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Effects of Contaminated St. Lucie River Saltwater Sediments on an Amphipod (Ampelisca abdita) and a Hard-Shell Clam (Mercenaria mercenaria)

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Effects of St. Lucie River (FL) saltwater sediments on the amphipod (*Ampelisca abdita*) and the hard shell clam (*Mercenaria mercenaria*)

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Abstract

The St. Lucie estuary ecosystem in South Florida has been noted to be contaminated with metals and pesticides. Our earlier studies showed that aquatic organisms, especially benthic species in the St. Lucie estuarine ecosystem are at high risk of copper (Cu) exposures. The objectives of this study are to conduct tests with separate groups of organisms exposed to 7 field-collected sediment samples from the St. Lucie River according to standard procedures to evaluate toxicity and tissue concentrations of Cu and zinc (Zn). Short term and long term whole sediment acute toxicity tests were conducted with *Ampelisca abdita* and *Mercenaria mercenaria*. Analysis of sediment chemical characteristics showed that Cu and Zn are most concern because their concentrations in 86% of the sediments were higher than the threshold effect concentrations for Florida sediment quality assessment and the NOAA SQuiRTsnational Cu sediment quality guidelines. There was no significant effect on survival of the tested organisms. Elevated Cu and Zn concentrations in the test organisms were found. Dry weight of the tested organisms was inversely related to Cu and Zn concentrations in sediments and organisms. The effects on organism weight and Cu and Zn uptake raise a concern about the organism population dynamics of the ecosystem because benthic organisms are primary food sources in the St. Lucie system and are continuously exposed to the Cu and Zn contaminated sediments for their life cycle. The present study also indicates that Cu and Zn exposures via sediment ingestion were more important than pore water exposure.

Key words: Cu uptake, Cu-contaminated sediment, St. Lucie River sediments, *Ampelisca abdita*, *Mercenaria mercenaria*

Introduction

The St. Lucie Estuary (SLE) watershed is composed of five major drainage basins and several smaller basins in the northern portion of St. Lucie County, Florida. It contains the most concentrated citrus agriculture acreage in South Florida. The SLE is located on the Martin/St. Lucie County line. The inner SLE is comprised of the North Fork and the South Fork of the St. Lucie River (SLR) and has a total surface area of 6.4 square miles. The two forks converge to form a single middle estuary with a surface area of 4.7 square miles. The middle estuary extends east from approximately 5 miles until it meets the Indian River Lagoon, which opens to the Atlantic Ocean at the St. Lucie Inlet. A heavier concentration of citrus agriculture (~60%) land use potentially affects the drainage basins into the North Fork compared to the South Fork (~45%) of the SLR. In 1972, the Florida Trustees recognized the ecological importance of the North Fork of the St. Lucie River by designating it an Aquatic Preserve/Outstanding Florida Water.

Copper has a long history of use in agriculture (e.g., citrus groves) as a fungicide and fertilizer in south Florida (Alva et al. 1995). In the early 1900's copper containing fertilizers for citrus groves accounted for as much as 34 kg Cu/ha annually and fungicidal sprays contributed an additional 10kg Cu/ha annually. Surface soils (0-15 cm) for mature citrus groves contained as much as 540kg Cu/ha. Increased levels of copper in South Florida soils have been a result of repeated applications of copper over several decades to agricultural areas and soil copper concentrations increase proportional age of citrus production (Reuther and Smith, 1952). According to the U.S. Department of Agriculture in 2005, over 500,000 kg of copper (as copper hydroxide, copper sulfate or basic copper) were applied to grapefruit, orange, tangelo, tangerine and temple crops on 259,563 ha in Florida (USDA 2006). These quantities do not reflect use of Cu on other citrus crops or the use of copper sulfate and chelated Cu formulations (e.g., Cutrine-Plus, Komeen, etc.) as algaecides-herbicides, which are permitted by the

