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DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-76-5

A HYDROPONIC STUDY OF HEAVY METAL UPTAKE BY SELECTED MARSH PLANT SPECIES

by

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Final Report

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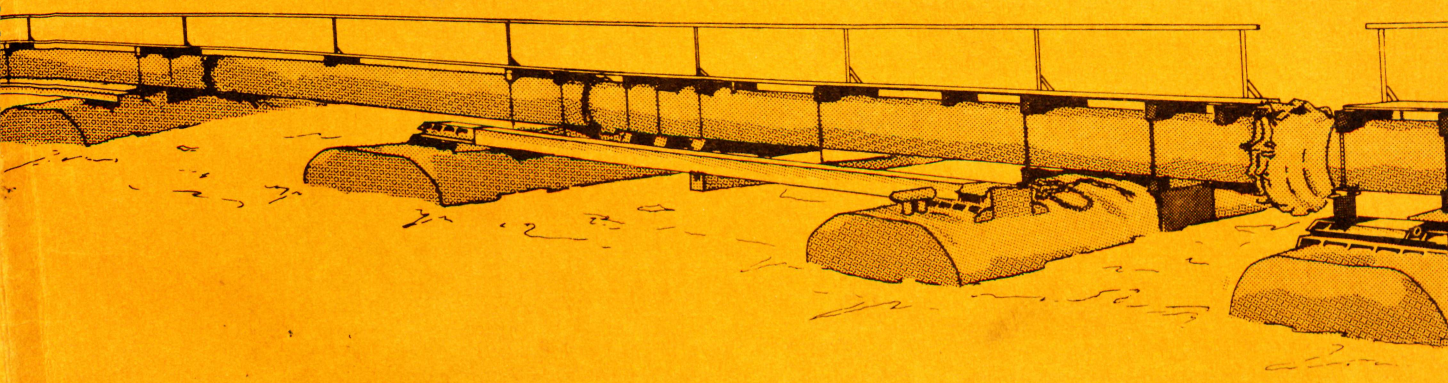

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SUBJECT: Transmittal of Technical Report D-76-5

TO: All Report Recipients

1. The technical report transmitted herewith represents the results of a greenhouse hydroponic study on the uptake of heavy metals by selected marsh plants. The study is one of 19 research efforts initiated to date in Task 4A (Marsh Development) of the Corps of Engineers' Dredged Material Research Program (DMRP). This task, included as part of the Habitat Development Project of the DMRP, is concerned with the evaluation of the methodologies for developing marsh and wildlife habitats with dredged material.

2. The development of marsh and wildlife habitat with dredged material in an environmentally acceptable manner is one of the major goals in the DMRP. Movement of contaminants such as heavy metals via plant uptake is a possible mechanism for heavy metal mobilization from dredged material used in marsh development. The potential for biomagnification of heavy metals by marsh plants is important because of the direct impact on the food chains leading to man.

3. Results of the study indicate that Cyperus esculentus, Spartina patens, Distichlis spicata and Spartina alterniflora appear to have more potential in taking up zinc, cadmium and nickel than other marsh plants studied. Lead and chromium accumulated in the roots of all species with very little translocation into plant tops.

4. This research was designed as an initial step in the evaluation of the potential for heavy metal uptake by marsh plants growing on dredged material. In many aspects these data present a worst case situation, and should be interpreted as such. Several detailed field and laboratory investigations have been initiated, and are continuing, in order to more precisely define potential problem areas and apply these findings to real world situations. These studies comprise all or part DMRP Work Units 2A05, 4A06, 4A11, and 4A15.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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Eight marsh plants were grown in chemically controlled hydroponic solutions containing three concentrations of heavy metals to evaluate the ability of each plant species to take up and accumulate heavy metals. The marsh plants studies were Cyperus esculentus, Scirpus validus, Spartina patens, Scirpus robustus, Distichlis spicata, Triglochin maritima, Spartina alterniflora, and Spartina foliosa. The heavy metals studied were zinc, cadmium, nickel, lead, and chromium, each at a concentration of 0.0, 0.5, and 1.0 ppm. (Continued)

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20. ABSTRACT (Continued).

Marsh plants were exposed to heavy metals for six weeks and harvested. Plants were separated into tops, lower stems, rhizomes, tubers, and roots and analyzed for heavy metals to locate plant parts where heavy metals may accumulate.

Exposure to heavy metals adversely affected the growth of S. validus, S. patens, D. spicata, and S. alterniflora more than the other plant species evaluated. The species that appeared to have more potential in taking up zinc, cadmium, and nickel were C. esculentus, S. patens, D. spicata, and to some extent S. alterniflora. Lead and chromium accumulated in the roots of all species with very little translocation into plant tops. Phosphorus and iron content in the roots appeared to be a major factor in determining the ability of a marsh plant to translocate heavy metals from the roots into other plant parts.

The chemical data used to prepare figures in the main text are included as Appendix A.

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EXECUTIVE SUMMARY

Marsh creation with dredged material represents a potential contribution of contaminants from dredged material into food chains. Movement of contaminants via plant uptake is one possible mechanism for heavy metal mobilization from dredged material used in marsh creation. There is a need to evaluate the ability of various marsh plants to take up and accumulate contaminants such as heavy metals. Information on heavy metal uptake by various marsh plant species is limited for two of the eight species studied and virtually nonexistent for the other six species.

A hydroponic study was conducted to obtain a preliminary indication of the ability of selected marsh plants to take up and accumulate certain heavy metals. The eight marsh plants studied were Cyperus esculentus, Scirpus validus, Spartina patens, Scripus robustus, Distichlis spicata, Triglochin maritima, Spartina alterniflora, and Spartina foliosa. Marsh plants were grown in chemically controlled hydroponic solutions containing 0.0, 0.5, and 1.0 ppm of each of the heavy metals zinc, cadmium, nickel, lead, and chromium. Marsh plants were exposed to heavy metals for six weeks and harvested. Plants were separated into tops, lower stems, rhizomes, tubers, and roots and were analyzed for selected heavy metals to locate plant parts where heavy metals may accumulate.

Exposure to heavy metals adversely affected the growth of S. validus, S. patens, D. spicata, and S. alterniflora. These plant species appeared to be more sensitive to heavy metals than the other species studied. Tissue analysis for heavy metals indicated different abilities among plant species for heavy metal uptake. Those species that appeared to have more potential in taking up zinc, cadmium, and nickel were C. esculentus, S. patens, D. spicata, and to some extent S. alterniflora. Those plant species of lower potential appeared to be S. validus, S. robustus, T. maritima, and, to some extent, S. foliosa. Lead and chromium accumulated in the roots of all species with very little translocation into plant tops.

Phosphorus and iron concentrations in plant roots appeared to be

correlated closely with the accumulation of zinc, nickel, lead, and chromium in the roots of all marsh plants. Phosphorus and iron content in the roots may be a major factor in determining the ability of a marsh plant to translocate heavy metals from the roots into other plant parts. Cadmium was the only heavy metal unaffected by concentrations of phosphorus and iron in the roots.

It was concluded that C. esculentus, S. patens, D. spicata, and, to some extent, S. alterniflora appeared to have more potential for heavy metal uptake than the other species studied. Further research is recommended to evaluate the ability of these marsh plants to take up and accumulate heavy metals such as zinc, cadmium, nickel, and mercury from dredged material under varying laboratory and field conditions.

PREFACE

This is a report on an experimental greenhouse study of heavy metal uptake by selected marsh plants. This investigation was conducted as part of the Corps of Engineers Dredged Material Research Program (DMRP). The DMRP is sponsored by the Office, Chief of Engineers (DAEN-CWO-M), and was formally authorized by letter, "Study Program for Disposal of Dredged Material," dated 27 December 1971.

The study was conducted during the period November 1974 to September 1975 at the U. S. Army Engineer Waterways Experiment Station (WES) by Dr. C. R. Lee, Mr. T. C. Sturgis, and Ms. M. C. Landin of the Ecosystem Processes Research Branch, Ecosystem Research and Simulation Division, Environmental Effects Laboratory (EEL). Assistance was received from Messrs. R. E. Hoeppel and I. F. Behr III. This research was conducted under the direction of Dr. R. T. Saucier, Special Assistant, EEL, and Dr. H. K. Smith, Project Manager, Habitat Development Project, DMRP. The study was under the general supervision of Dr. R. L. Eley, Chief, Ecosystem Research and Simulation Division, and Dr. John Harrison, Chief of EEL. Technical consultants for the study were Dr. R. H. Chabreck, Associate Professor of Forestry and Wildlife Management, Louisiana State University; Dr. C. B. Loadholt, Professor of Biometrics, Medical College of South Carolina; and Dr. N. R. Page, Head of Agricultural Chemical Services, Clemson University. Directors of WES during the study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
ounces	0.0296	litres
gallons	3.785	litres

A HYDROPONIC STUDY OF HEAVY METAL UPTAKE BY SELECTED MARSH PLANT SPECIES

PART I: INTRODUCTION

Background

1. Marsh creation with dredged material in an environmentally acceptable manner is one of the major goals in the Dredged Material Research Program. Movement of contaminants such as heavy metals via plant uptake is a possible mechanism for heavy metal mobilization from dredged material used in marsh creation. In the marsh ecosystem, there are two predominant pathways for biomagnification of heavy metals involving the marsh plant. The more direct route is the consumption of marsh plants by a host of organisms such as insects, waterfowl, and small animals. The other pathway for biomagnification is the detritus food chain wherein a marsh plant dies, decays, and is flushed into the estuary in either particulate or dissolved form. Both pathways are integral parts of food chains leading to man; and in either case, it is important to know whether or not a given marsh plant is able to concentrate toxic heavy metals from its environment. While there is considerable information being published on heavy metal uptake by agricultural crops from sludge and sludge-amended soils, the extent to which nonagricultural plants take up heavy metals is essentially unknown.

Literature Review

2. Much of the available literature lists elemental concentrations in marsh plants under natural conditions. Among the elements reported are zinc, manganese, copper, and iron. Other heavy metals such as lead, mercury, nickel, cadmium, or chromium have received little attention.

3. The marsh plant species which has received the most research attention is Spartina alterniflora. Dunstan et al. have studied the

effects of five heavy metals on the growth of S. alterniflora in hydroponic nutrient solutions.[1,2] S. alterniflora was exposed for eight weeks to 100 ppm each of zinc, lead, copper, cadmium, inorganic mercury, and methylmercury. This level of heavy metals was excessive and resulted in the death of S. alterniflora seedlings after two weeks of exposure to copper. Over 35 percent of the seedlings died after eight weeks of exposure to zinc and inorganic mercury, while lead and methylmercury killed over 50 percent of the seedlings. S. alterniflora was not adversely affected by 100 ppm of cadmium and after eight weeks of exposure, plants contained as much as 94 ppm of cadmium with no apparent toxicity. Since the highest cadmium contents were found in the below-ground portions of the plant, it was concluded that cadmium was not transported readily within the plant but was concentrated through adsorption and absorption in plant roots. Another available study evaluated the uptake of mercury by S. alterniflora plants grown in seawater containing from 0.001 to 1.0 ppm of mercury.[3] S. alterniflora took up mercury rapidly when either inorganic mercury or methylmercury was present in the seawater. However, methylmercury was found to be translocated to the leaves and stalks more readily than inorganic mercury.

4. These studies indicate that S. alterniflora is sensitive to high concentrations of copper, lead, methylmercury, inorganic mercury, and zinc and appears to be able to take up cadmium and mercury.

5. Other available literature reports heavy metal contents of a limited number of marsh plant species growing in natural marshes or in dredged material. Drifmeyer and Odum sampled S. alterniflora and S. patens in a natural marsh and on dredged material and analyzed the plants for lead and zinc.[4] Both S. alterniflora and S. patens were found to take up small quantities of these elements. Another study analyzed S. alterniflora from eight marshes extending from South Carolina to Florida for zinc, lead, copper, cadmium, and mercury.[2] It was found that S. alterniflora was able to tolerate concentrations of heavy metals several times greater than the highest concentrations found in nature. It was suggested that S. alterniflora possesses a mechanism which serves to control the levels of all heavy metals in its tissues.

6. The remaining literature on heavy metal uptake by marsh plant species other than S. alterniflora and S. patens is limited or non-existent.

Purpose and Scope

7. This study was undertaken as an initial step to evaluate the ability of marsh plants to take up heavy metals from their environment. The results obtained are only an indication of the relative uptake and accumulation of selected heavy metals by eight marsh plants and are by no means an end in themselves. For example, those plant species that showed relatively slow rates of absorption or limited translocation of heavy metals from plant roots to other plant parts may over longer periods of exposure to heavy metals (greater than six weeks) show some translocation of heavy metals. However, for the purposes of this study, if a plant species did not take up significant amounts of heavy metals, it would be considered to have a low potential for biomagnification of heavy metals. Additionally, plant species that had relatively high absorption and accumulation of heavy metals would be identified as those species that should be given priority in an evaluation of their ability to take up heavy metals from dredged material. Hydroponic studies are very useful for indicating those plant species that likely have the greater potential for accumulation of heavy metals and concomitantly those species that may be the greater potential problem. Further research is required to supplement the information obtained in this study and to further define the potential biomagnification of heavy metals by marsh plants grown on dredged material.

Approach

8. The study was conducted in two phases: (a) an information review and (b) a greenhouse hydroponic experiment. Information on each plant species was collected from available literature and through personal communications with known authorities on the eight marsh plant

species selected. After careful evaluation of this information, it was concluded that a hydroponic experiment could be a viable method for obtaining an indication of the relative uptake and accumulation of heavy metals by marsh plants. Normally, if a plant can take up heavy metals, relatively large amounts will be absorbed from hydroponic solutions. Conversely, those plants that normally do not take up large amounts of heavy metals will absorb very little heavy metals from hydroponic solutions.

9. Using the hydroponic method and controlled conditions, the roots of marsh plants were in contact with ionized heavy metals (dissolved salts), the more readily available form for plant uptake. Eight marsh species, obtained from natural marshes, were grown in nutrient solutions containing three levels of zinc, cadmium, nickel, lead, and chromium. After six weeks of exposure to the heavy metal solutions, plants were harvested, separated into the various plant parts, and analyzed for each of the heavy metals.

PART II: DESCRIPTION OF STUDY

Source of Marsh Plants

10. Each plant species was obtained from a natural marsh stand except for Spartina alterniflora and Cyperus esculentus. The following paragraphs describe the location and procedures used for the collection of each species.

11. Scirpus validus plants were obtained from a freshwater marsh on Lake Pontchartrain near Slidell, Louisiana, on 5 November 1974. Plant rhizomes and roots were washed to remove as much marsh sediment as possible and were planted in riverine sand in undrained containers.

12. Cyperus esculentus tubers were obtained from Mr. John D. Newsom, Louisiana Cooperative Wildlife Unit, Louisiana State University. Mr. Newsom collected tubers from Catahoula Lake, Louisiana, in the spring of 1974, planted them in containers of marsh sediment, and grew the resultant plants outdoors during the summer of 1974. Tubers were harvested from the containers in November and sent to the U. S. Army Engineer Waterways Experiment Station (WES) for this study. The moist tubers were then refrigerated at 5°C for seven days. Upon removal from refrigeration, the tubers were placed in a plastic bag, watered, and placed in full sunlight in the greenhouse to sprout. As tubers sprouted, they were planted in a drained 16-oz* cup of riverine sand.

