Current permissible levels of heavy metal pollutants harm terrestrial invertebrates

Coline Monchanin[1,2], Jean-Marc Devaud[1], Andrew B. Barron[2], Mathieu Lihoreau[1]

[1] Research Center on Animal Cognition (CRCA), Center for Integrative Biology (CBI); CNRS, University Paul Sabatier – Toulouse III, France; coline.monchanin@univ-tlse3.fr, jean-marc.devaud@univ-tlse3.fr; mathieu.lihoreau@univ-tlse3.fr

[2] Department of Biological Sciences, Macquarie University, Sydney, Australia; andrew.barron@mq.edu.au

Correspondence:

Coline Monchanin and Mathieu Lihoreau

CRCA-CBI, Bât 4R4, Univ. Paul Sabatier, 118 route de Narbonne, 31062 Toulouse, France

Email: Coline.monchanin@univ-tlse3.fr; Mathieu.lihoreau@univ-tlse3.fr

Tel: +33 5 61 55 64 71

Type of article: Reviews and Synthesis

Short title: Heavy metals harm terrestrial invertebrates

Keywords: arsenic, cadmium, mercury, lead, meta-analysis, invertebrate decline, international guidelines, environmental pollution

Statement of authorship: CM and ML designed the study. CM collected the data, analyzed the data, and wrote the first draft of the manuscript. All authors contributed substantially to revisions.

Data accessibility statement: Raw data used of the analyses are available in Table S1. Should the manuscript be accepted, the data supporting the results will be archived in Dryad.

Number of words in abstract: 133

Number of words in main text: 3058

Number of references: 95

Number of tables: 1

Number of figures: 3

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Abstract

The current decline of invertebrates worldwide is alarming. Several potential causes have been proposed but heavy metals, while being a widespread and major pollutants of air, soils and water, have so far been largely overlooked. Here, we ran a meta-analysis of 527 datasets on the effects of arsenic, cadmium, lead and mercury on terrestrial invertebrates. These four well-studied metals, for which international guidelines exist, significantly impact the physiology and behavior of invertebrates, even at levels below those recommended as 'safe' for humans. Our results call for a revision of the regulatory thresholds to better protect terrestrial invertebrates, which appear to be more sensitive to metal pollution than vertebrates. More fundamental research is needed to improve international guidelines for metal pollutants, and to develop conservation plans to mitigate invertebrate declines and protect ecosystem services.

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INTRODUCTION

Terrestrial invertebrate bioabundance and biodiversity are declining (Wagner 2020). Since invertebrates are basal to terrestrial food webs and provide key ecosystem services, the short-term ecological consequences of invertebrate decline could be very severe (Goulson 2019; Sánchez-Bayo & Wyckhuys 2019). The rate of decline is especially alarming as it has been estimated that land-dwelling insects disappear at a rate of ca. 1% every year since a century (van Klink *et al.* 2020). Many factors have been proposed to explain this loss. These include climate change (Wilson *et al.* 2007), habitat reduction due to intensive agriculture and urbanization (Fattorini 2011; Dudley & Alexander 2019), introduced pathogens, predators and competitors (Goulson *et al.* 2015), as well as chronic exposure to agrochemicals (van Lexmond *et al.* 2015).

Here we argue that heavy metal pollution is a major, yet currently overlooked, stressor to insects and other terrestrial invertebrates that needs urgent attention from scientists and stakeholders. At trace levels, metals such as cobalt, copper, iron, manganese, selenium and zinc are essential micronutrients for animals and plants (Phipps 1981; WHO/FAO/IAEA 1996). Others, such as arsenic, cadmium, chromium, mercury, lead and nickel have no useful biological function and exert toxic effects even at low concentrations (He *et al.* 2005; Tchounwou *et al.* 2012). While these metals are naturally present in the Earth's crust, mining and smelting operations, combustion of fossil fuels, industrial production, domestic and agricultural use of metals and metal-containing compounds (Bradl 2005), have considerably increased environmental concentrations of these metals above natural baselines (Zhou *et al.* 2018), contaminating air (Suvarapu & Baek 2017), soils (Wuana & Okieimen 2011), water (Mance 1987) and plants (Krämer 2010).

Despite our knowledge of the detrimental impact of this heavy metal pollution on vertebrates, which include cellular damage, carcinogenesis and neurotoxicity (Tchounwou *et* *al.* 2012; Chen *et al.* 2016), metal pollution is still increasing, calling for a more systematic assessment on the impact on biodiversity. For example, in 2019, the World Health Organization (WHO) stated that there was no safe level of lead for vertebrates (WHO 2019), yet the majority of industrial activities are consistently elevating the level of lead in the environment (Järup 2003; Li *et al.* 2014). The recent report that bees and flies in densely urbanized areas suffer from exposure to metallic air particles (Thimmegowda *et al.* 2020) suggests that the consequences of heavy metal pollution on terrestrial invertebrates could be extremely important and widespread (for a review on aquatic invertebrates see (Rainbow 2002)).

Here, we assessed the impact of heavy metals on terrestrial invertebrates through a meta-analysis of the scientific literature on four well-studied metals over the past 45 years. We found that these metals have detrimental effects on a wide diversity of species at levels below those considered safe for humans. Based on these results, we discuss the need for more fundamental research into the impacts of heavy metal pollutants on insects to improve international guidelines for the regulation of metal pollutants, and better inform conservation plans.

METHODS

Literature review and data extraction

We focused on the four most hazardous heavy metals documented for humans (ATSDR 2019), for which international regulatory implementations exist (Table 1): arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb). We searched articles in the ISI Web of Knowledge database (search performed on 25/03/2020) using the keywords: heavy metals, metalloids, arsenic, cadmium, lead, mercury, insects, invertebrates. The search was restricted to articles published between 1975 and 2020 (maximum available year range on ISI Web of

Knowledge). Among the 460 hits, we selected those studies focusing on terrestrial invertebrates (i.e. protostomes) from the abstracts, and excluded review articles. This filtering yielded a subset of 154 articles from which we extracted 527 datasets of studies investigating effects of heavy metals on terrestrial invertebrates (see raw data in Table S1).

From each dataset, we extracted: (1) the name of targeted invertebrate species, (2) the heavy metal(s) used, (3) the experimental conditions (field, laboratory), (4) the mode of exposure to the metal (food, water, soil), (5) the type of exposure (acute: < 24h, chronic: > 24h), (6) the range of metal concentrations tested (min- max in ppm), (7) the biological responses measured (e.g. survival, reproduction, behavior), and (8) the lowest metal concentration for which an effect was observed.

