

BIOMONITORING OF METALS USING PLANTS AND FISH SPECIES AFTER A MINING SPILL: THE CASE OF THE SONORA RIVER, NORTHWESTERN MEXICO

Biomonitoreo de metales usando plantas y peces después de un derrame minero: el caso del río Sonora, noroeste de México

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Key words: pollution, aquatic ecosystems, mine impacts, bioindicator species, metal(loid)s.

ABSTRACT

Aquatic ecosystems are under constant pressure from anthropogenic activities, which frequently release many contaminants that may have adverse impacts. In August 2014, a spill of 40 000 m³ of acid solution occurred in the Sonora River Basin (SRB), which contained elevated levels of metal(loid)s. These elements are persistent in the environment and may have adverse health effects on organisms. In this study, the impact of the spill on the accumulation of metals was evaluated in SRB, using two plants and three fish species. Organisms were collected from sites affected by the spill and from sites not affected by the spill. The samples were analyzed for Al, Cu, Fe, Mn, Pb, and Zn contents. The levels of all elements in the organisms at all sites exhibited spatial and seasonal variations, without discernible patterns. In most cases, metal accumulations were similar between sites affected and not affected by the spill. However, Pb levels in fish exceeded international regulations, implying risks associated with consuming these species. Some positive correlations were determined between Pb and other metals, which may indicate that they occur in similar routes of exposure and/or are linked to the same minerals. Although there were no defined metal accumulation patterns between affected and non-affected sites by the spill, the studied species were useful for determining metal exposure in the two ecosystems investigated.

Palabras clave: contaminación, derrame minero, cuenca del río Sonora, especies bioindicadoras, metales y metaloides.

RESUMEN

Los ecosistemas acuáticos son impactados de manera constante por las actividades antrópicas que se desarrollan en sus alrededores, al recibir descargas de contaminantes que producen efectos adversos. El derrame de 2014 de 40 000 m³ de una solución ácida con altas concentraciones de metales y metaloides recorrió gran parte de la

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cuenca del río Sonora (CRS). Estos elementos son persistentes y producen diversos efectos adversos en los organismos. En este estudio se evaluaron los contenidos de Al, Cu, Fe, Mn, Pb y Zn en organismos recolectados en diferentes sitios de la CRS y en sitios no afectados por el derrame. La acumulación de metales mostró variaciones espaciales y estacionales, con niveles similares de acumulación entre sitios afectados y no afectados por el derrame. Los niveles de Pb superaron los límites establecidos por la legislación internacional, lo que implica riesgos para la salud por el consumo de esas especies. Además, hubo correlaciones entre Pb y otros metales, lo que indica que siguen rutas de exposición similares y/o están asociados a los mismos minerales. Aunque hay patrones de acumulación de metales diferentes entre sitios afectados y no afectados por el derrame, las especies estudiadas resultaron ser buenas bioindicadoras para medir la exposición a metales en los ecosistemas estudiados.

INTRODUCTION

Aquatic ecosystems provide ecological, social, and economic support. However, anthropogenic activities provoke constant pressures that impact their components (Tamim et al. 2016). This is particularly problematic in aquatic ecosystems from desert regions, where water is a limiting resource for development (Bashir et al. 2020). The waste generated by human activities contains many contaminants, such as organic matter, plastics, pesticides, and metal(loid)s. Metal(loid)s are persistent contaminants that are mobilized between reservoirs by abiotic and biotic factors such as pH, redox potential, chemical species, feed habits, and sex (Häder et al. 2020). The adverse effects of these contaminants on different organisms are widely documented, including at levels considered as low (Huang et al. 2014, Ali et al. 2018, Feki et al. 2021, USEPA 2021, 2025).

Among anthropogenic activities, mining is one of the most significant in terms of its impact on the economy and development of the countries. However, it is also considered a contaminant activity due to the hazardous wastes it generates. When these wastes are not adequately confined, the risks of dispersion and contamination of aquatic ecosystems increase significantly (Beck et al. 2020, Luckeneder et al. 2021). This was the case of a mine spill occurring in August 2014 on the Sonora River Basin (SRB), in which Buena Vista del Cobre spilled 40 000 m³ of acid solution that contained high levels of metal(loid)s. Several studies have evaluated the impacts of this spill on reservoirs in areas affected by SRB (Romo-Morales et al. 2020, Archundia et al. 2021, Gutiérrez-Ruiz et al. 2022). However, the use of a group of organisms to elucidate the impact of the spill on the biota of SRB was not reported. The patterns of accumulation of metal(loid)s that provide plants and fish are different but complementary (Häder et al. 2020, Zhao

et al. 2020, Feki et al. 2021) to elucidate the impacts of sudden and uncontrolled events, such as spills.

Considering the usefulness of organisms with diverse biological habits, the aim of this study was to elucidate the impact of the spill on two plants and three fish species from different sites of SRB, as well as the same species from sites of an ecosystem that was not affected by the spill. Our hypothesis is that metal accumulation is higher in organisms from sites affected by the spill than in those from sites not affected by the spill.

