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ASSESSMENT OF METAL CONCENTRATIONS AND UPTAKE IN WATERFOWL FOOD ITEMS FROM A TREATMENT WETLAND

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INTRODUCTION

Wetlands are ecologically important ecosystems, and their value for fish and wildlife populations are well known. Wetlands support extensive food webs, abundant biodiversity, and play a major role in providing unique habitats for a wide variety of flora and fauna (Mitsch & Gosselink 1993). Both natural and constructed wetlands are important for providing habitat and food for many types of wildlife, fish, waterfowl, shorebirds, and migrating neotropical birds. Of the approximately 600 bird species in North America, about 200 species are either partially or wholly dependent on wetlands for some part of their life history (Kroodsma 1978). Also, the ability of natural wetlands to improve many aspects of water quality has long been recognized. One aspect of the natural wetland functions that has been capitalized on is the biogeochemical cycling and storage processes that occur in these systems (Nelson et al. 2006).

Constructed wetlands are human made, complex biological and physical environments that collectively alter the chemical nature of contaminants. They detoxify wastewater by immobilizing and/or transforming pollutants to less-toxic forms (Ye et al. 2003). The growth and adaptation of plants to the anoxic conditions in wetland sediments drives many of these processes (Horne 2000). The deliberate use of wetlands (both natural and constructed) as biological treatment systems for effluent purification has developed rapidly over the last 25-30 years. Constructed wetlands are attractive for water treatment because they are relatively inexpensive to build and operate, and require little or no energy for operation (Dunbabin & Bowmer 1992). Wetlands provide the benefits of removing nutrients and suspended solids, and reducing non-point source pollution (Stamenkovic et al. 2005). However, researchers have also pointed out

potential problems that might result from the use of wetlands for receiving wastewaters. Bioaccumulation of toxins that are present in some wastewaters create potential hazards that might outweigh the benefits of some treatment wetland projects (Knight et al. 2001). Organisms living in treatment wetlands can be exposed to contaminants through the water column, sediments, and successive food-web pathways. Highly toxic contaminants, such as metals, are known to accumulate in wetlands from certain kinds of wastewater.

In 2003, the Tarrant Regional Water District and Texas Parks and Wildlife Department entered into a cooperative agreement to build and maintain constructed wetlands at Richland Creek Wildlife Management Area. The initial phase of the project consists of four wetland cells that were constructed to treat water from the Trinity River before discharge into nearby Richland Chambers Reservoir. These wetlands, as part of the agreement, are also under moist-soil management to make them suitable habitat for migrating and wintering waterfowl and other wildlife. High concentrations of contaminants in sediments and wildlife food items present a potential risk to the waterfowl foraging in these wetlands. In addition, there could be potential risks to humans consuming waterfowl from the public hunting areas of the wetlands. Due to water quality data from the Trinity River and the nature of metals in water, Texas Parks and Wildlife and Stephen F. Austin State University initiated a research project to evaluate the potential for harmful levels of these metals to occur in waterfowl food items at RCWMA. A list of metals of concern, particularly lead, arsenic and mercury were compiled in consultation with TPWD personnel. The following objectives were addressed in this study:

1. Determine the existing concentrations and potential risks of wastewater-derived lead, arsenic and mercury in waterfowl food from treatment wetlands at RCWMA.
2. Quantify uptake factors and lead, arsenic and mercury accumulation potential for wetland plant species consumed by waterfowl.
3. Determine and evaluate waterfowl exposure pathways for metals in constructed wetland systems

METHODS

Study Area

The study was conducted at Richland Creek Wildlife Management Area (RCWMA) on the north unit which includes the four treatment wetlands created as a cooperative effort between the Texas Parks and Wildlife Department and the Tarrant County Regional Water District (Fig. 1).

The RCWMA is located about 80 miles southeast of Dallas in the area between the Richland-Chambers Reservoir and the Trinity River in Freestone and Navarro Counties. The north unit access is about 30 miles southeast of Corsicana, Texas on U.S. Highway 287. Richland Creek Wildlife Management Area is located in an ecotone separating the Post Oak Savannah to the east and Blackland Prairie ecological regions and the area lies almost entirely within the Trinity River floodplain. The area is subject to periodic and prolonged flooding. Average annual rainfall is 40 inches. Soils consist primarily of Trinity and Kaufman clays. These bottomland soils are highly productive and support a wide array of bottomland and wetland dependent wildlife and vegetation communities (TPWD 2008).

The north unit is a large non-forested area that is characterized by a diverse herbaceous community (TPWD 2008). Much of the area is maintained as a mix of open water and emergent vegetation suitable for habitation by wintering waterfowl. Common herbaceous species found within this area include wild millet (*Echinochloa walterii*), barnyard grass (*Echinochloa crusgalli*), delta duck potato (*Sagittaria spp*.), erect burhead (*Echinodorus spp*.), and square-stem spike rush (*Eleocharis quadrangulata*). The treatment wetlands in the north unit are horizontal surface flow wetlands. They are constructed in a way that the water is first pumped from the river into a sediment chamber where the river sediment is allowed to settle before entering the wetlands. The water then flows into the first cell and ends at the fourth cell. Once it reaches the fourth cell, it is then pumped into Richland Chambers Reservoir.

Objectives 1 & 3

Using ArcGIS 9.2, we randomly located ten sample points in each of the four treatment wetland cells and in a background, reference area (Fig. 2). A separate marsh on the North Unit RCWMA ("Compartment 2") that did not receive pumped water from the Trinity River served as the background sampling area (Fig 3). All sample points were marked using GPS and painted t-posts for visibility.

Sediment samples were collected at each of the ten random sample point within each wetland cell. We used a soil corer to obtain sediment from the root zone (the top 5 to 10 centimeters of soil profile). Samples were homogenized, placed in labeled plastic containers and placed immediately in a cooler of ice for transport to minimize mercury volatilization.

The plant species selected for sampling were based on a previous study at RCWMA where the food habits of waterfowl inhabiting those wetlands were examined. The study identified several plant species and their relevant parts that were most abundant in the diet of waterfowl feeding at RCWMA (D.P. Collins, Stephen F. Austin State University, unpublished data). Our primary species selected for seed consumption include barnyard grass (*Echinochloa crusgalli*), wild millet (*Echinochloa walterii*), and nodding smartweed (*Polygonum lapathifolium*). As nodding smartweed was not present in all wetland cells, we used mild water pepper (*Polygonum hydropiperoides*) as a secondary species in that genus. The species selected for tubers and underground parts was the delta duck potato (*Sagittaria* sp.). Finally, we selected a plant species for which the primary part consumed by waterfowl was the foliage: coontail (*Ceratophyllum demersum*). We collected samples of all target plant species at each of the ten random points in each wetland cell. If the target plant species was not available at the random point, then the sample was taken from the closest stand of the target plant to the sample point. All plant samples were hand clipped and placed into properly labeled paper bags and placed immediately in a cooler of ice for storage and transport. The geographic coordinates for each plant sample were recorded. Plants samples were collected seasonally depending on the availability of appropriate parts (e.g., *Polygonum* and *Echinochloa* spp. were collected in late summer/early fall when seeds are available).

Invertebrates were sampled monthly from February to April when the waterfowl were present and foraging in the wetlands. Because waterfowl feed on both benthic and water column invertebrates, we collected and analyzed two samples from each wetland cell and the background area. Benthic samples were collected using an Eckman dredge and water

column samples were collected using sweep nets. Invertebrates were collected near vegetation throughout each wetland cell until at least ten grams of wet weight had been attained for each composite sample. Samples were placed in labeled plastic containers and immediately placed on ice for transport. All samples were transported back to the Environmental Assessment Laboratory at Stephen F. Austin State University and stored at -20° C until they were ready to be analyzed.

Objective 2

Knowledge of uptake rates for metals by wetland plants is important for assessment of future potential risks regardless of current contaminant concentrations at RCWMA. We conducted a controlled laboratory study using known contaminant concentrations on common plant species known to be consumed by waterfowl in RCWMA. We grew plants for this study in the growth chambers located in the Environmental Assessment Laboratory at the Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University. Based on their use by waterfowl at RCWMA and widespread importance to waterfowl, we chose barnyard grass (*Echinochloa crusgalli*) and nodding smartweed (*Polygonum lapathifolium*) as representative grass and forb species, respectively, for this study.

Each plant species was evaluated tested for uptake of two metals: lead and mercury. To avoid potential uptake interactions between the target metals, we evaluated each in a separate set of treatments. Because uptake can vary depending on concentration of the contaminant, we evaluated four known contaminant levels varying by roughly an order of magnitude for each metal. Each treatment (e.g., combination of metal concentration and plant species) was replicated 5 times for a total of 100 pots (5 treatments [4 metals

concentrations plus control]*5 replicates*2 plant species*2 metals). Target plant seeds were planted in one-gallon buckets filled with washed sand to minimize effects of soil clay or organic matter on uptake. We planted ten to twelve seeds of the appropriate species in each pot and place them in the growth chambers to allow for germination. Following germination, the seedlings were culled down to five plants per container. We spiked the initial watering with metals to reach the desired concentrations in each pot. Target concentrations for lead (in the form of lead nitrate) were 1, 10, 100, and 500 mg Pb/kg soil. Target concentrations for mercury were 0.01, 0.1, 1, and 5 mg Hg/kg soil. We watered all pots as necessary with deionized water to maintain water approximately 5 cm below the soil surface and supplemented with a nutrient solution two to three days after the spiking with metals. All plants were grown until seed out at approximately 60 days. We then harvested and composited seed samples from within each pot for metals concentration analysis. We also collected whole plants from 10% of the pots for analysis to examine partitioning within the plants. Finally, we collected a single composite soil samples from each pot to determine final metal concentration. All remaining contaminated soil was discarded according to appropriate guidelines.

Laboratory Analysis

All samples collected during this study were analyzed in the Soil, Plant, and Water Analysis Laboratory and Environmental Assessment Laboratory at Stephen F. Austin State University. Samples were kept at -20° C following collection to avoid volatilization of mercury. When they were ready for processing and analysis, all samples were freeze dried to remove water while avoiding mercury volatilization that would be possible in oven drying. Once the samples were dried, a 0.5 grams (dry weight) of each

sample was weighed and placed into a digestion tube. Invertebrate and plant samples were digested using the EPA Nitric-Hydrogen Peroxide method. Sediment samples were digested using the EPA 3050b Nitric-Hydrochloric acid "Metal" digest. Concentrations of mercury were determined using the PerkinElmer A Analyst 700 Cold Vapor Atomic Absorption Spectroscopy (CVAA) in the Environmental Assessment Laboratory. Lead and arsenic concentrations were determined using the PerkinElmer A Analyst 700 graphite furnace system.

Data Analysis

Objective 1: We used a combination of statistical and graphical analyses to identify potential risks to waterfowl using habitats at RCWMA. In addition to calculating frequency tables and descriptive statistics for metals in each wetland cell, we used analysis of variance (ANOVA) to compare mean concentrations among cells. Where ANOVA indicated differences among cells, we used Tukey's test for multiple comparisons to delineate individual differences among cells.

To identify potential risks to waterfowl using the wetland cells at RCWMA, we used toxicity reference values (TRVs) from the toxicological literature for arsenic, lead and mercury (Table X). The Texas Council on Environmental Quality publishes sediment quality guidelines for various potential contaminants of concern, including arsenic, lead, and mercury (TCEQ 2010). We used these values as screening TRVs for exposure to sediments at RCWMA. For metals in food items, we used values from the literature. Mercury is a highly toxic metal that is known to bioaccumulate and cause reproductive impairment and death in many species of aquatic birds. According to the US EPA (1997), a reference dose (RfD) for mercury, defined as the chronic no observed adverse

effect level (NOAEL), was derived for avian species from studies by Heinz (1979) in which three generations of mallard ducks (*Anas platyrhynchos*) were dosed with methylmercury dicyandiamide. Methylmercury is the most toxic and bioaccumulative form of this metal, so our TRV represents a conservative estimate of potential toxicity.

Lead has caused severe concern for adverse health effects to humans and wildlife. With chronic exposure, lead causes anemia and neurological dysfunction. In a study by Pain (1996), in which waterfowl consumed lead contaminated sediment, the authors concluded that <0.20 µg/ml of blood lead was a background concentration. We derived our food TRV for lead from a study of lead exposure in Japanese quail (*Coturnix* spp.) as cited in published toxicity benchmark values for wildlife (Sample et al. 1997).

