Title

Environmental Consequences in Coastal Wetland Following World's largest Lithium-Ion Battery Storage Facility Fire: Vegetation and Soil Influences

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Environmental Consequences in Coastal Wetland Following World's largest Lithium-Ion Battery Storage Facility Fire: Vegetation and Soil Influences

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of the requirements for the degree of

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in

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by

Amy M. Fuller

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The thesis of Amy Fuller is approved:

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Interim Vice Provost and Dean of Graduate Studies

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blue line represents the fitted Ni:Co line for vegetated sediments. The dashed black line is the 2:1 reference line for Ni:Co while the black dotted line represents a 1:1 reference Ni:Co line.

Figure 7: The Ni:Co relationship displayed over time. The two study sites are graphed alongside one another. Dashed line represents the 2:1 geochemical identifier of Ni:Co characteristic in NMC type lithium-ion batteries.

Abstract

Environmental Consequences in Coastal Wetland Following World's largest Lithium-Ion Battery Storage Facility Fire: Vegetation and Soil Influences

Amy Fuller

On January 16, 2025, a major fire occurred at the Moss Landing Power Plant Facility located adjacent to the Elkhorn Slough, one of the largest remaining coastal wetlands in California. The fire burned 3 days becoming the largest battery-facility fire in the world to date. Lithium-ion battery fires potentially pose a risk to human and ecological health, as they can release trace metals, specifically: nickel, manganese, and cobalt that can be dangerous when surpassing safety exposure limits (Pennington, 2025). As societies shift towards alternative energy formats, there is a greater demand for battery energy storage infrastructure; however, these infrastructures carry risks. This study aimed to extend initial post-fire assessments by examining long-term effects of trace metal release and metal transport pathways. Sediment samples and random quadrat vegetation surveys were collected from 2 marsh sites, in the Elkhorn Slough. Samples were analyzed utilizing field portable X-ray fluorescence (FpXRF) and ICP-OES to quantify the concentrations of Ni, Mn, and Co in sediment cores collected from vegetated regions and unvegetated regions for both study sites. Trace metal concentrations were consistent with those of NMC 523 batteries, which were variable throughout study, while the overall concentration of Mn, Ni, and Co generally decreased in surface sediments over time. This study sheds light onto the persistence and spatial distribution of battery-

derived trace metals over time post-fire to provide insight into contaminant behavior after a historical battery fire event.

Acknowledgements

To begin, I’d like to extend my gratitude to Dr. Adina Paytan, my undergraduate and graduate advisor who guided me through navigating higher education. Additionally, I’d like to thank Dr. Ivano Aiello and Seth Staten for welcoming me to Moss Landing Marine Laboratories and allowing me to learn from their expertise and analyze samples in their lab. Thank you to Dr. Donald Smith, who also served on my advising committee for my thesis. I have a deep appreciation for Aliya Khan who served as my graduate student mentor. When I started as an undergraduate at the Paytan Lab, Aliya was my first mentor who guided me through the research ‘world’. She has extended her help beyond this into my graduate degree, and I would not be the student or researcher I am today undoubtedly without her. Additionally, I’m grateful to all my undergraduate assistants for their help processing my samples specifically Sayre Hackworth and Drake Howard who helped me immensely progress in my data processing stage. Thank you to our lab technician Lucas Ognibene, who trained and guided me through using the ICP-OES.

Dedication

My work is dedicated to family. My father, James Fuller Jr., passed away soon after I turned 17 years old. Unfortunately, he had been an addict all my life, and it took a toll on his physical health. He was unable to see me graduate high school, receive my bachelor's degree, or receive my master's degree, so a dedication in this research is the closest I will get to experiencing him present while reaching these milestones. My mother, Elizabeth Fuller, and grandma or "abuela," Maria Nova were there for every step of my academic trajectory. Although growing up, there were limited financial recourses, my mom and abuela were there to pick me up every step of the way. Often, (even as I commuted to university as an adult), they'd make my coffee in the morning, prepare me dinner, or hold me while I cried about the stress higher education created. Finally, my brother, William Fuller. He is my older brother, and after our father died, he assumed the roles in many ways our father should have played in my life. He is my role model and was always present when I needed him to be in hard moments and celebratory ones. I love my family and they continue to be the backbone of my success.

Introduction

Wetlands are vital ecosystems that provide numerous ecosystem benefits including carbon sequestration, shoreline stabilization, and natural water filtration (U.S. EPA, nhttps://www.epa.gov/wetlands/about-coastal-wetlands). In the United States, California has experienced the loss of more than 90% of the state's historic wetlands in the last century (U.S. EPA, https://www.epa.gov/wetlands/about-coastal-wetlands).

This loss is primarily attributed to agricultural expansion as well as urban and industrial development. Many of the remaining wetlands in California continue to face threats from land use change, pollution, and global climate change (California Environmental Protection Agency, https://www.energy.ca.gov/news/2026-08/california-surpasses-21000-megawatts-battery-resources-supporting-states). The Elkhorn Slough, located in the central coast region of California, is one of the largest remaining coastal wetlands tracts in the state. The wetland is connected to Monterey Bay and is open to tidal action. The broader landscape around the slough is primarily agricultural communities, and small suburban development, both within a 1 to 5 miles distance (Elkhorn Slough Foundation, https://elkhornslough.org/visit/). It is a National Estuarine Research Reserve, hosting over 340 bird species as well as southern sea otters, harbor seals, and several other endangered species (Elkhorn Slough Foundation, https://elkhornslough.org/visit/). Approximately 50,000 people visit the estuary each year for recreation, including kayaking, birdwatching, and research activities

(Elkhorn Slough Foundation, https://elkhornslough.org/visit/). The wetland is located less than 2 miles from the Moss Landing Power Plant Facility which ceased operation in 2023 as a power plant, as it was transitioned in 2021 to be an active battery energy facility to date (Vistra Corp., https://investor.vistracorp.com/2021-01-06-Vistra-Brings-Worlds-Largest-Utility-Scale-Battery-Energy-Storage-System-Online). The Moss Landing Power Plant facility currently hosts one of the largest battery storage facilities in the world, managed by Vistra Corporation.