MATERIALS AND METHODS

Study area

The SRB is located in the state of Sonora, north-west Mexico, in the north-central region, bounded by coordinates 30°18'-30°59' N, and 110°05'-110°34' W (**Fig. 1**). The SRB has a surface area of 1776 km², with three predominant climatic conditions: (a) mild-subhumid with summer raining and annual temperature average from 13 to 22 °C and precipitation average from 550 to 750 mm; (b) arid-subtropical with annual temperatures from 18 to 20 °C and precipitations ranging from 450 to 550 mm; and (c) dry-desert with annual temperatures from 20 to 30 °C and precipitations ranging from 350 to 400 mm. El Molinito Dam (EMD) is located in the Hermosillo municipality, at coordinates 29° 12' 55" N and 110° 43' 26" W (**Fig. 1**), with predominant climate of desert-dry conditions, an annual average temperature range of 20 to 24 °C, and an annual average precipitation range of 350 to 400 mm (CONAGUA 2022).

The Yaqui River Basin is located between coordinates 27° 04'-32° 05' N and 107° 03'-110° 70' W, with a surface of 71 776 km² and average precipitation of 527 mm/year. El Cajón de Onapa Dam (COD) is located at coordinates 28° 41' N and 109° 07' W

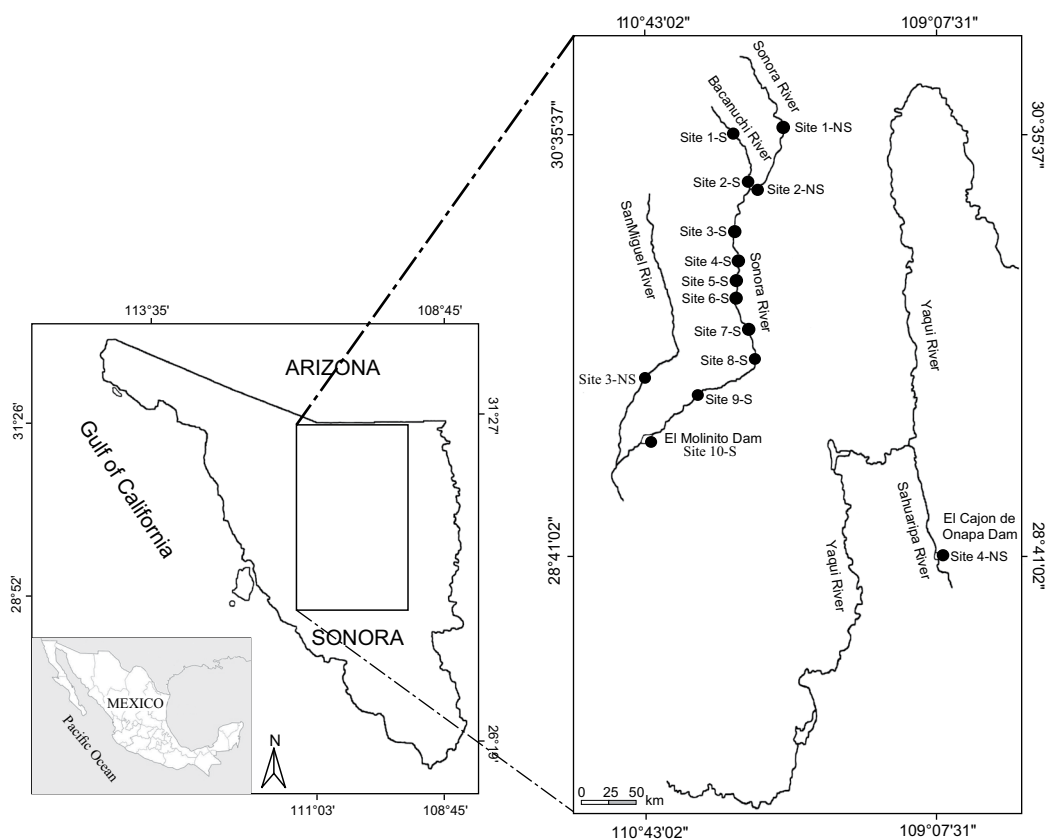


Fig. 1. Study area and sampling sites affected (Site 1-S to Site 10-S) and not affected (Site 1-NS to Site 4-NS) by the spill of August 2014 in the Sonora and Yaqui rivers, northwest of Mexico.

(**Fig. 1**). The predominant climatic conditions are temperate subhumid (C(wa)), with an annual average temperature of 23.6 °C and a range of annual precipitation of 500-700 mm (CONAGUA 2022).

Sampling and processing

The selection of sampled organisms was based on their abundance, distribution, and longevity through the seasons in the studied ecosystems (Luoma and Rainbow 2008). Two plant species (*Baccharis salicifolia* [seepwillow] and *Hymenoclea monogyra* [burrobrush singlewhorl]) and three fish species with different feeding habits (*Oreochromis niloticus* [Nile tilapia, benthic], *Ictalurus punctatus* [catfish, omnivorous], and *Micropterus salmoides* [largemouth bass, predator]) were collected during May, August, and November 2015 for biomonitoring metal exposure. The leaves of plant species were collected from 10 sites affected by the spill (from Site 1-S to Site 10-S) and from three sites not affected by the spill (Site 1-NS, Site 2-NS, and Site 3-NS). The fish species were collected using a 4 cm commercial gill net

from one site affected by the spill (Site 10-S, EMD) and from one site not affected by the spill (Site 4-NS, COD; **Fig. 1**). Fishes were sacrificed by brain spiking, according to the Guidelines for the Use of Fishes in Research of the American Fisheries Society (Jenkins et al. 2014) to minimize animal suffering, and their total length and total weight were registered. Plant and fish samples were labeled in polyethylene bags, transported to the laboratory, washed three times with distilled water, frozen at -25 °C, and freeze-dried (-48 °C and 32×10^{-3} mbar for 48 h). The leaves and whole fish species were homogenized in an agate mortar and stored at 4 °C until digestion.

