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Pim de Voogt *Editor*

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Editor
Pim de Voogt

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Foreword

International concern in scientific, industrial, and governmental communities over traces of xenobiotics in foods and in both abiotic and biotic environments has justified the present triumvirate of specialized publications in this field: comprehensive reviews, rapidly published research papers and progress reports, and archival documentations These three international publications are integrated and scheduled to provide the coherency essential for nonduplicative and current progress in a field as dynamic and complex as environmental contamination and toxicology. This series is reserved exclusively for the diversified literature on "toxic" chemicals in our food, our feeds, our homes, recreational and working surroundings, our domestic animals, our wildlife, and ourselves. Tremendous efforts worldwide have been mobilized to evaluate the nature, presence, magnitude, fate, and toxicology of the chemicals loosed upon the Earth. Among the sequelae of this broad new emphasis is an undeniable need for an articulated set of authoritative publications, where one can find the latest important world literature produced by these emerging areas of science together with documentation of pertinent ancillary legislation.

Research directors and legislative or administrative advisers do not have the time to scan the escalating number of technical publications that may contain articles important to current responsibility. Rather, these individuals need the background provided by detailed reviews and the assurance that the latest information is made available to them, all with minimal literature searching. Similarly, the scientist assigned or attracted to a new problem is required to glean all literature pertinent to the task, to publish new developments or important new experimental details quickly, to inform others of findings that might alter their own efforts, and eventually to publish all his/her supporting data and conclusions for archival purposes.

In the fields of environmental contamination and toxicology, the sum of these concerns and responsibilities is decisively addressed by the uniform, encompassing, and timely publication format of the Springer triumvirate:

Reviews of Environmental Contamination and Toxicology [Vol. 1 through 97 (1962–1986) as Residue Reviews] for detailed review articles concerned with any aspects of chemical contaminants, including pesticides, in the total environment with toxicological considerations and consequences.

Bulletin of Environmental Contamination and Toxicology (Vol. 1 in 1966) for rapid publication of short reports of significant advances and discoveries in the fields of air, soil, water, and food contamination and pollution as well as methodology and other disciplines concerned with the introduction, presence, and effects of toxicants in the total environment.

Archives of Environmental Contamination and Toxicology (Vol. 1 in 1973) for important complete articles emphasizing and describing original experimental or theoretical research work pertaining to the scientific aspects of chemical contaminants in the environment.

The individual editors of these three publications comprise the joint Coordinating Board of Editors with referral within the board of manuscripts submitted to one publication but deemed by major emphasis or length more suitable for one of the others.

Coordinating Board of Editors

Preface

The role of *Reviews* is to publish detailed scientific review articles on all aspects of environmental contamination and associated (eco)toxicological consequences. Such articles facilitate the often complex task of accessing and interpreting cogent scientific data within the confines of one or more closely related research fields.

In the 50+ years since *Reviews of Environmental Contamination and Toxicology* (formerly *Residue Reviews)* was first published, the number, scope, and complexity of environmental pollution incidents have grown unabated. During this entire period, the emphasis has been on publishing articles that address the presence and toxicity of environmental contaminants. New research is published each year on a myriad of environmental pollution issues facing people worldwide. This fact, and the routine discovery and reporting of emerging contaminants and new environmental contamination cases, creates an increasingly important function for *Reviews.* The staggering volume of scientific literature demands remedy by which data can be synthesized and made available to readers in an abridged form. *Reviews* addresses this need and provides detailed reviews worldwide to key scientists and science or policy administrators, whether employed by government, universities, nongovernmental organizations, or the private sector.

There is a panoply of environmental issues and concerns on which many scientists have focused their research in past years. The scope of this list is quite broad, encompassing environmental events globally that affect marine and terrestrial ecosystems; biotic and abiotic environments; impacts on plants, humans, and wildlife; and pollutants, both chemical and radioactive; as well as the ravages of environmental disease in virtually all environmental media (soil, water, air). New or enhanced safety and environmental concerns have emerged in the last decade to be added to incidents covered by the media, studied by scientists, and addressed by governmental and private institutions. Among these are events so striking that they are creating a paradigm shift. Two in particular are at the center of ever increasing media as well as scientific attention: bioterrorism and global warming. Unfortunately, these very worrisome issues are now superimposed on the already extensive list of ongoing environmental challenges.