Briefly, the vast majority of the datasets focused on cadmium (46%) and lead (37%), while less information was available on arsenic (10%) and mercury (7%) (Figure 1A). 59% of the datasets were obtained in field surveys and 41% in laboratory experiments with controlled exposure. 79% of the studies were published in the last 13 years, indicating only recent attention to this issue. Since the effects can greatly vary depending on the duration of exposure and time of assessment, here we considered as acute exposure any case where individuals were exposed to a single dose and assessed within 24h. Despite the diversity of protocols, most studies used chronic exposure (95%), through the diet (49%) or the soil (43%).

Concentration ranges

International permissible limits (i.e. recommended maximum concentrations) are based on values established for humans in food, water and soil (see Table S2). These limits vary across types of food, water (i.e. drinking, irrigation) and soils (i.e. allotment, commercial, residential, agricultural). For each of these matrices, we thus considered the

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minimal and the maximal estimates of permissible limits. We defined three concentration ranges: below the minimal estimated limit, between the minimal and maximal estimated limits, and above the maximal estimated limit (Table 1). Note that for water, whenever possible, we considered the minimal value for drinking water and the maximal value for irrigation water.

RESULTS

Few studies focus on functionally important species

The 527 datasets covered 100 species (83% Arthropoda, 15% Annelida, 1.2% Rotifera, 0.4% Tardigrada, 0.2% Mollusca; Figure 1B). Studies were biased toward pest species with an economic impact (34% of datasets; e.g. the gypsy moth *Limantria dispar,* the grasshopper *Aiolopus thalassinus,* the beet armyworm *Spodoptera exigua*) and model species in biology (10%; e.g. fruit fly *Drosophila melanogaster,* large milkweed bug *Oncopeltus fasciatus*). Other groups were comparatively under-represented, including important bioindicators, such as decomposers (15%; e.g. *Lumbricus terrestris, Eisenia fetida* and *E. andre)*, predators (10%; e.g. ants *Formica* spp., spiders *Araneus* spp. and *Pardosa* spp.) and pollinators (13%; e.g. the honey bee *Apis mellifera*). Some taxonomic orders that include large numbers of species with key functional roles for nutrient cycling (e.g. proturans, diplurans, earwigs), soil aeration (e.g. centipedes), or pollination (e.g. thrips) were not represented at all. Research is thus needed on these important invertebrate orders to get a more accurate picture of how metallic pollution disturb key ecological functions (Skaldina & Sorvari 2019).

Heavy metals have detrimental effects below permissible limits

Deleterious effects were reported in 70% of the datasets (Figure 2A), be them collected in the laboratory (84%, N=263) or in the field (49%, N=104), following chronic (79%, N=348) or acute exposure (69%, N=19). When considering only the datasets reporting deleterious effects, 73% of these effects (N=269) were measured at concentrations above the maximal estimated permissible limit (see Table 1). Yet, 12% (N=45) were measured in between the regulatory thresholds and 15% (N=53) below the minimal estimated limit (Figure 2A). In addition, a majority (57%, N=53) of the datasets using at least one concentration below the minimal estimated permissible limit found a negative effect, irrespective of the metal.

When considering only the laboratory studies, in which exposure concentrations were controlled (Figure 2B-C), 67% of the studies that examined levels below the permissible limits (N=29) reported deleterious effects on invertebrates. Of the laboratory studies investigating acute exposure below the permissible limits (N=10), seven found deleterious effects (Figure 2B). Hence, acute exposure, while presumably rare in nature, can have deleterious effects on invertebrates below current permissible exposure levels. This suggests that the permissible limits designed for humans are not appropriate for terrestrial invertebrates, who seem to be more sensitive to metal pollutants.

Few studies address the behavioral effects of heavy metals

Research on the impact of heavy metals on terrestrial invertebrates has developed quite recently. This is illustrated by the fact that 79% of the studies sampled for our analysis were published after 2007 (Figure 3A). About half of the experiments focused on physiology (52%), followed by studies on development (17%), survival (13%), population dynamics (6%), reproduction (6%) and behavior (6%) (Figure 3B). It has become increasingly clear that understanding the sublethal behavioral effects of a stressor (e.g. mobility, navigation, feeding behavior, learning, memory) is crucial to assess the long-term impact of that stressor on invertebrate populations (Mogren & Trumble 2010). This has become evident for bees, for instance, for which any impairment of the cognitive functions involved in foraging is a direct threat for the larvae or the whole colony that cannot appropriately access nutrients (Klein *et al.* 2017). In our meta-analysis, 33 experiments reported behavioral effects (Figure 3B), but only two explored cognitive effects (Philips *et al.* 2017; Piccoli *et al.* 2020). This is a very low number considering the well-known neurotoxic effects of the four metals on humans (Wright & Baccarelli 2007; Chen *et al.* 2016) and other animals, including aquatic invertebrates (Salanki 2000).

Few studies investigated co-occurrences despite clear synergistic effects

In nature, pollutants rarely occur alone. Heavy metals are no exception since they share common emission sources (Vareda *et al.* 2019). For instance, cadmium, copper, zinc and lead frequently co-occur due to the output from smelters, or the application of sewage sludge as fertilizer (Bradl 2005). High positive correlations between chromium, cadmium and arsenic amounts have been found in soil samples (Chen *et al.* 1999; Navas & Machín 2002), and many studies have shown the co-accumulation of several trace metals in insects (Wilczek & Babczy 2000; Nummelin *et al.* 2007; Goretti *et al.* 2020). As such, co-occurring metals could have additive, antagonistic or synergistic effects (Jensen & Trumble 2003). These interactive effects may also be influenced by the presence of other environmental stressors, such as pesticides or parasites (Alaux *et al.* 2010).

Only 7 out of the 154 studies addressed the question of combined effects in laboratory conditions (Figure 1A). Nonetheless the effects are clear: 55% of the experiments (N=10) reported synergistic detrimental consequences. For instance, ants (*Formica aquilonia*) chronically exposed to both cadmium and mercury failed to develop compensatory mechanisms to maintain energetic balance, causing colony collapse, while being able to cope when exposed to each metal alone (Migula *et al.* 1997). Similarly, the lethal effects of cadmium and zinc on aphids (*Myzus persicae*) were potentiated when the two metals were combined, which led to accelerated extinction of the treated population (Stolpe & Müller 2016). These two metals were reported to be either synergistic or antagonist on earthworms (*E. fetida*) depending on their concentrations (Wu *et al.* 2012). Finally, the joint exposure of honey bees (*A. mellifera*) to cadmium and copper induced increased development duration and mortality, and decreased food intake and sucrose response (Di *et al.* 2020). Thus, the effects of metal co-exposure are complex and variable. The paucity of studies may be because they require more sophisticated experimental designs, larger sample sizes (factorial designs) and may yield results that are more difficult to interpret. Yet, these studies are crucial if we are to revise the current regulations which presently only consider permissible limits for metals in isolation (Tables 1 and S2).