Arsenic is considered a carcinogen and an acute toxin. In a study by Pascoe et al. (1996), it was found that nine-week exposures of ducklings to sodium arsenate in the diet resulted in a NOAEL of 1.25 mg/kg-day (30 ppm in diet). Higher doses at 12.5 mg/kg-day were related to significant effects on the schedules of bathing, resting, and alertness (Whitworth et al. 1991). In a study of 99 pairs of breeding mallards fed sodium arsenate in the diet throughout the reproductive cycle, a NOAEL of 4.2 mg/kg-day (100 ppm in diet) was observed, with a LOAEL of 16.7 mg/kg-day for reduced weight gain, reduced liver weight, delayed egg laying, reduced egg weight, and eggshell thinning (Stanley et al. 1994). In another study, duckling mallards fed As in the diet showed decreased growth at 12.5 mg/kg-day (300 ppm in diet), with a NOAEL at 4.2 mg/kg-day (Camardese et al. 1990; Pascoe et al. 1996). We used the NOAEL level from Stanley et al. (1994) as a conservative food TRV for this study.

Objective 2: We derived uptake factors independently for each pot in the growth chamber experiment by calculating the ratio of lead or mercury in seeds to that measured in the soil from that pot. We then calculated mean uptake ratios for each treatment and plotted those on an uptake curve to identify how concentration affected uptake of lead and mercury.

Objective 3: Using the concentrations measured in various media at RCWMA and the comparisons with established TRVs, we determined the most significant exposure pathways for waterfowl at RCWMA and estimated the ecological risk associated with potential arsenic, lead, and mercury exposure at the site.

RESULTS

Wetland Soils

Lead was detected in all 50 samples collected from the wetland cells and the control. All values were below the 91.3 ppm TRV for soil. The highest lead concentration was found in Cell 1 at 0.0293 ppm. The lowest concentration was found in the control at 0.0075 ppm. Lead concentrations varied among cells ($P = 0.0025$), with Cell 1 greater than Cell 3 and all other cells (including background) not different (Table 2, Figure 6). Cell 1 had the highest mean and Cell 3 had the lowest. Arsenic was detected in all soil samples from each wetland cell and the control. All values were below the 17.0 ppm TRV. The highest arsenic concentration was 0.327 ppm and obtained from Cell 4. The lowest concentration was 0.003 ppm from the control. Arsenic concentrations differed ($P<0.0001$) among cells. Cell 4 had greater arsenic levels than the other cells and all wetland cells were elevated compared to the background marsh (Table 2, Figure 5). Mercury was detected in all wetland samples and the control area. All samples were

below the TRV of 0.486 ppm for soil. Mean mercury concentrations did not vary among cells. The highest mercury value was reported in Cell 1 at 14.07 ppb. The lowest value was 0.199 ppb from Cell 4 (Figure 4).

Invertebrates

Lead was detected in all 30 water column and benthic invertebrate samples from the wetland cells and the control. However, all concentrations were well below the TRV of 50 ppm. The highest concentration of lead obtained for water column samples was 0.0134 ppm from Cell 1. The lowest concentration was found in the control at 0.001 ppm. The highest lead concentration for benthic samples was 0.0773 ppm from Cell 3. This was also the highest lead value for both benthic and water column samples. The lowest value for benthic samples was 0.0012 ppm from the control. Lead for both water column ($P = 0.50$) and benthic ($P = 0.62$) invertebrates showed no significant differences among the cells (Table 3, Table 4; Figure 9, Figure 12).

Arsenic was detected in 17 of 30 water column and benthic invertebrate samples (Table 3, Table 4). The TRV for Arsenic was not exceeded in any sample. The highest level of arsenic found in water column samples was 0.174 ppm from Cell 1. The lowest values were non-detections that were reported from both Cell 3 and Cell 4. For benthic invertebrates, the highest arsenic concentration was 0.134 ppm from the control. The lowest values were non-detections from all four treatment cells, including the control. The p-values for arsenic for both water column and benthic samples showed no significant differences among the cells (Table 3, Table 4; Figure 8, Figure 11).

Mercury was detected in all 30 water column and benthic invertebrate samples. All sample concentrations were well below the TRV. The highest level of mercury for water

column samples was 3.867 ppb from Cell 1 (Table 3, Figure 7). The lowest level obtained was also from Cell 1 at 0.050 ppb. The maximum level of mercury in the benthic samples was 45.28 ppb from Cell 4. The lowest level was also found in Cell 4 at 2.968 ppb (Table 4, Figure 10). The benthic samples tended to accumulate higher concentrations of Hg than the water column samples. Mercury p-values for both water column (P = 0.94) and benthic (0.73) samples showed no significant differences among the cells.

Plant Forage

Duck Potato

Lead was detected in all 50 samples from the wetland cells and the control. All of the samples were lower than the TRV. The highest lead concentration for duck potato was from Cell 2 at 0.0462 ppm. The lowest lead concentration was 0.0024 ppm from Cell 3. The p-value for lead did not result in a significant difference among the cells (Table 5, Figure 15). Arsenic was detected in 49 of the 50 duck potato samples. The only non-detection was from Cell 4. All samples were below the TRV. The highest arsenic level was 0.277 ppm from Cell 3. The lowest level was the non-detection from Cell 4. The p-value of 0.009 for arsenic showed significant differences in that Cell 2 had the highest mean, Cell 3 and the control averaged about the same, and Cells 1 and 4 had the lowest means (Table 5, Figure 14). Mercury was only detected in 3 out of the 50 samples of duck potato, which were all from the control. All three detections were well below the TRV. The highest level was 0.068 ppm and the lowest level was 0.022 ppm. According to the p-value for mercury, there were no significant differences among the cells (Table 5, Figure 13).

Coontail

Lead was detected in 18 out of 20 samples of coontail. All levels were below the TRV. The highest level of lead was 0.0672 ppm from Cell 4. The lowest concentration was the non-detections that were also from cell 4. The p-value for lead resulted in no significant differences among cells (Table 6, Figure 18). Arsenic was detected in 15 out of 20 samples from Cell 4 and the control. The highest Arsenic level was 0.126 ppm from the control. The lowest levels were non-detections from both of those areas. The p-value for arsenic also resulted in no significant differences among the cells (Table 6, Figure 17). Mercury was detected in all 20 samples. The highest level was 0.758 ppb from the control. The lowest level was 0.017 ppb from Cell 4. The p-value of 0.0003 for mercury showed that Cell 4 and the control were significantly different in that the control had a higher mean (Table 6, Figure 16). All values for Lead, Arsenic and Mercury were also below the TRV's.

Barnyard Grass

Lead was detected in only 35 of the 50 samples of Barnyard Grass. Cell 1 was the only cell with detections in all 10 samples. The highest level of lead was 0.0491 ppm from Cell 4. The lowest levels were the non-detections from the rest of the cells and the control. There were no significant differences among the cells according to the p-value for lead (Table 7, Figure 20). Arsenic was not detected in any of the 50 samples from all cells and the control. There was no p-value associated with arsenic since there was no data for those cells. Mercury was only detected in 17 out of the 50 samples. The only cell with all 10 detections was the control. The highest mercury value was 0.035 ppb from the control. The lowest levels were the non-detections from all other cells. The p-

value for mercury was <.0001. The difference was that the control had the highest mean concentration than all of the cells (Table 7, Figure 19). All of the sample concentrations were below the TRV's.

Nodding Smartweed/Water Pepper

Lead was detected in 47 out of the 50 samples. The highest concentration was 0.0053 from the control. The lowest values were the three non-detections from Cells 2 and 3. The p-value for lead was 0.0173, which showed that the control had the lowest mean concentrations. Cells 1, 2 and 4 had the highest (Table 8, Figure 23). Arsenic was only detected in 5 of the 50 samples. Cell 1 had the most detections with 4 out of 10 samples. The highest level was 0.004 ppm from Cell 1. The lowest values were the non-detections from all of the cells and the control. The p-value for arsenic was 0.005. This showed that Cell 1 had the highest mean concentrations (Table 8, Figure 22). Mercury was detected in 28 out of 50 samples. The control had the highest number of detections with 9 out of 10 samples. The highest value for mercury was 0.054 ppb from the control. The lowest values were non-detections from all of the cells and control. The p-value for mercury was 0.0036. The control had the highest mean concentrations (Table 8, Figure 21). All levels for each element were below the TRV's.

Uptake of Mercury Nitrate in Barnyard Grass *(Echinochloa crusgalli*) Seeds

Average uptake ratios for each treatment showed that as soil concentrations increased, the accumulations within the plants decreased (Table 8, Figure 26). The 0.01 ppb treatment had an average plant/soil ratio of 0.5. The 0.1 ppb treatment had a decreasing plant/soil ratio of 0.112. The highest treatment, 1 ppm, had the smallest average plant/soil ratio of 0.004. We ran 20% of the samples as whole plants to see if there were

any differences in uptake between the seeds and the whole plant. All of the whole plants analyzed had higher plant/soil uptake factors than the seeds. For one replicate out of the 0.1 ppb treatment, the whole plant accumulated 16.31 ppb while the seeds of that replicate accumulated 2.943 ppb. That is a 0.576 plant/soil ratio versus a 0.104 plant/soil ratio for the seeds.

Uptake of Lead Nitrate in Barnyard Grass *(Echinochloa crusgalli*) Seeds

Average uptake ratios for each treatment did not show as great a trend as that of the mercury nitrate treatments. As the soil concentrations increased, the accumulations in the seeds tended to increase and then decrease some. The 1 ppm treatment had a 0.511 plant/soil ratio that increased in the next treatment to 1.91. In the 100 ppm treatment it decreased to 0.032, but then increased again in the highest treatment to a 0.129 plant/soil ratio (Table 8, Figure 24). We also ran two whole plants from treatments 500 and 10 ppm. Lead tended to accumulate less in the whole plant than it did in the seeds.

DISCUSSION

Based on our survey of metals contamination, risks to waterfowl and presumably other wildlife using the constructed wetland cells at RCWMA appear to be low. Concentrations of arsenic, lead, and mercury were all below relevant toxicity reference values. Furthermore, we did not see a consistent pattern where any of the contaminants of concern were elevated in wetland cells compared to background areas that did not receive input water from the Trinity River. Mercury tended to be higher in plant tissue from the background marsh area than in the wetland cells for all plants tested. Arsenic

was elevated in sediments from wetland cells compared to background, particularly in Cell 4; however, this did not translate to elevated arsenic in the waterfowl food items. Lead was also slightly elevated in sediment from Cell 1 compared to other cells but no effect was seen in the waterfowl food items.

The growth chamber experiment suggests that both lead and mercury are taken up from wetland soils by barnyard grass. The uptake kinetics are not clear at this time, but it appears that uptake rates decline as the soil concentration increases. This is consistent with the presence of a threshold beyond which additional metal is not absorbed by the plant and may help mitigate against accumulation of harmful lead or mercury levels in these common waterfowl food plants. Further study will be necessary to fully describe uptake and partitioning in wetland plants.