Samples digestion and metals analysis

Biological samples were digested in a single step using a microwave system (MARS-X), according to Martínez-Durazo et al. (2021). Briefly, 5 mL of concentrated HNO_3 were added to 0.250 ± 0.003 g of sample and heated to 100 °C for 5 min, 120 °C for 5 min, and 140 °C for 10 min. The sample was diluted to 50 mL for metal analyses and analyzed for

Al, Cu, Fe, Mn, Pb, and Zn contents using a flame atomic absorption spectrophotometer (F-AAS, Varian, SpectrAA-240-FS). The elements were chosen because they were present in the August 2014 spill. The limits of detection for metal analyses in the digested samples were estimated ($\mu\text{g/g}$) as: Al = 0.60; Cu = 0.032; Fe = 0.049; Mn = 0.51; Pb = 0.072; and Zn = 0.054. The sample was diluted to 25 mL for metal analyses, and element concentrations were obtained on a dry weight basis (DW). The accuracy of the biological samples analysis was assessed by using certified reference materials: apple leaves (SRM-1515) from the National Institute of Standards and Technology, USA, and dogfish muscle (DORM-2) from the National Research Council, Canada. Results were within the certified range values, and the variation coefficients were less than 13 % for all measured analyses, with a range of recovery percentages of 87–113 %. Additionally, quality control of the analysis was ensured through the use of analytical blanks and triplicate analysis.

Statistical analysis

Normality and variance of homogeneity tests for metal concentrations in biological samples were performed using the Kolmogorov-Smirnov D and Bartlett tests. The spatial and seasonal comparisons of metal contents in the organisms were compared using the Kruskal-Wallis and Student-Newman-Keuls tests (Glantz 2002). Spearman correlations were also determined among metals in the collected biological samples. All statistical analyses were performed with the Minitab software (v. 17.0).

RESULTS

The metal contents in seepillow (*B. salicifolia*) and burrobrush singlewhorl (*H. monogyra*) in the sites affected and not affected by the spill are presented in figures 2 and 3, respectively. The levels of all elements at the studied sites exhibited spatial and seasonal variations, without defined patterns.