On January 16, 2025, a major fire occurred at the Moss Landing Power Plant Facility. Due to the size of the facility and the extent of the fire, this was the largest battery facility fire in the world (U.S. EPA, 2026). The main fire burned over the course of two days with smoldering continuing for the following few days. The fire remained physically contained on-site within the power plant grounds; however, the airborne emission plumes could not be controlled and dispersed into the surrounding counties. During this fire, 55 percent of the batteries in this facility burned (U.S. EPA, 2026). Plume modeling data suggested that two counties experienced plume drift from the fire, Monterey and Santa Cruz Counties (Peters & Torrez, 2025).

NMC lithium-ion battery combustion has the potential to release hazardous contaminants that can pose significant risks to human and ecological health. Specifically, NMC 523 batteries contain a suite of trace metals including cobalt, nickel, copper, and manganese (Armand et al., 2020). At physiological levels, biologically essential trace metals support enzyme functions in organisms and chlorophyll production in plants, while overexposure to these same trace metals can inhibit photosynthesis, productivity, and cause oxidative stress in plants and other organisms (Riyazuddin et al., 2022; Andresen et al., 2018). Trace metals are persistent in the environment and known to accumulate within soil, sediments, and biological material (Bryan et al., 1992).

With the current global shift towards electrification of the energy grid, the importance and demand for battery energy storage systems is increasing, as these systems serve a role in storing energy and stabilizing electrical grids. Over 170 countries and subnational governments have joined the COP29 Global Energy Storage and Grids Pledge, committed to deploying more energy storage and increasing grid infrastructure by 2030 (Global Renewables Alliance, 2026). In California alone, there are 310 operational battery energy facility sites (State of California, 2026). The Moss Landing Power Plant fire event raises concerns regarding the environmental risks associated with the release of pollution from these facilities (Never Again Moss Landing, https://neveragainmosslanding.org). Despite the rapid increase in energy storage infrastructure, there remains limited regulatory and scientific research-based understanding of the environmental risks associated with large scale battery facility failures, particularly those close to sensitive ecosystems. As battery energy storage systems continue to expand globally, there is a growing need to understand local ecosystem effects of battery energy storage infrastructure failure. Fire emissions have the potential to transport contaminants across landscapes; moreover, the plume deposits from a lithium-ion battery fire may persist in sediments and impact various ecological functions of regional landscapes, such as the Elkhorn Slough.

While during a lithium-ion battery fire (thermal runaway), lithium (Li), manganese (Mn), nickel (Ni), and cobalt (Co) are released primarily as solid particulate matter, aerosols, and metal-bearing dust or soot rather than as free metal vapors or specific gases (Buston et. al, 2023), limited research on the mobilization and environmental transport of heavy metals associated with lithium-ion batteries post deposition in the environment exists. When water interacts with these particulates, ionic forms may dissolve into the liquid water as dissolved metal ions (J. Pennington, 2025). Initial studies post-fire confirmed the Moss Landing Battery Storage facility as the primary source of the source increased Ni, Mn, and Co metal concentrations immediately after the battery facility fire (Aeillo et al., 2025). This study also illustrated how a thin (<0.5 mm) surficial layer of trace metals from the fire was deposited while traditional soil sampling methods collect deeper depths of soil, that may potentially dilute the thin deposition layer (Aeillo et al., 2025).

Building on these findings, the present study performed sampling of surface sediments and vegetation to evaluate spatial deposition and potential pathways of metal accumulation in the adjacent coastal marsh ecosystems. This study aims to determine the fate of trace metals over time and to improve understanding of environmental risks posed by the battery fire and to inform future safety considerations on energy storage facilities.

Methods

Field Sampling and Study Area

The Moss Landing Power Plant is located at the mouth of the Elkhorn Slough, where Monterey Bay connects to the estuary. Two pre-establish research marsh sites were chosen due to their proximity to the fire, preliminary data collected in the region at one of those sites, and because soil and vegetation sampling had occurred there prior to the fire providing a unique opportunity to compare post-fire sediment to a pre-fire baseline. (Aeillo et al., 2025). Previous immediate post-fire analysis focused on samples from Hester Marsh by other researchers (Aeillo et al., 2025), which is a restored salt marsh site. The site was restored in 2019, and the area was filled with roughly 500,000 cubic meters of soil to make it more resilient against sea level rise (Fountain et al., 2022). Restoration efforts also included planting the dominant vegetation cover, *Salicornia Pacifica* (pickleweed) as well as other grassland plants to increase diversity (Fountain et al., 2022). At the time of the sampling period, the restored marsh remained with about 40% vegetation cover and 60% bare sediment. Yampah Marsh has remained relatively unaltered and has a heavy vegetation cover of pickleweed. During the high tide, Yampah Marsh becomes inundated during the high tide, and is projected to be more vulnerable to inundation from sea level rise (Xu et al., 2025).