The ultimate role of publishing scientific environmental research is to enhance understanding of the environment in ways that allow the public to be better informed or, in other words, to enable the public to have access to sufficient information. Because the public gets most of its information on science and technology from internet, TV news, and reports, the role for scientists as interpreters and brokers of scientific information to the public will grow rather than diminish. Environmentalism is an important global political force, resulting in the emergence of multinational consortia to control pollution and the evolution of the environmental ethic. Will the new politics of the twenty-first century involve a consortium of technologists and environmentalists, or a progressive confrontation? These matters are of genuine concern to governmental agencies and legislative bodies around the world.

For those who make the decisions about how our planet is managed, there is an ongoing need for continual surveillance and intelligent controls to avoid endangering the environment, public health, and wildlife. Ensuring safety-in-use of the many chemicals involved in our highly industrialized culture is a dynamic challenge, because the old, established materials are continually being displaced by newly developed molecules more acceptable to federal and state regulatory agencies, public health officials, and environmentalists. New legislation that will deal in an appropriate manner with this challenge is currently in the making or has been implemented recently, such as the REACH legislation in Europe. These regulations demand scientifically sound and documented dossiers on new chemicals.

Reviews publishes synoptic articles designed to treat the presence, fate, and, if possible, the safety of xenobiotics in any segment of the environment. These reviews can be either general or specific, but properly lie in the domains of analytical chemistry and its methodology, biochemistry, human and animal medicine, legislation, pharmacology, physiology, (eco)toxicology, and regulation. Certain affairs in food technology concerned specifically with pesticide and other food-additive problems may also be appropriate.

Because manuscripts are published in the order in which they are received in final form, it may seem that some important aspects have been neglected at times. However, these apparent omissions are recognized, and pertinent manuscripts are likely in preparation or planned. The field is so very large and the interests in it are so varied that the editor and the editorial board earnestly solicit authors and suggestions of underrepresented topics to make this international book series yet more useful and worthwhile.

Justification for the preparation of any review for this book series is that it deals with some aspect of the many real problems arising from the presence of anthropogenic chemicals in our surroundings. Thus, manuscripts may encompass case studies from any country. Additionally, chemical contamination in any manner of air, water, soil, or plant or animal life is within these objectives and their scope.

Manuscripts are often contributed by invitation. However, nominations for new topics or topics in areas that are rapidly advancing are welcome. Preliminary communication with the Editor-in-Chief is recommended before volunteered review manuscripts are submitted. *Reviews* is registered in WebofScience™. Inclusion in the Science Citation Index serves to encourage scientists in academia to contribute to the series. The impact factor in recent years has increased from 2.5 in 2009 to 7.0 in 2017. The Editor-in-Chief and the Editorial Board strive for a further increase of the journal impact factor by actively inviting authors to submit manuscripts.

Amsterdam, The Netherlands Pim de Voogt
February 2020

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Metalliferous Mining Pollution and Its Impact on Terrestrial and Semi-terrestrial Vertebrates: A Review

Esperanza Gil-Jiménez, Manuela de Lucas, and Miguel Ferrer

Contents

Abstract Metalliferous mining, a major source of metals and metalloids, has severe potential environmental impacts. However, the number of papers published in international peer-reviewed journals seems to be low regarding its effects in terrestrial wildlife. To the best of our knowledge, our review is the first on this topic. We used 186 studies published in scientific journals concerning metalliferous mining or mining spill pollution and their effects on terrestrial and semi-terrestrial vertebrates. We identified the working status of the mine complexes studied, the different biomarkers of exposure and effect used, and the studied taxa. Most studies (128) were developed in former mine sites and 46 in active mining areas. Additionally, although several mining accidents have occurred throughout the world, all papers about effects on terrestrial vertebrates from mining spillages were from Aznalcóllar

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(Spain). We also observed a lack of studies in some countries with a prominent mining industry. Despite >50% of the studies used some biomarker of effect, 42% of them only assessed exposure by measuring metal content in internal tissues or by non-invasive sampling, without considering the effect in their populations. Most studied species were birds and small mammals, with a negligible representation of reptiles and amphibians. The information gathered in this review could be helpful for future studies and protocols on the topic and it facilitates a database with valuable information on risk assessment of metalliferous mining pollution.