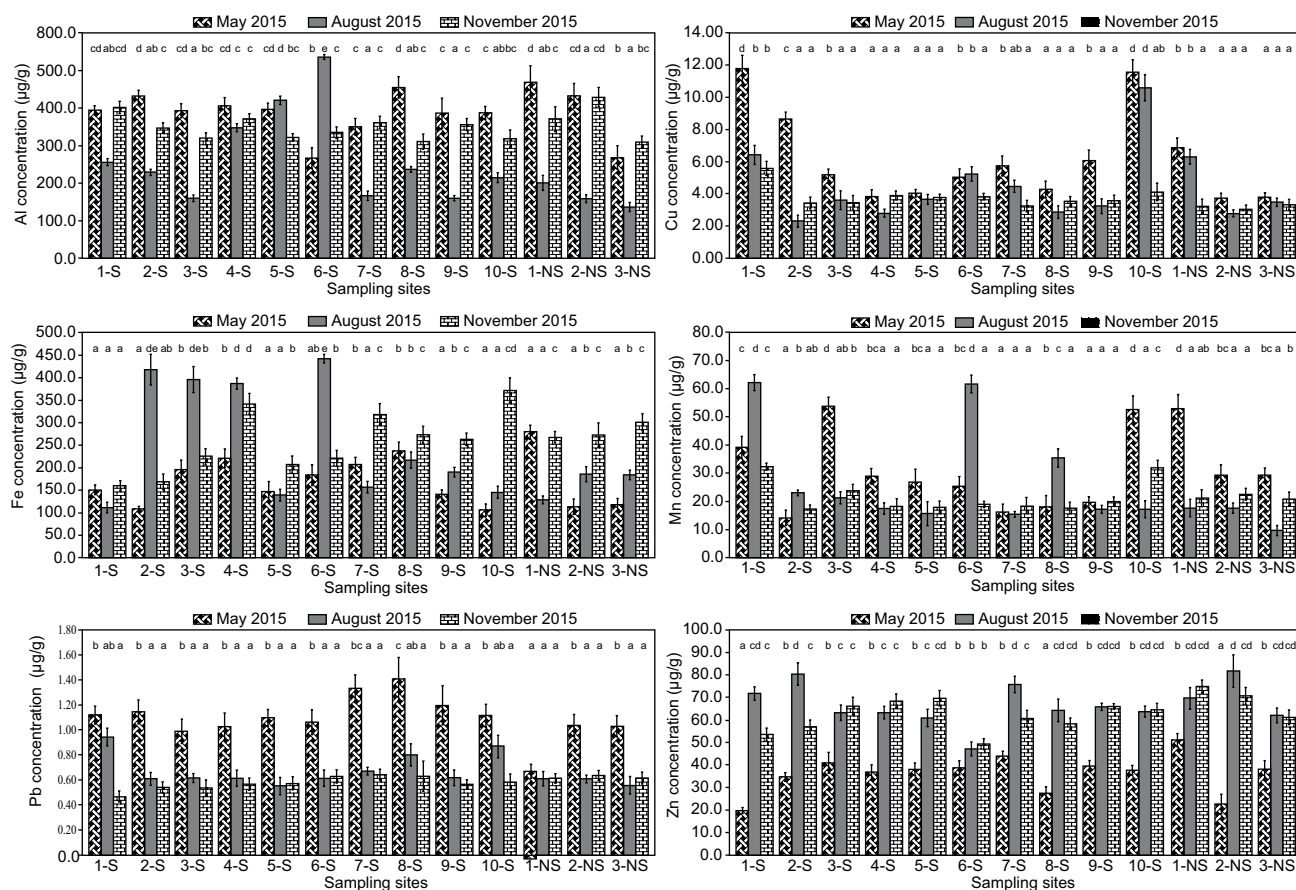


Fig. 2. Concentration of metals in seepillow (*Baccharis salicifolia*) in sites affected (Site 1-S to Site 10-S, Sonora River) and not affected (Site 1-NS to Site 3-NS, Yaqui River) by the spill of August 2014, ecosystems of the northwest of Mexico.

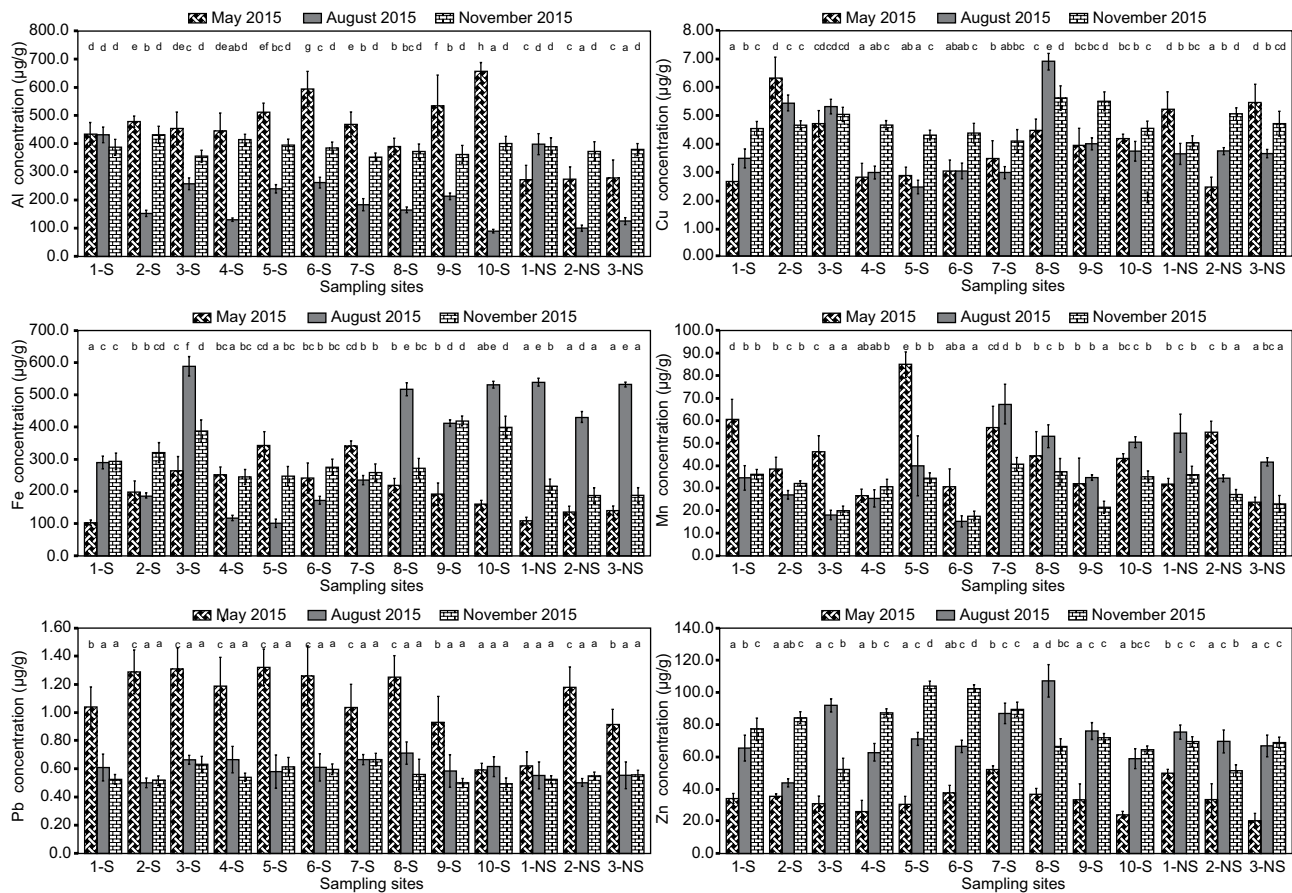


Fig. 3. Concentration of metals in burrobush singlewhorl (*Hymenoclea monogyra*) in sites affected (Site 1-S to Site 10-S, Sonora River) and not affected (Site 1-NS to Site 3-NS, Yaqui River) by the spill of August 2014, ecosystems of the northwest of Mexico.

