

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.

Cambridge University Press
978-1-108-47093-3 — Trace Metals in the Environment and Living Organisms
Philip S. Rainbow
Frontmatter
[More Information](#)

Trace Metals in the Environment and Living Organisms

The British Isles as a Case Study

PHILIP S. RAINBOW

Natural History Museum



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781108470933

DOI: 10.1017/9781108658423

© Cambridge University Press 2018

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2018

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data

Names: Rainbow, P. S., author.

Title: Trace metals in the environment and living organisms : the British isles as a case study / Philip S. Rainbow, Natural History Museum, London.

Description: Cambridge, United Kingdom ; New York, NY : Cambridge University Press, 2018. |

Includes bibliographical references and index.

Identifiers: LCCN 2018017273 | ISBN 9781108470933 (hardback) | ISBN 9781108456869 (paperback)

Subjects: LCSH: Metals--Environmental aspects--British isles.

Classification: LCC QH545.M45 R35 2018 | DDC 572/.51--dc23

LC record available at <https://lcn.loc.gov/2018017273>

ISBN 978-1-108-47093-3 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

CONTENTS

- Preface *page* xiii
 Acknowledgements xvi
- 1 Introduction 1**
- 1.1 Metals 2
 1.2 Metals and Humans 4
 1.3 Sources and Global Cycles of Metals 10
 1.4 Trace Metals and Living Organisms 17
 1.5 Pollution Hazard and Environmental Regulation 21
- 2 Metals and Mining 22**
- 2.1 Introduction 24
 2.2 Geological Origin of Metal Ores 24
 2.3 Ores 27
- 2.3.1 Tin 27
- 2.3.1.1 Cassiterite 27
 2.3.1.2 Stannite 27
- 2.3.2 Copper 27
- 2.3.2.1 Chalcopyrite 27
 2.3.2.2 Chalcocite 27
 2.3.2.3 Malachite 27
 2.3.2.4 Azurite 27
 2.3.2.5 Cuprite 27
 2.3.2.6 Tenorite 27
- 2.3.3 Arsenic 27
- 2.3.3.1 Arsenopyrite 27
- 2.3.4 Lead 28
- 2.3.4.1 Galena 28
 2.3.4.2 Other Lead Ores 28
- 2.3.5 Zinc 28
- 2.3.5.1 Sphalerite 28
 2.3.5.2 Smithsonite, Hemimorphite and Calamine 28
- 2.3.6 Silver 28
- 2.3.6.1 Argentiferous Galena 28
 2.3.6.2 Acanthite 29
- 2.3.7 Iron 29
- 2.3.7.1 Pyrite 29
 2.3.7.2 Other Iron Ores 29
- 2.3.8 Manganese 29
- 2.3.8.1 Pyrolusite 29
- 2.3.9 Tungsten 29
- 2.3.9.1 Wolframite 29
 2.3.9.2 Scheelite 29
- 2.3.10 Antimony 29
- 2.3.10.1 Antimonite, Jamesonite and Bournonite 29
- 2.3.11 Cobalt, Nickel and Molybdenum 29
- 2.3.12 Uranium 30
 2.3.13 Gold 30
 2.3.14 Aluminium 30
- 2.3.14.1 Bauxite 30
- 2.4 Geographical Distribution of Ores and Mining Districts 30
- 2.4.1 Cornwall and Devon 31
 2.4.2 Pennines 31
 2.4.3 Wales 33
 2.4.4 Scotland 33
 2.4.5 Other Mining Regions 34
- 2.5 History of Mining for Metals in the British Isles 34
- 2.5.1 Bronze Age and Iron Age 34
 2.5.2 Roman Britain 35
 2.5.3 The Middle Ages 35
- 2.5.3.1 Pennines 36
 2.5.3.2 Cornwall and Devon 37
 2.5.3.3 Lake District 39
 2.5.3.4 Scotland and Wales 39
 2.5.3.5 Iron 39
- 2.5.4 Sixteenth and Seventeenth Centuries 40
- 2.5.4.1 Lake District 40
 2.5.4.2 Cornwall and Devon 41
 2.5.4.3 Pennines 42
 2.5.4.4 Scotland 42
 2.5.4.5 North Wales, Staffordshire and the Mendips 43
 2.5.4.6 Iron 43