13. Spartina patens plants were obtained from a brackish water marsh on Lake Pontchartrain near Slidell, Louisiana. Plant roots were planted in undrained containers of riverine sand.

14. Scirpus robustus culms were obtained from a brackish marsh at Lake St. Catherine near Fort Pike where the Pearl River and Lake St. Catherine join the Gulf of Mexico. Culms were washed with tap water to remove sediment and refrigerated at 5°C in fresh water for seven days, removed from refrigeration, and planted in riverine sand in undrained containers.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 6.

15. Distichlis spicata plants were obtained from the same brackish marsh at Lake St. Catherine as Scirpus robustus. After washing the marsh sediment from plant roots with tap water, plants were planted in riverine sand in undrained containers.

16. Triglochin maritima plants were obtained from a brackish marsh located at South Slough on the Suislaw River east of Florence, Oregon. Mr. Wilbur Ternyik of Florence, Oregon, and Mr. Robert J. Young from Oregon State University, Corvallis, Oregon, dug up the plants, removed most of the root and shoot mass from the culms, wrapped the culms in plastic, and shipped them to WES by airfreight. Upon arrival at WES, the culms were broken into small clumps and planted in riverine sand in drained containers.

17. Spartina alterniflora plants were grown from field-collected seed at Louisiana State University by Dr. R. T. Parrondo. Dr. Parrondo collected the seed from Baritaria Bay, Louisiana, in the fall of 1973, stored the seed in a moist condition under refrigeration until May 1974, and planted the seed in 16-oz cups of marsh sediment (one seed per cup) in the greenhouse. Tap water was added to the cups as needed. On 30 September 1974, the plants were delivered to WES. Each plant was removed from the cup of sediment, washed to remove marsh sediment from the roots, and planted in riverine sand in undrained containers.

18. Spartina foliosa plants were obtained from a saltwater marsh at Black Point on the Petaluma River in San Pablo Bay, California, by Dr. Curtis Newcombe, San Francisco Bay Marine Research Center. Plants were wrapped in plastic bags and shipped by airfreight to WES on 21 December 1974. Upon arrival at WES, the plants were planted in riverine sand in undrained containers.

Experimental Unit

19. Twenty-four galvanized metal watering troughs measuring 2 by 2 by 6 ft with a 167-gal capacity were lined with four layers of 4-mil-thick polyethylene plastic sheeting (Figure 1). Each unit was aerated through a perforated polyethylene tube (1/8-in. ID) to continually mix

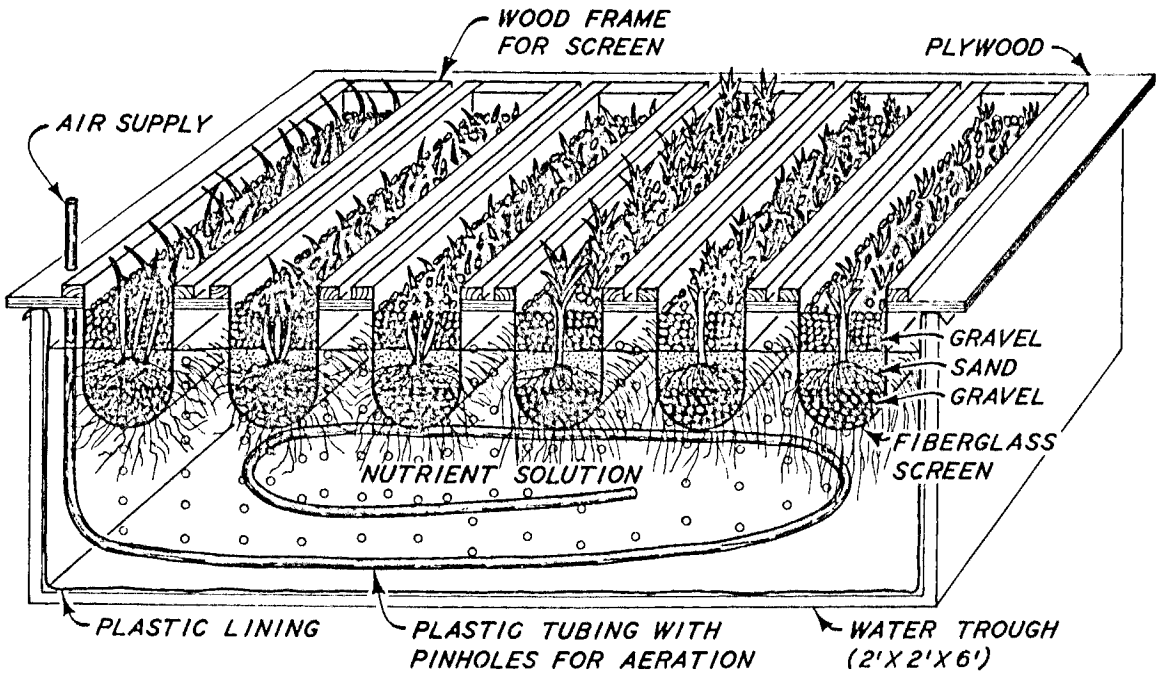


Figure 1. Hydroponic system for heavy metal uptake study

the nutrient solution. Air was supplied from an air compressor (Worthington, Model 5CV8) connected to a water trap which moistened the air and removed oils or other foreign substances from the air before it entered the experimental units. The water trap consisted of a Plexiglas column, 6 in. in diameter and 48 in. long, sealed at both ends. The bottom was sealed permanently, and the upper end was bolted with wing nuts to enable access into the column. A filter of fiberglass hardware cloth (18- by 16-in. mesh, Chicopee Company) was placed at the upper end of the column. Air from the compressor entered the column at the bottom, bubbled through the water column, and passed through the fiberglass filter into a 1/2-in.-ID tygon tubing line connected to a series of 1/4-in.-ID tygon tubing connected to the polyethylene air line in each unit. Airflow into each unit was regulated with a Hoffman screw clamp (Curtin, No. 059-121). Each unit (trough) was covered with a 2- by 8-ft piece of 3/4-in. exterior plywood. Six rectangular holes (each 8 by 18 in.) were cut out to fit six planters (Figure 1). Each plywood cover had a 2-in. hole at each end through which nutrient solution ingredients were added and removed. The plywood covers were painted with three coats of

exterior varnish (No. 550 Dedoa 87-Spar). Planters consisted of a rectangular frame (8 by 18 in.) made from 3/4- by 3/4-in. wood painted with three coats of varnish. Reinforced fiberglass hardware cloth (18- by 16-in. mesh, Chicopee Company) was stapled to the frame and made into a 10-in.-deep planter. The frames were covered with gray tape to eliminate corrosion of the staples. Five inches of deionized water-washed pea gravel was placed in each planter. A 4-in. layer of deionized water-washed coarse silca sand (Crystal Silica Company, No. 6-14) was placed on the pea gravel. After the marsh plants were transplanted in the sand layer, an additional inch of pea gravel was placed over the sand to minimize algal growth on the surface of the sand.

Chemical Composition of the Hydroponic Solution

Essential nutrients

20. The chemical composition of the nutrient solution used in all experimental units and also a modified Hoagland's solution are given in Table 1. Preliminary greenhouse and laboratory tests indicated that Spartina alterniflora grew as well in the experimental nutrient solution as it did in the modified Hoagland's solution that has been used successfully in heavy metal uptake studies with potatoes, Solanum tuberosum.[5] The nutrient solutions described in Table 1 differ in a number of respects. The experimental nutrient solution contains only ammonium nitrogen. This change was made after noting that ammonium is the predominant form of nitrogen found in marshes. The modified Hoagland's solution contains 97 percent of the nitrogen as nitrate and has been used successfully for a number of agronomic crops. These crops, however, are normally grown in well-drained, aerated soils and are exposed predominantly to the nitrate form of nitrogen. Most agronomic crops are grown in soils with a calcium-to-magnesium ratio approximating three; Hoagland's nutrient solution also contains this calcium-to-magnesium ratio. However, available information indicates that most brackish and saltwater marsh plants grow under conditions in which there are three times as much magnesium as calcium. Therefore, in the experimental

nutrient solution, the concentration of magnesium was increased to give a three-to-one ratio of magnesium-to-calcium. Since the sulfate form of magnesium was used to increase the magnesium content of the nutrient solution, the sulfate content also increased. As chloride compounds were used in place of nitrate compounds, the experimental nutrient solution had a higher chloride concentration.

21. The experimental nutrient solution contained ten times as much iron as the modified Hoagland's solution. The iron concentration was increased for two reasons. The heavy metals zinc and nickel have been shown to induce iron deficiencies in a number of plants.[6,7] Raising iron levels in the growth medium has been shown to control zinc-induced iron deficiencies.[6,7] The second reason for raising the iron concentration is because most marsh plants are exposed to reduced growing conditions which favor the reduction of less soluble ferric-iron oxides to the more soluble ferrous-iron compounds. This causes relatively large concentrations of soluble iron to be available for plant uptake.

22. The standard pharmaceutical grade (SP) of ammonium chloride (NH_4Cl), potassium chloride (KCl), potassium dihydrogen phosphate (KH_2PO_4), calcium chloride ($CaCl_2$), magnesium sulfate ($MgSO_4 \cdot 7H_2O$), and sodium chloride (NaCl) was used. Iron was supplied as sodium ferric ethylenediamine di-(O-hydroxyphenylacetate) (FeEDDHA), commonly known as Sequestrene 138 Fe Chelate and manufactured by CIBA-Geigy Corporation, Greensboro, North Carolina. This iron chelate was selected because of its stability over a wide range of pH values and in the presence of as much as 1.0 ppm of zinc.[7] One serious problem in hydroponic solution experimentation is the precipitation of iron from solution. Inorganic sources of iron normally precipitate within 24 hr. Iron chelates, however, remain soluble and normally allow plants to take up sufficient amounts of iron to eliminate iron deficiency within the plant. Each of the above chemicals was added to each experimental unit (trough) in the dry form.

23. Reagent grade copper (0.02 mg/ℓ) and manganese (1.4 mg/ℓ) were added to each unit in liquid form as copper chloride ($CuCl_2 \cdot 2H_2O$) and manganese chloride ($MnCl_2 \cdot 4H_2O$), respectively.

Heavy metals

24. Reagent grade heavy metals zinc, cadmium, nickel, lead, and chromium were added in liquid form as zinc sulfate ($ZnSO_4 \cdot 7H_2O$), cadmium chloride ($CdCl_2, \cdot 2\text{-}1/2H_2O$), nickel chloride ($NiCl_2 \cdot 6H_2O$), lead acetate ($Pb(CH_3COO)_4 \cdot 3H_2O$), and chromium chloride ($CrCl_3 \cdot 6H_2O$), respectively. Each heavy metal was added at a rate of 0.0, 0.5, and 1.0 mg/ℓ. All five heavy metals were added to those experimental units designated to receive heavy metals.

Salinity levels

25. Marsh plant species were paired according to four salinity environments as shown in Table 2. Salinity levels were obtained by adding an appropriate amount of sodium chloride to the hydroponic solution. The salinities in Table 2 were selected after careful consideration of available information indicating the salinity levels at which other researchers have found optimum growth of these species in hydroponic solutions (personal communications with Dr. J. L. Gallagher, University of Georgia, and Dr. R. T. Parrondo, Louisiana State University). Additional information relating the salinity levels under which these species are found in natural marsh conditions was also considered.[8]

Treatments and Experimental Design

26. Treatments consisted of eight plant species (two each at four salinity levels) grown at three levels of heavy metals and replicated twice for a total of 24 experimental units. A split plot design was employed for the experiment. Whole plots were the experimental units (troughs) to which the different levels of heavy metals were applied. The split in whole plots consisted of the planters within a unit (trough). The three sizes of each species were randomly assigned to the six planters within the unit. This design gives a sensitive test for the interaction of species and heavy metal levels and the interaction of plant size within species and heavy metal levels.

27. The experimental whole plots were arranged in a randomized complete block design within the greenhouse. The experiment consisted

of two blocks, each of which contained all plant species and sizes and all levels of heavy metals.

Greenhouse Propagation of Marsh Plants

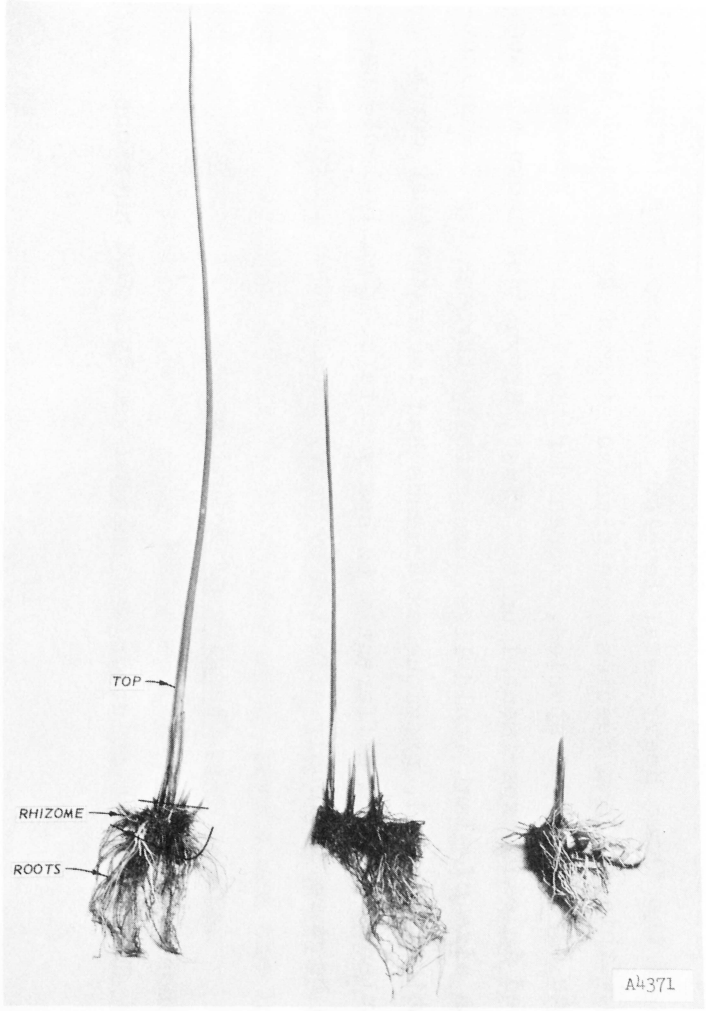
28. After plants were transplanted into riverine sand in November 1974, the experimental nutrient solution with either 0, 3, 6, or 9 ppt of NaCl was applied once a week to the appropriate marsh plants as described in Table 2. Deionized water was used as necessary on a daily basis to keep containers wet. In order to reduce any salt buildup in containers, in January drainage holes were made on the side of each container to enable excess salt and water to drain out.

Transplant

29. To prepare plants for transplanting into hydroponic units, new growth of each plant species was separated into large, medium, and small plants. The relative sizes for each plant species are shown in Figures 2a-h. The number and initial fresh weight of each plant species are given in Table 3. In addition, initial plant heights and number of stems were recorded. Groups of uniform-sized plants were randomly assigned to a planter in each of the experimental units designated to receive one of the three heavy metal levels. In this way, similar initial biomasses within a plant species were planted at each heavy metal level. Three sizes of each plant species, chosen for the following reasons, were placed in each experimental unit. First, it was not known at the time which size of plant would live successfully through the transplanting operation. Second, previous experience had indicated that certain sizes of plants respond differently to heavy metals. Small plants appeared to be more seriously affected by heavy metals than large plants.