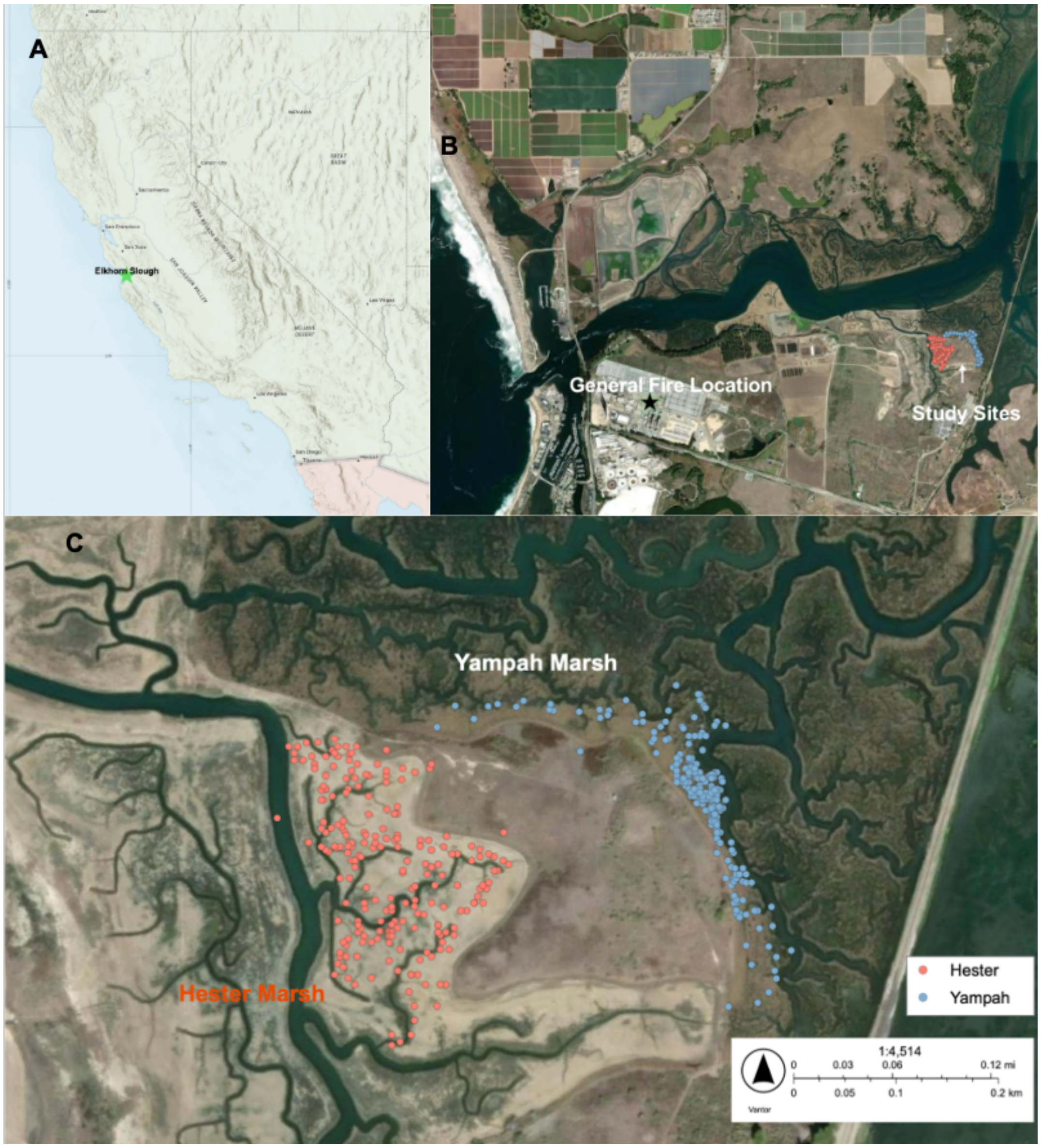

Figure 1: (Top left) Location of the Elkhorn Slough wetland location in California. (Top right) Study sites relative to the fire location. (Bottom) Yampah and Hester Marsh sampled sites.

Sample Collection

Sediment samples and random quadrat surveys were collected monthly from March 2025 to January of 2026 at each site. As we aimed to assess only surface deposition, sediment samples were collected to a depth of 1cm. Sediment samples were collected in 9cm diameter, 1 cm deep plastic petri dishes by placing the petri dish directly into the soil and slicing a plastic sediment core knife beneath the dish to remove the sample with the intention of preserving the samples' vertical structure. Sampling locations were chosen at random across both marshes. Ten surface sediment samples were collected from non-vegetated locations, and an additional 10 surface sediment samples were collected from vegetated locations at both study sites. In the same vegetated locations and plant surveys were collected as well. All samples were collected using a random quadrat survey design, and GPS locations were recorded. Sampling events were conducted on the same day at both sites during low tide. The range of sampling locations at Yampah Marsh is limited due to accessibility restraints crossing larger water channels in the marsh.

Figure 2: A) A photo upland of Hester Marsh, with the Moss Landing facility seen in the background, identified by two non-operational smokestacks. B) A photo of Yampah Marsh. C) Amy Fuller conducting a random quadrat vegetation survey at Hester Marsh. D) A photo of the Moss Landing facility during the fire event, January 16, 2025.

Initial Sample Processing and Sediment Analysis

Sediment samples were weighed wet and set out to air dry with their respective lid on to minimize contamination until a constant weight was achieved (4-5 weeks). After air drying, samples were weighed again to quantify moisture content. Samples were then stored at room temperature in petri dishes, until utilized for further analysis.

All sediment samples were analyzed with a Field-portable Hitachi XMET 8000 XRF (FpXRF). Both the top and bottom side of the sediment sample were analyzed for an array of elements, including Mn, Ni, and Co, using the FpXRF for comparative analysis. The 'top' of the sediment sample is identified as the surface sediment sample while the 'bottom' of the sediment sample was sediment 1 cm deep.

After being analyzed with the FpXRF, samples were then prepared for analysis with a Thermo iCap 7400 radial view ICP-OES (Optical Emission Spectroscopy). Samples were initially homogenized through manual grinding. 0.5 grams of each sample were then weighed into 10% HNO3 acid wash cleaned 15 mL centrifuge tubes. Then, 2 mL of concentrated trace metal grade nitric acid (J.T. Baker) was added into each sample tube. Samples were left for 15 hours on a New Brunswick Scientific C1 Platform Shaker to leach at room temperature. After 15 hours, 10g of concentrated trace metal grade nitric acid were added to each sample and left on the shaker plate for an additional hour at room temperature. Afterwards, the supernatant was then placed in another cleaned 15 mL centrifuge tube, to then be analyzed with the ICP-OES.

Results

Spatial and Temporal Distribution of Trace Metals

Considerable variability was observed from soil samples collected during the same sampling campaign for every campaign; even more, concentrations differed between Yampah Marsh and Hester Marsh (Figure 3). Linear mixed-effect models were used to evaluate patterns across time, sampling depth, and vegetation cover for both surface and bottom (1cm deep) sediment samples. Concentrations of Ni ($F(1, 416.27)=421.65$, $p<0.001$), Mn ($F(1, 422.84)=102.04$, $p<0.001$), and Co ($F(1, 416.27)=421.65$, $p<0.001$) differed between Yampah Marsh and Hester Marsh.

