PRELIMINARY REPORT

Investigation of potential bioaccumulation of metals resulting from Vistra battery storage fire: preliminary findings

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Report by Biota Team of **EMBER**

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Overview

The purpose of this report is to share preliminary findings from initial sampling of biota for battery material metals in estuarine plants, algae, invertebrates, and fish in Elkhorn Slough following the Vistra battery storage fire in January 2025.This is work conducted by the Biota team of **EMBER** (**E**stuary **M**onitoring of **B**attery **E**missions and **R**esidues resulting from the Moss Landing battery fire).

The report briefly describes the approach and methods for biological sampling, provides graphs and tables summarizing initial results, and includes some information that is helpful for readers to contextualize the findings.

This is a living document sharing preliminary results. As more samples are analyzed, from more sites and dates, our understanding of potential bioaccumulation will increase. We will continue to release results as analyses continue and as funding allows. **No conclusions about ecological impacts of the battery fire should be drawn yet from these initial data**, which are being shared in the interest of transparency with interested stakeholders. When funding becomes available to analyze the remainder of collected samples, the team will complete a scientific publication that will be peer-reviewed and then published in a scientific journal, with more definitive findings.

BACKGROUND AND METHODS

Background and rationale for study

On 16 January 2025, one of the largest battery storage facilities in the world caught fire and burned for several days in Moss Landing, central California. Models of the smoke plume from the Vistra fire project that particulates from the fire drifted and may have settled over nearby communities, farm fields, and the environmentally sensitive Elkhorn Slough estuary. Early surveys of surface sediments show nickel, manganese, and cobalt at concentrations up to 10 to 1000 times greater than pre-fire (Aiello et al. 2025). Over time, these metals may become bioavailable and be taken up by plants and animals living in the estuary. The process of bioaccumulation could pose particular threats to top predators such as sea otters and leopard sharks in the estuary, as well as to human fishers or clam harvesters.

Immediately following the fire, a group of scientists began collaborating to study potential impacts on the adjacent estuarine environment. Members are from several institutions: Moss Landing Marine Laboratories (MLML) and San Jose State University (SJSU), Marine Pollution Studies Lab (MPSL), Elkhorn Slough National Estuarine Research Reserve (ESNERR), Amah Mutsun Land Trust (AMLT), California State University Monterey Bay (CSUMB) and the Monterey Bay Aquarium (MBA). This group goes by the acronym **EMBER** (**E**stuary **M**onitoring of **B**attery **E**missions and **R**esidues resulting from the Moss Landing battery fire). The Biota team of EMBER is coordinating the study of metal concentrations in plants and animals, and possible bioaccumulation. The team quickly developed an immediate sampling strategy and collected the first samples less than two weeks after the fire. Methods, sampling sites, target species, laboratory processing, and timelines were then refined and adapted in real-time. These methods may serve as an approach for monitoring future battery fires, and also for collecting baseline monitoring data near battery storage facilities. These methods may serve as a guide for future efforts.

One component of the biological investigation is to sample a diversity of plants and animals regularly over time, at various stations across the estuary. Since it is not known which taxa or functional groups may accumulate the metals, it is important to include breadth in sampling. Another component of the biological investigation is to use Musselwatch protocols (see below) to conduct very consistent and standardized tracking of changes in metal concentrations in mussels over time, in different periods and sites. Additional study components, such as laboratory experiments examining metal uptake in controlled conditions, may be added in the future. Taken together, these study components should enhance understanding of whether and how battery metals enter food webs in the estuary. As the need for battery facilities expands along with society's growing demand for electricity, so too does the need to understand potential effects of fires, and the uptake and pathways of contaminants of emerging concern at the terrestrial-aquatic interface.

Field sampling across sites, dates and biodiversity

The Biota team mobilized to collect samples less than two weeks after the battery fire began, largely because of low tide fieldwork that had previously been scheduled by ESNERR and AMLT and could be re-directed. The Amah Mutsun Native Stewards are critical to this sampling campaign, leading dozens of partners and volunteers contributing time to field collections.

Four main sites in the estuary are sampled, at varying distances from the Moss Landing Battery Fire and with different degrees of tidal flushing: North Harbor, Hester Marsh, Shark Flats / Whistlestop, and Kirby Park (Figure 1). Funding from MBA and anonymous donors has been used to analyze samples only from North Harbor and Kirby Park; funding from CDFW (pending) will be used to analyze samples from the two CDFW-owned sites (Hester Marsh, Shark Flats) and data will be released in a future iteration of this report.

Sampling occurred monthly for the first months after the January 2025 fire (January, February, March 2025), then at decreasing intervals (May, July, November 2025). Sampling will continue at less frequent intervals in 2026.

