.410509	.048820		69.859	.0000

Table 14. (continued).

SAMPLE ID: K RAPP.BC.18

Multiple R	.39784	-------- Analysis of Variance -------			
R Square	.15827		DF	Sum of Squares	Mean Square
Adjusted R Square	.10216	Regression	1	.07093	.07093
Standard Error	.15858	Residual	15	.37723	.02515
		F =	2.82054	Signif F =	.1138

-------- Variables in the Equation -------

Variable	B	SE B	Beta	T	Sig T
b	.176305	.104978	.397837	1.679	.1138
a	3.251504	.075989		42.789	.0000

The Piankatank River

SAMPLE ID: N PIANK.GP.15

Multiple R	.21487	-------- Analysis of Variance -------			
R Square	.04617		DF	Sum of Squares	Mean Square
Adjusted R Square	-.00994	Regression	1	.03170	.03170
Standard Error	.19629	Residual	17	.65500	.03853
		F =	.82283	Signif F =	.3770

-------- Variables in the Equation --------

Variable	B	SE B	Beta	T	Sig T
b	.123040	.135642	.214865	.907	.3770
a	3.414067	.089536		38.130	.0000

Table 15. Zinc in oyster shells

	SOFT TISSUE			SHELL			RATIO*	
ID	DryWgt. (gram)	Conc. (ppm)	Total Zn (microgram)	Dry Wgt. (gram)	Conc. (ppm)	Total Zn (microgram)	Conc.	Total
C24	0.0316	5499	173.7834	0.4748	57	27.2451	0.0104	0.1568
D13	0.0263	3372	88.6894	-		-	-	-
D33	0.0086	3810	32.7753	0.6009	13	7.4787	0.0034	0.2281
H18	0.0898	934	83.8954	-	10	-	0.0107	-
K14	0.0162	1332	21.5731	-	7	-	0.0053	-

*: Concentration (or total zinc) in oyster soft tissue devided by concentration (or total zinc) in oyster shell.

-: Missing values

Table 16. Contribution of gut contents[*1] to measurements of dry weights and zinc concentrations

	HOST OYSTER[*2]		GUT CONTENTS		CONTRIBUTION		
ID	DRY WGT (gram)	BIO-CONC (ppm)	DRY WGT. (gram)	CONC. (ppm)	DRY WGT. (% of total)	BIO-CONCENTRATION (ppm)[*3]	(% change)
C17	0.3812	10454	0.0345	1872	8.30	9742	-6.8
D10	0.7580	5574	0.0603	4561	7.37	5499	-1.3
D35	0.2354	3201	0.0285	2441	10.80	3119	-2.6
F07	1.7480	2084	0.0584	2640	3.23	2102	0.86
H08	0.1293	1205	0.0217	2189	14.37	1346	11.7
J12	0.8636	3414	0.0279	1262	3.13	3347	-2.0
K17	0.1736	1657	0.0127	3030	6.82	1750	5.6
N10	0.6486	4620	0.0743	1857	10.28	4336	-6.1

*1: "gut contents" include all of the sedimenteous materials inside of the shell cavity of an oyster such as gut contents, faeces and psuedofaeces

*2: all measurements of oyster tissue are without gut contents

*3: concentration of zinc including dry weights and zinc of both oyster tissue and gut contents

Table 17. Zinc in mussels from Morattico Bar-Rappahannock River (Fall-10/2/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
F37	0.0257	0.010	0.0240	100	2.40	93
F27	0.0260	0.006	0.0144	100	1.44	55
F12	0.0314	0.009	0.0216	100	2.16	69
F23	0.0350	0.018	0.0431	100	4.31	123
F29	0.0451	0.010	0.0240	100	2.40	53
F30	0.0477	0.015	0.0360	100	3.60	75
F36	0.0491	0.016	0.0384	100	3.84	78
F20	0.0502	0.014	0.0336	100	3.35	67
F26	0.0539	0.017	0.0407	100	4.07	76
F28	0.0558	0.017	0.0407	100	4.07	73
F22	0.0695	0.018	0.0431	100	4.31	62
F18	0.0912	0.032	0.0767	100	7.67	84
F21	0.0952	0.023	0.0551	100	5.51	58
F13	0.1793	0.119	0.2852	100	28.52	159

Table 18. Zinc in mussels from Parrot Rock-Rappahannock River (Fall-10/9/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
H39	0.0038	0.001	0.0024	100	0.24	63
H34	0.0138	0.005	0.0120	100	1.20	87
H11	0.0141	0.004	0.0096	100	0.96	68
H01	0.0340	0.009	0.0216	100	2.16	63
H20	0.0363	0.013	0.0312	100	3.12	86
H26	0.0496	0.011	0.0264	100	2.64	53
H14	0.0524	0.014	0.0336	100	3.36	64
H37	0.0536	0.011	0.0264	100	2.64	49
H07	0.0691	0.016	0.0384	100	3.84	56
H17	0.0818	0.019	0.0455	100	4.55	56
H38	0.1058	0.023	0.0551	100	5.51	52
H38	0.1128	0.023	0.0551	100	5.51	49
H24	0.1157	0.028	0.0671	100	6.71	58
H16	0.1165	0.030	0.0719	100	7.19	62
H28	0.2854	0.059	0.1414	100	14.14	50

Table 19. Zinc in mussels from Ginney Point-Piankatank River (Fall-10/12/87)

ID	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (microgram)	BIO-CONC. (ppm)
N39	0.0566	0.015	0.0360	100	3.60	64
N34	0.0832	0.021	0.0503	100	5.03	61
N36	0.0961	0.027	0.0647	100	6.47	67

Table 20. Summary statistics of mussel data

SAMPLE CODE	NUMBER (samples)	DRY WGT. (gram) ±std.dev.	BODY BURDEN (μg) ±std.dev.	BIO-CONC. (ppm) ±s.d.	CORR.COEF.*1
all	29	0.0696 ±0.0512	4.27 ±2.59	65 ±12	
Rapp.MO.12	12	0.0534 ±0.0225	3.74 ±6.17	70 ±12	0.920xx
Rapp.PA.15	14	0.0815 ±0.0689	4.54 ±3.36	60 ±12	0.990xx
Piank.GP.15	3	0.0786 ±0.0201	5.03 ±1.04	64 ± 3	0.981

*1: correlation between mussel dry weights and zinc concentrations.
xx denotes that the numbers are significant at 1% level.

Table 21. Regression of mussel zinc body burden on body weight. Dependent variable is $\log_{10}$(Body Burden) and indenpendent variable is $\log_{10}$(Dry Meat Weight). 'a' is a constant and 'b' is the coefficient of the independent variable (i.e., Y = a + bX).

CODE	VARIABLE	ESTIMATE	STD.ERROR	t VALUE[*1]
Rapp.MO.12	b	0.975876	0.127143	7.675[xx]
	a	1.809501	0.167811	10.783[xx]
Rapp.PA.15	b	0.840141	0.045367	18.519[xx]
	a	1.582066	0.057509	27.510[xx]

*1: xx denotes t value being significant at 1% level.

Table 22. Presence of pea crabs in oysters

SAMPLING SITE	CODE	OYSTER*1	PEA CRAB*2
The James River			
Nansemond Ridge	NR.20	16	9
Wreck Shoal-Fall	WR.15.FALL	10	5
Wreck Shoal-Spring	WR.15.SPRING	14	3
Horse Head Rock	HH.10	27	0
Mulberry Island	MI.14.WINTER	27	1
The Rappahannock River			
Broad Creek	BC.18	19	2
Parrot Rock	PR.15	19	0
Morattico Bar	MB.12	10	0
The Piankatank River			
Ginney Point	GP.14	26	0

*1: Number of oysters examined.

*2: Number of oysters with female pea crabs inside of shell.

Table 23. Zinc in Pea Crabs

ID*1	CODE	DRY WGT. (gram)	ABSORB.	PPM	DILUT.	BODY BURDEN (µg)	BIO-CONC. (ppm)
D05	JAMES.NR.12	0.0536	0.105	0.2517	100	25.17	470
D06	JAMES.NR.12	0.1252	0.207	0.4962	100	49.62	396
D10	JAMES.NR.12	0.1418	0.299	0.7393	100	73.93	521
D15	JAMES.NR.12	0.1444	0.115	0.2757	100	27.57	191
D16	JAMES.NR.12	0.1397	0.202	0.4842	100	48.42	347
D20	JAMES.NR.12	0.1016	0.102	0.2445	100	24.45	241
D27	JAMES.NR.12	0.0248	0.063	0.1510	100	15.10	609
D29	JAMES.NR.12	0.0775	0.218	0.5242	100	52.42	676
G02	J.WS.15.FALL	0.0398	0.044	0.1055	100	10.55	265
G08	J.WS.15.FALL	0.0311	0.105	0.2517	110	27.69	890
G15	J.WS.15.FALL	0.0130	0.094	0.2253	100	22.53	1733
G19	J.WS.15.FALL	0.0433	0.160	0.3835	100	38.35	886
J06	J.WS.15.SPRING	0.0855	0.063	0.1510	100	15.10	177
J09	J.WS.15.SPRING	0.0963	0.101	0.2421	100	24.21	251
J19	J.WS.15.SPRING	0.1463	0.139	0.3332	100	33.32	228
K06	RAPP.BC.18	0.0299	0.045	0.1079	100	10.79	361
K10	RAPP.BC.18	0.0461	0.030	0.0719	100	7.19	156

