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STATUS OF EELGRASS IN PORTSMOUTH HARBOR AND ITS USE IN ASSESSING HEAVY METAL CONTAMINANTS IN THE GREAT BAY ESTUARY NEAR THE PORTSMOUTH NAVAL SHIPYARD

Final Report

by

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Status of Eelgrass in Portsmouth Harbor and Its Use in Assessing Heavy Metal Contaminants in The Great Bay Estuary Near the Portsmouth Naval Shipyard

Introduction

Eelgrass, *Zostera marina* L., in the Great Bay Estuary has been monitored extensively for the last decade (Short 1992). However, the major foci of these observations have been Great and Little Bays, with little opportunity to monitor eelgrass distribution in the Piscataqua River and Portsmouth Harbor. Prior to the present investigation, only one site in Portsmouth Harbor had been recently assessed as part of a study of eelgrass ecology along the East Coast of the U.S. (Short et al. 1993). The health and abundance of eelgrass at that site were found to be comparable to other sites along the East Coast and less impacted by the eelgrass wasting disease than sites within Great Bay. The work reported here provided the opportunity to test the utilization of eelgrass as an indicator of heavy metal contamination and at the same time to investigate the health and status of eelgrass in the lower Great Bay Estuary.

Eelgrass was investigated as part of the Portsmouth Naval Shipyard Environmental Risk Assessment because it is the dominant vegetation that characterizes an important depositional environment where heavy metals accumulate in the Estuary (Johnston et al. 1993). A major role of eelgrass in the estuarine environment is to filter out particulate material that moves around in estuarine waters, and, in doing so, to trap and bind suspended sediment from the water column (Short and Short 1984). Such filtering and trapping ability means that eelgrass beds function as depositional areas where fine particles and associated contaminants will accumulate. Eelgrass tissue was sampled to provide a measure of its exposure to contaminants from the water column and from the sediment.

A detailed assessment was made of eelgrass abundance and plant vigor as part of Phase I of the Portsmouth Naval Shipyard Ecological Risk Assessment (Johnston et al. 1993). That survey,

made in September 1991, forms the basis of our description of the overall characteristics of eelgrass beds in Portsmouth Harbor and the Piscataqua River (Fig.1). Additionally, as a reference sampling location in the 1991 survey, an assessment of eelgrass beds in York Harbor, Maine was completed.

I. Eelgrass in Portsmouth Harbor and the Great Bay Estuary.

Eelgrass in the Great Bay Estuary shows the greatest plant biomass (Fig. 2) at stations near the main channel in Portsmouth Harbor (Short 1993). Like biomass, leaf length was found to be greatest in beds influenced by tidal flow adjacent to the main channel of the river, particularly stations 9 and 16. Eelgrass rhizome length, an indicator of belowground root and rhizome development, showed the highest values at stations 1, 24, and 33 (Fig. 3). Assessment of sexual reproduction and degree of flowering for eelgrass populations throughout the Estuary was not possible from the September 1991 data, because this sampling occurred after the time of peak flowering.

Overall, the biomass and vigor of eelgrass plants in the Portsmouth Harbor area were high with some of the greatest biomasses and largest plants found directly adjacent to Seavey Island (Figs. 2 and 3). Additionally, eelgrass beds were found to occur at a number of sites around Seavey Island: stations 3, 9, 12a, 17, 18 and 19. However, eelgrass was not found at some locations where we expected to see it. Specifically, within Clark Cove no eelgrass was found except for a small bed at station 3, although numerous other areas in Clark Cove are of suitable depth and sediment type for eelgrass growth. The paucity of eelgrass in Clark Cove is a concern because the reasons for its absence from the inner parts of Clark Cove remain unresolved.

II. Eelgrass as a Sentinel Accumulator

A sentinel accumulator is an organism, fixed in one location, which accumulates contaminants from the surrounding media. When sampled and analyzed, the organism is used as

an indicator of the presence, absence, or level of specific contaminants in an ecosystem. Numerous studies of seagrasses around the world growing in sediments contaminated with various heavy metal concentrations have documented the accumulations of these metal compounds into seagrass tissues (Stenner and Nickless 1975, Pulich et al. 1976, Harris et al. 1979, Brix et al. 1983a,b, Maher 1986a,b, Nienhuis 1986, Tiller et al. 1989, Ward 1989, Catsiki and Panayotidis 1993, Güven et al. 1993). Several of these studies have found lead, chromium, zinc, cadmium, copper and nickel accumulate to very high concentrations in seagrass tissue (Table 1). In a bay downstream from a metal smelting plant in Australia, concentrations of lead in seagrass exceeded 402 μg/g dry wt (Tiller et al. 1989). Bioaccumulation (see below) of lead in some seagrass species was found to greatly exceed the tissue lead concentrations that are considered to be background levels (Table 1).

Bioaccumulation of metals is defined to be metal absorption by an organism from its ambient environment and the retention of some part of that absorbed metal (Ward 1989). Ward states that "seagrasses are bioaccumulators...of metals." Additionally, Tiller et al. 1989 state that seagrass tissue metal composition may provide a more sensitive measure of metal dispersion than the assessment of metals in sediments.

In reviewing the literature concerning levels of metals in seagrass tissues, it can be seen that the background concentrations of heavy metals in seagrass leaf and root (root plus rhizome) tissue vary between species and between sample locations (Table 1). Background levels (Table 1) of lead in leaves are below 3 ppm, below 80 ppm for zinc, below 1 ppm for cadmium, and below 10 ppm for copper. No literature was found which gives background concentrations for chromium, nickel or mercury. The concentrations of various metals in the leaves compared to the roots of seagrass plants show different degrees of bioaccumulation for different metals. Some studies have shown varying degrees of translocation of copper between various parts of the seagrass plant (Lyngby and Brix 1989, Carter and Eriksen 1992). Our data provides additional support for the idea that some, but not all, metals do translocate between roots and leaves of eelgrass.

The ability of seagrass plants to bioaccumulate metals from the sediment or the water column and register these in the root and leaf tissue, respectively, suggests that seagrasses function effectively as sentinel accumulators of specific metal contaminants (Table 2). Eelgrass grows rooted at a specific location where its exposure to contaminants can be monitored over time. Additionally, studies on the kinetics of copper uptake by a seagrass species, *Zostera muelleri*, clearly demonstrate the ability of seagrass to accumulate metals in direct relationship to the degree of exposure to that metal in the environment (Carter and Eriksen 1992). In a separate study of eelgrass, *Zostera marina*, the accumulation of lead, copper, cadmium, and zinc was clearly shown to occur both in the roots and the leaves, with a strong seasonal signal (Lyngby and Brix 1982). Thus, seagrasses in general, and eelgrass in particular, have the potential to function as sentinel accumulators of metal contaminants in the environment.

Methods

Metal concentrations in eelgrass leaf and root tissues were analyzed for the initial baseline data collected in September, 1991 and then quarterly starting in December of 1991 through September of 1992. Eelgrass samples were collected according to JEL SOP 1.01 (Mueller et al. 1992), returned to the Jackson Estuarine Laboratory, scraped free of epiphytes, washed clean of sediments, rinsed in distilled water, and frozen for chemical analysis. Subsequently, frozen plants were packed into freezer chests and shipped via overnight mail to Ceimic Corporation in Narragansett, Rhode Island (samples from September and December 1991, March 1992) and Battelle Marine Science Laboratory in Sequim, Washington (samples from June, September, and December of 1992 and selected samples from September 1991 for intra-laboratory validation). Eelgrass composite samples for tissue metal analysis were analyzed according to methods established by Battelle Marine Science Laboratory (Battelle 1992) and Ceimic Corporation (Mueller et al. 1992). The initial samples run by Ceimic (September and December 1991) were dried before

analysis; all other samples were shipped as fresh frozen material. Samples analyzed by Battelle were dried before analysis. For all stations, single samples of leaf and root tissue were sent for analysis. Replicate samples were run for samples from two locations, station 23 for leaves and station 1 for roots, to test reproducibility of the analytical method. Metal concentrations in leaf and root tissue were calculated in micrograms of metal per gram dry weight of plant tissue. Statistical analysis included analysis of variance (Super ANOVA), correlation analysis, and regression analysis (Snedecor and Cochran 1968).

Results

Eelgrass tissues were collected and analyzed from a number of stations in Portsmouth Harbor, up the Great Bay Estuary, and in the York River to determine if eelgrass is a useful indicator of heavy metals, what levels of metals accumulated in the leaves and roots of the plants, if these levels indicate sources of contamination in the estuary, and what effects heavy metals have on eelgrass distribution and population characteristics. Metal concentrations in eelgrass leaves and root/rhizome tissue were analyzed separately using analysis of variance to determine what factors had the greatest effect on tissue metal concentrations. Factors analyzed included the year of sampling, month of sampling, the station where samples were collected, the analytical laboratory where samples were processed, and whether or not samples were dried before analysis.

Eelgrass Leaves as Sentinel Accumulators

Seagrass leaves have proved to be useful as sentinel accumulators of metals (Table 1). However, the factor that most contributed to the variation in leaf tissue concentration for some metals in our early samples was the likelihood of contamination during the drying process prior to analysis. The September and December 1991 samples were inadvertently dried in aluminum foil. In an analysis of variance, this factor showed a significant effect for a whole series of metals (Table 3). The effect of drying in aluminum foil clearly created a contamination factor in all samples that were processed in that manner. After statistically removing the effect of this

contamination, the next most important factor showing a significant effect was station, which showed significant differences between stations for mercury (Hg), zinc (Zn), and manganese (Mn) (Table 3). The remainder of this report is based on samples of leaf tissue which were not contaminated during sample processing.

Eelgrass leaf tissue background concentration was based on the analysis of metal concentrations in eelgrass leaves collected from the two reference sites, station 1 in Portsmouth Harbor and station 23 in the York River. The eelgrass tissue cut-off (ETC: an indicator to identify samples significantly above a particular background level) for eelgrass leaf tissue is defined here as the mean of the reference site concentrations plus 3 standard deviations (Table 4). The remainder of our analysis of eelgrass leaf tissue as a sentinel accumulator for heavy metals is discussed relative to the cut-off above background tissue levels, expressed as the ETC concentration. Eelgrass tissue metal levels are defined as "high" or "elevated" if they exceed the ETC derived from background eelgrass metal concentrations for Portsmouth Harbor and York River (Stations 1 and 23).

Examination of metal concentrations in eelgrass leaf tissue collected from Portsmouth Harbor and the York River indicates a general elevation in metal contaminants within Portsmouth Harbor relative to ETC values (Fig. 4). Particularly lead, mercury, chromium, and copper show elevated concentrations in the vicinity of Seavey Island. Examination of tissue concentration in all samples collected during Phase I and Phase II of our study shows elevated lead concentrations at stations 3, 9, 16, 17, 18 and 19 (Fig. 5), elevated mercury concentrations at stations 9, 16 and 19 (Fig. 6), elevated chromium at stations 3, 9, 18, and 19 (Fig. 7), and copper concentrations elevated at stations 12a, 16, 18, and 19 (Fig. 8). Nickel concentration in eelgrass leaf tissue was found to be higher at station 3, at the mouth of Clark Cove, than elsewhere in Portsmouth Harbor (Fig. 4).

The data on eelgrass leaf tissue metal concentrations suggests there were higher levels of heavy metal contaminants around Seavey Island than at other places in Portsmouth Harbor (Fig. 4). Further, these data from eelgrass leaf tissue suggest the existence of sites of highly elevated concentrations where contaminants may originate from point sources.

Eelgrass Roots as Sentinel Accumulators

For eelgrass root tissue (roots plus rhizomes), a background concentration was determined based on the analysis of metal concentrations in eelgrass root tissue collected from the two reference sites, station 1 in Portsmouth Harbor and station 23 in the York River. The ETC for eelgrass root tissue is defined as the mean of metal concentrations at the reference sites plus 3 standard deviations, the same definition used for eelgrass leaf tissue. The remainder of this analysis for eelgrass root tissue as a sentinel accumulator for heavy metals is discussed relative to this tissue level, expressed as the ETC concentration. For eelgrass roots, the effect of drying samples in aluminum foil before analysis was significant for mercury (Hg) and these dried samples were excluded from the mercury analysis. Analysis of variance also showed a significant effect due to the analytical laboratory used for chromium (Cr), zinc (Zn), and nickel (Ni), but this is an artifact of different sample pools being distributed to different laboratories, (eg. stations 24-33 analyzed by Ceimic only), and did not require the elimination of data.

Eelgrass root tissue was analyzed to provide an indicator of the biologically available metals in the sediment of sites of known sedimentary deposition. Since eelgrass roots bioaccumulate many metals from the sediment surrounding the root zone, they represent excellent sentinel accumulators for many metal contaminants in the sediment.