Given the large variability in trace metal concentrations between Hester and Yampah Marshes, there were clear temporal trends recorded for the lithium-ion battery associated trace metals (Figure 3). Temporal regression (Figure 3) illustrated significant declines in surface sediment concentrations across vegetation cover type at both marshes whereas another element, such as Copper (Cu) did not display the same pattern. Ni ($F(1, 416.05)=20.63$, $p<0.001$) and Co ($F(1, 396.68)=18.85$, $p<0.001$) illustrated significant temporal effects while Mn ($F(1, 423.1)=2.41$, $p<0.122$) and Cu ($F(1, 324.97)=3.63$, $p=0.058$) were not found to be significant. Site-specific models did not differ significantly for Co ($F(1, 392.31=0.32$, $p=0.572$), Mn ($F(1, 423.07)<0.01$, $p=0.997$) and Cu ($F(1, 318.05)=0.70$, $p=0.405$). Even though temporal declines were statistically detectable, time only explained a small proportion of the observed variation ($R^2 = 0.191$). Therefore, spatial heterogeneity remained a dominant aspect of the battery-related sediment metal distributions throughout the study period.

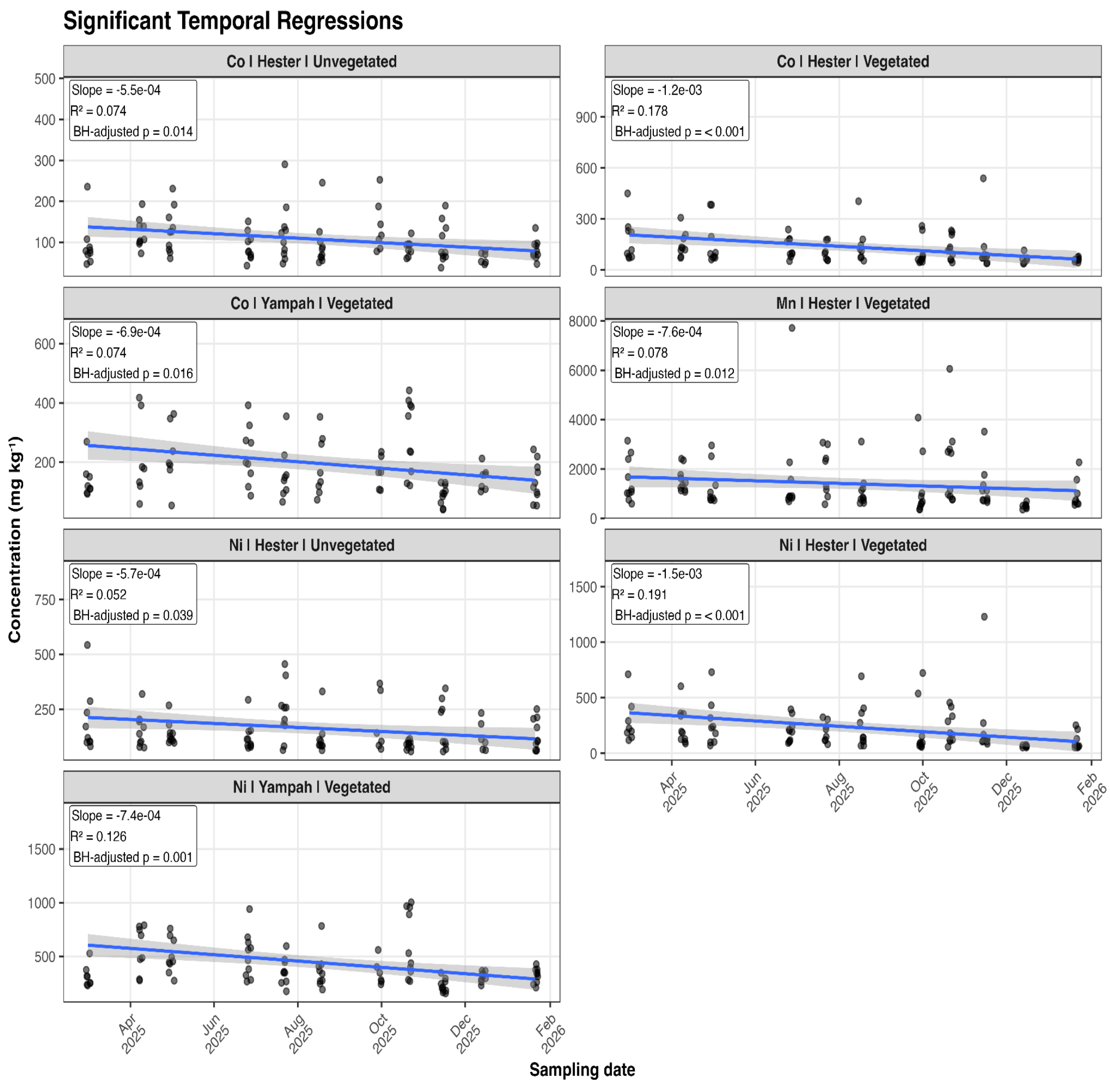

Figure 3: Temporal regressions of surface sediment FpXRF measurements starting from the first sampling event to the last (March 2025 to January 2026) for Ni, Co, and Mn, at each site and vegetation cover type of the surface of the sediment sample

Trace Metal Surface Enrichment

Sediment depth was significantly associated with concentrations of Co (F(1, 403.27)=4.02, p-0.046), Ni (F(1, 430.23)=130.42, p<0.001), and Mn (F(1, 436.21)=136.46, p<0.001) whereas Cu (F(1, 282.89)=1.64, p=0.201) did not illustrate a significant difference overall between surface and bottom (1cm deep) sediment measurement.

Between all four Site x Vegetation Cover groups, Ni concentrations were significantly higher at the surface in all four sites: Yampah Marsh without vegetation cover (model estimate=0.199, 95% Cl [0.149, 0.248], adjusted p <0.001), Yampah Marsh with vegetated cover (model estimate=0.260, 95% Cl [0.209, 0.310], adjusted p <0.001), Hester Marsh with vegetation cover (model estimate=0.139, 95% Cl [0.089, 0.190], adjusted p <0.001) and Hester Marsh without vegetation cover (model estimate= 0.078, 95% Cl [0.028-0.129], p <0.05). Not only so, Mn exhibited the same pattern of higher surface concentrations: Hester Marsh unvegetated (model estimate=0.153, 95% CI [0.111, 0.195], adjusted p < 0.001), Hester Marsh vegetated (model estimate=0.224, 95% CI [0.182, 0.266], adjusted p < 0.001), Yampah Marsh unvegetated (model estimate=0.065, 95% CI [0.023, 0.107], adjusted p = 0.003), and Yampah Marsh vegetated sediments (model estimate = 0.136, 95% CI [0.093, 0.178], adjusted p < 0.001).