*1: identification number of host oyster

Table 24. Contribution of pea crabs to measurements of dry weights and zinc concentrations

ID	HOST OYSTER DRY WGT. (gram)	HOST OYSTER BIO-CONC. (ppm)	PEA CRAB DRY WGT. (gram)	PEA CRAB BIO-CONC. (ppm)	CONTRIBUTION WGT.*1 (% of total)	CONTRIBUTION BIO-CONCENTRATION (ppm)*2	CONTRIBUTION BIO-CONCENTRATION (% change)
D05	1.1254	3344	0.0536	470	4.55	3213	-3.9
D06	1.2807	2995	0.1252	396	8.91	2763	-7.7
D10	0.7580	5574	0.1418	521	15.76	4777	-14.3
D16	0.5990	3602	0.1397	347	18.91	2986	-17.1
D20	0.4947	2423	0.1016	241	17.04	2051	-15.4
D27	0.6121	2007	0.0248	609	3.89	1953	-2.7
D29	1.0411	3914	0.0775	676	6.93	3690	-5.7
G02	0.1866	3931	0.0398	265	17.58	3286	-16.4
G08	0.3235	6298	0.0311	890	8.77	5824	-7.5
G15	0.5562	3577	0.0130	1733	2.28	3535	-1.2
G19	0.7714	9196	0.0433	886	5.31	8754	-4.8
J06	1.1940	10687	0.0855	177	6.68	9985	-6.6
J09	1.1062	8121	0.0963	251	8.01	7491	-7.8
J19	1.9463	7031	0.1463	228	6.99	6556	-6.8
K06	0.9328	3109	0.0299	361	3.11	3024	-2.7
K10	0.6496	1218	0.0461	156	6.63	1147	-5.8

*1: (dry weight of pea crab)/(dry weight of pea crab and oyster)

*2: (body burden of pea crab and oyster)/(dry weight of pea crab and oyster)

Table 25. Zinc and organic contents in bottom sediments

Sampling site	Zinc Conc. (ppm-dry wgt.)	Organic Carbon	Organic Nitrogen
The James River:			
Nansemond Ridge			
Wreck Shoal-Fall	296	7.79	1.32
Wreck Shoal-Spring	404	5.65	0.74
Horse Head Rock	237		
Mulberry Island	226		
The Rappahannock River:			
Broad Creek	140	6.96	1.12
Parrott Rock	85	6.38	0.97
Morattico Bar	63	3.59	0.45
The Piankatank River:			
Ginney Point			

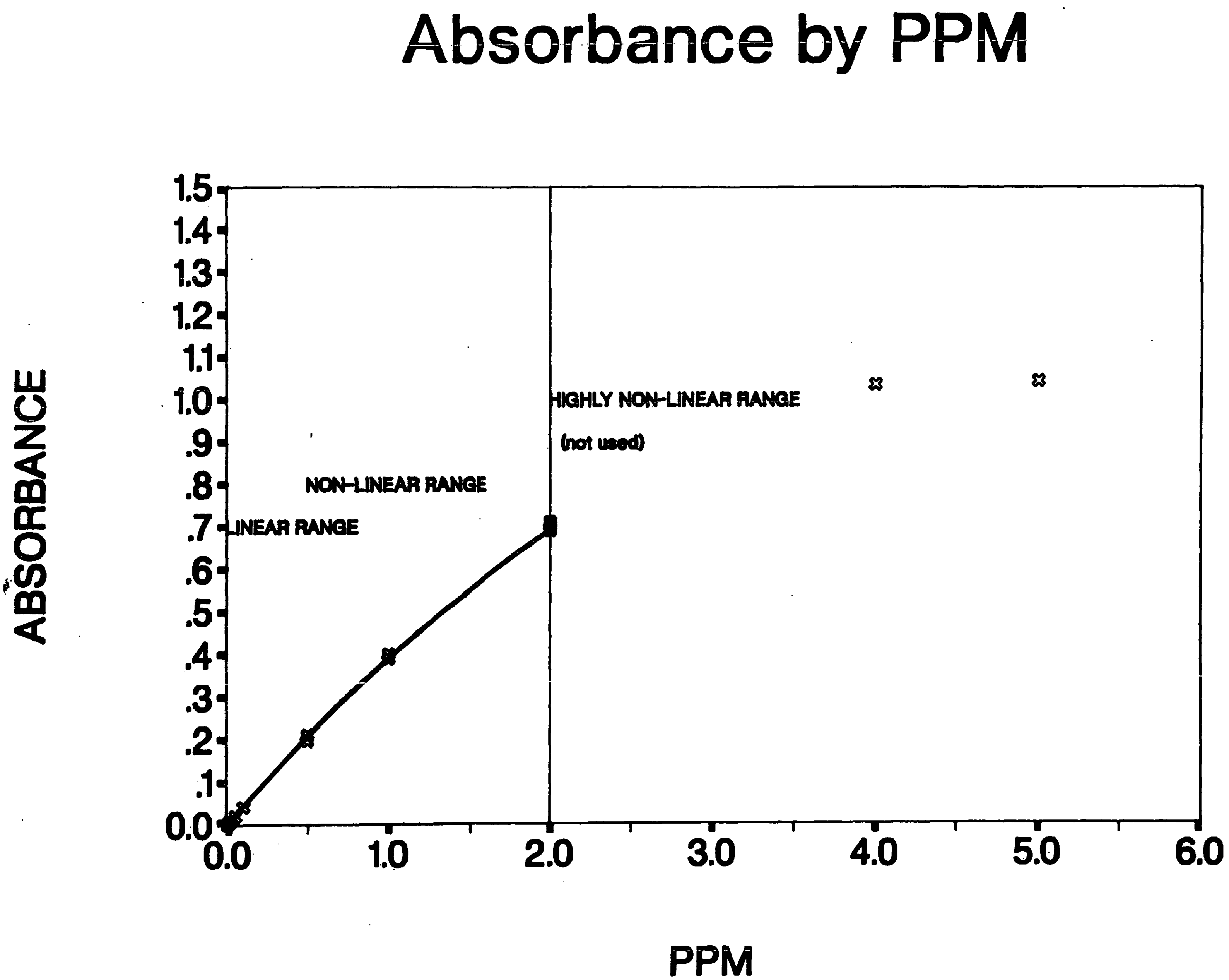

Figure 1. Absorbance values of blanks and standards in zinc measurements by atomic absorption spectrophotometer.

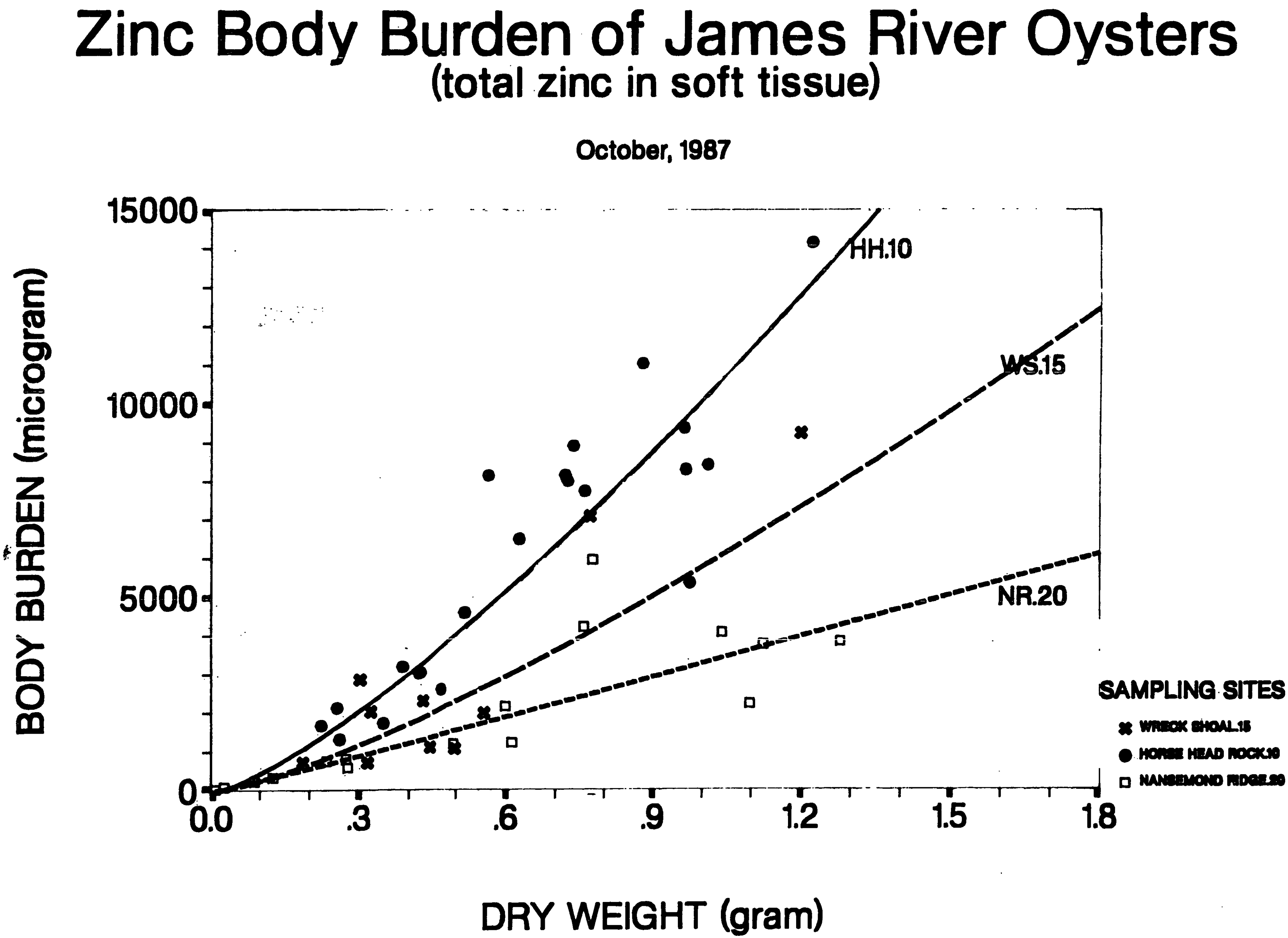

Figure 2. Zinc body burden of American osyters, Crassostrea virginica (Gmelin), from the James River, Virginia.

