Trace Metals in the Environment and Living Organisms

The British Isles as a Case Study

Trace metals play key roles in life – all are toxic above a threshold bioavailability, yet many are essential to metabolism at lower doses. It is important to appreciate the natural history of an organism in order to understand the interaction between its biology and trace metals. The countryside and indeed the natural history of the British Isles are littered with the effects of metals, mostly via historical mining and subsequent industrial development. This fascinating story encompasses history, economics, geography, geology, chemistry, biochemistry, physiology, ecology, ecotoxicology and, above all, natural history. Examples abound of interactions between organisms and metals in the terrestrial, freshwater, estuarine, coastal and oceanic environments in and around the British Isles. Many of these interactions have nothing to do with metal pollution. All organisms are affected, from bacteria, plants and invertebrates to charismatic species such as seals, dolphins, whales and seabirds. All have a tale to tell.

Philip S. Rainbow has more than 40 years' experience of research into the biology of trace metals. As lecturer, reader and professor at Queen Mary University of London, he taught students at undergraduate, master's and PhD levels, and often ran courses overseas. From 1997 to 2013, he was Keeper of Zoology and subsequently the head of the Department of Life Sciences at the Natural History Museum in London. He has published more than 250 refereed scientific publications, including two co-authored and seven edited books, and also upwards of 30 popular articles. In 2002, he was awarded the Environmental Pollution Kenneth Mellanby Review Award.

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PREFACE

This is a book about the natural history of metals. Without metals, there would be no life, and there are habitats in the world where, because of metals, there is no life. This is neither a story of metals in their elemental form, not a discourse on a lump of lead or an ingot of gold. It is a tale of how metals, whether in ionic form in a salt such as zinc chloride, or bound in a molecule as is iron in the protein haemoglobin in our red blood cells, have an all-important role in the biology of life around us.

This is a story of the biology of so-called trace metals, the metals that are to be found in very small 'trace' amounts in the physical environment of the rocks, soils, sediments and waters of the world, and in all forms of life from bacteria to algae and land plants, to fungi, and to invertebrates and vertebrates. The actors in this story are metals such as copper, zinc, lead, iron, manganese, tin, silver, cadmium and arsenic. Pedantic chemists will query whether some of the elements to be considered in this book fall strictly into a precise chemical definition of a metal, and will favour the term metalloid for the likes of arsenic. That argument can be left to another place and another time. There are other metals, the so-called major metals, such as sodium, potassium, calcium and magnesium, that occur in greater abundance on earth, including in living organisms, but again this book is not about them. Trace metals have a biological importance in stark contrast to their tiny concentrations in the physical and biological compartments of the world. All are toxic to life above a threshold concentration, a concentration that may still be staggeringly small to our first impressions, for these toxic concentrations often register only on a parts per million scale. And yet, many of these same metals are actually essential to life at doses below this toxic threshold – in the case of selenium, not far below this toxic threshold. Without enough of an essential metal such as zinc, copper or iron, organisms suffer deficiency symptoms and ultimately just cannot survive without a minimum supply. We have not found (if we ever will) an essential role in metabolism, as part of an enzyme or a key biological molecule such as haemoglobin, for the non-essential metals such as lead or mercury, but these metals are still taken up into organisms with the potential to interfere with life's processes. The division into non-essential or essential is not a division into toxic or non-toxic. All trace metals are toxic if present in high enough concentrations, and indeed some essential metals, for example copper, are amongst the most toxic metals known, if present above that toxic threshold.

The biology of trace metals is not a simple story. Life has evolved in the presence of these toxic metals, and indeed life has evolved because of the presence of these metals. Trace metals have a vast range of potential chemical reactions with the likes of proteins and other key molecules in the metabolism of organisms. The resulting chemical associations have provided a fantastic resource for the action of natural selection on the evolution of the biochemistry of life in all its variants. The biochemical basis of our respiration to deliver energy could not exist without the binding of iron to key molecules called cytochromes, nor could many of our enzymes function without the incorporation of a trace metal to play a key catalytic role. And yet, simultaneously there have evolved the systems within organisms to stop these potentially vital, but potentially toxic, metals binding in the wrong place to the wrong protein at the wrong time. We have evolved in a toxic world but have the systems to cope.