Keywords Biomarker · Metals · Mine site · Mining spill · Risk assessment · Sentinel species · Trace elements · Wildlife

1 Introduction

Historically, human activities have caused diverse effects on ecosystems, contaminating both their abiotic components and organisms (Nriagu and Pacyna 1988; Rattner 2009). Agriculture, industry, smelting, and metallic and non-metallic mining are among the major sources of metals in the environment (Sharma and Agrawal 2005; van Ooik et al. 2008). Particularly, mining is an important source of metals and metalloids with severe potential environmental impacts (UNEP 2000; Pereira et al. 2006; Satta et al. 2012), posing a risk to wildlife inhabiting, breeding, or feeding in the surrounding zones (Baos et al. 2006c; Berglund et al. 2011). Mining industry has cohabited with humans for thousands of years (Nocete et al. 2005), but between 1930 and 1985 the production of several elements increased between 2- and 35-fold (Nriagu and Pacyna 1988). Nowadays, it is estimated that there are over 30,000 mines around the world, of which over a third are currently being explored, developed, or mined (IRP 2020). In addition, the output of the global metal production in 2017 was about two billion tons (Reichl and Schatz 2019). Within mining industry, metalliferous mining comprehends the extraction and processing of metals and metalloids (referred to hereafter as metals or elements) by different methods. These processes have significantly increased the levels and bioavailability of naturally occurring elements in environmental compartments (Pereira et al. 2006; Sánchez-Chardi et al. 2007a). Some of them are physiologically essential elements, e.g. zinc (Zn), iron (Fe), or copper (Cu), which can cause pathological conditions when in deficiency, but in excess can have toxic effects (Damek-Poprawa and Sawicka-Kapusta 2003). Other elements, such as arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb), are naturally occurring in the environment but toxic for the organisms even at low levels (Drouhot et al. 2014; Camizuli et al. 2018). Thus, when they enter the food chain, they can accumulate and be hazardous for wildlife and even for humans inhabiting the surrounding area (Pereira et al. 2006; Sánchez-Chardi et al. 2009; Alvarenga et al. 2014).

Besides the fact that this kind of contamination persists for hundreds of years (Younger et al. 2002), dispersion of metal particles occurs not only during the lifetime of the mine, but also after being closed or abandoned. Mining waste is produced in all stages of mining and processing operations, with the amount of solid waste produced representing 90% or more of the material mined (Gutiérrez et al. 2016). In the past, after ceasing mining activity, many mine sites were completely abandoned and their mine tailings were left at open air without any treatment, posing several threats to the environment (Laurinolli and Bendell-Young 1996; Satta et al. 2012). These abandoned mine lands, also known as "derelict" or "orphan" mines, are referred to as "areas or sites of former mining activity for which no single individual, company or organization can be held responsible" (Venkateswarlu et al. 2016). The worldwide estimated number of abandoned mine lands is more than one million. Thus, derelict mines are nowadays considered one of the major contributors of severe degradation of the environment (Venkateswarlu et al. 2016) and abandoned wastes are among the worst environmental problems and hazard to ecosystems and human health (Gutiérrez et al. 2016). Regarding modern operational mines and their wastes, nowadays there exists a stricter legislation about mining pollution, remediation, and restoration of mining areas in many countries. However, mining is one of the main economic activities in several developing countries such as Colombia, Zimbabwe, Brazil, Ghana, or Zambia, where the environmental legislation is still scarce (Ikenaka et al. 2012; Deikumah et al. 2014).