Florida Department of Environmental Protection (FDEP) for control of nuisance planktonic and filamentous algal and vascular plants (Leslie, 1990). Note that Cu also does leach from boats into both fresh- and salt-water (e.g., harbors and marinas) because it is a component of antifouling pants. More recently, statewide pesticide usage data (based on total lbs a.i. applied) compiled by the Florida Department of Agriculture and Consumer Services (FDACs 2010) from 2007-2009 for 14 crops and 169 active ingredients (a.i.) ranked copper hydroxide (1,176,500 lbs. a.i. applied) number 5 out of 10 pesticides and the most applied fungicide (number 1 out of 10 fungicides).

A comparison of aqueous Cu concentrations in agriculture and non-agriculture watersheds shows higher concentrations in runoff where agriculture was practiced compared to runoff near non-agriculture land (Dietrich et al., 2001). Copper loads in surface runoff are related to total Cu in soils, soil properties, metal characteristics and environmental factors, especially in sandy soils (He et al., 2006). Enrichment of Cu in runoff will adversely affect receiving surface water quality (Moore et al., 1998). As a result of the use of copper in agriculture in St. Lucie County, it appears that concentrations of copper (and other contaminants, such as Zn) from drift and/or from surface runoff of contaminated soils (or soil erosion) may also produce exposures that adversely affect saltwater benthic communities, when the Cu-contaminated soils reach and become incorporated as part of the sediments of the St. Lucie River system. Sediment chemistry data indicate that Florida coastal sediments in several areas are contaminated with metals (Long and Morgan 1990, Delfino et al. 1991, FDEP 1994), especially Cu (Haunert 1988, Trefry and Trocine 2011, Trocine and Trefry 1993, 1996).

Our early laboratory results indicate that copper-contaminated Florida agricultural soils that are flooded likely promote the release of Cu from soils producing adverse effects on freshwater organisms (Hoang et al. 2008a, 2009a, b). In addition, we showed high potential ecological risks to aquatic species as a result of Cu exposures in sediment and water and high probability of exceedences of the Florida

Department of Environmental Protection Sediment Quality Assessment Guideline values for the Threshold Effect Concentration and the Probable Effect Concentration (FDEP SQAGs TECs and PECs) for Cu (FDEP 2003) in the St. Lucie River (Schuler et al. 2008). More recently, Carriger and Rand 2013 (in press) also showed high ecological risks of Cu in this system to aquatic organisms. The objectives of the present study are to conduct whole sediment toxicity studies with the clam (*Mercenaria mercenaria*) and the benthic amphipod (*Ampelisca abdita*) exposed to field-collected sediment samples from the St. Lucie River to evaluate uptake (bioconcentration) and toxicity of Cu and Zn.

Materials and Methods

Sediments used in the present study (n=7; 6 test and 1 reference site) were collected by the National Oceanic and Atmospheric Administration (NOAA) from the St. Lucie River, south Florida, USA and transferred to the Ecotoxicology and Risk Assessment Laboratory (ERAL) of Florida International University on April 5-7, 2011 for toxicity testing (Figure 1). ERAL is a NELAC-accredited laboratory facility for fresh- and salt-water toxicity testing. Sediment samples were labeled NOA2581 (reference site in the South Fork of the SLE) along with six test sites as NOA2569, NOA2334, NOA2640, NOA2639, NOA 2333, and NOA2570 (sites in the North Fork of the SLE). Prior to aquatic testing, sediments were physically characterized and background concentrations of metals and organic pollutants were analyzed. The sediments were also analyzed for acid volatile sulfide (AVS) and simultaneously extracted metals (SEM). Using the AVS/SEM ratio, we can predict the bioavailability of metals (Berry et al. 1996).

