Lead and biomagnification in food webs

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Abstract. Trophic biomagnification is often considered a hallmark of heavy metal contamination in ecosystems; however, global empirical evidence demonstrates that this phenomenon is highly metal-specific. Unlike methylmercury (MeHg), which consistently amplifies across food webs, lead (Pb) frequently exhibits a distinct pattern of attenuation or biodilution toward apex predators, despite showing strong bioaccumulation at the base of the food chain. This review provides an integrative overview of the geochemical, physiological, and toxicokinetic mechanisms that drive lead biodilution in both terrestrial and aquatic ecosystems. A synthesis of multi-trophic studies reveals that the elevated lead concentrations recorded in primary producers and detritivores are largely a reflection of passive surface adsorption rather than true internal assimilation. As lead transfers up the food web, multiple physiological barriers drastically limit its bioavailability to higher consumers. In aquatic chains (e.g., alga–zooplankton–fish networks), efficient detoxification routes, low dietary assimilation efficiency, and excretion pathways effectively prevent trophic transfer. In vertebrate consumers, lead acts as a chemical analog to calcium and is heavily sequestered into inert, mineralized matrices like bones and fish skeletons. This structural trapping removes lead from the rapidly exchanged soft-tissue pools, minimizing the fraction available for dietary assimilation by apex predators.

Key Words: biomagnification, lead (Pb), biodilution, food webs, toxicokinetic, trophic transfer.

Introduction. Biomagnification means systematic increase of a contaminant with trophic level (Petrescu-Mag, 2025). For lead (Pb), many empirical food chain studies show strong bioaccumulation at the base, but attenuation or biodilution toward predators, in contrast to metals like mercury that consistently biomagnify (Petrescu-Mag & Oroian, 2015). While mercury accumulates in the muscle tissue that predators consume, lead behaves like calcium and is stored mostly in bones or shells. Once trapped in these hard structures, lead becomes difficult for predators to absorb. Additionally, the high amounts of lead found at the bottom of the food chain are often just stuck to the outside surfaces of small organisms, rather than being truly absorbed into their bodies. As a result, less lead is passed up the food chain, leading to the observed biodilution instead of biomagnification (Figure 1).

The aim of this mini-review is to provide an updated and integrative overview of lead (Pb) trophic transfer and bioaccumulation dynamics across terrestrial and aquatic food webs, with a particular focus on the mechanisms driving its frequent attenuation or biodilution. Specifically, this review seeks to: (i) summarize the general conceptual patterns of lead bioaccumulation and contrast them with robustly biomagnifying metals like methylmercury; (ii) compile and synthesize empirical evidence from key terrestrial chains, such as soil–plant–arthropod systems, and aquatic networks; (iii) evaluate the specific roles of environmental speciation, physiological regulation, active excretion, and skeletal sequestration in limiting lead bioavailability to predators; and (iv) contextualize lead findings within broader ecotoxicological frameworks, highlighting the nonessential status of this metal and its impact on homeostatic control. Through this approach, the review aims to identify emerging patterns, highlight current limitations, and outline future directions for heavy metal risk assessment in diverse ecosystems.

Lead in Food Webs: Why It Rarely Biomagnifies. Lead (Pb) is a non essential, toxic metal that can strongly contaminate soils and waters, yet it usually does not show clear, monotonic biomagnification across food webs, especially compared with methylmercury. Instead, many studies report biodilution or neutral patterns at higher trophic levels, with key exceptions in some marine systems. The reasons lie in Pb's environmental speciation, low dietary transfer efficiency, and powerful detoxification and excretion mechanisms in consumers.