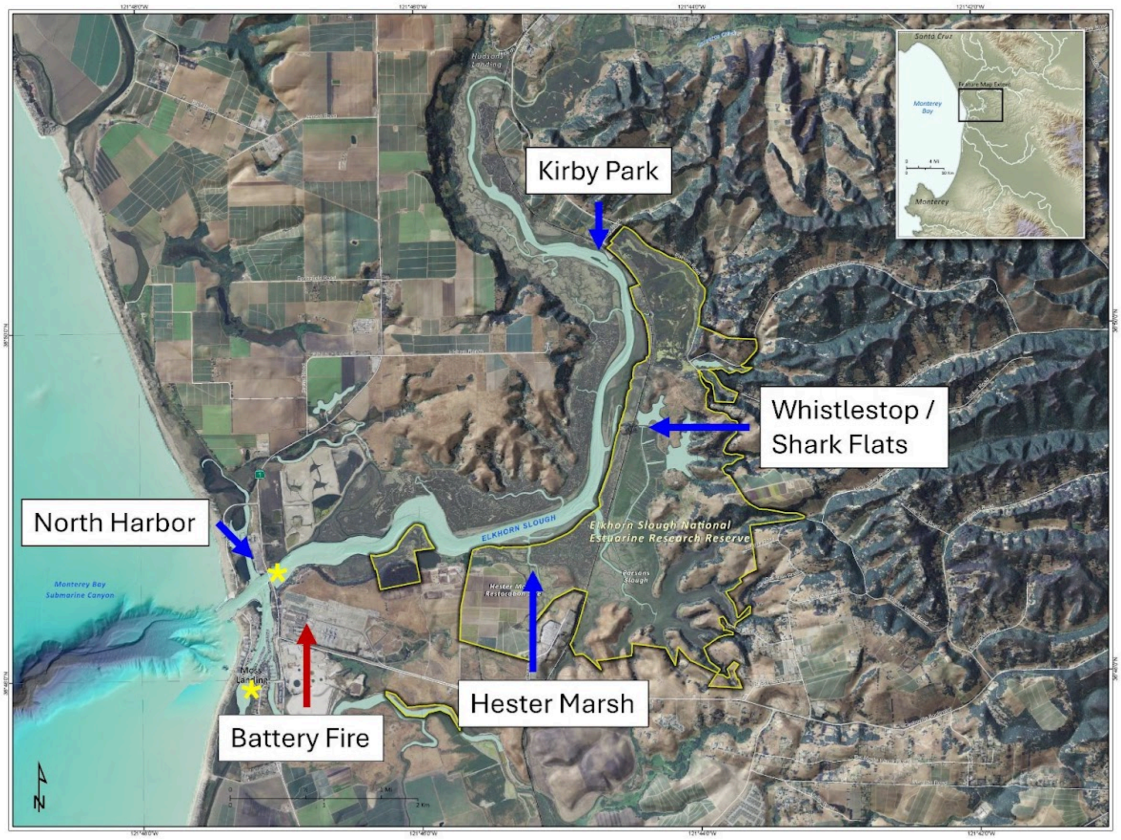

Figure 1. Map of Elkhorn Slough showing four main sampling sites for biotic diversity (blue arrows), sites of mussel transplants (yellow asterisks) and battery storage fire location (red arrow).

Sampling targeted a diversity of plants, invertebrates and fish. One goal was to conduct consistent comparisons of sites and time periods using the same species as indicators; for this, a set of common species were collected. These include primary producers (sea lettuce, eelgrass, pickleweed), bivalves (oysters, mussels, clams), crabs (shore crabs, green crabs), and fish (gobies, sculpins).

A second goal was to understand how different functional groups and taxa may respond, and for this, a variety of species were collected, somewhat opportunistically, based on availability at different sites and dates. This includes nori, sponges, tunicates, mud snails, chitons, and anemones.

A final goal was to characterize species that are consumed by the top predator in the system (sea otters) and by human fishers. Whenever possible, large clams, large crabs, and large fish were collected for this purpose.

A future goal is to put current data into context using legacy samples collected before the fire, for other reasons.

Collection was conducted at each site by teams consisting of EMBER members, Amah Mutsun Native Stewards, ESNERR staff and volunteers, and students from MLML, CSUMB, and UCSC. Collection of most samples was by hand, assisted with shovel or clippers as needed (Figure 2A, B). Fish and crabs were also collected with baited minnow traps deployed 24 hours in advance of the survey day.

Mussel transplant study

Both NOAA and California's State Mussel Watch (SMW) programs have successfully used California mussels (*Mytilus californianus*) as bioindicators of potentially toxic metal(loid)s. Historic data from these programs are available for sites across coastal California and include Hwy 1 bridge and the Sandholdt bridge at Moss Landing. These data provide a picture of pre-fire background levels for which to compare post fire data. The EMBER team designed a Mussel Transplant Study to use this bioindicator approach to study the fate and transport of metals, specifically nickel and cobalt. The approach is to use mussels transplanted from Montana de Oro, far from the zone of influence of the fire, as bioindicators by transplanting mussels at Hwy 1 and Sandholdt Bridges. Triplicate samples are deployed at each site on a quarterly time scale. New samples are deployed at the same time of collection of samples deployed three months prior. Data generated from this work give a time series of metals accumulation in mussel tissue. This data complements the field survey described above but is a more controlled study to examine changes in metal concentrations over time.

Sample processing

Collected material was brought to Moss Landing Marine Laboratories. All were rinsed in 1-µm filtered seawater and animals with hard shells or carapaces were scrubbed gently to clean debris and sediments (Figure 2C). Plants and algae were frozen at -20°C immediately. Animals were left to depurate for 24 h overnight in filtered seawater. Depurated samples were individually bagged and frozen at -20°C (Figure 2D).

Laboratory analyses methods

A compositing strategy was developed for each genus or species, detailing the number of individuals in each composite and which tissues would be incorporated. Effort was made to standardize the size of samples collected and used in each composite. Composites were dissected and homogenized in a controlled laboratory with a positive pressure filtered air supply and non-contaminating laboratory surfaces (Figure 2E). Tools and equipment were cleaned with dilute Micro-90®, then rinsed with tap water and deionized water prior to use.

