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RESEARCH ARTICLE

Lost or discarded lead fishing weights contribute significant amounts of lead to freshwater sediments in California

Robert J. Rossi[1] · Cathleen D. Valentine[1] · Justin R. Laine[1] · Yuk-Shing Lai[1] · Robert Brushia[2] · Anne-Cooper Doherty[2]

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Abstract

Lead (Pb) or Pb-alloys have been used for fishing weights since at least the Roman Period and are generally the most popular type used by Californian anglers. Fishing weights are often lost or discarded in or near the waters where fishing occurs. Given their popularity and long history of use, significant masses of Pb may have been deposited in freshwater sediments in California via lost or discarded fishing weights. While Pb is a notorious contaminant, loadings of Pb to the environment via this pathway are poorly understood. To fill this knowledge gap we calculated low, median, and high estimates of the average number of Pb fishing weights in Californian freshwater sediments using a Markov Chain Monte Carlo simulation. Our analysis suggests there are anywhere between 404 million and 2.6 billion Pb fishing weights located in freshwater sediments in California. Assuming a typical fishing weight mass of 7.09 g, this equates to 2,870–18,600 tons of Pb. These estimates generally align with similar calculations referenced in the scientific literature when adjusted for Californian angler numbers. Our findings fill a critical knowledge gap in the most biodiverse state in the US and provide a methodological approach for others to apply elsewhere.

Keywords Lead · Lead contamination · Fishing equipment · Fishing weights · Recreational fishing · Freshwater sediments

Introduction

Lead (Pb) is a naturally occurring element that is an infamous environmental contaminant (ATSDR 2020). Pb has been used by humans for various purposes (e.g., building materials, decorative purposes) for at least 5,000 years (National Minerals Information Center 2023). Due to its high density, Pb has been used in fishing weights — in a pure form or as an ingredient in an alloy — since antiquity (Aleem 1972; Dütting and Hoss 2014). Pb fishing weights remain a popular option for anglers in contemporary times (Scheuhammer et al. 2003; Martin 2019; MPCA 2022).

Pb fishing weights are often lost or discarded in, or immediately near, surface waters where fishing occurs. Weights may be discarded by anglers either intentionally or unintentionally (e.g., by spillage). Weights may also be lost when a fishing line becomes snagged on an underwater obstruction and is subsequently broken or cut. In general, the number of lost fishing weights accumulated per square meter in a given area is likely to be proportional to the amount of fishing in that area (Jacks et al. 2001). A review conducted by Wood and Newth (2024) suggests densities of these lost weights may be as much as 339 weights per square meter. The environmental persistence of lost Pb fishing weights in sediments depends on a variety of factors including the depositional environment and the chemistry of the overlying water column (Jacks et al. 2001; Soeder and Miller 2003; Potysz et al. 2023). Over time, lost Pb fishing weights may release Pb and other metals to overlying waters and pose toxicity concerns to aquatic biota (Beggel et al. 2026).

Lost Pb fishing weights pose a potential exposure pathway for wildlife, especially bird species — either via ingestion

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✉ Robert J. Rossi
robert.rossi@dtsc.ca.gov

[1] Safer Consumer Products Program, California Department of Toxic Substances Control, 700 Heinz Avenue, Berkeley, CA 94710, USA

[2] Safer Consumer Products Program, California Department of Toxic Substances Control, 1001 I Street, Sacramento, CA 95814, USA

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or dissolution into the water column. A 2019 global review identified 33 species of birds, 3 species of mammals, and 2 species of reptiles with documented cases of Pb fishing weight ingestion (Grade et al. 2019). Bird species that consume fish and any species that feed in near-shore soils and sediments are at risk of Pb poisoning from the inadvertent consumption of lost or discarded fishing weights (Scheuhammer et al. 2003). Additionally, there is a potential for scavengers to feed on animals that have ingested Pb, thereby exposing them to Pb (Haig et al. 2014). Consumption of Pb can lead to neurological, immunological, and reproductive effects in bird species (Haig et al. 2014).