Generally, organisms living in and around mining areas are continuously exposed to high levels of metals. Besides this chronic exposure, acute episodes such as accidental spills are of major concern because of the consequences they may have on wildlife (Grimalt et al. 1999; Baos et al. 2006c). Mining ore processing, lead smelting, and artisanal small-scale gold mining ranked the 2nd, 3rd, and 5th, respectively, among the worst polluting industries according to Green Cross Switzerland and Pure Earth (2016). In addition, the Agency for Toxic Substances and Disease Registry (ATSDR 2019) placed As, Pb, and Hg in the 1st, 2nd, and 3rd position in their Substance Priority List. Although this list is not a list of "most toxic" substances, it highlights their hazard. It is important to consider that, although a high number of laboratory experiments link metals with adverse health effects in animals, they do not reflect the variability of natural ecosystems, and therefore field studies are essential too (Damek-Poprawa and Sawicka-Kapusta 2004; Vanparys et al. 2008). There are many studies on how metals, resulting from several activities, accumulate and affect plants (DalCorso 2012) and animals (Rattner 2009). On the one hand, the latter author states that wildlife toxicology has been shaped by chemical use and misuse, ecological mishaps, catastrophic human poisonings, and research in the allied field of human toxicology. On the other hand, Mateo et al. (2016) stated that the motivation of researchers to work in wildlife ecotoxicology has largely related to the conservation of higher vertebrates, and by seeking to identify health risks in vertebrates that are closely related to us, potential hazards to humans are sometimes also highlighted. Either way, assessment of both ecosystem and human health are closely related. Because of that, it is necessary to highlight the use of certain wild animals as *sentinel species*, defined as an "animal system to identify potential health hazards to other animals or humans" (Basu et al. 2007). Thus, many studies developed in polluted areas, including mining sites, have used sentinel species for human and environmental health risk assessment (Custer 2011; Gómez-Ramírez et al. 2014; Mateo et al. 2016; Rodríguez-Estival et al. 2020). The multiple negative effects of exposure to metals on animal and human health are well known (Tchounwou et al. 2012; Mateo et al. 2016), and they have been assessed through different approaches. Historically pollution monitoring was based exclusively on chemical analyses of water, soil, sediments, or tissue samples. Nowadays, studies usually not only focus on the level of exposure or tissues levels, but also go one step beyond and make use of biomarkers of effect to assess the repercussions of these contaminants on the organisms (Kakkar and Jaffery 2005; Baos et al. 2006c; Mussali-Galante et al. 2013b). Thus, a *biomarker of exposure* is considered to be the detection of a contaminant itself or its metabolites, whereas a *biomarker of effect* is the alteration of a biochemical or physiological parameter associated with contaminant exposure (Chaousis et al. 2018). But this definition of biomarker of effect should be extended not only to the individual level, but also to effects that can be deleterious at population or ecosystem levels, such as reproductive parameters (Berglund et al. 2010; Mussali-Galante et al. 2013b).

The purpose of the present review is to analyze and synthesize the existing literature on metal pollution produced specifically by metalliferous and non-radioactive mining activities or problems derived from them, such as spillages, which affect semi-terrestrial and terrestrial vertebrates. Thus, we have focused on the temporal and worldwide distribution of these mining studies and their working status, on the different effects found according to different biomarkers and on an overview of studied taxa. There are several scientific papers about aquatic ecosystems and/or plants, but studies focused on mine products and terrestrial or semi-terrestrial animals are not as large as expected according to the high number of mines and the riskiness of this pollution on terrestrial ecosystems. To the best of our knowledge, the present study is the first review regarding effects of metalliferous mining activity on semi-terrestrial and terrestrial animals. The compilation of all scientific studies available on this topic is important to highlight the gaps and unevenness that exist in these studies. But also to establish a starting point on what is necessary to be done in the future, both scientifically and in the application of this scientific knowledge in mining industry, including regulation, policy, and decision making.