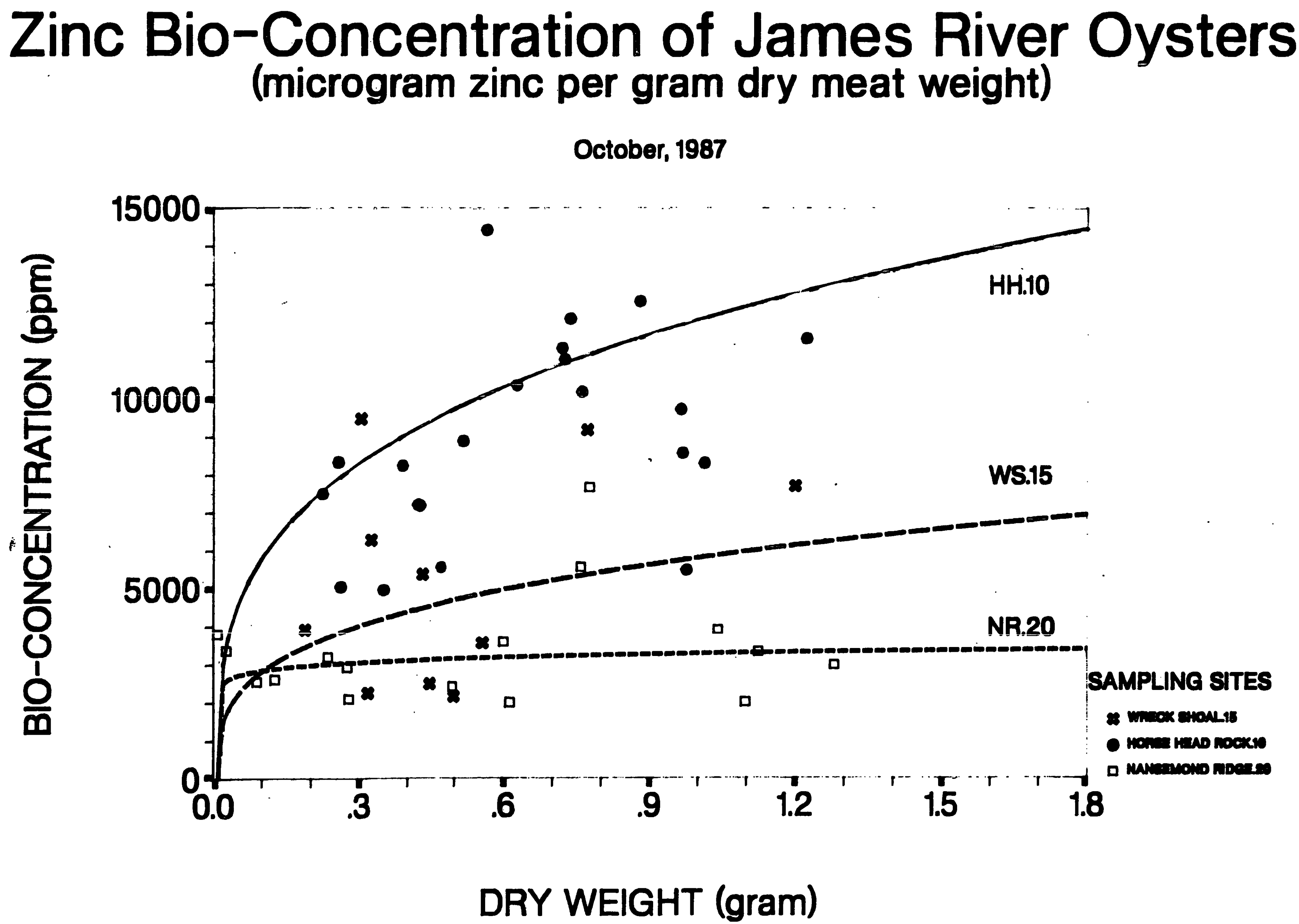

Figure 3. Zinc bio-concentrations of the oysters from the James River.

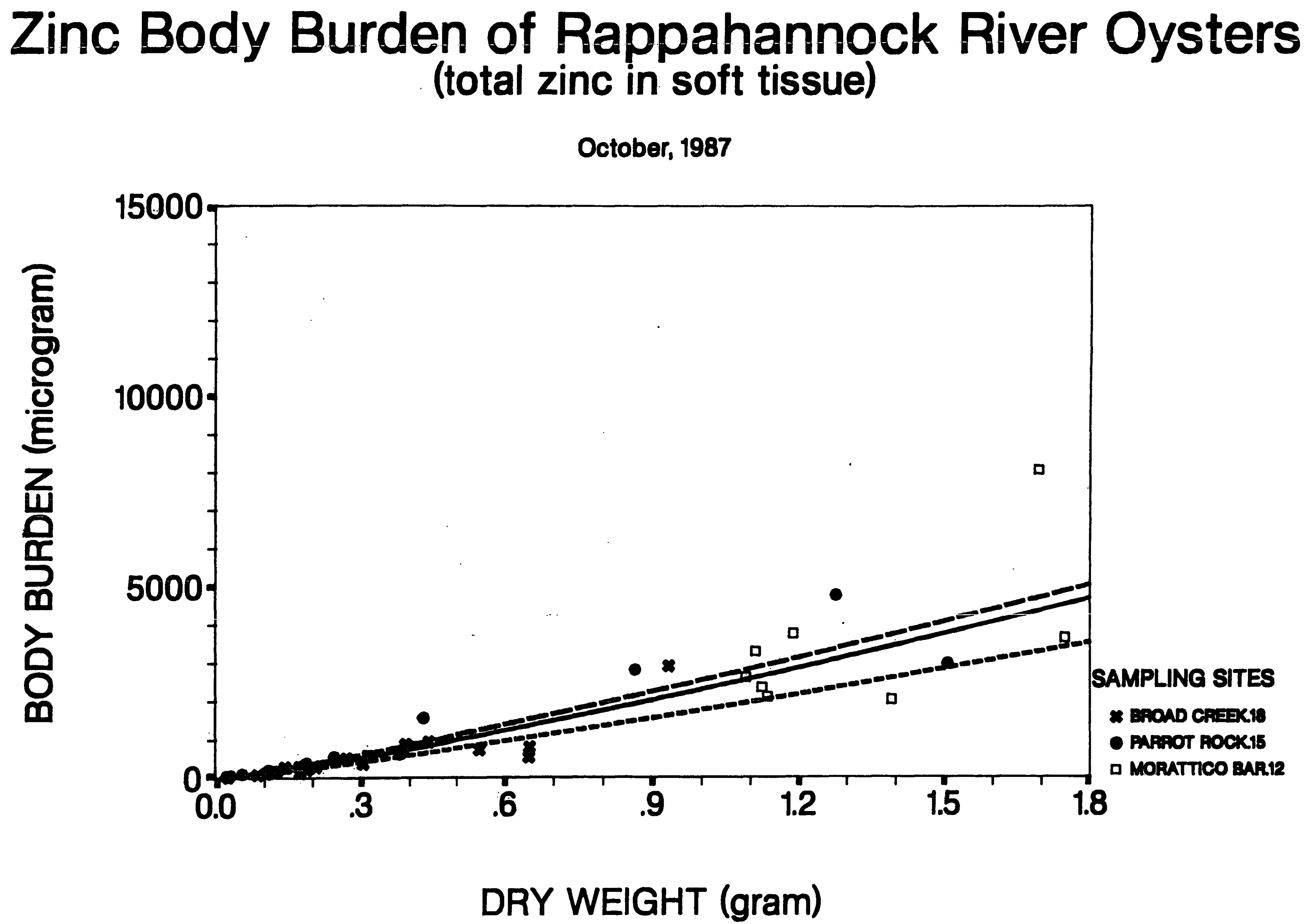

Figure 4. Zinc body burden of the oysters from the Rappahannock River, Virginia.