Although some jurisdictions have determined the environmental concerns posed by Pb fishing weights necessitate regulatory action (Secretary of State for the Environment, England et al. 1987; 321 CMR 4.01 2016; NY ENV 11–0308 2014), others have determined that more information is needed. For example, in February 2018 Assembly Bill (AB) 2787 was introduced to the California Legislature to eliminate the manufacture, sale, or purchase of all Pb fishing weights less than 50 g in weight (Quirk 2018a). Following stakeholder engagement, AB 2787 was amended to remove the ban and call for a study of "the impacts of lead fishing tackle on wildlife, rivers, lakes, streams, and potential drinking water sources" (Quirk 2018b), and further amended to call for a review of existing research on the impacts of Pb fishing tackle (Quirk 2018c). Although several peer-reviewed studies have characterized the environmental impacts of Pb fishing weights lost to freshwater bodies in other regions (Table S1), to date, no such study has been conducted in California.

Here we estimate the mass loading of Pb fishing weights to freshwater sediments in California using market data and coupled statistical and geospatial methods. We also use publicly available geospatial data to highlight areas where threatened and/or endangered species may be particularly impacted. To our knowledge, our work is the first of its kind in California. It provides a foundation that may be used to fill the current knowledge gap and inform future efforts to characterize environmental impacts of Pb fishing weights in the most biodiverse region in the US (Harrison et al. 2024). Furthermore, our approach can serve as a basis for others to apply to other regions.

Methods

Data synthesis

Although several peer-reviewed studies have characterized the number of Pb fishing weights lost to freshwater bodies (Table S1), to date, no such study has been conducted in California. To generate a California-specific estimate, we conducted a literature review of peer-reviewed studies that recorded densities (i.e., number of weights per square meter) of Pb fishing weights found in freshwater sediments.

This review consisted of a search of Google Scholar and the California State Library Database (CSL 2024) for the keywords "lead fishing weights," "Pb fishing weights," "fishing weights," "fishing equipment," "fishing tackle," "California fishing," and "sinker." We determined additional sources by reviewing the references these results had cited, as well as sources that had included the results in their bibliographies. We also reviewed the grey literature by searching the keywords above in Google. All results were reviewed to determine if they considered lead deposition in inland environments. If a reference solely considered marine fishing, it was not included in our review. If any reference reported the results of another study, those results were not included unless we reviewed the original data source. Our review was conducted in March 2024 and only considered references that were available in English.

Estimating yearly purchases of Pb fishing weights in California

Because there is relatively little data concerning the volume of consumer expenditure on Pb fishing weights, we used angler purchasing data to estimate the expenditures on Pb fishing weights. In 2019, the approximately 49.4 million anglers in the United States (U.S.) spent an estimated $648.5 million on hooks, sinkers, and other terminal tackle (Olds et al. 2020). That value corresponds to each angler spending roughly $12.94 in 2019 dollars, or $15.38 in 2023 dollars as adjusted for inflation. We searched for "Lead Sinkers" on Amazon Marketplace, and aggregated the top five search results, which we assume reflect the most purchased products. As of February 2024, Pb fishing weights were sold on Amazon for $0.06/g on average, or $19.22 per package. Fishhooks sold for an average of $5.37 per pack, and terminal tackle sold for an average of $6.77 per item. Assuming a $15.38 yearly budget for combinations of fishhooks, weights, and terminal tackle, and using the average prices per product, anglers buy one package each of fishhooks, weights, and terminal tackle every 2 years. Thus, we estimate each angler buys 326 g of Pb fishing weights once every 2 years, or 163 g each year.

In 1994, U.S. EPA estimated that Pb comprised approximately 85% of the fishing weight market but noted specific market share information for fishing weights is not readily available and is complicated to calculate (40 CFR Part 745 1994). In the absence of more recent information, our calculations assume 85% of Californian anglers use Pb fishing weights, and 15% use Pb-free alternatives. To estimate the mass of Pb fishing weights purchased annually by

Californian anglers, $Total\ mass\ Pb\ weights_{CA}$ we used the formula:

$$Total\ mass\ Pb\ weights_{CA} = Total\ number\ anglers_{CA} \times \alpha_{Pb\ weights} \times yearly\ mass_{Pb\ weights,\ CA}$$

where $Total\ number\ anglers_{CA}$ is the total number of Californian anglers, $\alpha_{Pb\ weights}$ is the proportion of Californian anglers that use Pb fishing weights (0.85), and $yearly\ mass_{Pb\ weights,CA}$ is the mass of Pb fishing weights purchased per year per angler (163 g).