Two separate types of studies were conducted with the 7 field-collected sediment samples to evaluate mortality, growth and accumulation; one study with the tube-dwelling amphipod (*A. abdita*), which is a common standard saltwater benthic test species used for whole-sediment toxicity and bioaccumulation tests and one study with the hard shell clam (*M. mercenaria*) which is a native species in the St. Lucie system. Exposures to the field-collected sediments in both studies were in a flow-through water system to ensure consistent water quality conditions (e.g., low ammonia concentrations). Flow-through systems were calibrated prior to testing to ensure correct water placements in test chambers over each 24-hour time period. Saltwater for the flow-through system was obtained from a saltwater well (with Biscayne Bay water) which was air-sparged, carbon-filtered and UV-sterilized with a salinity of 31ppt and a pH of 8.0-8.5.

Toxicity tests with *A. abdita* were 10 days in duration and were conducted according to the methods for measuring the toxicity and bioaccumulation of sediment-associated contaminants with marine invertebrates (U.S. EPA. 1994). *A. abdita* were obtained from a commercial supplier. An initial subsample of the *A. abdita* population was used for length and weight measurements and tissue analyses (Cu, Zn) for background data. There were 10 organisms per replicate with 8 replicates per sediment sample site. Organisms (10) were randomly distributed in each test chamber with 350ml of water and 150 ml of sediment (8 test chambers /site; 80 organisms exposed/site) in the water bath of the flow-through water system (2 test chamber water volume turnovers/24h). Water quality monitoring for the tests included salinity, ammonia and pH measurements at test initiation and at test termination. Temperature and dissolved oxygen were measured daily. Salinity, ammonia, and pH were measured using a YSI conductivity/salinity meter (YS Inc, Yellow Springs, Ohio, USA), an Accumet® Ammonia Electrode (Fisher Scientific, Pittsburgh, PA, USA), and an Accumet pH meter (Vernon Hills, Illinois, USA), respectively. Water temperature and dissolved oxygen concentrations were measured using a YSI dissolved oxygen meter (YS Inc., Yellow Springs, Ohio, USA). Mortality of *A. abdita* was measured at test termination along with growth (dry weight and length) of surviving organisms. The quality criterion for control survival was 80%. Tissue concentrations (whole body) of Cu and Zn were measured at test initiation and again at test termination. To increase the detection limits for Cu and Zn, surviving organisms from all replicates were combined for each treatment and digested with HNO_3 acid using a Hotblock and based on the U.S. EPA Method 3050B (U.S. EPA 1996a) for tissue Cu and Zn analyses. Analysis of Cu, Zn, and other minerals were conducted with an inductively coupled plasma spectrometer (Thermo Scientific Inc. 5225 Verona Road, Madison, WI 53711).

In addition, a 28-day bioconcentration study was conducted similarly to U.S. EPA Ecological Effects Test Guidelines (U.S. EPA, 1996b) except that sediment was the source of the contaminants (not water exposure). The hard shell clam (*M. mercenaria*), an economically important native species in the SLR system was the test species and only a 28-day uptake phase (without a depuration phase) was used. *M. mercenaria* juveniles were obtained from a commercial supplier. An initial subsample of the *M. mercenaria* juvenile population was used for weight measurements and tissue analyses of Cu and zinc. There were 50 organisms per replicate with 2 replicates per sediment sample site used. Organisms (50) were randomly distributed to an 18L test chamber with 12L of water and 3-4 cm of sediment (2 test chambers /site; 100 organisms exposed/site) in a flow-through water system (4 tank water volume turnovers/24h). Water quality monitoring for the test included salinity, conductivity, and pH measurements for the first 3 days, daily and again at the end of the test. Temperature and dissolved oxygen were measured daily. Mortality was measured on days 3, 7, 14, 21 and 28. Tissue samples (n=4) were also collected and measured on days 3, 7, 14, 21 and 28 of surviving organisms for Cu and Zn. The quality criterion for control survival was 80%. Overlying and porewater samples were also collected when the tissue samples were collected for analyses of Cu, Zn and dissolved organic carbon (DOC). Porewater was collected by centrifuging the sediments at 2500g and 4° for 30 minutes (Ankley et al. 1991). The samples were filtered with 0.45 µm filters prior to analysis. DOC was analyzed with a Shimadzu TOC-5000 (Shimadzu Scientific Instruments, Columbia, MD, USA). Measurement of water quality and tissue Cu and Zn concentrations were conducted as described for the *A. abdita* test above. Digestion of sediment, clam, and amphipod samples for analysis of Cu and Zn were conducted at Loyola University Chicago.