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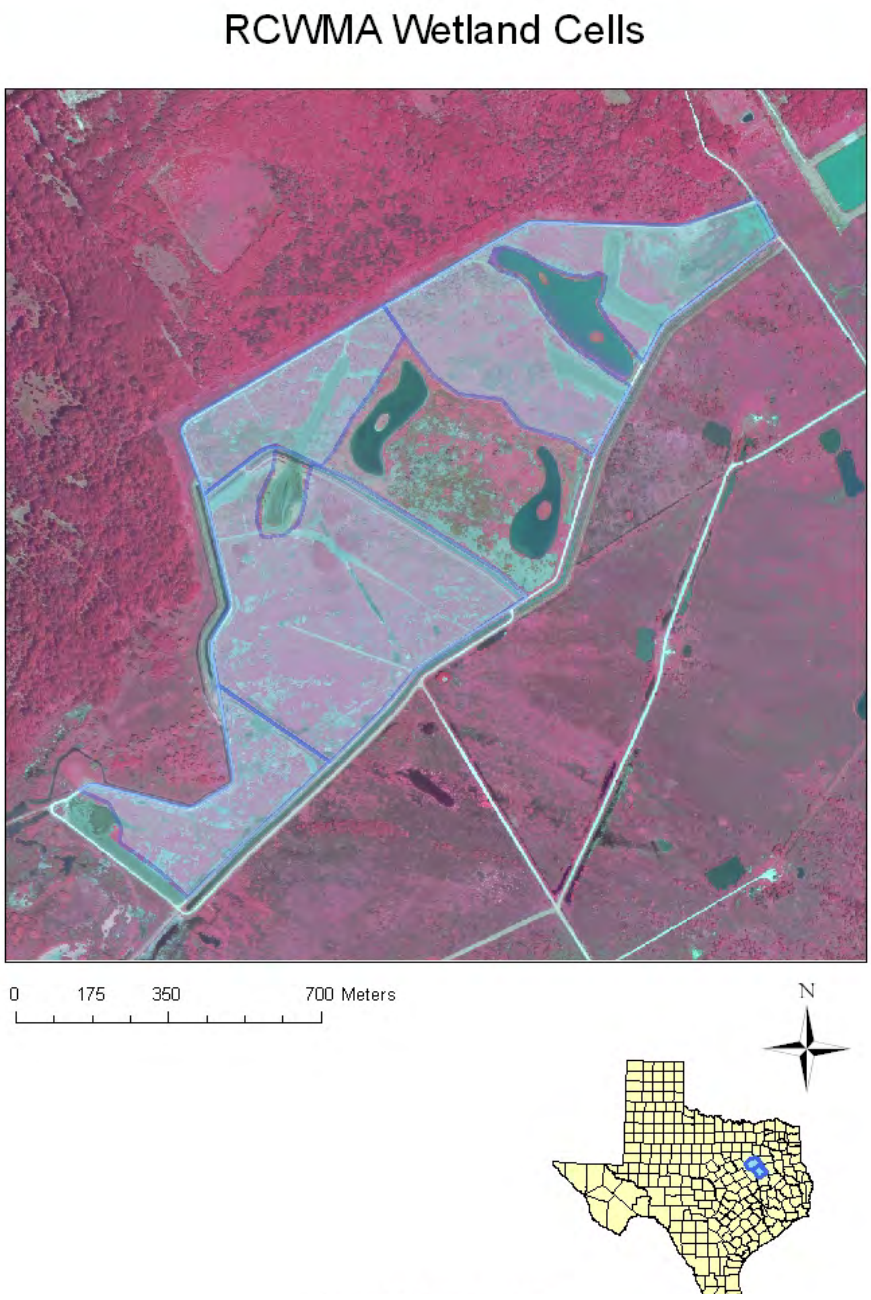

Figure 1. Treatment Wetland cells at Richland Creek WMA, Streetman, Texas.

Figure 2. Random sample locations for sediment and vegetation samples analyzed for arsenic, lead, and mercury concentrations in each of 4 wetland cells at Richland Creek Wildlife Management Area, Streetman, Texas in 2008.

Figure 3. Random sample locations for sediment and vegetation samples analyzed for arsenic, lead, and mercury concentrations in untreated reference area at Richland Creek Wildlife Management Area, Streetman, Texas in 2008.

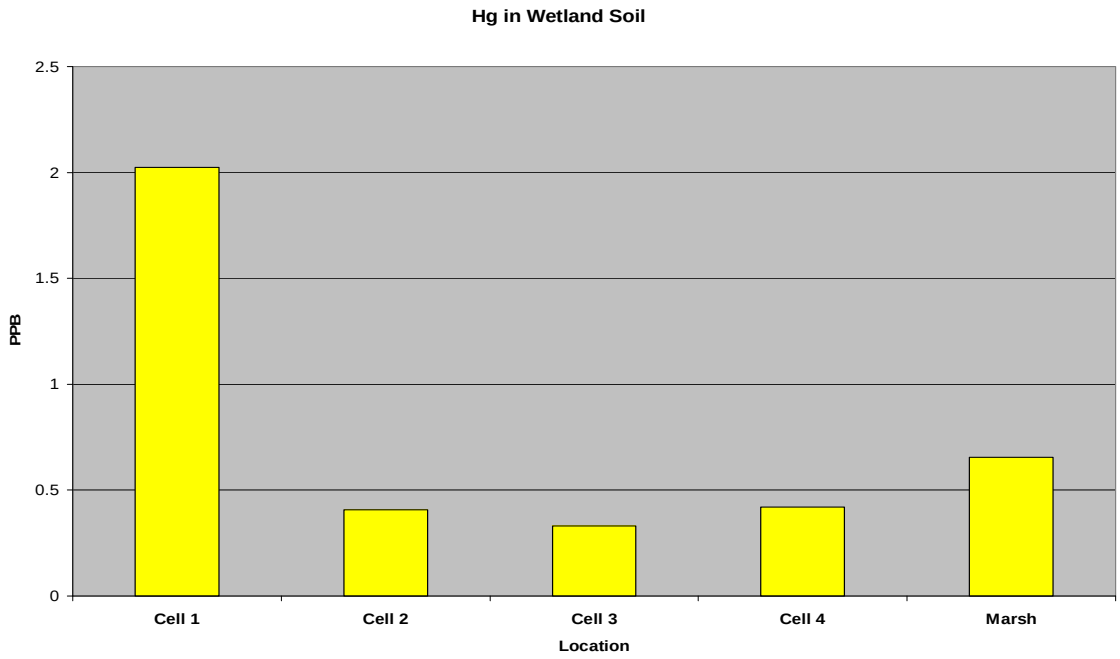

Figure 4. Mean mercury concentrations in sediments in 4 wetland cells and background marsh at RCWMA, 2007.

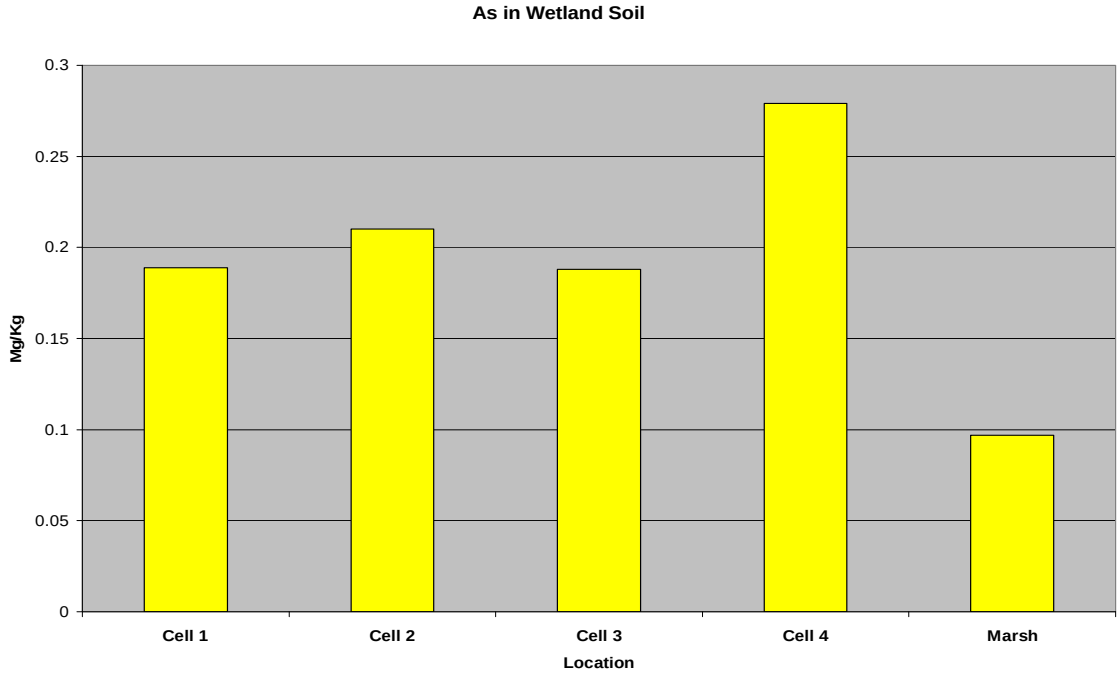

Figure 5. Mean arsenic concentrations in sediments in 4 wetland cells and background marsh at RCWMA, 2007.

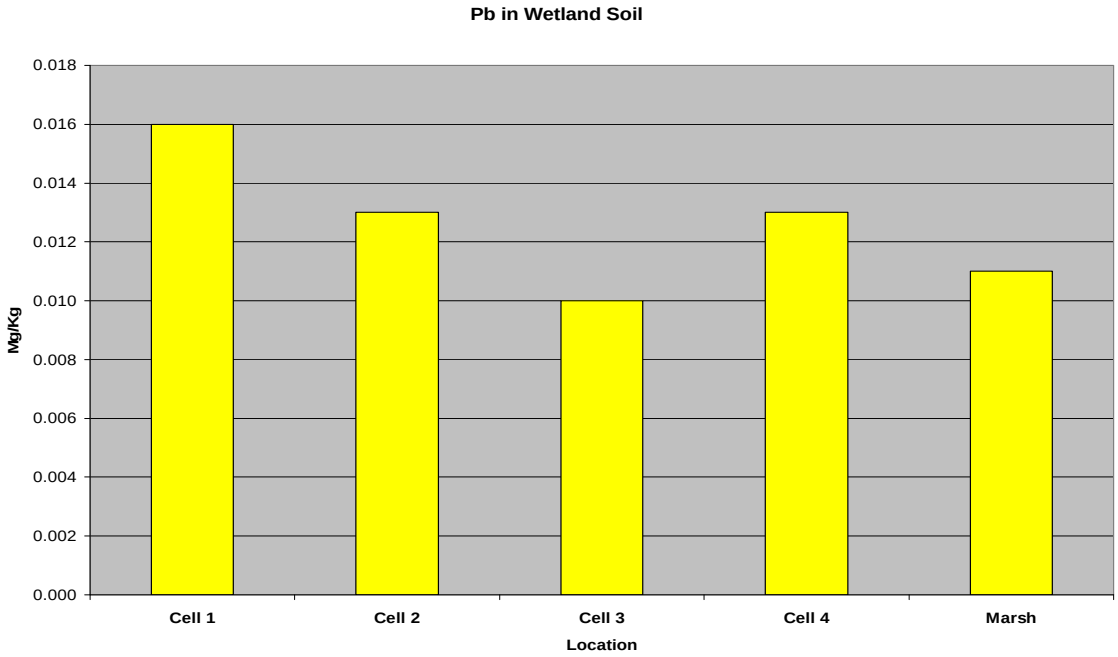

Figure 6. Mean lead concentrations in sediments in 4 wetland cells and background marsh at RCWMA, 2007.

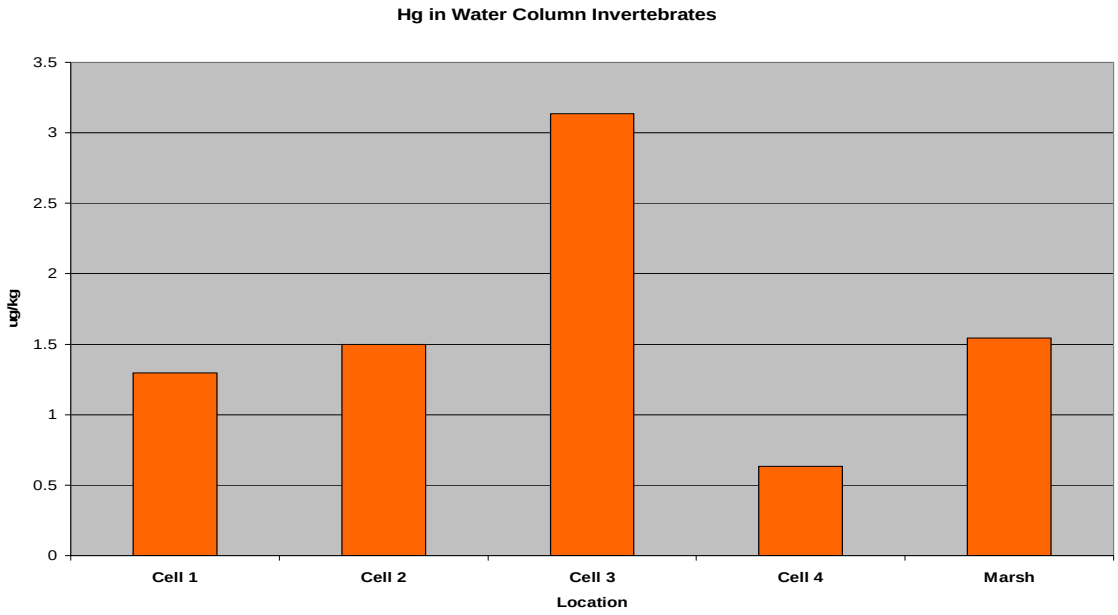

Figure 7. Mean mercury concentrations in water column invertebrates from 4 wetland cells and background marsh at RCWMA, 2008.