Geospatial analyses

Identification of fishing lakes

Given that the deposition of Pb fishing weights generally should reflect the fishing pressure in that water body, we wanted to identify lakes that are popular fishing spots (hereinafter referred to as "fishing lakes"). To do so, we retrieved the coordinates of fishing locations from CDFW's fishing guide map viewer (CDFW 2024b). We then filtered these data for locations that were planted during 2023 to eliminate lakes that may no longer support fisheries. This method provides the most conservative method for determining popular fishing lakes in California. The remaining data points were then intersected with the location of lakes in California (CDFW 2023) using the sf package in R v.4.2.1 (Pebesma 2018; Pebesma and Bivand 2023). To get accurate estimates of the surface area of each lake, fishing lakes were clipped to the boundary of California (USCB 2023).

Endangered, threatened, or rare species

We examined the potential for adverse impacts to rare species by comparing the intersection of lakes in CDFW's fishing guide map viewer (CDFW 2024b) with areas of rare species richness delineated in CDFW's Areas of Conservation Emphasis (ACE) 3.0 (CDFW 2020). Rare species richness refers to the total number of unique rare species in a defined area. Rare species include State and Federally-listed species, Species of Special Concern, fully-protected species, and California Rare Plant Rank 1B and 2 rare plants (CDFW 2018).

The Terrestrial Rare Species Richness dataset is comprised of a grid of 6.47 km^2 hexagons that each have a rare species rank normalized by ecosystem type to highlight the areas of greatest species richness across different types of habitats (CDFW 2018). Normalizing the rare species richness rank by ecosystem type helps determine the conservation value of a location within an ecologically similar area. Otherwise, this value may be difficult to determine when the assessment is made across a single geographic region with a wide distribution of ecosystem types.

Ranks range from 1 to 5, with a rank of 5 representing the highest rare species richness. To identify areas having high rare species richness and also experiencing relatively higher Pb fishing weight deposition, we intersected popular fishing lakes with areas having a rare species rank of 4 or 5.

Estimating a typical fishing weight mass

We determined a typical mass of lost weights by taking the median value of Pb weights sold on a popular fishing equipment retailer's website. Our search yielded a total of 322 weights, 152 of which were less than 14.2 g (Table S2). We selected this threshold because our estimation only considered Pb weights lost in freshwaters, and saltwater fishing often requires heavier weights to keep baits in place (EC 2004). Including heavier masses could bias our mass loss estimates resulting in a less realistic estimate of the type of weight typically lost in freshwater environments.

The median value of the remaining 152 weights was 7.09 g ±4.69 g (1 SD), which is in line with the average of the masses of lost weights reported in our literature review (7.94 g), and the median (7.75 g) of the range of commonly used Pb fishing weight masses in Canada reported by Twiss and Thomas (1998).

To determine the impact of the assumed typical fishing weight mass on our total mass estimates, we performed a rudimentary sensitivity analysis. This analysis consisted of both decreasing and increasing the typical fishing weight mass by one standard deviation (4.69 g). These adjusted masses (2.40 g and 11.78 g, respectively) were then used in the comparison of our estimations to other studies (described below) to determine if our estimated typical mass was reasonable.

Markov Chain Monte Carlo simulation

We constructed a Markov Chain Monte Carlo (MCMC) simulation to estimate the mass loss of Pb fishing weights to California freshwater sediments. MCMC simulation is a method that can be used to generate predictive distributions of unobserved phenomena (Link and Eaton 2012). The simulation does so by creating a Markov chain that simulates draws from a target distribution (known as the posterior distribution). The initial draws are not from the posterior distribution and are discarded. These are known as burn-in. Markov Chains may be biased by the starting value that is used, and eliminating the burn-in draws eliminates this potential bias.

To determine the posterior distribution for the MCMC model, we conducted a literature review of peer-reviewed

studies that recorded densities (i.e., number of weights per square meter) of Pb fishing weights found in freshwater sediments. In total we found 7 studies (Table S1) containing a total of 86 observations. Prior to running the MCMC, we used the bestNormalize package to transform these data to a normal distribution (Peterson 2021). Zero values were changed to 0.000001 to preserve the shape of the distribution but not prevent the transformation from being applied.

