Kristi Webb[1], Morrison Maierle, Inc., 3011 Palmer Street, Missoula, Montana 59808

Chris Craft, School of Public and Environmental Affairs, Indiana University, 1315 East Tenth Street, Bloomington, Indiana 47405

and

Erika Elswick, Department of Geological Sciences, Indiana University, 1001 East Tenth Street, Bloomington, Indiana 47405

The Evaluation of the Freshwater Western Pearl Mussel, *Margaritifera falcata* (Gould, 1850), as a Bioindicator Through the Analysis of Metal Partitioning and Bioaccumulation

Abstract

We assessed the effectiveness of the western pearl mussel (*Margaritifera falcata,* Gould, 1850) as a bioindicator of aquatic system health. Fifty-years ago a large dredge mining operation for columbite-tantalite ores [$(Fe,Mn)(Nb,Ta)_2O_6$] disturbed a substantial portion of the Middle Fork of the Salmon River headwaters in Idaho. The disturbance likely increased concentrations of dissolved metals at the time. To evaluate the potential long-term impacts, if any, concentrations of Fe, Mg, Mn, and Zn in shell and soft tissues of western pearl mussels, collected from five reaches in Bear Valley Creek, were analyzed. We quantified the partitioning and bioaccumulation with respect to age of the four metals in the shell, gills and mantle, and remaining soft tissue of the western pearl mussel. Overall, gills and mantle had higher concentrations of Fe, Mg, Mn, and Zn than the remaining soft tissue and shell. Bioaccumulation with respect to age was not uniform among elements or mussel material. We did not detect significant metal accumulation along an upstream gradient approaching the historic dredge site. Metal accumulation downstream did not appear to be in response to the physical disturbance or potential enhancement of dissolved metals during dredging activities in the mid-1950s. However, no mussels were located within the historic dredging zone. Possible reasons for no mussels in the dredging zone are discussed, but not reconciled. We conclude that using freshwater mussels and a water quality assessment might provide a useful approach to biological monitoring of past and current exposures to essential and non-essential elements.

Introduction

Freshwater mussels are an inexpensive secondary indicator of water pollution compared to water or sediment analysis (Phillips 1976). However, the relationship between bioavailability and bioaccumulation is not completely understood regarding freshwater mussels (Tessier et al. 1984).

The pearl mussel family Margaritiferidae have been recommended as good biomonitors for studying seasonal, annual, past, and present water quality conditions and exposures to various pollutants (Havlik and Marking 1987). The rationale is based on the following factors: (1) responsiveness to environmental change, (2) widespread distribution, (3) dependence on salmonids as a host fish for distribution and survival, (4) sedentary life style after the glochidia stage, (6) visible annual growth rings, and (7) long lifespan (>100 yr) (Imlay 1982; Bauer 1983; Havlik and Marking 1987; Carell et al. 1987). However, most studies utilizing *Margaritifera* spp. have focused on the impacts of nutrient enrichment (Bauer 1980, 1983) leaving issues about metal accumulation or partitioning in *Margaritifera* spp. largely unexplored.

Between 1955 and 1959, the Porter Brothers Corporation dredged approximately 0.73 km^2 of private land, extending over 4 km of stream, in the Bear Valley watershed in west-central Idaho. An estimated 6,500 m^3 of stream gravel were removed per day totaling an estimated 181,437 megagrams of dredge product during dredging (USDOE 2005, 2007). As a result of the massive amount of dredge material containing columbite-tantalite ores [$(Fe,Mn)(Nb,Ta)_2O_6$] and uranium oxide byproducts excavated from the watershed (USDOE 2005, 2007), it is likely concentrations of dissolved metals increased in Bear Valley Creek. However, no studies have been conducted to evaluate potential long-term impacts.

Since the Bear Valley watershed (Bear Valley Creek and Elk Creek) provides important habitat

[1]Author to whom correspondence should be addressed.
E-mail: kwebb@m-m.net

for a myriad of aquatic species, our goal was to asses the usefulness of the western pearl mussel (*Margaritifera falcata, Gould*) as a bioindicator. The usefulness of the western pearl mussel as a bioindicator was assessed by analyzing metal concentrations in mussels 50 years after a large dredge mining disturbance. Our study objectives were to (1) describe the age distribution of mussels sampled for metal analysis; (2) quantify the partitioning and bioaccumulation of essential nutrient metals including those dominant elements in the columbite-tantalite ores (Fe, Mg, Mn, Zn) in the shell, gills and mantle, and remaining soft tissue of the mussels; and (3) quantify current ambient water conditions. Concentrations of each metal were quantified along a spatial and temporal gradient for each mussel material. The shell analysis served as a proxy for past water quality conditions, while the soft tissue analyses represented present water quality conditions (Havlik and Marking 1987) allowing a comparison for temporal trends.

Material and Methods

Study Area

Bear Valley watershed (495.76 km^2) is located in west-central Idaho (UTM 620587 E, 4904943 N) approximately 160 km northeast of Boise (Figure 1). The drainage is part of the Cretaceous Idaho batholiths province primarily comprised of granitic parent material (Wendt et al. 1973). Bear Valley watershed has 632 km of streams and establishes the headwaters of the Middle Fork of the Salmon River. In the watershed, Bear Valley (370 km of stream) and Elk creeks (261 km of stream) constitute 59% and 41% of the total stream length, respectively. Elk Creek serves as a reference site due to similar physical and biological characteristics to Bear Valley Creek.