Changing of Solutions

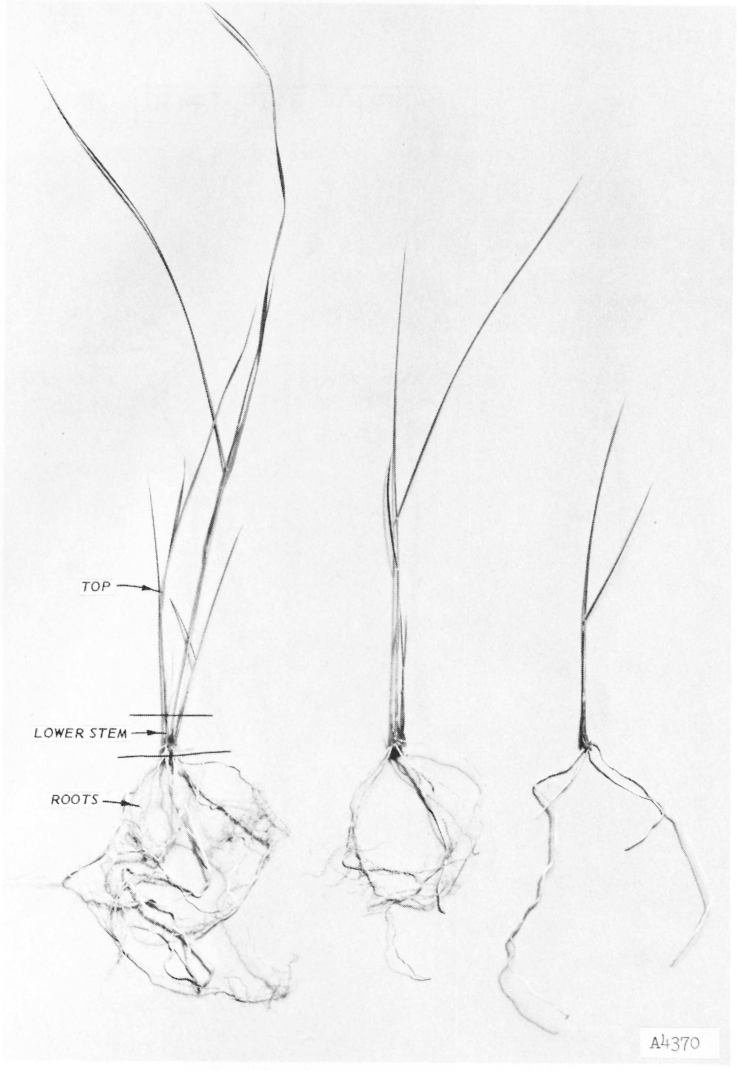
30. The nutrient solution was changed weekly. Old nutrient



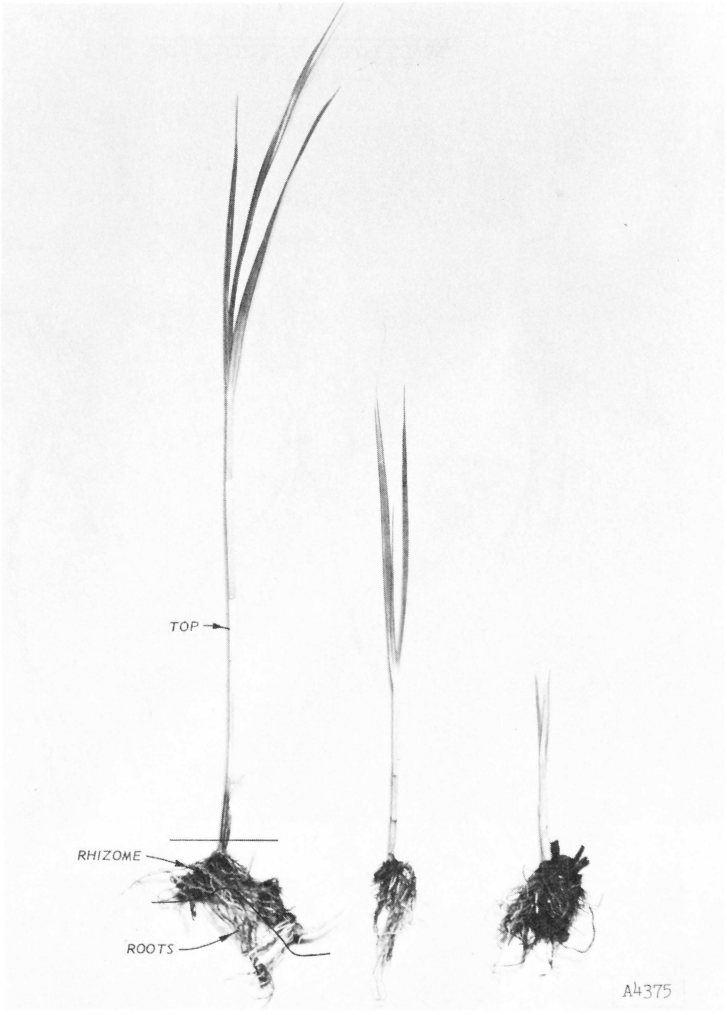
a. Scirpus validus

b. Cyperus esculentus

Figure 2. Sizes and parts used of each plant species (sheet 1 of 4)

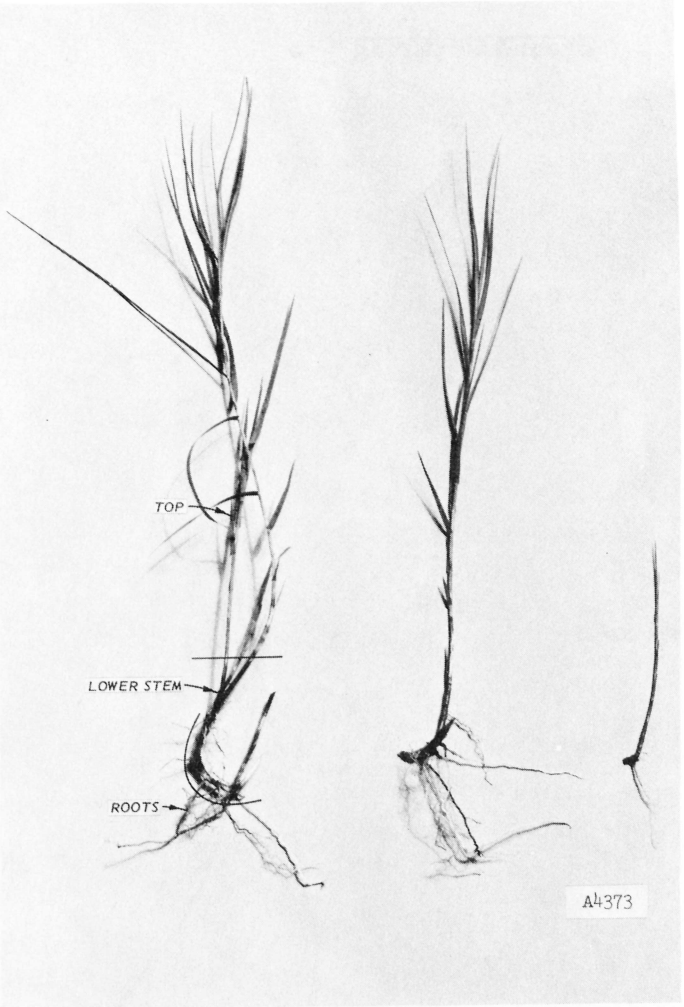


c. Spartina patens

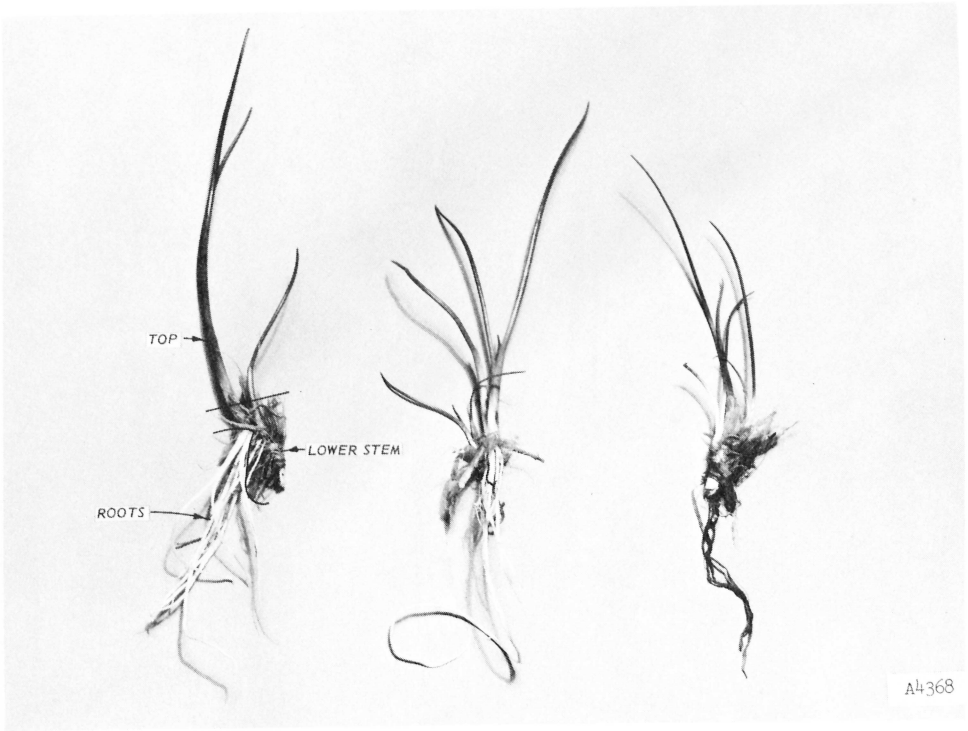


d. Scirpus robustus

Figure 2 (sheet 2 of 4)

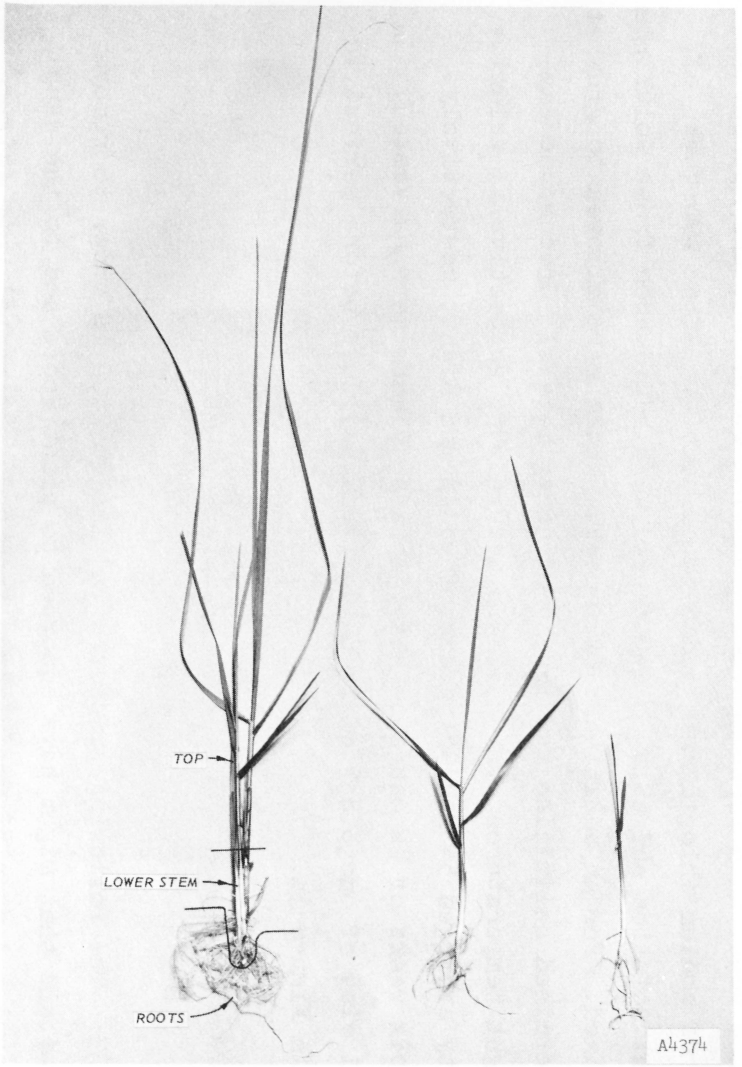


e. Distichlis spicata

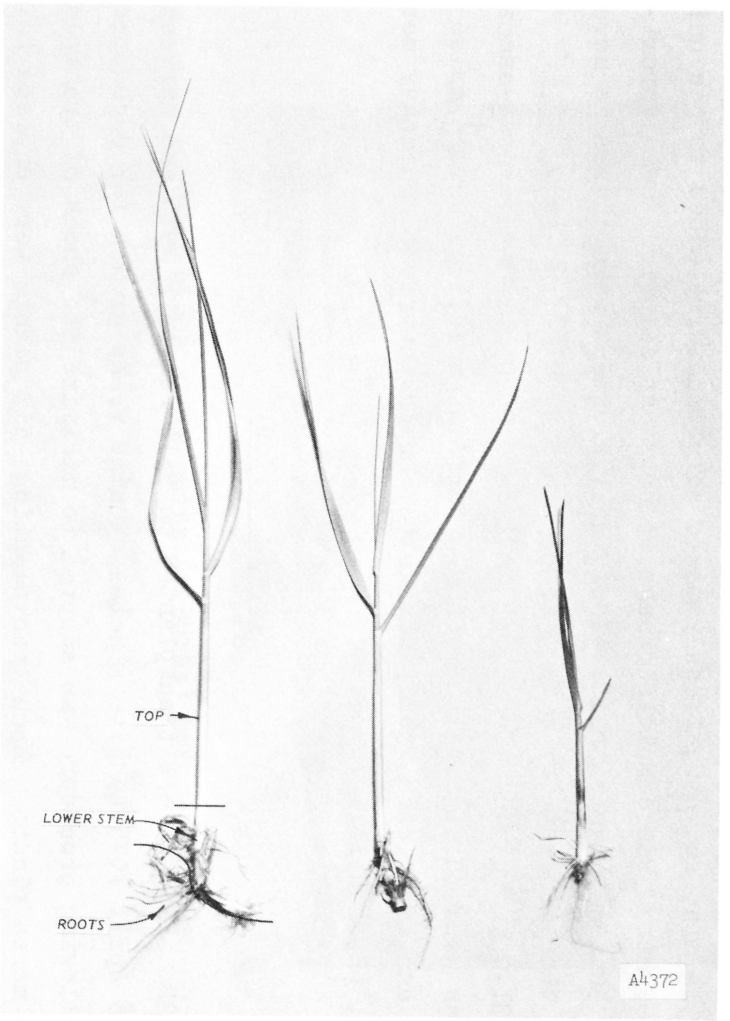


f. Triglochin maritima

Figure 2 (sheet 3 of 4)



g. Spartina alterniflora



h. Spartina foliosa

Figure 2 (sheet 4 of 4)

solutions were pumped out of each unit with an electric pump (4000 B Oberdorfer and Daten motor 5K454); each unit was emptied in approximately 14 min, and new, freshly mixed solutions were added to the unit within 7 min. The complete change of nutrient solution took approximately 30 min for each unit. Individual planters were therefore never out of the solution for more than 30 min a week.