Samples were digested with reagent grade nitric acid following EPA 3052 “Microwave Assisted Acid Digestion of Siliceous and Organically Based Matrices”. Each digestion, designated as a batch, included at least 1 certified reference material and 2 method blanks. At least 1 sample of every 10 digested was spiked with known quantities of the metals of interest, and 1 sample of every 20 was digested in duplicate.

Figure 2. EMBER team members from MLML, ESNERR, AMLT, MPSL, and many volunteers contributed to A,B) sample collection in Elkhorn Slough; C,D) sorting, depurating, and bagging samples at MLML, and E) preparing and processing samples for analysis at MPSL.

Metals analysis was conducted on a Perkin Elmer NexION 1000 Inductively Coupled Plasma - Mass Spectrometer (ICP-MS) following MPSL-120, based on EPA 200.8 “Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry”. Target analytes were Mn, Ni and Co, however the following were also analyzed: Ag, Al, As, Cd, Cr, Cu, Pb, Se, and Zn.

Funding
All **EMBER** partner organizations have provided support for staff members participating in this work, as well as facilities, equipment and supplies. Funding for laboratory analyses was provided by Monterey Bay Aquarium, California Department of Fish and Wildlife, and three anonymous donors.

PRELIMINARY RESULTS
Here we report on a small subset of samples that have been collected to date. Based on currently available funds, we report results from two sites, and only for a subset of taxa, and only for three sample dates. The additional sites on CDFW property and additional taxa and dates will be analyzed when funds are available.

To date, 57 unique composited samples have been analyzed, mostly bivalves and crustaceans collected in January, February, and March. All are from Kirby Park or North Harbor (Table 1). All reported here were depurated (kept in filtered seawater overnight); additional samples were frozen without being depurated but have not been analyzed.

Table 1. Invertebrates analyzed to date. The final columns list the number of samples analyzed for each site-month. All are composite samples, with the number of individuals per composite sample reported in the column “Comp”, except for R. antennarium (which was large enough that single individuals were used as sample).

Phylum	Scientific name	Common Name	Comp	Site	Jan	Feb	Mar
Arthropoda	*Carcinus maenas*	Green crab	3	Kirby Park	-	-	3
	Hemigrapsus oregonensis	Square shore crab	8	North Harbor	1	-	3
	Pachygrapsus crassipes	Lined shore crab	5	Kirby Park	-	3	3
			5	North Harbor	-	1	-
	Romaleon antennarium	Red rock crab	1	North Harbor	5	-	1
Mollusca	*Clinocardium nuttallii*	Cockle	4	North Harbor	1	1	1
	Leukoma staminea / Ruditapes philippinarum	Littleneck clam	3	Kirby Park	-	1	-
			3	North Harbor	1	2	3
	Macoma nasuta	Bentnose clam	3	North Harbor	2	3	2
	Mytilus californianus	California mussel	9	North Harbor	-	3	3
	Mytilus trossulus / galloprovincialis	Bay mussel	9	Kirby Park	-	3	3
			9	North Harbor	3	3	3
	Ostrea lurida	Olympia oyster	3	Kirby Park	-	3	3
	Tresus nuttallii	Gaper clam	3	North Harbor	1	-	-

Metal concentrations measured from collected biological samples

Our focus was on cobalt, manganese, and nickel as the three metals used in battery cathodes, and detected at high concentrations from nearby sediments (Aiello et al. 2025). All values are reported in µg/g dw (dry weight) and are reported from Kirby Park and North Harbor sites. The units µg/g are equivalent to parts per million (ppm) and the two unit names are thus used interchangeably in the text and figures below. Cobalt concentrations ranged from 0.29 µg/g dw to 7.5 µg/g dw, with mean concentrations of 2.34 ± 1.70 (± SD). Manganese concentrations ranged from 3.4 to 52.5 µg/g dw with mean concentrations of 17.17 ± 12.04 µg/g dw. Nickel concentrations ranged from 0.8 to 32.8 µg/g dw with mean concentrations of 6.74 ± 7.28 µg/g dw. These concentrations are calculated across all species and dates shown in Table 1; means and ranges will likely change as more species and dates are analyzed.

Different bivalve species had different overall concentrations of metals in their tissues, with white bentnose clams (*Macoma nasuta*) having the highest overall concentrations of all three metals than other species (Figure 3). These concentrations remained high for the three months of sampling to date. Metal concentrations did not change over the three months sampled for some species (Olympia oyster, California mussel, bentnose clam), while they declined from January to March for bay mussels and littleneck clams, and rose for cockles over that time.