2.5.5 Eighteenth and Nineteenth Centuries	44	3.7 Biomarkers	115
2.5.5.1 Cornwall and Devon	45	3.7.1 Community Effects	120
2.5.5.2 Pennines	53	3.8 Tolerance	121
2.5.5.3 Wales	55		
2.5.5.4 Scotland	57	4 Terrestrial Environment	124
2.5.5.5 Lake District	58	4.1 Introduction	128
2.5.5.6 Shropshire, Staffordshire and Somerset	59	4.2 Metal Concentrations in Soils	135
2.5.5.7 Isle of Man	60	4.2.1 Mining Sites	135
2.5.5.8 Ireland	60	4.2.2 Smelter and Refinery Sites	139
2.5.5.9 Iron	61	4.2.3 Smelter and Refinery Emissions	139
2.5.6 Twentieth Century Forward	62	4.2.4 Other Anthropogenic Input into Soils	140
2.5.6.1 Cornwall and Devon	63	4.2.5 Bioavailability of Trace Metals in Soils	140
2.5.6.2 Pennines	65	4.2.6 Bioaccessibility	144
2.5.6.3 Lake District	65	4.2.7 Trace Metals and Soil Types	145
2.5.6.4 Wales	65	4.2.7.1 Calcicoles and Calcifuges	145
2.5.6.5 Scotland	66	4.2.7.2 Aluminium and Laterites	147
2.5.6.6 Ireland	66	4.2.7.3 Serpentine Group of Soils	147
2.5.6.7 Aluminium Smelting	66	4.3 Microbial Community	148
2.5.6.8 Avonmouth	66	4.4 Lichens	151
2.5.7 Conclusions	67	4.4.1 Metallophytic Lichen Assemblages	152
		4.4.2 Detoxification of Trace Metals	155
3 Biology of Trace Metals	68	4.5 Mosses and Ferns	156
3.1 Introduction	74	4.5.1 Mosses	156
3.2 Evolution and Trace Metals	75	4.5.2 Ferns	158
3.3 Uptake of Trace Metals	76	4.6 Flowering Plants	158
3.4 Bioavailability	79	4.6.1 Uptake, Accumulation and Detoxification	158
3.4.1 Dissolved Bioavailability	80	4.6.2 Metallophytes	160
3.4.2 Effects of Physiology	83	4.6.3 Accumulation from Metal-Contaminated Soils	162
3.4.3 Bioavailability from Food	85	4.6.3.1 Mining Sites	162
3.4.4 Uptake from Sediments	89	4.6.3.2 Smelter Emissions	164
3.5 Accumulation	90	4.6.3.3 Roadside Lead	166
3.5.1 Metabolic Requirements for Essential Trace Metals	94	4.6.4 Hyperaccumulation	167
3.5.2 Detoxification	95	4.6.5 Metal tolerance	172
3.5.3 Accumulation, Detoxification and Toxicity	98	4.6.5.1 Occurrence of Tolerant Populations	172
3.5.4 Accumulation Patterns	99	4.6.5.2 Evolution of Tolerance	173
3.5.5 Biodynamic Modelling	104	4.6.5.3 Mechanisms of Tolerance	175
3.5.6 Food Chains and Trace Metals	106	4.6.6 Aluminium	176
3.5.7 Significance of Bioaccumulated Trace Metal Concentrations	108		
3.6 Biomonitors	111		