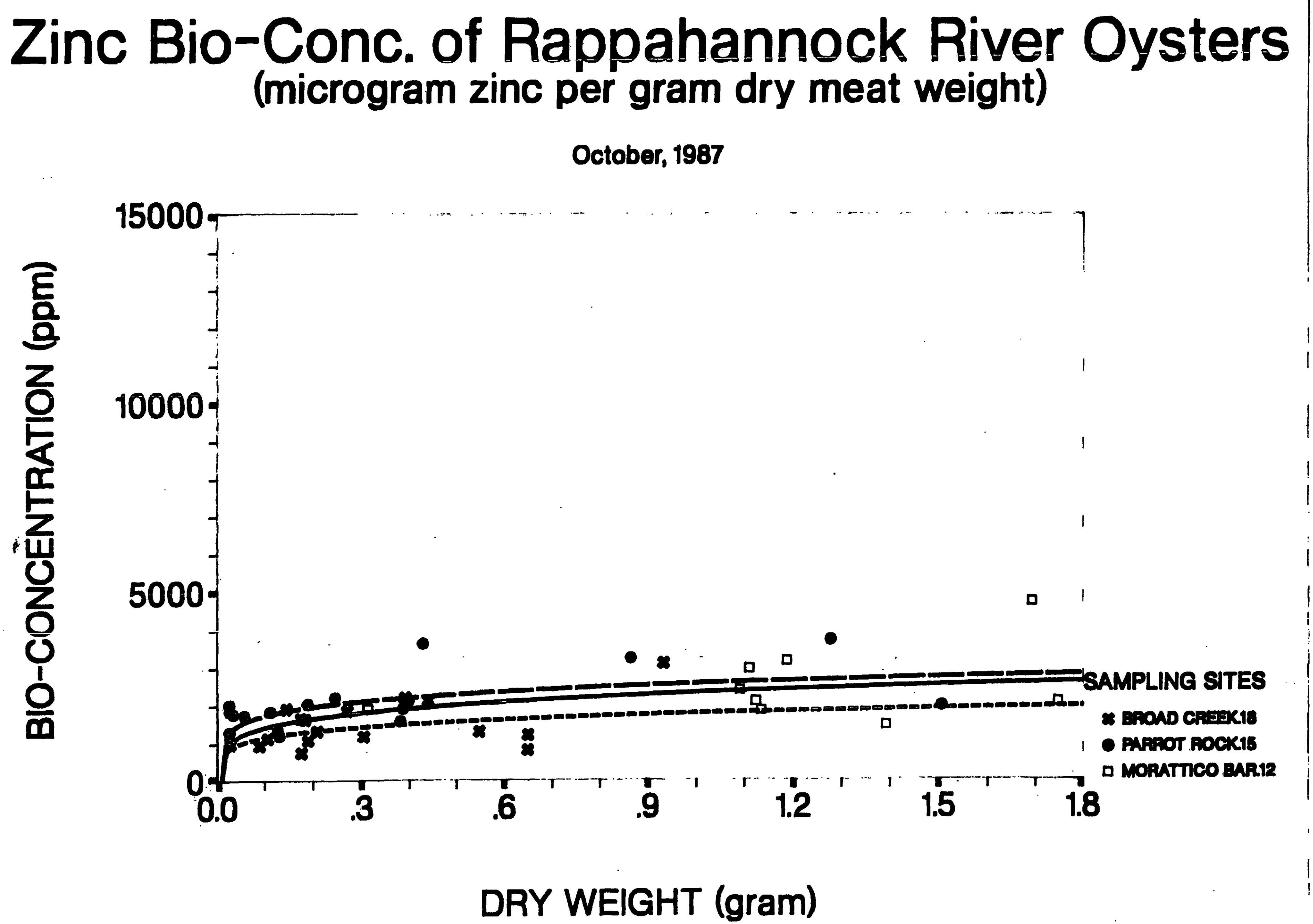

Figure 5. Zinc bio-concentrations of the oysters from the Rappahannock River.

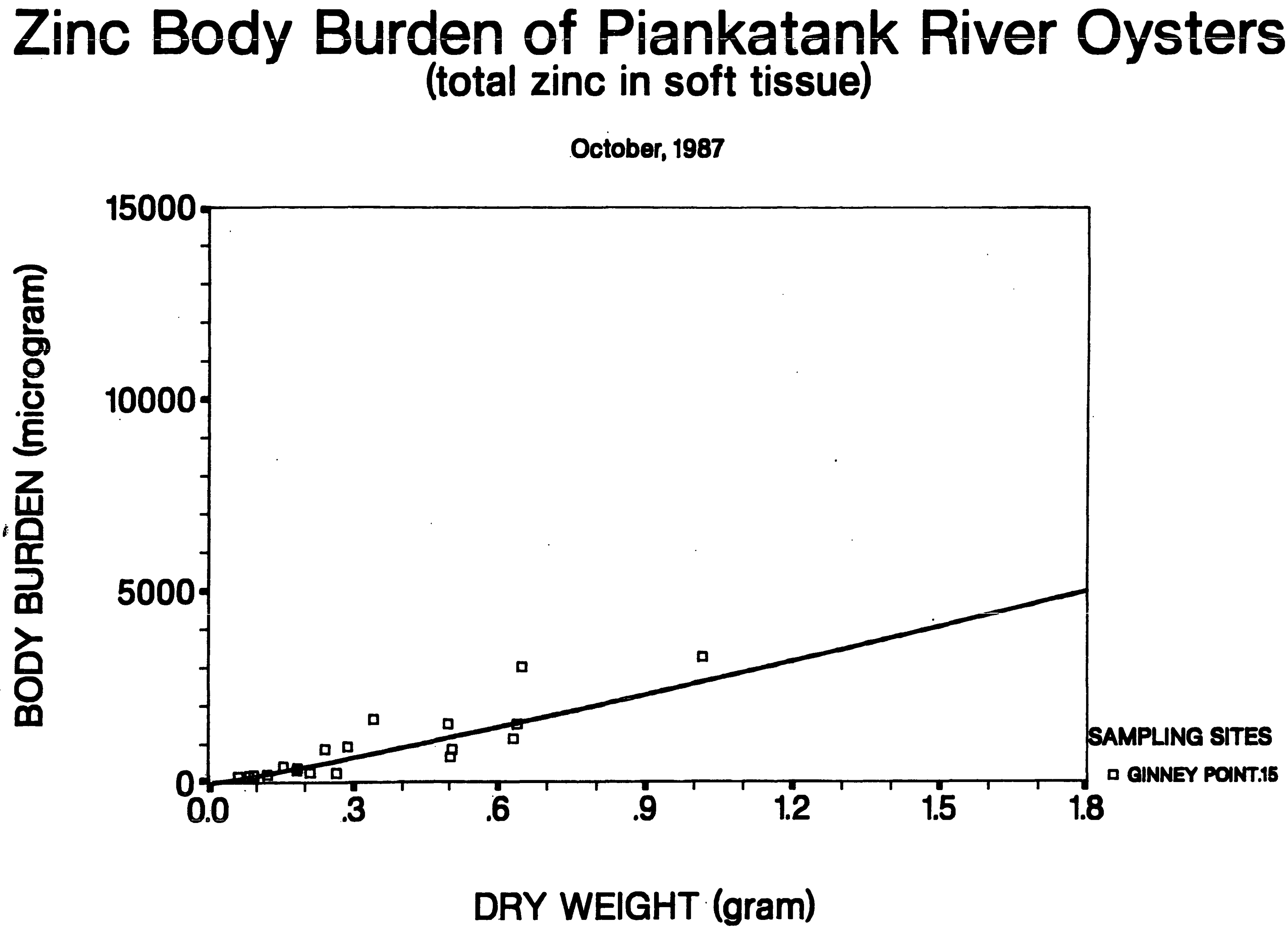

Figure 6. Zinc body burden of the oysters from the Piankatank River, Virginia.