Sampling

Forty-eight mussels were handpicked from the streambed, immediately placed in a container of 95% ethanol, and refrigerated. Seven mussels were collected from the reference site in Elk Creek (Elk 0) and 41 mussels were collected from five locations in Bear Valley Creek (BVC 1, BVC 2, BVC 3, BVC 5, and BVC 8). Six of the 41 mussels were only shells (non-living). Four to eleven mussels were collected from each site. A representative sample of the various sizes observed at each site was collected. Figure 1 shows the location of water and mussel sampling sites. The linear distance of sites BVC 8, BVC 5, BVC 3, BVC 1, and BVC 2 downstream from the dredge site located in Big Meadows was 3.6 km, 6.1 km, 10.0 km, 16.2 km, and 16.4 km, respectively. No mussels were observed upstream of site BVC 8.

Age Analysis

Age was determined by counting annual lines on the shell under a MEIJI dissecting microscope at 20x magnification following techniques used for *Margaritifera* spp. by Hendelberg (1961) in Sweden and by Stober (1972) in Montana. The ligament growth curve Stober (1972) developed for *Margaritifera* spp. sampled from the Madison River, Montana was used to calculate age equivalence corresponding to the distance of the eroded umbo, which was added to the age calculated by the number of annuli. Of the 48 mussels sampled in this study, the distance of an eroded umbo ranged from 0 to 15 mm representing 0-4 additional years.

Metal Analysis

After air drying, the weight for the whole organism was recorded. The soft tissue was removed from the shell and separated into two groups: (1) gills and mantle, and (2) remaining soft tissue. Both were freeze dried and weighed. The shells were ground using a ball mill (8000 SPEX CertiPrep Mixer/Mill) with a hardened steel vial set. The remaining soft tissues were ground using a stainless steel coffee grinder. Gills and mantle were homogenized using forceps in the vial. Ethanol was used to clean equipment and tools used to separate and grind mussel material to prevent cross-contamination. All ground samples were stored in a desiccator prior to the digestion and metal analysis.

Methods for digesting mussel material (shells, gills and mantle, and remaining tissue) were modified from Borg et al. (1981) and Tessier et al. (1984). Ground and homogenized shell samples from each mussel (~500 mg) were placed in a muffle furnace at 500 °C for 4 hr to remove any residual soft tissue before digesting. Soft tissues were not put in the muffle furnace.

For digestion, a homogenized sample (50-150 mg) of the shells, gills and mantle, and remaining

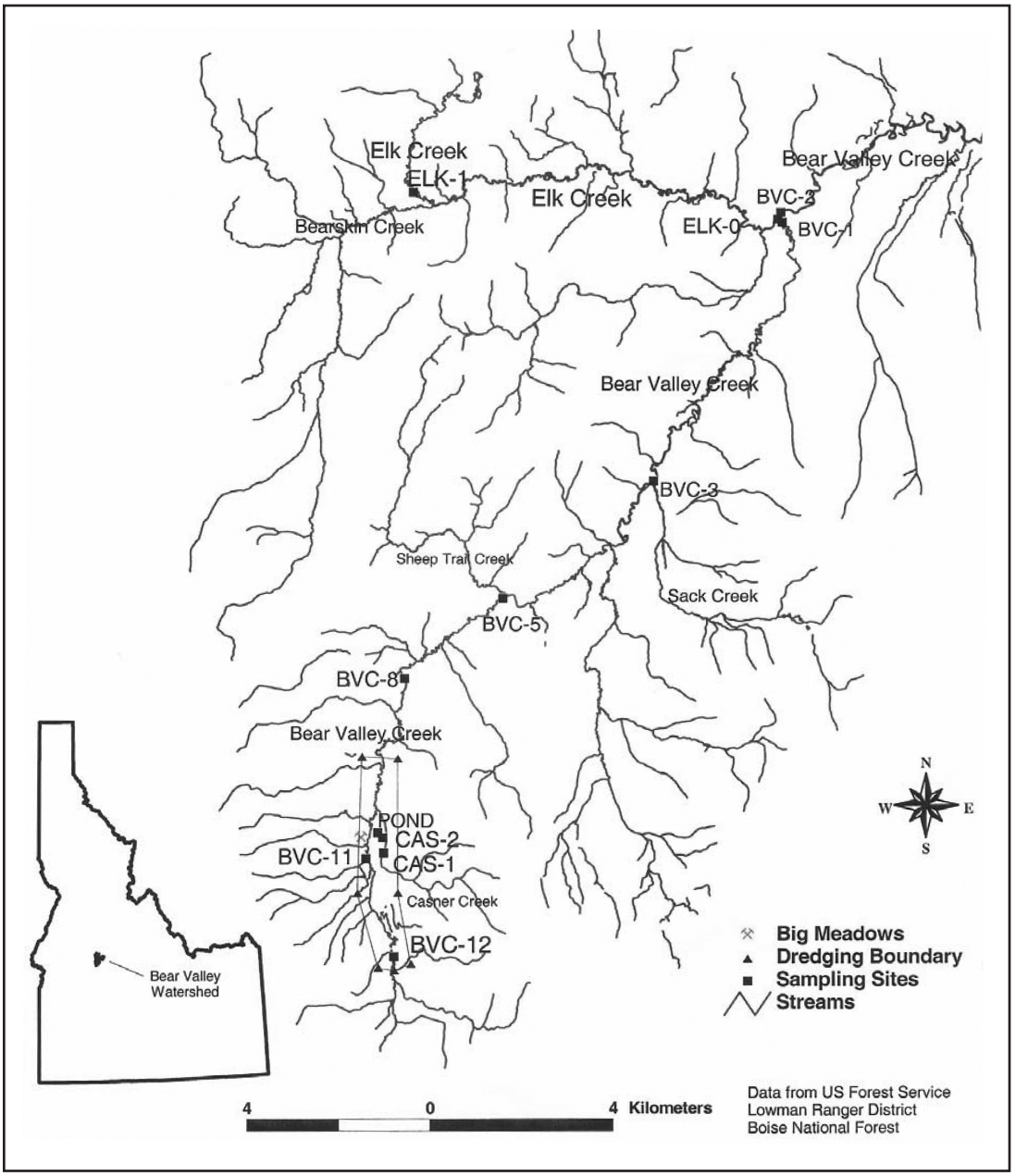

Figure 1. Map of Bear Valley watershed including sampling sites.