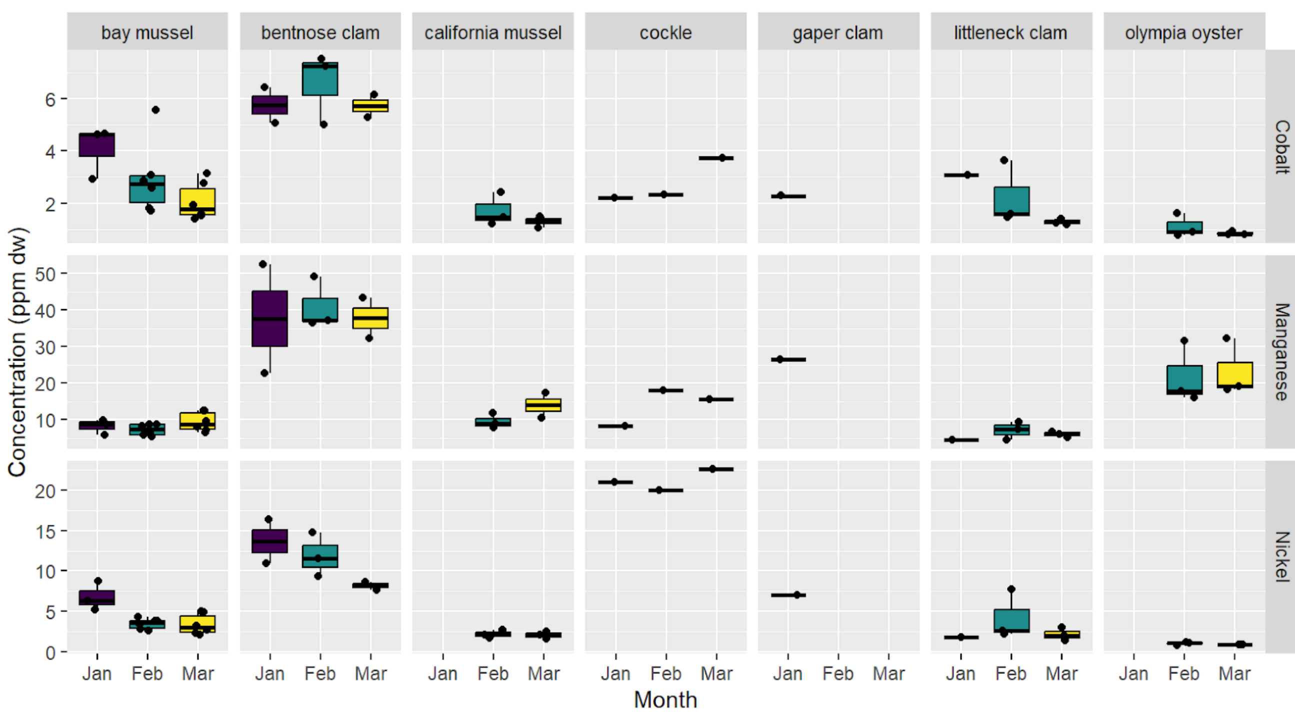

Figure 3. Metal concentrations measured from composited, depurated bivalve tissue samples collected from Kirby Park and North Harbor in January, February, and March. Boxes contain the middle 50% of data (the interquartile range). Median values are indicated by a thick line. Lines extending from boxes (whiskers) are 1.5 times the interquartile range. Points that fall past the whiskers are outliers. Note the differing scales of concentrations for each metal, here and in other related figures.

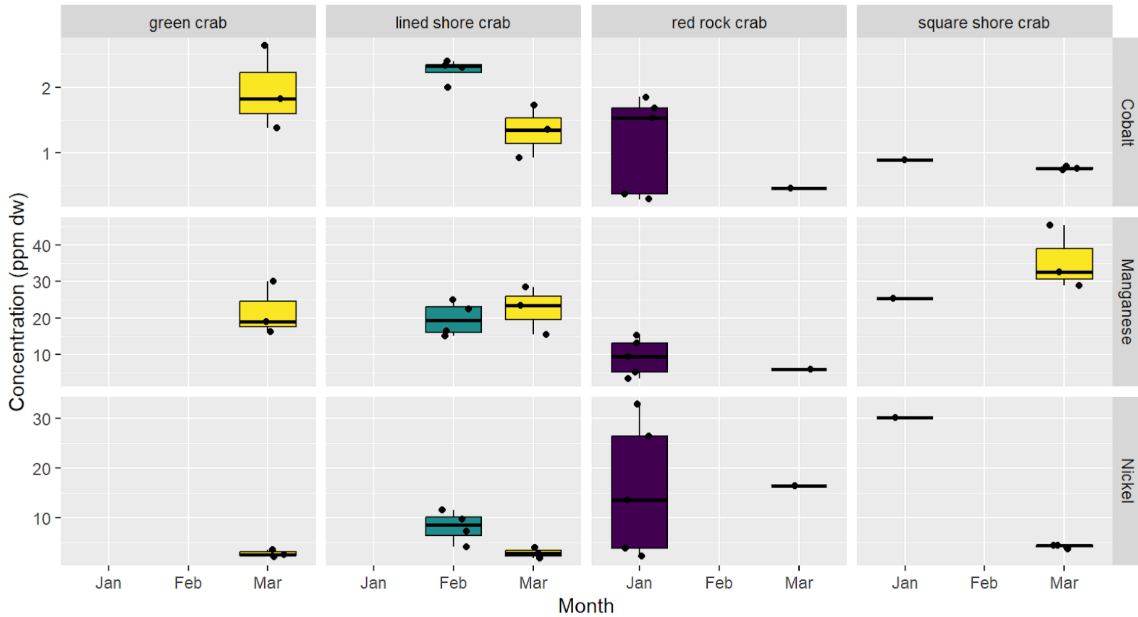

Figure 4. Metal concentrations measured from composited, depurated crustacean tissue samples collected from Kirby Park and North Harbor in January, February, and March. Boxes contain the middle 50% of data (the interquartile range). Median values are indicated by a thick line. Lines extending from boxes (whiskers) are 1.5 times the interquartile range. Points that fall past the whiskers are outliers. Note the differing scales of concentrations for each metal, here and in other related figures.

Crab tissues had lower concentrations of cobalt and manganese compared to bivalves, while nickel concentrations for some crab species were much higher than those of bivalves (Figure 4). Fewer data have been analyzed for crustaceans so far.