The analysis of metals in eelgrass root tissue shows elevated concentrations of most metals (as defined above) throughout Portsmouth Harbor and the upper Great Bay Estuary. Particularly, levels of lead (Pb), mercury (Hg), chromium (Cr), arsenic (As) and nickel (Ni) were elevated in root tissues, suggesting elevated concentrations of these metals in the sediments (Fig. 9). Very

high concentrations above ETC of lead, mercury, silver, copper, and arsenic were found around Seavey Island (stations 9, 12a, 17, 18, and 19; Fig. 9). Additionally, levels significantly above background of chromium, lead, arsenic and nickel were found near the General Sullivan Bridge (station 27), close to where a brook draining from the former Pease Air Force Base enters Little Bay. In the upper Estuary, levels of these same contaminants decreased in eelgrass both upstream and downstream of the station 27 sampling site. Of the stations around Seavey Island, only station 3 at the mouth of Clark Cove had no metal concentrations substantially above the ETC. Elsewhere in Portsmouth Harbor, stations 2, 14, 15, and 16, somewhat removed from Seavey Island, showed metal contaminant concentrations above the ETC, but at levels generally lower than those sites immediately adjacent to Seavey Island. Station 11 in Little Harbor showed metal concentrations at or below the ETC. Seasonally, root tissue metal concentrations were greatest in June and September, but there was a high degree of variability (Figs. 10-13).

Elevated levels of lead above the ETC in eelgrass root tissue were evident at all stations in Portsmouth Harbor and the Great Bay Estuary, except station 11 (Fig. 10) and the stations used to determine the ETC (Stations 1, 22, and 23). Multiple peaks are evident for lead, one up-estuary and at least two down-estuary (Fig. 10). At most stations around Seavey Island, samples with lead concentrations below the ETC were only collected in December. Mercury concentrations in eelgrass roots were above the ETC at stations 3, 9, 12a, 16, 17, 18 and 19, with the highest levels found by the Dry Docks at station 12a and in the Back Channel at station 18 (Fig. 11). Chromium in eelgrass root tissue showed similar patterns to lead, with the only station in Portsmouth Harbor having no samples above the ETC being station 11 (Fig. 12). However, unlike lead, which showed peaks in the Back Channel, the highest chromium concentration was found at station 27 in Little Bay. Copper in eelgrass root tissue was generally below the ETC throughout the Estuary, except at a few stations around the Shipyard, including stations 9, 12a, 17, 18, and 19, with 12a, 18, and 19 substantially above the ETC (Fig. 13). A peak was found at station 18 in the Back Channel where copper concentrations reached 58 ppm. Elevated silver concentrations occurred at

station 12a, where they reached 11 ppm in eelgrass root tissue and at station 17 where concentrations were 1 ppm. Concentrations of cadmium in eelgrass root tissue were low throughout the entire Estuary, rarely exceeding the ETC for cadmium. Arsenic concentrations were found to be the highest at stations 9 and 12a near Seavey Island and station 27 in Little Bay. Additionally, nickel concentrations were highest at station 27, but were elevated in the Back Channel as well (Fig. 9).

Correlations with Eelgrass Leaf and Root Accumulation

Correlation of leaf tissue and root tissue metal concentrations was made to investigate possible translocation of some metals within the plant. Correlation can imply but not prove translocation; experimental evidence for each metal would be required for proof of translocation. Our correlation examined whether elevated metal concentrations found in eelgrass leaves were directly associated with high concentrations in eelgrass roots, likely resulting from translocation from the belowground tissue, or if eelgrass leaves were bioaccumulating metals independently of eelgrass roots. For six heavy metals (silver, cadmium, chromium, copper, manganese and zinc) the leaf and root portions of the same plants showed significant correlations ($P< 0.01$), suggesting translocation between the roots, where the higher tissue metal concentrations were found, and the leaves, where concentrations of these metals were relatively lower although elevated above background (Table 5). Other metals, including lead and mercury, did not show root-leaf correlations which suggests either these metals are not translocated or that the transfer process is more complex.

Comparison of metal concentrations in the leaf tissue of eelgrass with metal levels measured in sediments (Johnston et al. 1993) from the same stations indicates a significant correlation between mercury in leaf tissue and mercury in the sediments but no significant correlation for any other contaminant (Table 6). Although lead, chromium and copper all showed evidence of bioaccumulation in eelgrass leaf tissue, their leaf tissue concentrations did not

significantly correlate with the respective metal concentrations in the sediment. The significant correlation for mercury in eelgrass leaves suggests that eelgrass leaves may be a good sentinel accumulator for sediment mercury.

Correlation analysis of eelgrass root metal concentrations and sediment metal concentrations measured at the same stations showed significant relationships for lead, chromium and copper (Table 7). For these metals, the amount of biologically available metal, as indicated by eelgrass root tissue concentrations, is directly related to the total concentration of metal in the sediment. Although mercury in eelgrass leaf tissue was highly correlated with sediment mercury levels (Table 6), mercury in root tissue did not show a similar correlation (Table 7); nor did root tissue correlate with leaf tissue mercury (Table 5). The correlation between leaf and sediment mercury likely results from the mobility of mercury in marine systems (Windom 1972, Furness and Rainbow 1990) and the possibility of rapid mercury translocation from roots to leaves (Kabata-Pendias and Pendias 1992). Overall, the data suggests that eelgrass root tissue is an excellent sentinel accumulator of lead, chromium, and copper, but not of mercury.

For other metals that show significant elevations above the ETC but do not correlate with total sediment metal concentrations, root tissue metal concentrations may be indicating the amount of bioavailable contaminant within these sediments, as seen in highly elevated seagrass tissue metal concentrations from areas of high contaminant exposure (Table 1).

Correlations were also examined between metals in eelgrass leaf and root tissues and metals in blue mussel tissue (Tables 8 and 9). Positive correlations were found between metal concentration in eelgrass leaf and root tissues and mussel tissues for samples collected from the same stations, but the only significant correlation was for manganese (Mn) in root and mussel tissue (Table 9). The eelgrass and mussel samples were not always collected at the same time or in the same season, which likely contributes to the lack of significant correlation. The greater

correlation between roots and mussels suggests that the sediments are the main source of metals for these two tissues.

Contaminant Effects

Preliminary analysis of eelgrass biomass, morphology, and stature measurements in conjunction with our results on tissue contaminant levels demonstrated only one significant negative correlation. Rhizome length, a measure of the extent of below-ground root/rhizome development, was significantly correlated with the log of root (root plus rhizome) tissue lead concentration for the June 8, 1992 sampling (r^2= 0.912, Fig. 14). That is, increasing concentrations of lead in the roots of eelgrass were associated with significant reduction in rhizome length in this case. Although the mechanism for a relationship between rhizome development and tissue lead concentration is unknown, these results suggest a possible inhibition of eelgrass growth as a result of lead contamination in the sediments. More data on metal concentrations in eelgrass root tissue and on rhizome length measurements remains to be analyzed.

Discussion

Our study confirms what has been found in other studies around the world: that seagrasses, including eelgrass, *Zostera marina*, function as bioaccumulators of metal contaminants from sediments and the water column. This present study shows background concentrations of metals in eelgrass tissue at the reference sites (stations 1, 22, and 23) to be within the range of background metal concentrations elsewhere (Table 1), confirming that seagrasses in the Piscataqua-York region bioaccumulate background metal concentrations predictably, and indicating that eelgrass may be used as a sentinel accumulator. Additionally, data from eelgrass root and leaf tissue clearly shows elevated concentrations of metal contaminants at specific sites within Portsmouth Harbor and the upper Great Bay Estuary (Table 1). Again, these elevated levels are within the range of levels found in heavily contaminated estuaries worldwide.

Elevated concentrations of nearly all the heavy metals studied were found around the Portsmouth Naval Shipyard. Specific metals were high at some locations and not at others, but for the most part metals were at lower concentrations away from Seavey Island than at stations near the Island. Within the Great Bay Estuary, elevated metal concentrations were also found at a location in Little Bay.

Lead concentrations were elevated above the ETC for leaves and for roots at station 9 just south of the DRMO storage yard where lead contamination has been identified in the PNS onshore study (McLaren/Hart 1992). The elevated levels of lead in leaf tissue suggest a water-borne input of lead at this location. Lead was also elevated in eelgrass leaves and roots at station 19 in the Back Channel near the seeps originating close to the Jamaica Island landfill (Johnston et al 1994). The lead levels in the leaves again suggest a water-borne source (or sources) originating closer to station 19 than to stations 3 or 18 (Figs. 4 and 9). However, root lead levels were also high at stations 18 and 19, indicating a sediment-associated source affecting both stations.

The concentration of lead in eelgrass root tissue was significantly correlated ($P=0.02$) with sediment lead levels (Table 7). In general, the amount of lead in eelgrass roots suggests elevated sediment contamination throughout most of Portsmouth Harbor (Fig 9). The only station with lead at or below the ETC (aside from the reference stations) was station 11 in Little Harbor. These findings suggest multiple sources of particle-associated lead to the estuary, one at the mouth of Little Bay and two around Seavey Island (in the Back Channel and in the vicinity of station 9). The lead source in Little Bay may originate from Flagstone Brook and Railroad Ditch which drain five hazardous material landfill sites on the former Pease Air Force Base (Short 1992). The reduction in lead concentrations of eelgrass tissue upstream and downstream from station 27 suggests that, whatever the source, it does not impact the entire Estuary. The DRMO may account for the elevated level of lead in roots at station 9, since station 9 represents a depositional environment close to the DRMO. The source of lead to the Back Channel behind Seavey Island is as yet unknown.

Eelgrass root samples from the Back Channel adjacent to Seavey Island (stations 18 and 19) show a sediment signal of several elevated metal contaminants in addition to lead, including chromium and copper (Fig. 9). Mercury and zinc also showed elevated concentrations in root tissue, although these did not correlate significantly with levels of these same two metals in the sediments. Chromium at both stations was elevated in leaf tissue (Fig. 4). The concentrations of chromium and copper in eelgrass root tissue each significantly correlated to sediment chromium and copper levels (Table 7) as well as to leaf tissue chromium and copper levels (Table 5). Elevated chromium concentrations in eelgrass roots likely reflect the known historic contamination of the Great Bay Estuary with chromium (Short 1992). The elevated copper concentrations in the roots of eelgrass at stations 18 and 19 indicate copper contamination in the Back Channel sediments. Copper was also highly elevated in eelgrass leaves at station 12a near Dry Dock 2, suggesting a source of copper near that station.

Mercury concentrations in eelgrass root tissue were found to be consistently greater at areas around the Shipyard than at sites away from the Shipyard. The lack of correlation between mercury in the roots and mercury in the sediments suggests that the bioavailability of sediment mercury differs from that of other metals. Additionally, the highly significant correlation between mercury in eelgrass leaves and mercury in the sediments ($P=0.01$, Table 6) suggests that eelgrass leaf tissue is a particularly good indicator of mercury contamination. To understand the complex nature of mercury biogeochemistry, investigations of mercury bioaccumulation and volatility are needed, especially considering the potential for mercury to be biomagnified in marine environments (Ward 1989).

Several other metals showed elevated concentrations in eelgrass tissue at various stations around the Shipyard, although the sources of these metals are unknown (Figs. 4 and 9). Of these, the extremely high concentration of silver at station 12a and the high silver concentration at station

17, and the elevated levels of arsenic at stations 9, 12a and 17, are of concern and require further investigation to determine the contaminant source.

Comparison of heavy metal concentrations measured in both eelgrass root and mussel tissue revealed consistent areas of concern around the Shipyard (Table 10). Despite the lack of significant correlation between eelgrass root and mussel tissue (Short and Hoven 1995) for any metal except manganese, a handful of stations consistently showed elevated metal concentrations of concern in both eelgrass and mussel analyses. Using the highest level of designation for eelgrass (ETC) and for mussels (very high), stations in the Back Channel behind Seavey Island (station 18) and in the Dry Dock area (station 12a) showed problems for lead, mercury and chromium. Station 9 off Sullivan Point and station 2 at the Coast Guard Station showed elevated lead, while station 19 in the Back Channel and station 3 in Clark Cove showed elevated mercury and chromium in both eelgrass and mussels. Additionally, as mentioned above, other stations throughout the estuary demonstrated high chromium concentrations.

Examination of eelgrass for possible detrimental effects from exposure to elevated contaminant levels showed only one plant characteristic having a significant response. Eelgrass rhizome length (the measure of below-ground root system development) decreased with increasing lead concentration. The reduction in rhizome length with the log of lead concentration ($r^2 = 0.912$) was significant at $P=0.01$. This potential response of eelgrass to increasing lead in root tissue suggests a possible indication of contamination stress on the plant. However, additional analysis relating rhizome length and other eelgrass characteristics to metal concentrations is needed to support this finding.

Conclusion

Both eelgrass leaves and roots are useful as sentinel accumulators for evaluating the distribution of metal contaminants in Portsmouth Harbor and the Great Bay Estuary. Elevated metal contaminants were identified from water-borne sources around PNS using eelgrass leaf tissues. Additionally, contaminant sources in the sediment are indicated both in the upper Estuary and at multiple sites near Seavey Island from eelgrass root tissue assessment. Correlation analysis of eelgrass leaf and root tissue metal contents suggests that eelgrass plants translocate some metals (copper, chromium, cadmium, nickel, zinc, silver) from the roots to the leaves, a finding confirmed by some earlier studies (Lyngby and Brix 1989, Carter and Eriksen 1992). However, other metals (eg. lead, mercury) do not show significant correlation between root tissue and leaf tissue, suggesting roots and leaves may independently accumulate some metals from the sediment and water column, respectively. Previous studies of seagrasses as bioaccumulators of heavy metals have suggested that seagrasses are better able to indicate sources of some metal contaminants than measurements of those metals in mussels (Lyngby and Blix 1984) or in the sediments themselves (Ward 1989). While the present study cannot confirm these suggestions, it does clearly demonstrate that eelgrass in Portsmouth Harbor is a good indicator of the presence and magnitude of heavy metal contamination.