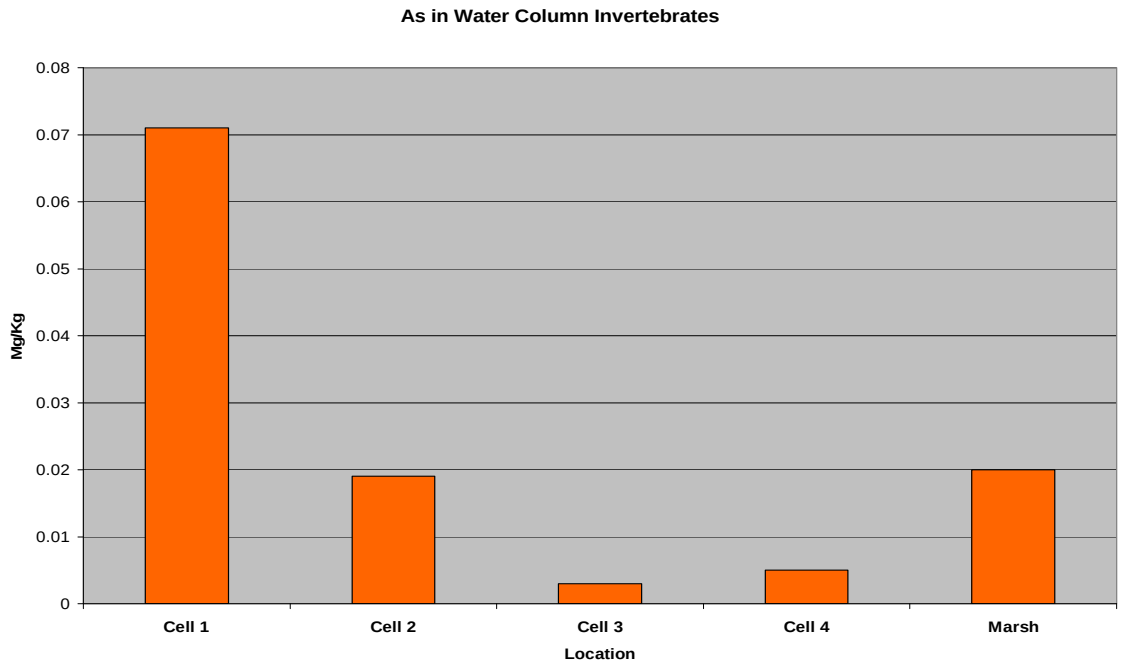

Figure 8. Mean arsenic concentrations in water column invertebrates from 4 wetland cells and background marsh at RCWMA, 2008.

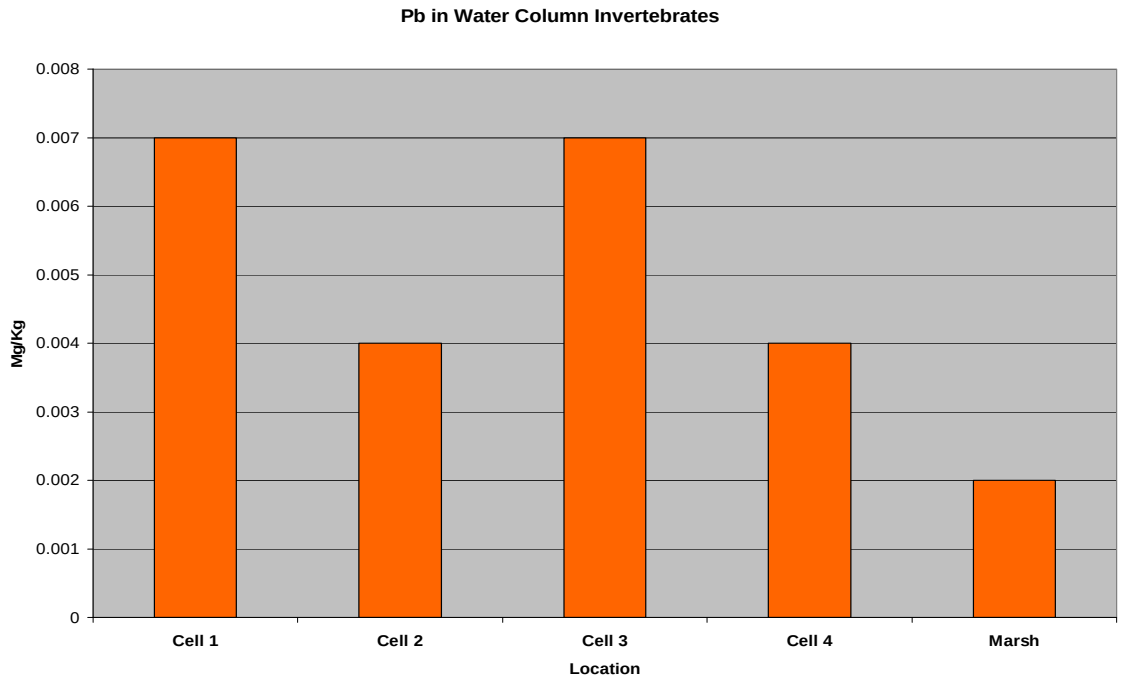

Figure 9. Mean lead concentrations in water column invertebrates from 4 wetland cells and background marsh at RCWMA, 2008.

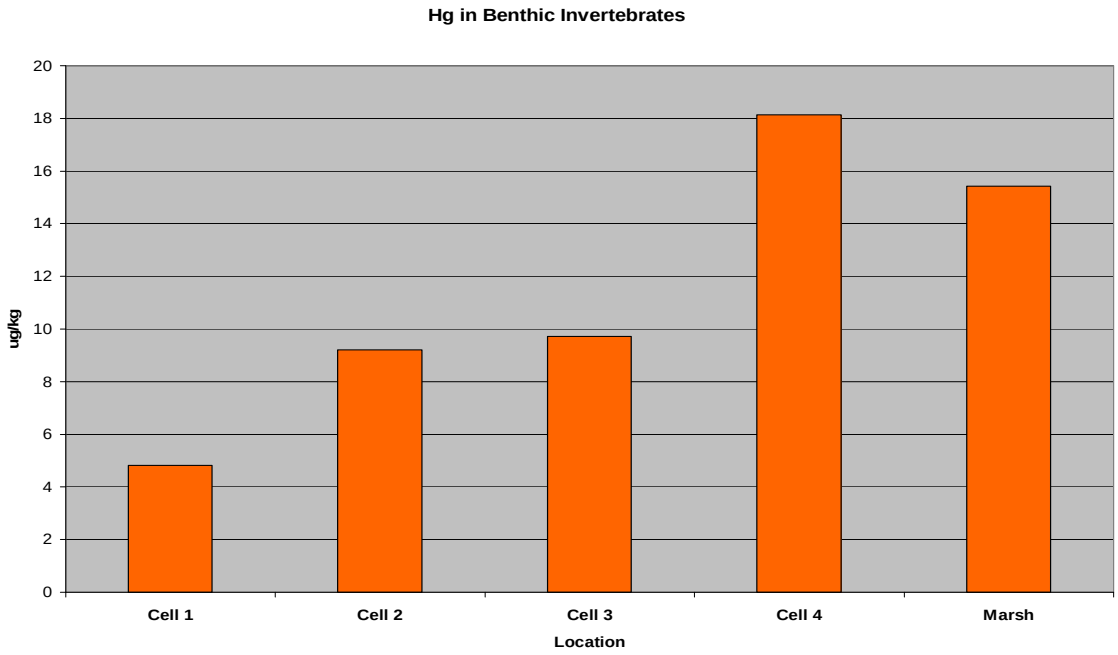

Figure 10. Mean mercury concentrations in benthic invertebrates from 4 wetlands cells and background marsh at RCWMA, 2008.

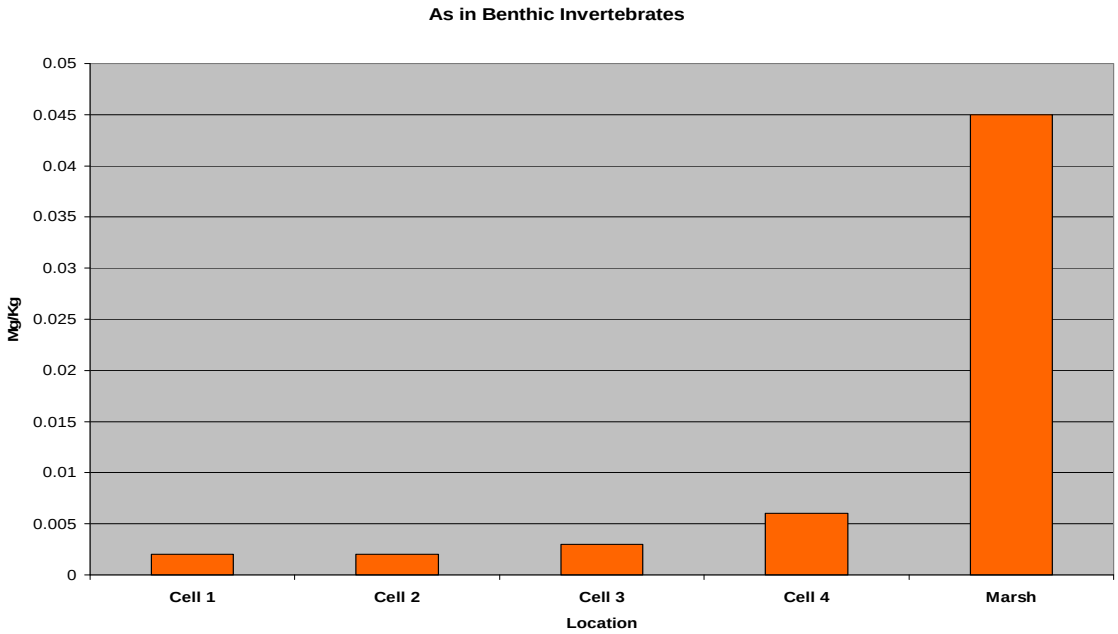

Figure 11. Mean arsenic concentrations in benthic invertebrates from 4 wetlands cells and background marsh at RCWMA, 2008.

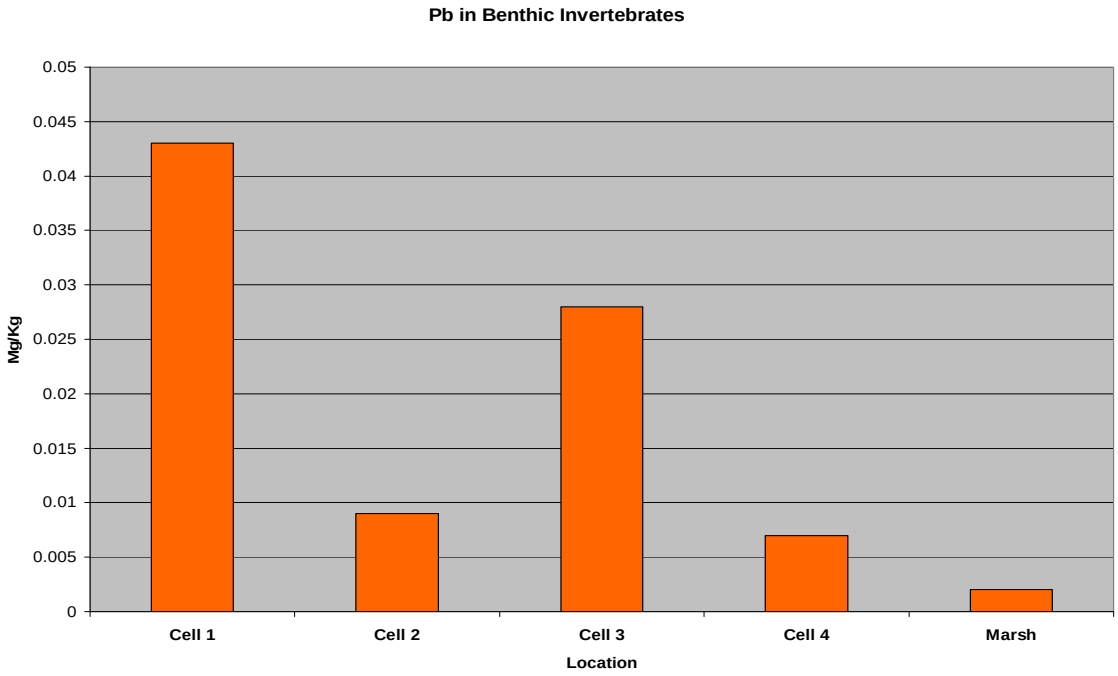

Figure 12. Mean lead concentrations in benthic invertebrates from 4 wetlands cells and background marsh at RCWMA, 2008.