4.7 Invertebrate Herbivores	177	4.12.1 Avonmouth Smelter	244
4.7.1 Slugs and Snails	177	4.12.2 Merseyside Smelter	248
4.7.1.1 Detoxification	178	4.12.3 Spoil Tips	250
4.7.1.2 Biomonitoring	180	4.12.3.1 Northern Pennine Lead	
4.7.2 Insect Herbivores	181	Mines	250
4.8 Invertebrate Detritivores	183	4.12.3.2 Tamar Valley	251
4.8.1 Earthworms	184	4.12.4 Sewage Sludge Application	254
4.8.1.1 Trace Metal		4.12.5 Hyperaccumulation: Ecological	
Accumulation	186	Effects	258
4.8.1.2 Detoxification of Trace		4.12.6 Ecotoxicological Risk	
Metals	190	Assessment	259
4.8.1.3 Ecotoxicology: Tolerance and		4.12.6.1 Chemical Criteria	259
Resistance	191	4.12.6.2 Biological Criteria	265
4.8.2 Woodlice	193	4.13 Livestock	270
4.8.2.1 Trace Metal Accumulation	193	4.13.1 Ecotoxicology	270
4.8.2.2 Detoxification	195	4.13.1.1 History	270
4.8.2.3 Ecotoxicology	198	4.13.1.2 Critical Soil	
4.8.3 Collembolans	199	Concentrations	272
4.8.4 Millipedes	200	4.13.2 Deficiency	273
4.9 Invertebrate Predators	202	4.14 Human Health	275
4.9.1 Spiders	203	4.14.1 Risk to Human Health	275
4.9.2 Pseudoscorpions	206	4.14.1.1 Environmental Geochemistry	
4.9.3 Centipedes	206	and Human Health	275
4.9.4 Beetles	206	4.14.1.2 Food	276
4.9.5 Parasitoid Wasps	208	4.14.1.3 Drinking Water	279
4.10 Mammals	209	4.14.1.4 Soil	279
4.10.1 Small Mammals	209	4.14.1.5 Dust	280
4.10.1.1 Kidneys	210	4.14.1.6 Soil Guideline Values	283
4.10.1.2 Livers	219	5 Freshwater	286
4.10.1.3 Whole Bodies	220	5.1 Introduction	289
4.10.1.4 Hair	221	5.1.1 Biology of Trace Metals in	
4.10.1.5 Ecotoxicology	222	Freshwater	290
4.10.2 Bats	225	5.2 Metal Concentrations in	
4.11 Birds	225	Freshwater	292
4.11.1 Birds of Prey	226	5.3 Metal Concentrations in Freshwater	
4.11.2 London Pigeons	230	Sediments	293
4.11.3 Pheasants, Partridges and Lead		5.4 Metal-Contaminated Freshwater	
Shot	234	Systems	295
4.11.4 Biomonitoring and		5.4.1 Southwest England	299
Ecotoxicology	234	5.4.1.1 River Carnon	299
4.11.4.1 Feathers	234	5.4.1.2 River Hayle	304
4.11.4.2 Blood	239	5.4.1.3 Red River	305
4.11.4.3 Eggs	241	5.4.1.4 River Gannel	305
4.12 Environmental Effects: Community		5.4.1.5 River Tamar	306
Ecotoxicology	243		