soft tissue were weighed in separate 20 mL beakers and each beaker covered with a watch glass. All glassware and centrifuge tubes were acid washed in a 10% HNO_3 and rinsed three times with deionized water. Concentrated HNO_3 (Fischer-trace metal grade) was added to each sample in a beaker (3 mL to shells and 5 mL to soft tissues), covered with a watch glass, and left unheated for 20-24 hr resulting in total dissolution of material. Beakers were then heated to 60-80 °C on a hotplate for 15-60 min until the solution had been reduced to about 1 mL before removing from heat and cooled. An aliquot of 30% Suprapur H_2O_2 (Merck) was added and the sample was reheated to 60-80 °C

for 15-30 min until all material was dissolved and the solution was colorless and again reduced to about 1 mL. Once the beakers had cooled, samples were diluted to 25 mL with 2% HNO_3 and stored in centrifuge tubes. Soft tissue samples required further dilutions with 2% HNO_3 when analyzing for Fe, Mn, and Mg.

All samples were analyzed by flame atomic adsorption spectrophotometry on a Perkin Elmer AAnalyst 800 for Fe, Mg, Mn, and Zn with detection limits 0.03, 0.001, 0.01, and 0.005 µg/g, respectively in the Department of Geological Sciences at Indiana University. Other elements such as Cd, Cu, and Ni were also tested, but not detected.

Test of Metal Analysis Methodology

To verify the accuracy and precision of the digestion methodology of mussel material, 2-3 replicates of 100 mg of a known biological standard reference (1577a bovine liver) from the National Institute of Standards and Tests (NIST), Washington, DC, was included in every digestion run. Results from each digestion run were internally consistent and mean recovery rates of all the digestions runs for bovine liver 1577a used in this study were 64% for Fe, 78% for Mn, 85% for Zn, and 93% for Mg.

Internal standards for shell, gills and mantle, and remaining soft tissue were used as a secondary check and as a match to shell material to verify precision among digestion runs (Table 1). Three samples of gills and mantle were used due to the small amount of material. Overall, the internal standards depicted good precision among digestion runs and verified the consistency of the methodology.

Statistics

All statistical analyses on metal data were completed using SPSS 11.0 (SPSS Inc., Chicago, IL 60606, USA). We used one-way analysis of variance (ANOVA) and Tukey HSD (α=0.05) to conduct various metal analyses. First we compared metal concentrations of the three mussel materials in Bear Valley Creek (BVC) sites collectively to the reference site. Second, we compared metal concentrations of the three mussel materials at different distances from the old dredge site. Third, we compared metal concentrations of the three mussel materials among different age classes of mussels in the BVC sites collectively.

A simple nonlinear regression was used to develop a growth curve. A Kruskal-Wallis ANOVA was used to compare the growth curve developed for Bear Valley Creek to the reference site.

Water Chemistry

During the summer of 2002, water samples were collected at Casner Creek (CAS 1 and CAS 2), the pond (POND), and Bear Valley Creek (BVC 11) shown in Figure 1 and analyzed for dissolved oxygen, pH, total nitrogen and total phosphorus by Analytical Laboratories, Inc. in Boise, Idaho. In October of 2002, additional water samples and field measurements (specific conductivity, pH, redox, temperature) were taken in Bear Valley Creek (BVC 12, BVC 11, BVC 8, BVC 5, BVC 3, BVC 1, BVC 2), Casner Creeks (CAS 1 and CAS 2), Pond, and Elk Creek (Elk 0 and Elk 1). Water samples were acidified with HNO_3, filtered with a 0.2 µm Whatman cellulose nitrite filter, stored in a cooler, and shipped to Indiana University for elemental analysis (Fe, Mn, Mg, Zn) via flame and graphite flame atomic adsorption spectrophotometry (Perkin Elmer AAnalyst 800).

Results

Age and Morphology

The ages of mussels sampled in Bear Valley Creek ranged from 8-36 years at BVC 2, 9-28 years at

TABLE 1. Internal standards for each mussel material and respective sampling site. Percent standard deviation (% SD) represents the largest standard deviation from the mean (µg g^{-1} dry weight), n = sample size, BVC = Bear Valley Creek.

	Shell (µg g^{-1})		Remaining Soft Tissue (µg g^{-1})		Gills and Mantle (µg g^{-1})					
	BVC 5		BVC 8		Elk 0		BVC 8		BVC 3	
	n	mean (%SD)	n	mean (%SD)	n	mean (%SD)	n	mean (% SD)	n	mean (%SD)
Fe	25	282 (29)	11	3252 (53)	3	3817 (5)	4	2175 (11)	7	2527 (24)
Mn	25	258 (19)	11	685 (74)	3	5575 (10)	4	9093 (17)	7	10241 (30)
Mg	25	30 (27)	11	1028 (16)	3	2059 (2)	4	1072 (8)	7	2371 (16)
Zn	25	4 (329)	11	96 (26)	3	235 (2)	4	275 (9)	7	274 (17)

TABLE 2. Sample size (n), range and mean values for age, length (L), thickness of umbo (H), width of shell (W), and dry weight (Wt) of the western pearl mussel sampled in Bear Valley Creek (BVC) and a reference site (Elk Creek, REF).