DISCUSSION

Our meta-analysis of the literature on lead, arsenic, cadmium and mercury shows many negative effects of these heavy metal pollutants on terrestrial invertebrates. Particularly worrisome are the reports of negative effects observed at doses below permissible limits in most of the studied taxa. There are reported lethal effects on grasshoppers (Schmidt *et al.* 1991), moths (Andrahennadi & Pickering 2008), flies (Massadeh *et al.* 2008) and other groups (Osman *et al.* 2015; Polykretis *et al.* 2016; Stolpe *et al.* 2017). Metal exposure induces a number of sublethal effects, sometimes difficult to assess, such as impaired fertility (grasshoppers: Schmidt *et al.* 1991; springtail: Crouau & Pinelli 2008; earthworm: Konečný *et al.* 2014), developmental defects (blowfly: Nascarella *et al.* 2003; moth: van Ooik *et al.* 2007; ant: Skaldina *et al.* 2018), resistance to pathogens (ant: Sorvari *et al.* 2007; honey bee:

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Polykretis *et al.* 2016) but also altered feeding behavior (aphid: Stolpe *et al.* 2017; honey bee: Burden *et al.* 2019).

The impact of heavy metal pollutants is poorly understood

At present, it is likely that the severity of these effects is underestimated. Many laboratory experiments gave animals rather limited exposure times, rarely reaching the duration of a complete life cycle. Besides, most studies overlooked any consequences of exposure to multiple metal contaminants, which would be a common occurrence in nature. There is now clearly growing interest in assessing the sublethal impacts of metals. This trend echoes the recent shift seen in pesticide research on beneficial insects, especially pollinators, which has moved from decades of standard survival assays to experimental designs aiming at characterizing the effects on behavior and cognition (Desneux *et al.* 2007; Klein *et al.* 2017). Just like pesticides, heavy metal pollutants have subtle, but potentially serious, effects on pollinators' behavior by disturbing foraging activity (Sivakoff & Gardiner 2017; Xun *et al.* 2018), food perception (Burden *et al.* 2019) as well as the learning and memory abilities required for efficient foraging (Burden *et al.* 2016; Monchanin *et al.* 2020). Through all of these mechanisms, heavy metal exposure can compromise food supply to the offspring, and hence the viability of a colony or population.

There are potentially complex interactions between behavior and pollutant exposure. Since an animal's behavior can influence how much metal pollution it is exposed to (Mogren & Trumble 2010; Gall *et al.* 2015), behavioral disturbances may affect exposure and sensitivity to metals. For example, impaired locomotion may reduce the capacity of individuals to avoid contaminated sites (Hirsch *et al.* 2003) and indiscriminate oviposition may jeopardize the survival of offspring if they are deposited on an unfavorable food plant (Cervera *et al.* 2004; Tollett *et al.* 2009). It is thus likely that we are currently underestimating

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the impact of metal pollution on invertebrates, due to a lack of understanding of their sublethal effects on most species.

Multiple possible causes of invertebrates' high sensitivity to metal pollution

Our survey of the literature suggests that invertebrates may be more sensitive to the damaging effects of heavy metals than the mammals (e.g. humans, rodents) typically used to determine "safe" environmental levels. Sensitivity varies between species and depends on the considered metals (Malaj *et al.* 2016). Some can discriminate metal contaminated food from uncontaminated food (Mogren & Trumble 2010), but other species seem unable to (Stolpe *et al.* 2017; Burden *et al.* 2019). This is particularly critical for animals feeding on resources that can accumulate metals, such as leaves (Krämer 2010) or nectar (Gutiérrez *et al.* 2015).

Perhaps more importantly, there is also emerging evidence that invertebrates may have higher levels of exposure to heavy metals in the field than large mammals. Surveys of terrestrial biotopes show that non-essential metals tend to be more highly accumulated in invertebrates than in vertebrates (Hsu *et al.* 2006), which seems also the case for aquatic taxa (Xin *et al.* 2015). Due to their small size, their relatively high surface area/volume ratio and the niches they occupy, invertebrates are frequently in intimate contact with soils and vegetation and can get contaminated by specific feeding modes such as filter-feeding or deposit-feeding (De Lange *et al.* 2009). Their limited dispersive capacities may greatly reduce their ability to move away from polluted areas, even if they can detect harmful levels of trace elements. As a result, metals accumulate in the bodies of individuals (Nannoni *et al.* 2011; Mukhtorova *et al.* 2019; Schrögel & Wätjen 2019; Goretti *et al.* 2020) and in the nest in the case of social species (Skaldina *et al.* 2018; Veleminsky *et al.* 1990). Some terrestrial invertebrates (e.g. ants, earthworms, bees, Isopoda) could therefore be relevant and sensitive bioindicators due to their particular vulnerability to metal contamination.

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Invertebrates do have mechanisms to process heavy metals. Excessive metals can be eliminated through feces (Przybyłowicz *et al.* 2003), accumulated in insect exoskeleton before molting (Borowska *et al.* 2004), or stored in specific organs (Nica *et al.* 2012). They can also induce expression of proteins involved in excretion and/or detoxification (for reviews, see Janssens *et al*. 2009; Merritt *et al.* 2017). Yet, while these detoxification mechanisms may protect species to a point, they are unlikely to spare them from the sublethal effects resulting from impaired brain or organ function. We clearly need a better characterization of the physiological and molecular mechanisms underlying metal transfer, toxicity and tolerance in invertebrates in order to better understand their sensitivity to heavy metals.

A need to revise guidelines of safe environmental levels of heavy metals

Since heavy metals are such widespread and persistent pollutants in the environment, it is a priority to develop a better assessment of their impacts on invertebrates. Our most concerning finding is the evidence that terrestrial invertebrates are highly sensitive to heavy metals, but our meta-analysis also highlights important gaps in our knowledge. We need to study a larger diversity of species, consider potential cocktail effects, and extend studies beyond the four metals addressed here. Other heavy metals have been reported to negatively impact terrestrial invertebrate populations at low doses, such as selenium (deBruyn & Chapman 2007), zinc (e.g. Cheruiyot *et al.* 2013), copper (e.g. Di *et al.* 2016), cobalt (e.g. Cheruiyot *et al.* 2013), manganese (Ben-Shahar 2018) and chromium (e.g. Sgolastra *et al.* 2018). Characterizing the impacts of heavy metals on insect fitness is going to demand an integrative and interdisciplinary research agenda, just like what has been established to assess pesticide impacts on beneficial insects. In particular, focusing on the sublethal effects of neonicotinoids on pollinators (Henry *et al.* 2012; Crall *et al.* 2018), triggered a revision of the risk assessments scheme and their ban in the European Union in 2018.