In addition to documenting the tissue concentrations of individual metals, we examined the ratio of metals. If a dominant source of metals in the sample tissues was battery cathode material, one would expect concentrations of the three metals to be correlated. A Ni:Co ratio of 2:1 measured in the sample would be consistent with battery cathode material and with nickel manganese cobalt NMC532 cathode chemistry; however, a match of that ratio does not confirm that concentrations were linked with battery metal concentrations–only that they are consistent with them. In addition, fractionation within tissues and differential rates of uptake of different materials may affect these ratios, so that the absence of a 2:1 ratio isn't clear evidence that the metals are not associated with cathode material. The ratio in January was ~1.2 and was not a tight correlation (linear regression; $m = -1.2$, $R = -0.21$, $p = 0.47$). The Ni:Co ratio in samples collected in February was 1.5 and was tightly correlated ($m = 1.5$, $R = 0.55$, $p = 0.0064$). The Ni:Co ratio in samples collected in March was 1.46 and still well correlated ($m = 1.46$, $R = 0.41$, $p = 0.029$). Some species followed the 2:1 ratio more closely than others (Figure 5).

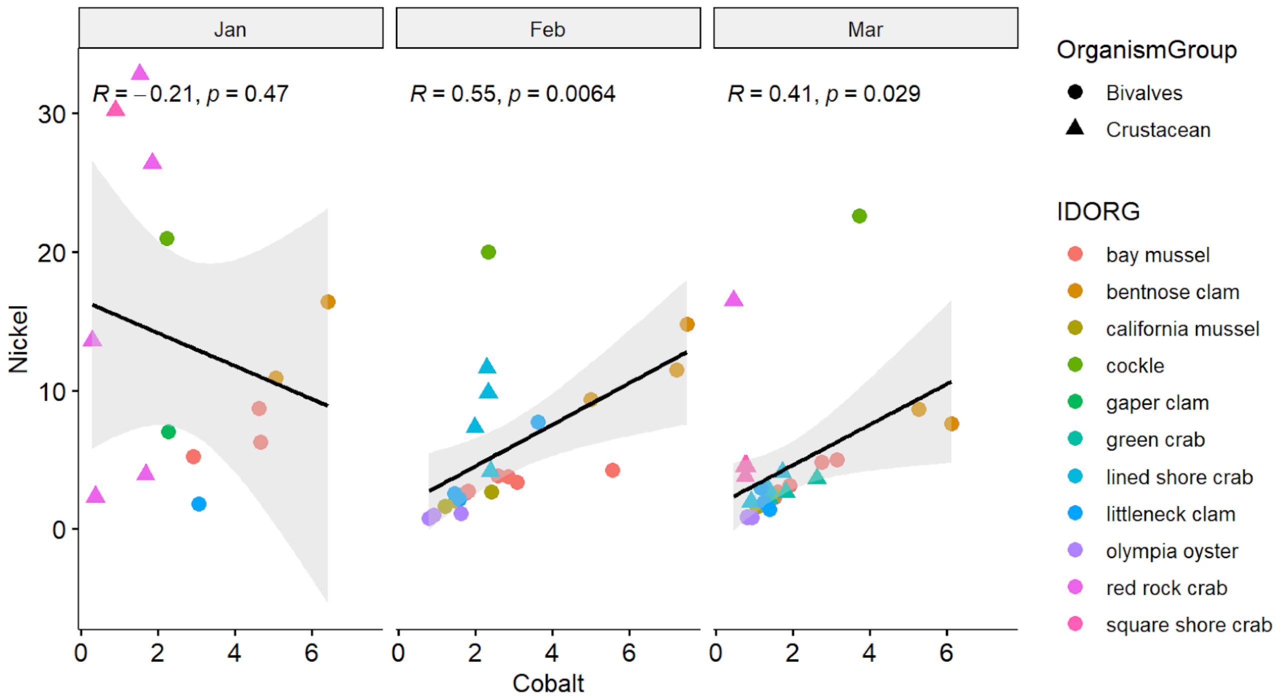

Figure 5. Biplot of Ni:Co concentrations (µg/g dw) from composite tissue samples collected in the first three months of sampling. Colors indicate different species of bivalves (●) and crustaceans (▲). Shading indicates 95% confidence interval.

Other metal concentrations

Each ICPMS analysis returned concentrations for 12 different metals. While nickel, manganese, and cobalt are known to occur in battery cathodes, other metals also used in batteries or in surrounding infrastructure, such as aluminum and lithium (Koech et al. 2024), may have also been released. In addition, behaviors of non-battery metals may be useful as context for understanding other temporal changes occurring in Elkhorn Slough. These will be compared with historical NOAA and SMW data (see Past Baselines below). Temporal patterns for Cobalt and Nickel are remarkably similar, and different from those for other metals (Figure 6).