In general, the metals accumulated in both plants were $\text{Al} \approx \text{Fe} > \text{Zn} > \text{Mn} > \text{Cu} > \text{Pb}$. There were seasonal variations in metal contents in these species, without a defined pattern; moreover, most of the metal accumulation patterns were similar among those affected and not affected by the spill sites. Some elements showed patterns in plants: (a) mean Al concentrations were significantly ($p < 0.05$) elevated in most sites during May 2015 in both species; (b) mean Cu contents were significantly ($p < 0.05$) higher in November 2015 for seepillow, while Cu concentrations were significantly ($p < 0.05$) elevated in May 2015 for burrobush singlewhorl; (c) the most elevated concentrations of Fe for both plants occurred in August 2015; (d) the lowest Mn accumulation for both plants occurred in November 2015; (e) the highest Pb concentrations were determined during May 2015 for both plant species; (f) finally, the lowest Zn levels occurred in May 2015 for both plant species.

Figure 4 shows the concentrations of metals in the three whole fish species during the sampling seasons in the two ecosystems (affected and not affected by the spill). Similar to plants, fish showed spatial and seasonal variations in metal contents. There were some general patterns in metals accumulations: (a) in both ecosystems, the lowest Al and Fe accumulation levels were found in largemouth bass, while tilapia presented the lowest Cu and Mn accumulation levels; (b) the accumulation of Fe was higher in the COD ecosystem (not affected by spill); (c) tilapia presented the highest Pb accumulation levels in both ecosystems; and (d) catfish showed the highest Zn accumulation levels in both ecosystems.

The comparisons of ranges of metal contents in biological samples with international and national legislations (**Table I**) show that detected levels of Pb in fishes exceed those of the Food Safety Authority of Ireland (FSAI 2009) and the Official Mexican Standard NOM-242-SSA1-2009 ($\text{Pb} > 0.50 \text{ mg/g}$).