	Site	Age (yrs)	L (mm)	W (mm)	H (mm)	Wt (g)
N	BVC	41	41	41	36	36
	REF	7	7	7	7	7
Range	BVC	8 – 48	32 – 97	16 – 45	9 – 45	3 – 49
	REF	6 – 39	28 – 85	15 – 40	7 – 25	3 – 46
Mean (SD)	BVC	19.7 (9.5)	60.5 (16.9)	30.1 (7.5)	17.3 (5.2)	18.0 (13.3)
	REF	20.3 (11.3)	61.3 (19.2)	29.6 (8.8)	17.0 (6.3)	22.0 (15.9)

BVC 1, 11-31 years at BVC 3, 11-48 years at BVC 5, and 20-31 years at BVC 8. Mean age of mussels sampled in the reference site ranged from 6-39 years, similar to the sampled population in Bear Valley Creek. The lengths of all mussels sampled (n=48) ranged from 28-97 mm, and approximately half (n=23) were less than 60 mm in length. The mean and range for age, length, width, umbonal height, and total weight (shell and tissue) for mussels sampled in Bear Valley Creek and the reference site are summarized in Table 2.

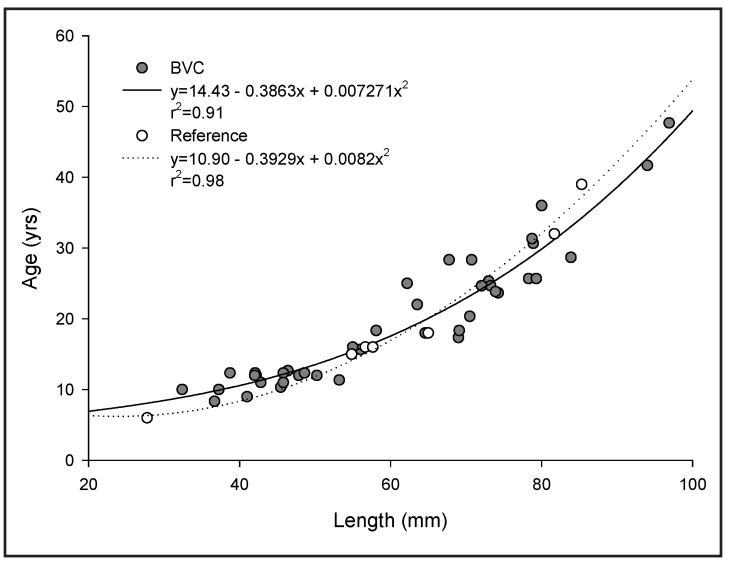

Figure 2. Non-linear growth curve of the western pearl mussel in Bear Valley Creek and reference site.

A growth curve to estimate age based on the length of the mussel showed growth was nonlinear in our Bear Valley Creek samples (r^2=0.91) (Figure 2). No statistical difference in growth rates was detected between Bear Valley Creek and reference site samples (Kruskal-Wallis ANOVA, $P > 0.05$). According to the growth curve, the largest mussel measured in the field (121 mm in the upper reaches of Elk Creek) was over 100 years of age.

Metal Analysis

Metal Partitioning in the Different Mussel Materials

There was a similar pattern in both Bear Valley Creek and reference site regarding preferential partitioning of metals among the shell, gills and mantle, and remaining soft tissue (Figure 3). All metal concentrations (Fe, Mg, Mn, Zn) above the detection limit were highest in the gills and mantle. Mg, Mn, and Zn concentrations in the remaining soft tissue were less than half of that in the gills and mantle, and only Fe was slightly lower (depending on site) in the remaining soft tissue (Figure 3). Shells sequestered significantly lower concentrations of Fe, Mg, and Zn compared to the gills and mantle, and remaining soft tissue (Tukey HSD, $P \leq 0.009$) (Figure 3). There was no significant difference in Mn sequestered in the shell relative to the remaining soft tissue. Overall sequestration of metals in all mussel material collectively decreased in the following sequence: Mn > Fe > Mg > Zn.

Bioaccumulation of Metals with Proximity to Big Meadows Dredge Site

There was no continuous or significant change in the accumulation of metals along an upstream