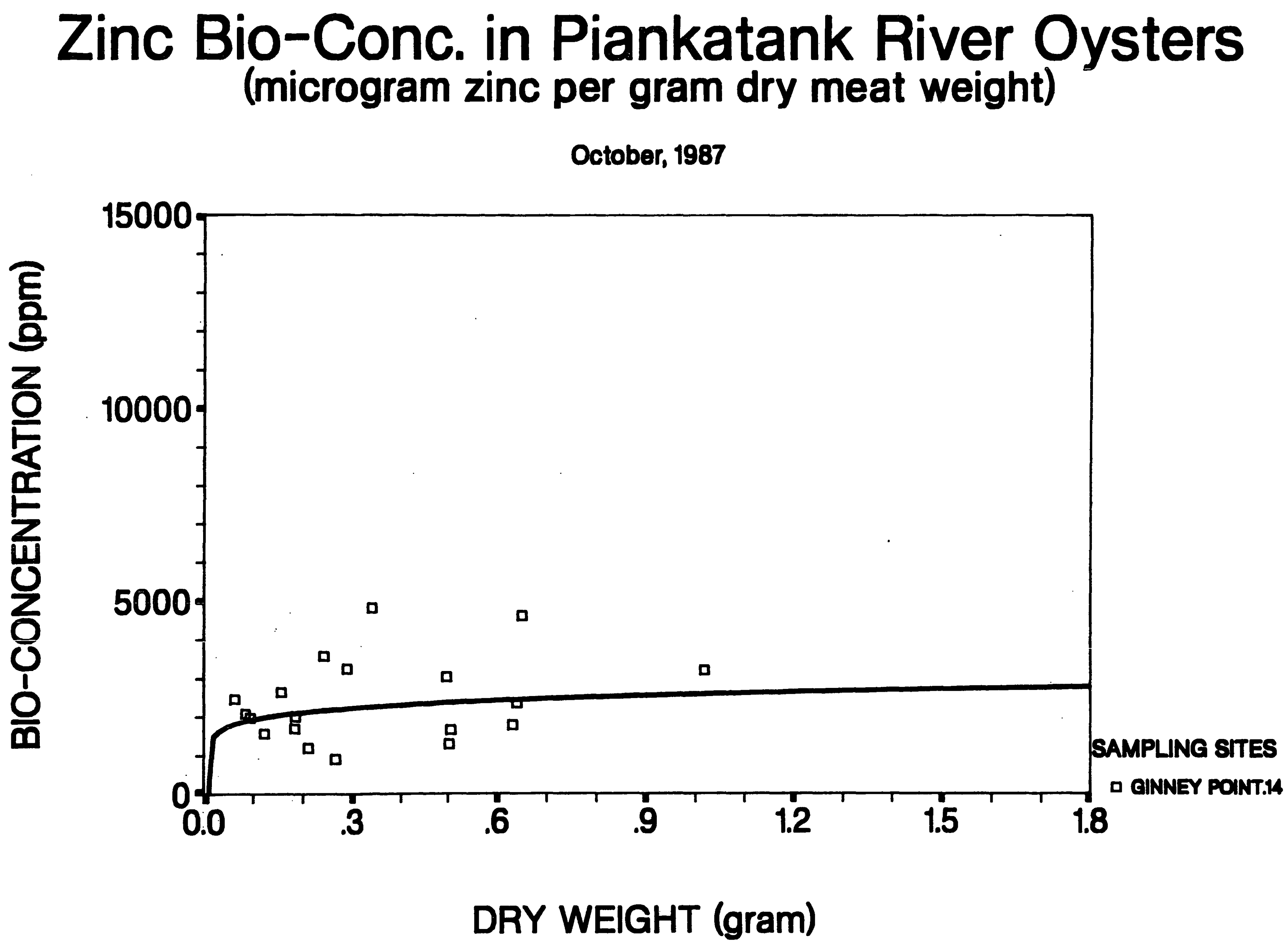

Figure 7. Zinc bio-concentrations of the oysters from the Piankatank River.

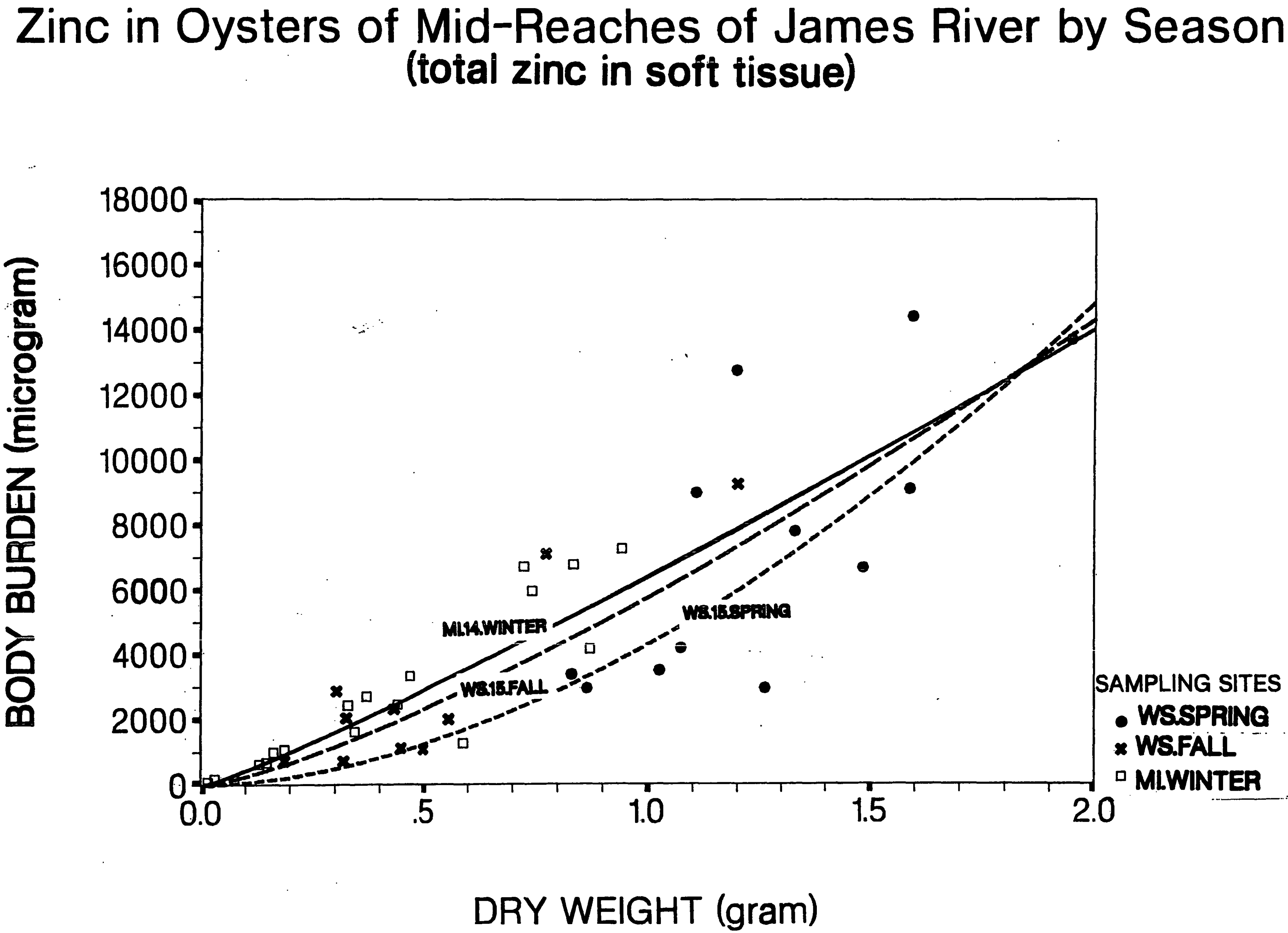

Figure 8. Comparison of zinc body burdens of the oysters from the mid-reaches of the James River by the season of collection.

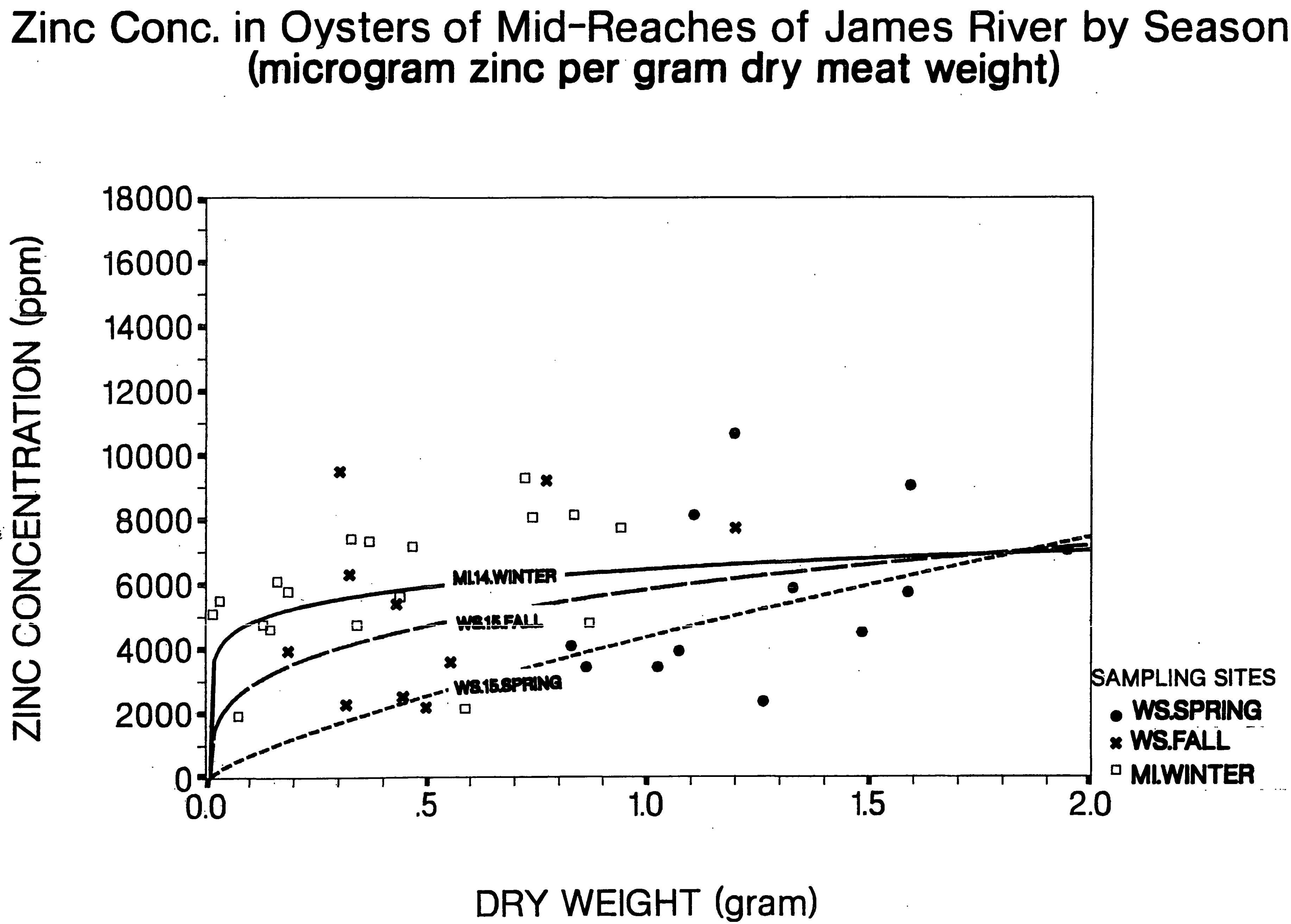

Figure 9. Zinc bio-concentrations of the oysters from the mid-reaches of the James River by the season of collection.