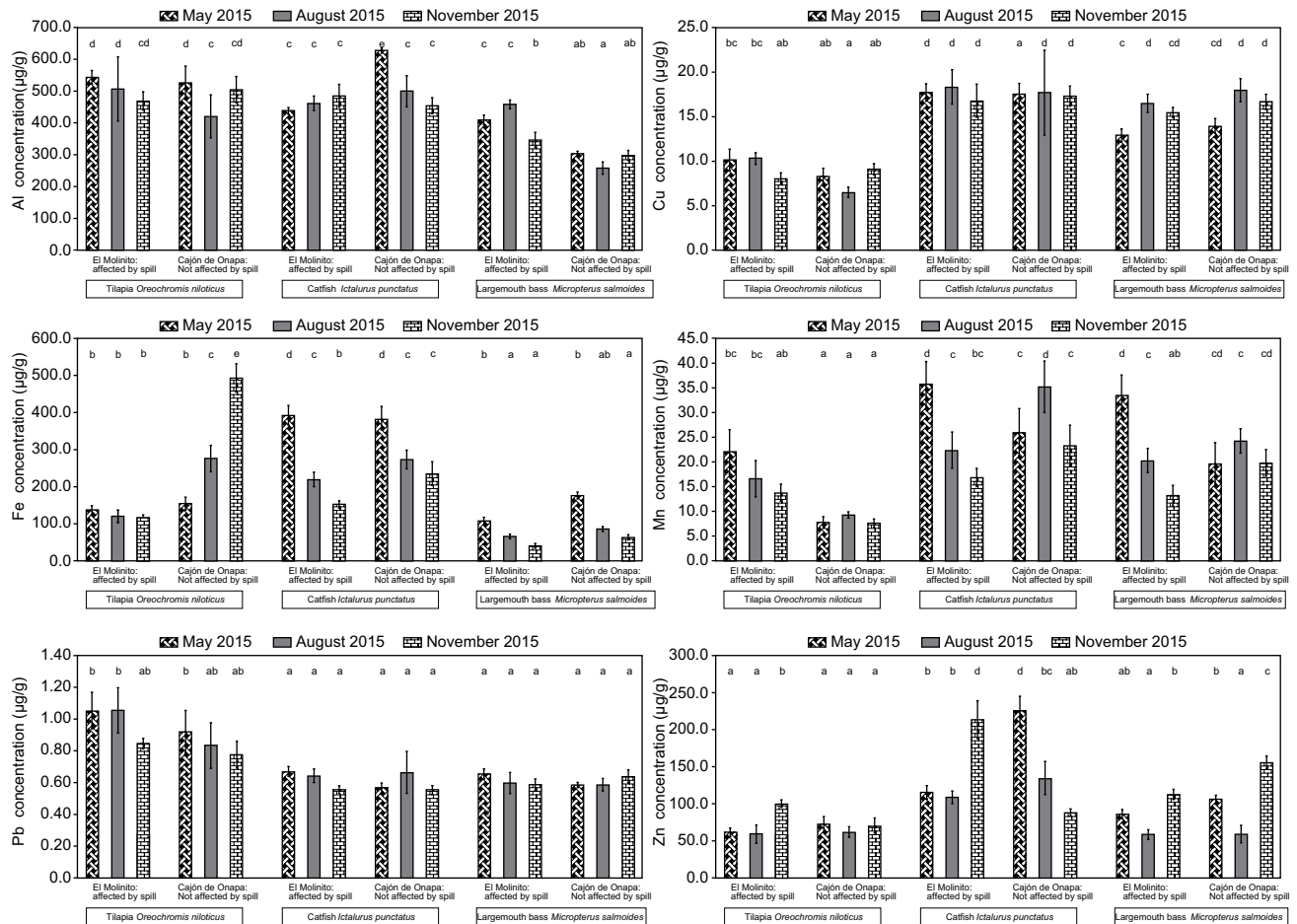


Fig. 4. Concentration of metals in whole fish in ecosystems from the northwest of Mexico, affected (El Molinito, Sonora River) and not affected (El Cajón de Onapa, Yaqui River) by the spill of August 2014.

(SSA 2011). Also, the levels of Pb are higher than the limits established in the Codex Alimentarius (WHO 2015) for fish and leafy vegetables ($Pb > 0.30$ mg/g for both types of food) and Australian and New Zealand regulations ($Pb > 0.10$ mg/g for leafy vegetables and $Pb > 0.50$ mg/g for fish) (FSANZ 2026). The other elements are not regulated by any legislation, although some of them are associated with certain health disorders, as reported for Cu and Mn (Kozłowski et al. 2014).

The correlations among metals in the organisms are presented in **tables II and III**. There are significant ($p < 0.05$) positive correlations for seepwillow between Cu:Fe, Cu:Zn, Fe:Zn, Mn:Pb, Mn:Al, and Pb:Al; this species also showed significant ($p < 0.05$) negative correlations between Cu:Mn, Cu:Pb, Fe:Pb, Fe:Al, Mn:Zn, Zn:Pb, and Zn:Al. Similarly, burrobush singlewhorl showed significant ($p < 0.05$) positive correlations between Cu:Fe, Cu:Zn, Fe:Zn,

Mn:Pb, and Pb:Al; also showed significant ($p < 0.05$) negative correlations between Cu:Mn, Cu:Pb, Mn:Zn, Zn:Pb, and Zn:Al.

Regarding fish species, there are similarities in metal correlations among species from the two ecosystems. In the case of tilapia, many correlations were found: (a) it shows significant ($p < 0.05$) positive correlations between Cu:Fe, Cu:Mn, Cu:Zn, Fe:Zn, Fe:Al, Mn:Zn, Mn:Al, and Zn:Al, and negative correlations between Fe:Pb, Mn:Pb, and Zn:Pb, in both ecosystems; (b) in EMD, it showed significant ($p < 0.05$) positive correlations between Mn:Zn and Mn:Al, but significant ($p < 0.05$) negative correlation between Pb:Al; (c) in COD, it showed a significant ($p < 0.05$) negative correlation between Mn:Al.

In the case of catfish, there are also similarities in the correlations: (a) it presented significant ($p < 0.05$) positive correlations between Cu:Zn, Fe:Al, Mn:Zn, and negative correlations between Cu:Pb, in both

TABLE I. RANGES OF CONCENTRATIONS (MEAN $\pm$ STANDARD DEVIATION) OF METALS (mg/g) IN ORGANISMS COLLECTED FROM SITES AFFECTED (S) AND NOT AFFECTED (NS) BY THE AUGUST 2014 SPILL IN THE SONORA RIVER BASIN DURING THE THREE SEASONS STUDIED*. COMPARISON WITH VALUES ESTABLISHED IN INTERNATIONAL REGULATIONS.

Site	Al	Cu	Fe	Mn	Pb	Zn
Seepwillow						
S	88.8 – 656.9 (364.7 $\pm$ 138.6)	2.49 – 6.90 (4.22 $\pm$ 1.11)	101.4 – 589.0 (286.0 $\pm$ 122.7)	15.03 – 85.06 (37.82 $\pm$ 15.57)	0.50 – 1.32 (0.77 $\pm$ 0.29)	24.05 – 20.38 (62.43 $\pm$ 25.13)
NS	99.5 – 398.2 (287.7 $\pm$ 112.2)	2.49 – 5.47 (4.23 $\pm$ 0.96)	109.1 – 538.9 (275.5 $\pm$ 174.7)	22.95 – 54.83 (36.31 $\pm$ 11.95)	0.50 – 1.18 (0.66 $\pm$ 0.23)	20.38 – 75.41 (56.22 $\pm$ 18.90)
Burrobrush singlewhorl						
S	159.9 – 536.4 (335.0 $\pm$ 90.4)	2.33 – 11.78 (4.99 $\pm$ 2.50)	106.6 – 448.1 (228.6 $\pm$ 98.12)	14.04 – 62.21 (26.52 $\pm$ 13.96)	0.47 – 1.34 (0.78 $\pm$ 0.26)	19.49 – 80.34 (54.22 $\pm$ 15.35)
NS	136.3 – 469.0 (308.4 $\pm$ 125.1)	2.77 – 6.86 (4.06 $\pm$ 1.47)	112.9 – 301.3 (205.8 $\pm$ 75.74)	9.72 – 52.94 (24.53 $\pm$ 12.24)	0.55 – 1.03 (0.71 $\pm$ 0.19)	23.05 – 81.77 (59.17 $\pm$ 18.79)
Fishes						
S	346.9 – 543.7 (457.8 $\pm$ 56.83)	8.04 – 18.33 (14.1 $\pm$ 3.76)	40.84 – 392.9 (150.6 $\pm$ 104.0)	13.21 – 35.94 (21.65 $\pm$ 8.14)	0.56 – 1.05 (0.74 $\pm$ 0.20)	59.17 – 213.9 (102.0 $\pm$ 47.96)
NS	257.8 – 628.3 (432.7 $\pm$ 123.7)	6.52 – 18.02 (13.9 $\pm$ 4.65)	63.6 – 493.7 (237.9 $\pm$ 138.4)	7.66 – 35.33 (19.24 $\pm$ 9.43)	0.55 – 0.92 (0.68 $\pm$ 0.13)	59.23 – 225.5 (108.2 $\pm$ 55.19)
Leafy vegetables	–	–	–	–	0.30 ^{1,2} /0.10 ³	–
Fish	–	–	–	–	0.50 ^{1,2} /0.30 ^{3,4}	–