Eelgrass tissue analysis and assessment of plant status indicate problems of metal contamination which may be originating from Seavey Island. High levels of lead, mercury and copper in both eelgrass leaf and root tissue point out areas of specific concern near the Portsmouth Naval Shipyard. The absence of eelgrass from Clark Cove and the negative correlation between root development and tissue lead concentrations suggest potential impacts of contaminants directly on eelgrass populations, an area where additional research is needed.

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Table 1. Heavy metals measured in seagrasses from around the world showing background levels and the bioaccumulation of metal contaminants. Metal concentrations in µg/g dry wt. Leaf and root (root plus rhizome) tissue concentrations are shown separately.

Metals (ppm)	Pb	Zn	Cd	Cu	Cr	Ni	Hg	Source
Background Metal Concentrations								
Indonesian seagrass (9 spp leaf)	1.7-2.8	15-24	0.2-0.7	3.9-7.0				Nienhuis 1986
Texas seagrass (5 spp. leaf)		22	0.7	4.9				Pulich et al. 1976
Posidonia australis (leaf)	2.1	33						Maher 1986a,b
Posidonia australis (leaf)	0.2	10						Ward 1989
Zostera marina (leaf)	1.1	78	0.6	4.8				Brix et al. 1983a,b
Zostera marina (leaf)	1.0±0.2	46±9	1.3±0.6	9.2±2.9	0.9±0.3	1.3±0.3	0.01±0.00	This Study (stations 1&23)
Zostera marina (root)	0.3	55	0.3	3.3				Brix et al. 1983a,b
Zostera marina (root)	2.6±1.3	24±5	0.4±0.2	6.7±2.6	3.4±1.4	1.5±0.6	0.03±0.03	This Study (stations 1&23)
Bioaccumulation								
Seagrasses from heavily contaminated estuaries								
Posidonia australis (leaf)	379	4241	541					Ward 1989
Posidonia sp. (leaf)	402	1050	11.0	47				Tiller et al.1989
Zostera sp. (leaf)	1800	1480		1350				Stenner & Nickless 1975
Zostera muelleri (leaf)				10.6				Harris et al. 1979
Zostera marina (leaf)	32	91	2.3	39.8	13.6	17.5		Güven et al. 1993
Posidonia oceanica (leaf)				45.8	13.1	60.9		Catsiki & Panayotidis 1993
Cymodocea nodosa (leaf)				43.7	7.1	49.4		Catsiki & Panayotidis 1993
Posidonia sp. (root)	230	430	4.1	32				Tiller et al.1989
Posidonia oceanica (root)				58.6	25	45.2		Catsiki & Panayotidis 1993
Cymodocea nodosa (root)				11.1	8.8	9.0		Catsiki & Panayotidis 1993
Portsmouth Harbor								
Zostera marina (leaf)	5.1	126	3.0	62.6	5.7	6.6	0.03	This Study (maximum values)
Zostera marina (root)	24.0	93	1.0	36.7	42.8	10.0	0.08	This Study (maximum values)

Table 2. Heavy metals measured in seagrasses from around the world show species used as sentinel accumulators. Metal concentrations in µg/g dry wt. are shown .

Metal	Pb	Zn	Cd	Cu	Cr	Ni	Hg	Source
Sentinel Accumulator								
Zostera muelleri (leaf)				up to 1600				Carter & Eriksen 1992
Zostera marina (leaf)	17			~ 12.3				Lyngby & Brix 1982

Table 3: Analysis of variance (ANOVA) for metals in eelgrass tissue from stations in Portsmouth Harbor, the upper Great Bay Estuary and York River. Data include all samples collected from Phase I and monitoring. Bold indicates the predominating effect of the three tested, significant at P≤0.01. The effect of drying in aluminum foil precludes the use of these samples in the analysis of some metals. Month effects reflect sampling date. Station effects show differences between sites.

LEAVES (n=61)	**Sample Drying Effect**		**Month Effect**		**Station Effect**	
Metal	F	P	F	P	F	P
Al	9.290	**0.0043**	0.777	0.3838	1.400	0.1807
As	7.520	**0.0095**	0.389	0.5370	1.519	0.1297
Cr	7.650	**0.0089**	0.432	0.5151	1.960	0.0360
Fe	11.840	**0.0015**	1.008	0.3221	1.870	0.0465
Hg	26.380	**0.0001**	0.018	0.8934	8.880	0.0001
Ni	7.570	**0.0092**	0.665	0.4201	1.547	0.1198
Pb	12.020	**0.0014**	1.341	0.2545	1.214	0.2959
Mn	6.980	0.0121	1.574	0.2178	103.000	**0.0001**
Zn	2.179	0.1486	0.930	0.3412	3.640	**0.0006**
Ag	0.117	0.7348	1.005	0.3229	0.496	0.9573
Cd	0.257	0.6156	0.651	0.4251	1.415	0.1736
Cu	0.072	0.7902	0.014	0.9069	1.175	0.3263

ROOTS (n=59)	**Sample Drying Effect**		**Month Effect**		**Station Effect**	
Metal	F	P	F	P	F	P
Zn	13.397	**0.0009**	0.976	0.3307	2.426	0.012
Al	3.078	0.0892	0.005	0.9451	4.364	**0.0001**
Cd	4.898	0.0344	1.685	0.2038	3.130	**0.0018**
Cr	0.012	0.9125	0.853	0.3629	3.679	**0.0005**
Fe	0.023	0.8796	0.622	0.4363	4.005	**0.0002**
Hg	5.185	0.0298	0.048	0.8286	4.553	**0.0001**
Mn	0.001	0.9741	0.000	0.9955	10.315	**0.0001**
Ag	0.299	0.5887	0.889	0.3505	1.040	0.4518
As	0.206	0.6533	1.616	0.2131	2.186	0.0224
Cu	2.176	0.1503	0.050	0.8243	1.498	0.1478
Ni	0.094	0.7614	0.581	0.4515	2.290	0.0169
Pb	0.008	0.9294	0.494	0.4874	1.513	0.1419

Table 4: Eelgrass tissue cut-off (ETC) concentrations, ppm (µg/g dry wt.), for Portsmouth Harbor/ Great Bay Estuary study of metal contaminant distribution. Background levels for the Piscataqua region based on data from stations 1 and 23 for leaves (n=7) and stations 1, 22, and 23 for roots (n=11).

Metals (ppm)	Al	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
Leaf Tissue												
Background mean	70	0.29	1.05	1.27	0.86	9.17	169	0.010	152	1.26	1.01	45.9
sd	27	0.22	0.21	0.60	0.26	2.90	43	0.003	88	0.26	0.19	9.4
ETC =x+3sd	150	0.94	1.67	3.08	1.63	17.86	296	0.019	417	2.05	1.57	74.0
Root Tissue												
Background mean	568	0.27	1.57	0.44	3.43	6.72	1471	0.016	22	1.53	2.63	24.3
sd	305	0.17	0.75	0.18	1.41	2.58	380	0.005	11	0.64	1.31	5.1
ETC =x+3sd	1484	0.78	3.81	0.99	7.66	14.48	2610	0.032	54	3.44	6.55	39.8

Table 5. Correlation matrix for heavy metals in Portsmouth Harbor eelgrass leaves (e) and roots (r) collected from the same plants. Significance level for alpha{0.01}=0.47 (enlarged bold), box indicates metals having significant correlation between eelgrass leaves and roots. Data analyzed represent samples where eelgrass leaves and roots were not dried in aluminum foil, n=29.

	rAg	rAs	rCd	rCr	rCu	rFe	rHg	rMn	rNi	rPb	rZn	eAg	eAs	eCd	eCr	eCu	eFe	eHg	eMn	eNi	ePb	eZn
rAg	1.00																					
rAs	0.36	1.00																				
rCd	-0.03	0.26	1.00																			
rCr	0.27	**0.49**	0.22	1.00																		
rCu	**0.49**	0.11	-0.18	0.35	1.00																	
rFe	0.42	**0.89**	0.19	**0.74**	0.32	1.00																
rHg	0.45	**0.60**	0.09	**0.84**	**0.51**	**0.79**	1.00															
rMn	0.16	0.33	**0.47**	0.39	0.19	0.26	0.36	1.00														
rNi	0.38	**0.57**	0.33	**0.85**	**0.47**	**0.73**	**0.84**	**0.61**	1.00													
rPb	0.32	**0.60**	0.20	**0.72**	**0.61**	**0.72**	**0.73**	**0.52**	**0.74**	1.00												
rZn	**0.50**	0.39	0.33	**0.67**	**0.54**	**0.55**	**0.75**	**0.59**	**0.78**	**0.65**	1.00											
eAg	**0.57**	0.03	0.12	0.25	0.44	0.10	0.44	**0.53**	0.46	0.26	**0.71**	1.00										
eAs	-0.05	0.02	0.06	0.18	-0.11	0.06	0.12	0.18	0.25	0.01	0.27	0.17	1.00									
eCd	-0.19	0.24	**0.55**	0.09	-0.30	0.08	0.00	0.25	0.12	0.04	0.04	-0.19	0.09	1.00								
eCr	0.17	-0.03	0.11	**0.51**	0.30	0.19	**0.56**	0.28	**0.52**	0.27	**0.70**	**0.54**	0.46	0.07	1.00							
eCu	**0.50**	-0.16	-0.29	-0.05	**0.52**	-0.10	-0.01	0.09	-0.02	0.05	0.16	0.37	-0.30	-0.38	0.05	1.00						
eFe	0.35	0.01	0.07	0.34	0.30	0.22	0.46	0.26	0.44	0.22	**0.67**	**0.64**	0.44	-0.11	**0.83**	0.08	1.00					
eHg	0.29	0.02	0.15	0.29	0.24	0.12	0.35	0.37	0.40	0.24	**0.61**	**0.60**	0.27	0.15	**0.72**	0.09	**0.80**	1.00				
eMn	-0.17	0.34	**0.62**	0.27	-0.15	0.22	0.06	**0.60**	0.33	0.32	0.18	-0.08	0.17	0.63	0.12	-0.31	-0.05	0.14	1.00			
eNi	-0.13	0.04	-0.02	0.15	-0.10	0.04	0.19	0.16	0.11	-0.01	0.22	0.11	0.13	0.05	0.30	-0.08	0.12	0.05	0.09	1.00		
ePb	0.26	0.15	0.18	**0.47**	0.29	0.31	**0.55**	0.29	**0.47**	0.40	**0.69**	**0.52**	0.30	0.13	**0.87**	0.04	**0.82**	**0.84**	0.19	0.26	1.00	
eZn	0.46	0.26	0.44	0.41	0.13	0.30	0.44	0.56	0.53	0.27	**0.72**	**0.70**	0.32	0.25	**0.55**	0.08	0.56	**0.66**	0.33	0.22	**0.60**	1.00

Table 6. Correlation matrix for heavy metals in Portsmouth Harbor sediment and eelgrass leaves(e) collected from the same stations but at different times of year. Significance level for alpha{0.01}=0.96 (enlarged bold), box indicates metals having significant correlation between eelgrass leaves and sediment. Data analyzed represent samples having the maximum lead levels of replicate samples for eelgrass and sediment, n=5.

Metal	AG	AS	CD	CR	CU	PB	HG	NI	ZN
eAG	0.31	-0.22	0.13	0.21	0.37	-0.27	-0.71	-0.25	0.07
eAS	0.02	0.73	-0.24	0.27	-0.05	0.21	0.26	0.16	0.25
eCD	-0.12	0.52	-0.75	-0.02	-0.54	-0.39	0.24	-0.27	-0.23
eCR	0.72	0.58	0.54	0.83	0.88	0.82	0.44	**0.97**	**0.97**
eCU	0.45	0.12	0.56	0.44	0.62	0.68	0.47	0.81	0.63
ePB	0.72	0.31	0.64	0.75	0.93	0.73	0.25	0.87	0.89
eHG	0.56	0.56	-0.30	0.49	0.07	0.15	**0.96**	0.67	0.39
eNI	0.83	0.51	0.27	0.87	0.84	0.33	-0.05	0.55	0.80
eZN	-0.07	-0.07	-0.76	-0.20	-0.54	-0.91	-0.32	-0.70	-0.55

Table 7. Correlation matrix for heavy metals in Portsmouth Harbor sediment and eelgrass roots (r) collected from the same stations but at different times of year. Significance level for alpha{0.02}=0.63 (enlarged bold); box indicates metals having significant correlation between eelgrass roots and sediment. Data analyzed represent samples having the maximum lead levels of replicate samples for eelgrass and sediment, n=13.

Metal	AG	AS	CD	CR	CU	PB	HG	NI	ZN
rAG	0.44	0.54	0.13	0.48	0.37	0.37	0.20	0.39	0.40
rAS	0.27	0.42	0.09	0.21	0.12	0.35	0.17	0.26	0.17
rCD	-0.13	-0.02	-0.45	-0.31	-0.29	-0.27	-0.16	-0.23	-0.32
rCR	**0.80**	**0.80**	0.15	**0.67**	0.50	0.57	0.32	**0.67**	0.56
rCU	0.12	0.41	0.88	0.28	**0.66**	**0.73**	0.04	0.58	0.48
rPB	0.51	0.59	0.55	0.42	0.53	**0.64**	0.09	0.58	0.45
rHG	0.50	0.17	0.08	0.25	0.07	-0.07	-0.19	0.10	0.08
rNI	0.20	0.46	0.27	0.15	0.26	0.46	0.04	0.38	0.19
rZN	0.17	0.72	0.46	0.39	**0.66**	0.61	0.11	**0.68**	0.53

Table 8. Correlation matrix for heavy metals in Portsmouth Harbor eelgrass leaves (e) and mussels (m) collected from the same stations but at different times of year. Significance level for alpha{0.02}=0.93 (enlarged bold). No metal was found to have a significant correlations between eelgrass leaf tissue and mussel tissue samples. Data analyzed represent mussel samples having the maximum lead levels and replicate samples for eelgrass leaves in September, n=5.