In contrast, Co exhibited more variable vertical separation across all vegetation types and sites, depending on the marsh site. Surface Co concentrations were significantly lower than the bottom (1cm deep) sediment measurements in both Hester Marsh groups without vegetation (model estimate=-0.165, 95% Cl [-0.231, -0.100], adjusted p <0.001) and with vegetation (model estimate=-0.102, 95% Cl [-0.168, -0.036], adjusted p < 0.05). However, at Yampah Marsh, the surface Co concentrations were significantly higher, but only in vegetated sediments (model estimate=0.089, 95% Cl [0.025, 0.154], adjusted $p < 0.05$).

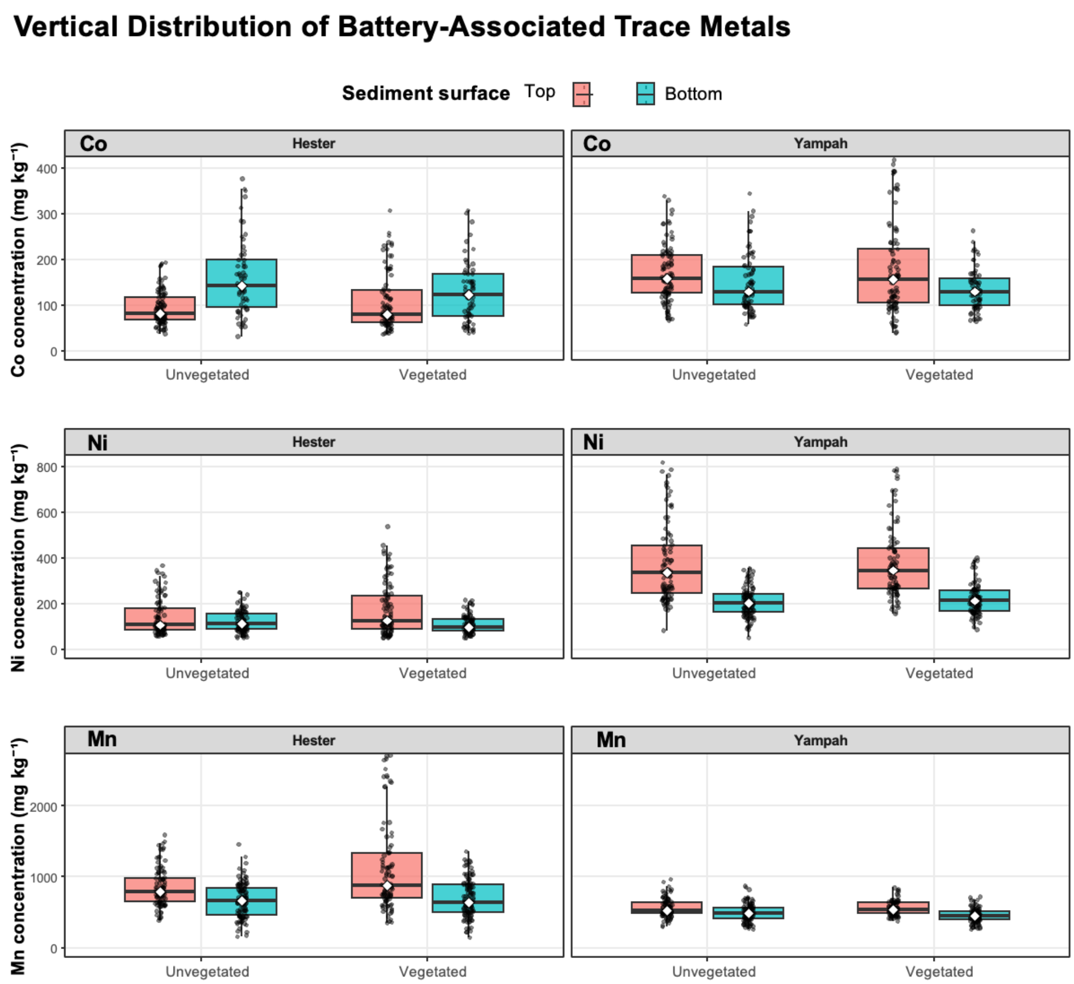

Figure 4: The vertical distribution of Co, Ni, and Mn from FpXRF data. Red represents the surface soil, while blue represents concentrations values from 1 cm below the soil. Unvegetated represents samples collected from areas with no vegetation cover while vegetated represent samples with vegetation cover.

Influence of Vegetation

The influence of vegetation on the temporal persistence of battery related trace metals was evaluated at both marsh sites. Samples were specifically collected from vegetated versus unvegetated sites. After FpXRF analysis, temporal regressions were compared between vegetated and unvegetated sediments at both marshes (Figure 3). Linear-mixed effect models did not identify significant effect on concentrations after accounting for marsh location, month, and sediment depth for Ni ($F(1, 416.23)=2.82$, $p=0.094$), Co ($F(1, 398.32)=2.34$, $p=0.127$), or Mn ($F(1, 422.85)=2.52$, $p=0.114$). Overall, concentrations of the Ni, Mn, and Co did not consistently differ between sampling locations with or without vegetation cover, for the duration of the sampling period.

Temporal Trends of a Battery-Derived Ni:Co 'Footprint'

Previous studies identified a characteristic relation between the concentrations of Ni and Co immediately following the fire event that was consistent with NMC lithium-ion battery cathode materials (Aiello et al., 2025). More specifically, Ni:Co shared a unique 2:1 ratio as an environmental post-fire fingerprint (Aiello et al., 2025). To evaluate whether this geochemical 'footprint' persisted throughout the first year after the fire relationships among the three lithium-battery associated metals were examined across both marshes, vegetation cover type, and sediment depths (Figure 5).