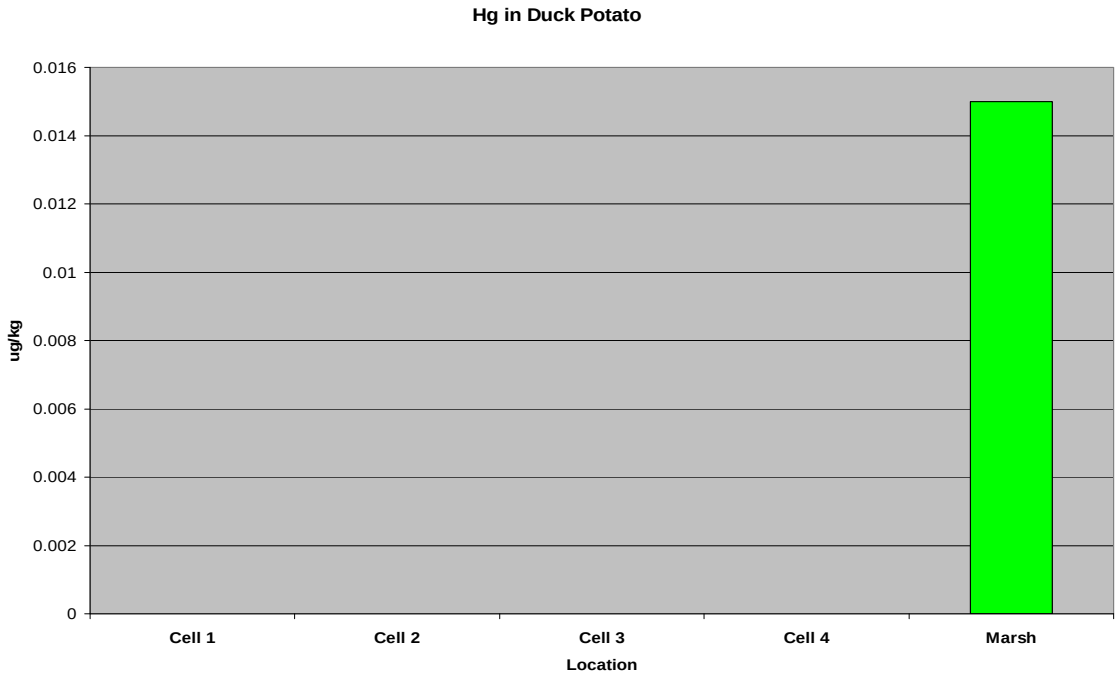

Figure 13. Mean mercury concentrations in duck potato (*Sagittaria* spp.) tubers from 4 wetland cells and background marsh at RCWMA 2007.

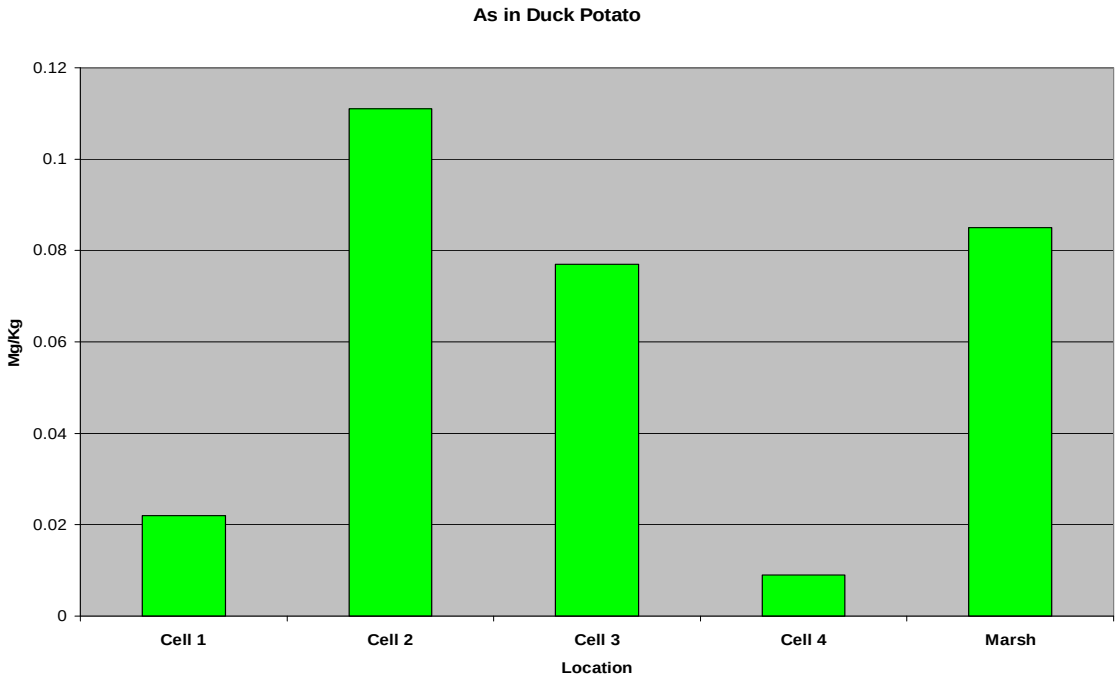

Figure 14. Mean arsenic concentrations in duck potato (*Sagittaria* spp.) tubers from 4 wetland cells and background marsh at RCWMA 2007.

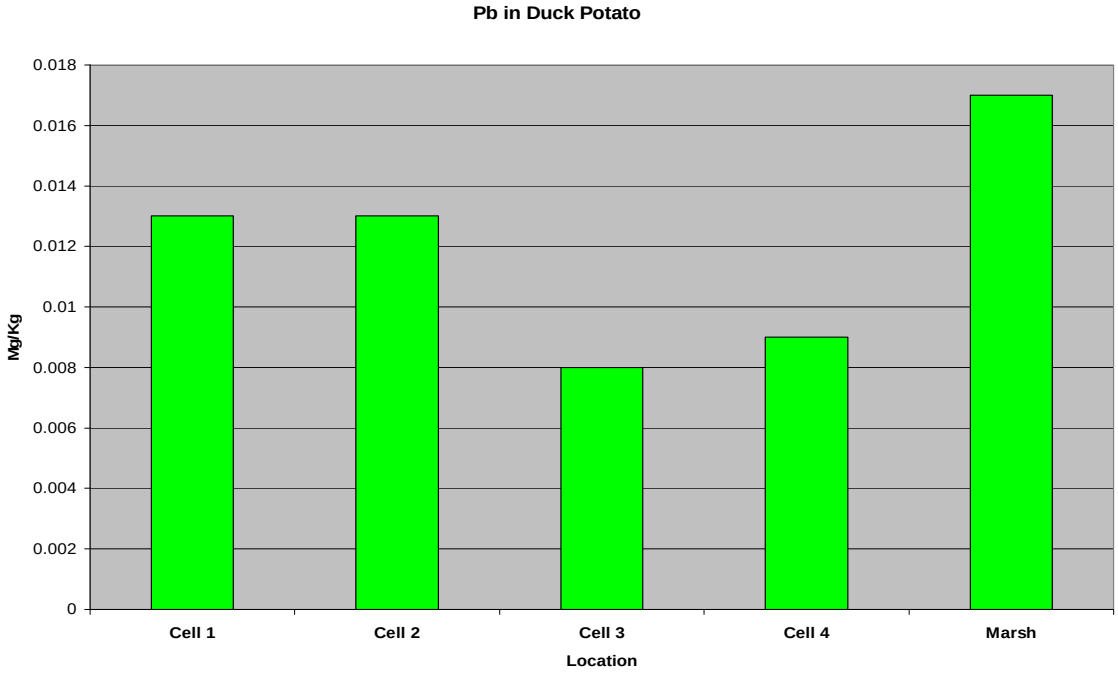

Figure 15. Mean lead concentrations in duck potato (*Sagittaria* spp.) tubers from 4 wetland cells and background marsh at RCWMA 2007.

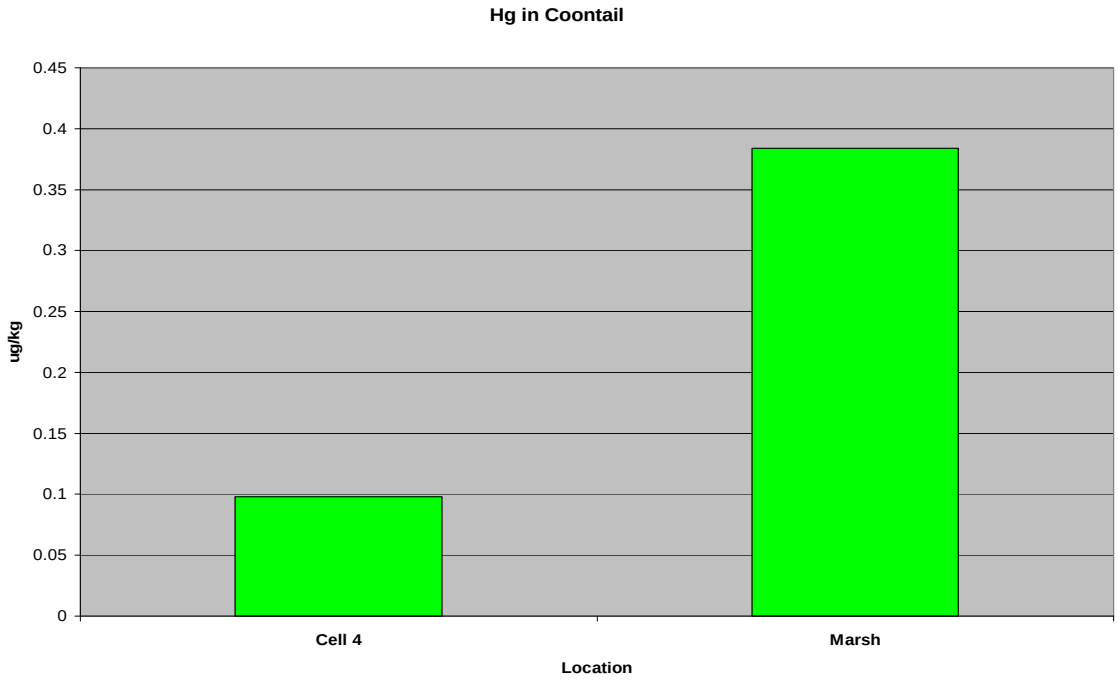

Figure 16. Mean mercury concentrations in coontail (*Ceratophyllum demersum*) foliage in 4 wetland cells and background marsh at RCWMA 2007.

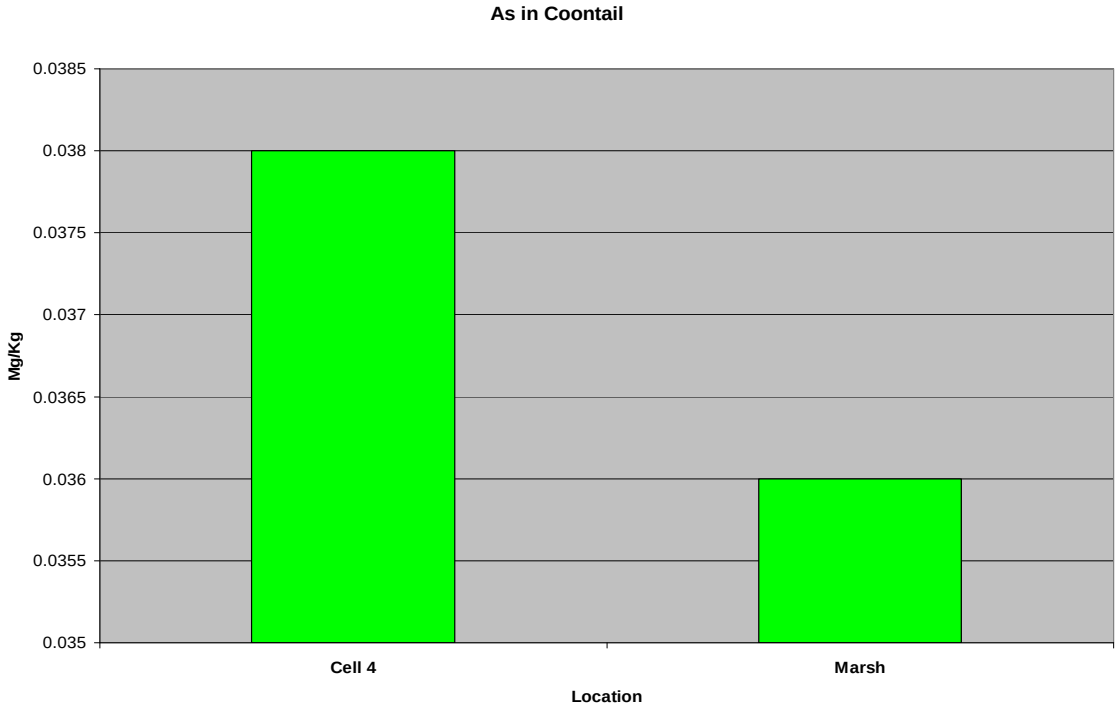

Figure 17. Mean arsenic concentrations in coontail (*Ceratophyllum demersum*) foliage in 4 wetland cells and background marsh at RCWMA 2007.