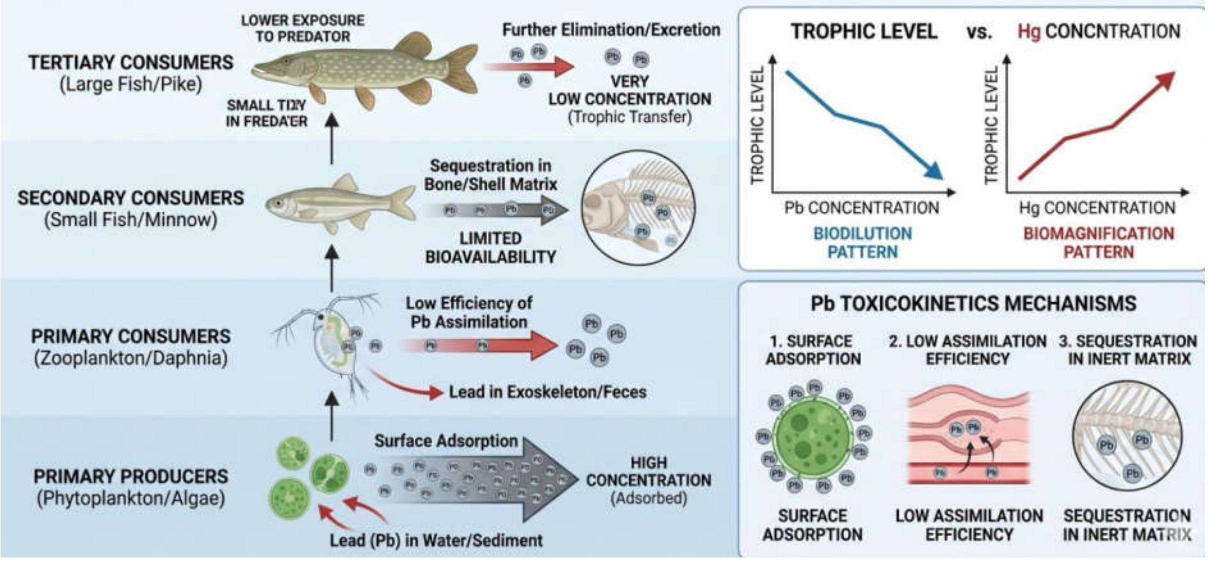

Figure 1. Schematic comparison between lead (Pb) biodilution and mercury (Hg) biomagnification patterns across different trophic levels, highlighting the main physiological and toxicokinetic mechanisms of lead regulation in aquatic consumers.

Conceptual Patterns of Lead vs Other Metals. In global marine food webs, a meta analysis of eight metals found overall trophic biomagnification (FWMF > 1) for Hg, Pb and Zn, and biodilution for As and Ni (Sun et al., 2019). Yet predator–prey comparisons revealed that Pb biodiluted between tertiary consumers and top predators (BMF < 1), indicating that Pb does not increase consistently with trophic level (Sun et al., 2019). A broader review of non essential metals (Cd, Pb, Hg, As) stresses that biomagnification is a controversial, metal specific phenomenon and not a general property of food chains (Ali & Khan, 2019); for many plant–arthropod and arthropod–arthropod systems, biomagnification is explicitly rejected as a generic expectation (Tibbett et al., 2021).

In aquatic systems, Hg shows robust, global biomagnification, with highly consistent trophic magnification slopes for MeHg across temperate, tropical and Arctic ecosystems (Córdoba-Tovar et al., 2021; Lavoie et al., 2013). MeHg biomagnification factors between zooplankton and fish are relatively uniform and often high (Wu et al., 2019; Kim et al., 2023; Hilgendag et al., 2022). Reviews of marine fish highlight Hg as a leading biomagnifying metal of concern for apex predators and human consumers (Oros, 2025; Wu & Zhang, 2023; Wang et al., 2021).

Empirical Evidence: Lead in Terrestrial Food Chains

Soil–plant–aphid–ladybird systems. Several multi trophic experiments in agroecosystems provide detailed mechanistic data.

In a Pb amended broad bean–aphid–ladybird chain, Pb increased with soil contamination in all compartments, but transfer coefficients showed biomagnification only from soil to roots, not along the biotic chain: root→shoot, shoot→aphid, and aphid→ladybird transfer coefficients were all < 1 (Naikoo et al., 2019). Pb thus biominimized at both herbivore and predator levels. The study documented dose dependent elimination of Pb via aphid honeydew and ladybird pupal exuviae, highlighting these excreta as detoxification routes limiting trophic build up (Naikoo et al., 2019).