The MCMC simulation was run on the transformed data, and implemented using the wiqid package in R v.4.2.1 (Meredith 2022). The MCMC consisted of 10 chains that each made 1,000,000 draws. Our simulation used a burn-in of 5000. Chains were thinned by 15 (i.e., all but every 15th observation was discarded) to reduce bias introduced by correlation. We assessed convergence and model error using the built-in diagnostic features in wiqid (Fig. S1). The Rhat value (a comparison of between and within variances of chains) of the transformed mean was 1.0, indicating convergence was reached (Brooks and Gelman 1998). The Monte Carlo error was 3% of the standard deviation of the transformed mean. Low, medium, and high estimates of the number of lost weights were determined by taking the 10th, 50th, and 90th percentiles, respectively, of the mean fishing weight density generated by the MCMC.

Fishing weight densities were converted to a total number of lost fishing weights for each fishing lake by calculating the surface area and multiplying this area by the fishing weight density. These fishing weight counts were summed, yielding the total number of lost fishing weights for the State. The total number of lost fishing weights was converted to a mass (in tons) by multiplying an assumed typical fishing weight mass (7.09 g) by the number of total fishing weights and converting to tons.

Comparison of MCMC estimates with other studies

During our literature review we only found a national (U.S.) level estimate of Pb fishing tackle losses per year (2003). To convert this national level estimate to a California level estimate, we first calculated the average proportion of Californian anglers to U.S. anglers over the period 2010-2022 (0.047) (Table S4) (CDFW 2021, 2024a; Statista 2022; U.S. Fws 2023). Next, we assumed a deposition period of 1950–2023, or 73 years. We selected a start of 1950 for the deposition period because 1950 marks the start of California's rapid population growth (Johnson et al. 2024), and the assumed average proportion of Californian anglers to the total number of U.S. anglers would likely not be valid prior to this. Lastly we assumed the proportion of freshwater anglers to all anglers in California reflects the proportion at the national level, which according to U.S. Fish and Wildlife Service's 2022 survey, is 87.8% (U.S. Fws 2023).

Consequently, we used the following formula to convert Scheuhammer et al.'s (2003) national level estimate to a California level estimate (*Total mass loss*$_{CA}$ in tons):

$$Total\ mass\ \text{loss}_{CA} = Total\ mass\ \text{loss}_{US} \times \alpha_{CA\ anglers} \times \alpha_{fw\ anglers} \times (2023 - 1950)$$

where *Total mass* loss$_{US}$ is the total annual mass loss of Pb fishing weights in the U.S. (3,977 tons), $\alpha_{CA\ anglers}$ is the proportion of Californian anglers to U.S. anglers (0.047), $\alpha_{fw\ anglers}$ is the proportion of Californian anglers that are freshwater anglers (0.878), and (2023 − 1950) is the deposition period (73 years).

Results and discussion

Pb fishing weight losses estimated via purchasing data

Estimating angler purchasing data of Pb weights is one approach to estimate mass losses of Pb fishing weights. In 2023, 1.68 million California fishing licenses were purchased (CDFW 2024a), and we estimate all Californian anglers purchased over 233 tons of Pb fishing weights during that year. This value equates to a consumption of 0.14 kg/year per California angler, which falls within the range of estimates of 0.10–0.30 kg/year made by the European Commission for anglers in the European Union (EC 2004).

Estimates of statewide Pb fishing weight losses

We synthesized the peer-review literature for recorded densities (i.e., number of weights per square meter) of Pb fishing weights found in freshwater sediments (Table 1&Table S1) and used these data to construct a Markov Chain Monte Carlo (MCMC) simulation of an average lost fishing weight density for Californian freshwater sediments. Our simulation suggests anywhere between 404 million and 2.62 billion (median = 1.1 billion) Pb fishing weights are deposited in freshwater sediments in California. Assuming a typical Pb weight mass of 7.09 g, this equates to 2,870–18,600 tons of Pb (Table 2).