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CONCLUDING REMARKS

This survey of the existing literature clearly indicates that terrestrial invertebrates appear particularly vulnerable to heavy metal pollutants, and that most existing standards are not suited to protect them. We now need more integrative toxicological studies, on a broader range of invertebrate species, to better assess the impact of metal pollutants on fitness, and to update the current environmental regulation of metals. Only by addressing these important challenges will we be able to mitigate consequences on ecosystems and food safety, in a context of rapid and widespread decline of invertebrate biodiversity.

Acknowledgements

We thank Valentine Lisant for assistance with the literature search. This work was supported by the CNRS. CM was funded by a PhD fellowship from French Ministry of Higher Education, Research and Innovation. ABB was funded by a Future Fellowship from the Australian Research Council (FT140100452) and the Eldon and Anne Foote Trust. ML was funded by grants of the Agence Nationale de la Recherche (ANR-16-CE02-0002-01, ANR-19-CE37-0024) and the European Regional Development Fund (project ECONECT).

References

Alaux, C., Brunet, J.-L., Dussaubat, C., Mondet, F., Tchamitchian, S., Cousin, M., *et al.* (2010). Interactions between *Nosema* microspores and a neonicotinoid weaken honeybees (*Apis mellifera*). *Environ. Microbiol.*, 12, 774–782.

Al-Momani, F.A. & Massadeh, A.M. (2005). Effect of different heavy-metal concentrations on *Drosophila melanogaster* larval growth and development. *Biol. Trace Elem. Res.*, 108, 271–278.

 14

Andrahennadi, R. & Pickering, I.J. (2008). Arsenic accumulation, biotransformation and localisation in bertha armyworm moths. *Environ. Chem.*, 5, 413.

ATSDR. (2019). *The ATSDR 2019 Substance Priority List*. Available at: https://www.atsdr.cdc.gov/spl/index.html. Last accessed 13 May 2020.

Ayers, R.S. & Westcot, D.W. (1994). *Water quality for agriculture*. FAO irrigation and drainage paper. Food and Agriculture Organization of the United Nations, Rome.

Ben-Shahar, Y. (2018). The impact of environmental Mn exposure on insect biology. *Front. Genet.*, 9, 1–7.

Bischof, C. (1995). Effects of heavy metal stress on carbohydrate and lipid concentrations in the haemolymph and total body tissue of parasitized *Lymantria dispar* L. larvae (Lepidoptera). *Comp. Biochem. Physiol. C Pharmacol. Toxicol. Endocrinol.*, 112, 87–92.

Borowska, J. & Pyza, E. (2011). Effects of heavy metals on insect immunocompetent cells. *J. Insect Physiol.*, 57, 760–770.

Borowska, J., Sulima, B., Niklinska, M. & Pyza, E. (2004). Heavy metal accumulation and its effects on development, survival and immuno-competent cells of the housefly *Musca domestica* from closed laboratory populations as model organism. *Fresenius Environ. Bull.*, 13, 1402–1409.

Bradl, H.B. (2005). Sources and origins of heavy metals. In: *Interface Science and Technology* (ed. Bradl, H.B.). Elsevier, pp. 1–27.

Burden, C.M., Elmore, C., Hladun, K.R., Trumble, J.T. & Smith, B.H. (2016). Acute exposure to selenium disrupts associative conditioning and long-term memory recall in honey bees (*Apis mellifera*). *Ecotoxicol. Environ. Saf.*, 127, 71–79.

Burden, C.M., Morgan, M.O., Hladun, K.R., Amdam, G.V., Trumble, J.J. & Smith, B.H. (2019). Acute sublethal exposure to toxic heavy metals alters honey bee (*Apis mellifera*) feeding behavior. *Sci. Rep.*, 9, 4253.

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Cervera, A., Maymó, A.C., Sendra, M., Martínez-Pardo, R. & Garcerá, M.D. (2004). Cadmium effects on development and reproduction of *Oncopeltus fasciatus* (Heteroptera: Lygaeidae). *J. Insect Physiol.*, 50, 737–749.

Chen, M., Ma, L.Q. & Harris, W.G. (1999). Baseline concentrations of 15 trace elements in Florida surface soils. *J. Environ. Qual.*, 28, 1173.

Chen, P., Miah, M.R. & Aschner, M. (2016). Metals and neurodegeneration. *F1000Research*, 5, 366.

Cheruiyot, D.J., Boyd, R.S., Coudron, T.A. & Cobine, P.A. (2013). Biotransfer, bioaccumulation and effects of herbivore dietary Co, Cu, Ni, and Zn on growth and development of the insect predator *Podisus maculiventris*. *J. Chem. Ecol.*, 39, 764–772.

Codex Alimentarius. (2015). *Codex general standard for contaminants and toxins in food and feed - CODEX STAN 193-1995*. Joint FAO/WHO.

Crall, J.D., Switzer, C.M., Oppenheimer, R.L., Ford Versypt, A.N., Dey, B., Brown, A., *et al.* (2018). Neonicotinoid exposure disrupts bumblebee nest behavior, social networks, and thermoregulation. *Science*, 362, 683–686.

Crouau, Y. & Pinelli, E. (2008). Comparative ecotoxicity of three polluted industrial soils for the Collembola *Folsomia candida*. *Ecotoxicol. Environ. Saf.*, 71, 643–649.

De Lange, H.J., Lahr, J., der Pol, J.J.C.V., Wessels, Y. & Faber, J.H. (2009). Ecological vulnerability in wildlife: an expert judgment and multicriteria analysis tool using ecological traits to assess relative impact of pollutants. *Environ. Toxicol. Chem.*, 28, 2233.

deBruyn, A.M.H. & Chapman, P.M. (2007). Selenium toxicity to invertebrates: Will proposed thresholds for toxicity to fish and birds also protect their prey? *Environ. Sci. Technol.*, 41, 1766–1770.

Desneux, N., Decourtye, A. & Delpuech, J.-M. (2007). The sublethal effects of pesticides on beneficial arthropods. *Annu. Rev. Entomol.*, 52, 81–106.