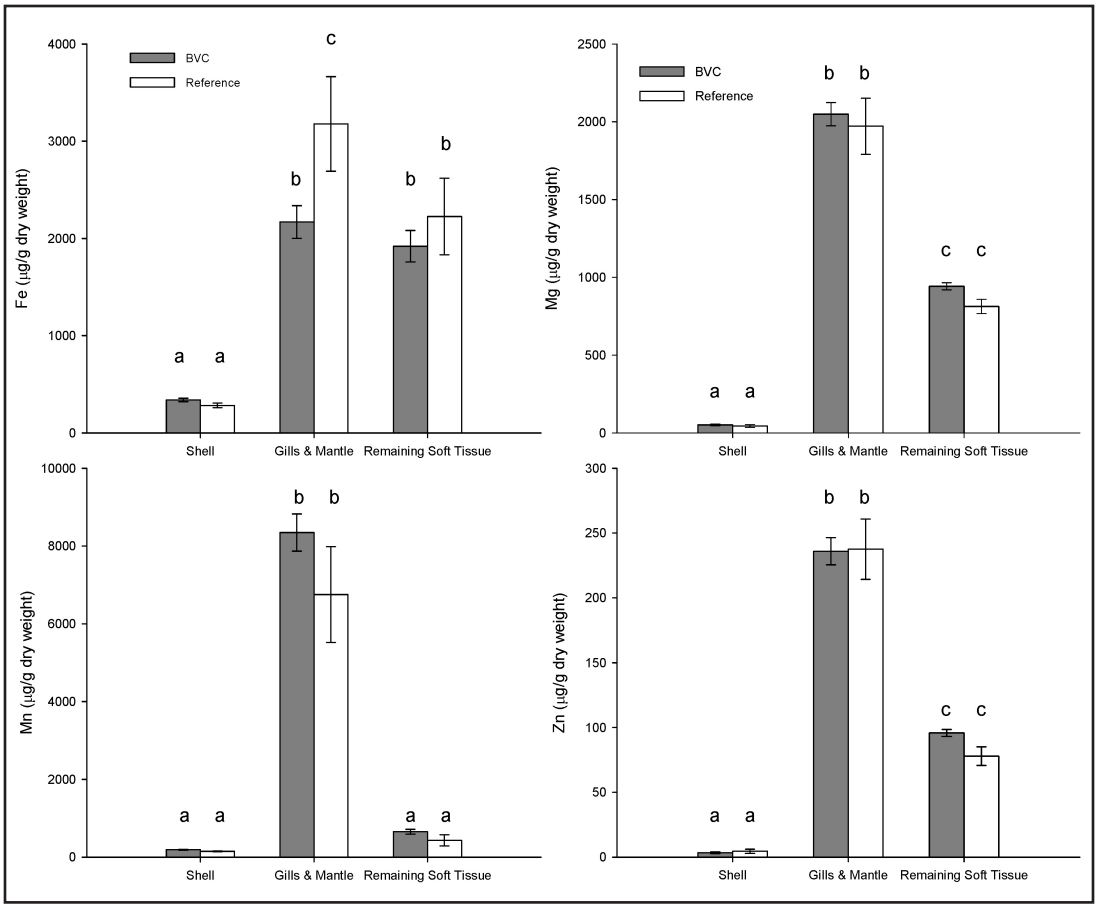

Figure 3. Partitioning of Fe, Mg, Mn, and Zn (µg g^{-1} dry weight) in the shell, gills and mantle, and body of the western pearl mussel in Bear Valley Creek and Elk Creek (Reference). The data present the mean with the standard error. a, b, and c indicate statistical significance at $\alpha = 0.05$ from the other letters with respect to each element.

gradient approaching Big Meadows, in the shell, gills and mantle, or remaining soft tissue (Figure 4). In the shell, the sequence of metal concentrations decreased in the following order: Fe > Mn > Mg > Zn. In the gills and mantle, the sequence of the metal concentrations decreased in the following order: Mn > Fe > Mg > Zn. Mn concentrations showed an increasing trend with closer proximity to the dredge site although no statistical difference was detected among BVC sites or between BVC sites and the reference site. In the remaining soft tissue, the sequence of the metal concentrations decreased in the following order: Fe > Mg > Mn > Zn. Fe concentrations showed an increasing trend along an upstream gradient from sites BVC 2 to BVC 8, however there was no statistical difference among BVC sites.

Mean metal concentrations in the reference site were most often similar to Bear Valley Creek concentrations. There were only a few cases where Fe and Mn concentrations in the shell were statistically different and greater in some Bear Valley Creek sites compared to the reference site (Figure 4).

Bioaccumulation by Age Class

All samples from Bear Valley Creek sites were compiled, separated into five age classes of 0-10, 11-20, 21-30, 31-40, and 41-50 years, and analyzed by material type (shell, gills and mantle, and remaining soft tissue) (Figure 5). The reference site was not evaluated for metal accumulation over time since an adequate representation of each age class was not available.