31. Deionized water obtained from a 9600-gal/day reverse-osmosis unit was used throughout the study. Nutrient solutions were sampled before and after each weekly change to monitor nutrient and heavy metal levels, pH, and salinity.

Growth Period

32. Plants were transplanted on 3-14 February 1975 and harvested on 7-18 April 1975 to give a total of nine weeks growth for each species. The following procedure was adopted to minimize the shock of transplant to the marsh plants. Upon transplanting, all plants were exposed to the experimental nutrient solution without sodium chloride and heavy metals. After one week, when fresh nutrient solution was mixed, the appropriate amount of sodium chloride was added to each unit. After two weeks of nutrient solution and salt, heavy metals were added when fresh solutions were mixed. For an additional six weeks, plants were allowed to grow at predetermined salinities and levels of heavy metals. Greenhouse day and night temperatures averaged 29.6 and 16.3°C, respectively; relative humidity averaged 54 and 98 percent for day and night, respectively. After six weeks of exposure to heavy metals, plants were harvested. An overall view of one block of 12 units (troughs) just before harvest is shown in Figure 3a.

Harvest

33. The following procedure was implemented in order to remove heavy metals that might have adsorbed to plant roots and to the sand and gravel. A planter was removed from an experimental unit (Figure 3b),

a. One block of 12 units (troughs) before harvest

b. A planter of *Spartina patens* at harvest

Figure 3. Greenhouse hydroponic study

rinsed three times in a bath of 0.1 N hydrochloric acid (HCl), and rinsed three times in a bath of deionized water. Plant tops were cut at the surface of the pea gravel in a planter. Belowground plant parts were separated into lower stems, rhizomes, tubers, and roots. The final number of shoots and plant heights and the fresh and dry weights of plant parts were recorded.

Chemical Analysis

Hydroponic solution

34. Water samples collected before and after each weekly change of nutrient solution were analyzed for nitrogen, phosphorus, zinc, cadmium, nickel, lead, chromium, iron, pH, and salinity. Nitrogen and phosphorus were determined with a technicon autoanalyzer II. Zinc, cadmium, nickel, lead, chromium, and iron were determined by atomic absorption spectroscopy. Salinity was determined with a salinity meter (Yellow Springs-Instrument Co., Model 33), and pH was determined with the glass electrode using a pH meter (Orion Research, Model 801).

Plant material

35. Plant parts were oven-dried at 70°C until constant weights were obtained. Dried plant materials were ground in a stainless steel Wileymill (Model 4, A. H. Thomas Company) whenever possible. In a number of samples, the entire sample was used for analysis; otherwise, 2 g of plant material were wet-ashed on a hot plate at 100°C with 20 ml of concentrated nitric acid and taken to dryness without charring. An additional 20 ml of concentrated nitric acid and 8 ml of red fuming nitric acid were added, and the mixture was heated on a hot plate at 200°C until a clear solution appeared. The digests were diluted, filtered, and increased to 50 ml by the addition of 1.2 N HCl. Digest solutions were analyzed for zinc, cadmium, nickel, lead, chromium, and iron by atomic absorption spectroscopy and for phosphorus with a technicon autoanalyzer II.

PART III: RESULTS AND DISCUSSIONS

36. It is important to remember throughout the discussion of the results that marsh plants were exposed to heavy metals for six weeks only. Though some marsh plants did not show rapid uptake of heavy metals, this does not mean that these plants will not take up heavy metals. Over a longer period of exposure such as a natural growth period of four months or more, these plant species might take up and accumulate more heavy metals; however, during the six weeks exposure time of this study, the rate of uptake was relatively slow compared with those plant species that showed a more rapid uptake of heavy metals.

37. Generally, smaller sized plants either contained similar or slightly higher concentrations of heavy metals in plant parts than did larger plants (Table 4). However, on a total uptake basis, the larger plants contained more of the heavy metals than the smaller plants (Table 4). This is merely a dilution effect whereby the total uptake of heavy metals in small plants is not spread out over a larger biomass as in the case of the larger plants. The larger plants, while containing similar or lower concentrations of heavy metals, actually took up more heavy metals when their larger biomass is considered.

38. Since there were eight plant species (two each in one of four salinity levels), the experiment was analyzed as four separate experiments. Also, the variability among the pairs of plant species regarding plant growth factors and tissue concentrations of heavy metals was sufficiently large enough that a combined analysis for all eight species did not appear advisable. Therefore, the data for each pair of plant species were analyzed separately. This resulted in the analysis of four small experiments rather than one large experiment with all the data. While some species tended (but not significantly) to increase in heavy metal concentrations, over a longer growth period it is possible that these species would demonstrate a statistically significant uptake of heavy metals.

39. Most of the significant differences obtained in this study were found in the concentrations of heavy metals in the various plant

parts of each plant species when the three sizes of plants were combined to give an average heavy metal content of a plant part. Therefore, the results to be discussed will consider mainly the heavy metal concentrations in various plant parts of each species, disregarding size of plants.

40. Differences discussed are significant at the 10 percent level of significance according to the least significant difference (LSD) test.[9] The 10 percent level of significance was chosen because of the small degrees of freedom associated with error terms and because of the nature of experiments. The LSD test was used primarily to determine the nature of the response of the observed variable to the quantitative treatment variable. Differences are designated in some tables using one or more alphabet letters and footnoted accordingly. Comparisons of tissue concentrations of heavy metals for each set of data for each pair of species were made using three LSD values since the experimental design was a split plot and different error terms were associated with different treatment comparisons. Incorporation of these LSD values in Figures 4-10 would detract from the data presentation. Therefore, the data and LSD values for the comparisons made are presented in Appendix A for further reference.

Hydroponic Solution Analysis

41. Water samples collected 24 and 168 hr after mixing new hydroponic solutions were analyzed for heavy metals, essential elements, salinity, and pH. Since there was no change in values for the above factors during the seven days (168 hr), average values are presented in Table 5. Water concentrations of zinc, cadmium, and nickel were maintained at slightly higher than the expected 0.5- and 1.0-ppm levels of heavy metals. Lead and chromium concentrations were generally below the expected levels. The lesser amounts of lead and chromium were found in both the 0- and 3-ppt salinity levels. At the higher salinity levels of 6 and 9 ppt, more of the added lead and chromium appeared to remain in the solution. Lead and chromium are two of the heavy metals that

are more difficult to maintain in a soluble form in hydroponic solutions. Adequate amounts of iron, manganese, phosphorus, and ammonium-nitrogen were maintained in the hydroponic solutions. Slight variations in concentrations of the above elements could be attributed to dilution errors.

42. Actual salinity levels were above the expected values. The increase in the concentration of magnesium sulfate in the nutrient solution, in addition to other salts comprising the nutrient solution, would account for the 2-ppt salinity level for freshwater plants. The salinity level for the 3-ppt brackish plants approached the salinity level of the 6-ppt brackish plants. The salt-marsh plants were exposed to 11-ppt salinity. Solution pH values ranged from pH 5.08 to 5.73 (Table 5).

Plant Growth Factors

43. Plant growth was measured in terms of four factors: (a) yield (oven-dry weight), (b) number of live and dead stems that were observed above and below the surface of the gravel in a planter, (c) final plant heights, and (d) plant growth index. These factors can give an indication of plant response, either inhibitory or stimulatory, to exposure of plant roots to heavy metals.

Plant dry weight yield

44. The addition of heavy metals to the hydroponic solutions suppressed the yield of plant tops for *S. validus*, *S. patens*, *D. spicata*, and *S. alterniflora* (Table 6). Heavy metals had no effect on the weight of plant tops for *C. esculentus*, *S. robustus*, *T. maritima*, and *S. foliosa*. Yield of *S. validus* rhizomes and *S. patens* lower stems was reduced when heavy metals were applied. However, yield of plant rhizomes, lower stems, or tubers for the remaining plant species was not affected by heavy metal additions. Dry weights of plant roots were reduced for *S. validus*, *S. patens*, and *S. alterniflora*.

Number of plant stems

45. The addition of heavy metals reduced the number of live stems observed above the gravel in a planter for *S. validus* and *S. patens*

(Table 6). This reduction in live stems for S. validus was also observed by the concomitant increase in the number of dead stems (Table 6). The number of new young stems observed on plant rhizomes and lower stems was reduced for S. validus, S. robustus, and S. alterniflora when heavy metals were applied.

Final plant height

46. The addition of heavy metals to the hydroponic solutions suppressed the height of plant tops for S. validus, S. patens, and D. spicata. The other plant species studied did not exhibit any suppression in plant-top height when exposed to heavy metals.

Plant growth index

47. Another way to look at the above results of plant growth is an index of growth obtained by dividing the final biomass by the initial biomass. When the results are presented in this way, it is revealed that certain plant species grew more rapidly than other species (Table 7). While similar effects of heavy metals on plant growth as described above are still evident, those plant species that were affected by heavy metals are those with more rapid growth rates or larger growth indexes.

48. Growth of C. esculentus in hydroponic solutions was much less than the other species studies. Plants remained green for approximately four weeks after transplant and then all plants began to die gradually. By harvest, very few green leaves were observed on the plants. Two reasons might explain this lack of growth. During transplant, many tiny tubers were observed on the green healthy plants that were used in this study. At harvest, many larger matured tubers were observed. The shock of transplanting may have caused C. esculentus to go into tuber production rather than vegetative growth. The poor growth might also be related to an adverse reaction to the hydroponic solution with a salinity of 2 ppt.

49. Large plants of S. robustus showed a lower growth rate than either the medium or small plants (Table 7). Upon transplant, it was observed that the larger lush green plants were damaged easily by bends and breaks in the plant stems. Those plants so damaged eventually died. The remaining large plants that were not damaged underwent enormous

stress when the roots tried to supply sufficient mositure to meet the requirements of a large plant top. Consequently, the resultant growth rate was low. Medium and small plants survived the transplant well and showed good growth.

50. These data suggest that heavy metals caused those plant species with higher growth rates such as S. validus, S. patens, D. spicata, and, to some extent, S. alterniflora to exhibit a reduction in the plant growth factors measured in this study. These plant species may be more sensitive to exposure of heavy metals than the other plant species studied.

Heavy Metal Contents of Plant Parts

51. While the concentrations of heavy metals in plant parts are of interest, the actual concentration or content observed is that obtained after six weeks of exposure to heavy metals and would probably be different at shorter or longer exposures. Since C. esculentus plants grew poorly and eventually died, their exposure to and uptake of heavy metals were less than six weeks. Therefore, the concentrations of heavy metals in this species may be lower than those that might have been observed at six weeks of exposure. It is more important to evaluate the potential ability of a plant species to take up heavy metals. Consequently, the discussion of the results will be centered around the potential of a plant species to take up and accumulate one or more heavy metals in portions of the plant rather than the actual concentrations in a given plant.

Zinc

52. Freshwater marsh plants (0 ppt). Plant roots of S. validus and C. esculentus increased in zinc content when zinc was added to the hydroponic solutions (Figure 4). However, their tops, rhizomes, and tubers did not show a significant increase in zinc content with heavy metal additions. C. esculentus tops contained more zinc than S. validus tops at each heavy metal level. Since each species was collected from a different environment, it is not surprising that the plants grown in

solutions not receiving heavy metals contained different concentrations of zinc.

53. Brackish water marsh plants (3 ppt). While plant roots of both S. patens and S. robustus increased in zinc content when zinc was added to the hydroponic solution, S. patens roots contained larger zinc concentrations (679 ppm) than S. robustus roots (124 ppm) at the 1.0-ppm heavy metal level (Figure 4). S. patens tops and lower stems also contained more zinc than S. robustus tops and rhizomes at the 1.0-ppm heavy metal level. Both species contained similar amounts of zinc in comparable plant parts when no heavy metals were applied. These data suggest that S. patens may absorb and translocate zinc from the roots into other plant parts more rapidly than S. robustus.

54. Brackish water marsh plants (6 ppt). While plant parts of D. spicata and T. maritima tended to increase in zinc content when zinc was applied, only D. spicata roots showed an increase in zinc content (Figure 4). D. spicata roots contained much more zinc at the 0.5- and 1.0-ppm heavy metal level than roots of T. maritima. D. spicata also translocated over 150 ppm of zinc into plant tops. While this increase in zinc content of plant tops was not statistically significant, it does suggest that D. spicata may have the ability to translocate more zinc from plant roots into plant tops than T. maritima.

55. Saltwater marsh plants (9 ppt). S. alterniflora and S. foliosa responded similarly to zinc additions; their lower stems and roots increased in zinc content when zinc was added to the nutrient solutions (Figure 4). Their tops also tended to increase in zinc content with zinc additions; however, these differences in plant tops were not significant.

Cadmium

56. Freshwater marsh plants (0 ppt). The addition of 1.0 ppm of heavy metals to the hydroponic solutions increased the cadmium content in all plant parts of C. esculentus, but only in the rhizomes and roots of S. validus (Figure 5). Since tops of C. esculentus contained significantly more cadmium than tops of S. validus and roots of S. validus contained significantly more cadmium than roots of C. esculentus, it would

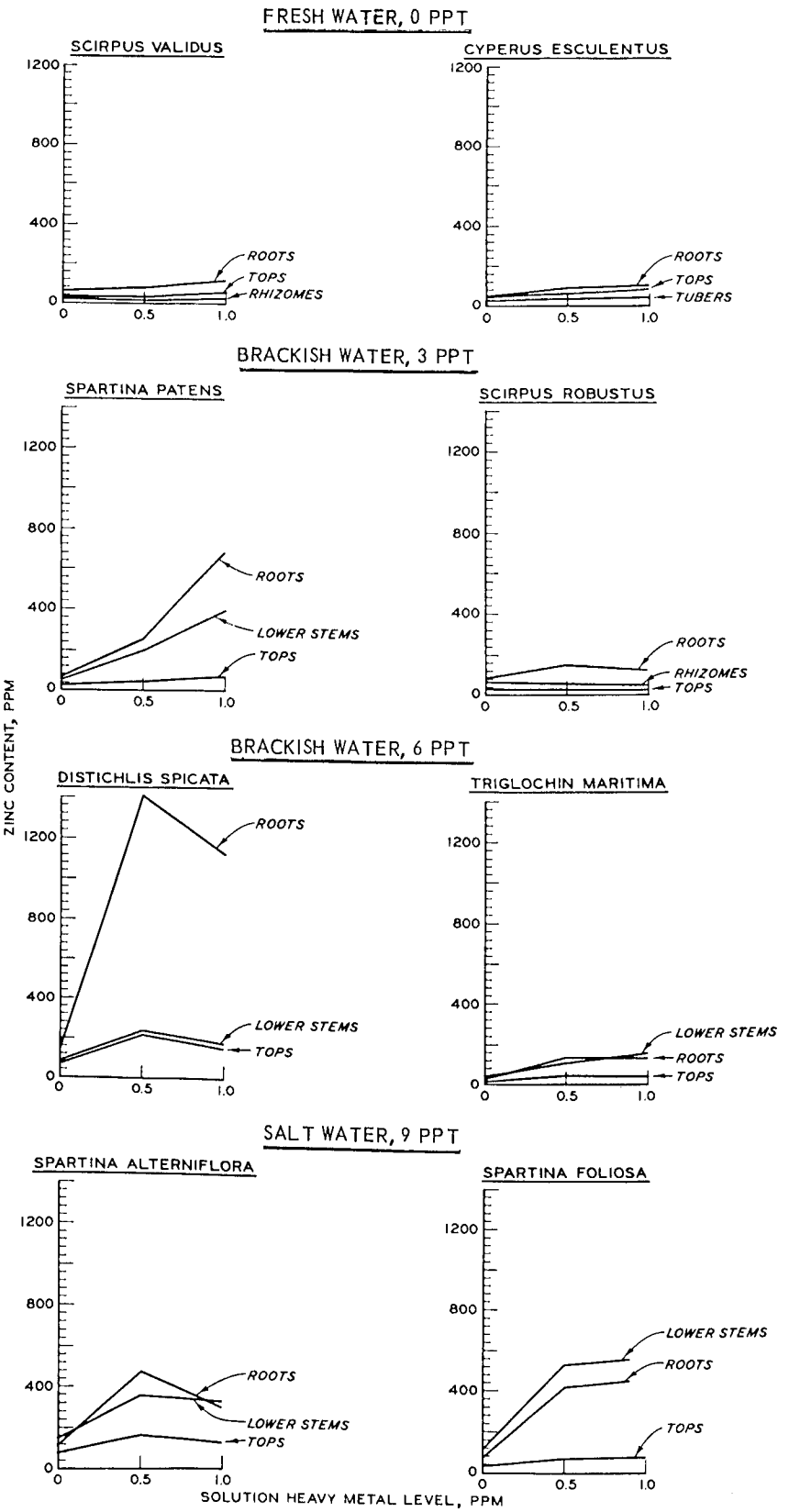


Figure 4. Zinc content of the parts of eight marsh plant species grown at three levels of heavy metals