5.4.2	Wales	306	5.11.1.3	Lake District	327
5.4.2.1	Afon Goch	306	5.11.2	Accumulation and Biomonitoring	328
5.4.2.2	Rivers Ystwyth and Rheidol	307	5.12	Flowering Plants	334
5.4.2.3	River Conwy	308	5.13	Invertebrates	334
5.4.3	Northern Pennines	309	5.13.1	Stoneflies	344
5.4.3.1	River Nent	310	5.13.2	Mayflies	348
5.4.3.2	River West Allen	310	5.13.3	Caddisflies	352
5.4.3.3	River Derwent	310	5.13.4	Chironomid Midges	358
5.4.4	Derbyshire	311	5.13.5	Further Insects	360
5.4.4.1	River Ecclesbourne	311	5.13.5.1	Blackflies	360
5.4.5	Lake District	311	5.13.5.2	Craneflies	360
5.4.5.1	Threlkeld, Keswick	311	5.13.5.3	Dagger Flies	361
5.4.6	Scotland	312	5.13.5.4	Alderflies	361
5.4.6.1	Leadhills	312	5.13.5.5	Dragonflies	361
5.4.6.2	Tyndrum	312	5.13.5.6	Beetles	361
5.4.7	Isle of Man	312	5.13.6	Crustaceans	362
5.5	Concentration and Bioavailability	313	5.13.6.1	Amphipods	362
5.5.1	Dissolved Bioavailability	313	5.13.6.2	Isopods	362
5.5.2	Sediment Bioavailability	314	5.13.7	Oligochaetes	365
5.6	Acid Mine Drainage	315	5.13.8	Molluscs	366
5.7	Iron-Rich Streams	317	5.13.8.1	Gastropods	366
5.8	Aluminium	318	5.13.8.2	Bivalves	367
5.9	Microscopic Life	319	5.14	Fish	369
5.9.1	Bacteria	320	5.14.1	History of Fish in Metal-Contaminated River Systems	370
5.9.2	Periphyton	320	5.14.2	Accumulation	372
5.9.2.1	Diatoms	320	5.14.2.1	Metals in the Flesh of Freshwater Fish	377
5.9.3	Meiofauna	322	5.15	Birds	378
5.10	Algae	323	5.15.1	Mercury	379
5.10.1	Blue-Green Bacteria	323	5.15.2	Cadmium	380
5.10.2	Green Algae	323	5.15.3	Lead	381
5.10.2.1	Mid-Wales	324	5.15.3.1	Lead Shot	382
5.10.2.2	Northern Pennines	324	5.16	Mammals	384
5.10.2.3	Cornwall	325	5.17	Community Ecotoxicology	386
5.10.3	Red Algae	325	5.17.1	Metal-Resistant Species	387
5.10.4	Golden-Brown Algae	325	5.17.2	Community Analysis and Biotic Indices	388
5.10.5	Accumulation and Detoxification in Algae	326	5.17.3	Biomonitoring, Bioaccumulated Metal Guidelines and Ecotoxicological Effects	390
5.11	Bryophytes	326			
5.11.1	Mining-Affected Streams and Rivers	326			
5.11.1.1	Mid-Wales	326			
5.11.1.2	Northern Pennines	327			

5.17.3.1 Is There an Easier Way? 390	6.8.2 <i>Arenicola marina</i> : The Lugworm 452
5.17.4 Biomarkers 391	6.9 Deposit-Feeding Bivalves 455
5.17.5 Tolerance 393	6.9.1 <i>Scrobicularia plana</i> : The Peppery Furrow Shell 455
5.17.6 Water Framework Directive 394	6.9.2 <i>Macoma balthica</i> : The Baltic Tellin 461
5.17.6.1 Environmental Quality Standards 395	6.10 Deposit-Feeding Amphipod Crustaceans 464
5.17.7 Weight of Evidence (WOE) 398	6.10.1 <i>Corophium volutator</i> 464
5.18 Human Health 399	6.11 Suspension Feeders 465
6 Estuaries 401	6.11.1 Mussels 465
6.1 Introduction 403	6.11.1.1 Biomonitoring 466
6.2 Metal Concentrations in the Waters of Estuaries 404	6.11.1.2 Bioaccumulation and detoxification 471
6.2.1 Speciation and Bioavailability 409	6.11.1.3 Ecotoxicology 473
6.3 Metal Concentrations in Estuarine Sediments 411	6.11.2 Oysters 474
6.3.1 Bioavailability of Sediment-Associated Metals 417	6.11.2.1 Accumulation and detoxification 474
6.3.2 Organometals in Estuarine Sediments 419	6.11.2.2 Ecotoxicology 479
6.4 Trace Metals in Selected British Estuaries 420	6.11.3 Cockles 480
6.4.1 Restronguet Creek 421	6.11.4 Clams 484
6.4.2 Hayle 423	6.11.5 Scallops 484
6.4.3 Gannel 423	6.11.6 Importance of Family 486
6.4.4 Looe 424	6.11.7 Slipper Limpets 492
6.4.5 Tamar and Tavy 424	6.11.8 Barnacles 494
6.4.6 Dulas Bay 425	6.11.8.1 Accumulation and Detoxification 495
6.4.7 Thames 426	6.12 Grazing Gastropods 499
6.4.8 Severn 428	6.12.1 Periwinkles 499
6.4.9 Mersey 430	6.12.1.1 Detoxification of Accumulated Trace Metals 504
6.4.10 Humber 432	6.12.1.2 Tolerance and Ecotoxicology 506
6.4.11 South Wales 434	6.12.2 Limpets 506
6.4.12 Poole Harbour 435	6.12.2.1 Limpets as Biomonitors 507
6.5 Salt Marshes and Seagrasses 436	6.13 Detritivores in the Strandline 510
6.6 Seaweeds 436	6.13.1 Talitrid Amphipod Crustaceans 510
6.7 Meiofauna 441	6.13.1.1 Body Concentrations of Trace Metals 511
6.8 Deposit-Feeding Polychaetes: Ragworms and Lugworms 442	6.13.1.2 Talitrids as Trace Metal Biomonitors 512
6.8.1 <i>Hediste diversicolor</i> : A Ragworm 442	6.14 Predators 515
6.8.1.1 Bioaccumulation 443	
6.8.1.2 Biomonitoring 444	
6.8.1.3 Tolerance and Ecotoxicology 451	