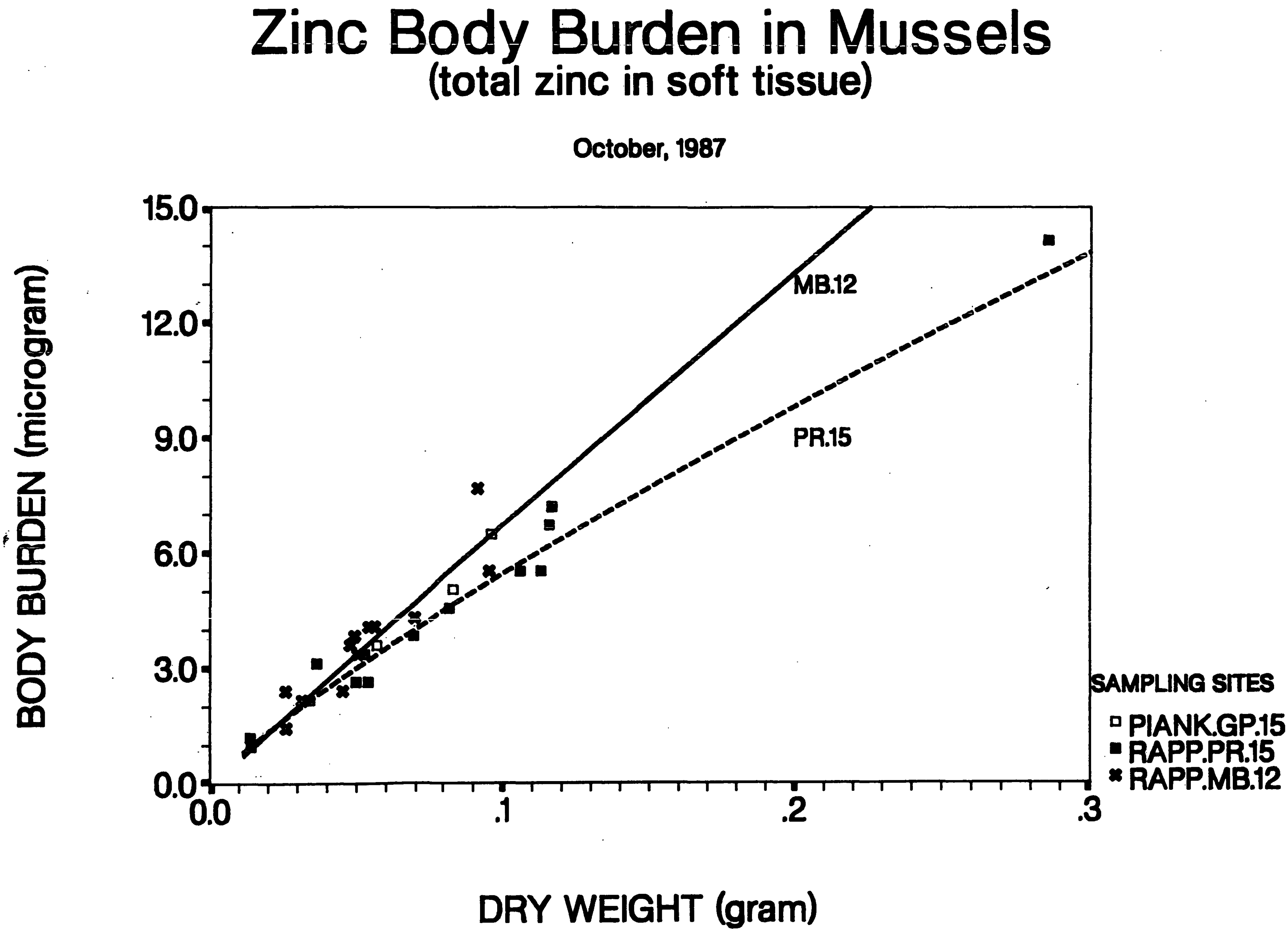

Figure 10. Zinc body burdens of the common mussels, Mytilus edulis (L.), from the sub-systems of the Chesapeake Bay Estuary, Virginia.

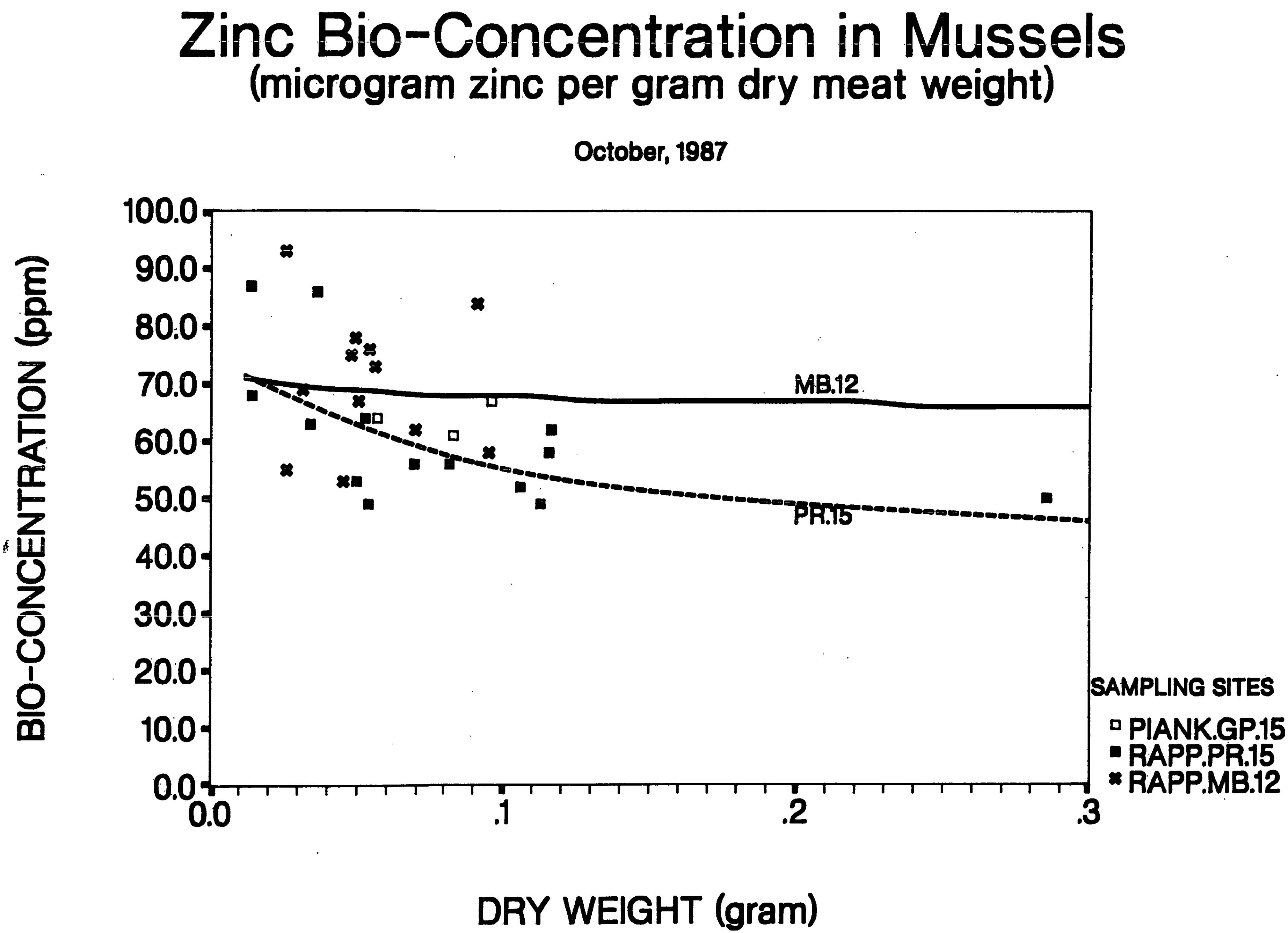

Figure 11. Zinc bio-concentrations of the mussels.