Although we lack studies for direct comparison, median estimates of Pb fishing weights lost in freshwater sediments generated by our MCMC simulation generally align with others made in the literature, when adjusted for the

Table 1 Peer-reviewed studies that have characterized the number of Pb fishing weights lost to freshwater bodies

Study	Study Location	Method	Sample Location	Number of samples
Bell et al. (1985)	Woodstock Pool, UK	Direct collection	Shoreline	15
Forbes (1986)	Llandrindod Wells Lake, UK	Direct collection	Shoreline	11
Cryer et al. (1987)	South Wales and West Midlands, UK	Direct collection	Shoreline	12
Sears (1988)	Thames River, UK	Direct collection	Bed sediments	29
Duerr (1999)	US*	Direct collection	Lake bottom Shoreline	29
Radomski et al. (2006)	Minnesota, US	Angler survey	NA	5
Pander et al. (2022)	Lake Eixendorf, Germany	Direct collection	Lake bottom	1

*Study locations include Arkansas, Florida, Idaho, Maine, Michigan, Nevada, New Hampshire, North Carolina, Vermont, and Wisconsin

Table 2 Estimates of the number and mass (tons) of Pb fishing weights located in freshwater lake sediments in California

Scenario	Number of Pb fishing weights	Mass of Pb (tons)*
Low	404,000,000	2,870
Median	1,090,000,000	7,730
High	2,620,000,000	18,600

*Assumes a typical Pb fishing weight is 7.09 g

number of California anglers. For example, Scheuhammer et al. (2003) estimated U.S. anglers lose 3,977 tons of Pb fishing tackle per year. Limiting this estimate to Californian freshwater anglers only and assuming a deposition period of 1950–2023 yields a total of 11,980 tons of Pb lost to freshwaters, a value between our median and high MCMC simulation estimates.

The median estimate from our MCMC simulation adjusted to a per year basis also generally agrees with an estimate of the total mass of Pb fishing weights purchased each year by Californian anglers (163 g per angler) when adjusted for 2022 data. Considering the number of anglers in 2022 (1.64 million), adjusting for the assumed proportion that are freshwater anglers (88%), and assuming that Pb fishing weights are purchased to replace lost weights, 200 tons of Pb fishing weights have been lost in freshwaters in California every year (Table 3). This value is roughly double the average amount (106 tons/year) that is calculated by assuming that the total mass generated by the median MCMC estimate occurred over a period of 73 years (1950–2023) (Table 3).

The total yearly loss estimated by the median from our MCMC simulation is also similar to other estimates when converted to an annual per angler loss (Table 3). For example, Scheuhammer et al.'s (2003) estimate only differs from the median from our MCMC simulation by ~41 g (or about 6 typically sized weights). Our estimate based off market sales of Pb fishing weights is double the median from our MCMC simulation. The largest discrepancy is with the median of the European Commission's (2004) estimated range, although their estimate is within ~126 g (or ~18 typically sized weights) of our MCMC estimate. Thus, the total losses estimated by our MCMC are not only in line with previously published estimates but are also in line with estimates reached using a different methodology.

Sensitivity analysis

Because the typical fishing weight mass was directly used to convert the raw number of lost fishing weights to a mass, the mass loss estimates from our MCMC scenarios are

Table 3 Comparison our estimates of total yearly losses (tons Pb/year) and yearly per angler losses (kg Pb/year) with those in the literature. Losses estimated by market sales and the MCMC only consider Pb fishing weights lost in freshwaters

Estimate	Source	Anglers	Total Yearly Loss (tons Pb/year)	Per angler loss (kg Pb/year)
U.S. annual losses	Scheuhammer et al. (2003)	35,000,000	3,977	0.114
Market sales*	This study	1,440,000	200	0.142
EU25 – median	EC (2004)	19,952,000	4,000	0.200
MCMC – median*	This study	1,440,000	106^	0.074

*Californian freshwater specific losses

^This is an average rate over the assumed 73-year period

unsurprisingly sensitive to the typical mass value used. Manipulating the assumed typical weight mass by one standard deviation changed the total estimated mass loss in each scenario by about ±66% (Table S3). Ranges (± 1 SD) of the total mass loss were 970–4,760, 2,620–12,800, and 6,280–30,800 tons for the low, median, and high scenarios, respectively (Table S3, Fig S2a). Converting the total mass losses to an annual per angler loss results in ranges of 0.009–0.045, 0.025–0.122, and 0.060–0.293 (kg Pb/year) for the low, median, and high scenarios, respectively (Table S3, Fig S2b).

Despite the typical weight mass we assumed, our median and high scenarios still align with estimates reported in the literature and with our market sales-based estimate. Specifically, the range of our high scenario encapsulates nearly the entire range of the other estimates, and the upper range of the median estimate is relatively close with the lower end of the EU 25, U.S. annual losses, and market sales estimates. Although there appears to be ~50–100 g of difference between the median and high MCMC scenarios and the other per angler loss estimates, it is important to remember that this difference corresponds to a relatively small number (i.e., <20) of typically sized fishing weights. Thus, although the total mass loss estimated by our MCMC simulation is sensitive to the assumed typical weight mass (7.09 g), the median MCMC scenario appears to nonetheless be a conservative estimate.