In a mustard–aphid–beetle chain on fly ash amended soil, Cd and Zn frequently biomagnified, but Pb was the only metal whose transfer coefficient was < 1 at both the second and third trophic levels, meaning no biomagnification in aphids or beetles (Dar et al., 2017). Pb was present in shoots and aphids, yet a substantial fraction was eliminated in honeydew, again indicating preferential excretion; honeydew:aphid ratios for Pb (0.16–0.20) were higher than for Zn (0.07–0.09) (Dar et al., 2017).

A sewage sludge soil–barley–aphid–ladybird system showed the same pattern: Pb transfer coefficients < 1 from shoot→aphid and aphid→ladybird (biominimization), whereas Zn biomagnified from shoot→aphid but biodiluted from aphid→ladybird (Jahan et al., 2023). Pb elimination via honeydew was particularly efficient, with honeydew:aphid ratios of 0.18–0.25 vs 0.07–0.10 for Zn, supporting the view that Zn is bioretained and Pb bioeliminated (Jahan et al., 2023).

A compartment based review of soil–plant–arthropod transfer reinforces these observations: the magnitude of metal transfer depends on metal form and location in the lower trophic level, and on organismal regulation, detoxification and excretion; overall, biomagnification is not a general property of plant–arthropod and arthropod–arthropod food chains (Tibbett et al., 2021).

Broader terrestrial patterns. Other terrestrial work (e.g. agro industrial gradients) similarly emphasizes that trophic transfer of metals can be strong at the soil–plant step but attenuated at animal levels, reflecting both geochemical constraints and physiological regulation (Tibbett et al., 2021; Ali & Khan, 2019; Soliman et al., 2022). Reviews of Pb toxicity underline that in vertebrates about 90% of Pb is stored in bone, where it mimics Ca^{2+} and is largely removed from rapidly exchanged soft tissue pools relevant for trophic transfer (Generalova et al., 2025). This long term skeletal sequestration further reduces the fraction of Pb that predators can assimilate from prey tissues.

Empirical Evidence: Lead in Aquatic Food Webs. A laboratory microalga–rotifer–prawn study showed substantial Pb bioconcentration in *Nannochloropsis* microalgae and high bioaccumulation in rotifers (BAF ≈ 2948), but a much lower BAF in prawns (≈ 42.1) (Benítez-Fernández et al., 2023). The authors concluded that Pb concentrates and is transferred from algae to rotifers and prawns, but does not biomagnify among invertebrates, attributing this to detoxification mechanisms in higher trophic levels (Benítez-Fernández et al., 2023).

At larger scales, the marine meta analysis reported a food web magnification factor > 1 for Pb, but also clear biodilution in specific predator–prey steps and much stronger, more consistent biomagnification for Hg (Sun et al., 2019). A synthesis on non essential metals stresses that evidence for Pb biomagnification remains mixed and context dependent, with many cases of biodilution in both aquatic and terrestrial webs (Ali & Khan, 2019). A review of heavy metals in marine fish focuses more strongly on Hg and Zn, which are consistently biomagnified or retained, whereas Pb patterns are more variable and often influenced by local pollution and species specific physiology (Oros, 2025; Wang et al., 2021).

Mechanistic Explanations: Why Lead Rarely Shows Strong Biomagnification

Environmental speciation and limited bioavailability. Pb speciation and binding in soils strongly constrain its bioavailability. In soils, Pb commonly occurs in relatively insoluble mineral or sorbed forms, influenced by pH, organic matter, clay minerals, organic colloids and Fe oxides (Kushwaha et al., 2017). This reduces freely available ionic Pb for plant uptake and thus for entry into terrestrial food chains (Kushwaha et al., 2017; Tibbett et al., 2021). In many cases, strong sorption and low mobility mean that Pb accumulates in roots with restricted translocation to shoots, as observed in mustard and barley, limiting the fraction available to herbivores (Dar et al., 2017; Jahan et al., 2023; Kushwaha et al., 2017).