At the end of the study, survival, dry weights, Cu and Zn tissue concentrations were analyzed to determine whether there were statistically significant (p<0.05) treatment-related effects (responses) of the test substance. The ANOVA F-test was used to test the null hypothesis; that the effects of all sediments including the reference sediment are the same. Tissue Cu and Zn concentrations at the end of the tests or at time intervals during the test (*M. mercenaria* test only) were compared with initial Cu and Zn concentrations (background) using Dunnett's procedure. Multiple correlations between dry weight, tissue Cu and Zn concentrations, sediment Cu and Zn concentrations were conducted to determine cause-effects (response) relationship. All statistical analysis was conducted using SAS (version 9.2).

Results and discussion

Sediment characteristics and chemistry

Characteristics of the sediments are shown in Table 1. In general, the cation exchange capacity was high which suggests that the sediments have high potential to retain metals. Results of AVS and total SEM are shown in Table 1. AVS for sediments NOA2333, NOA2334, NOA2569 and NOA2570 were below the detection limits. The total SEM/AVS ratios for these sediments were estimated based on the detection limits of AVS for those samples. The ratio of total SEM/AVS for all sediments was greater than 1 which suggests that metals in the sediments are more bioavailable to benthic organisms (Ankley et al.1996, McGrath et al. 2002).

Concentrations of metals and minerals in the sediments from the sites are shown in Table 2a. Concentrations of the metals and minerals varied from site to site. Among the toxic metals, Cu and Zn were of most concern because concentrations of both metals exceeded (with Cu 6 out of 7 sediments; with Zn 5 out of 7 sediments) the sediment quality assessment guideline (SQAGs) threshold effect levels (TELs) for coastal and marine waters set by the Florida Department of Environmental Protection (FDEP) for Cu (18.7 mg/kg) and Zn (124 mg/kg, dw) (MacDonald et al.1996). Cu concentrations of the 6 sediments also exceeded the informal quick screening marine sediment value (effect range low (ERL) concentration = 34 mg/kg) used for the NOAA SQuiRTs (Buchman, 1999; Long et al. 1995). Zn concentrations were equal to or greater than the ERL (150 mg/kg) for 3 sediments. Neither copper nor zinc concentrations exceeded the NOAA SQuiRTs ERM (effects range median) values which are representative of concentrations above which effects frequently occur (Cu ERM = 270 mg/kg; Zn ERM = 410 mg/kg). Concentrations of the other toxic metals (e.g., As, Cd, Cr, Ni, Pb) in the sediments were not detected or were less than the FDEP TEC SQAGs and the NOAA SQuiRTs ERLs. In a sediment survey in 1982 from the St. Lucie Estuary (SLE) the mean concentration of Cu and Zn were 41 (maximum: 229 mg/kg) and 67 (maximum: 235 mg/kg) mg/kg, respectively (Haunert, 1988). Metal concentrations were related to particle size and organic content; as the quantity of clay- and silt-sized particles increased the concentrations of these metals increased. The sediment in the central part of the North Fork of the SLE had the highest concentrations of organic material with the highest concentrations of metals. In 1992, a sediment survey in the Indian River Lagoon, system also showed high concentrations of Cu above background in sediments and clams (Trocine and Trefry, 1993, 1996). In a follow-up sediment survey in 2006-2007, the mean concentrations of Cu (44mg/kg; maximum: 162 mg/kg) and Zn (95 mg/kg; maximum: 231 mg/kg) increased from the 1992 survey (Trefry and Trocine, 2011).