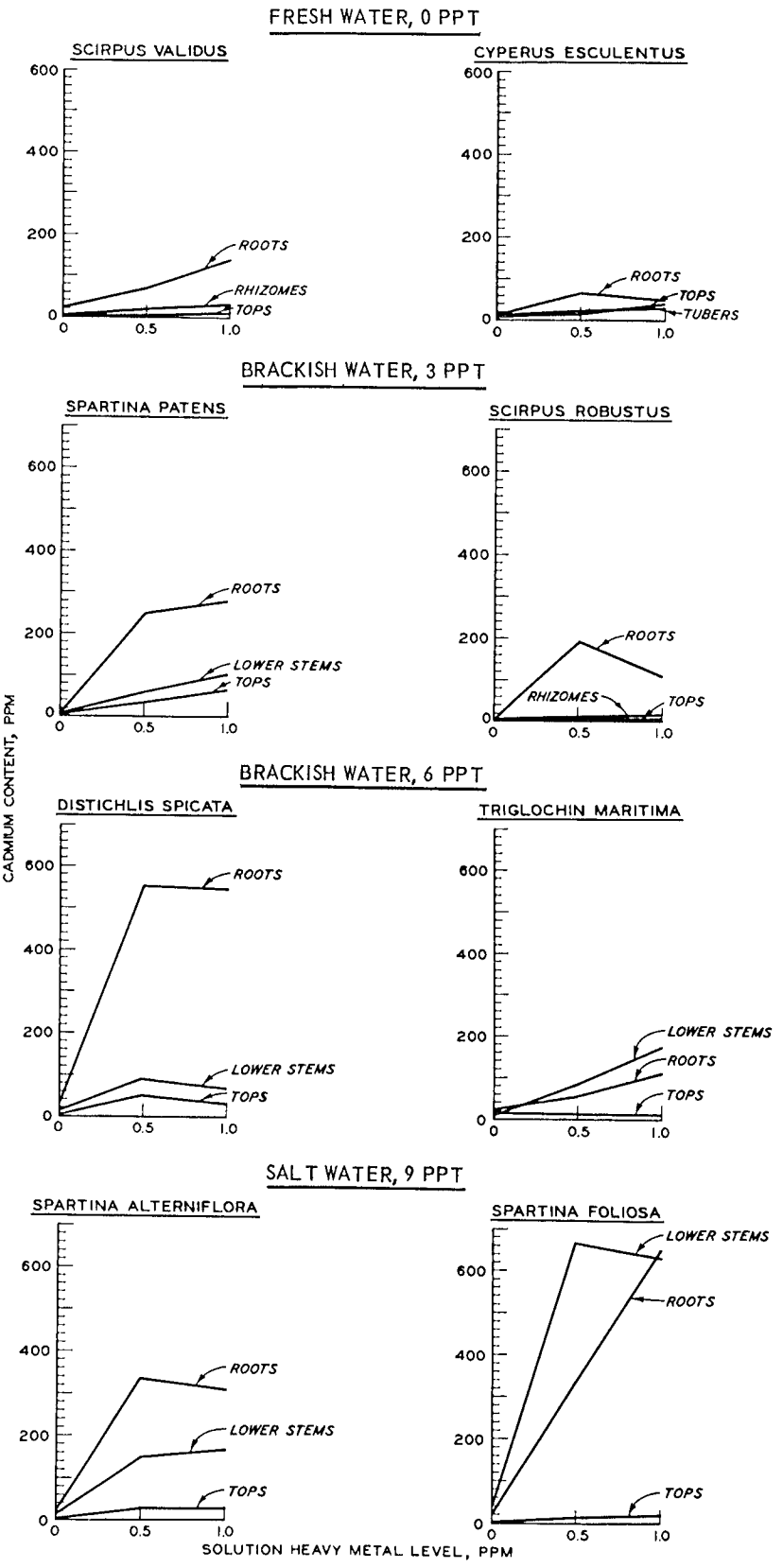


Figure 5. Cadmium content of the parts of eight marsh plant species grown at three levels of heavy metals

appear that C. esculentus can translocate more cadmium from plant roots to tops than S. validus.

57. Brackish water marsh plants (3 ppt). The addition of heavy metals to the hydroponic solutions increased the cadmium content of all plant parts of S. patens; however, only the roots of S. robustus showed significant increases in cadmium (Figure 5). S. patens contained more cadmium in its plant parts than S. robustus when heavy metals were applied. These data indicate that S. patens translocates more cadmium from plant roots to other plant parts than S. robustus.

58. Brackish water marsh plants (6 ppt). The lower stems and roots of both D. spicata and T. maritima increased in cadmium content when heavy metals were applied (Figure 5). D. spicata tended to contain slightly higher cadmium content in the tops than T. maritima when heavy metals were applied; however, these differences were not significant. These data suggest that while both plant species increased in cadmium in lower stems and roots, D. spicata may show greater cadmium content in plant tops than T. maritima at longer heavy-metal exposure periods.

59. Saltwater marsh plants (9 ppt). The addition of heavy metals to the hydroponic solutions increased the cadmium content of lower stems and roots for both S. alterniflora and S. foliosa (Figure 5). The tops of both species contained similar amounts of cadmium and did not increase in cadmium content when heavy metals were applied. These data suggest that S. alterniflora and S. foliosa may not translocate large amounts of cadmium rapidly. However, on prolonged exposure to cadmium, increased content might occur in plant tops.

Nickel

60. Freshwater marsh plants (0 ppt). Tops of C. esculentus increased in nickel content when 1.0 ppm of heavy metals was added to the hydroponic solutions (Figure 6), but the nickel concentration of the tops of S. validus did not change. The roots of both species increased in nickel content when heavy metals were applied. These data suggest the C. esculentus may translocate more nickel into plant tops than S. validus.

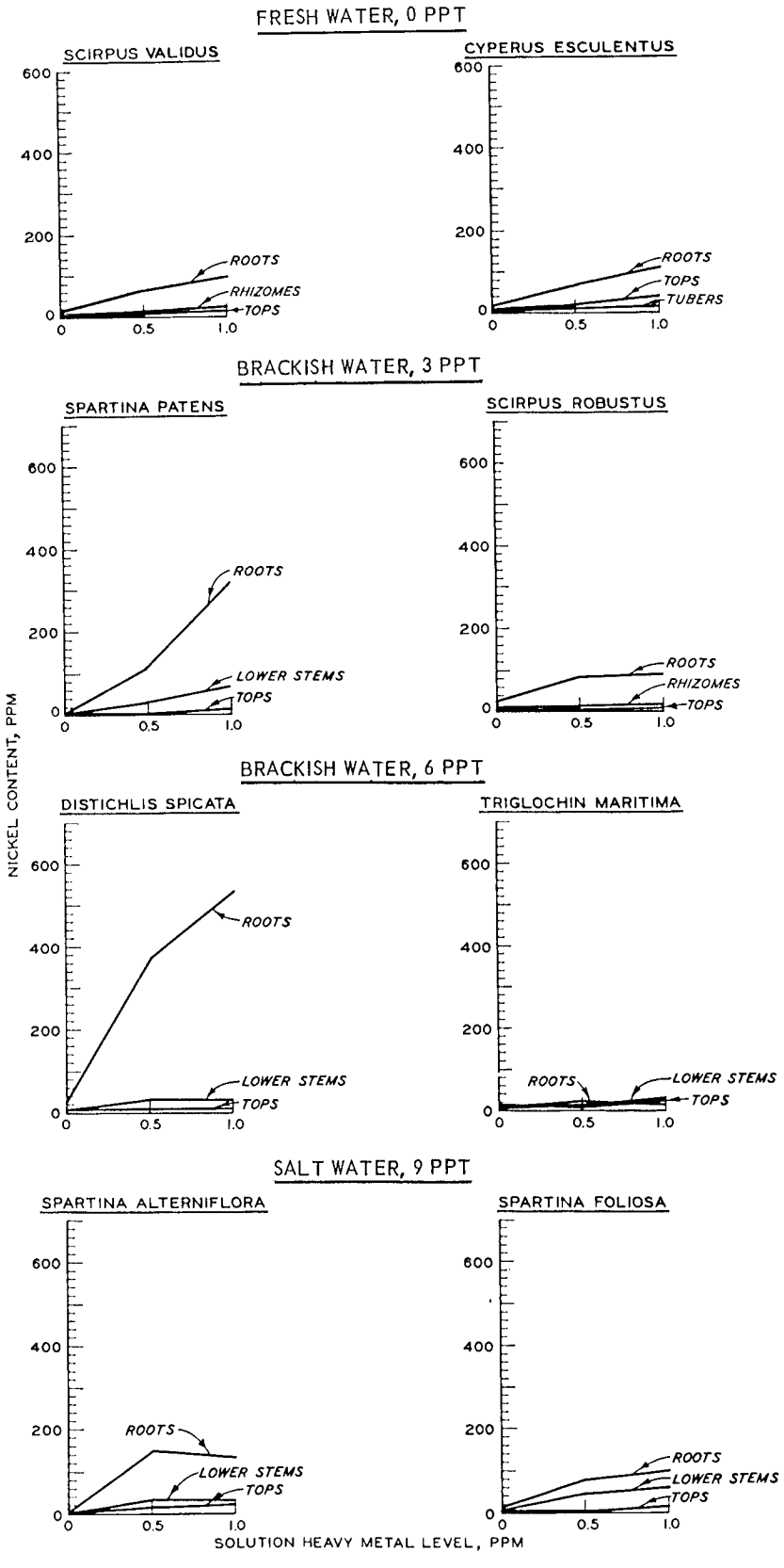


Figure 6. Nickel content of the parts of eight marsh plant species grown at three levels of heavy metals

61. Brackish water marsh plants (3 ppt). The tops of S. patens and S. robustus did not increase in nickel content when heavy metals were applied (Figure 6). While lower stems and roots of S. patens increased in nickel content when 1 ppm of heavy metals was added, only the roots of S. robustus increased in nickel content. S. patens contained more nickel in lower stems and roots than S. robustus at the 1.0-ppm level of heavy metals. These data suggest that nickel may move from plant roots of S. patens into other parts more rapidly than for S. robustus.

62. Brackish water marsh plants (6 ppt). The addition of heavy metals to the hydroponic solutions did not change the nickel content in the plant parts of T. maritima or the tops and lower stems of D. spicata (Figure 6). However, the nickel concentration of the roots of D. spicata increased drastically. The results indicate that nickel is not translocated rapidly from plant roots to other plant parts for either D. spicata or T. maritima.

63. Saltwater marsh plants (9 ppt). Although the lower stems and roots of both species increased in nickel content when heavy metals were applied, the tops for each species did not increase (Figure 6). These results indicate that both S. alterniflora and S. foliosa tops do not increase in nickel content during six weeks of exposure to heavy metals. However, since lower plant parts increased in nickel, longer periods of exposure to heavy metals may result in increased nickel content in plant tops.

Lead

64. Freshwater marsh plants (0 ppt). There was no increase in lead content of the tops, rhizomes, or tubers for either species with the addition of heavy metals (Figure 7). The rhizomes and tubers tended to increase in lead content but these differences were not significant. Roots of both species increased in lead content rapidly at the 0.5-ppm level of heavy metals. There was no difference between the lead content of roots at 0.5- and 1.0-ppm heavy metal levels. This probably resulted from the actual average lead concentration in solution being 0.266 and 0.108 ppm, respectively, for the 0.5- and 1.0-ppm level of

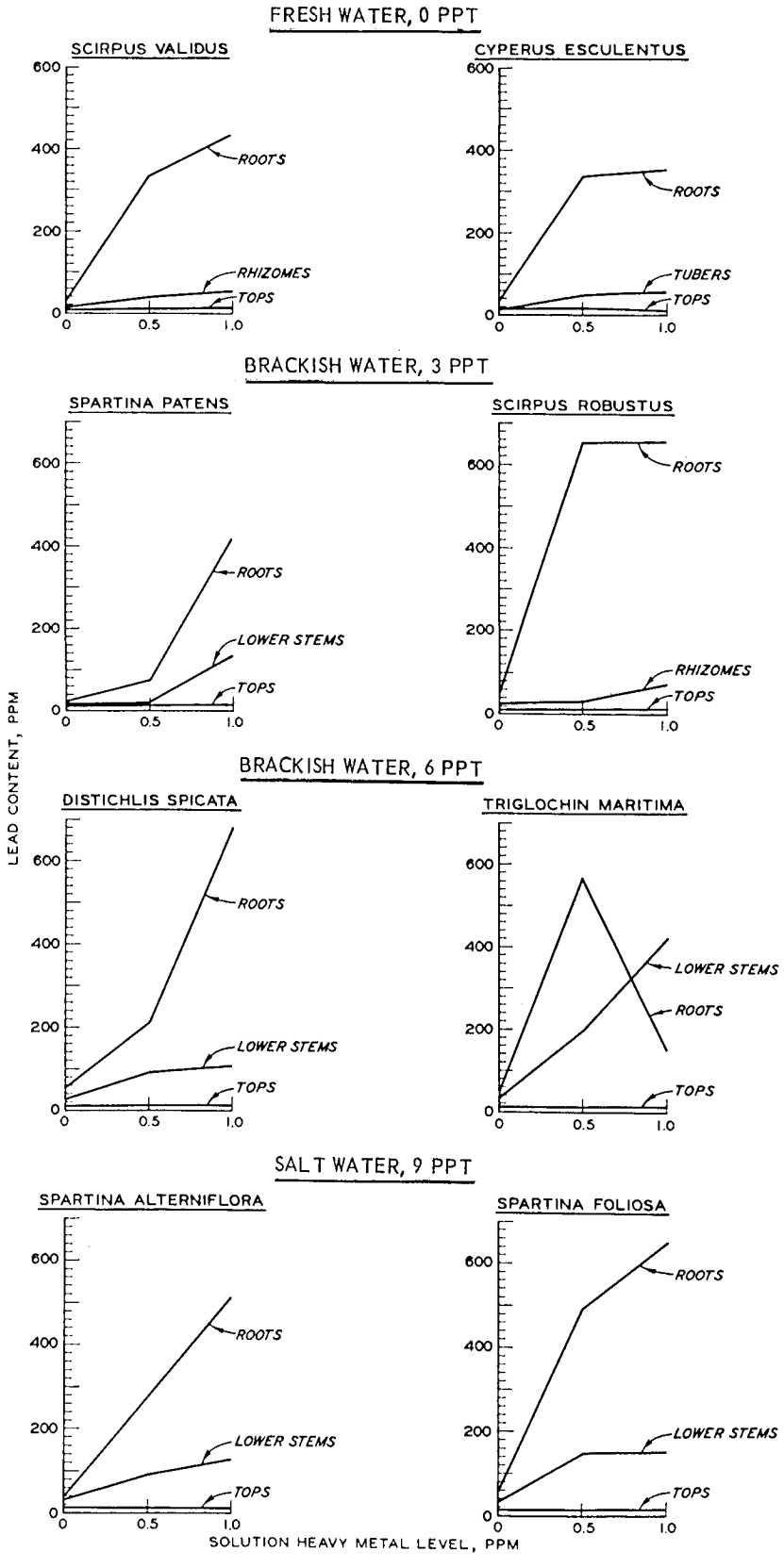


Figure 7. Lead content of the parts of eight marsh plant species grown at three levels of heavy metals

heavy metals (Table 5). Both plant species contained similar amounts of lead. These results suggest that lead is concentrated in plant roots or the belowground portions of plants with very little translocation into plant tops.