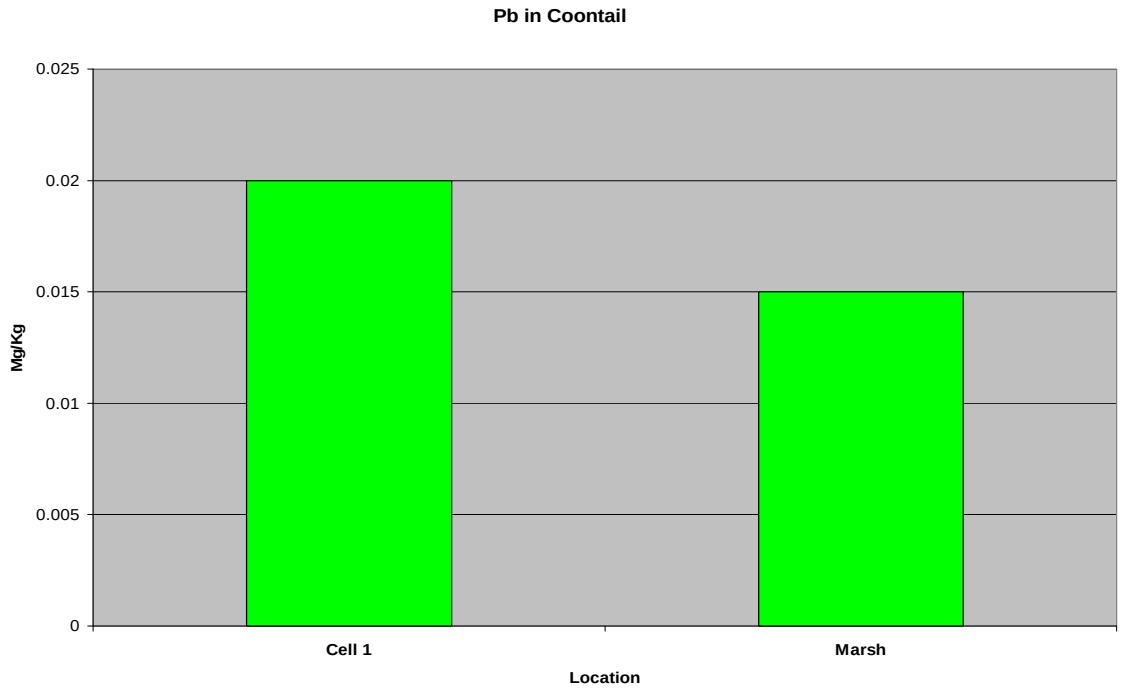

Figure 18. Mean lead concentrations in coontail (*Ceratophyllum demersum*) foliage in 4 wetland cells and background marsh at RCWMA 2007.

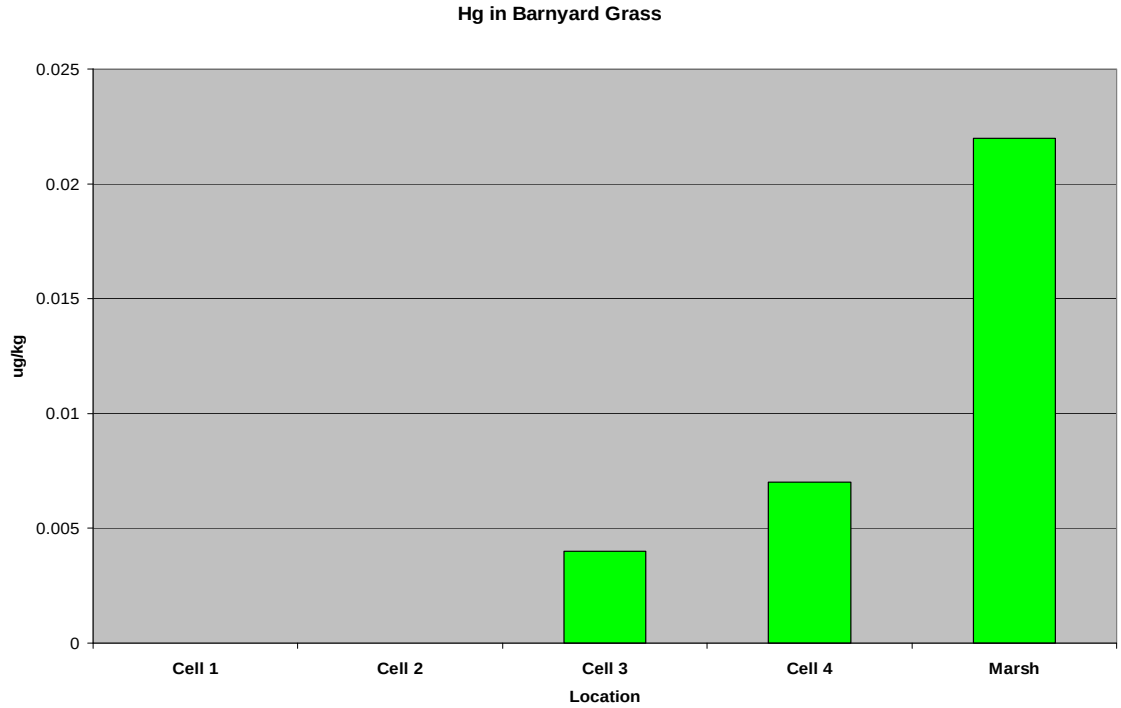

Figure 19. Mean mercury concentration in barnyard grass (*Echinochloa crusgalli*) seeds in 4 wetland cells and background marsh at RCWMA 2007.

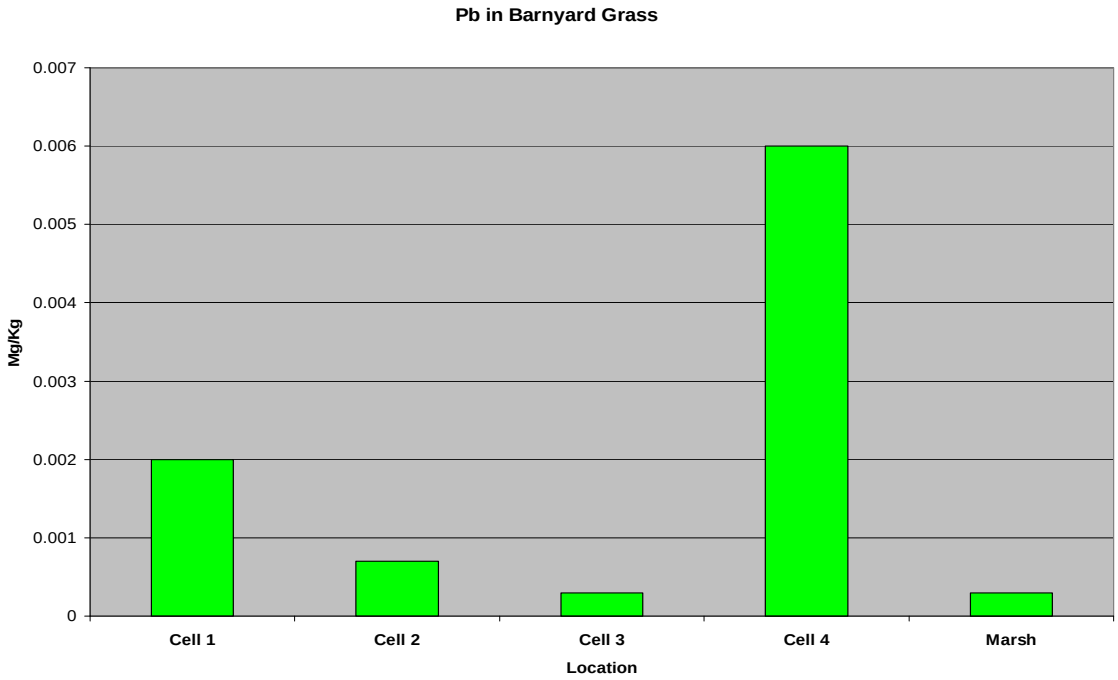

Figure 20. Mean lead concentrations in barnyard grass (*Echinochloa crusgalli*) seeds in 4 wetland cells and background marsh at RCWMA 2007.

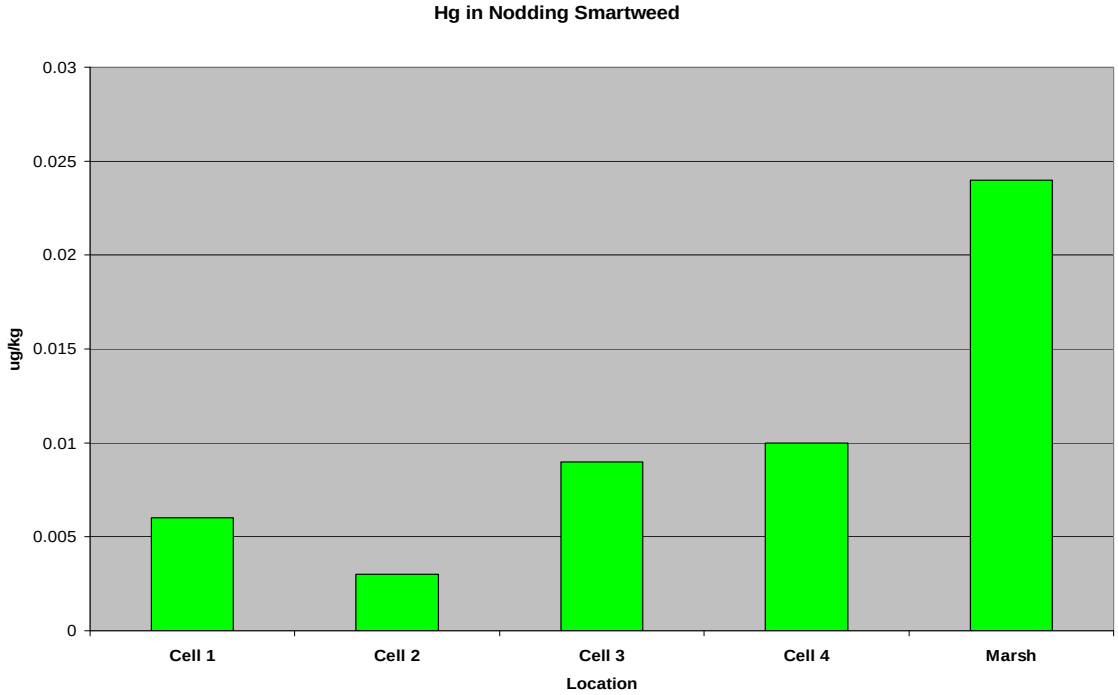

Figure 21. Mean mercury concentration in smartweed (*Polygonum* spp.) seeds in 4 wetland cells and background marsh at RCWMA 2007.