*May, August, and November, 2015.

¹ Irish legislation (FSAI 2009).² Mexican legislation (SSA 2009).³ WHO (2015).⁴ Australia and New Zealand Food Standards and Schedules (FSANZ 2008).

ecosystems; (b) in EMD, it showed significant ($p < 0.05$) positive correlations between Fe:Mn, Fe:Zn, Fe:Al, Mn:Al, and Zn:Al, but significant ($p < 0.05$) negative correlation between Zn:Pb; (c) and in COD, it exhibited significant ($p < 0.05$) positive correlations between Cu:Mn and Fe:Pb, and significant ($p < 0.05$) negative correlation between Cu:Al, Fe:Mn, Fe:Zn, Mn:Pb, Mn:Al, and Zn:Al.

In the case of largemouth bass, similarities were also found in the correlations among metals: (a) there were significant ($p < 0.05$) positive correlations between Cu:Mn and Fe:Zn, and negative correlations between Cu:Pb and Mn:Pb, in both ecosystems; (b) in EMD, it showed significant ($p < 0.05$) positive correlations between Cu:Zn and Mn:Zn, and a negative correlation between Zn:Al; (c) and in COD, there were significant ($p < 0.05$) positive correlations between Cu:Fe, Fe:Pb, Fe:Al, Zn:Pb, Zn:Al, and Pb:Al.

DISCUSSION

The plants studied showed spatial and seasonal variations in metal contents, without defined patterns. In most cases, the levels of metals accumulated among those affected and not affected by the spill were similar, which may imply that the spill did not have a significant effect on the increments of metal content in the EMD. The accumulation of these elements by plants is a complex process influenced by various factors, including concentration and duration of exposure, chemical species, tissue type, and the presence of other elements (Zhao et al. 2020, Feki et al. 2021). The levels and duration of metal exposure are not necessarily reflected in plant accumulation: plants with low accumulation are frequently exposed to high metal concentrations, and vice versa. Then, hyperaccumulator plants are used to remove or

TABLE II. CORRELATION COEFFICIENTS OF METAL CONCENTRATIONS IN THE SEEPWILLOW (*B. salicifolia*) AND BURROBRUSH SINGLEWHORL (*H. monogyra*)¹.

	Cu	Fe	Mn	Zn	Pb	Al
Seepwillow						
Cu	1.000					
Fe	0.346	1.000				
Mn	-0.344	-0.084	1.000			
Zn	0.305	0.318	-0.407	1.000		
Pb	-0.533	-0.326	0.247	-0.544	1.000	
Al	-0.190	-0.248	0.361	-0.590	0.452	1.000
Burrobrush singlewhorl						
Cu	1.000					
Fe	0.249	1.000				
Mn	-0.246	-0.146	1.000			
Zn	0.223	0.501	-0.332	1.000		
Pb	-0.293	-0.170	0.272	-0.659	1.000	
Al	-0.021	-0.184	0.165	-0.325	0.373	1.000

¹ Spearman coefficients in bold indicate a significant difference at $p = 0.05$.

TABLE III. CORRELATION COEFFICIENTS OF METAL CONCENTRATIONS IN FISH SPECIES FROM EL MOLINITO ECOSYSTEM¹.