Metal	eAg	eAs	eCd	eCr	eCu	eFe	eHg	eMn	eNi	ePb	eZn
mAg	0.06	-0.19	-0.65	0.34	0.39	0.20	-0.46	-0.60	0.07	0.42	-0.70
mAs	0.11	-0.20	-0.74	0.77	0.74	0.61	-0.04	-0.88	0.46	0.84	-0.82
mCd	-0.19	0.29	-0.30	0.92	0.67	0.91	0.26	-0.61	0.52	0.81	-0.82
mCr	-0.03	-0.16	-0.66	0.42	0.48	0.29	-0.35	-0.63	0.07	0.48	-0.78
mCu	-0.51	-0.39	-0.54	-0.05	0.40	-0.09	-0.10	-0.31	-0.63	0.02	-0.66
mFe	-0.20	-0.71	-0.79	-0.03	0.49	-0.18	-0.13	-0.53	-0.46	0.17	-0.57
mHg	-0.09	-0.56	-0.71	0.69	**0.94**	0.56	0.66	-0.84	0.30	0.82	-0.59
mMn	-0.61	-0.47	-0.25	-0.43	0.17	-0.40	0.15	0.07	-0.90	-0.35	-0.23
mNi	-0.33	-0.40	-0.75	0.33	0.66	0.23	-0.05	-0.64	-0.25	0.42	-0.86
mPb	0.05	0.56	-0.02	0.57	0.14	0.58	-0.29	-0.25	0.48	0.42	-0.50
mZn	-0.51	0.63	0.92	-0.48	-0.59	-0.21	0.20	0.92	-0.47	-0.73	0.47

Table 9. Correlation matrix for heavy metals in Portsmouth Harbor eelgrass roots (r) and mussels (m) collected from the same stations but at different times of year. Significance level for alpha{0.02}=0.66 (enlarged bold); box indicates metals having significant correlation between eelgrass roots and mussels. Data analyzed represent mussel samples having the maximum lead levels and replicate samples for eelgrass roots in September, n=12.

Metal	rAg	rAs	rCd	rCr	rCu	rFe	rHg	rMn	rNi	rPb	rZn
mAg	0.06	0.21	-0.53	0.13	**0.82**	0.41	0.09	-0.05	0.27	**0.66**	0.23
mAs	0.42	0.26	-0.05	0.37	**0.68**	0.46	0.47	0.01	0.29	0.60	0.44
mCd	0.21	0.02	-0.21	0.29	**0.74**	0.40	-0.10	0.24	0.37	0.46	**0.68**
mCr	0.30	0.29	-0.37	0.31	**0.71**	0.50	0.27	0.07	0.29	0.60	0.35
mCu	0.14	0.55	-0.21	0.18	0.63	0.49	-0.08	0.33	0.56	0.56	0.31
mFe	0.31	0.47	-0.20	0.35	0.56	0.46	0.46	0.17	0.39	0.61	0.30
mHg	0.34	0.32	0.34	0.58	0.40	0.47	0.57	0.12	0.38	0.52	0.53
mMn	0.49	**0.70**	0.37	0.65	0.46	**0.68**	0.35	**0.68**	**0.82**	0.65	0.62
mNi	0.16	0.43	-0.28	0.38	**0.79**	0.62	0.22	0.18	0.50	**0.74**	0.45
mPb	0.54	0.16	-0.38	0.40	0.57	0.33	0.40	0.23	0.24	0.46	0.42
mZn	**0.71**	0.44	0.06	0.64	0.12	0.49	0.00	0.58	0.43	0.25	0.47

Table 10. Stations having heavy metal concentrations elevated in both eelgrass roots and mussels (Short and Hoven 1995). To be included, stations must exceed the ETC for eelgrass and the very high designation for mussels. Stations are listed in order of decreasing metal concentration for eelgrass root tissue.

METAL	EELGRASS	MUSSELS
Pb	18	18
	9	9
	12a	12a
	2	2
Hg	19	19
	18	18
	12a	12a
	3	3
Cr	12a	12a
	19	19
	18	18
	17	17
	24	24
	16	16
	9	9
	3	3

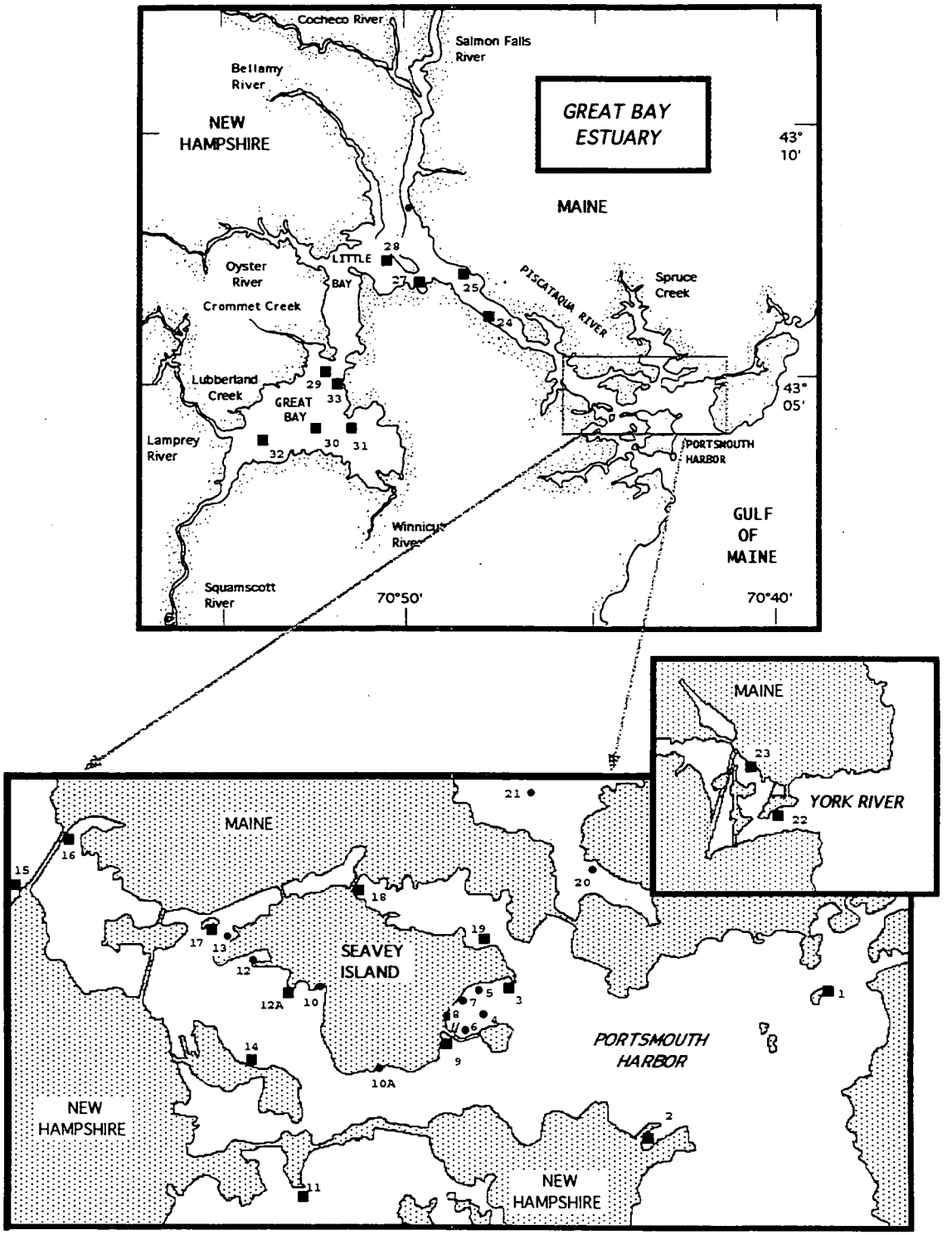

Figure 1. Map of PNS Ecological Risk Assessment sampling stations where eelgrass was sampled (■) and where no eelgrass was present (•) in the Great Bay Estuary, Portsmouth Harbor, and York River, ME.

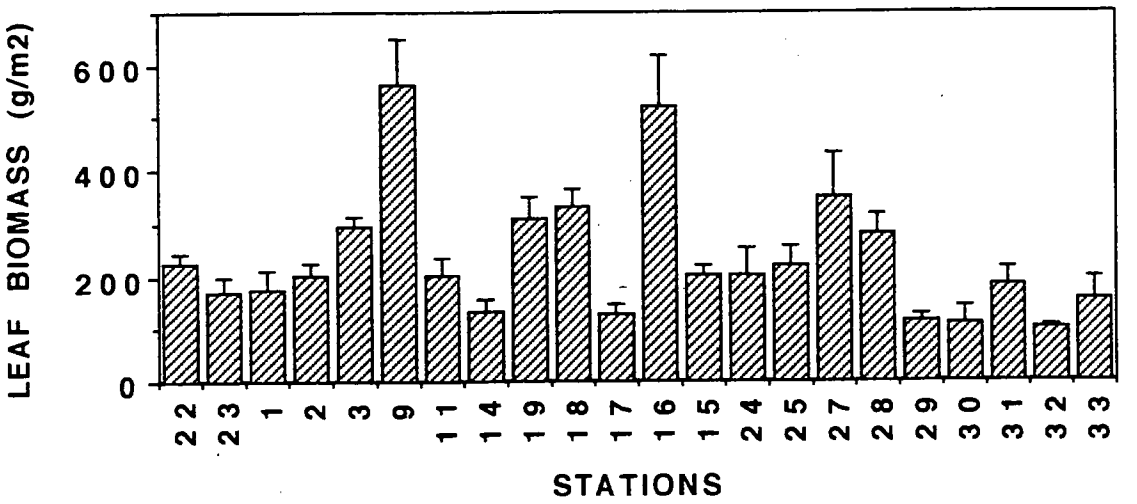

Figure 2: Eelgrass leaf biomass for September 1991 in York River (stations 22 and 23), Portsmouth Harbor (stations 1-19) and upper Great Bay Estuary (station 24-32).

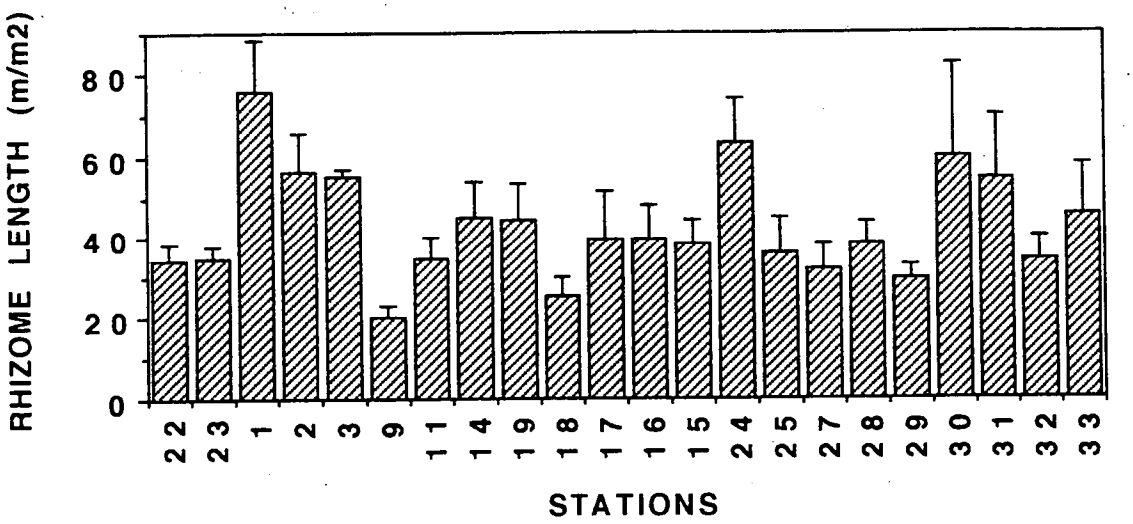

Figure 3: Eelgrass rhizome length for September 1991 in York River (stations 22 and 23), Portsmouth Harbor (stations 1-19) and upper Great Bay Estuary (station 24-32).