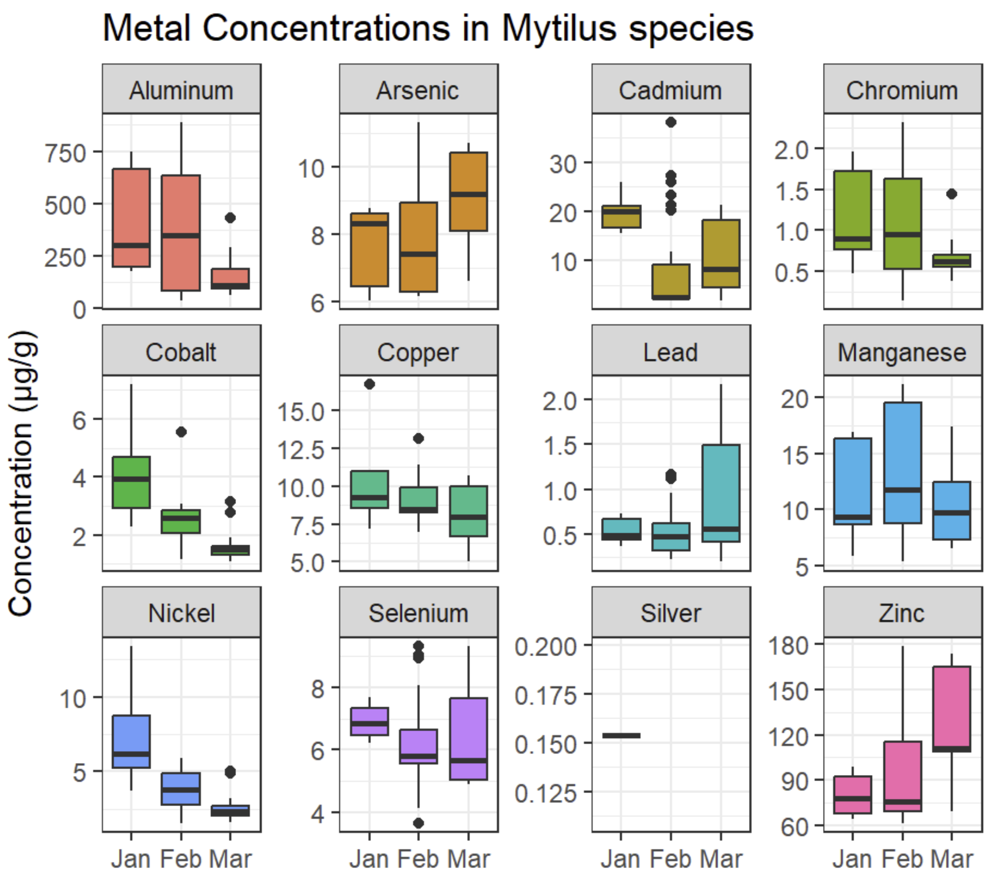

Figure 6. Concentrations (ug/g dw) of 12 metals measured from bay and California mussel composited tissues, collected from Kirby Park and North Harbor. Boxes contain the middle 50% of data (the interquartile range). Median values are indicated by a thick line. Lines extending from boxes (whiskers) are 1.5 times the interquartile range. Points that fall past the whiskers are outliers. Note the differing scales of concentrations for each metal.

Metals concentrations measured from mussel transplant study

Concentrations of nickel, manganese, and cobalt reported in µg/g dw at Sandholdt and Hwy 1 bridge sites are shown in Figure 7. Concentrations of nickel, manganese, and cobalt in mussels transplanted at Sandholdt bridge were 1.41 ± 0.12, 7.87 ± 0.13, and 0.797 ± 0.064 µg/g dw respectively. Concentrations of nickel, manganese, and cobalt in mussels transplanted at Hwy 1 bridge were 1.28, 4.98, and 0.805 µg/g dw respectively. The second round of transplanted mussels were collected September 2025 and metals analysis is ongoing and will be presented in a future report.

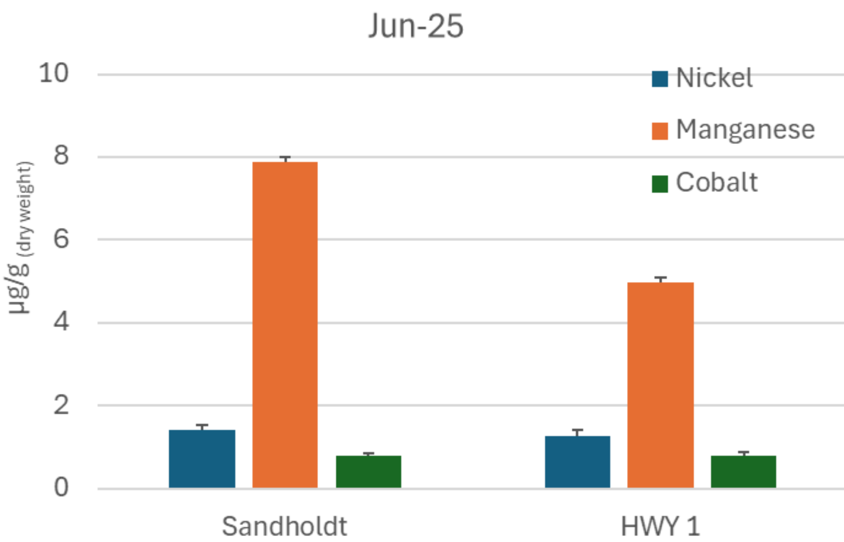

Figure 7. Metal concentrations measured from composited bivalve tissue samples transplanted at Sandholdt and Hwy 1 bridge sites. Mussels were deployed for a three month period from March 24 to June 5, 2025.

RELEVANT CONTEXT

Past baselines

To understand how the metal concentrations detected post-fire in 2025 compared to metal concentrations from pre-fire monitoring, we drew on various baseline datasets. The NOAA National Mussel Watch and SMW programs measured metal concentrations in mussels collected from Elkhorn Slough between 1990 and 2012 (data downloaded from California Environmental Data Exchange Network CEDEN, https://ceden.org/). Nickel concentrations were variable over those years of sampling. The nickel concentrations measured in January, February, and March 2025 were within the range of values measured during the Mussel Watch monitoring period (Figure 8).