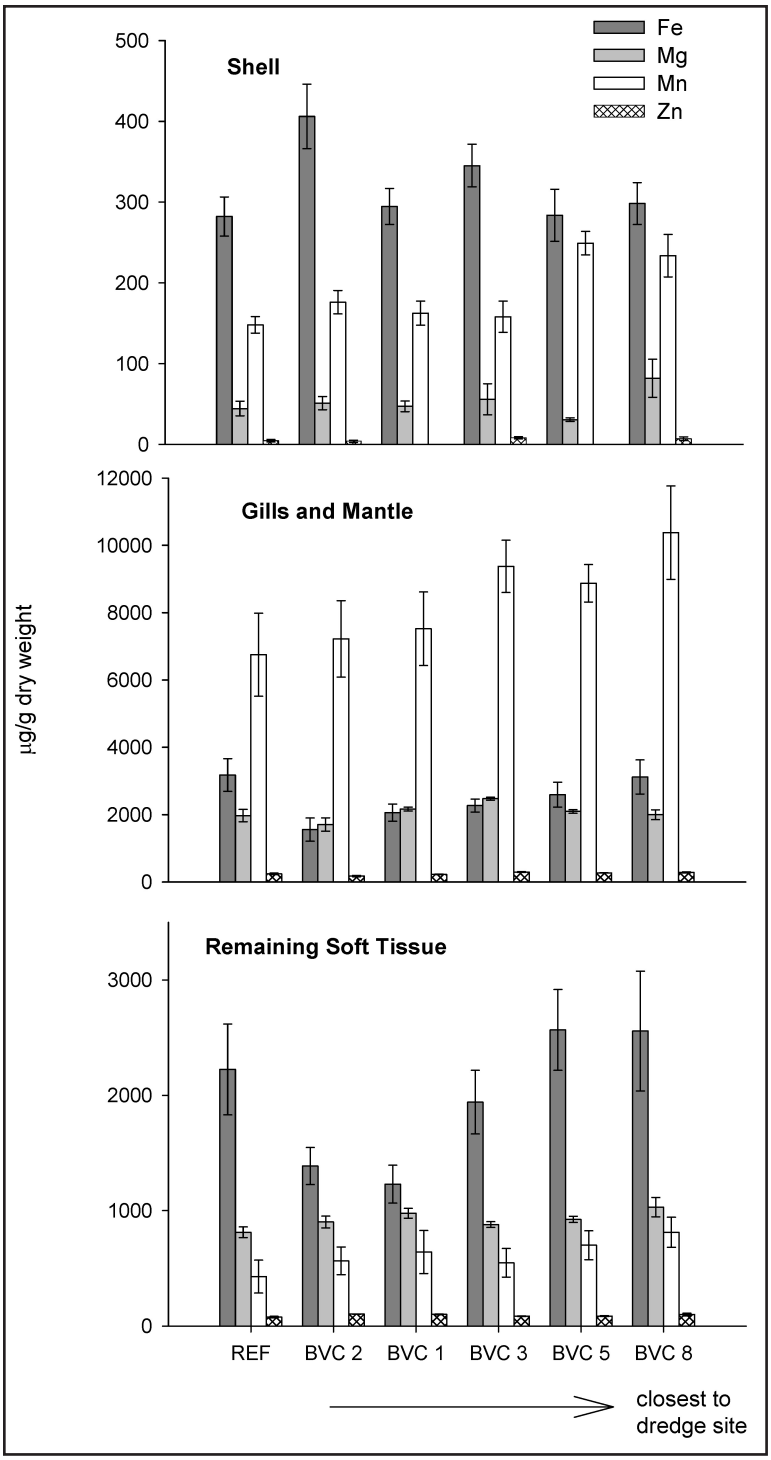

Figure 4. Concentration of Fe, Mn, Mg, and Zn in the shell, gill and mantle, and remaining soft tissue in Bear Valley Creek (BVC) and the reference (REF, Elk Creek). Data represent the mean (µg g^{-1} dry weight) with the standard error.

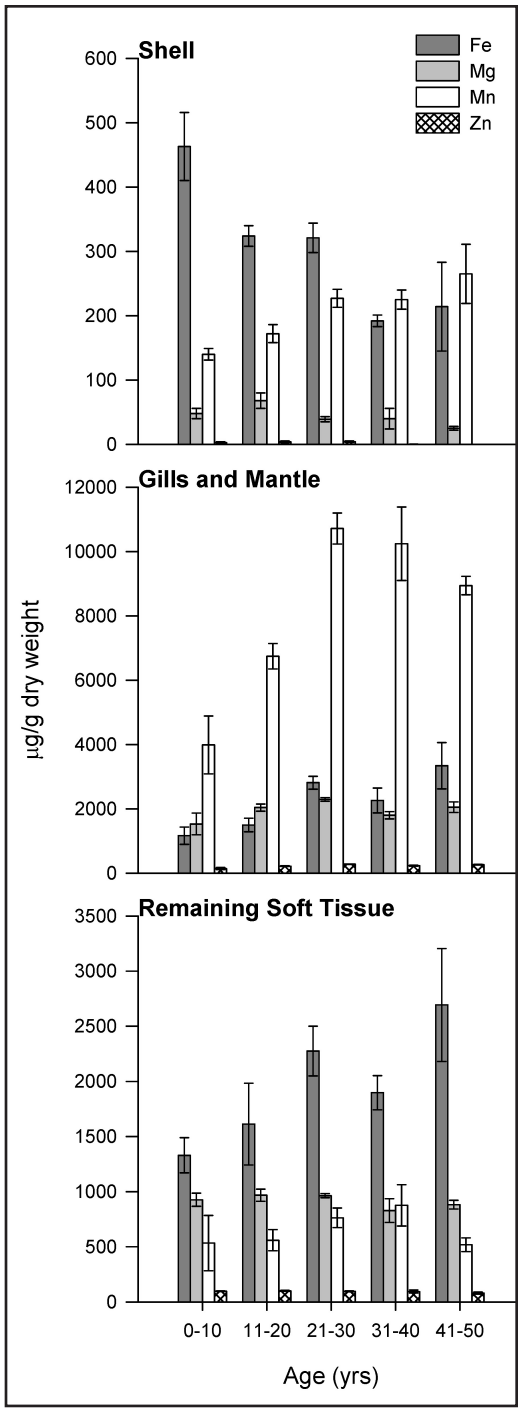

Figure 5. Concentration of Fe, Mn, Mg, and Zn in the shell, gill and mantle, and remaining soft tissue in Bear Valley Creek (BVC) for five age classes. Data represent the mean (µg g^{-1} dry weight) with the standard error.

Mn concentration in the shell increased with age, Fe decreased, and Mg and Zn were relatively constant (Figure 5). Mg and Zn showed no significant accumulation with respect to age. Fe had the highest concentration in the shell from age zero to 30 and then Mn became the most highly concentrated metal from age 31 to 50. Mean concentrations of Mn were significantly lower in the 0-20 year age class than the 21-30 year age class (Tukey HSD, $P \leq 0.03$). In contrast, Fe depicted an inverse relationship with age revealing 0-10 year age class was statistically higher than other age classes (Tukey HSD, $P \leq 0.027$).

In the gills and mantle, Mn was the most dominant metal for all age classes followed by Fe and Mg, and then Zn (Figure 5). As in the shell, Mn concentrations increased significantly with age in the gills and mantle. In contrast to Fe in the shell, Fe in the gills and mantle increased significantly between the 0-20 and the 21-50 year age classes. Zn and Mg did not change significantly with age.

In the remaining soft tissue, Fe had the highest concentration for all age classes followed by Mg and Mn, and then Zn (Figure 5). Metal concentrations in the remaining soft tissue showed a similar, but less pronounced pattern for each element as described for the gills and mantle. There was no significant change in accumulation of Fe, Mg, Mn, or Zn with age.