65. Brackish water marsh plants (3 ppt). Roots of S. robustus increased in lead content whenever heavy metals were applied, whereas S. patens roots increased in lead content only at the 1.0-ppm level of heavy metals (Figure 7). Neither plant species accumulated lead in the tops. The lead content of S. patens lower stems approached a significant increase and perhaps with longer exposure to heavy metals would have continued to increase in lead. These results suggest that lead is not translocated rapidly from plant roots to other plant parts; however, S. patens may translocate more lead from plant roots into other plant parts with longer exposure to heavy metals.

66. Brackish water marsh plants (6 ppt). Lower stems and roots of T. maritima increased in lead content when heavy metals were applied, whereas only the roots of D. spicata increased in lead (Figure 7). D. spicata lower stems tended to increase in lead content at the 1.0-ppm level of heavy metals but at a slower rate than the lower stems of T. maritima. The tops of each species did not show any change in lead content when heavy metals were applied. These data suggest that lead is not rapidly translocated into plant tops. However, lead may move from roots to lower stems in T. maritima more than in D. spicata.

67. Saltwater marsh plants (9 ppt). Roots for both S. alterniflora and S. foliosa increased in lead content when heavy metals were applied (Figure 7). Lower stems and tops did not increase in lead content following heavy metal additions. These results suggest that translocation of lead from plant roots to other plant parts is an equally slow process for both S. alterniflora and S. foliosa.

68. Since it was difficult to keep lead in solution at 0.5- and 1.0-ppm levels, there is the possibility that lead complexes may have formed in the hydroponic solution and these may have adsorbed to any surfaces that came in contact with the complexes including belowground portions of plants. Rinsing belowground plant parts in 0.1 N HCl may

not have been sufficient to remove adsorbed lead complexes. While a lead precipitate may have occurred in or on plant roots, there are numerous reports that lead has been found to accumulate in or on plant roots with very little translocation into aerial portions of the plant.[10-13] The chemistry of lead may be such that it forms complexes that tend to reduce the movement of lead into and through plant roots into aboveground parts.

Chromium

69. Freshwater marsh plants (0 ppt). Chromium content in plant parts was similar to lead. Plant tops, rhizomes, and tubers did not increase in chromium content when heavy metals were applied (Figure 8). Roots increased in chromium content whenever heavy metals were added to the hydroponic solutions. Both species contained similar amounts of chromium in plant parts. These results suggest that chromium may act similar to lead in that chromium may concentrate in plant roots with very little translocation into plant tops.

70. Brackish water marsh plants (3 ppt). Plant tops, lower stems, and rhizomes did not increase in chromium content when heavy metals were added (Figure 8). Plant roots for S. robustus increased in chromium content whenever heavy metals were added, whereas roots of S. patens increased in chromium content only at the 1.0-ppm level of heavy metals. These results suggest that chromium may move very slowly out of plant roots into other plant parts for both S. patens and S. robustus.

71. Brackish water marsh plants (6 ppt). The lower stems and roots of both species increased in chromium when heavy metals were added (Figure 8). Plant tops did not show any change in chromium content. These results indicate some movement of chromium out of the roots into lower stems for both D. spicata and T. maritima. Longer exposure to heavy metals may result in further movement of chromium into other plant parts for each plant species.

72. Saltwater marsh plants (9 ppt). Plant roots increased in chromium content when heavy metals were added (Figure 8). While lower stems tended to increase in chromium at the 1.0-ppm level of heavy metals, the differences were not significant. Plant tops were not

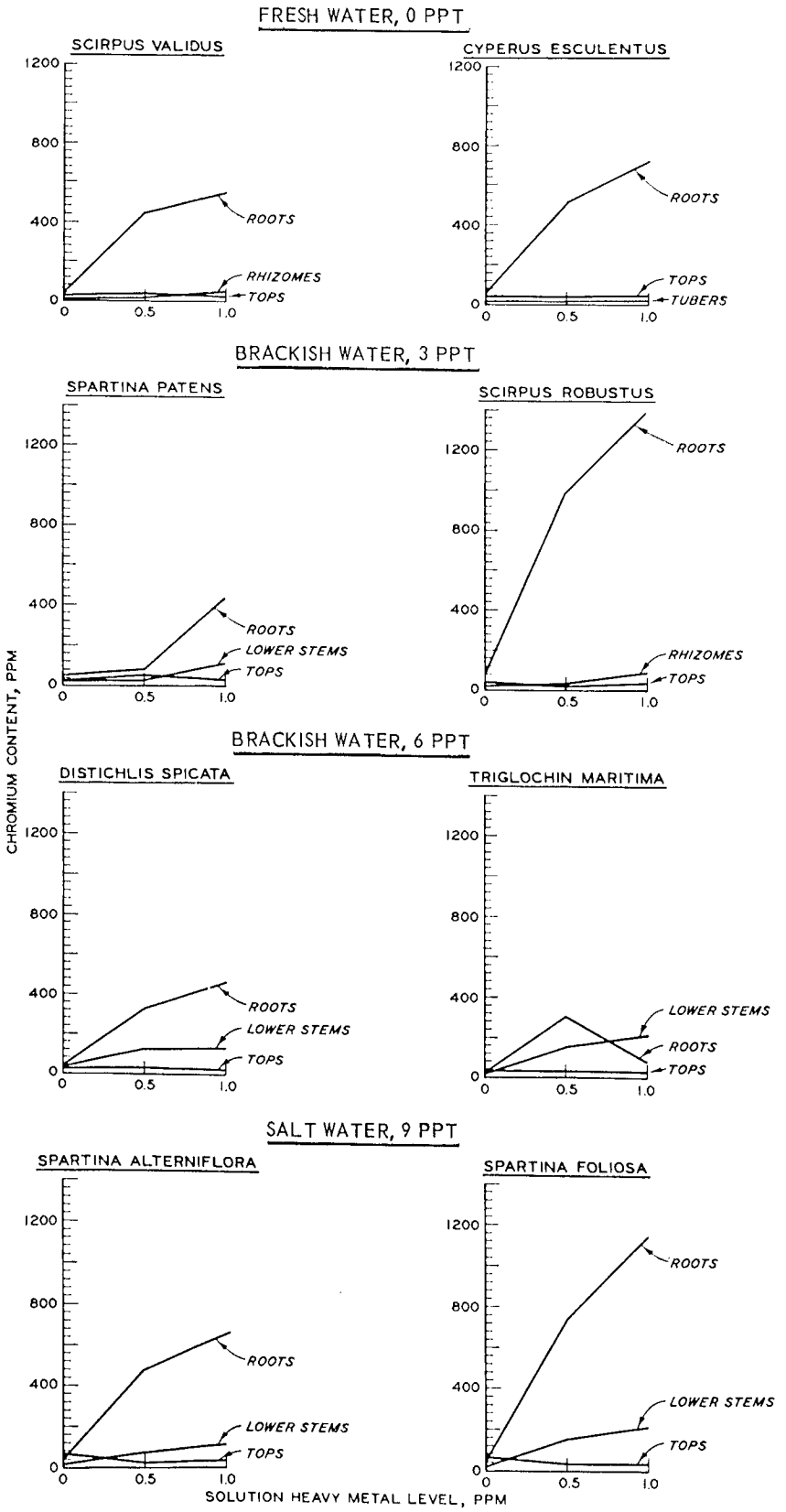


Figure 8. Chromium content of the parts of eight marsh plant species grown at three levels of heavy metals

changed in chromium content after heavy metal additions. These results suggest chromium translocation from plant roots to other plant parts is slow for S. alterniflora and S. foliosa.

73. Maintaining the concentration of chromium in solution was difficult as indicated by the water data (Table 5). Formation of complexes may have occurred similar to lead, and adsorption of chromium to surfaces including roots could explain the lower chromium concentrations found in solution. Very little chromium was translocated to plant tops in this study. In a recent study in which up to 400 ppm of chromium was added to soil as chromium chloride, very little chromium was translocated into plant tops even when plant growth was severely suppressed.[14]

Phosphorus and Iron Contents of Plant Parts

74. The phosphorus and iron contents of plants are important factors to consider when studying heavy metals. These elements interact with each other and also may influence the amounts of heavy metals taken up by plant roots and translocated into other plant parts. Some of the heavy metal data discussed previously can be explained to some extent by consideration of tissue concentrations of phosphorus and iron. For the purposes of this discussion, only the salient observations will be mentioned.

75. Phosphorus. The addition of heavy metals to the hydroponic solutions reduced the phosphorus content in plant tops of S. validus, C. esculentus, and S. alterniflora (Figure 9). Root phosphorus was reduced at the 1.0-ppm heavy metal level for S. validus, D. spicata, T. maritima, and S. foliosa. These results suggest that one or more heavy metals may influence the absorption and translocation of phosphorus in some marsh species.

76. Two of the four pairs of marsh plant species showed differences in phosphorus content of plant tops. Tops of S. patens contained more phosphorus than the tops of S. robustus, and the tops of S. alterniflora contained more phosphorus than those of S. foliosa.

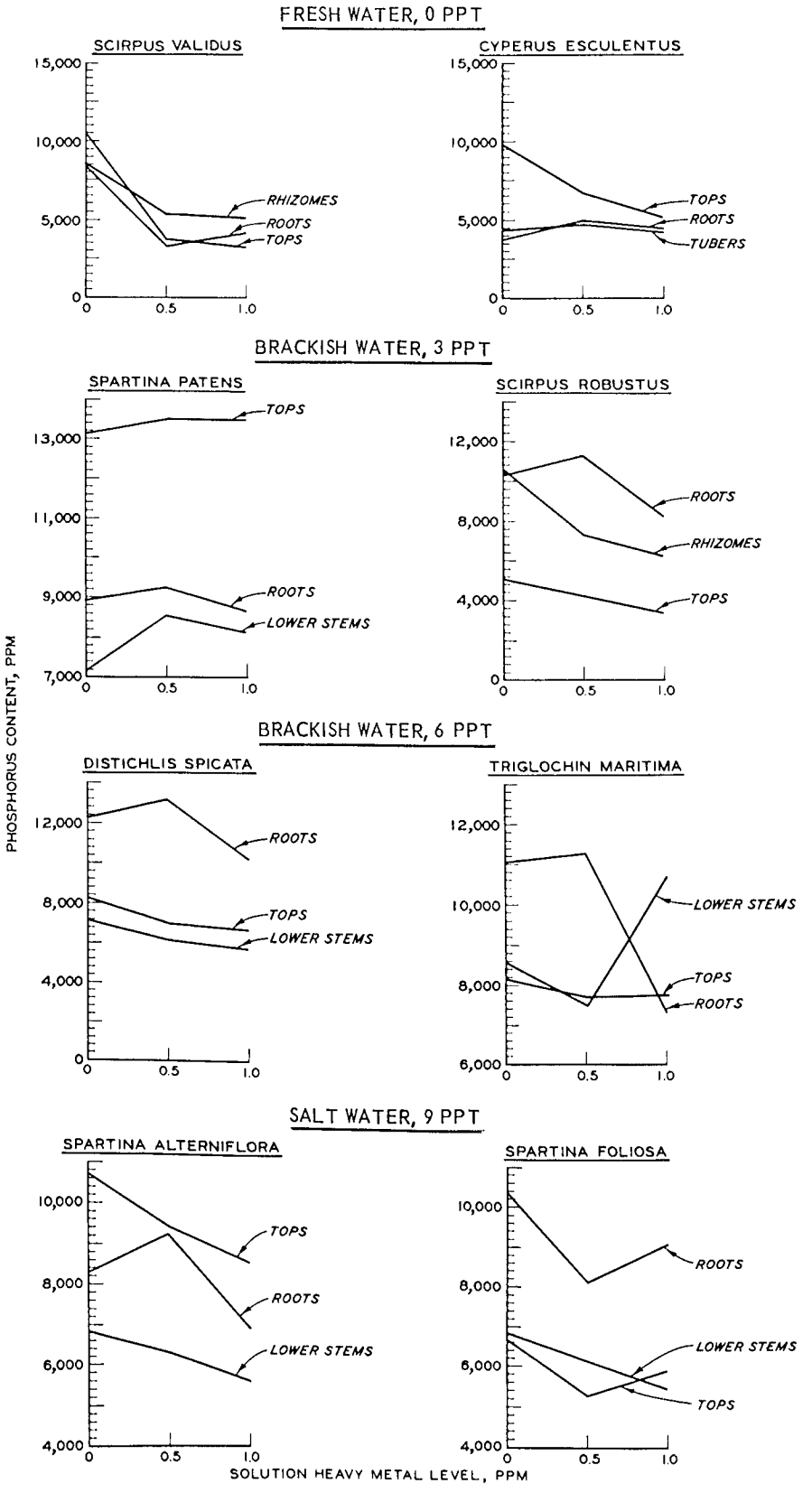


Figure 9. Phosphorus content of the parts of eight marsh plant species grown at three levels of heavy metals

77. Iron. For saltwater plants, iron content varied considerably in plant parts ranging from approximately 80 ppm in plant tops to over 16,000 ppm in the roots (Figure 10). Of the plant parts analyzed, the roots contained the most iron. There were differences in the iron content of the roots in two of the four pairs of marsh plants. Roots of S. robustus contained over ten times the iron content as roots of S. patens. Roots of S. foliosa also contained approximately eight times the iron content as roots of S. alterniflora. S. foliosa tended to have greater iron content in lower stems than S. alterniflora; however, this increase was not significant. S. foliosa did contain an overall higher iron content than S. alterniflora, combining all plant parts. S. alterniflora exhibited what appeared to be severe iron chlorosis, while S. foliosa showed very little chlorosis. These results suggest that S. alterniflora may be more sensitive to heavy metals toxicity than S. foliosa due to a lower capability to absorb and translocate iron.