Minimal concentrations of chlorinated organic pollutants were detected in the sediments (7) from the sites except for DDT metabolites (e.g., p,p-DDD) (Table 2b). The total concentrations of DDTs in 3 out of the 7 sediments were higher than the NOAA SQuiRTs ERL concentration (1.58 mg/kg, dw).

At the end of the *M. mercenaria* bioconcentration study, sediments samples were collected for Cu and Zn analysis. In general, Zn and Cu concentrations at the beginning (day 0) and the end (day 28) of the study were not significantly different except for NOA 2581 and 2639, Cu and Zn concentrations at the end of the study appeared to be higher than those at the beginning (Table 3). This result indicates that Cu and Zn did not desorb to the overlying water. The high percent of silt, clay, and organic matter in the sediments explains why little Cu and Zn release occur during the study. Zn and Cu concentrations in the sediments were also significantly correlated, revealing that Zn and Cu would come from the same source.

Water quality and chemistry

Water quality conditions for both studies were within U.S. EPA test guideline requirements. For the *A. abdita* test, the 10-d average temperature, DO, pH, and salinity of the overlying water during the test were $21 \pm 1^{\circ}$ C, 7.1 ± 1.2 mg/L, 8.26 ± 0.07, and 30 ± 1 ppt, respectively. Ammonia concentration ranged from 0.4 to 1 mg/L which were less than the U.S. EPA criteria at a pH of 8.26 (3.4 mg/L). Concentrations of dissolved Cu in the overlying and pore water were at the background level (6 µg/L Cu in saltwater used for testing). Concentration of dissolved Zn in the overlying and pore waters ranged from the background level (6 µg/L Zn) to 33µg/L Zn. These results may be explained by the high percent of silt, clay, and organic matter in the sediments, resulting in negligible desorption of Cu and Zn from the sediments to water. These results also suggest low bioavailability of Cu and Zn in pore water. Concentrations of dissolved organic matter in the overlying water were low (< 5mg/L). For the *M.*

mercenaria study, the 28-d average temperature, DO, pH, and salinity of the overlying water were 24 ± 0.1° C, 6.6 ± 0.2 mg/L, 8.24 ± 0.11, and 30 ± 1 ppt, respectively. Similar to the *A. abdita* study, concentrations of dissolved Cu and Zn in the overlying and pore water were at the background levels, suggesting low Cu and Zn bioavailability. Concentrations of DOM in the overlying water were also low (< 4mg/L).

Effects on survival, Cu and Zn uptake, and growth

Since concentrations of Cu and Zn exceeded both the Florida sediment quality guidelines and the NOAA SQuiRTs and the other toxic metals (e.g., As, Cd, Cr, Ni, Pb) were below these numerical values, the discussion in this section considers only Cu and Zn. Results of organism survival are shown in Table 4. Mortality of *A. abdita* and *M. mercenaria* ranged from 14% (NOA2333) to 28% (NOA2581) and 0% (NOA2639, NOA2570) to 4% (NOA2569), respectively. In general, there was no significant difference between mortality of the tested organisms for the field-collected reference and contaminated sediments. Although the results of SEM and AVS indicate metal bioavailability, the high organic matter content in the sediments most likely decreased Cu and Zn bioavailability and toxicity. No mortality was reported in a similar study conducted by Rule (1985) with *M. mercenaria* and sediments collected from the Port of Hampton Roads, Virginia which had similar total sediment concentration of Zn, Pb, Ni, and Cu (3 µmol/g) compared to the present study.