Limitations of MCMC-based estimates

Our MCMC simulation assumes Pb fishing weights are deposited uniformly across the lakebed. In reality, deposition would likely be heaviest near shorelines, and Pb weights may also be lost or discarded on the land surface. Thus, at face value the MCMC overestimates the amount of Pb fishing weights lost in Californian lakebed sediments. However, we did not calculate deposition amounts in three other types of environments in California where Pb fishing weights are discarded or lost — marine, streams, and rivers, and consequently any overestimation is countered by the omission of streams and rivers.

We did not consider marine sediments in our simulation due to data limitations. The hydrologic differences in marine systems (e.g., oceanic currents, wave action), mean the density of lost Pb weights observed in freshwater systems (Table S1) is likely not comparable. This complicates determining an appropriate posterior (i.e., target) distribution. Additionally, these hydrologic differences greatly complicate estimating a depositional area of lost weights. Furthermore, saltwater fishing often requires heavier weights to keep baits in place (EC 2004), and thus, an assumed typical fishing weight mass of 7.09 g is likely not valid. Because studies in our input dataset primarily considered freshwater environments, they may not reflect the typical mass for Pb weights used for saltwater fishing and consequently we did not consider deposition to marine environments.

Pb weights lost in streams and rivers were not considered due to the difficulty of calculating a depositional area. Currents may carry lost or discarded weights far from the location where they were originally deposited. Estimating these transport distances requires a knowledge of water flow velocities in each stream or river. However, not all streams in the state have water flow monitoring data, and estimating these data in unmonitored watersheds is one of the grand challenges in the field of hydrology (Blöschl et al. 2019), and is thus out of scope of this study. Additionally, streams and rivers are more dynamic systems than lakes, and as such, the morphology of these systems rapidly changes. Geospatial data of rivers and streams generally are represented by lines, as opposed to the polygons used to represent lakes. Consequently, estimating the surface areas of streams and rivers would necessitate high-resolution (i.e., sub 1 m) imagery, which is not widely available.

In summary, we have likely underestimated the mass of Pb fishing weights that have accumulated in Californian freshwater ecosystems due to fishing activities. Streambed and riverbed sediments were not explicitly included in our analysis, and the mass of Pb weights lost in these environments is thus unaccounted. This likely offsets any overestimation that may be inherent to our MCMC simulation.

Comparison of MCMC-based estimates to in situ measurements

Our approach provides an alternative to traditional in situ measurements of deposited Pb fishing weights. While field sampling campaigns such as Pander et al. (2022) provide concrete measurements of lost or discarded weights, these campaigns may be impractical to conduct at large spatial scales (e.g., millions of hectares), in rugged terrain, or in remote areas. Although our MCMC-based estimation relies on several assumptions (e.g., a uniform distribution of weights across the lakebed, a typical fishing weight mass), it provides a reasonable estimate.

Because the MCMC approach requires relatively few resources, it is an economical method for characterizing the environmental losses of Pb fishing weights at large spatial scales. Nonetheless, estimates generated via our approach could be further refined by conducting field campaigns in targeted areas (e.g., lakes with a gradient of fishing pressure) to improve the posterior distribution used to generate the MCMC.

Colocation of rare species with fishing lakes

To estimate potential impacts of deposited Pb fishing weights to threatened and/or endangered species in California, we determined if popular fishing locations are located within areas of rare species richness. Specifically, the incidence of Pb fishing weight consumption and impacts on wildlife are generally related to the intensity of fishing pressure (Grade