2 Methodology

We searched in Web of Science and Google Scholar for articles published or available online until the end of 2019. We used different keywords and combination of terms, such as "mining," "mine," "heavy metal," "trace element," "wildlife," "animals," "contamination," or "mining spill," and then we also checked for subsequent references as well as authors bibliographies. From our preliminary search of published literature, we identified all relevant peer-reviewed papers reporting metalliferous mining or mining spill contamination in terrestrial and semi-terrestrial vertebrates. We included waterfowl as semi-terrestrial vertebrates because they are also related to terrestrial ecosystem and are usually present at mining sites. We excluded those studies focused exclusively on metallurgical processing (e.g., only reporting smelter pollution without mineral extraction); with other pollution sources (e.g., coal mines or marble and stone quarries) or no clear specification of the source; with different pollutants like cyanide; or those studying plants or aquatic species. Our final set for assessment included 186 studies that met the criteria specified. Then, we organized the information identifying the specific source of contamination (closed or abandoned mine, active mine, spillage), the main metal(s) extracted, the year of publication, the studied species and the biomarkers utilized (exposure or effects) (Table 1). Also, when a study assessed metal pollution from different sources, we focus only on our source of interest. Some of the articles studied more than one species or included data from mines before and after being closed. All data and their references are included in Supplemental Data (Annex 1).

3 Results and Discussion

3.1 Geographical and Temporary Distribution and Operational Status

Studies were classified according to the operational status of the mine at the time when research was performed, classifying them in three main categories: closed or abandoned mines (both terms were used interchangeably in the present review), operational mines, and mining spillages. These studies were distributed over 24 countries, and they were not equally distributed worldwide for any of the groups (Figs. 1 and 2).

The temporal trend of scientific research on pollution by metalliferous mining in terrestrial and semi-terrestrial vertebrates (Fig. 3) showed an increment in the number of papers per year in the last 20 years. Particularly, between 1999 and 2009, the increase in the number of publications related to mining spillages, due to the Aznalcóllar accident (later discussed) is noteworthy. The general trend is in line with that found in scientific research on the use of bioindicators (Burger 2006) and on metal and metalloid pollution studies on wildlife in Latin America (Di Marzio et al. 2019).

Regarding abandoned or closed mines, more than half of studies about metalliferous mining pollution were related with them. 111 of 186 (60%) studies assessed pollution exclusively from former mines, 16 studies were both at a former mine and an active mine (most of them in big mining complexes), and one was developed both in an old mine and a spillage site. In total, 128 studies included an old mine site. Ten of these studies were carried out in closed mines which had undergone partially or

Table 1 Species used in the studies

Species	N	Metal ore	Biomarker	Country (continent)	Mine status	Reference
AVES						
Accipitriformes (9 species)						
Black kite (*Milvus migrans*)	5	Pb/Zn/Cu	EF	Spain (E)	Mining spill	Baos et al. (2006b)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Baos et al. (2006c)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Benito et al. (1999)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Pastor et al. (2004)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
Booted eagle (*Hieraaetus pennatus*)	1	Pb/Zn/Cu	EF	Spain (E)	Mining spill	Gil-Jiménez et al. (2017)
Marsh harrier (*Circus aeruginosus*)	1	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
Northern Harrier (*Circus cyaneus*)	1	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Henny et al. (1994)
Osprey (*Pandion haliaetus*)	2	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Henny et al. (1991)
		Ag/Au	EXP	USA (NA)	Old	Langner et al. (2012)
Red-tailed Hawk (*Buteo jamaicensis*)	1	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Henny et al. (1994)
Sparrowhawks (*Accipiter nisus*)	1	Cu/As	EXP	United Kingdom (E)	Old	Erry et al. (1999a)
Wild turkey vulture (*Cathartes aura*)	1	Cu	EXP	Chile (SA)	Old	Valladares et al. (2013)
Bald eagle (*Haliaeetus leucocephalus*)	1	Hg	EF	Canada (NA)	Old	Weech et al. (2006)
Anseriformes (17 species)						
Canada goose (*Branta canadensis*) [And 14 other species in Sileo et al. (2001)]	6	Pb/Zn (Ag/Au)	EXP	USA (NA)	Old	Beyer et al. (1998)
		Pb/Zn	EF	USA (NA)	Old	van der Merwe et al. (2011)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1995)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Sileo et al. (2001)
		Pb/Zn	EF	USA (NA)	Old	Sileo et al. (2003)
		Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
Common goldeneye (*Bucephala clangula*)	1	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1995)
Common pintail (*Anas acuta*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)