Water Chemistry

Water data collected in July 2002 from the upper reach (BVC 11) and tributaries (CAS 1, CAS 2, POND) in Bear Valley Creek were representative of oligotrophic stream conditions. Nitrogen, total phosphorus, dissolved oxygen and pH ranged from <0.1 to 0.25 mg L^{-1}, < 0.5 to 0.14 mg L^{-1}, 9.5-12 mg L^{-1}, and pH 6.5-8.3, respectively for the sites sampled in July. Results from field measurements taken in October 2002 were consistent upstream and downstream in Bear Valley Creek and at the reference site. Specific conductivity ranged between 25-50 µS·cm^{-1}; redox ranged between 118-128 mV; and pH ranged between 5 and 6. Ambient levels for Fe, Mg, Mn, and Zn are shown in Table 3.

Discussion

Our data indicate the western pearl mussel in Bear Valley Creek have experienced no long-term

TABLE 3. October 2002 ambient water concentrations for Fe, Mg, Mn, and Zn in Bear Valley Creek (BVC) and a reference site (Elk Creek, REF). Mean concentrations (μg L^{-1}) are presented with the standard deviation (SD); n = sample size.

Site	Statistics	Fe	Mg	Mn	Zn
BVC	N	10	10	10	10
REF	2	2	2	2	
BVC	Mean (μg L^{-1}) (SD)	57 (27.7)	424 (86)	18 (7.8)	3.5 (0.8)
REF	42 (11.2)	647 (49.5)	18 (1.2)	4.0 (0.1)	
BVC	Range (μg L^{-1})	5 – 103	279 – 562	7 – 36	1 – 4

impacts or recent exposure to excessive amounts of Fe, Mn, Mg, or Zn. The sample population had a diverse range of ages, appeared healthy, and ambient metal concentrations in the water were low indicating the current metal concentrations has not resulted in any acute toxicity.

Age and Morphology

The range of ages of the sampled population indicated a much broader age group in Bear Valley Creek with lengths 28-97 mm compared to studies of *Margaritifera* spp. in Montana (Stober 1972) or in Sweden (Hendelberg 1961), reporting ranges in length between 61-100 and 61-150 mm, respectively. An aggregate analysis of the sampled group of mussels in Bear Valley Creek appeared to include a more evenly diverse mix of young (<60 mm) and old (>60 mm) aged mussels compared to populations studied in Montana (Stober 1972) and in Sweden (Hendelberg 1961) where populations were, on average, older. However, our study was not designed to probabilistically sample the population. Therefore our data only describes the Bear Valley Creek samples and not the age structure of the Bear Valley Creek western pearl mussel population.

Based on stream walks, mussels were not observed upstream of the uppermost reach sampled (BVC 8). Potential reasons explaining the limitation in mussel distribution include: (1) range of host fish may be limited since the host has not yet been identified, (2) chemical constituents (e.g., Ca) in the water needed to create shell material are limiting, or (3) the physical disturbance from dredging and restoration activities may have buried or removed some mussels in the past, thus delaying recolonization.

The host fish or fishes for the western pearl mussel in the Bear Valley watershed has not been identified, but there are several potential candidates. Potential hosts native to the system include westslope cutthroat trout (*Oncorhynchus clarki lewisi)*, redband trout (*O. mykiss*), steelhead (*O. mykiss*), and Chinook salmon (*O. tschawytscha*). Snorkel surveys conducted by the Forest Service show a definitive overlap of potential host fish with the observed locations of mussels, although density or abundance estimates of the fish species was not available (unpublished data, USFS Lowman Ranger District).

The host may be the limiting factor if their abundance, density, and/or distribution has experienced periodic declines or a gradual decline over time that could have resulted in fewer fish present in the uppermost reaches in Bear Valley Creek. Periodic declines of host fish could have occurred when stream conditions were less favorable as a result of past dredging (1955-1959) and restoration (mid-1980s) activities increasing the turbidity and suspended solids. Poor stream conditions could have precluded fish movement and consequently mussel recruitment in the upper stream reaches. However, if the fish abundance, density, and distribution remained relatively stable over time throughout the watershed, then the host fish theory would not be a limiting factor to mussel distribution or density.

Metals

Our analysis on metal partitioning supports other studies of freshwater mussels that suggest the gills and mantle are subjected to higher concentrations of Fe, Mg, Mn, and Zn compared to the rest of the remaining soft tissue and shell (Hobden 1970; Manly and George 1977; Imlay 1982; Tessier et al. 1984; Naimo et al. 1992). Our data showed the highest affinity of metals analyzed in the soft tissues in this study, specifically the gills and mantle, were for Mn, Mg, and Zn. Fe showed little difference in the gills and mantle versus the

remaining soft tissue. Our data also showed a more pronounced bioaccumulation of Mn in the gills and mantle of the western pearl mussel over time compared to the remaining soft tissue and shell. Naimo (1995) suggests the metal concentration within a specific tissue may be related to certain binding sites and perhaps mechanisms for detoxification within that tissue. We found that bioaccumulation of Mn in the gills and mantle does not appear to be in response to the physical disturbances and potential enhancement of dissolved metals during dredging activities in the 1950s.

As a result of the variability in tolerance of freshwater mussels to metals and lack of information specific to *Margaritifera* species; the metal data cannot be extrapolated to depict toxic concentrations that are lethal or sub-lethal (Rainbow 1996). Studies found metal concentrations in the water and biota to vary diurnally Bäckström et al. 2002), seasonally (Gunderson et al. 2001), spatially and temporally Sullivan and Drever 2001), and with altitude (Kiffney and Clements 1996). We collected water and mussel samples during the daytime in the summer and early fall, thus cannot address these variables. Long range monitoring of water quality in Bear Valley might quantify the range of possible maximum values or the percentage of time at peak toxicity that may occur seasonally, diurnally, and/or spatially.