 16

Di, N., Hladun, K.R., Zhang, K., Liu, T.-X. & Trumble, J.T. (2016). Laboratory bioassays on the impact of cadmium, copper and lead on the development and survival of honeybee (*Apis mellifera* L.) larvae and foragers. *Chemosphere*, 152, 530–538.

Di, N., Zhang, K., Hladun, K.R., Rust, M., Chen, Y.-F., Zhu, Z.-Y., *et al.* (2020). Joint effects of cadmium and copper on *Apis mellifera* foragers and larvae. *Comp. Biochem. Physiol. Part C Toxicol. Pharmacol.*, 237, 108839.

Dudley, N. & Alexander, S. (2019). Agriculture and biodiversity: A review. *Biodiversity*, 18, 45–49.

Fattorini, S. (2011). Insect extinction by urbanization: A long term study in Rome. *Biol. Conserv.*, 144, 370–375.

Goretti, E., Pallottini, M., Rossi, R., La Porta, G., Gardi, T., Cenci Goga, B.T., *et al.* (2020). Heavy metal bioaccumulation in honey bee matrix, an indicator to assess the contamination level in terrestrial environments. *Environ. Pollut.*, 256, 113388.

Goulson, D. (2019). The insect apocalypse, and why it matters. *Curr. Biol.*, 29, R967–R971.

Goulson, D., Nicholls, E., Botias, C. & Rotheray, E.L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, 347, 1255957.

Gutiérrez, M., Molero, R., Gaju, M., van der Steen, J., Porrini, C. & Ruiz, J.A. (2015). Assessment of heavy metal pollution in Córdoba (Spain) by biomonitoring foraging honeybee. *Environ. Monit. Assess.*, 187, 651.

He, Z.L., Yang, X.E. & Stoffella, P.J. (2005). Trace elements in agroecosystems and impacts on the environment. *J. Trace Elem. Med. Biol.*, 19, 125–140.

Henry, M., Beguin, M., Requier, F., Rollin, O., Odoux, J.-F., Aupinel, P., *et al.* (2012). A common pesticide decreases foraging success and survival in honey bees. *Science*, 336, 348–350.

Hirsch, H.V.B., Mercer, J., Sambaziotis, H., Huber, M., Stark, D.T., Torno-Morley, T., *et al.*

 17

(2003). Behavioral effects of chronic exposure to low levels of lead in *Drosophila melanogaster*. *NeuroToxicology*, 24, 435–442.

Hsu, M.J., Selvaraj, K. & Agoramoorthy, G. (2006). Taiwan's industrial heavy metal pollution threatens terrestrial biota. *Environ. Pollut.*, 143, 327–334.

Järup, L. (2003). Hazards of heavy metal contamination. *Br. Med. Bull.*, 68, 167–182.

Jensen, P. & Trumble, J. (2003). Ecological consequences of bioavailability of metals and metalloids in insects. *Recent Res. Dev. Entomol.*, 4, 1–17.

Klein, S., Cabirol, A., Devaud, J.-M., Barron, A.B. & Lihoreau, M. (2017). Why bees are so vulnerable to environmental stressors. *Trends Ecol. Evol.*, 32, 268–278.

van Klink, R., Bowler, D.E., Gongalsky, K.B., Swengel, A.B., Gentile, A. & Chase, J.M. (2020). Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*, 368, 417–420.

Konečný, L., Ettler, V., Kristiansen, S.M., Amorim, M.J.B., Kříbek, B., Mihaljevič, M., *et al.* (2014). Response of *Enchytraeus crypticus* worms to high metal levels in tropical soils polluted by copper smelting. *J. Geochem. Explor.*, 144, 427–432.

Krämer, U. (2010). Metal hyperaccumulation in plants. *Annu. Rev. Plant Biol.*, 61, 517–534.

van Lexmond, M.B., Bonmatin, J.-M., Goulson, D. & Noome, D.A. (2015). Worldwide integrated assessment on systemic pesticides. Global collapse of the entomofauna: Exploring the role of systemic insecticides. *Environ. Sci. Pollut. Res.*, 22, 1–4.

Li, Z., Ma, Z., van der Kuijp, T.J., Yuan, Z. & Huang, L. (2014). A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Sci. Total Environ.*, 468–469, 843–853.

Malaj, E., Guénard, G., Schäfer, R.B. & von der Ohe, P.C. (2016). Evolutionary patterns and physicochemical properties explain macroinvertebrate sensitivity to heavy metals. *Ecol. Appl.*, 26, 1249–1259.

 18

Mance, G. (1987). *Pollution threat of heavy metals in aquatic environments*. Springer Science & Business Media, The Netherlands.

Massadeh, A., Al-Momani, F. & Elbetieha, A. (2008). Assessment of heavy metals concentrations in soil samples from the vicinity of busy roads: Influence on *Drosophila melanogaster* life cycle. *Biol. Trace Elem. Res.*, 122, 292–299.

Migula, P., Glowacka, E., Nuorteva, S.-L., Nuorteva, P. & Tulisalo, E. (1997). Time-related effects of intoxication with cadmium and mercury in the red wood ant. *Ecotoxicology*, 6, 307–320.

Mogren, C.L. & Trumble, J.T. (2010). The impacts of metals and metalloids on insect behavior. *Entomol. Exp. Appl.*, 135, 1–17.

Monchanin, C., Blanc-Brude, A., Drujont, E., Negahi, M.M., Pasquaretta, C., Silvestre, J., *et al.* (2020). Chronic exposure to lead impairs honey bee learning. *Authorea*. doi: 10.22541/au.158680339.91889439

Mukhtorova, D., Hlava, J., Száková, J., Kubík, Š., Vrabec, V. & Tlustoš, P. (2019). Risk element accumulation in Coleoptera and Hymenoptera (Formicidae) living in an extremely contaminated area — A preliminary study. *Environ. Monit. Assess.*, 191, 432.

Nannoni, F., Protano, G. & Riccobono, F. (2011). Uptake and bioaccumulation of heavy elements by two earthworm species from a smelter contaminated area in northern Kosovo. *Soil Biol. Biochem.*, 43, 2359–2367.

Nascarella, M.A., Stoffolano, J.G., Stanek, E.J., Kostecki, P.T. & Calabrese, E.J. (2003). Hormesis and stage specific toxicity induced by cadmium in an insect model, the queen blowfly, *Phormia regina* Meig. *Environ. Pollut.*, 124, 257–262.