Gadwall (*Anas strepera*)	2	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Benito et al. (1999)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Taggart et al. (2006)
Green-winged teal (*Anas crecca*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
Greylag goose (*Anser anser*)	2	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Mateo et al. (2006)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Martinez-Haro et al. (2013)
Lesser scaup (*Aythya affinis*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
Mallard (*Anas platyrhynchos*)	8	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1995)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Benito et al. (1999)
		Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
		Pb/Zn (Ag/Au)	EXP	USA (NA)	Old	Beyer et al. (1998)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Henny et al. (2000)
		Pb/Zn	EF	USA (NA)	Old	Sileo et al. (2003)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Taggart et al. (2006)
Common Pochard (*Aythya ferina*)	2	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Benito et al. (1999)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Taggart et al. (2006)
Red-crested pochard (*Netta rufina*)	1	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Taggart et al. (2006)
Ring-necked duck (*Aythya collaris*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
Shaoxing duck (reared under natural conditions)	1	Hg	EF	China (AS)	Old	Ji et al. (2006)
Shoveler (*Anas clypeata*)	1	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
Trumpeter swan (*Cygnus buccinator*)	1	Pb/Zn	EF	USA (NA)	Old	Carpenter et al. (2004)
Tundra swans (*Cygnus columbianus*)	5	Pb/Zn/Ag	EXP	USA (NA)	Old	Benson et al. (1976)
		Pb/Zn (Ag/Au)	EXP	USA (NA)	Old	Beyer et al. (1998)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1991)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1999)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Sileo et al. (2001)

(continued)

Table 1 (continued)

Species	N	Metal ore	Biomarker	Country (continent)	Mine status	Reference
Western Canada geese (*Branta canadensis moffitti*)	1	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Henny et al. (2000)
Wood duck (*Aix sponsa*)	1	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1993)
Charadriiformes (1 species)						
Yellow-legged gull (*Larus michahellis*)	1	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Benito et al. (1999)
Ciconiiformes (1 species)						
White stork (*Ciconia ciconia*)	11	Pb/Zn/Cu	EF	Spain (E)	Mining spill	Baos et al. (2006a)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Baos et al. (2012)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Pastor et al. (2001)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Smits et al. (2005)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Smits et al. (2007)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Benito et al. (1999)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Baos et al. (2006b)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Baos et al. (2006c)
		Pb/Zn/Cu	EF	Spain (E)	Mining spill	Pastor et al. (2004)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Meharg et al. (2002)
Columbiformes (2 species)						
Laughing dove (*Spilopelia senegalensis*)	1	Au	EF	Saudi Arabia (AS)	Active	Almalki et al. (2019a)
Mourning doves (*Zenaida macroura*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
Coraciformes (2 species)						
Common Kingfisher (*Alcedo atthis*)	1	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
European bee-eaters (*Merops apiaster*)	1	Cu	EXP	Portugal (E)	Old	Lopes et al. (2010)
Falconiformes (3 species)						
American Kestrel (*Falco sparverius*)	1	Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Henny et al. (1994)
Kestrels (*Falco tinnunculus*)	1	Cu/As	EXP	United Kingdom (E)	Old	Erry et al. (1999a)