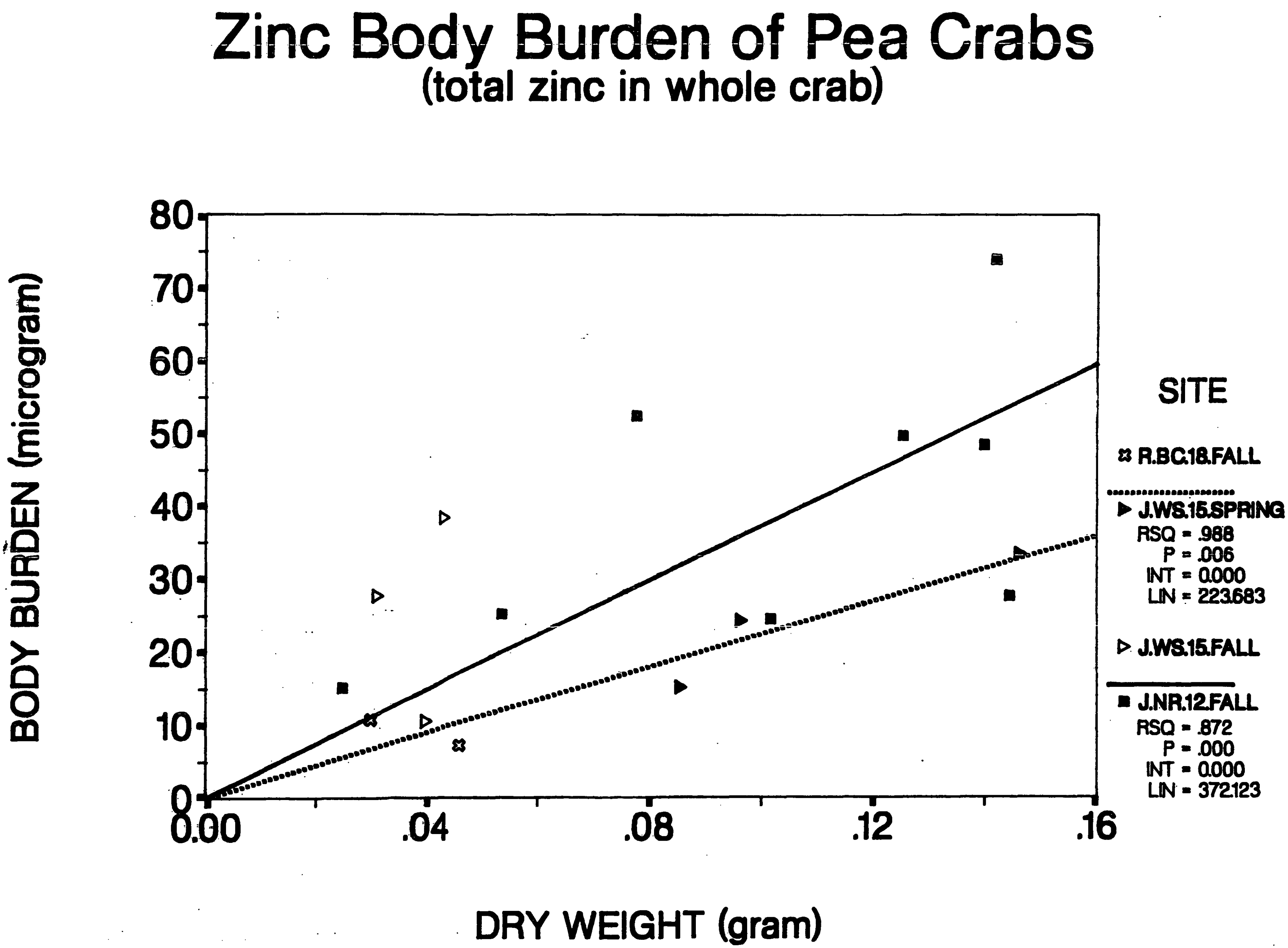

Figure 12. Zinc body burdens of the commensal pea crabs, Pinnotheres ostreum (Say).

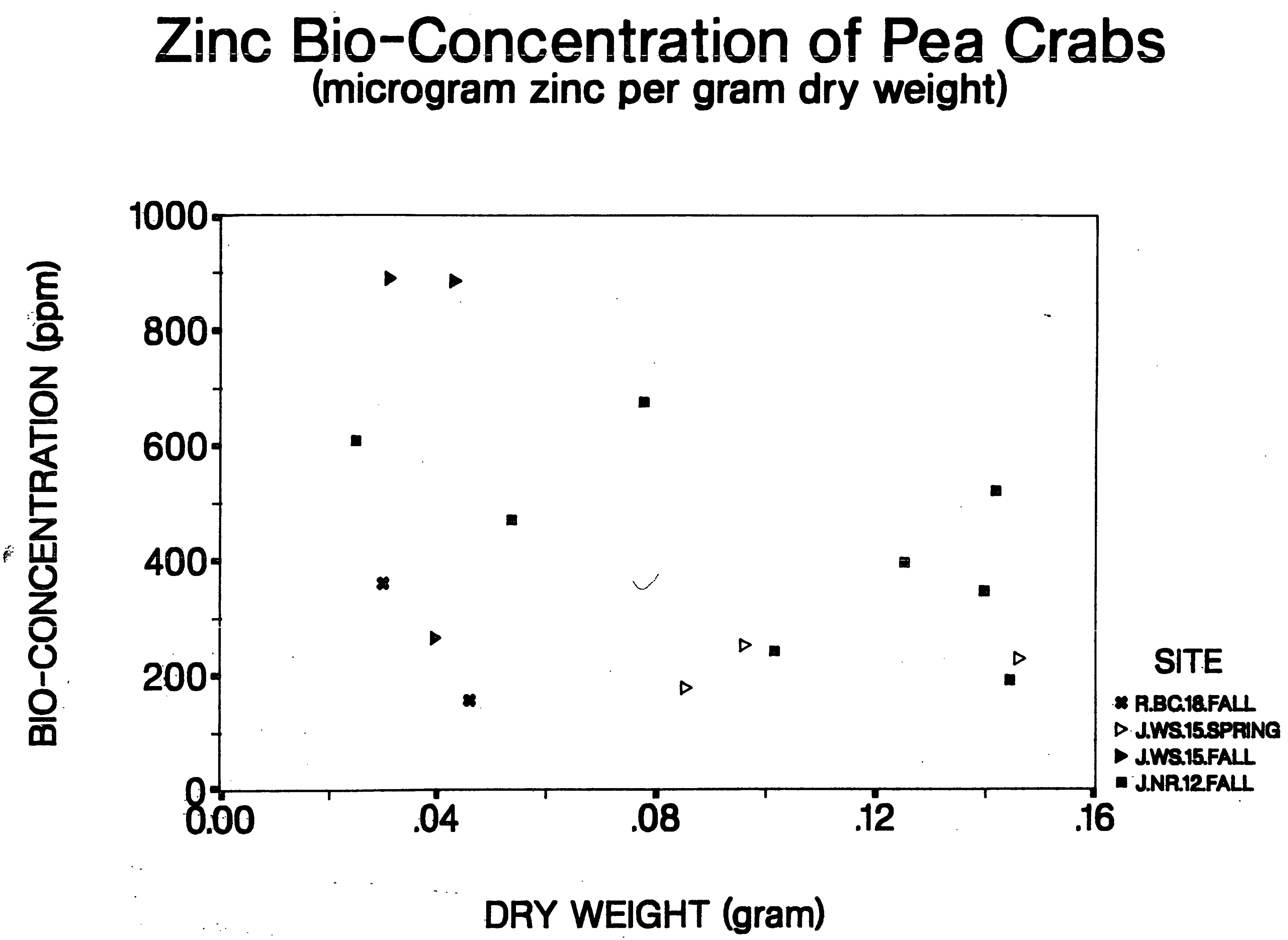

Figure 13. Zinc bio-concentrations of the pea crabs.

REFERENCES

Alying,G.M. (1974). Uptake of cadmium, zinc, copper, lead and chromium in the Pacific oyster, Crassostrea gigas, grown in the Tamar River, Tasmania. Water Res. 8:729-738.

APHA (1985). Standard Methods - for the examination of water and waste water. 6th ed., American Public Health Association, Washington, D.C., p.143.

Batley,G.E., Gardner,D. (1977). Sampling and storage of natural waters for trace metal analysis. Water Res. 11:745.

Boyden,C.R. (1974). Trace element content and body size in molluscs. Nature 251:311-314.

Boyden,C.R. (1977). Effect of size upon metal content of shellfish. J. Mar. Biol. Ass. U.K. 57:675-714.

Draper,N.R., Smith,H. (1966). Applied Regression Analysis. Wiley, N.Y., N.Y.

Eisenberg, M., Topping,J.J. (1984). Trace metal residues in shellfish from Maryland waters, 1976 -1980. J. Environ. Sci. Health, B19(7):649-671.

Engel,D.W., Sunda,W.G. (1981). Factors affecting trace metal uptakes and toxicity to esturaine organisms. I. Environmental parameters. In Vernberg,F.J., Calabrese,A., Thurberg,F.P., Vernberg,W.B. [eds.] "Biological Monitoring of Marine Pollutants." Academic Press, N.Y., N.Y., 1981, pp127-144.

Frazier,J.M. (1975). The dynamics of metals in the American oyster, Crassostrea virginica. I. Seasonal effects. Chesapeake Sci. 16:162-171.

Frazier,J.M. (1976). The dynamics of metals in the American oyster, Crassostrea virginica. II. Environmental effects. Chesapeake Sci. 17:188-197.

Galtsoff,P.S. (1964). The American Oyster, Crassostrea virginica Gmelin. Fish. Bull. Fish and Wildlife Serv., Vol. 64, U.S. Government Printing Office, Washington, D.C.

George,S.G., Frazier,J.H. (1982). Some aspects of the relationship between tolerance to heavy metal pollution and metabolism of cadmium, copper and zinc in oysters. Thalassia Jugoslavica 18(1-4):203-219.

Gilinsky,E., Roland,J.V. (1983). A Summary and Analysis of Metal and Concentrations in Shellfish and Fish Tissues from Virginia Estuarine Waters. State Water Control Board.