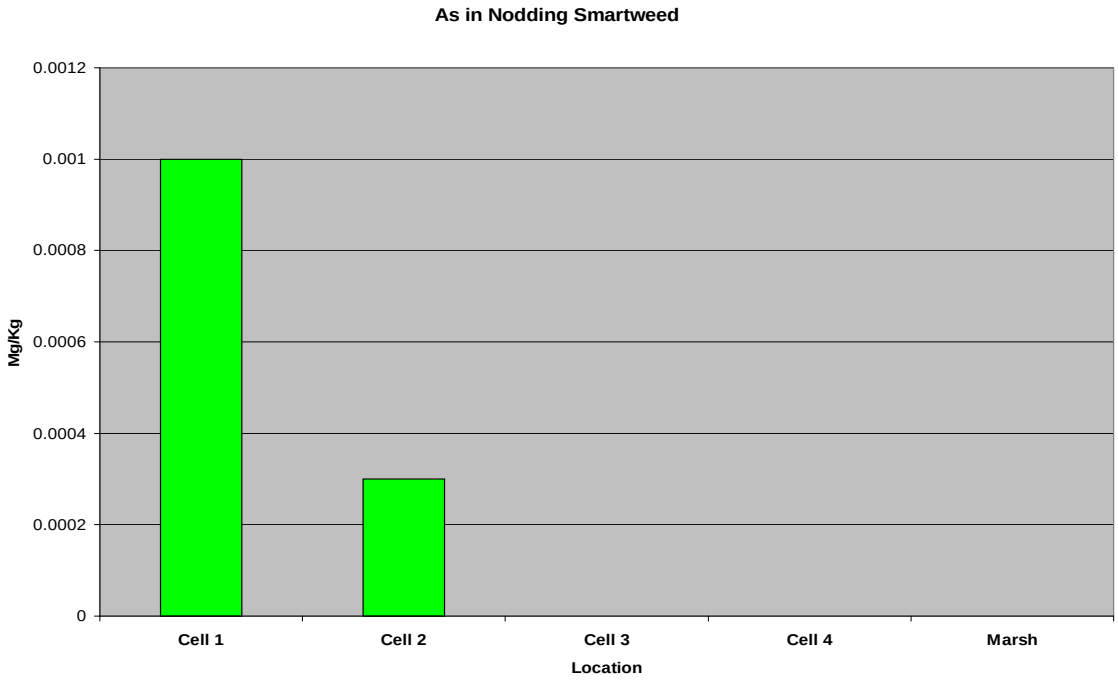

Figure 22. Mean arsenic concentrations in smartweed (*Polygonum* spp.) seeds in 4 wetland cells and background marsh at RCWMA 2007.

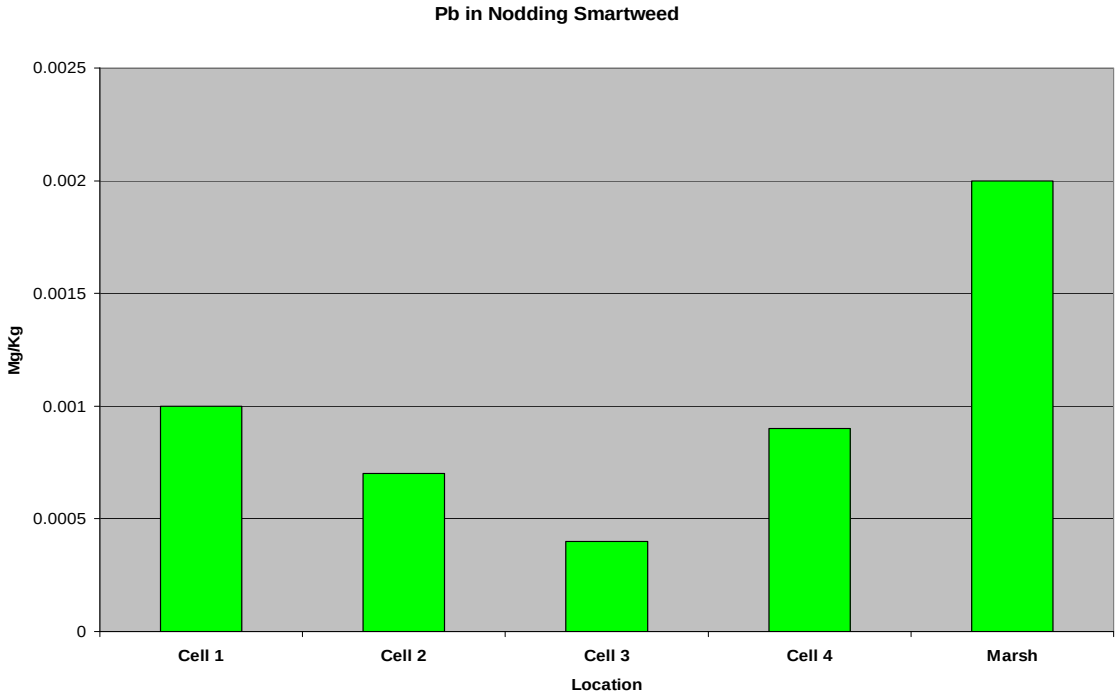

Figure 23 Mean lead concentrations in smartweed (*Polygonum* spp.) seeds in 4 wetland cells and background marsh at RCWMA 2007.

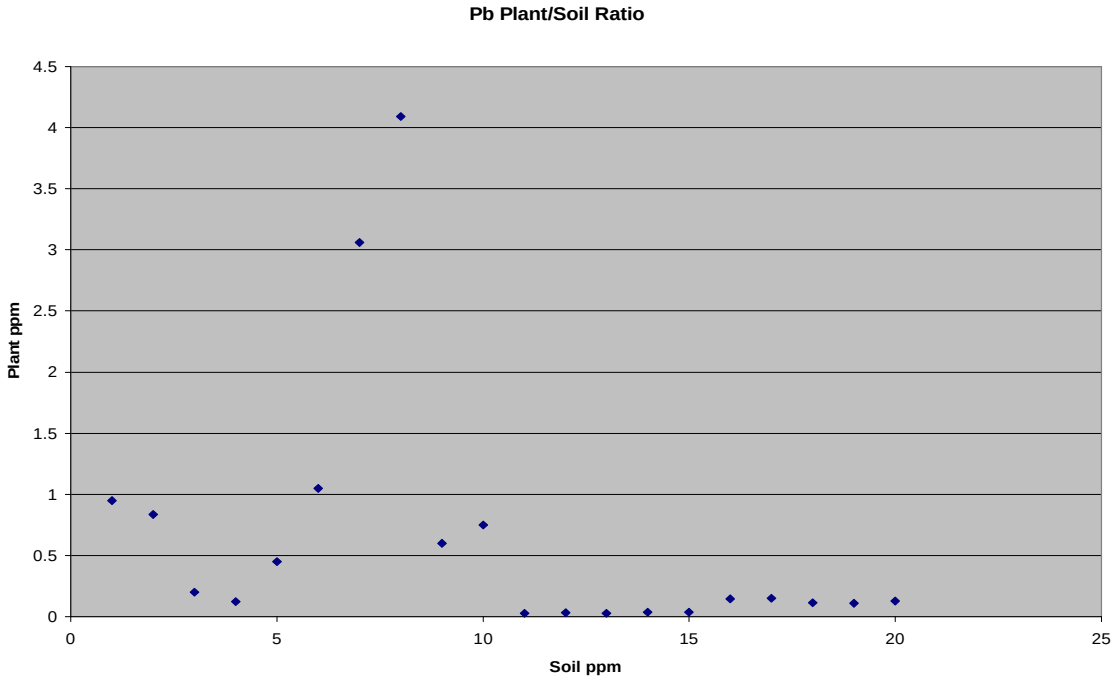

Figure 24. Comparison of soil and seed lead concentrations for barnyard grass (*Echinochloa crusgalli*) grown in 25 pots with known lead concentrations.

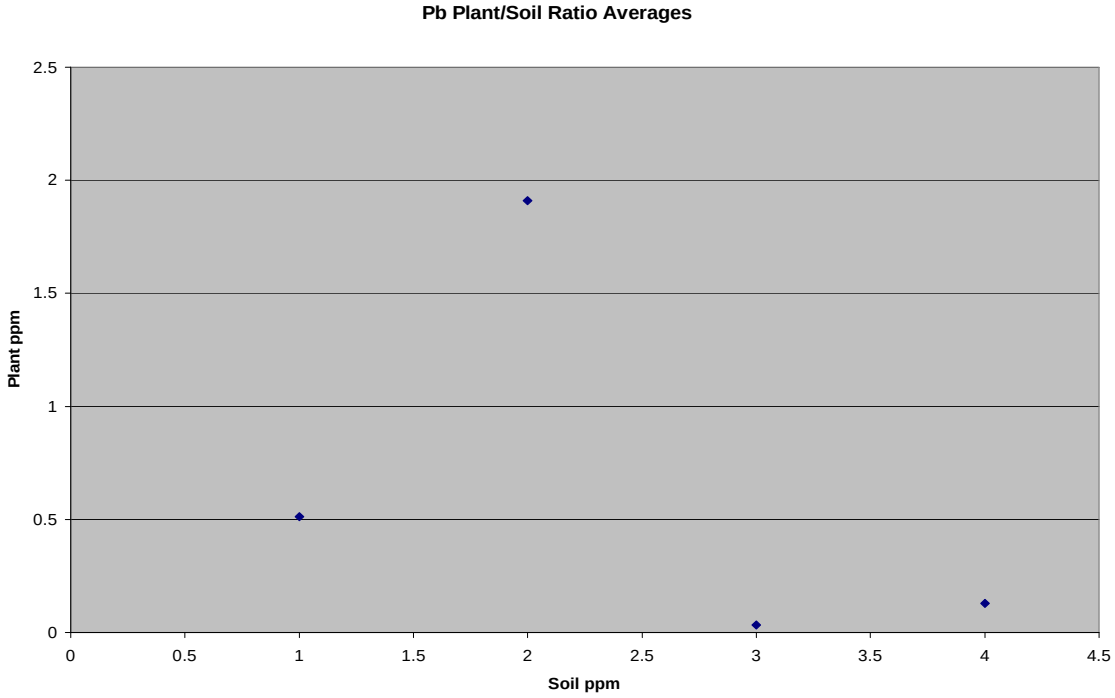

Figure 25 Mean ratios of soil and seed lead concentrations for barnyard grass (*Echinochloa crusgalli*) grown in pots with 4 known lead levels.

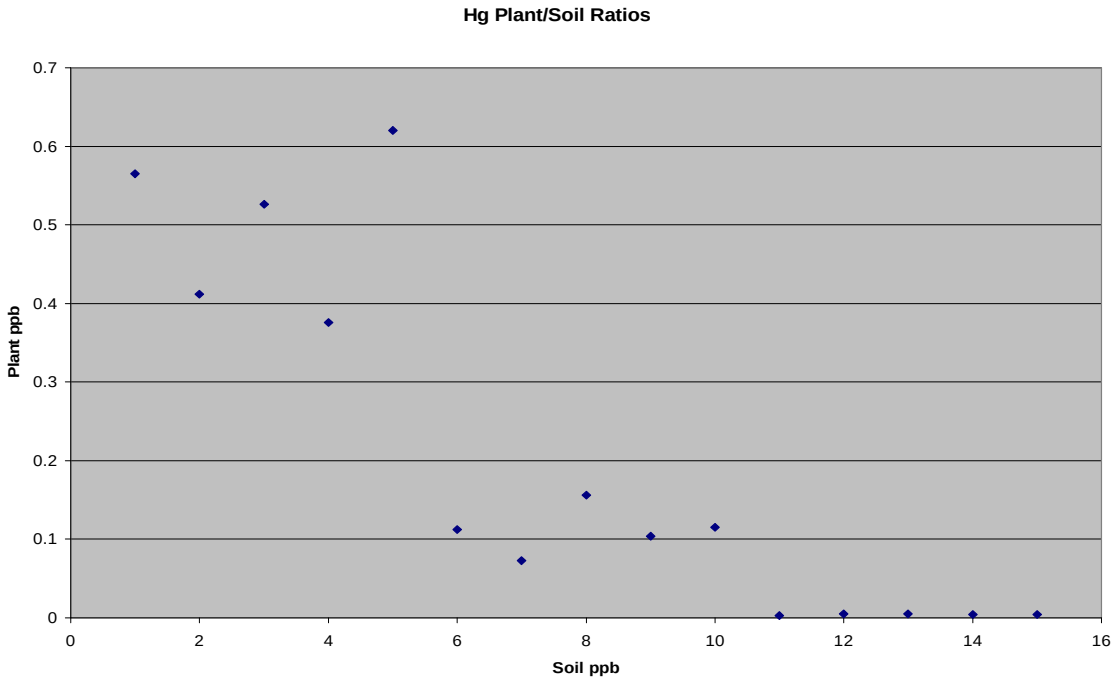

Figure 26. Comparison of soil and seed mercury concentrations for barnyard grass (*Echinochloa crusgalli*) grown in 25 pots with known mercury concentrations.