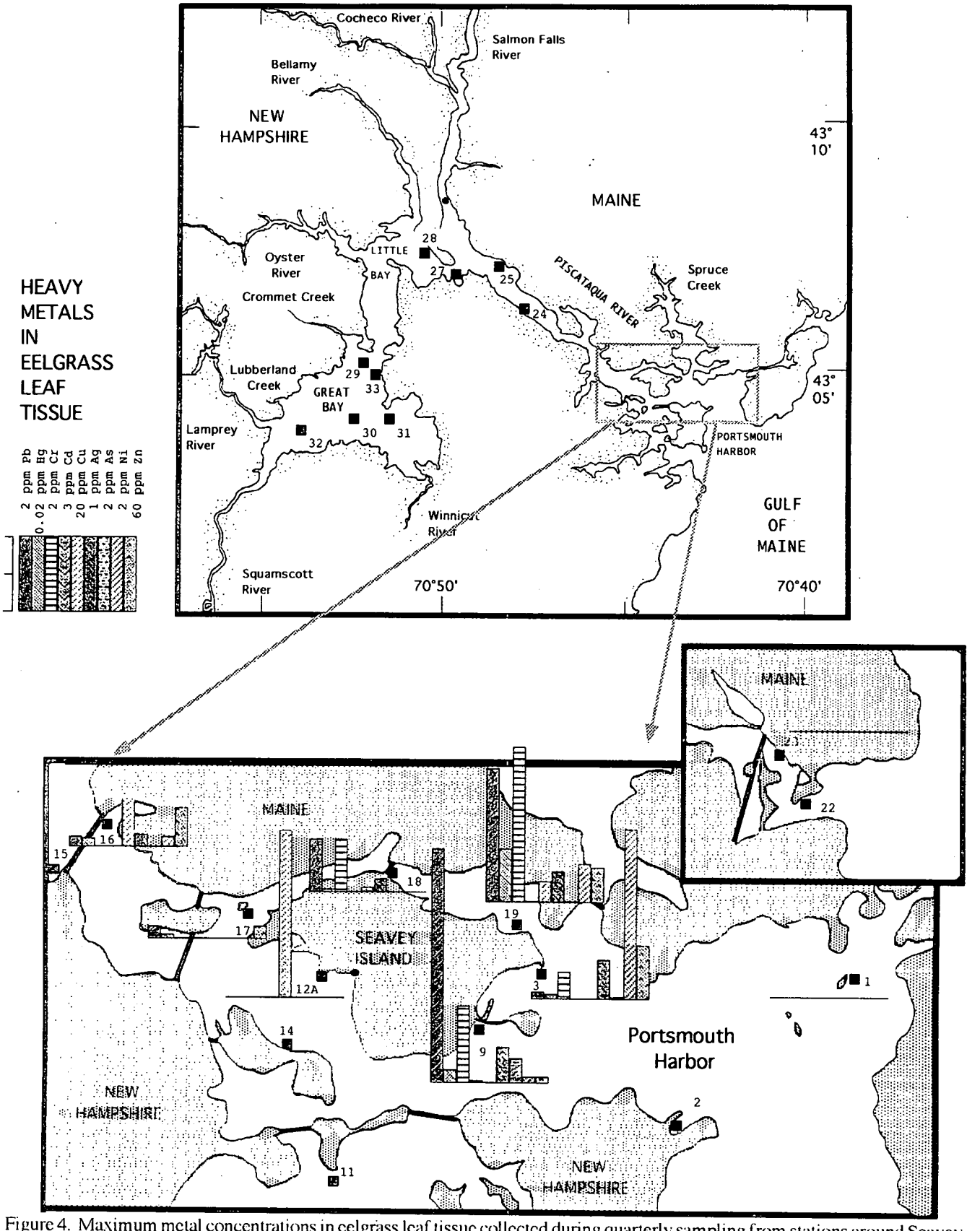

Figure 4. Maximum metal concentrations in eelgrass leaf tissue collected during quarterly sampling from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), and at York River (Sta. 23). Data is expressed as the concentration above the Eelgrass Tissue Cut-off (ETC), which is derived from the average metal concentrations in eelgrass tissue at reference stations (Sta. 1 and 23) plus 3 standard deviations. The relative bar height for each metal is adjusted to place all metals into a comparative range (see scale for the comparative concentration for each metal).

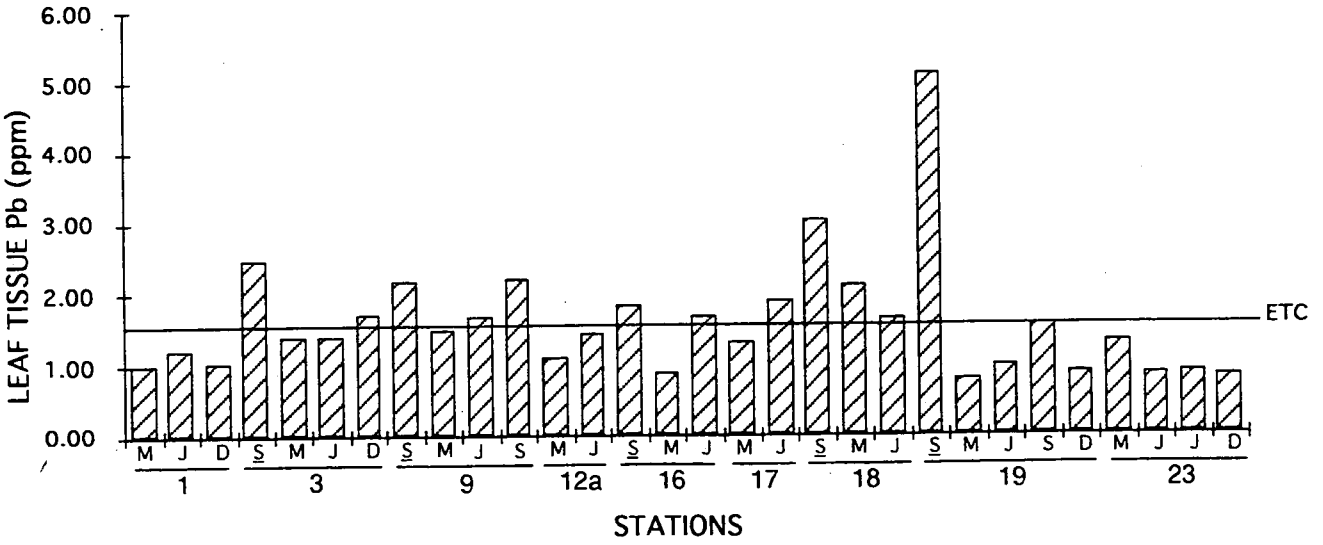

Figure 5. Lead (Pb) concentrations in eelgrass leaf tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

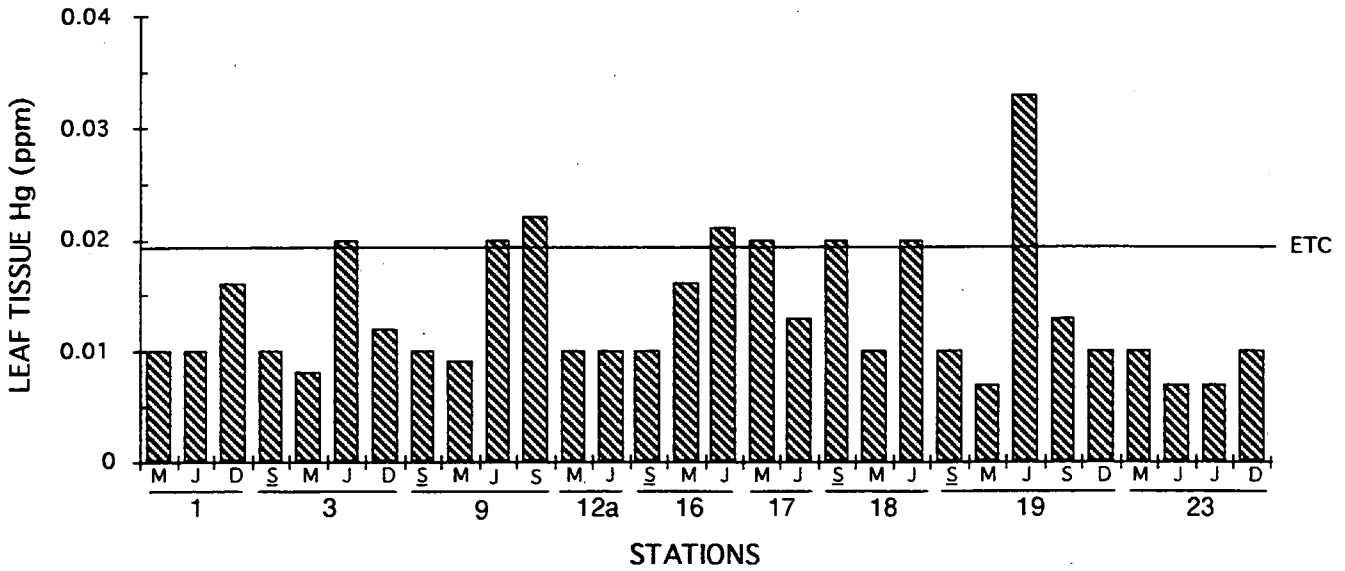

Figure 6. Mercury (Hg) concentrations in eelgrass leaf tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

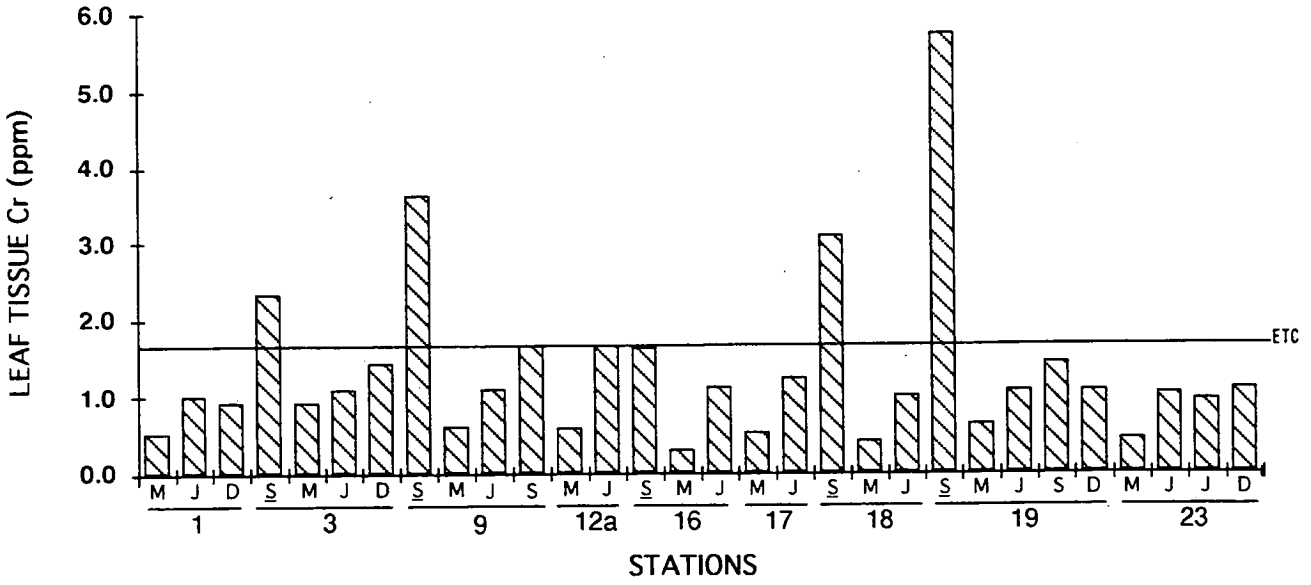

Figure 7. Chromium (Cr) concentrations in eelgrass leaf tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

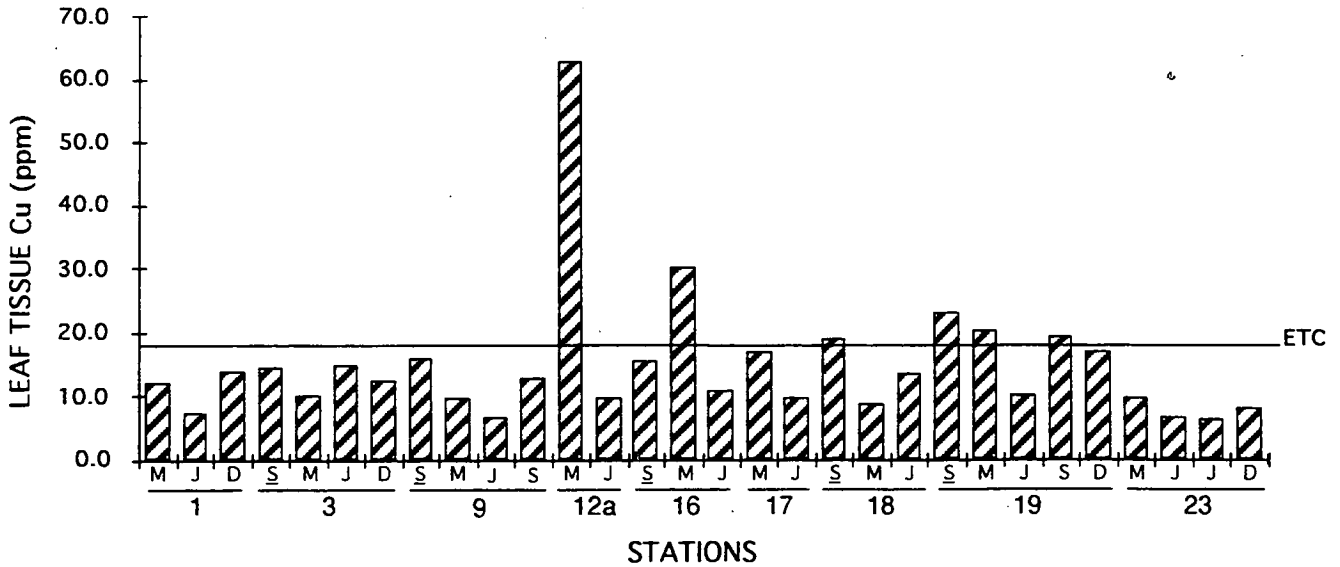

Figure 8. Copper (Cu) concentrations in eelgrass leaf tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