SMW augmented the NOAA mussel watch program with increased spatial and temporal mussel sampling of California's coastline, bays, and estuaries. Figure 9 shows cumulative frequency percent for nickel concentration of California mussel tissue for samples collected by SMW from San Diego to Del Norte counties from 1979 to 2004 (n=730). Ninety percent of the nickel concentrations in California mussels were below 5 µg/g dw and seventy five percent were below 3.75 µg/g dw. Post fire Elkhorn Slough California mussel nickel concentrations are at the sixty five percent cumulative frequency meaning thirty five percent of all measured concentrations were above the nickel concentrations measured in post fire Elkhorn Slough California mussels.

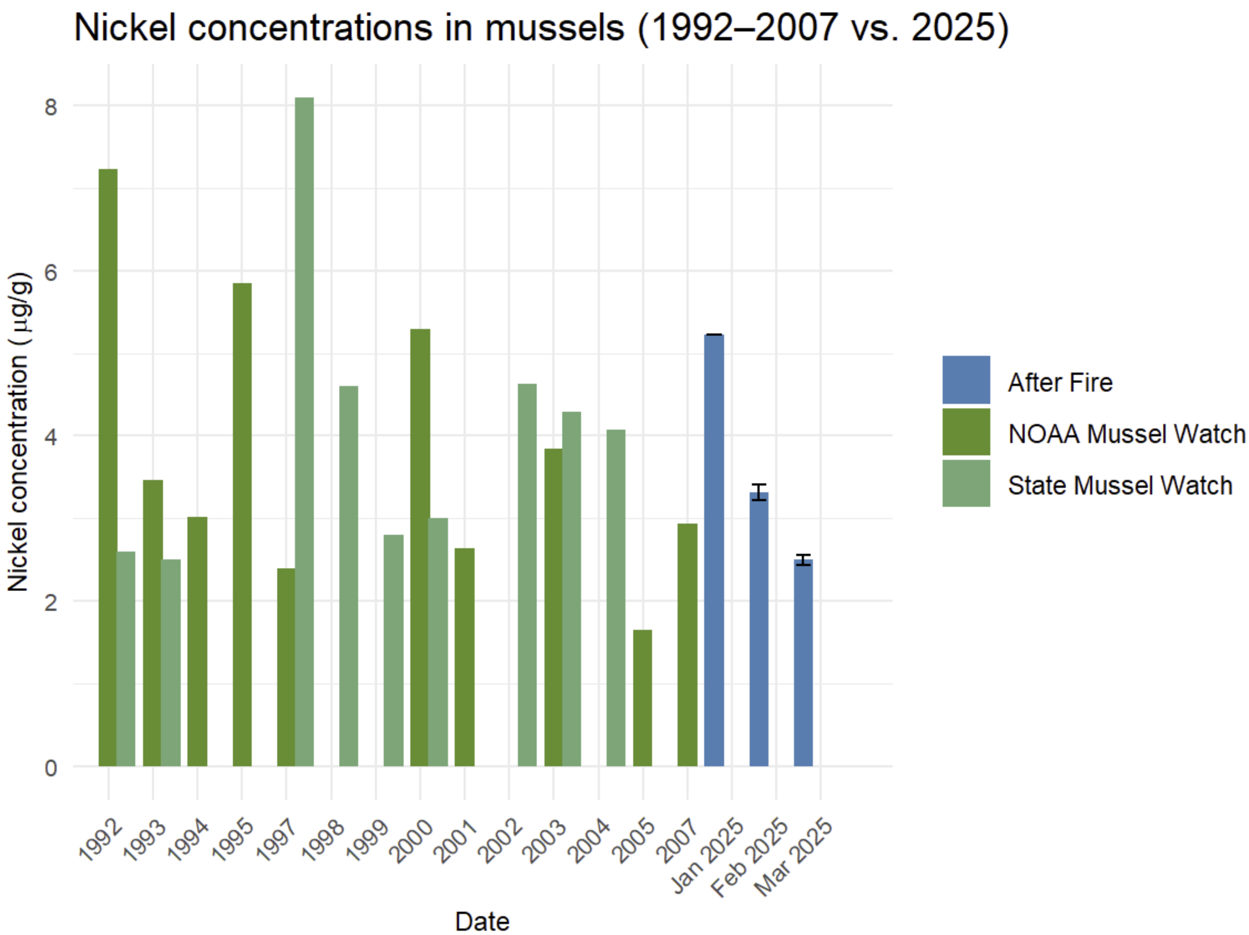

Figure 8. Nickel concentrations (mean ± SE µg/g dw) measured from wild Mytilus mussels (California and bay mussels) in Elkhorn Slough during the NOAA Mussel Watch Program monitoring period (green and orange) and in 2025 following the Vistra battery fire (blue). The plot includes data from NOAA Mussel Watch and California State Mussel Watch programs. Following similar methods to Mussel Watch, wild mussels were collected from Kirby Park and North Harbor and depurated for 24 h.