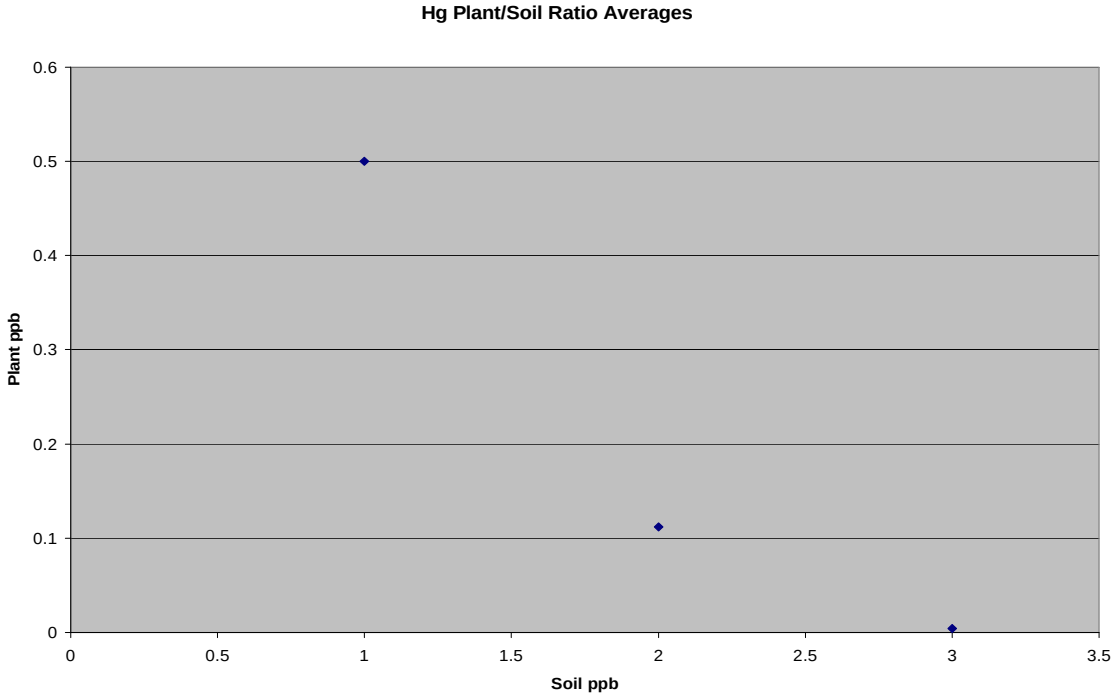

Figure 27. Mean ratios of soil and seed mercury concentrations for barnyard grass (*Echinochloa crusgalli*) grown in pots with 4 known mercury levels.

Table 2. Concentrations of Contaminants of Concern (As, Pb, and Hg) measured in treatment wetland soil at RCWMA in 2007.

Metal	Detection Freq.	Mean[1]	Max	Min	P value[2]
Lead (mg/kg)					
Cell 1	10/10	0.0161 **A**	0.0293	0.0128	**0.0025**
Cell 2	10/10	0.0129 **AB**	0.0154	0.0109	
Cell 3	10/10	0.0104 **B**	0.0119	0.0089	
Cell 4	10/10	0.013 **AB**	0.0185	0.0087	
Control	10/10	0.011 **AB**	0.0136	0.0075	
Arsenic (mg/kg)					
Cell 1	10/10	0.189 **D**	0.22	0.149	**<.0001**
Cell 2	10/10	0.21 **D**	0.266	0.159	
Cell 3	10/10	0.188 **D**	0.207	0.166	
Cell 4	10/10	0.279 **C**	0.327	0.208	
Control	10/10	0.098 **E**	0.269	0.003	
Mercury (ug/kg)					
Cell 1	10/10	2.024	14.07	0.462	**0.2452**
Cell 2	10/10	0.408	0.542	0.282	
Cell 3	10/10	0.331	0.448	0.276	
Cell 4	10/10	0.419	0.594	0.199	
Control	10/10	0.655	0.938	0.435	

[1]Different letters within a column indicate means were different with Student-Newman-Keul's test in ANOVA.
[2]P-Value is for overall ANOVA comparing means for each COC.

Table 3. Concentrations of Contaminants of Concern (As, Pb, and Hg) measured in water column invertebrates at RCWMA in 2008.

Metal	Detection Freq.	Mean	Max	Min	P value[1]
Lead (mg/kg)					
Cell 1	3/3	0.007	0.0134	0.0026	**0.5042**
Cell 2	3/3	0.004	0.0051	0.0033	
Cell 3	3/3	0.007	0.0129	0.0027	
Cell 4	3/3	0.004	0.0088	0.0017	
Control	3/3	0.002	0.0026	0.001	
Arsenic (mg/kg)					
Cell 1	3/3	0.071	0.174	0.008	**0.3212**
Cell 2	3/3	0.019	0.028	0.007	
Cell 3	1/3	0.008	0.008	0	
Cell 4	2/3	0.005	0.008	0	
Control	3/3	0.02	0.037	0.011	
Mercury (ug/kg)					
Cell 1	3/3	1.312	3.867	0.050	**0.9383**
Cell 2	3/3	1.497	3.308	0.459	
Cell 3	3/3	1.046	2.544	0.136	
Cell 4	3/3	0.634	0.902	0.454	
Control	3/3	1.546	2.916	0.169	

[1]P-Value is for overall ANOVA comparing means for each COC.

Table 4. Concentrations of Contaminants of Concern (As, Pb, and Hg) measured in benthic invertebrates at RCWMA in 2008.

Metal	Detection Freq.	Mean	Max	Min	P value[1]
Lead (mg/kg)					
Cell 1	3/3	0.014	0.0335	0.0032	**0.6179**
Cell 2	3/3	0.011	0.0184	0.006	
Cell 3	3/3	0.028	0.0773	0.0017	
Cell 4	3/3	0.007	0.0098	0.0019	
control	3/3	0.002	0.0034	0.0012	
Arsenic (mg/kg)					
Cell 1	1/3	0.006	0.006	ND	**0.5282**
Cell 2	1/3	0.006	0.006	ND	
Cell 3	1/3	0.009	0.009	ND	
Cell 4	1/3	0.018	0.018	ND	
Control	1/3	0.044	0.134	ND	
Mercury (ug/kg)					
Cell 1	3/3	4.808	6.295	3.740	**0.7341**
Cell 2	3/3	9.207	8.303	3.017	
Cell 3	3/3	9.720	21.670	3.074	
Cell 4	3/3	18.136	45.280	2.968	
Control	3/3	15.416	28.360	7.298	

[1]P-Value is for overall ANOVA comparing means for each COC.

Table 5. Concentrations of Contaminants of Concern (As, Pb, and Hg) measured in duck potato (*Sagittaria* sp.) tubers at RCWMA in 2007.

Metal	Detection Freq.	Mean[1]	Max	Min	P value[2]
Lead (mg/kg)					
Cell 1	10/10	0.01301	0.0331	0.0045	**0.6228**
Cell 2	10/10	0.01321	0.0462	0.01	
Cell 3	10/10	0.00847	0.0102	0.0024	
Cell 4	10/10	0.00948	0.027	0.0032	
Control	10/10	0.0165	0.0266	0.0064	
Arsenic (mg/kg)					
Cell 1	10/10	0.0228 **B**	0.109	0.002	**0.009**
Cell 2	10/10	0.1105 **A**	0.242	0.007	
Cell 3	10/10	0.0773 **AB**	0.277	0.003	
Cell 4	9/10	0.0091 **B**	0.023	ND	
Control	10/10	0.0848 **AB**	0.199	0.007	
Mercury (ug/kg)					
Cell 1	0/10	ND	ND	ND	**0.0233**
Cell 2	0/10	ND	ND	ND	
Cell 3	0/10	ND	ND	ND	
Cell 4	0/10	ND	ND	ND	
Control	3/10	0.05	0.068	0.022	

[1]Different letters within a column indicate means were different with Student-Newman-Keul's test in ANOVA.

[2]P-Value is for overall ANOVA comparing means for each COC.

Table 6. Concentrations of Contaminants of Concern (As, Pb, and Hg) measured in coontail (*Ceratophyllum demersum*) foliage at RCWMA in 2007.

Metal	Detection Freq.	Mean[1]	Max	Min	P value[2]
Lead (mg/kg)					
Cell 4	8/10	0.02027	0.0672	0	**0.5093**
Control	10/10	0.01534	0.0279	0.0051	
Arsenic (mg/kg)					
Cell 4	8/10	0.0357	0.124	0	**0.9122**
Control	7/10	0.0271	0.126	0	
Mercury (ug/kg)					
Cell 4	10/10	0.0979 **B**	0.235	0.017	**0.0003**
Control	10/10	0.3842 **A**	0.758	0.184	

[1]Different letters within a column indicate means were different with Student-Newman-Keul's test in ANOVA.

[2]P-Value is for overall ANOVA comparing means for each COC.

Table 7. Concentrations of Contaminants of Concern (As, Pb, and Hg) measured in barnyard grass (*Echinochloa crusgalli*) seeds at RCWMA in 2007.

Metal	Detection Freq.	Mean[1]	Max	Min	P value[2]
Lead (mg/kg)					
Cell 1	10/10	0.00158	0.0081	0.0002	**0.3483**
Cell 2	9/10	0.0007	0.0018	0	
Cell 3	5/10	0.0003	0.0012	0	
Cell 4	8/10	0.0058	0.0491	ND	
Control	3/10	0.0002	0.0022	ND	
Arsenic (mg/kg)					
Cell 1	0/10	ND	ND	ND	**N/A**
Cell 2	0/10	ND	ND	ND	
Cell 3	0/10	ND	ND	ND	
Cell 4	0/10	ND	ND	ND	
Control	0/10	ND	ND	ND	
Mercury (ug/kg)					
Cell 1	0/10	ND **B**	ND	ND	**<0.0001**
Cell 2	0/10	ND **B**	ND	ND	
Cell 3	3/8	0.004 **B**	0.023	ND	
Cell 4	4/10	0.007 **B**	0.034	ND	
Control	10/10	0.022 **A**	0.035	0.008	

[1]Different letters within a column indicate means were different with Student-Newman-Keul's test in ANOVA.

[2]P-Value is for overall ANOVA comparing means for each COC.

Table 8. Concentrations of Contaminants of Concern (Ar, Pb, and Hg) measured in smartweed (*Polygonum* spp.) seeds at RCWMA in 2007.

Metal	Detection Freq.	Mean[1]	Max	Min	P value[2]
Lead (mg/kg)					
Cell 1	10/10	0.001 **AB**	0.0027	0.0001	**0.0173**
Cell 2	9/10	0.0007 **AB**	0.0009	0	
Cell 3	8/10	0.0004 **B**	0.0009	ND	
Cell 4	10/10	0.0009 **AB**	0.0018	0.0002	
Control	10/10	0.002 **A**	0.0053	0.0003	
Arsenic (mg/kg)					
Cell 1	4/10	0.001 **C**	0.004	ND	**0.005**
Cell 2	1/10	0.003 **D**	0.003	ND	
Cell 3	0/10	ND **D**	ND	ND	
Cell 4	0/10	ND **D**	ND	ND	
Control	0/10	ND **D**	ND	ND	
Mercury (ug/kg)					
Cell 1	4/10	0.005 **F**	0.021	ND	**0.0036**
Cell 2	2/10	0.003 **F**	0.014	ND	
Cell 3	5/10	0.009 **F**	0.031	ND	
Cell 4	8/10	0.01 **F**	0.036	ND	
Control	9/10	0.024 **E**	0.054	ND	

[1]Different letters within a column indicate means were different with Student-Newman-Keul's test in ANOVA

[2]P-Value is for overall ANOVA comparing means for each COC.

Table 9. Mean soil concentration, seed concentration, and uptake factors for barnyard grass (*Echinochloa crusgalli*) grown in known soil concentrations of lead and mercury.

Treatment	Soil	Plant Seeds	Plant/Soil Ratio
Pb			
1	0.16	0.06	0.511
2	0.2	0.38	1.91
3	73.8	2.31	0.032
4	74.5	9.58	0.129
Hg			
1	0.007	0.093	0.5
2	0.025	0.073	0.112
3	0.574	0.07	0.004
4	2.5	NA[1]	NA

[1]Plants in Hg treatment 4 died, so no seeds were available