For the three NMC-532 type battery trace metal pairs (Ni-Co, Ni-Mn, and Co-Mn), from the surface samples examined utilizing a FpXRF, Ni and Co demonstrated the strongest positive association across the study periods. Pearson correlation coefficients for Ni:Co ranged from 0.506 to 0.972 for all the site and vegetation cover groups ($r=0.824$). On the other hand, the mean correlations observed for Co:Mn ($r=0.608$) and Ni:Mn ($r=0.662$), highlight concentrations of Ni were more associated with Co than Mn.

To observe if there were significant changes or deviations temporally, the Ni:Co relationship of 2:1 from the start of the sampling period (March 2025) to the last sampling event (January 2026) were compared. In March 2025, Ni and Co concentrations were strongly correlated in the surface sediment measurements (Pearson's $r=0.932$, Spearman's $\rho=0.937$, $n=40$) while in January of 2026 these associations were weaker (Pearson's $r=0.767$, Spearman's $\rho=0.729$, $n=35$). The estimated Ni:Co slope was 2.06 in March 2025, close to the identified 2:1 relationship by other studies and decreased to 0.73 in January 2026. These results demonstrate that the 2:1 Ni:Co relationship was not as strongly correlated as a year-post the fire event when compared to the first sampling month.

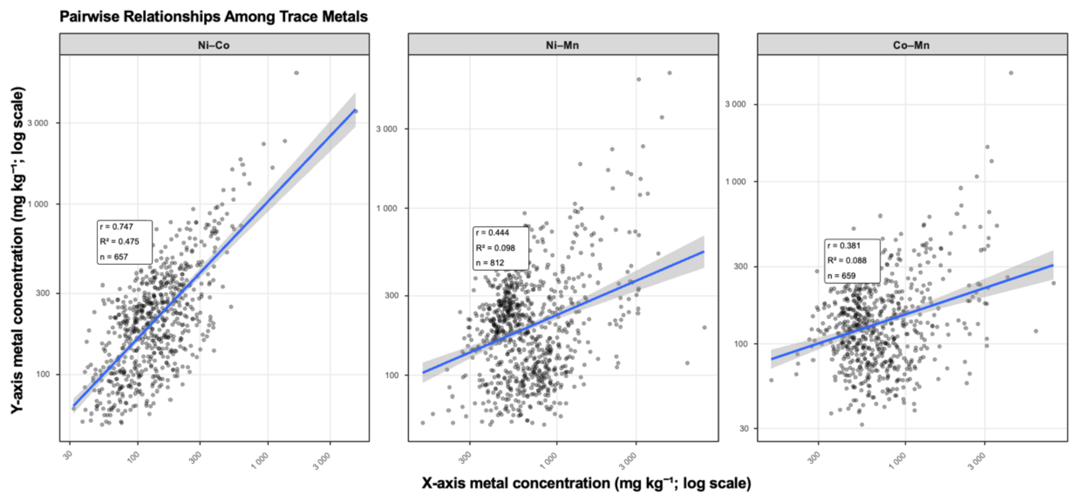

Figure 5: Pairwise relationships among the three studied trace metals from surface sediment FpXRF data. Ni:Co share the most significant relationship to one another.

Among the three metal pairs evaluated (Ni-Co, Mn-Co, Ni-Mn), Ni-Co consistently exhibited a strong, positive relationship throughout the monitoring period where Pearson correlation coefficients ranged from 0.506 to 0.972 across all site and vegetation groups. Mean Pearson correlation coefficients were greatest for Ni-Co ($r = 0.824$), surpassing those observed for Ni-Mn ($r = 0.662$) and Co-Mn ($r = 0.608$). Similarly, Ni-Co exhibited the highest mean coefficient of determination ($R^2 = 0.481$), demonstrating that any Ni concentration variation was more consistently explained by Co than by Mn.