El Molinito dam (affected by the August 2014 spill)						
	Cu	Fe	Mn	Zn	Pb	Al
Tilapia						
Cu	1.000					
Fe	0.783	1.000				
Mn	0.694	0.332	1.000			
Zn	0.896	0.728	0.729	1.000		
Pb	-0.798	-0.374	-0.897	-0.851	1.000	
Al	0.805	0.387	0.901	0.859	-0.978	1.000
Catfish						
Cu	1.000					
Fe	-0.217	1.000				
Mn	0.303	0.521	1.000			
Zn	0.661	0.535	0.621	1.000		
Pb	-0.933	0.225	-0.304	-0.644	1.000	
Al	-0.318	0.933	0.454	0.404	0.286	1.000
Largemouth bass						
Cu	1.000					
Fe	0.220	1.000				
Mn	0.674	0.238	1.000			
Zn	0.578	0.804	0.551	1.000		
Pb	-0.843	0.029	-0.525	-0.003	1.000	
Al	-0.279	0.122	0.157	-0.387	0.272	1.000

¹ Spearman coefficients in bold indicate a significant difference at $p = 0.05$.

accumulate metals in contaminated environments, while moderately accumulating plants are used for biomonitoring metal exposure (Zhao et al. 2020). In this study, both plants (seepwillow and burrobrush singlewhorl) exhibited similar patterns of metal accumulation, suggesting they were exposed to similar metal levels. However, this may also indicate that both plants have similar physiological mechanisms for processing and eliminating metals (Feki et al. 2021).

Similar to plant species, fish species exhibited spatial and seasonal variations in metal content, without discernible patterns. Additionally, metal accumulation levels among those affected and unaffected by the spill were similar, suggesting that the spill did not significantly increase metal content in EMD (**Table IV**). This may also imply that both ecosystems are in metal-enriched areas (Tamim 2016, Birch 2017).

Fish in different aquatic environments tend to accumulate metals in their tissues depending on factors such as metal concentration, time of exposure,

TABLE IV. CORRELATION COEFFICIENTS OF METAL CONCENTRATIONS IN FISH SPECIES FROM EL CAJÓN DE ONAPA ECOSYSTEM¹.

El Cajón de Onapa (not affected by the August 2014 spill)						
	Cu	Fe	Mn	Zn	Pb	Al
Tilapia						
Cu	1.000					
Fe	0.809	1.000				
Mn	0.617	0.119	1.000			
Zn	0.883	0.967	0.269	1.000		
Pb	-0.899	-0.629	-0.738	-0.723	1.000	
Al	0.079	0.600	-0.694	0.475	0.110	1.000
Catfish						
Cu	1.000					
Fe	-0.716	1.000				
Mn	0.952	-0.627	1.000			
Zn	0.640	-0.946	0.558	1.000		
Pb	-0.814	0.408	-0.767	0.311	1.000	
Al	-0.554	0.939	-0.495	-0.924	0.216	1.000
Largemouth bass						
Cu	1.000					
Fe	0.367	1.000				
Mn	0.923	-0.181	1.000			
Zn	0.011	0.717	0.220	1.000		
Pb	-0.588	0.573	-0.522	0.369	1.000	
Al	-0.235	0.879	0.018	0.790	0.412	1.000

¹ Spearman coefficients in bold indicate a significant difference at $p = 0.05$.

route of metal uptake, environmental conditions (water temperature, pH, hardness, salinity, organic matter contents, etc.), and biological factors (fish age, feeding habits, health status, etc.). Then, some fish species with low mobility in aquatic ecosystems have been used as bioindicators, considering that their differences in dietary habits are among the most critical determinants of metal accumulation (Balzani et al. 2022). It was therefore expected that different fish species would exhibit distinct responses to the accumulation of metal pollution. However, there are no seasonal or spatial patterns in metal accumulation among the species studied in affected and non-affected spill ecosystems, suggesting similar exposure levels to metals. Top predator fish usually accumulate significant quantities of metals such as Hg, Se, and As, which are frequently reported to be biomagnified in aquatic food webs (Valladolid-Garnica et al. 2023). Omnivores and benthic fish usually accumulate high quantities of elements such as Cu, Mn, Pb, and Zn, based on their feeding habits (Ali et al. 2018).

The levels of Pb in biological samples exceeded the regulatory limits set by Mexico, Ireland, and the Codex Alimentarius, implying potential health risks from their consumption. Pb is considered one of the most toxic metals, which acts on a wide range of organs and tissues. Chronic exposure to Pb is related to adverse effects on the central nervous and cognitive systems, which are more vulnerable in populations such as children and pregnant women (Skerfving and Bergdahl 2015, USEPA 2025). However, more precise studies are required to assess these risks.

Some correlations between Pb and other metals were determined to be remarkable (Mn:Pb, Cu:Pb, Zn:Pb, Fe:Pb) in plants and fish species in the studied ecosystems. Positive correlations among metals indicate that they occur in similar routes of exposure and/or are linked to the same minerals, such as pyrites and oxihydroxides of Fe and Mn (Horowitz 2009, Rahman et al. 2013). Moreover, these correlations are also indicative of similar physiological routes within organisms, for example, linked to metallothionein or calcium granules (Huang et al. 2014, Skerfving and Bergdahl 2015). In contrast, negative metal correlations indicate behaviors that are opposite to positive correlations.

CONCLUSIONS

The plant and fish species exhibited spatial and seasonal variations in metal accumulation, with no discernible patterns. The species used were useful for

determining metal exposure in the two ecosystems studied. However, they must be used as a batch of organisms to elucidate metal exposure. Additionally, the same or similar species from pristine or low-impact ecosystems must be used to compare element accumulation patterns and elucidate potential sources of metals. The accumulation patterns of metals were similar between impacted and non-impacted sites affected by the spill, likely due to mineralized areas in the SRB. Nevertheless, special attention has to be paid to the most toxic elements, such as Pb.

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