In aquatic systems, comparable constraints arise: only certain dissolved and particulate Pb species are efficiently assimilated by plankton. While Pb can bioconcentrate in algae, detoxification and storage in non digestible compartments (e.g. cell walls) may reduce dietary transfer efficiency to zooplankton and fish (Benítez-Fernández et al., 2023; Saidon et al., 2023). By contrast, methylmercury is highly bioavailable, strongly lipophilic, and efficiently assimilated, supporting robust and predictable biomagnification (Wu et al., 2019; Córdoba-Tovar et al., 2021; Lavoie et al., 2013; Kim et al., 2023; Hilgendag et al., 2022; Wu & Zhang, 2023).

Physiological regulation, sequestration and excretion. Experimental food chain studies consistently demonstrate that arthropods and other invertebrates possess effective excretion and sequestration mechanisms for Pb. In aphids and ladybirds, large fractions of ingested Pb are excreted via honeydew and shed in pupal exuviae, with elimination increasing with exposure level (Naikoo et al., 2019; Dar et al., 2017; Jahan et al., 2023). Honeydew consistently contains a higher proportion of Pb relative to body burden than Zn, indicating preferential excretion of Pb vs retention of essential Zn (Dar et al., 2017; Jahan et al., 2023).

A broader soil–plant–arthropod review documents multiple physiological processes that limit trophic transfer: immobilization of metals in the gut, binding to metallothioneins or other ligands, sequestration in exoskeleton or inert tissues, and periodic excretion during molting and metamorphosis (Tibbett et al., 2021). In vertebrates, Pb is largely sequestered in bone, reducing its presence in soft tissues eaten by predators (Generalova et al., 2025). Such mechanisms mean that although organisms may bioaccumulate Pb, especially at low trophic levels, the fraction that is both assimilated and retained in forms digestible to predators declines with each trophic step, leading to biodilution or weak biomagnification patterns.

Non essential status and homeostatic control. Pb is strictly non essential and toxic. Reviews emphasize that organisms tend to limit internal concentrations of non essential metals via avoidance, reduced absorption, active efflux, and sequestration, whereas essential metals such as Zn and Cu are maintained at relatively high and stable tissue levels through homeostatic regulation (Tibbett et al., 2021; Ali & Khan, 2019; Dar et al., 2017; Jahan et al., 2023). This difference is clearly illustrated in experimental chains: Zn biomagnified from plant shoots to aphids and from aphids to beetles or ladybirds, while Pb did not, despite co exposure (Dar et al., 2017; Jahan et al., 2023). Zn’s essentiality favors retention, while Pb is actively eliminated. Similar contrasts occur with Hg and Cd in aquatic systems, where highly bioavailable forms (MeHg, in some cases Cd) are efficiently assimilated and retained (Saidon et al., 2023; Wu et al., 2019; Córdoba-Tovar et al., 2021; Lavoie et al., 2013; Kim et al., 2023; Hilgendag et al., 2022).

Comparison with metals that do biomagnify. The contrast with Hg is particularly instructive. A worldwide meta analysis of Hg in 205 aquatic food webs found consistent positive trophic magnification slopes, especially for MeHg, with higher biomagnification in cold, low productivity systems (Lavoie et al., 2013). Another meta analysis showed that MeHg concentration in seston (food web base) explained 63% of fish MeHg variability, and that MeHg biomagnification between zooplankton and fish was relatively invariant across ecosystems (Wu et al., 2019). Reviews highlight that Hg, As and Se can biomagnify, but Hg has by far the greatest biomagnification potential (Córdoba-Tovar et al., 2021).

In contrast, a synthesis of biomagnification metrics in coastal and marine webs identified only two metals—Hg and Zn—as consistently biomagnifying; Pb did not emerge as a robustly biomagnifying metal across the surveyed literature (Wang et al., 2021). A general review of heavy metal trophic transfer underscores that while specific cases of Pb biomagnification exist, especially in contaminated marine systems, the prevailing pattern for Pb across ecosystems is high accumulation at low trophic levels with attenuation or variable trends at higher levels (Saidon et al., 2023; Ali & Khan, 2019; Oros, 2025; Sun et al., 2019; Tibbett et al., 2021; Naikoo et al., 2019; Dar et al., 2017; Jahan et al., 2023; Benítez-Fernández et al., 2023).