Navas, A. & Machín, J. (2002). Spatial distribution of heavy metals and arsenic in soils of Aragón (Northeast Spain): Controlling factors and environmental implications. *Appl. Geochem.*, 17, 961–973.

19

Nica, D.V., Bura, M., Gergen, I., Harmanescu, M. & Bordean, D.-M. (2012). Bioaccumulative and conchological assessment of heavy metal transfer in a soil-plant-snail food chain. *Chem. Cent. J.*, 6, 55.

Nieminen, M., Nuorteva, P. & Tulisalo, E. (2001). The effect of metals on the mortality of *Parnassius apollo* larvae (Lepidoptera: Papilionidae). *J. Insect Conserv.*, 5, 1–7.

Nikolić, T.V., Kojić, D., Orčić, S., Vukašinović, E.L., Blagojević, D.P. & Purać, J. (2019). Laboratory bioassays on the response of honey bee (*Apis mellifera* L.) glutathione S-transferase and acetylcholinesterase to the oral exposure to copper, cadmium, and lead. *Environ. Sci. Pollut. Res.*, 26, 6890–6897.

Noret, N., Josens, G., Escarré, J., Lefèbvre, C., Panichelli, S. & Meerts, P. (2007). Development of *Issoria lathonia* (Lepidoptera: Nymphalidae) on zinc-accumulating and nonaccumulating viola species (Violaceae). *Environ. Toxicol. Chem.*, 26, 565.

Nummelin, M., Lodenius, M., Tulisalo, E., Hirvonen, H. & Alanko, T. (2007). Predatory insects as bioindicators of heavy metal pollution. *Environ. Pollut.*, 145, 339–347.

van Ooik, T., Rantala, M.J. & Saloniemi, I. (2007). Diet-mediated effects of heavy metal pollution on growth and immune response in the geometrid moth *Epirrita autumnata*. *Environ. Pollut.*, 145, 348–354.

Osman, W., M. El-Samad, L., Mokhamer, E.-H., El-Touhamy, A. & Shonouda, M. (2015). Ecological, morphological, and histological studies on *Blaps polycresta* (Coleoptera: Tenebrionidae) as biomonitors of cadmium soil pollution. *Environ. Sci. Pollut. Res.*, 22, 14104–14115.

Philips, K.H., Kobiela, M.E. & Snell-Rood, E.C. (2017). Developmental lead exposure has mixed effects on butterfly cognitive processes. *Anim. Cogn.*, 20, 87–96.

Phipps, D.A. (1981). Chemistry and biochemistry of trace metals in biological systems. In: *Effect of heavy metal pollution on plants: effects of trace metals on plant function*, Pollution

20

Monitoring Series (ed. Lepp, N.W.). Springer Netherlands, Dordrecht, pp. 1–54.

Piccoli, B.C., Alvim, J.C., da Silva, F.D., Nogara, P.A., Olagoke, O.C., Aschner, M., *et al.* (2020). High level of methylmercury exposure causes persisted toxicity in *Nauphoeta cinerea*. *Environ. Sci. Pollut. Res.*, 27, 4799–4813.

Polykretis, P., Delfino, G., Petrocelli, I., Cervo, R., Tanteri, G., Montori, G., *et al.* (2016). Evidence of immunocompetence reduction induced by cadmium exposure in honey bees (*Apis mellifera*). *Environ. Pollut.*, 218, 826–834.

Przybyłowicz, W.J., Mesjasz Przybyłowicz, J., Migula, P., Głowacka, E., Nakonieczny, M. & Augustyniak, M. (2003). Functional analysis of metals distribution in organs of the beetle *Chrysolina pardalina* exposed to excess of nickel by Micro-PIXE. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At.*, 210, 343–348.

Rainbow, P.S. (2002). Trace metal concentrations in aquatic invertebrates: why and so what? *Environ. Pollut.*, 120, 497–507.

Salanki, J. (2000). Invertebrates in neurotoxicology. *Acta Biol. Hung.*, 51, 287–307.

Sánchez-Bayo, F. & Wyckhuys, K.A.G. (2019). Worldwide decline of the entomofauna: a review of its drivers. *Biol. Conserv.*, 232, 8–27.

Schmidt, G.H., Ibrahim, N.M.M. & Abdallah, M.D. (1991). Toxicological studies on the long-term effects of heavy metals (Hg, Cd, Pb) in soil on the development of *Aiolopus thalassinus* (Fabr.) (Saltatoria: Acrididae). *Sci. Total Environ.*, 107, 109–133.

Schrögel, P. & Wätjen, W. (2019). Insects for food and feed-safety aspects related to mycotoxins and metals. *Foods*, 8, 288.

Sgolastra, F., Blasioli, S., Renzi, T., Tosi, S., Medrzycki, P., Molowny-Horas, R., *et al.* (2018). Lethal effects of Cr(III) alone and in combination with propiconazole and clothianidin in honey bees. *Chemosphere*, 191, 365–372.

Sivakoff, F.S. & Gardiner, M.M. (2017). Soil lead contamination decreases bee visit duration

21

at sunflowers. *Urban Ecosyst.*, 20, 1221–1228.
Skaldina, O., Peräniemi, S. & Sorvari, J. (2018). Ants and their nests as indicators for industrial heavy metal contamination. *Environ. Pollut.*, 240, 574–581.
Skaldina, O. & Sorvari, J. (2019). Ecotoxicological effects of heavy metal pollution on economically important terrestrial insects. In: *Networking of Mutagens in Environmental Toxicology* (ed. Kesari, K.K.). Springer International Publishing, Cham, pp. 137–144.
Sorvari, J., Rantala, L.M., Rantala, M.J., Hakkarainen, H. & Eeva, T. (2007). Heavy metal pollution disturbs immune response in wild ant populations. *Environ. Pollut.*, 145, 324–328.
Søvik, E., Perry, C.J., LaMora, A., Barron, A.B. & Ben-Shahar, Y. (2015). Negative impact of manganese on honeybee foraging. *Biol. Lett.*, 11, 20140989.
Stolpe, C., Krämer, U. & Müller, C. (2017). Heavy metal (hyper)accumulation in leaves of *Arabidopsis halleri* is accompanied by a reduced performance of herbivores and shifts in leaf glucosinolate and element concentrations. *Environ. Exp. Bot.*, 133, 78–86.
Stolpe, C. & Müller, C. (2016). Effects of single and combined heavy metals and their chelators on aphid performance and preferences. *Environ. Toxicol. Chem.*, 35, 3023–3030.
Suvarapu, L.M. & Baek, S.O. (2017). Determination of heavy metals in the ambient atmosphere: a review. *Toxicol. Ind. Health*, 33, 79–96.
Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K. & Sutton, D.J. (2012). Heavy metal toxicity and the environment. In: *Molecular, Clinical and Environmental Toxicology* (ed. Luch, A.). Springer Basel, Basel, pp. 133–164.
Thimmegowda, G.G., Mullen, S., Sottilare, K., Sharma, A., Mohanta, S.S., Brockmann, A., *et al.* (2020). A field-based quantitative analysis of sublethal effects of air pollution on pollinators. *Proc. Natl. Acad. Sci. USA*, 117, 20653–20661.
Tollett, V.D., Benvenutti, E.L., Deer, L.A. & Rice, T.M. (2009). Differential toxicity to Cd, Pb, and Cu in dragonfly larvae (Insecta: Odonata). *Arch. Environ. Contam. Toxicol.*, 56, 77–