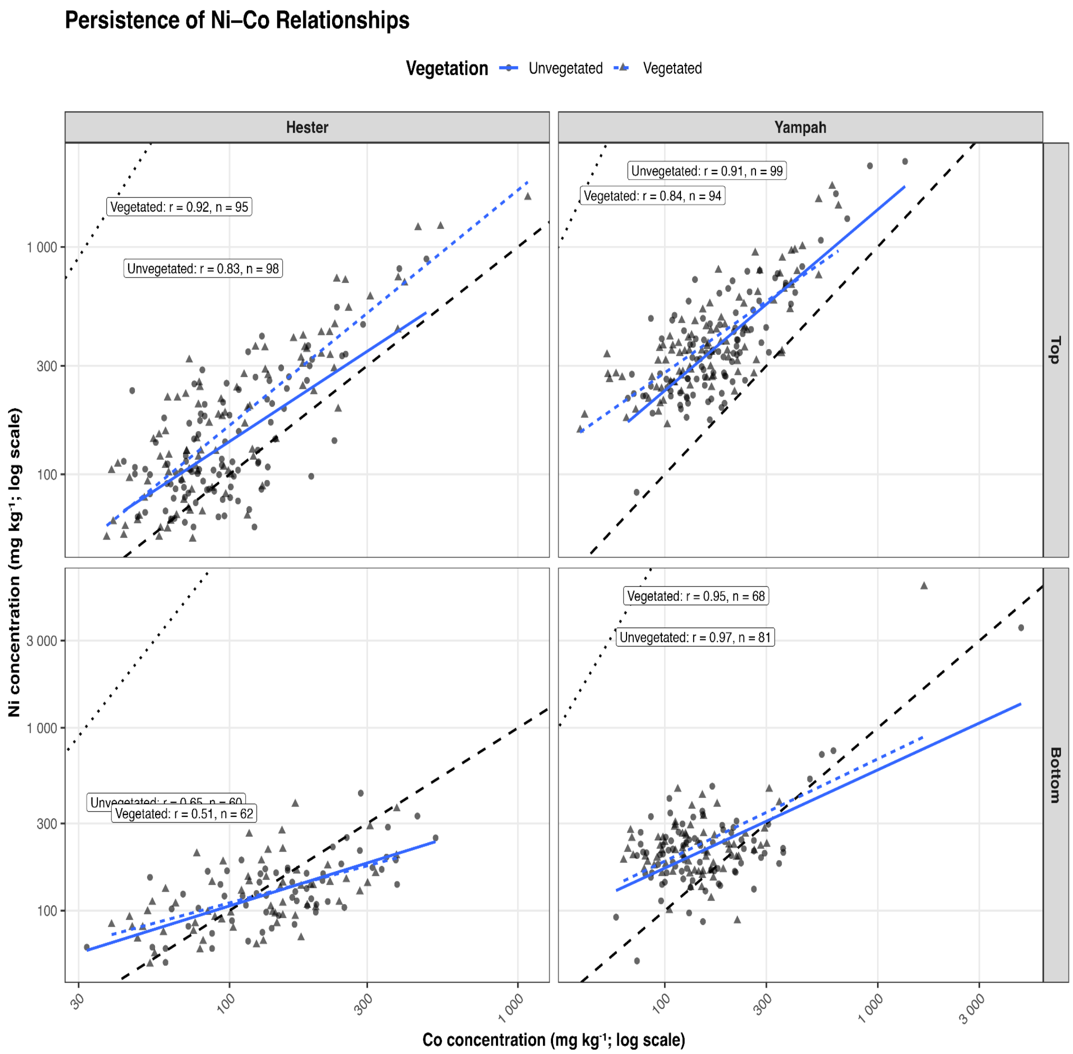

Figure 6: Ni:Co pairwise relationship concentration values compared between the surface (top) sediment to the bottom of the sample (1 cm below surface) of unvegetated and vegetated sediment samples. The dashed black line is the 2:1 reference line for Ni:Co while the black dotted line represents a 1:1 reference Ni:Co line.

Ni:Co Relationship through ICP-OES analysis

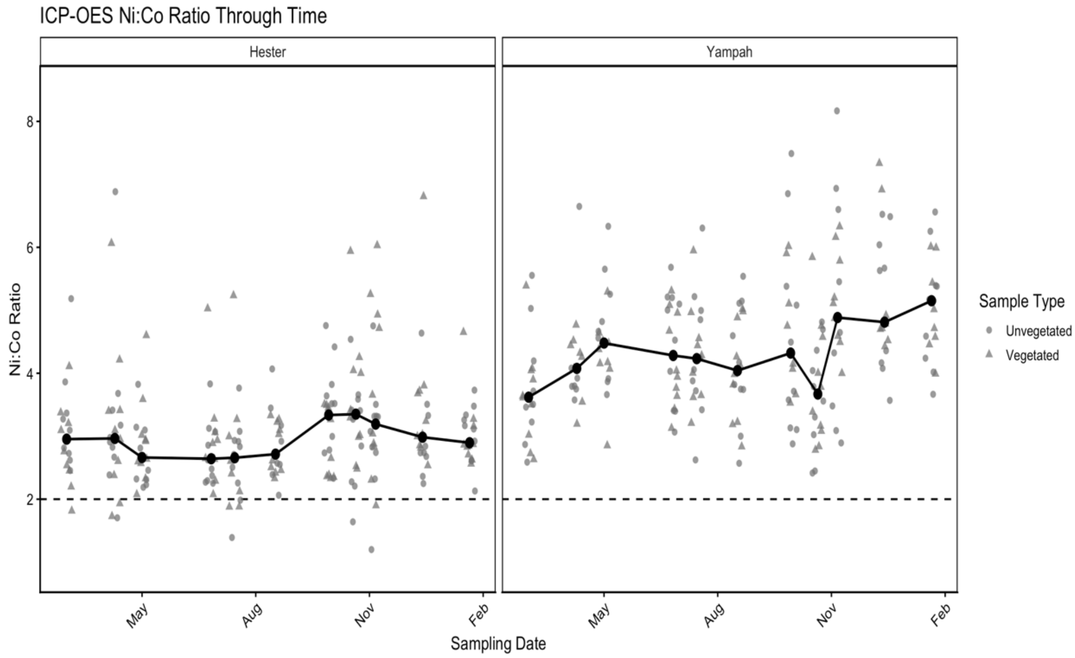

Figure 7: The Ni:Co relationship displayed over time from ICP-OES measurements. The two study sites are graphed alongside one another. Dashed line represents the 2:1 geochemical identifier of Ni:Co characteristic in NMC type lithium-ion batteries.

ICP-OES measurements indicated a strong, positive relationship between Ni and Co across the sampling period (Spearman's $\rho = 0.840$, $p < 0.001$; Pearson's $r = 0.861$, $p < 0.001$; n = 423); however, these values did not align with the characteristic 2:1 ratio of Ni:Co, previously identified in the NMC type lithium-ion batteries. The mean Ni:Co ratio across all samples was 3.51, therefore homogenized samples analyzed in the ICP-OES did not reproduce the 2:1 tracer identified in samples analyzed with the FpXRF.

Discussion

Persistence of Battery Derived Trace Metals

This study demonstrated the persistence of trace metals over the course of approximately one year following the January 2025 Moss Landing battery energy storage system (BESS) fire at two sites. Concentrations of Ni, Mn, and Co, were found to decline over the course of the study (Figure 3), consistent with reporting of a rapid decline in battery associated trace metal concentrations after an immediate post month study period after the first fire in January 2025 (Aeillo et al., 2025). Despite the observed decline in Ni, Mn, and Co concentrations, the NMC 532 lithium-ion battery relationship between Ni and Co was still detectable in surface sediments throughout the sampling period and concentrations were still above background soil levels. Concentrations generally declined throughout the monitoring period, and the surface enrichment which was first identified immediately following the fire remained detectable a year after the fire event. At the end of the study concentrations remained elevated compared to the pre-fire baseline concentrations reported by Aiello et al. (2025) for Hester Marsh, indicating the trace metal concentrations decreased but have not returned to pre-fire baseline conditions a year after the fire event. This suggests that after the enrichment from the fire event, biogeochemical and physical processes remove and redistribute a portion of the trace metals but have not yet removed the metals completely.

The initial enrichment was driven by atmospheric deposition of the battery material burned in the fire (Aeillo et al., 2025). The plume blew eastward, towards the direction of the two marsh sites (Figure 1) and would have been deposited in the form of soot or metal bearing dust.