78. Although the level of iron in the hydroponic solutions was increased to 1.0 ppm, the concentrations of iron in the plant tissues were comparable with data reported for marsh plants under natural conditions. Gosselink et al.[15] found ranges of iron concentrations of 70 to 106 ppm and 86 to 301 ppm for the tops of S. patens and D. spicata under natural marsh conditions over a four-month period. Iron concentrations in S. alterniflora were reported as 154 to 325 ppm which are more than that found in S. alterniflora but comparable with that of S. foliosa in this study.

79. Interactions of phosphorus and iron with heavy metals. Correlation analyses were performed on all the tissue chemical data combined over salinity levels to determine the existence and strength of the relationship of heavy metal contents in each plant part with the content of phosphorus and iron in that plant part. The more salient correlations are presented in Table 8.

80. There was a definite correlation between phosphorus and iron concentrations in the roots ($r = +0.78$). While iron concentrations of the roots were not correlated with the concentration of zinc, cadmium, and nickel in the roots, there was a low degree of correlation between

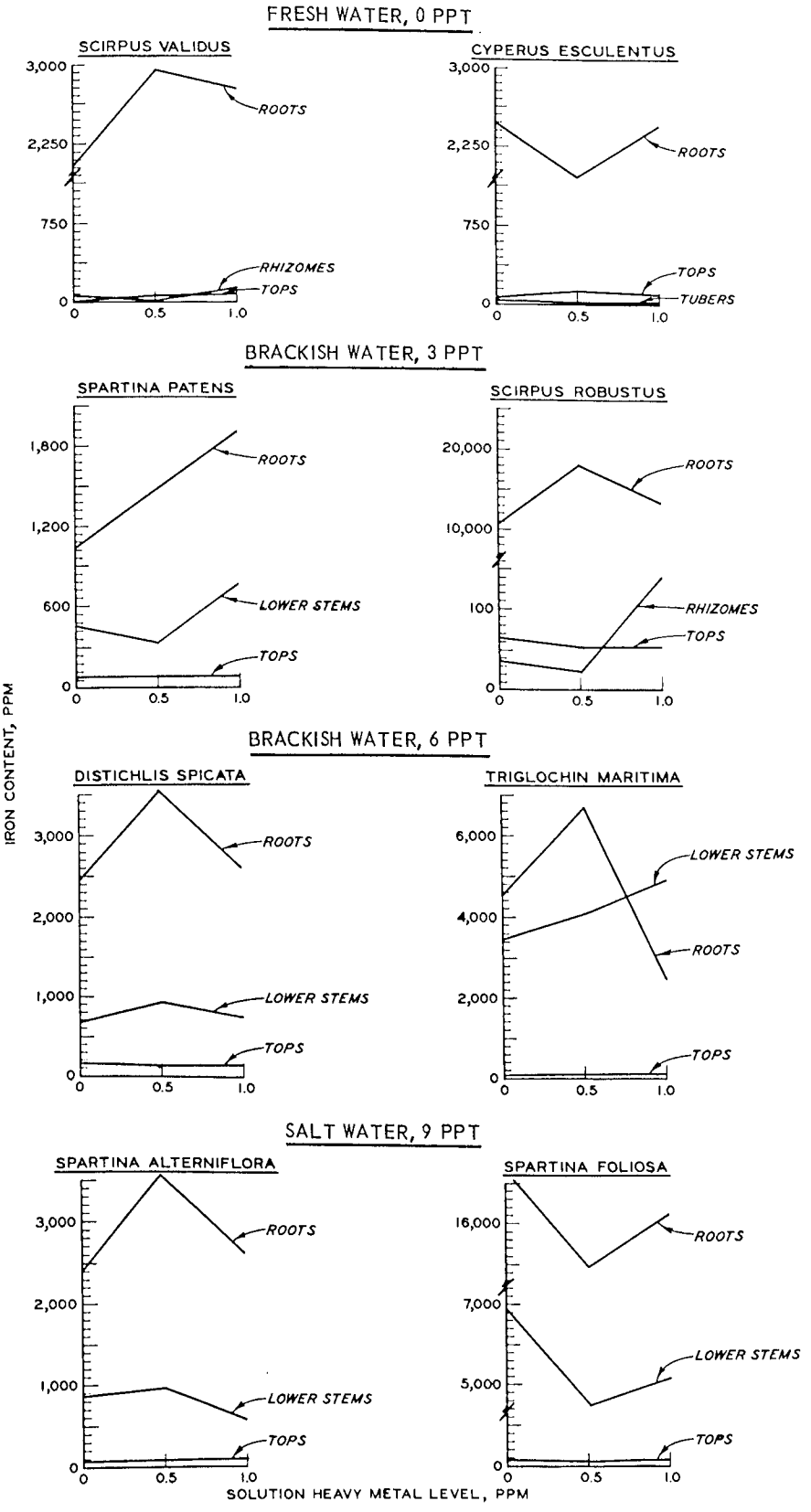


Figure 10. Iron content of the parts of eight marsh plant species grown at three levels of heavy metals

iron concentration and lead content of the roots (r = +0.60) and also between iron content and chromium content of the roots (r = +0.59). The phosphorus content of the roots also showed a low degree of correlation with lead (r = +0.40) and chromium (r = +0.34) contents of the roots.

81. At harvest, there was visual evidence that some type of iron oxide precipitate had formed during the growth period. As each planter was rinsed in 0.1 N HCl, a fine reddish-brown powder was observed to drain out of the planter. This observation along with the results described above suggests that iron-phosphorus complexes may have formed on or inside of the plant root and that lead and chromium may have adsorbed to these complexes and therefore accumulated on or in plant roots, unable to be translocated into other plant parts. Definite coprecipitation of heavy metals with iron oxides has been reported.[16] Root content of zinc, cadmium, and nickel apparently was not affected by the iron content of the roots; however, both the concentrations of zinc and nickel in the roots were correlated with phosphorus contents (Table 8). Therefore, phosphorus may affect zinc and nickel accumulations in or on plant roots more than iron.

82. Collectively, iron and phosphorus levels in the roots affected all of the heavy metals studied except cadmium. Cadmium contents in the roots were not correlated with either phosphorus or iron levels in roots. These interactions of phosphorus and iron levels in plant roots may be the mechanism that serves to control the levels of heavy metals in S. alterniflora tissues to which Dunstan et al. alluded.[2]

PART IV: CONCLUSIONS AND RECOMMENDATIONS

83. Results of this study suggest that certain marsh plant species are sensitive to the adverse effects of heavy metals on plant growth. S. validus, S. patens, D. spicata, and, to some extent, S. alterniflora appear to be more sensitive than C. esculentus, S. robustus, T. maritima, and S. foliosa.

84. Marsh plant species which appeared to have a greater potential for uptake and translocation within plant parts of zinc, cadmium, and nickel were C. esculentus, S. patens, and, to some extent, D. spicata. Both S. alterniflora and S. foliosa appear to take up heavy metals rapidly in plant roots and lower stems but then are slow to translocate them to plant tops. All of the marsh plant species studied appeared to accumulate lead and chromium in or on plant roots with little translocation into plant tops.

85. Levels of phosphorus and iron in plant roots were major factors related to the accumulation of zinc, nickel, lead, and chromium in plant roots and may determine the ability of a marsh plant to translocate these heavy metals from the roots to other plant parts. This study provides a preliminary indication of the ability of certain marsh plant species to rapidly take up certain heavy metals from hydroponic solutions. Further research is necessary to evaluate the ability of C. esculentus, S. patens, D. spicata, and S. alterniflora to take up heavy metals from dredged material.

86. Further research is recommended to evaluate the ability of C. esculentus, S. patens, D. spicata, and S. alterniflora to absorb and accumulate heavy metals from dredged material under varying laboratory and field conditions.

87. Since heavy metal absorption and accumulation are dependent upon the time of exposure of plants to heavy metals, it is recommended that further research consider longer time periods of exposure than those in the present study.

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Table 1

Chemical Composition of Experimental Nutrient Solution and a Modified Hoagland's Solution

Compound	Concentration, mg/ℓ	Elements, ppm								
		NH_4	NO_3	K	P	Ca	Mg	SO_4	Cl^-	Fe
Experimental Nutrient Solution										
NH_4Cl	402.0	135.2	-	-	-	-		-	266.7	-
KCl	178.9	-	-	93.8	-	-	-	-	85.2	-
KH_2PO_4	30.0	-	-	8.6	6.8	-	-	-	-	-
$CaCl_2$	200.2	-	-	-	-	72.3	-	-	128.1	-
$MgSO_4 \cdot 7H_2O$	2231.0	-	-	-	-	-	220.0	868.8	-	-
FeEDDHA	16.7	-	-	-	-	-	-	-	-	1.0
		135.2	0.0	102.4	6.8	72.3	220.0	868.8	480.0	1.0
Modified Hoagland's Solution*										
NH_4NO_3	60.0	13.5	46.5	-	-	-	-	-	-	-
KNO_3	243.0	-	149.1	93.8	-	-	-	-	-	-
KH_2PO_4	30.0	-	-	8.6	6.8	-	-	-	-	-
$Ca(NO_3)_2 \cdot 4H_2O$	426.0	-	223.8	-	-	72.3	-	-	-	-
$MgSO_4 \cdot 7H_2O$	296.0	-	-	-	-	-	29.2	115.3	-	-
FeEDDHA	1.67	-	-	-	-	-	-	-	-	0.1
		13.5	419.4	102.4	6.8	72.3	29.2	115.3	0.0	0.1

* As described by Lee.[5]

Table 2

Pairing of Marsh Plant Species According to Habitat Salinity

Species	Salinity	Hydroponic Salt Concentration, ppt
Scirpus validus	Fresh	0-2
Cyperus esculentus	Fresh	0-2
Spartina patens	Brackish	3-5
Scirpus robustus	Brackish	3-5
Distichlis spicata	Brackish	6-8
Triglochin maritima	Brackish	6-8
Spartina alterniflora	Saline	9-11
Spartina foliosa	Saline	9-11

Table 3

The Number, Size, and Average Fresh Weight of Marsh Plants Initially Planted

Species	No. of Plants	Size Fresh Weight, g S	M	L
Scirpus validus	20	70	85	150
Cyperus esculentus	20	22	50	105
Spartina patens	40	32	60	105
Scirpus robustus	10	60	110	145
Triglochin maritima	10	52	75	110
Distichlis spicata	15	19	26	40
Spartina alterniflora	20	35	50	100
Spartina foliosa	10	40	75	140

Table 4

Main Effects of Plant Size on the Concentration and Total Uptake of Heavy Metals by Marsh Plants at Each Salinity

Salinity ppt	Concentration, ppm Plant Size			Uptake, µg Plant Size		
	Small	Medium	Large	Small	Medium	Large
			Zinc			
0	51 a	54 a	48 a	123 a	216 b	364 c
3	128 a	119 a	143 a	738 a	1238 a	2192 b
6	320 b	203 a	260 a	567 a	732 b	1295 c
9	271 a	209 a	240 a	604 a	1039 a	2558 b
			Cadmium			
0	25 a	32 a	28 a	46 a	118 b	177 c
3	64 a	62 a	70 a	360 a	522 a	837 b
6	116 b	88 a	90 a	262 a	316 a	424 b
9	252 b	146 a	159 a	521 a	615 a	1531 b
			Nickel			
0	33 a	31 a	27 a	53 a	89 b	149 c
3	43 a	43 a	53 a	203 a	348 b	581 c
6	67 a	67 a	59 a	94 a	166 b	223 c
9	48 b	36 a	40 a	85 a	138 b	385 c
			Lead			
0	96 a	108 a	92 a	127 a	234 a	423 b
3	96 a	104 a	162 a	315 a	572 b	959 c
6	165 a	141 a	147 a	376 a	680 b	1014 c
9	170 a	155 a	108 a	245 a	468 b	796 c
			Chromium			
0	139 a	150 a	148 a	142 a	233 a	459 b
3	154 a	148 a	243 b	415 a	650 a	1206 b
6	134 a	100 a	108 a	313 a	463 b	700 c
9	238 a	221 a	168 a	318 a	664 b	1242 c

Note: Values under concentration or uptake within a salinity level for each heavy metal followed by similar letters are not significantly different at $P = 0.10$ according to the LSD test.

Table 5

Average Heavy Metal and Essential Element Concentrations, Average Salinity, and pH Values of Hydroponic Solutions

Expected		Actual Concentration, ppm										
		Heavy Metal					Essential Element				Actual	
Salinity Level ppt	Heavy Metal Level ppm	Zn	Cd	Ni	Pb	Cr	Fe	Mn	P	NH_4	Salinity	pH
0	0.0	0.08	0.06	0.21	0.010	0.005	1.03	0.48	7.6	154.9	2.00	5.18
	0.5	0.63	0.60	0.57	0.266	0.118	0.93	0.45	6.8	144.5	1.99	5.34
	1.0	1.25	1.26	1.28	0.108	0.261	1.08	0.57	7.2	160.4	2.04	5.54
3	0.0	0.11	0.06	0.20	0.017	0.005	1.03	0.52	9.4	193.2	7.09	5.08
	0.5	0.83	0.72	0.73	0.364	0.389	1.01	0.52	8.7	191.8	6.95	5.35
	1.0	1.52	1.34	1.43	0.168	0.377	1.16	0.62	9.1	198.0	6.82	5.69
6	0.0	0.10	0.07	0.19	0.014	0.003	0.83	0.36	8.0	157.2	8.31	5.57
	0.5	0.66	0.60	0.55	0.243	0.213	0.84	0.35	7.2	150.5	8.02	5.54
	1.0	1.23	1.20	1.20	0.719	0.600	0.79	0.32	6.5	147.4	7.91	5.57
9	0.0	0.14	0.07	0.18	0.019	0.004	0.74	0.37	7.6	149.7	11.5	5.60
	0.5	0.68	0.63	0.62	0.657	0.425	0.90	0.40	7.7	158.0	11.1	5.73
	1.0	1.11	1.08	1.03	0.732	0.605	0.80	0.39	7.0	142.6	10.8	5.68

Note: All values are means of 12 determinations except Pb and Cr, which are means of 4 determinations, and salinity and pH, which are means of 6 determinations.