22

84.
Vareda, J.P., Valente, A.J.M. & Durães, L. (2019). Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: A review. *J. Environ. Manage.*, 246, 101–118.

de Vries, W., Schütze, G., Lots, S., Meili, M., Römkens, P., de Temmerman, L., *et al.* (2003). Critical limits for cadmium, lead and mercury related to ecotoxicological effects on soil organisms, aquatic organisms, plants, animals and humans. In: *Proceedings of the expert meeting on critical limits for heavy metals and methods for their application, Berlin, 2–4 December 2002. Held under the UN/ECE Convention on Long- Range Transboundary Air Pollution UBA-Texte 47/03* (eds. Schütze, G., Lorent, U. & Spranger, T.). Umweltbundesamt, Berlin, pp. 29–78.

Wagner, D.L. (2020). Insect declines in the Anthropocene. *Annu. Rev. Entomol.*, 65, 457–480.

WHO. (2019). *Lead poisoning and health*. *World Health Organ.* Available at: https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health. Last accessed 17 July 2020.

WHO/FAO. (2001). *Codex alimentarius commission. Food additives and contaminants. Food Standards Programme, ALINORM 10/12A*. Joint FAO/WHO.

WHO/FAO/IAEA (Ed.). (1996). *Trace elements in human nutrition and health*. World Health Organization, Geneva.

Wilczek, Y. & Babczy, A. (2000). Heavy metals in the gonads and hepatopancreas of spiders (Araneae) from variously polluted areas. *Ekologia Bratislava*, 19, 283–292.

Wilson, R.J., Davies, Z.G. & Thomas, C.D. (2007). Insects and climate change: Processes, patterns and implications for conservation. In: *Insect Conservation Biology: Proceedings of the Royal Entomological Society's 23nd Symposium* (eds. Stewart, A.J.A., New, T.R. & Lewis, O.T.). CABI Publishing, Wallingford, UK.

23

Wright, R.O. & Baccarelli, A. (2007). Metals and neurotoxicology. *J. Nutr.*, 137, 2809–2813.

Wu, B., Liu, Z., Xu, Y., Li, D. & Li, M. (2012). Combined toxicity of cadmium and lead on the earthworm *Eisenia fetida* (Annelida, Oligochaeta). *Ecotoxicol. Environ. Saf.*, 81, 122–126.

Wuana, R.A. & Okieimen, F.E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecol.*, 2011, 1–20.

Xin, Z., Wenchao, Z., Zhenguang, Y., Yiguo, H., Zhengtao, L., Xianliang, Y., *et al.* (2015). Species sensitivity analysis of heavy metals to freshwater organisms. *Ecotoxicology*, 24, 1621–1631.

Xun, E., Zhang, Y., Zhao, J. & Guo, J. (2018). Heavy metals in nectar modify behaviors of pollinators and nectar robbers: Consequences for plant fitness. *Environ. Pollut.*, 242, 1166–1175.

Zhang, Y., Lambiase, S., Fasola, M., Gandini, C., Grigolo, A. & Laudani, U. (2001). Mortality and tissue damage by heavy metal contamination in the German cockroach, *Blattella germanica* (Blattaria, Blattellidae). *Ital. J. Zool.*, 68, 137–145.

Zhou, X., Taylor, M.P., Davies, P.J. & Prasad, S. (2018). Identifying sources of environmental contamination in European honey bees (*Apis mellifera*) using trace elements and lead isotopic compositions. *Environ. Sci. Technol.*, 52, 991–1001.

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TABLES

Table 1: Permissible limits (ppm) for heavy metals in food, water and soil. All permissible limits are based on human toxicity data. Levels were determined from the international standards set by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations. The permissible limits are recommended values for: ‘food and drinking water’, as defined in the Codex Alimentarius (2015), to deal with ‘contaminants and toxins in food and feed’ and to be ‘applied to commodities moving in international trades’ (Codex Alimentarius 2015); guidelines for water quality in irrigation (Ayers & Westcot 1994); critical values in soil based on the Organization for Economic Co-operation and Development (OECD) risk assessment studies (de Vries *et al.* 2003) and FAO standards (WHO/FAO 2001). Local guidelines (see Table S2), when they exist, can vary across countries and are less conservative (higher thresholds) than the international standards, especially for soils and water. We defined three concentration ranges: below the minimal estimated permissible limit (green), between the minimal and maximal estimated permissible limits (orange), and above the maximal estimated permissible limit (red). Whenever only one threshold value was defined, no intermediate range could be defined (NA: not applicable). The same color codes for metals and concentration ranges were used in Figures 1 and 2.

Matrices	**Arsenic (As)**			**Cadmium (Cd)**			**Mercury (Hg)**			**Lead (Pb)**		
Food	<0.1	0.1-0.2	>0.2	>0.05	0.05-2	>2	<0.5	0.5-1	>1	<0.01	0.01-3	>3
Water	<0.01	0.01-0.1	>0.1	<0.003	0.003-0.01	>0.01	<0.001	NA	>0.001	<0.01	0.01-5	>5
Soil	<20	NA	>20	<0.9	0.9-3	>3	<0.03	0.03-2	>2	<30	30-50	>50