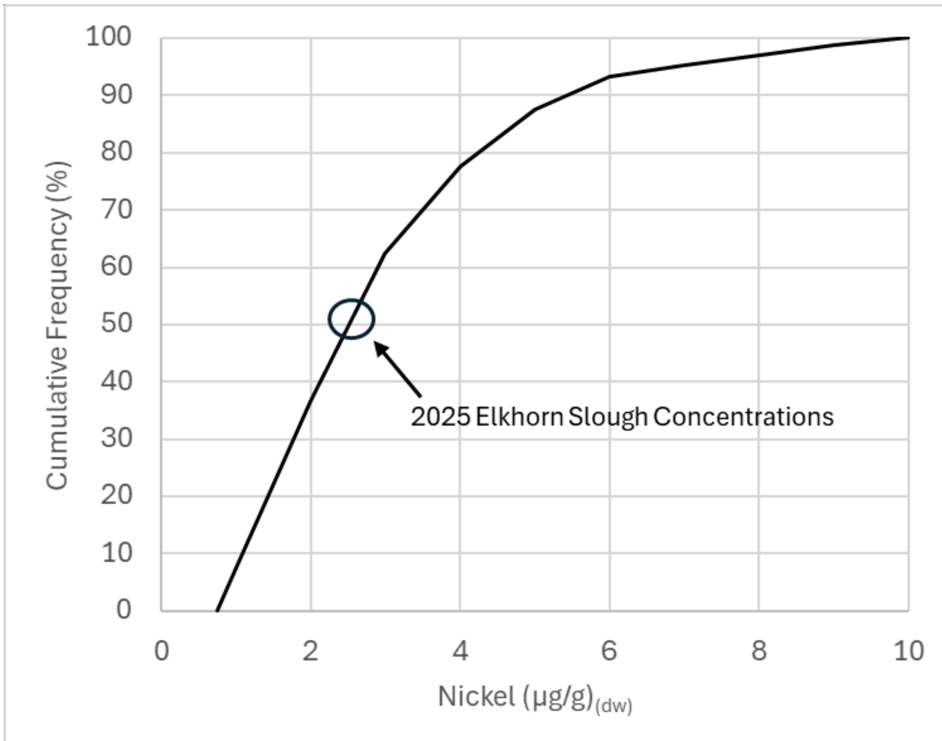

Figure 9. Cumulative frequency (%) for nickel concentrations µg/g dw of California mussels collected from San Diego to Del Norte counties between 1979 and 2004 by California's State Mussel Watch project. Data used to construct the plot were downloaded from California Environmental Data Exchange Network CEDEN, https://ceden.org/).

Metal bioaccumulation in animals

Bioaccumulation occurs when organisms concentrate contaminants from their environment in their tissues, and biomagnification occurs when these concentrations increase up the food chain (Luoma & Rainbow 2005; EPA 2007). A common example in marine systems is methylmercury (Hg), which is readily absorbed and retained, leading to strong biomagnification in top predators such as large fish, sharks, and marine mammals, posing risks to wildlife and humans (Danovaro et al. 2023). Metals from battery sources, such as manganese (Mn), cobalt (Co), and nickel (Ni), can follow similar pathways (Wang & Fisher 1991; Rainbow 2002).

Manganese is efficiently accumulated by lower-trophic organisms, including algae, phytoplankton, and mussels, with bioconcentration factors ranging from approximately 300 to over 20,000 depending on species (ATSDR 2012). Fish tend to accumulate less Mn, but repeated dietary exposure can elevate concentrations in higher trophic levels (Wang & Fisher 1999).

Cobalt uptake occurs in plants and aquatic invertebrates, though accumulation in edible or above-ground plant tissues is often limited (Keith et al 2024). In mollusks and crustaceans, much of the Co binds to shells or exoskeletons, with only a small fraction in tissues consumed by predators (Wang & Fisher 1991). Reported tissue concentrations in aquatic plants and invertebrates range from 0.01 to several hundred µg/g, depending on environmental exposure (Keith et al 2024).

Nickel is bioavailable to phytoplankton, benthic algae, and filter-feeding invertebrates, with bioconcentration factors on the order of 10^3–10^4 and tissue concentrations in primary producers reaching several ppm (EFSA 2020). Nickel can transfer to higher trophic levels through consumption, although accumulation in predators depends on feeding habits and metal speciation (Rainbow 2002; Luoma & Rainbow 2005). Environmental factors such as water hardness, pH, organic matter, and sediment chemistry influence Ni bioavailability and uptake (EPA 2007).

Battery fires can deposit fine ash and particles onto sediments, where metals may dissolve into porewater or remain particle-bound (Wang & Fisher 1991). Dissolved metals are available via gills or roots, while particle-bound metals can be ingested or filtered. Primary producers and invertebrates can rapidly take up these metals, which are then available to higher trophic levels (Wang & Fisher 1999; Danovaro et al. 2023). The timing and magnitude of Mn, Co, and Ni transfer depend on species, environmental conditions, and metal chemistry, highlighting the potential for long-term accumulation and biomagnification in local food webs (Luoma & Rainbow 2005; EPA 2007).

Conclusions

Preliminary results provide some indication that metals resulting from the Vistra battery fire have entered estuarine food webs. So far, metal concentrations are within range with what has been measured from Elkhorn Slough in the past, but ratios of nickel and cobalt concentrations shifted closer to a ratio of 2:1 and appear fairly tightly correlated, which is consistent with a battery metal source. EMBER will analyze samples from more taxa, sites and dates in the coming months as funding becomes available. It is too early to draw any conclusions about whether potential bioaccumulation poses threats to species living in Elkhorn Slough or humans eating fish or invertebrates out of the estuary, and how such threats compare in magnitude to those posed by other existing contaminants in the estuary. Continued investigations by EMBER will help provide answers to these questions in the future.

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