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Introduction to the biogeochemistry of the trace elements themed issue

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The goal of this themed issue is to showcase advances in research on the biogeochemistry of trace elements (TEs). Articles in this issue highlight a wide range of biogeochemical processes and environmental impacts of toxic and essential TEs. A main focus lies on research across phase- and compartment interfaces and coupled biogeochemical cycles between TEs and/or major elements.

TEs (including metals, metalloids and non-metals) are critical for many materials ranging from industrial products like steel to novel materials such as touch screens. There has been a revolution in materials science in recent years associated with a transition from mainly static materials with one functionality to new technologies for electronics and computing that require novel combinations of TEs not previously seen. Accordingly, global mining and use of TEs has increased massively over the last decades and there has been strong global demand for the production and use of rare earth elements and platinum-group elements.[1] Many of these elements are critical for the battery technology needed for electric vehicles and renewable energy.[2] The transition to a low-carbon economy is thus likely to require increased extraction of minerals and metals, including trace metals and metalloids.[3] A remaining concern is that historic mining activities are a major ongoing source of environmental contamination in air, water, biota and human populations (*e.g.*, ref. 4 and 5). Thus, better understanding of the environmental impacts of TEs and development of more sustainable mining technologies is essential for the future.

Among environmental contaminants, TEs are unique because they are naturally occurring with sources such as erosion and weathering, volcanic emissions and biogenic emissions that have sustained their biogeochemical cycles throughout earth history. Understanding natural variability in sources and geochemical factors that affect their accumulation in organisms is thus a key component of managing their potential public health impacts. Depending on the specific TE, the contribution from natural sources can exceed that from human activities such as mining and fossil fuel combustion. Most environmental TE distributions reflect both natural sources and human actions, including re-emissions of anthropogenically released TEs *via* "natural" sources (*i.e.*, legacy effects). Understanding the perturbations to these TE cycles due to human activity is thus a major area of research interest.

Organisms can be exposed to TEs *via* different pathways, most importantly dietary intake and direct exposure from water and air. While many TEs are toxic with no known function in cells (*e.g.*, the heavy metals such as Hg, and Pb, and the metalloid As), other TEs are essential in low quantities for normal cellular function and are referred to as micronutrients (*e.g.*, the metals Cu, Cd, Fe, Zn, and metalloid Se). Essential metals and metalloids are vital for the biochemistry of cells (*e.g.*, for proper functioning of enzyme systems), respiration, energy metabolism, tissue structure and function, growth, and neurological function. Almost half of all enzymes must associate with a particular metal to function.[6] Also undersupply of essential TEs can thus have serious health impacts.[7]

TEs are prevalent in air, terrestrial and aquatic ecosystems, including the ocean. Exchanges between these compartments across interfaces (*i.e.*, air–water transfer, terrestrial–atmospheric exchange, and riverine inputs to the oceans) have been strongly affected by changes in anthropogenic activities, environmental and climate change, leading to changes in environmental TE distributions and associated health risks. There is still a paucity of knowledge on many TE concentrations, loads and (bio)geochemical cycles and it is crucially important to better understand the factors driving these aspects.

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The articles in this themed issue broadly cover three topics. The first encompasses biotic processes involved in cycling of toxic and essential trace elements in soils and marine and brackish waters. For example, using an innovative multi-compartment modeling approach, Soerensen *et al.*, 2022 (**https://doi.org/10.1039/D1EM00418B**) combine information from marine and terrestrial environments and the atmosphere to show that over the last four decades, Se concentrations in herring in the Baltic Sea declined due to decreasing atmospheric and riverine inputs. A second topic addressed in this issue concerns sediments and soils and their interfaces to aquatic systems (*e.g.*, groundwater, river water and the hyporheic zone and lake systems). Mobilization and immobilization of TEs across these interfaces is of key importance in controlling their concentrations and thus potential ecotoxicological and human health risks in both aqueous and solid phases. This issue presents studies on contaminant (im)mobilization across interfaces investigated with combined analytical approaches, including stable isotope and liquid- and solid phase speciation analyses. In addition to these original research contributions, in a tutorial review, Shotyk, 2022 (**https://doi.org/10.1039/D2EM00049K**) addresses common misunderstandings regarding the presence and harmful effects of different TEs in the Athabasca Bituminous Sands in northern Alberta, Canada. The author uses published and unpublished data for TE levels in environmental matrices to clarify which TEs occur in bitumen and which elements in the mineral fractions, which is helpful to assess bioaccessibility of these TEs to biota. The third topic covered in this issue are TE distributions at large geographical scales in soils, sediments and porewater, lakes, oceans and in the atmosphere. These contributions illustrate the importance of measuring and modeling TE concentration patterns on a broad scale to gain improved understanding of regional- to global-scale biogeochemical TE cycling. Furthermore, such approaches give new insights into how changes in anthropogenic activities combined with environmental and climate factors affect the concentrations and speciation of TEs in and across different environmental compartments. We hope that environmental chemists from different research areas will enjoy reading about the biogeochemistry of TEs and find inspiration to address the many remaining open questions in this exciting research field.

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