Grimshaw,D.L., Lewin,J., Fuge,R. (1976). Seasonal and short-term variations in the concentration and supply of dissolved zinc to polluted aquatic environments. Environ. Pollut. 11:1-7.

Hamelink,J.L. (1977). Current bioconcentration test methods and theory. In "Aquatic Toxicology: Hazard Evaluation" ASTM STP 634, F.L. Mayer and J.L. Hamelink ed. ASTM, 1977, pp149-161.

Hamelink,J. (1979). Bioavailability of chemicals in aquatic environments. In A.W. Maki, K.L. Dickson and J. Cairns [eds.] "Biotransformation and fate of chemicals in the aquatic environment." Am. Soc. Microbiol., Wash., 1979, pp56-62.

Harvey,E.J.,Sr., Knight,L.A.,Jr. (1978). Concentration of three toxic metals in oysters (Crassostrea virginica). of Biloxi and Pascagoula, Mississippi Estuaries. Water, Air, and Soil Poll. 9:255-261.

Haven,D.S., Morales-Alamo,R. (1970). Filtration of particles from suspension by the American oyster, Crassostrea virginica. Biol. Bull. 139:248-264.

Huggett,R.J., Cross,F.A., Bender,M.E. (1975). Distribution of copper and zinc in oysters and sediments from three coastal-plain estuaries. In "Proceedings of a Symposium on Mineral Cycling in Southeastern Ecosystems." Augusta, Georgia 1974, U.S. Energy Res. & Devel. Administration, ERDA Symposium Ser., Conf-740513, pp432-446, [VIMS Contr. No. 631]

Jorgensen,C.B. (1981). A hydromechanical principles for particle retention in Mytilus edulis and other ciliary suspension feeders. Mar. Biol. 61:277-282.

Laws,E.A., Archie,J.W. (1981). Appropriate use of regression analysis in marine biology. Mar. Biol. 65:13-16.

Luoma,S.N., Bryan,G.W. (1981). A statistical assessment of the form of the trace metals in oxidized sediments employing chemical extractants. Sci. Total Environ. 17:165-196.

Luoma,S.N., Bryan,G.W. (1982). A statistical study of environmental factors controlling concentrations of heavy metals in the burrowing bivalve S. plana and the polychaeta N. diversicular. Estuar. Coast. Shelf Sci. 15(1):95-108.

Luoma,S.N., Jenne,E.A. (1976). Estimating bioavailability of sediment-bound trace metals with chemical extractants. In "Trace Substances in Environmental Health-X." A Symposium, 1976, Univ. of Missourri, Columbia, pp343-351.

Martincic,D., Nurnberg,H.W., Stoeppler,M., Branica,M. (1984). Bioaccumulation of heavy metals by bivalves from Lim Fjord (North Adriatic Sea). Mar. Biol. 81(2):177-188.

Mo,C., Neilson,B. (1988). Experimental studies of zinc-65 uptake rates by the American oyster, Crassostrea virginica with regard to salinity, sediment concentration, and body size. VIMS Data Report No. 29, Virginia Institute of Marine Science, Gloucester point, Virginia

Mo,C., Neilson,B. (in preparation). The relationship between body size and zinc-65 uptake rate for the American oyster, Crassostrea virginica Gmelin.

Norstrom,R.J., Mckinnon,A.E., DeFreitas,A.S.W. (1976). A bioenergetics-based model for pollutant accumulation by fish. Simulation of PCB and ethylmercury residue levels in Ottawa River yellow perch (Perca flavescens). J. Fish. Res. Bd. Can. 33:248-267.

Phelps,H.L., Wright,D.A., Mihursky,J.A. (1985). Factors affecting trace metal accumulation by estuarine oysters Crassostrea virginica. Mar. Ecol. Prog. Ser. 22 (2): 187-197

Phillips,D.J.H. (1977). The use of biological indicator organisms to monitor trace metal pollution in marine and estuarine environments - a review. Environ. Pollut. (A). 13: 281-317

Phillips,D.J.H., Muttarasin,K. (1985). Trace metals in bivalve molluscs from Thailand. Mar. Environ. Res. 15:215-234.

Phillips,D.J.H., Yim,W.W.-S. (1981). A comparative evaluation of oysters, mussels and sediment as indicators of trace metals in Hong Kong Waters. Mar. Ecol. Prog. Ser. 6:285-293.

Preston,A. (1966). The concentration of ^{65}Zn in the flesh of oysters related to the discharge of cooling pond effluent from the C.E.G.B. Nuclear Power Station at Bradwell-on Sea, Essex. In "Radioecological

Concentration Processes", Aberg,B. and Hungate,F.P. eds., Pergamon Press, Oxford, 1966, pp 995-1004.

Pringle,B.H., Hissong,D.E., Katz,E.L., Mulawka,S.T. (1968). Trace metal accumulation by estuarine mollusks. J. Sanitary Engineer. Div.,Proc. Am. Soc. Civil Engineers. 94(SA3),Proc. Paper 5970:455-475.

Ricker,W.E. (1973). Linear regression in fisheries research. J. Fish. Res. Bd. Can. 30:409-434.

Robertson,D.E. (1965). The absorption of trace elements in sea water on variour container surfaces. Anal. Chim. Acta 42:533.

Robertson,D.E. (1968). Role of contamination in trace metal analysis of sea water. Anal. Chem. 40:1067.

Romeril,M.G. (1971). The uptake and distribution of ^{65}Zn in oysters. Mar. Biol. 9:347-354.

Roosenburg,W.H. (1969). Greening and copper accumulation by the American oyster Crassostrea virginica in the vicinity of a stream electric generating station. Chesapeake Sci. 10:241-252.

SAS Institute Inc. (1985). SAS/Statistics User's Guide, Version 5 Edition. SAS Institute Inc., Cary, North Carolina.

Seymour,A.H., Nelson,V.A. (1972). Biological half lives for zinc and mercury in the Pacific oyster, Crassostrea gigas. In: Proc. Third National Symp. on Radioecology. Oak Ridge, Tennesee, May 10-12, 1971, CONF-710501, 1972, pp. 849-856.

Seymour,A.H. and Nelson,V.A. (1973). Decline of ^{65}Zinc in marine mussels following the shutdown of Hanford reactors. In "Symp. Interaction of Radioactive Contaminants with the Constituents of the Marine Environment", Seattle, Wash., July 10-14, 1972, IAEA, Vienna, 1973, pp 277-286.

Simkiss,K. (1983). Lipid solubility of heavy metals in saline solution. J. Mar. Biol. Assoc. U.K. 68:1-9.

Simkiss,K. and Mason,A.Z. (1984). Cellular responses of molluscan tissues to environmental metals. Mar. Environ. Res. 14:103-118.

Shellfish Sanitation Chemistry Task Force. (1976). Collection, Preparation and Analysis of Trace Metals in Shellfish. FDA Publ. No. 76-2006, Washington, D.C.

Snedocor,G.W., Cochran,W.G. (1967) Statistical Methods. 6th ed., Iowa State Univ. Press, Ames, Iowa, 1967.

Sokal,R.R., Rohlf,F.J. (1981). Biometry. 2nd ed., W.H.Freeman & Co., San Fransisco, 1981.

SPSS Inc. (1986). SPSS^x User Guide, 2nd. ed., McGraw-Hill Co., N.Y., 1986.

Strong,C.R, Luoma,S.N. (1981). Variations in correlation of body size with concentrations of copper and silver in bivalves. Can. J. Aquatic Sci. 38(9):1059-1064.

Struempler,A.W. (1973). Adsorption characteristics of silver, lead, cadmium, zinc and nickel on borosilicate glass, polyethylene and polypropylen container surfaces. Anal. Chem. 45:2251.

Subramanian,K.S., Chakrabarti,C.L., Suetias,J.E., Maines,I.S. (1978). Preservation of some trace metals in samples of natural waters. Anal. Chem. 50:444.

Thomson,E.A., Luoma,S.N., Cain,D.J., Johansson,C.E. (1980). Effect of sample storage on the measurements of copper, zinc, iron, manganese and organic materials for oxidized estuarine sediment. Water, Air, and Soil Poll. 14:215-233.

Thomson,J.D. (1982). Metal concentration changes in growing Pacific oysters, Crassostrea gigas, cultivated in Tasmania, Austrailia. Mar. Biol. 67:135-142.

Thomson,J.D. (1983). Short-term changes in metal concentration in the cultivated Pacific oyster, Crassostrea gigas hunberg, and the implications for food standards. Aust. J. Mar. Freshw. Res. 34:397-405.

Widdows,J. (1978). Combined effects of body size, food concentration and season on the physiology of Mytilus edulis. J. Mar. Biol. Ass. U.K. 58:109-124.

Winddom,H.L., Smith,R.G. (1972). Distribution of iron, magnesium, copper, zinc, and silver in oysters along the Georgia Coast. J. Fish. Res. Bd. Can. 29:450-452.

Wolfe,D.A. (1970). Levels of stable Zn and ^{65}Zn in Crassostrea virginica from North Carolina. J. Fish. Res. Bd. Can. 27: 47-57.

Wright,D.A., Mihursky,J.A., Phelps,H.L. (1985). Trace metals in Chesapeake Bay oysters: Intra-sample variability and its implications for biomonitoring. Mar. Environ. Res. 16:181-197.