Table 6

Effects of Heavy Metal on the Dry Yield, Number of Stems, and Final Height of Marsh Plants

Plant Species	Plant Part	Dry Yield, g			Number of Stems						Final Height, cm		
					Live			Dead					
Heavy Metal Level:		0	0.5	1.0	0	0.5	1.0	0	0.5	1.0	0	0.5	1.0
Scirpus validus	Tops	8.2 a	4.5 b	5.0 b	37 a	18 b	16 b	8 a	18 b	15 b	56 a	42 b	42 b
	Rhizomes	22.7 a	18.4 b	20.5 ab	121 a	79 b	84 b	46 a	31 b	34 b			
	Roots	1.4 a	1.0 ab	0.8 b									
Cyperus esculentus	Tops	2.5 a	2.3 a	2.4 a	0 a	0 a	0 a	20 a	20 a	20 a	0 a	0 a	0 a
	Tubers	8.5 a	8.0 a	8.7 a									
	Roots	1.5 a	1.6 a	1.5 a									
Spartina patens	Tops	41.7 a	37.0 b	25.1 c	248 a	268 a	185 b	0 a	0 a	0 a	74 a	76 a	64 b
	Lower stem	15.9 a	15.1 ab	12.7 b									
	Roots	8.6 a	8.8 a	6.5 b									
Scirpus robustus	Tops	8.1 a	8.3 a	9.9 a	10 a	9 a	10 a	3 a	4 ab	5 b	65 a	63 a	66 a
	Rhizomes	22.8 a	24.1 a	24.5 a	14 a	12 b	13 ab	14 a	13 a	13 a			
	Roots	0.7 a	0.8 a	0.9 a									
Distichlis spicata	Tops	12.4 a	8.7 b	9.0 b	58 a	46 a	49 a	0 a	0 a	0 a	54 a	46 b	41 b
	Lower stem	6.8 a	7.6 a	7.2 a	56 a	54 a	49 a	0 a	0 a	0 a			
	Roots	1.4 a	1.2 a	1.8 a									
Triglochin maritima	Tops	3.2 a	3.4 a	2.7 a	86 a	61 b	81 a	16 a	20 a	9 b	28 a	32 a	27 a
	Lower stem	7.9 a	8.0 a	8.4 a									
	Roots	5.0 a	4.7 a	5.1 a									
Spartina alterniflora	Tops	16.4 a	14.3 ab	12.6 b	36 a	32 a	30 a	3 ab	2 a	4 b	53 a	52 a	51 a
	Lower stem	5.9 a	6.3 a	6.1 a	44 a	40 a	33 b	0 a	0 a	0 a			
	Roots	4.3 ab	5.2 a	3.0 b									
Spartina foliosa	Tops	11.9 a	9.2 b	11.1 ab	13 ab	8 a	15 b	4 ab	6 a	3 b	49 a	42 a	46 a
	Lower stem	7.7 a	6.7 a	7.9 a	8 a	4 a	6 a	0 a	0 a	0 a			
	Roots	2.6 a	2.3 a	2.6 a									

Note: Means across heavy metal levels within a plant part followed by different letters are significantly different at the 10 percent level of significance.

Table 7

Effects of Heavy Metal Levels on the Plant Growth Index of the Various Sizes of Marsh Plants

Plant Species	Plant Size	Heavy Metal Level, ppm 0.0	0.5	1.0
		Growth Index		
Fresh Water, 0 ppt				
Scirpus validus	Large	1.8*	1.1	1.3
	Medium	1.7	1.2	1.0
	Small	1.5	0.9	1.0
Cyperus esculentus	Large	0.5	0.4	0.5
	Medium	0.4	0.4	0.4
	Small	0.6	0.5	0.5
Brackish Water, 3 ppt				
Spartina patens	Large	6.0	4.9	4.0
	Medium	6.2	5.5	3.7
	Small	5.8	6.2	3.5
Scirpus robustus	Large	0.9	0.8	0.8
	Medium	1.4	1.3	1.6
	Small	1.3	1.6	1.4
Brackish Water, 6 ppt				
Distichlis spicata	Large	3.0	2.5	2.4
	Medium	3.0	2.4	2.5
	Small	2.7	1.9	2.0
Triglochin maritima	Large	1.6	1.8	1.7
	Medium	1.8	1.9	1.5
	Small	1.6	1.4	1.6
Salt Water, 9 ppt				
Spartina alterniflora	Large	3.0	2.6	2.3
	Medium	2.9	2.7	2.1
	Small	2.0	1.8	1.7
Spartina foliosa	Large	1.4	1.2	1.4
	Medium	1.4	1.2	1.4
	Small	1.3	1.0	1.3

* Plant growth index equals final biomass divided by initial biomass.

Table 8

Correlation Coefficients for Selected Tissue Contents of Heavy Metals with Phosphorus and Iron

	Root Content	
Root Content	Phosphorus	Iron
Zinc	0.31*	0.09
Cadmium	0.11	0.05
Nickel	0.36*	0.28
Lead	0.40*	0.60*
Chromium	0.34*	0.59*
Iron	0.78*	

* Significant at the 5 percent level of significance.

APPENDIX A: CONTENTS OF HEAVY METALS, PHOSPHORUS, AND IRON IN PLANT PARTS

1. This appendix presents the chemical data used in Figures 4-10 in the Results and Discussion section of the main text. Tables A1-A7 present the means of tissue contents of an element for various plant parts of the eight marsh plants studied. Each value in a table is an average of three sizes of plants replicated twice or an average of six measurements. For comparison of means, three values of the least significant difference (LSD), calculated at the 10 percent level of significance, are presented for each pair of species at each salinity. The first LSD value is used to compare chemical contents in plant parts within a species at one heavy metal level. For example, in Table A1 an LSD of 23 ppm is used to compare the three mean zinc levels of 74, 37, and 99 ppm for tops, tubers, and roots, respectively, for C. esculentus at the 1.0-ppm heavy metal level. The same LSD value is used to compare similar means for S. validus at the 1.0 ppm of heavy metal level, i.e. values 27, 48, and 108 ppm, respectively.

2. The second LSD value is used to compare the chemical contents in one plant part within a species over each heavy metal level. For example, in Table A1 an LSD value of 28 ppm is used to compare the three zinc means of 52, 53, and 74 ppm for 0.0, 0.5, and 1.0 ppm of heavy metals, respectively, for C. esculentus tops. The same LSD value is used for zinc content of S. validus tops at each heavy metal level.

3. The third LSD value is used to compare the chemical content of one plant part of one species with the same plant part of the second species at a similar heavy metal level. For example, in Table A1 an LSD of 23 ppm is used to compare the mean zinc content of 74 ppm for C. esculentus tops at 1.0 ppm of heavy metals with the mean zinc content of 27 ppm for S. validus tops at the same level of heavy metals. In this case, C. esculentus tops contain 47 ppm more zinc than S. validus tops. This difference is greater than the LSD value of 23 ppm; therefore, it is concluded that C. esculentus tops contained a significantly higher content of zinc than S. validus. A similar procedure of LSD

comparison is followed to compare other means in each table. A difference between two means greater than the LSD value is significant at the 10 percent level of significance, that is to say, only 10 percent of the time or less will two sample means differ by this magnitude (LSD) while their corresponding population means are the same.

Table A1

Zinc Content for Various Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		Cyperus esculentus			Scirpus validus		
	Tops	52	53	74	23	20	27
	Tubers	28	30	37	--	--	--
	Rhizomes	--	--	--	29	30	48
	Roots	39	89	99	55	73	108
		LSD 0.10		1. 23	2. 28		3. 23
Brackish water (3 ppt)		Spartina patens			Scirpus robustus		
	Tops	20	45	77	22	22	19
	Lower stems	51	200	400	--	--	--
	Rhizomes	--	--	--	62	42	41
	Roots	60	256	679	71	148	124
		LSD 0.10		1. 45	2. 64		3. 58
Brackish water (6 ppt)		Distichlis spicata			Triglochin maritima		
	Tops	78	210	153	18	44	41
	Lower stems	78	221	171	40	102	146
	Roots	155	1820	1154	37	107	120
		LSD 0.10		1. 233	2. 240		3. 240
Salt water (9 ppt)		Spartina alterniflora			Spartina foliosa		
	Tops	73	149	112	42	64	69
	Lower stems	146	350	329	104	529	542
	Roots	114	440	299	74	423	463
		LSD 0.10		1. 134	2. 157		3. 158

Table A2

Cadmium Content for Various Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		*Cyperus esculentus*			*Scirpus validus*		
	Tops	2.2	18.0	38.0	1.2	3.1	11.0
	Tubers	3.0	20.0	28.0	--	--	--
	Rhizomes	--	--	--	0.9	20.0	36.0
	Roots	3.2	65.0	51.0	8.2	61.0	137.0
		LSD 0.10		1. 20	2. 24		3. 20
Brackish water (3 ppt)		*Spartina patens*			*Scirpus robustus*		
	Tops	1.2	35.0	61.0	1.3	2.3	3.5
	Lower stems	0.6	65.0	106.0	--	--	--
	Rhizomes	--	--	--	1.0	18.0	20.0
	Roots	1.8	256.0	285.0	3.8	198.0	116.0
		LSD 0.10		1. 50	2. 55		3. 51
Brackish water (6 ppt)		*Distichlis spicata*			*Triglochin maritima*		
	Tops	1.3	43.0	36.0	1.8	3.0	6.9
	Lower stems	1.4	88.0	67.0	0.6	81.0	170.0
	Roots	16.0	551.0	544.0	2.3	48.0	105.0
		LSD 0.10		1. 81	2. 78		3. 73
Salt water (9 ppt)		*Spartina alterniflora*			*Spartina foliosa*		
	Tops	1.2	30.0	29.0	1.3	9.0	19.0
	Lower stems	2.0	156.0	164.0	1.6	662.0	638.0
	Roots	3.7	334.0	312.0	2.9	332.0	645.0
		LSD 0.10		1. 134	2. 157		3. 158

Table A3

Nickel Content for Various Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		*Cyperus esculentus*			*Scirpus validus*		
	Tops	6.8	17.0	45.0	5.0	6.9	14.0
	Tubers	7.5	7.9	14.0	--	--	--
	Rhizomes	--	--	--	7.5	11.0	23.0
	Roots	14.0	69.0	112.0	15.0	67.0	101.0
		LSD 0.10		1. 17	2. 20		3. 19
Brackish water (3 ppt)		*Spartina patens*			*Scirpus robustus*		
	Tops	5.0	8.8	15.0	5.0	5.0	6.2
	Lower stems	7.5	27.0	70.0	--	--	--
	Rhizomes	--	--	--	13.0	12.0	15.0
	Roots	7.5	117.0	321.0	24.0	84.0	93.0
		LSD 0.10		1. 30	2. 31		3. 28
Brackish water (6 ppt)		*Distichlis spicata*			*Triglochin maritima*		
	Tops	5.0	6.2	7.5	7.6	10.0	24.0
	Lower stems	5.0	36.0	38.0	5.0	15.0	26.0
	Roots	9.6	376.0	539.0	5.8	17.0	22.0
		LSD 0.10		1. 43	2. 45		3. 42
Salt water (9 ppt)		*Spartina alterniflora*			*Spartina foliosa*		
	Tops	5.0	16.0	18.0	5.4	7.9	15.0
	Lower stems	5.0	28.0	30.0	6.6	40.0	76.0
	Roots	7.6	143.0	137.0	10.0	81.0	109.0
		LSD 0.10		1. 22	2. 23		3. 23

Table A4

Lead Content for Various Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		Cyperus esculentus			Scirpus validus		
	Tops	13	16	13	>10	11	11
	Tubers	12	44	56	--	--	--
	Rhizomes	--	--	--	12	40	46
	Roots	23	335	345	26	333	429
		LSD 0.10		1. 85	2. 99		3. 82
Brackish water (3 ppt)		Spartina patens			Scirpus robustus		
	Tops	>10	>10	>10	>10	>10	>10
	Lower stems	13	15	133	--	--	--
	Rhizomes	--	--	--	20	30	70
	Roots	13	69	410	40	651	654
		LSD 0.10		1. 148	2. 155		3. 154
Brackish water (6 ppt)		Distichlis spicata			Triglochin maritima		
	Tops	>10	>10	>10	15	12	12
	Lower stems	25	96	104	38	200	420
	Roots	42	289	680	33	562	159
		LSD 0.10		1. 100	2. 122		3. 119
Salt water (9 ppt)		Spartina alterniflora			Spartina foliosa		
	Tops	>10	>10	>10	11	10	12
	Lower stems	25	83	112	25	146	146
	Roots	28	289	518	35	483	646
		LSD 0.10		1. 157	2. 178		3. 171

Table A5

Chromium Content for Various Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		*Cyperus esculentus*			*Scirpus validus*		
	Tops	25	31	30	20	24	23
	Tubers	12	12	15	--	--	--
	Rhizomes	--	--	--	15	21	33
	Roots	59	525	763	30	439	546
		LSD 0.10		1. 144	2. 171		3. 137
Brackish water (3 ppt)		*Spartina patens*			*Scirpus robustus*		
	Tops	24	25	21	22	25	21
	Lower stems	12	17	108	--	--	--
	Rhizomes	--	--	--	21	27	72
	Roots	12	93	439	40	991	1293
		LSD 0.10		1. 197	2. 216		3. 201
Brackish water (6 ppt)		*Distichlis spicata*			*Triglochin maritima*		
	Tops	21	37	22	38	34	33
	Lower stems	12	118	131	12	160	200
	Roots	21	334	472	15	303	89
		LSD 0.10		1. 68	2. 84		3. 81
Salt water (9 ppt)		*Spartina alterniflora*			*Spartina foliosa*		
	Tops	28	22	28	27	24	25
	Lower stems	12	89	115	15	146	206
	Roots	14	478	646	21	713	1154
		LSD 0.10		1. 212	2. 253		3. 223

Table A6

Phosphorus Content for Various

Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		*Cyperus esculentus*			*Scirpus validus*		
	Tops	9940	6601	5171	10271	3454	3248
	Tubers	4188	4850	4050	--	--	--
	Rhizomes	--	--	--	8283	5399	5142
	Roots	3694	4936	4306	8241	3366	4067
		LSD 0.10		1. 1171	2. 1303		3. 1340
Brackish water (3 ppt)		*Spartina patens*			*Scirpus robustus*		
	Tops	13083	13450	13417	5170	4233	3696
	Lower stems	7183	8525	8054	--	--	--
	Rhizomes	--	--	--	10711	7899	7348
	Roots	8942	9204	8671	10196	11261	8375
		LSD 0.10		1. 2817	2. 2984		3. 3012
Brackish water (6 ppt)		*Distichlis spicata*			*Triglochin maritima*		
	Tops	8167	6933	6838	8182	7673	7695
	Lower stems	7138	6162	5921	8567	7550	10762
	Roots	12049	13772	10160	11075	11384	7168
		LSD 0.10		1. 1544	2. 1515		3. 1541
Salt water (9 ppt)		*Spartina alterniflora*			*Spartina foliosa*		
	Tops	10679	9288	8570	6617	5292	5958
	Lower stems	6800	6342	5600	6779	6183	5550
	Roots	8367	9243	6923	10304	8173	9177
		LSD 0.10		1. 2033	2. 2102		3. 2153

Table A7

Iron Content for Various Plant Parts of Eight Marsh Plants

Salinity	Plant Part	Heavy Metal Level, ppm					
		0	0.5	1.0	0	0.5	1.0
Fresh water (0 ppt)		Cyperus esculentus			Scirpus validus		
	Tops	129	150	111	33	50	56
	Tubers	79	31	27	--	--	--
	Rhizomes	--	--	--	73	44	72
	Roots	2395	1736	2344	2105	2971	2708
		LSD 0.10		1. 619	2. 637		3. 627
Brackish water (3 ppt)		Spartina patens			Scirpus robustus		
	Tops	88	88	88	63	51	52
	Lower stems	441	312	750	--	--	--
	Rhizomes	--	--	--	37	26	140
	Roots	1079	1508	1900	10797	18025	13017
		LSD 0.10		1. 6743	2. 7363		3. 6817
Brackish water (6 ppt)		Distichlis spicata			Triglochin maritima		
	Tops	152	131	132	96	92	97
	Lower stems	696	908	729	3458	4054	4971
	Roots	2412	3253	2650	4438	6629	2467
		LSD 0.10		1. 1723	2. 1688		3. 1657
Salt water (9 ppt)		Spartina alterniflora			Spartina foliosa		
	Tops	80	72	85	148	127	140
	Lower stems	896	946	529	6858	3192	5175
	Roots	2429	3556	2503	17135	14836	16207
		LSD 0.10		1. 2511	2. 2886		3. 2844

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