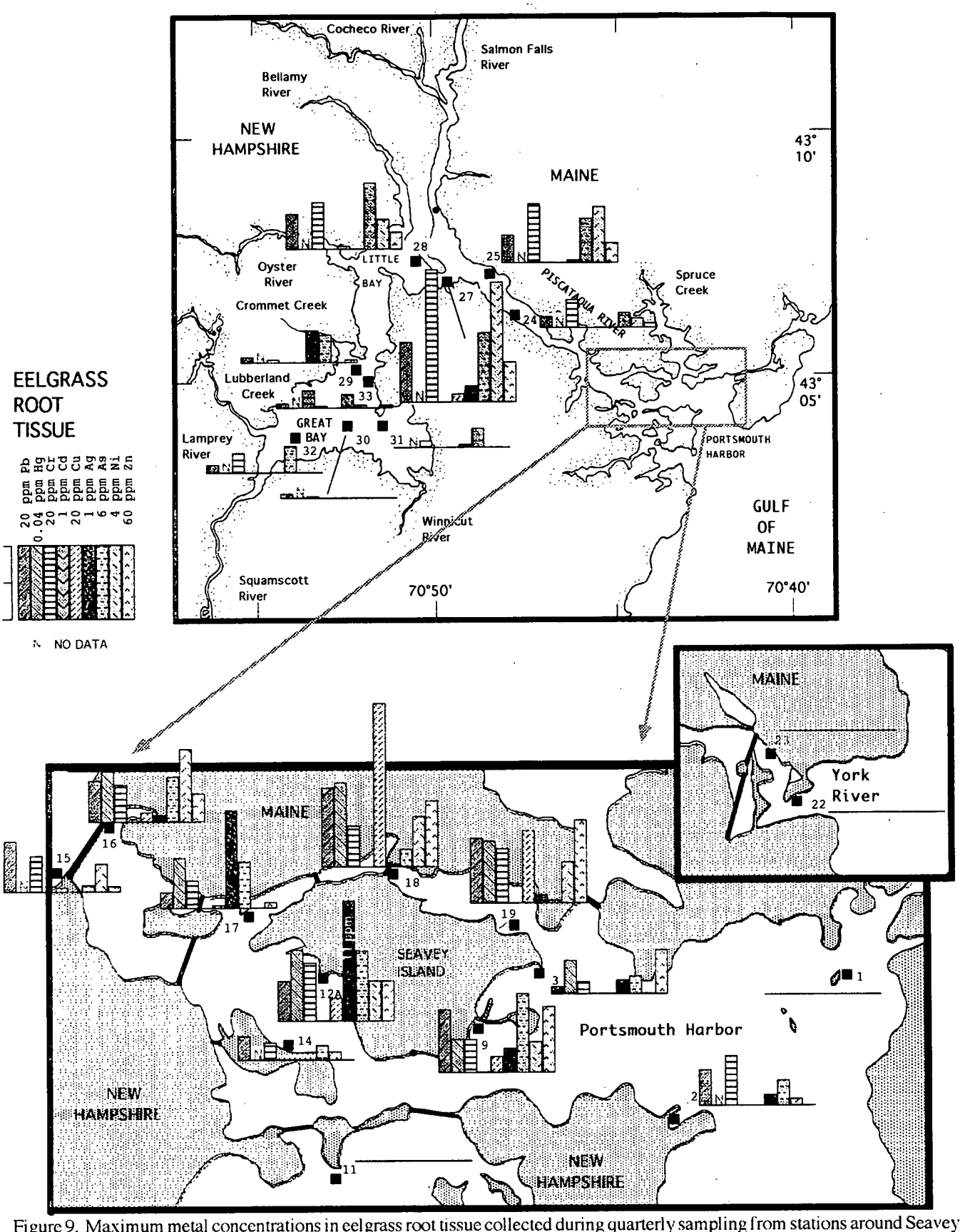

Figure 9. Maximum metal concentrations in eelgrass root tissue collected during quarterly sampling from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1, 2, 11, 14-16), up the Great Bay Estuary (Sta. 24-33), and at York River (Sta. 22 and 23). Data is expressed as the concentration above the Eelgrass Tissue Cut-off (ETC), which is derived from the average metal concentrations in eelgrass tissue at reference stations (Sta. 1, 22 and 23) plus 3 standard deviations. The relative bar height for each metal is adjusted to place all metals into a comparative range (see scale for the comparative concentration for each metal).

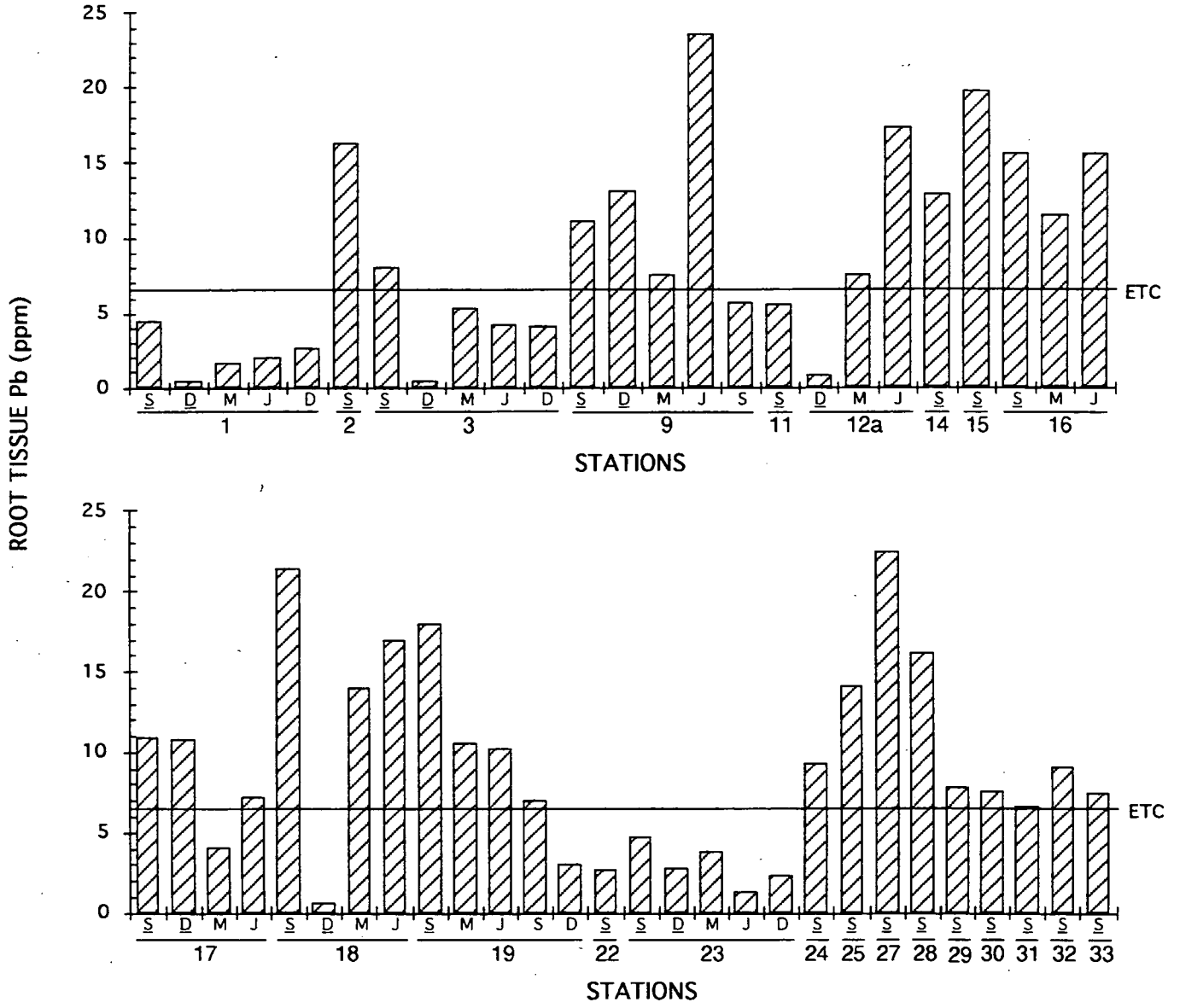

Figure 10. Lead (Pb) concentrations in eelgrass root tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), up the Great Bay Estuary (Sta. 24-33), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

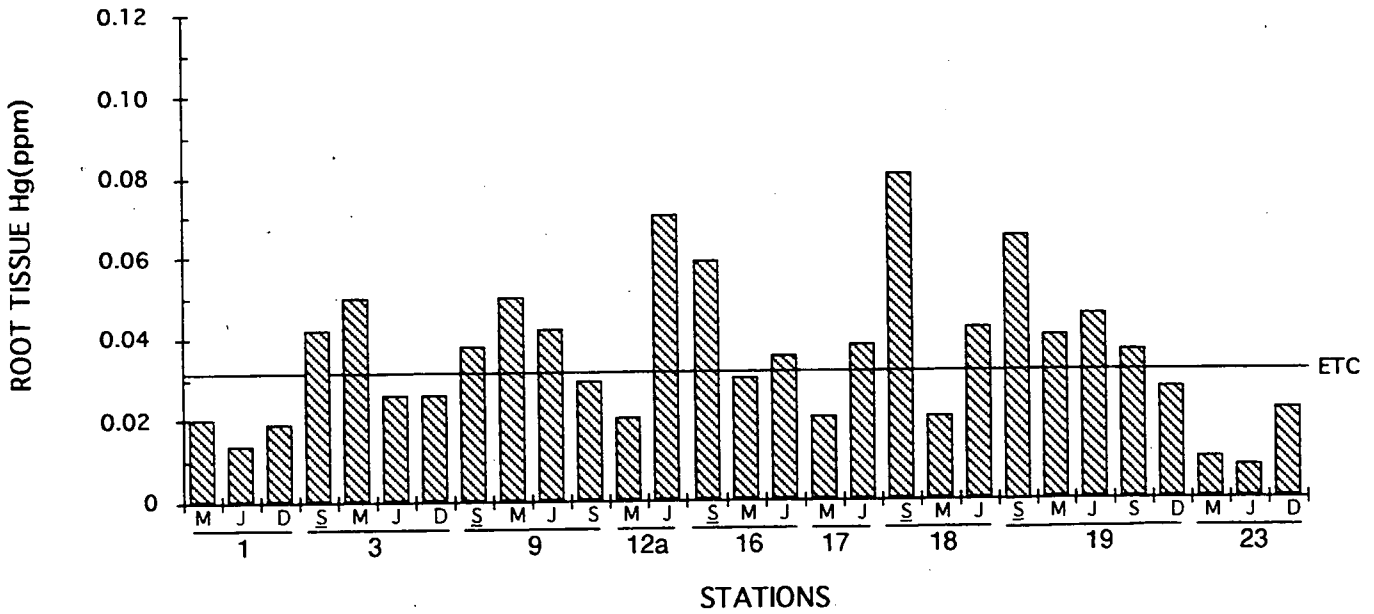

Figure 11. Mercury (Hg) concentrations in eelgrass root tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Only samples processed as wet tissue are presented since the drying process did significantly affect mercury analysis (Table 3). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