Peregrine falcon (*Falco peregrinus*)	1	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
Galliformes (3 species)						
Free-range chicken	1	Au Mn	EXP	Ghana (AF)	Active	Bortey-Sam et al. (2015)
Northern bobwhites (*Colinus virginianus*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
White-tailed ptarmigan (*Lagopus leucurus*)	1	No info	EF	USA (NA)	Active	Larison et al. (2000)
Gruiformes (2 species)						
Eurasian coot (*Fulica atra*)	2	Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Taggart et al. (2006)
		Pb/Zn/Cu	EXP	Spain (E)	Mining spill	Rodríguez Álvarez et al. (2013)
Purple gallinule (*Porphyrio porphyrio*)	1	Pb/Zn/Cu	EF	Spain (E)	Mining spill	Martinez-Haro et al. (2013)
Passeriformes (51 species)						
American dipper (*Cinclus mexicanus*)	2	Hg/Au/Ag	EF	USA (NA)	Old	Henny et al. (2005)
		Cu/Ag/Fe/Pb/Au/Zn	EF	USA (NA)	Old	Strom et al. (2002)
American robins (*Turdus migratorius*)	5	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
		Pb (Zn/Cu)	EF	USA (NA)	Active/old (whole district)	Beyer et al. (2013)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Hansen et al. (2011)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Johnson et al. (1999)
		Pb/Zn (Ag/Au)	EF	USA (NA)	Old	Blus et al. (1995)
American tree sparrow (*Spizella arborea*)	2	Pb/Zn	EF	USA (NA)	Active	Brumbaugh et al. (2010)
		Au	EXP	Canada (NA)	Old	Koch et al. (2005)
Bank swallows (*Riparia riparia*)	2	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
		Pb (Zn/Cu)	EXP	USA (NA)	Active/old	Niethammer et al. (1985)
Bhestnut Bulbul (*Hemixos castanonotus*)	1	Hg	EXP	China (AS)	Old	Qiu et al. (2019)
Blue jays (*Cyanocitta cristata*)	1	Pb (Zn/Cu)	EF	USA (NA)	Active/old (whole district)	Beyer et al. (2013)
Brown thrasher (*Toxostoma rufum*)	1	Pb/Zn	EF	USA (NA)	Old	Beyer et al. (2004)
Brown-breasted Bulbul (*Pycnonotus xanthorrhous*)	2	Hg	EXP	China (AS)	Old	Qiu et al. (2019)
		Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)

(continued)

Table 1 (continued)

Species	N	Metal ore	Biomarker	Country (continent)	Mine status	Reference
Brown-cheeked fulvetta (*Alcippe poioicephala*)	1	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
Cactus wren (*Campylorhynchus brunneicapillus*)	1	Ag/Pb/Zn/Cu/Fe Zn(Pb/Cu/Cd/Ag/Au)	EXP	Mexico (NA)	Old (PSG) Active (Charcas)	Monzalvo-Santos et al. (2016)
Canyon towhee (*Melozone fusca*)	1	Ag/Pb/Zn/Cu/Fe Zn(Pb/Cu/Cd/Ag/Au)	EXP	Mexico (NA)	Old (PSG) Active (Charcas)	Monzalvo-Santos et al. (2016)
Carolina wren (*Thryothorus ludovicianus*)	1	Pb (Zn/Cu)	EF	USA (NA)	Active/old (whole district)	Beyer et al. (2013)
Chestnut Bulbul (*Hemixos castanonotus*)	1	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
Chestnut-headed Tesia (*Oligura castaneocoronata*)	2	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
		Hg	EXP	China (AS)	Old	Qiu et al. (2019)
Collared Finchbill (*Spizixos semitorques*)	2	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
		Hg	EXP	China (AS)	Old	Qiu et al. (2019)
Common redpoll (*Carduelis flammea*)	1	Pb/Zn	EF	USA (NA)	Active	Brumbaugh et al. (2010)
Curve-billed thrasher (*Toxostoma curvirostre*)	1	Ag/Pb/Zn/Cu/Fe Zn(Pb/Cu/Cd/Ag/Au)	EXP	Mexico (NA)	Old (PSG) Active (Charcas)	Monzalvo-Santos et al. (2016)
Dark-eyed junco (*Junco hyemalis*)	1	Au	EXP	Canada (NA)	Old	Koch et al. (2005)
Eastern towhees (*Pipilo erythrophthalmus*)	1	Pb (Zn/Cu)	EF	USA (NA)	Active/old (whole district)	Beyer et al. (2013)
Gray jays (*Perisoreus canadensis*)	1	Au	EXP	Canada (NA)	Old	Koch et al. (2005)
Great tit (*Parus major*)	1	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
Grey-cheeked fulvetta (*Alcippe morrisonia*)	1	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
Grey-chinned Minivet (*Pericrocotus solaris*)	1	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
Grey-headed Parrotbill (*Paradoxornis gularis*)	2	Hg	EXP	China (AS)	Old	Abeysinghe et al. (2017)
		Hg	EXP	China (AS)	Old	Qiu et al. (2019)