Conclusion

The metal analysis of freshwater mussel materials, from a diversely aged sample population, coupled with a water quality assessment is an important and valid approach to assess the impact of past and current exposures to essential and non-essential elements to aquatic biota and on the aquatic system. Our study found that essential nutrient metals show a distinct affinity to partition among the mussel tissues as well as some metals, such as Mn, exhibit a greater affinity to bioaccumulate over time in the soft tissues. Overall, gills and mantle had higher concentrations of Fe, Mg, Mn, and Zn compared to the rest of the remaining soft tissue and shell. Bioaccumulation with respect to age was not uniform among elements or mussel material. There was no significant metal accumulation along an upstream gradient approaching the historic dredge site in any of the three mussel tissues tested. We conclude metal accumulation downstream of the dredging area did not appear to be in response to the physical disturbance or potential enhancement of dissolved metals during dredging activities in the mid-1950s. However, no mussels were located within the historic dredging zone. Potential explanations for not finding mussels in the historic dredging zone may be related to the host fish, chemical constituents in the water, or the physical burial of mussel populations during dredging and restoration activities. However, these hypotheses have not been tested.

Acknowledgements

We thank the Department of Geological Sciences at Indiana University for the use of their facilities and technical support. Thanks to the Lowman Ranger District, U.S. Forest Service through the cooperation with C. Zurstadt, K. Grover-Weir, and T. Giambra for field work support and historical information. We would also like to thank G. Gillin, D. Finkelstein, and S. Struck for comments, suggestions, and reviews of the manuscript.

Literature Cited

Bäckström, M., E. Börjesson, and S. Karlsson. 2002. Diurnal variations of abiotic parameters in a stream, recipient of drainage water in Ranstad, southwest Sweden. Journal of Environmental Monitoring 4:772-777.

Bauer, G. 1980. Relations between decline of the freshwater pearl mussel (*Margaritifera margaritifera*) in the Fichtelgebirge and water quality. Archiv für Hydrobiologie 88:505-513.

Bauer, G. 1983. Age, structure, age specific mortality rates and population trends of the freshwater pearl mussel (*Margaritifera margaritifera*) in North Bavaria. Archiv für Hydrobiologie 98:523-532.

Borg, H. A. Edin, K. Holm, and E. Sköld. 1981. Determination of metals in fish livers by flameless atomic absorption spectroscopy. Water Research 15:1291-1295.

Carell, B., S. Forberg, E. Grundelius, L. Henrickson, A. Johnels, U. Lindh, J. Mutvei, M. Olsson, K. Svärdström, and T. Westermark. 1987. Can mussel shells reveal environmental history? Ambio 16:2-10.

Gunderson, P., P. Olsvik, and E. Steinnes. 2001. Variations in heavy metal concentrations and speciation in two mining-polluted streams in central Norway. Environmental Toxicology and Chemistry 20:978-984.

Havlik, M. E. and L. L. Marking. 1987. Effects of contaminants in naiad mollusks (Unionidae): a review. Resource Publication 164. USDI Fish and Wildlife Service, Washington, D.C.

Hendelberg, J. 1961. The freshwater pearl mussel *Margaritifera margaritifera* (L.). Report of the Institute of the Freshwater Research Drottningholm 41:149-171.

Hobden, D. J. 1970. Aspects of iron metabolism in a freshwater mussel. Canadian Journal of Zoology 48:83-86.

Imlay, M. J. 1982. Use of shells of freshwater mussels in monitoring heavy metals and environmental stresses: a review. Malacological Review 15:1-14.

Kiffney, P. M. and W. H. Clements. 1996. Effects of metals on stream macroinvertebrate assemblages from different altitudes. Ecological Applications 6:472-481.

Manly, R. and W. O. George. 1977. The occurrence of some heavy metals in population of the freshwater mussel *Anadonta anatina* (L.) from the river Thames. Environmental Pollution 14:139-154.

Naimo, T. J. 1995. A review of the effects of heavy metals on freshwater mussels. Ecotoxicology 4:341-362. Naimo, T. J., D. L. Waller, and L. E. Holland-Bartels. 1992. Heavy metals in the three ridge mussel *Amblema plicata piicata* (Say, 1817) in the Upper Mississippi River. Journal of Freshwater Ecology 7:209-215.

Phillips, D. J. H. 1976. The common mussel *Mytilus edulis* as an indicator of pollution by zinc, cadmium, lead, and copper. II. Relations of metals in the mussel to those discharged by industry. Marine Biology 38:71-80.

Rainbow, P. S. 1996. Heavy metals in aquatic invertebrates. *In* W. N. Beyer, G. H. Heinz and A. W. Redmon-Norwood (editors), Environmental contaminants in Wildlife Interpreting Tissue Concentration, SETAC Special Publications, Clemson.

Received 27 August 2007
Accepted for publication 17 March 2008

Stober, Q. J. 1972. Distribution and age of *Margaritfera margaritifera* (L.) in a Madison River (Montana, U.S.A) mussel bed. Malacologia 11:343.

Sullivan, A. B. and J. I. Drever. 2001. Spatiotemporal variability in stream chemistry in a high elevation catchment affected by mine drainage. Journal of Hydrology 252:237-250.

Tessier, A., P. C. Campbell, J. C. Auclair, and M. Bisson. 1984. Relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the freshwater mollusc *Elliptio complanata* in a mining area. Canadian Journal of Fisheries and Aquatic Sciences 41:1463-1472.

USDOE. 2005. Long-term surveillance plan for the U.S. Department of Energy Lowman, Idaho, (UMTRCA Title I) Disposal Site. U.S. Department of Energy, Office of Legacy Management, Grand Junction, CO.

USDOE. 2007. Lowman, Idaho, disposal site. Fact Sheet. U.S. Department of Energy Grand Junction, Grand Junction, CO.

Wendt, G. E., W. T. Shiverdeck, and G. F. Cole. 1973. Soil-hydrologic reconnaissance survey. Lowman Ranger District, Boise National Forest, Lowman, ID.