x Table of Contents

6.14.1	Polychaete Worms	515	7.2.1	Coastal Waters	569
6.14.1.1	Catworms	516	7.2.2	Ocean Profiles	571
6.14.1.2	Glycerids	517	7.3	Plankton	573
6.14.2	Whelks	517	7.3.1	Phytoplankton	573
6.14.2.1	Dogwhelks	519	7.3.1.1	Trace Metal Uptake and Accumulation	574
6.14.2.2	Other Neogastropods	523	7.3.1.2	Adaptations of Oceanic Phytoplankton	576
6.14.3	Prawns and Shrimps	523	7.3.1.3	Deficiency and Toxicity	577
6.14.3.1	Accumulation and Regulation	523	7.3.2	Zooplankton	578
6.14.3.2	Copper	526	7.3.2.1	Calanoid Copepods	578
6.14.3.3	Cadmium and Lead	527	7.4	Pelagic Animals	581
6.14.3.4	Chromium	527	7.4.1	Krill	582
6.14.4	Crabs	527	7.4.2	Deep Sea Decapods and Copper Deficiency	584
6.14.4.1	Copper	528	7.4.3	Cadmium and Oceanic Invertebrates	587
6.14.4.2	Zinc	531	7.4.3.1	Hyperiid Amphipods	587
6.14.4.3	Cadmium and Lead	532	7.4.3.2	Squid	588
6.14.4.4	Detoxification	532	7.4.3.3	Ocean Striders	589
6.14.4.5	Ecotoxicology	533	7.4.4	Zinc-Tipped Arrow Worms	589
6.14.5	Fish	533	7.5	Horn-Headed Amphipods and a Dietary Iron Challenge	590
6.14.5.1	Flounder	533	7.5.1	<i>Stegocephaloides christianiensis</i>	590
6.14.5.2	Eelpout	535	7.5.2	<i>Parandania boeckii</i>	591
6.14.5.3	Eels	536	7.6	Sea Squirts and Vanadium	592
6.15	Wading Birds	537	7.7	Polychaetes and Predator Deterrence	595
6.15.1	Trace Metals in Waders	538	7.7.1	Fan Worms	595
6.16	Community Effects	540	7.7.1.2	Arsenic	596
6.16.1	Case Studies	541	7.7.1.3	Vanadium	597
6.16.2	Weight of Evidence	543	7.7.2	Copper in <i>Melinna palmata</i>	598
6.16.2.1	Biomonitors	544	7.8	Sediments	599
6.16.2.2	Environmental Quality Standards	545	7.8.1	Sediment Metal Concentrations	599
6.16.2.3	Biomarkers	547	7.8.2	Dump Sites	599
6.16.2.4	Tolerance	550	7.8.2.1	Firth of Clyde	603
6.16.2.5	Toxicity Tests	550	7.8.2.2	Liverpool Bay	604
6.16.2.6	Community Structure	552	7.8.2.3	Outer Thames	606
6.17	Fouling and Antifouling	553	7.8.2.4	Other dump sites	607
6.17.1	Resistance, Invasive Fouling Species and Tolerance	556	7.8.3	Hypoxia, Manganese and Scampi	608
6.17.2	Tributyl Tin	559	7.9	Fish	609
6.17.2.1	Imposex and Dogwhelks	560	7.9.1	Trace Metals in Fish	610
7	Coastal Seas and Oceans	565	7.10	Seafood	614
7.1	Introduction	568	7.10.1	Fish	616
7.2	Metal Concentrations in Coastal and Oceanic Waters	569	7.10.2	Crabs, Lobsters and Shrimps	618