Concise comparison of trophic behaviors. Overall, across terrestrial and aquatic ecosystems, Pb's environmental speciation, non essential status, efficient excretion and sequestration, and low assimilation efficiency at higher trophic levels jointly explain why it generally does not show strong, systematic biomagnification, in contrast to metals like methylmercury or, in specific pathways, zinc and cadmium (Table 1).

Table 1

Contrasting trophic behaviors of Pb vs other metals

Metal	*Typical trophic pattern*	*Key mechanisms*	*References*
Lead (Pb)	Often biodilution or weak, context-dependent biomagnification; strong soil→root transfer but low plant→herbivore→predator magnification	Low environmental mobility; root sequestration; preferential excretion (honeydew, exuviae); bone storage in vertebrates; non-essential, actively regulated	Sun et al., 2019; Tibbett et al., 2021; Ali & Khan, 2019; Naikoo et al., 2019; Dar et al., 2017; Jahan et al., 2023; Benítez-Fernández et al., 2023; Kushwaha et al., 2017; Generalova et al., 2025
Methylmercury (MeHg)	Strong, consistent biomagnification from seston to top predators in freshwaters and oceans	High bioavailability; efficient assimilation; long biological half-life; limited excretion; tight coupling between food-web base and fish	Wu et al., 2019; Córdoba-Tovar et al., 2021; Lavoie et al., 2013; Kim et al., 2023; Hilgendag et al., 2022; Wu & Zhang, 2023
Cadmium (Cd)	Historically viewed as non-biomagnifying; now known to biomagnify in some gastropod/epiphyte webs; in some terrestrial chains, biomagnifies plant→aphid but not aphid→predator	Species- and pathway-specific uptake; partial retention; some detoxification and excretion; non-essential but less effectively regulated than Pb in some taxa	Saidon et al., 2023; Dar et al., 2017
Zinc (Zn)	Frequently biomagnifies at certain steps (e.g., plant→aphid→beetle); can also biodilute at higher levels	Essential metal with strong homeostatic regulation and bioretention; lower excretion rates in honeydew vs Pb	Sun et al., 2019; Tibbett et al., 2021; Dar et al., 2017; Jahan et al., 2023; Wang et al., 2021.

Conclusions. Lead (Pb) trophic transfer represents a highly complex and non-linear regulatory behavior in food webs, characterized by strong bioaccumulation at the base followed by distinct attenuation or biodilution toward apex predators. Current evidence indicates that lead dynamics are deeply integrated into ecosystem-specific geochemical constraints and physiological regulation networks, largely through active detoxification and tissue-specific sequestration mechanisms. In particular, its involvement in key biological pathways—acting as a nonessential calcium analog and being sequestered into inert bone or shell matrices—underscores its unique toxicokinetics, which effectively limit its transfer and maintain homeostatic control in higher consumers.

Despite these advances, the complete mechanistic characterization of lead transfer remains variable across diverse ecosystems, with many insights derived from localized empirical studies and specific plant–arthropod or aquatic food chains rather than universal global models. Furthermore, the exact role of lead in specific physiological checkpoints across multiple trophic steps is still partially context-dependent, although comparative data from robustly biomagnifying metals like methylmercury suggest entirely different and highly conserved regulatory frameworks involving tissue tropism, efficient assimilation, and biological half-life control.

Future research should prioritize integrative multi-trophic studies, including the precise mapping of trophic positions using stable isotope datasets, the evaluation of metal speciation in food web bases, and the detailed investigation of insect-specific excretion networks like honeydew and exuviae elimination. Expanding research in these directions will not only clarify the ecotoxicological significance of lead biodilution but also strengthen the utility of trophic magnification factors (TMFs) and biomagnification metrics as precise tools in environmental risk assessment and wildlife management.

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