Concentrations of Cu and Zn in *M. mercenaria* tissue ranged from 9 (background) to 35 mg/kg dw and 102 (background) to 271 mg/kg dw, respectively (Table 5). In general, Cu and Zn concentrations in *M. mercenaria* tissue were higher on days 3 through 28 than the background concentrations (day 0). In addition, sediment Cu and Zn concentrations were positively correlated with tissue Cu and Zn concentrations (Table 9). These results indicate that *M. mercenaria* accumulated Zn and Cu from the sediments. As discussed above, results of the sediment chemistry (e.g., total SEM/AVS > 1) indicate metal bioavailability. This might explain the Cu and Zn accumulation in *M. mercenaria*. Rule (1985) also found that *M. mercenaria* accumulated Zn from the sediments which had a similar Zn sediment concentration to the present study. However, Zn accumulation by *M. mercenaria* in the Rule (1985) study was approximately half the Zn accumulation in the present study but Zn bioavailability in the present study was higher than in the Rule (1985) study.

Cu and Zn concentrations in *M. mercenaria* tissue in the present study did not increase over time. This is in contrast with our earlier studies with freshwater Florida apple snails (*Pomacea paludosa*) where apple snails accumulated Cu from sediment overtime (Hoang et al. 2008b, Hoang et al. 2011). Cu and Zn concentrations in *M. mercenaria* shell were also below the detection limits but in general, negligible Cu and Zn concentrations were detected in apple snail shells as well (Hoang et al. 2008b).

Zn and Cu concentrations in *A. abdita* varied from site to site and ranged from 111 (NOA2569) to 355 mg/kg dw (NOA2581) and 65 (background) to 364 mg/kg dw (NOA2570), respectively (Table 6). In general, Cu concentrations in *A. abdita* were higher at the end of the study than at the beginning of the study for all sites. There was a positive correlation between the *A. abdita* tissue Cu concentration and sediment Cu concentration (Table 10). Results of the present study indicate that *A. abdita* accumulated Cu from the sediments during the 10 day study. Results of the sediment chemistry suggest Cu bioavailability and therefore explain the Cu accumulation in *A. abdita*. The final tissue results obtained for *A. abdita* in the present study were similar to the tissue Cu concentrations found in our earlier 10 day study with the freshwater benthic amphipod, *Hyalella azteca* exposed to Cu-contaminated soils from citrus agricultural sites near the St. Lucie watershed (Hoang et al. 2009b). Hoang et al. 2009b showed that Cu tissue (whole body) concentrations ranged from 128 to 294mg/kg after 10 days exposure when initial Cu soil concentrations ranged from 5-234 mg/kg from these citrus agricultural sites. Note that in this *A. abdita* study, Cu tissue concentrations were up to 6 times the initial Cu tissue concentrations following only 10 days of exposure and similar to the response of the freshwater amphipod, *H. azteca* following 10 day exposures. Furthermore, the tissue results for both freshwater and saltwater benthic species, following exposures to Cu in sediment, raise some interesting issues for burrowing and tube dwelling in faunal benthic species which have habitats in close contact with sediment (pore water) for part or most of their life cycle. The influence on Cu uptake in these benthic species on upper trophic level diets and species has not been extensively investigated.

Also note that accumulated metal within and between invertebrate taxa, vary considerably, even in the absence of anthropogenic pollution (Rainbow, 2002). For trace metals like zinc and copper, which play essential roles in metabolism of most invertebrate, the quantity necessary to perform these functions may also vary widely within and between invertebrate taxa. For aquatic organisms used in toxicity tests, it is also critical to know the background holding, culture and water quality conditions because if test organisms are obtained from different aquaculture sources the trace metal concentrations in their tissues and organs may be different and will obviously reflect prior water quality and diet they were exposed to. Background tissue concentrations (day 0) of zinc (Table 6) for *A. abdita* were as high as concentrations at the end of the 10d treatment and therefore precluded any comparisons of zinc tissue concentrations. In addition, to being cautious when obtaining organisms from aquaculture sources for aquatic toxicity testing, the use of field-collected species requires even greater awareness for use in toxicity testing especially for the evaluation of hazards and risks.