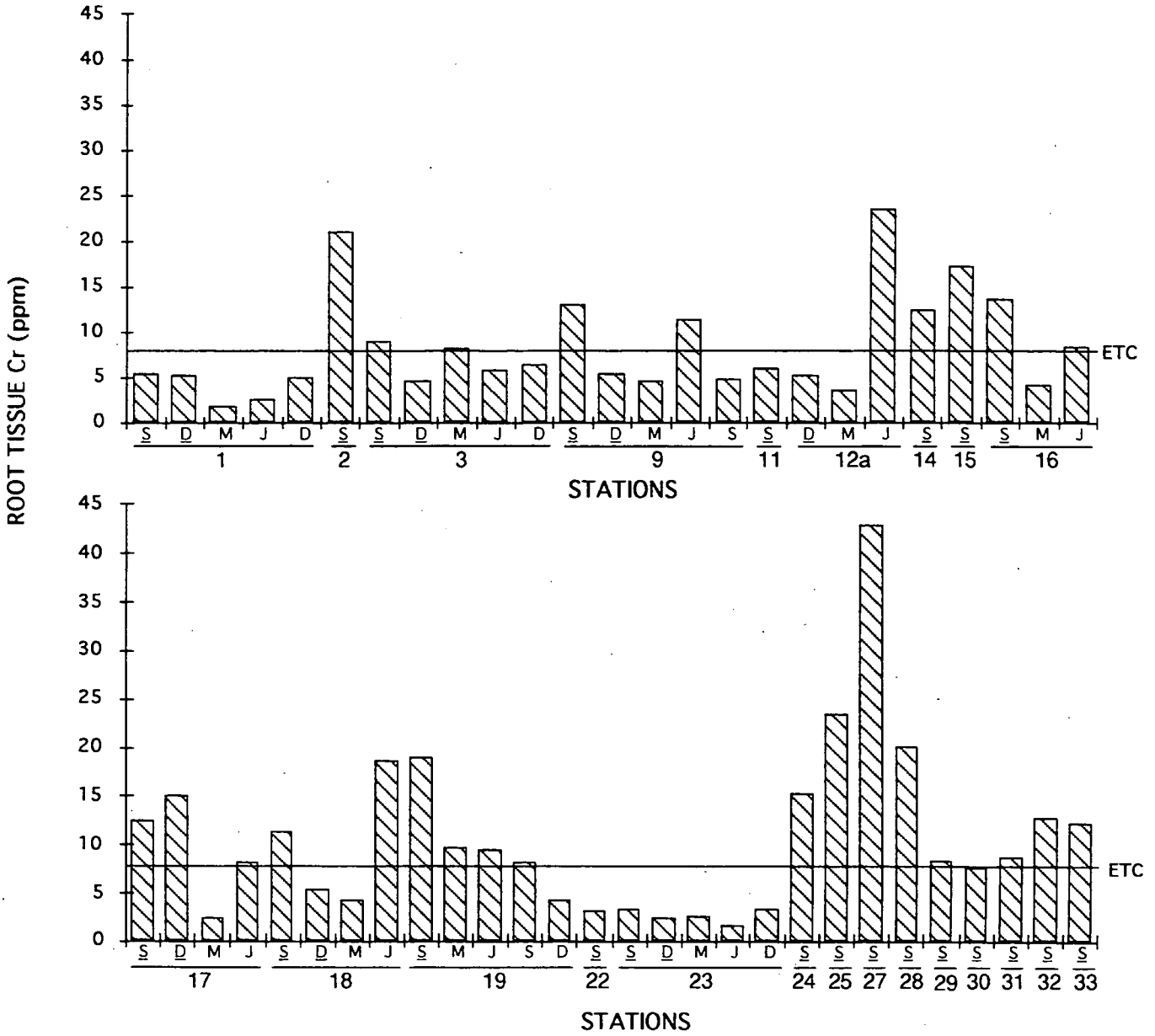

Figure 12. Chromium (Cr) concentrations in eelgrass root tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), up the Great Bay Estuary (Sta. 24-33), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

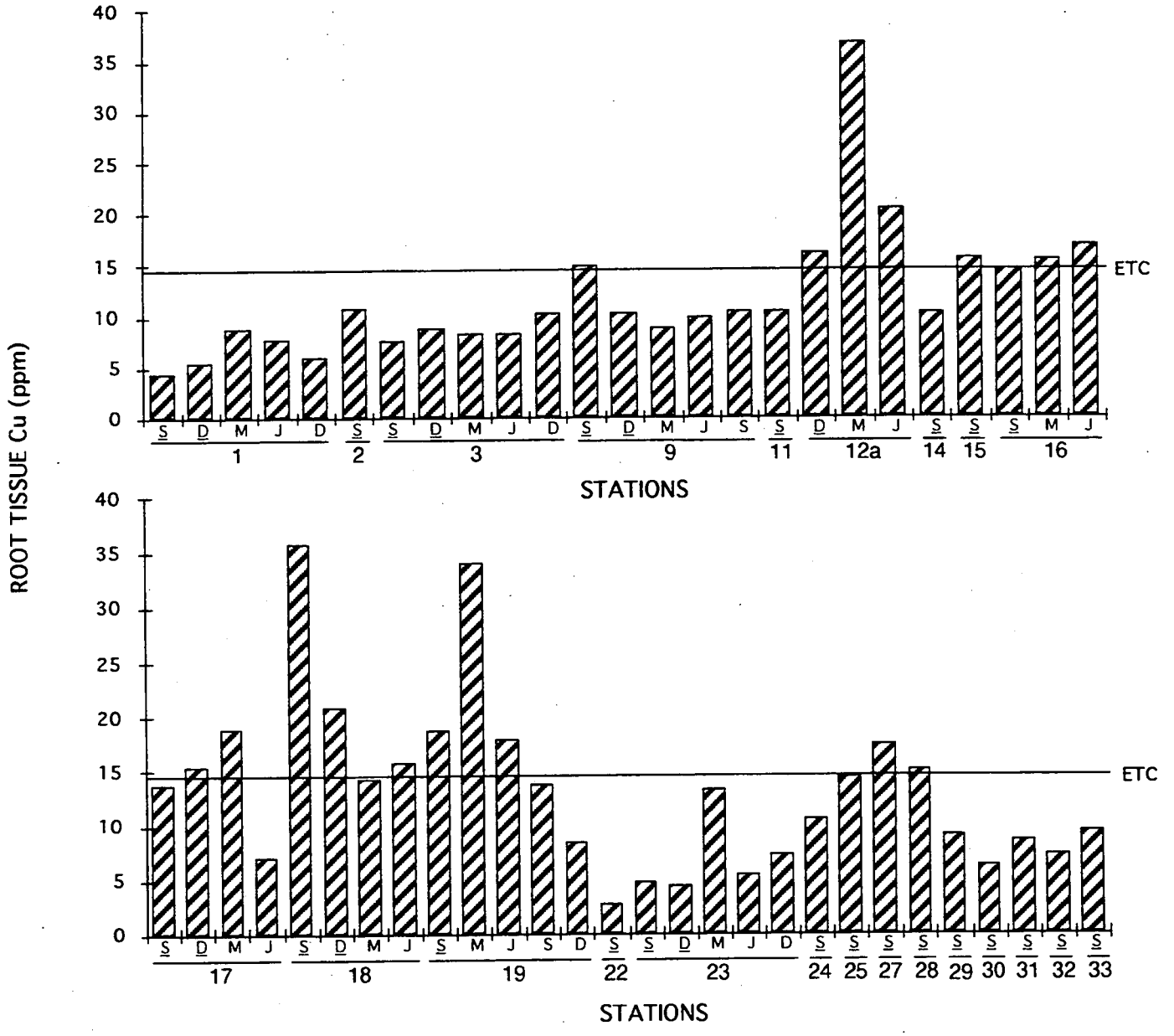

Figure 13. Copper (Cu) concentrations in eelgrass root tissue (ppm) collected from stations around Seavey Island (Sta. 3, 9, 12a, 17, 18, and 19), elsewhere in Portsmouth Harbor (Sta. 1 and 16), up the Great Bay Estuary (Sta. 24-33), and at York River (Sta. 23). Multiple samples for each station result from quarterly sampling (September (S) and December (D) 1991 and March (M), June (J), September (S), and December (D) 1992). Eelgrass Tissue Cut-off (ETC) is an index of comparison for metal concentrations in eelgrass tissue (see Table 4).

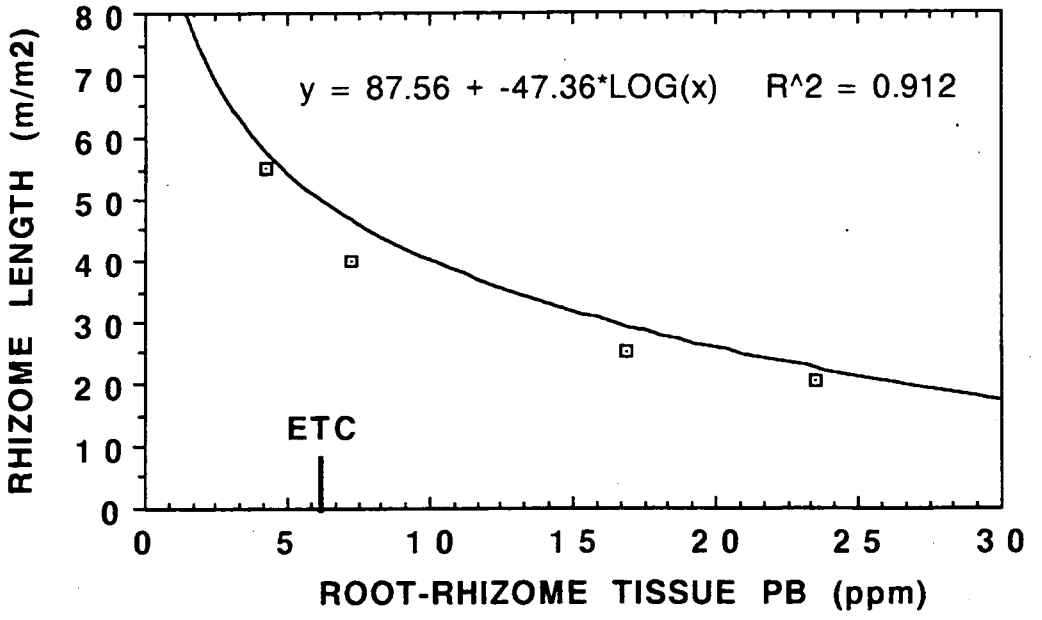

Figure 14. Eelgrass rhizome length, a measure of belowground vegetative expansion, as a function of the lead concentration in root-rhizome tissue. A significant regression was obtained using the log of root tissue lead concentrations ($P<0.01$).

Appendix I. Eelgrass leaf tissue samples showing metal concentrations (µg/g). Samples marked DRY = 0 were dried in aluminum foil before analysis. Underlining indicates data for metals that has been excluded from analysis due to this error.