7.10.3 Molluscs	622
7.10.3.1 Whelks	622
7.10.3.2 Scallops	622
7.10.3.3 Cockles and mussels	624
7.10.3.4 Oysters	625
7.11 Seabirds	626
7.11.1 Trace Metal Accumulation in Seabirds	627
7.11.1.1 Cadmium	630
7.11.1.2 Mercury	632
7.11.1.3 Ecotoxicology	637
7.12 Marine Mammals	639
7.12.1 Trace Metals and Marine Mammals	645
7.12.1.1 Copper and Zinc	646
7.12.1.2 Cadmium	646
7.12.1.3 Lead	646
7.12.1.4 Mercury	647
7.12.1.5 Organotin	648
7.12.1.6 Ecotoxicology	649

8 Epilogue 655

8.1 Biology of Trace Metals	655
8.2 Effects of Trace Metals and the Natural History of the British Isles	657
8.2.1 Past	658
8.2.2 Present	659
8.2.2.1 TBT and Antifouling	660
8.2.2.2 Mercury in Tuna	661
8.2.3 Future	662
8.2.3.1 Rehabilitation and Restoration	662
8.2.3.2 Conservation	666
8.2.3.3 Climate Change and Seawater Acidification	667
8.2.3.4 Ecotoxicology	668
8.3 Postscript	669

References 671

Index 720

Colour plates can be found between pages 368 and 369

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.

ACKNOWLEDGEMENTS

I have relied on the help, collaboration and friendship of many people over many years in order to arrive at a position to undertake the writing of this book. First and foremost, my very good friend Sam Luoma, who was my co-author on a tome on metal contamination in aquatic environments, has been an outstanding guide and colleague, as we have worked together to stress the role of biology in the chemistry-dominated world of metal ecotoxicology, and indeed put more 'eco' into 'ecotoxicology'. Claude Amiard-Triquet and Jean-Claude Amiard have similarly influenced my knowledge and thinking considerably, in our happy and productive research collaborations in the worlds of metal ecophysiology and ecotoxicology since the turn of the millennium. Wen-Xiong Wang has been another strong collaborator and friend, generous with his time and resources, as we have exploited the natural laboratory that is the coastal region of Hong Kong as a source of metal-related environmental questions. Over a longer period stretching further back in time, I have learnt so much marine biology from my great friend Geoff Moore. Bill Langston is a continuing source of good sense on the biology of trace metals, and the sadly now late Dave Phillips was a forceful and appreciated collaborator on research projects and a book on biomonitoring in the 1990s. I also owe debts of gratitude to Stephen White, Jason Weeks, Dayanthi Nuggeoda, Paul O'Brien, Darren Martin, Michael Depledge, Carmen Casado-Martinez, Wojciech Fialkowski, Farhan Khan, Judit Kalman and Islay Marsden for their productive research collaboration over many years. I would have achieved little without the support of Brian Smith over the last twenty years, and I gratefully acknowledge his considerable contribution.

It is a pleasure to thank Christopher Rainbow for the use of his colour photographs, and for his time and patience in their acquisition. I am also grateful to the Natural History Museum for permission to include colour photographs under their copyright. I thank Harry Taylor for these beautiful illustrations. My thanks too to Kevin Brix and Charlie Arneson for their kind permission to use their photographs. Mike Rumsey, Hölger Thues, Jeff Duckett and Emma Sherlock of the Natural History Museum provided much appreciated guidance through the worlds of ores, lichens, bryophytes and earthworms respectively. William Yeomans is to be thanked for his interest in the black-tailed trout of Leadhills, which he brought to my attention. Paul Henderson kindly read draft chapters for me, but remaining errors are down to me.

Arguably, this book is a culmination of research experience over a career of forty years. All would have been impossible without the love and support of my family, particularly my wife Mary. I am forever in her debt.