The dry weight of *M. mercenaria* and *A. abdita* are shown in Tables 7 and 8, respectively. Dry weight of *M. mercenaria* shell, tissue, and whole body from days 0-28 ranged from 194 to 355 mg/organism, 5 to 8 mg/organism, and 198 to 552 mg/organism, respectively. In general, dry weight was not affected by sediment exposure up to day 21. However, there was a slight negative correlation between *M. mercenaria* tissue weight and Cu and Zn concentrations in the sediments at the end of the study (day 28) (Table 9). This suggests that Cu and Zn concentrations in the sediments may have started to produce an effect on *M. mercenaria* growth (as measured by dry weight) after 28 days exposure and that in the experimental design the uptake (exposure) phase was too short and it should have been extended. Clams that live in these sediments will be continuously exposed to Cu and Zn for most of their life cycle in the in the St. Lucie system, with little time for depuration and recovery, hence the effect might be greater. Results of the present study thus raise concern about the population dynamics of bivalves in the St. Lucie ecosystem.

The St. Lucie estuarine ecosystem has been documented as a Cu-contaminated system for decades (Long and Morgan 1990, Delfino et al. 1991, FDEP 1994). The cause of Cu contamination is likely due to Cu release from the sandy soils of nearby citrus agriculture farms through surface runoff. Cu will continuously be used in citrus agriculture, with a long season of application thus increasing the Cu load and release from soils into runoff water, adding more Cu into the St. Lucie estuary and the Everglades ecosystems (Hoang et al. 2008a, Hoang et al. 2009a). This is also based on an exposure analyses of copper concentrations in water and sediment in south Florida aquatic systems for over 15 years from 1990-2008, which shows high Cu concentrations in aquatic systems and potential risks to mollusks in the North and South forks of the SLR and in the SLE (Carriger and Rand, in press).

Dry weight of *A. abdita* was negatively correlated with tissue Cu concentration (Table 10). This suggests that tissue Cu concentrations affected *A. abdita's* growth. Since water concentrations of Cu and Zn were at typical background levels, the effects of Cu and Zn on *M. mercenaria* tissue weight and *A. abdita* weight would be due to exposure via sediment ingestion. Furthermore, tissue Cu and Zn concentrations were correlated with both sediment Cu and Zn concentrations, suggesting that Cu and Zn simultaneously entered the organisms. Ingestion of Cu- and Zn-bound to organic matter in sediments was thus a major exposure route. Several studies have demonstrated that metal exposure to clams and amphipods via food and sediment ingestion was more important than pore water exposure (Eriksson and Sundelin 2002, Labreche et al. 2002, Forbes et al. 1998).

Summary and conclusions

The present study showed that sediments collected from the St. Lucie estuarine system contained Cu and Zn concentrations that exceeded both the Florida State sediment quality criteria and NOAA SQuiRTs sediment values. The total concentration of DDTs in 3 out of the 7 sediments was also higher than the NOAA SQuiRTs sediment values. *M. mercenaria* and *A. abdita* exposed to the St. Lucie sediments resulted in Cu accumulation in *A. abdita* and Cu and Zn accumulation in *M. mercenaria*. The present study also indicated that Cu and Zn exposures via sediment ingestion were most likely an important route of exposure. However, there was no effect of the contaminated sediments on organism survival.

Elevated Cu and Zn concentrations in the tissues and the effects on the weight of both *M. mercenaria* and *A. abdita* raise concerns for the long-term viability of invertebrate populations, for higher trophic organisms in the St. Lucie estuarine ecosystem and the population dynamics of the ecosystem because these are only two organisms that are primary food resources in the St. Lucie system which are exposed to the contaminated sediments for either part or their entire life cycles. The significance of these results can only be fully realized when studies are conducted with other organisms exposed to a greater number field-collected sediments from a larger number of sediment sites. These studies gain in importance in lieu of the continued input of these metals into the environment.

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