					Al	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
MINIMUM DETECTION LIMIT					34	0.3	1.2	0.44	0.4	2.7	26	0.006	1.8	0.54	0.09	27
MAXIMUN OBSERVED VALUE					8380	6.9	7.4	3.10	38.8	62.6	12100	0.17	5360.0	11.00	34.60	126
MONTH	EPA ID	DATE	STA	DRY	Al	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
9	110045	910920	1	0	337	0.33	0.91	0.73	2.5	5.3	634	0.03	109.0	1.10	3.70	37.3
12	110360	911217	1	0	432	0.26	0.06	0.62	3.0	12.1	934	0.03	77.6	2.50	0.48	72
9	110046	910920	2	0	2970	0.79	5.9	0.92	20.5	11.7	6610	0.03	166.0	4.70	15.90	47.9
12	110364	911217	3	0	209	0.99	0.05	1.10	1.6	17.4	654	0.05	56.9	1.70	0.29	53.6
9	110043	910917	9	0	4280	0.6	7.1	1.70	25.2	13.4	7180	0.07	524.0	6.40	20.50	71.9
12	110365	911217	9	0	280	1.3	0.68	0.51	1.7	15.6	614	0.02	140.0	2.10	5.50	67.3
9	110047	910924	11	0	3670	0.81	5.1	1.20	22.3	15.5	6480	0.03	519.0	6.90	18.60	72.9
12	110361	911217	12.5	0	164	0.8	0.04	1.70	1.3	28.4	526	0.03	121.0	3.40	0.34	62
9	110052	911002	14	0	1200	0.86	2.6	0.88	6.6	9.9	2110	0.01	262.0	2.90	8.50	46.5
9	110049	910924	15	0	5060	1.1	0.43	0.84	26.9	19.1	9110	0.08	494.0	7.90	24.20	78.6
9	110048	910924	16	0	524	0.33	3.4	1.30	2.7	7.2	987	0.02	546.0	1.80	5.10	61.3
9	110051	910930	17	0	2030	0.79	3.1	0.87	10.7	18.3	3910	0.08	332.0	3.80	13.50	71
12	110367	911217	17	0	332	1.4	3.5	0.46	2.4	17.1	295	0.04	53.6	1.50	4.80	46.4
9	110050	910930	18	0	8380	0.59	7.4	1.20	38.8	21.4	12100	0.08	787.0	11.00	34.60	94.9
12	110362	911217	18	0	391	6.9	0.03	0.79	2.2	21.3	1160	0.03	155.0	1.90	0.64	58.9
12	110363	911217	19	0	702	0.68	1.1	0.91	4.7	16.5	2220	0.04	52.4	2.80	0.54	62.4
9	110040	910913	22	0	319	0.56	0.69	1.10	1.1	3.5	562	0.02	138.0	1.00	1.20	27
9	110041	910913	23	0	2510	0.61	3.5	1.80	5.8	8.5	3870	0.01	255.0	5.30	7.00	43.7
12	110368	911218	23	0	113	0.1	3.4	0.44	0.6	5.2	243	0.02	69.4	1.20	1.50	38.8
9	110034	910912	24	0	1350	0.62	1.9	0.48	8.0	12.3	2390	0.05	413.0	3.20	7.10	102
9	110035	910912	25	0	3370	1.1	4.1	1.10	19.9	17.5	5280	0.08	630.0	7.70	14.50	87.9
9	110036	910912	27	0	5130	0.51	6.2	1.70	29.6	18.6	8900	0.08	974.0	7.20	14.90	106
9	110033	910911	28	0	2790	0.81	3.3	0.44	14.3	12.0	4280	0.04	1110.0	4.20	17.30	114
9	110037	911002	29	0	998	0.71	5	1.60	5.7	11.7	3760	0.04	3140.0	5.20	12.20	99.5
9	110031	910909	30	0	635	0.52	3.3	1.40	3.9	6.7	3290	0.17	2610.0	3.50	5.40	76.4
9	110032	910909	31	0	903	0.3	5.7	1.80	6.6	8.5	3890	0.04	5360.0	6.10	13.70	95.4
9	110030	910909	32	0	1230	0.37	3.2	1.40	7.9	9.3	2750	0.14	3220.0	6.30	12.90	82.6
9	110038	911002	33	0	764	0.47	3.2	3.10	4.1	8.3	1390	0.04	330.0	7.70	10.10	126
9	110053	911022	12.5	0	345	0.16	1.7	1.70	2.2	16.4	620	0.05	173.0	1.70	7.90	60.5
9	110044	910917	19	0	1150	0.53	3.8	1.60	7.4	12.5	2480	0.04	314.0	2.90	13.40	67.4
9	110042	910916	3	0	858	0.45	1.1	2.60	4.5	12.0	1220	0.04	317.0	3.00	6.60	80.1
3	110376	920317	1	1	37.5	0.6	0.68	0.53	0.5	12.1	117	0.01	75.3	1.70	1.00	51.4
6	110601	920608	1	1	56.5	0.28	1.2	0.89	1.0	7.3	133	0.01	182.0	1.32	1.21	38.4
12	110618	921201	1	1	52	0.53	1.2	0.89	0.9	13.9	204	0.016	22.5	0.83	1.04	51.5
3	110371	920310	3	1	120	0.61	0.8	1.00	0.9	9.9	517	0.01	71.0	2.10	1.40	56.5
6	110606	920616	3	1	42.3	0.28	1.2	0.94	1.1	14.9	135	0.008	90.6	6.61	1.40	66.9
9	110042	910915	3	1	256	1.46	1.2	1.31	2.3	14.3	495	0.02	173.0	2.26	2.47	126
12	110619	921201	3	1	119	0.7	1.7	1.69	1.4	12.3	299	0.012	65.1	1.40	1.72	63.5
3	110375	920310	9	1	62	1	1.4	1.20	0.6	9.8	337	0.01	60.3	1.80	1.50	79.2
6	110603	920610	9	1	91.5	0.43	1.2	1.35	1.1	6.6	187	0.009	250.0	1.30	1.68	59.3
9	110043	910915	9	1	481	1.4	2.3	0.91	3.6	15.9	951	0.02	230.0	2.19	2.15	107
9	110614	920901	9	1	151	0.473	1.1	3.01	1.6	12.7	317	0.022	265.0	1.57	2.19	97.2
3	110374	920310	12.5	1	24.1	0.77	0.72	0.25	0.6	62.6	232	0.01	14.2	0.37	1.10	60.2
6	110602	920610	12.5	1	112	0.38	1.2	1.69	1.6	9.9	198	0.01	212.0	2.01	1.44	59.8
3	110369	920310	16	1	9.1	1.1	0.62	1.30	0.3	30.2	58.3	0.01	201.0	2.30	0.89	65.5
6	110600	920608	16	1	74.4	0.76	1.2	2.40	1.1	10.9	179	0.016	483.0	2.07	1.67	89.4
9	110048	910915	16	1	165	0.93	1.1	1.31	1.6	15.6	426	0.021	214.0	1.27	1.83	106
3	110370	920310	17	1	32.6	0.72	1.2	0.57	0.5	17.0	396	0.02	55.1	1.10	1.30	60.5
6	110604	920611	17	1	104	0.31	1.2	1.25	1.2	9.6	255	0.013	249.0	1.36	1.88	83.3
3	110372	920310	18	1	54	0.53	1.1	0.99	0.4	8.8	590	0.02	111.0	0.63	2.10	66.8
6	110605	920611	18	1	66.9	0.24	1.2	1.32	1.0	13.6	188	0.01	269.0	1.65	1.63	64.4
9	110050	910915	18	1	427	1.11	1.2	0.78	3.1	19.0	626	0.02	96.4	1.95	3.02	68
3	110373	920310	19	1	58.1	1.1	0.66	0.73	0.7	20.1	265	0.01	14.3	1.10	0.80	73
6	110607	920616	19	1	73.2	0.28	1.2	0.74	1.1	10.0	199	0.007	81.7	0.95	0.97	66.7
9	110044	910915	19	1	584	1.35	1.2	1.28	5.7	23.0	1160	0.033	148.0	3.08	5.08	101
9	110613	920901	19	1	63.8	0.625	1.2	0.87	1.4	19.2	311	0.013	62.7	1.19	1.55	58.8
12	110620	921202	19	1	57.7	0.49	1.2	1.08	1.1	17.0	188	0.01	25.6	1.52	0.89	59.4
3	110377	920326	23	1	66.3	0.36	0.89	1.90	0.5	9.8	137	0.01	265.0	1.10	1.30	60.6
6	110608	920619	23	1	78.5	0.06	1.2	1.20	1.0	6.5	177	0.007	214.0	1.30	0.85	35.8
6	110608	920619	23	1	79.8	0.06	1.2	1.22	1.0	6.5	177	0.007	211.0	1.30	0.87	36.5
12	110621	921202	23	1	120	0.15	1	2.24	1.1	8.1	236	0.01	95.7	1.27	0.82	47.1

Appendix II. Eelgrass root tissue samples showing metal concentrations (µg/g). Samples marked DRY = 0 were dried in aluminumfoil before analysis. Underlining indicates data for metals that has been excluded from analysis due to this error.

					Al	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
MINIMUM DETECTION LIMIT					34	0.3	1.2	0.44	0.4	2.7	26	0.006	1.8	0.54	0.09	27
MAXIMUN OBSERVED VALUE					6860	11.6	10.9	1	42.8	36.7	12900	0.28	439	10	24	92.8
MONTH	EPA ID	DATE	STA	DRY	Al	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
9	110045	910920	1	0	755	0.47	1.5	0.34	5.3	4.5	1620	0.11	20.5	1.5	4.5	15.1
12	110360	911217	1	0	763	0.13	0.05	0.26	5.1	5.4	2050	0.03	15.7	1.5	0.41	25.3
9	110046	910920	2	0	2310	0.92	6.1	0.43	21	10.8	6270	0.1	55.7	3.8	16.3	39.5
9	110042	910916	3	0	1060	0.3	2.5	0.39	6.7	4.4	2200	0.11	33.6	1.9	8.3	20.1
12	110364	911217	3	0	494	0.36	0.05	0.5	4.5	8.8	1910	0.13	14.5	1.9	0.43	28.8
9	110043	910917	9	0	2870	0.47	4.8	0.55	16.5	10.9	5030	0.04	215	4.3	15.6	46
12	110365	911217	9	0	711	0.39	5.3	0.35	5.4	10.3	4250	0.03	78.4	2.4	13	48
9	110047	910924	11	0	868	0.77	3.6	0.42	5.9	10.4	2480	0.05	56.9	2.7	5.6	30.9
12	110361	911217	12.5	0	705	11.6	0.04	0.26	5.1	16.2	2430	0.03	46.3	2.3	0.75	32.9
9	110052	911002	14	0	1890	0.77	5.1	0.77	12.3	10.3	4380	0.14	46.4	3.9	12.8	34
9	110049	910924	15	0	2850	0.53	4.4	0.49	17.1	15.6	6540	0.09	95.3	4.9	19.7	43.4
9	110048	910924	16	0	1480	0.67	6.7	0.39	9.4	11.8	4010	0.04	120	3.9	13.4	37.5
9	110051	910930	17	0	1800	0.69	4.2	0.46	12.5	13.7	5280	0.04	47.9	3.3	10.9	45.1
12	110367	911217	17	0	1080	2.1	5.8	0.28	15	15.4	4140	0.07	31.9	2.6	10.8	41.9
9	110050	910930	18	0	1660	0.57	4.2	0.37	8.4	13.1	4340	0.06	78.7	3.3	14.7	39.3
12	110362	911217	18	0	759	0.41	0.05	0.23	5.4	20.8	4420	0.04	67.2	2.4	0.66	49.8
9	110044	910917	19	0	3110	0.44	3.2	0.53	21.8	16.9	5540	0.16	76.2	5.6	24	48.4
12	110363	911217	19	0	1440	0.61	4.1	0.42	12.5	13.3	4310	0.03	30.4	3.4	1	39.7
9	110040	910913	22	0	985	0.42	1.5	0.47	3.1	2.8	1730	0.01	26.6	2.2	2.7	17.3
9	110041	910913	23	0	1180	0.2	2.1	0.57	3.4	4.8	2060	0.02	44.2	3	4.7	18.3
12	110368	911218	23	0	682	0.05	3	0.32	2.4	4.5	1500	0.02	19.3	2	2.8	20.5
9	110034	910912	24	0	2030	0.21	5.1	0.53	15.2	10.6	4640	0.11	58.3	4	9.3	43.2
9	110035	910912	25	0	4070	0.81	7.8	0.62	23.5	14.4	8330	0.02	166	6.5	14.1	55.8
9	110036	910912	27	0	6860	1	9.9	0.57	42.8	17.3	12900	0.08	175	10	22.4	71.7
9	110033	910911	28	0	2800	0.72	9.7	0.34	20.2	15.1	9010	0.08	123	5.1	16.2	53.6
9	110037	911002	29	0	1240	1.2	6.3	0.82	8.4	9.1	6450	0.06	121	2.9	7.8	42.2
9	110031	910909	30	0	1160	0.46	2.5	0.33	7.7	6.2	3520	0.28	335	3.2	7.6	26
9	110032	910909	31	0	931	0.82	5.5	0.57	8.8	8.6	5540	0.04	439	2.3	6.7	31.4
9	110030	910909	32	0	1560	0.49	6.2	0.41	12.9	7.2	6860	0.2	124	3.1	9.1	34.2
9	110038	911002	33	0	1620	0.96	4.1	1	12.2	9.4	5800	0.05	143	2.9	7.5	41.6
3	110376	920317	1	1	213	0.63	1.5	0.3	1.7	8.8	1280	0.02	15.4	1.1	1.7	24.2
6	110623	920608	1	1	156	0.33	1.2	0.46	2.53	7.81	988	0.014	24.6	0.93	2.03	31.2
12	110640	921201	1	1	565	0.3	1.6	0.34	5.06	5.95	1360	0.018	12.1	1.54	2.74	25
12	110640	921201	1	1	580	0.25	1.2	0.32	4.82	6.1	1450	0.02	16.6	1.37	2.57	24.9
3	110371	920310	3	1	938	0.8	4.8	0.54	8.1	8.3	5940	0.05	26.5	2.9	5.4	36.1
6	110628	920616	3	1	407	0.32	3.4	0.42	5.68	8.36	3060	0.026	28.3	1.48	4.21	48.2
9	110042	910915	3	1	970	0.959	1.3	0.692	11.1	10.9	2260	0.042	95.6	3.34	7.73	75
12	110641	921201	3	1		0.54	1.7	0.59	6.27	10.3	2100	0.026	26.2	2.3	4.17	38.6
3	110375	920310	9	1	744	1.1	10.9	0.5	4.5	8.9	6200	0.05	57.6	2.5	7.6	64.5
6	110625	920610	9	1	1561	0.55	8	0.64	11.3	9.95	6620	0.042	76.8	3.81	23.5	63.7
9	110043	910915	9	1	1406	0.68	2.2	0.562	9.54	18.8	3370	0.036	185	5.08	6.7	92.8
9	110636	920901	9	1	464	0.705	5.2	0.732	4.84	10.5	4230	0.029	62.5	2.34	5.71	70.4
3	110374	920310	12.5	1	384	1.4	2.9	0.3	3.5	36.7	3210	0.02	20.6	1.5	7.6	45.3
6	110624	920610	12.5	1	2694	0.8	10	0.59	23.3	20.4	9720	0.07	77.5	7.15	17.2	72
3	110369	920310	16	1	635	0.3	3.8	0.65	4.2	15.5	2290	0.03	240	2.6	11.5	61.5
6	110622	920608	16	1	833	0.87	6.7	0.82	8.37	16.8	4200	0.035	193	3.58	15.5	51.2
9	110048	910915	16	1	2035	0.859	7.8	0.775	17.6	17.1	6400	0.059	196	7.35	17.5	84.9
3	110370	920310	17	1	203	0.7	2.3	0.3	2.4	18.9	2450	0.02	18.6	1.5	4.1	40.7
6	110626	920611	17	1	602	0.29	7.9	0.51	8.27	7.16	6770	0.038	31.9	2.49	7.31	35.6
3	110372	920310	18	1	713	0.69	5.3	0.65	4.3	14.2	4900	0.02	79.2	1.8	14	54.8
6	110627	920611	18	1		0.38	4.2	0.47	18.6	15.8	5100	0.042	87.6	2.85	16.9	54.9
9	110050	910915	18	1	1608	0.747	5.1	0.347	14.2	58.3	6260	0.081	97.1	6.14	28.2	92.4
3	110373	920310	19	1	627	0.89	3.5	0.63	9.7	34	4600	0.04	20.2	3	10.6	75.9
6	110629	920616	19	1		0.66	4	0.62	9.54	17.9	5180	0.045	27.5	2.67	10.2	60.8
9	110044	910915	19	1	1740	0.768	3.4	0.633	16.1	20.4	4690	0.065	89.6	4.42	11.9	107
9	110635	920901	19	1		0.7	2.3	0.531	8.26	13.8	2580	0.036	29.3	1.8	7.05	47.2
12	110642	921202	19	1	359	0.38	1.4	0.54	4.36	8.5	1670	0.027	6.2	1.29	3.01	31.9
3	110377	920326	23	1	742	0.18	2.3	0.81	2.5	13.3	1750	0.01	40.2	2.1	3.8	32.7
6	110630	920619	23	1	247	0.08	1.2	0.72	1.61	5.52	921	0.008	20.3	0.85	1.33	27.2
12	110643	921202	23	1	361	0.3	1.6	0.35	3.28	7.27	1200	0.022	10.8	0.98	2.32	23.3