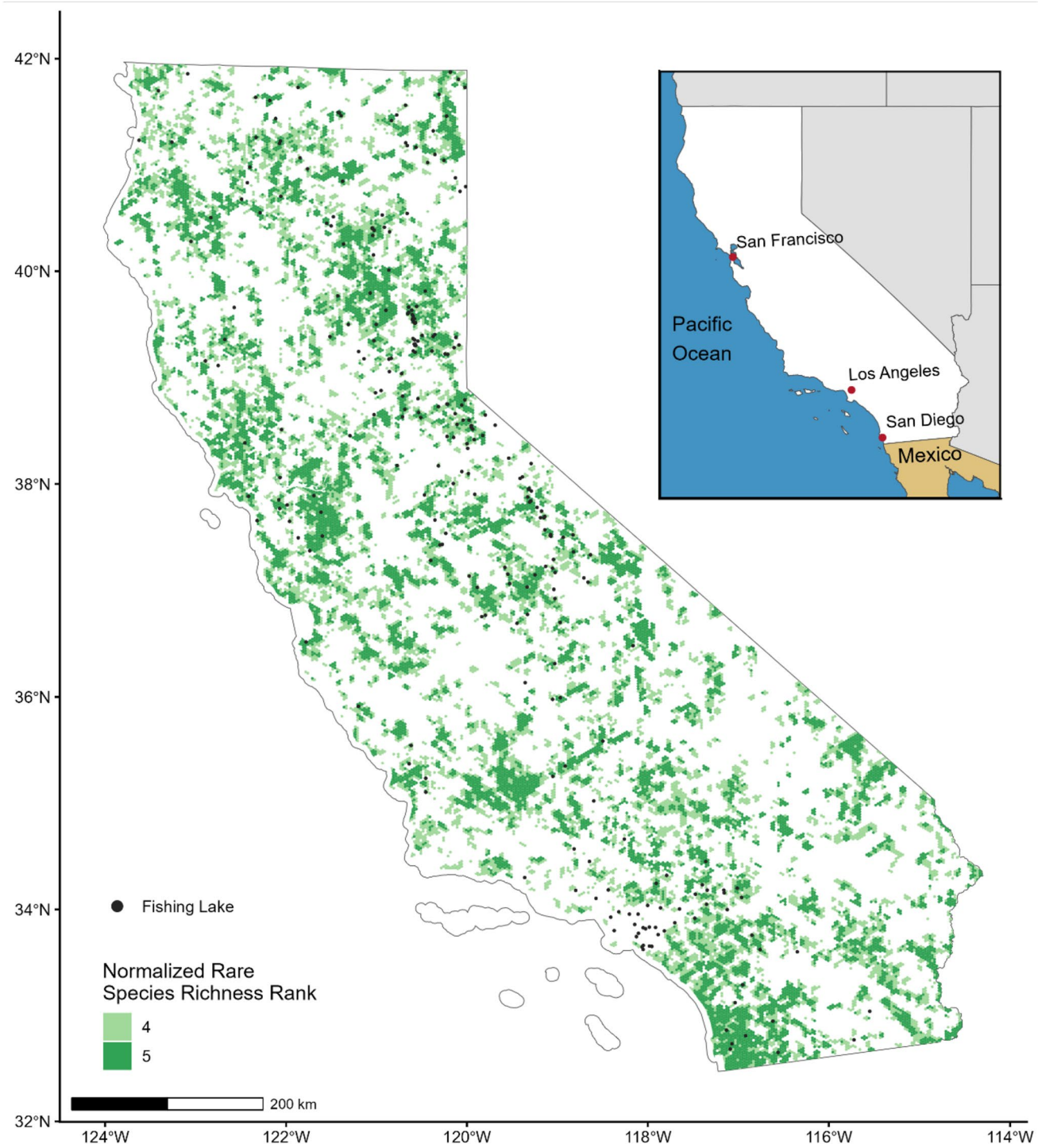


Fig. 1 Locations of areas in the Terrestrial Rare Species Richness dataset (CDFW 2020) normalized rare species richness ranks of 4 or higher (CDFW 2018). Black dots represent fishing lakes featured in CDFW's fishing guide map viewer (CDFW 2024b). Inset map shows locations of State and international boundaries (CEC 2022)

et al. 2019). Of the 278 fishing lakes identified in California Department of Fish and Wildlife's (CDFW) fishing guide map viewer (CDFW 2024b), 200 are within an area of rare species richness rank 4 or higher (Fig. 1). Fishing lakes and the land directly adjacent account for approximately 3% of all the grid cells having a rank of 4 or higher in the state. Thus, areas of high rare species richness located near lakes identified to the public as "good fishing locations" likely experience relatively higher deposition rates of Pb fishing weights and experience an increased likelihood of direct or indirect Pb consumption.