So how have different organisms coped with and exploited trace metals in their biology? The answer is wonderfully and diversely, and this book explores many such examples. Why do some animals contain huge concentrations of some trace metals and not others, while even relatively closely related animals have very different metal concentrations in their bodies? Why do oysters and mussels handle zinc so very differently, so that what is a very low zinc concentration in an oyster would be off the scale in a mussel? Why do some hymenopteran insects concentrate zinc in their ovipositors, and some polychaete worms copper in their jaws? Do other worms concentrate arsenic to deter the feeding efforts of would-be fish predators, and does the high vanadium content of the outer surface of some sea squirts stop them being fouled by barnacles and other sessile marine organisms? Why do some oceanic seabirds have fantastic concentrations of toxic metals in their kidneys, even in the absence of metal pollution? In the sea, how do chitons store potentially toxic amounts of iron before its transport to the radula to harden the developing teeth which will be used to rasp the surface of rocks to scrape off the algae growing there?

All such questions have an effect on the natural history of the organisms concerned, and in turn are affected by the natural history of these organisms. To understand the mechanisms controlling the uptake, accumulation and toxicity of trace metals in organisms, it is necessary to understand the role of natural history in these processes. Many specific aspects of the biology of an animal, such as its method of feeding and respiration or burrowing activity, critically affect how an animal interacts with metals. It is crucial to appreciate the importance of natural history in understanding the interaction of metals and organisms.

There is also an applied aspect to such a discussion, given the ability of metals to play such a significant ecotoxicological role in habitats affected by the output of historical activities such as mining or by other modern industrial effluents. How do some organisms cope better than others in streams or estuaries affected by metal-rich mining waste? How do communities change in such circumstances, and so what?

The British Isles offer an ideal template to explore such questions. The countryside and indeed the natural history of Britain are littered with the effects of metals, mostly via historical mining. The tale to be told encompasses history, geography, geology, chemistry, biochemistry, physiology, ecology, ecotoxicology and, above all, natural history.

The book is a natural history voyage from the ancient mines of Britain, usually situated in upland areas, through the catchments of the surrounding terrestrial regions, to streams, rivers, estuaries, coastal waters and the oceans. It is a story of how metals are found in ores, how they have been mined and consequently enter the local environment with consequences for the growth of plants and terrestrial animals associated with those plants, before affecting the life of upland streams by direct runoff or via the metal-rich sediments that are transported into these streams, either deliberately or accidentally. What changes occur to local freshwater communities, and what are the adaptations of those organisms that survive? From stream to river to estuary. Many of the estuaries in Cornwall, for example, are full of metal-rich sediments washed down in the heyday of local copper mining in the second half of the nineteenth century, lying there still and affecting the local biota. Out to sea, there are fewer examples of the metal-associated effects of humankind, but many examples of how marine organisms handle the metals that inevitably enter their bodies naturally and the physiological uses to which they may be put. Finally, oceanic life is still interacting with metals. While there is some entry of anthropogenically derived metals transported in the atmosphere into the ocean, particularly in polar regions, charismatic marine organisms such as whales still have remarkable physiological methods of handling the trace metals that are taken up quite normally from their often metal-rich diets. Similarly, the kidneys of some oceanic seabirds have no right to function given their naturally accumulated huge loads of the poisonous metal cadmium.

Many of the interactions between trace metals and organisms have nothing to do with metal pollution. All organisms are affected, from bacteria, plants and invertebrates to charismatic species such as seals, dolphins, whales and seabirds. All have a tale to tell.

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