The Elkhorn Slough is a coastal wetland, characterized by semidiurnal tides and distinct rainfall cycles (Wasson et al., 2025). Rainfall at Elkhorn Slough occurs annually from October through May, hence the fires occurred during the rainy season, and the average tidal range is about 1.6 m (Wasson et al., 2025). Therefore, the deposited material from the fire was subjected to many tidal cycles and rainfall events that may remobilize and redistribute the trace metals across the sites or transport them into the water channels (Gee et al., 2010). Trace metal concentrations declined over time, potential pathways for movement include sediment mixing, tidal flushing, rainfall driven sediment transport, plant uptake. As we did not find significant evidence of vertical movement it indicates that sediment mixing is not a primary pathway- leaving metals to primarily be washed into nearby waters.

Distribution of Battery Derived Metals

The vertical distribution provides insight into the behavior of the deposited metals across both sites. Previous work by Aiello et. al (2025) demonstrated that battery-related surface metals from the Moss Landing Power Plant fire were enriched at the very surface within the top 5 mm of the soil. To determine whether this surface enrichment persisted beyond the initial post-fire period surface and bottom sediment FpXRF measurements were collected and compared. Still, in the top, surface of the samples, Ni:Co ratios varied substantially throughout the study. Later sampling months demonstrated greater variability and the Ni:Co ratios were not uniform across the study period**.** Immediate post-fire sampling identified significant surface enrichment right after the fire event (Aeillo et al., 2025). The current study and the vertical distinction indicated that the deposited material did not become uniformly incorporated throughout the sediment and primarily remained on the surface layer. Bottom (1cm depth) sediment concentrations of the trace metals remained relatively stable over the sampling period consistent with any battery deposition from the fire remaining concentrated on the surface soil (Aeillo et. al, 2025).

The variability in the fire related trace metals concentrations at the surface layer between samples collected at the same time is consistent with heterogeneous soot deposition expected from an uncontrolled fire event (Aeillo et al., 2025). Variation in tidal inundation across the lower and middle marsh areas, sediment resuspension during high tides, and tidal erosion could further modify the initial distribution of the trace metals. Overall, these factors contribute to the heterogeneous distribution and observed variability of concentrations of Ni, Mn, and Co at both marsh sites. One explanation as to the strength of the Ni:Co relationship as a geochemical tracer can be the geochemical behaviors of these metals. Manganese is strongly influenced by redox conditions in wetlands where microbes utilize manganese oxides in wetland sediments (Patrick & Page, 1977). This may explain the strength of the Ni:Co correlation to one another when compared to Ni:Mn and Mn:Co due to manganese's redox properties.

In this study, vegetation coverage was explored as a potential control for differences in trace metal persistence. Marsh plants can affect hydrodynamics, sediment deposition, stabilize elements, or retain elements (Teuchis et al., 2013). *Salicornia Pacifica* (pickleweed) is the dominant plant vegetation cover at Elkhorn Slough. Like other marsh plants, pickleweed's above ground structure can reduce tidal flow, preventing or slowing sediment resuspension (Wasson et al., 2025). The root of marsh plants can also bind sediment. Due to this, we expected that vegetated sampling locations may have higher concentrations at the surface sediment, than samples collected from areas with no vegetation cover. Hester, the restored marsh had vast areas that were bare sediment with minimal vegetation cover, while Yampah Marsh, consists of dense vegetation cover (Wasson et al., 2025). Still, direct comparisons between unvegetated and vegetated sediments did not show consistent significant differences across both sites and the three metals. The overall patterns and results across all 3 metals (Ni, Co, and Mn) at both marshes, indicate there is not a specific vegetation-driven control in the sediment metal concentrations.

Detection of battery-derived contamination across various methods

The difference in the results from the different analytical methods underscores the importance of identifying the most appropriate environmental study methods when measuring soil trace metal concentrations. This study analyzed sediment samples with both FpXRF and ICP-OES. Both methods quantify trace metals, but samples are prepared for analysis differently. Field portable XRF measurements can preserve vertical information in the sediment surface versus the bottom (1 cm deep) by allowing them to be analyzed separately. In contrast, when sediments are homogenized across the entire sediment sample prior to acid digestion to be analyzed by the ICP-OES an integrated concentration for the whole sediment sample is obtained.

This difference in analysis is apparent when observing the Ni:Co relationship at both sites. The ICP-OES was able to capture a strong association between Ni and Co, yet it did not capture the 2:1 ratio characteristic of NMC-type lithium-ion batteries (Figure 7). The FpXRF was able to capture and detect this 2:1 ratio in the surface of the sediment samples. Therefore, the vertical distribution of the trace metals could not be accurately observed with just ICP-OES analysis unless care is taken to only sample the upper <0.5 mm which would be difficult.

As the demand for battery energy storage systems continues to rise, standard sediment sample processing is essential for obtaining an accurate outlook of the environmental fate of NMC lithium-ion battery associated trace metals after a contamination incident. Conventional sediment sampling protocols are designed to account for bulk sediment chemistry (U.S. Environmental Protection Agency, 2001). Protocols for ICP-OES and ICP-MS typically require homogenizing a sediment sample, which may integrate contamination with native soil. Future investigations may benefit from a coupled analysis to capture a more complete representation of the fate of contaminants in sediment.

Limitations

One of the most prevalent limitations of this study was the timing of the sampling period. Even though battery derived trace metal signatures were still detected during the study period, previous studies indicated the importance of immediate post-fire analysis and lower concentrations, taken just 6 weeks after the fire indicate that most of the sediment transport occurred in the first 4 weeks after the week. Rainfall, tidal flushing, and other biogeochemical processes could have altered or remobilized the trace metals (Gee et al., 2010).

Another limitation includes the spatial heterogeneity as sampling was conducted at random locations in each site. Month-to-month variation reflect not only temporal trends but also spacial variability.

Sediment samples alone cannot determine whether persistent battery derived trace metals were biologically available. The sediment concentrations from vegetated locations can provide complimentary environmental comparisons, still further analysis of vegetation and organism tissue would provide key insight into any potential biological exposure in organisms because of the fire.

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