Pb consumption by rare species is a concern because Pb is toxic to all organisms (ATSDR 2020). For example, Pb consumption by bird species causes neurological, immunological, and reproductive effects (Haig et al. 2014). Consumption of Pb fishing weights has also caused population-level mortality in bird species such as Mute Swans (Grade et al. 2019; Wood and Newth 2024) and Common Loons (Grade et al. 2019). Although not observed in California, consumption of Pb fishing weights has impacted Bald Eagles and Sandhill Cranes (Grade et al. 2019). These species are listed as endangered and threatened, respectively, by the State of California (CNDDB 2024). Additionally, in a laboratory experiment Beggel et al. (2026), observed exposure to leachate from Pb jigheads resulted in 100% mortality to a benthic organism (*Hyalella azteca*) commonly found in North American freshwater lakes and posed bioaccumulation concerns. Thus, the colocation of areas of high rare species richness and popular fishing locations may impact biodiversity.

Pb may be mobilized post-deposition

Although elemental Pb is generally persistent in the environment (Check and Marteel-Parrish 2013), it may cycle between environmental compartments due to geochemical and/or hydrological shifts. For example, sediment-bound Pb can dissolve in acidic conditions (i.e., pH< 7). Acidic conditions are commonly found in streams receiving legacy mine drainage waters. Likewise, streams draining watersheds experiencing heavy nitrogen deposition generally have more acidic waters (Murdoch and Stoddard 1992). Both mine drainage-impacted streams (SWRCB 1995) and watersheds experiencing nitrogen deposition are found throughout the state of California. In addition to human-driven acidification, acidic conditions may occur naturally via microbial-driven decomposition of organic matter in aquatic sediments (Ryan 2014).

Additionally, laboratory studies suggest Pb from deposited weights may still leach during typical environmental conditions. For example, Fäth et al. (2018) saw a relatively low (~0.06–2.35 µmol/L/day), leaching of Pb from Pb shot in synthetic freshwater samples over a 22-day experiment. Similarly, Beggel et al. (2026) also observed relatively low amounts of Pb (0.19–0.66 µmol/L) leached from Pb jigheads over a 14-day laboratory study. Although not freshwater, Jacks et al. (2001) observed that roughly 1% (by mass) of lead deposited in Swedish river mouths is dissolved per year. Assuming a total yearly loss of 106 tons Pb/year, as much as 1,060 kg of Pb may be dissolved in California freshwaters each year.

Lastly, perturbations caused by climatic or land use changes can also physically remobilize legacy trace metal contamination (Steding et al. 2000; Rossi et al. 2017), potentially transporting it to nearby ecosystems. This remobilization pathway is particularly pertinent for California as climate change is predicted to increase the occurrence of extreme flood events (Huang and Swain 2022). Thus, while deposited Pb fishing weights can generally be thought of as sequestered, human or climate driven shifts may reduce the persistence of deposited weights.

Conclusions

We estimate that between 2,870 to 18,600 tons of lost or discarded Pb fishing weights have been deposited in freshwater sediments in California. This number is likely much higher when considering Pb fishing weights lost during saltwater fishing activities. If these weights degrade at rates similar to those observed by Jacks et al. (2001), as much as 1,060 kg of Pb may be dissolved in California freshwaters each year. Pb that leaches from deposited weights can accumulate in benthic organisms (Beggel et al. 2026), posing an additional exposure route for wildlife.

Many publicized "good fishing locations" are located in areas with relatively higher counts of rare species. Specifically, ~72% of the fishing lakes identified in CDFW's fishing guide map viewer (CDFW 2024b), are within an area of a rare species richness rank 4 or higher, which accounts for approximately 3% of the rank 4 or higher grid cells in California. Consequently, the potential exists for lost or discarded weights to disproportionately impact these ecosystems.

Pb is a toxic chemical that is hazardous to both humans and wildlife. Given Pb's general persistence in the environment, eliminating the source of Pb loadings to the environment (i.e., the use of Pb-based fishing weights) is the most effective approach to reducing environmental exposures. Our approach provides a foundation for better constraining potential risks of deposited Pb fishing weights via environmental exposures and presents a more economical option as compared to traditional field sampling campaigns (e.g., Pander et al. (2022)). Future efforts can build on this approach by coupling MCMC-based estimates with geochemical and/or hydrologic modeling.

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Data availability Links to the data analyzed by this study, and the R code which performed the analyses are available in the electronic supplementary material.

Declarations

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