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FIGURES

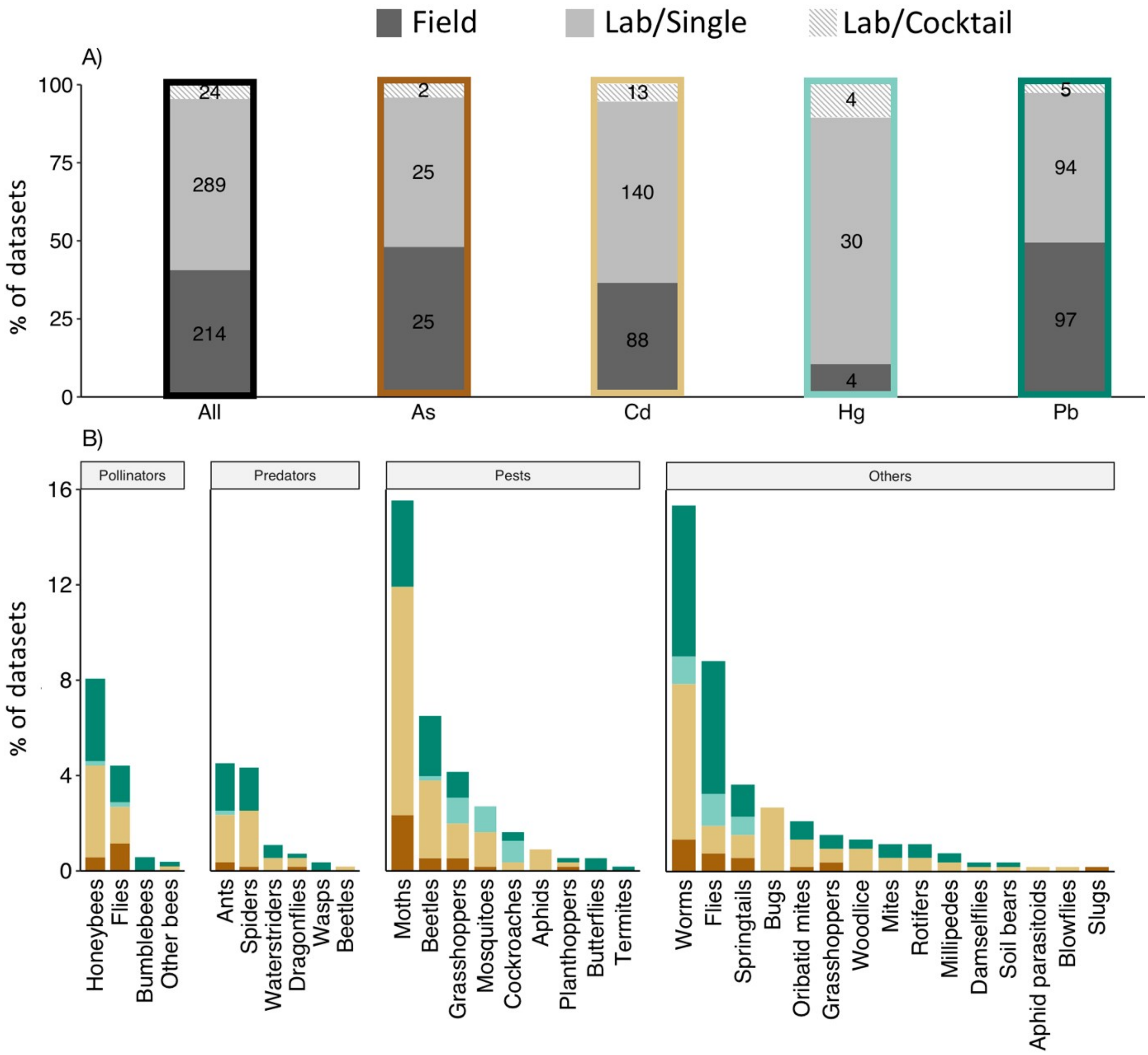

Figure 1: Diversity of groups of invertebrate species and experimental conditions. A) Percentage of experiments (sample sizes in black) conducted in the field (dark grey) or in the lab (light grey) per heavy metal. Experiments with mixtures of metals in the lab are displayed in textured light grey. Numbers of datasets are shown in bars. **B)** Diversity of invertebrate groups classified by economic importance (based on Skaldina and Sorvari (2019)). Datasets with different metals are marked by the same color code as Table 1 (As: brown, Cd: beige, Hg: light green, Pb: dark green).

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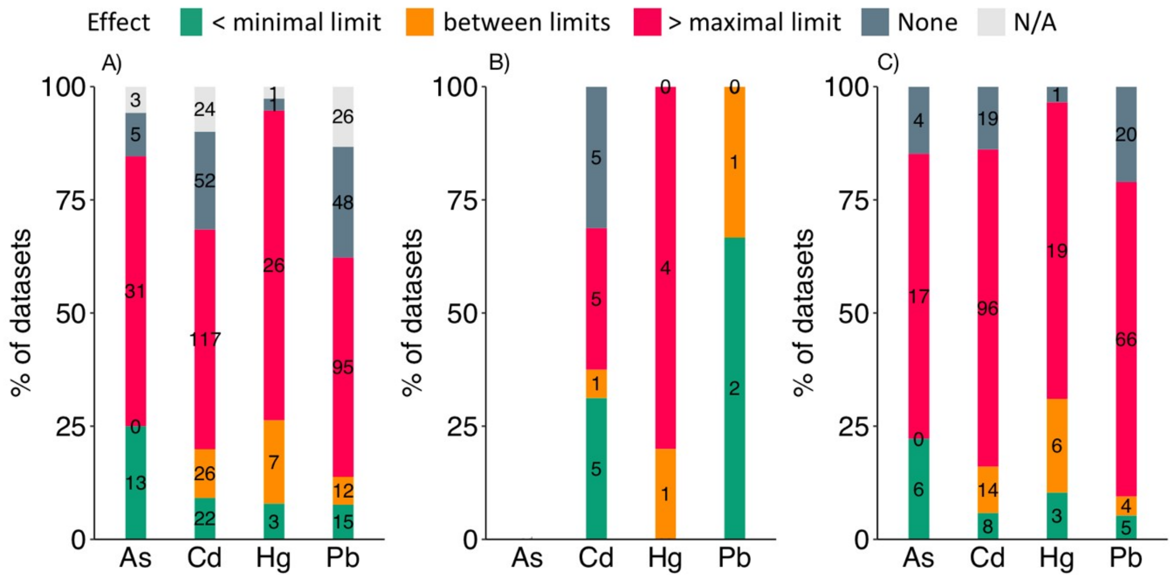

Figure 2: **Effects observed according to permissible limits**. We defined the following ranges below the minimal estimated limit, between the minimal and the maximal estimated limits, or above the maximal estimated limit. **A)** All studies (N=527). **B)** Laboratory studies with acute exposure (N=24) and **C)** chronic exposure (N=288). None: no observable effect, N/A: or no conclusion available. Sample sizes are in black. Concentration ranges were marked by the same color code as Table 1.

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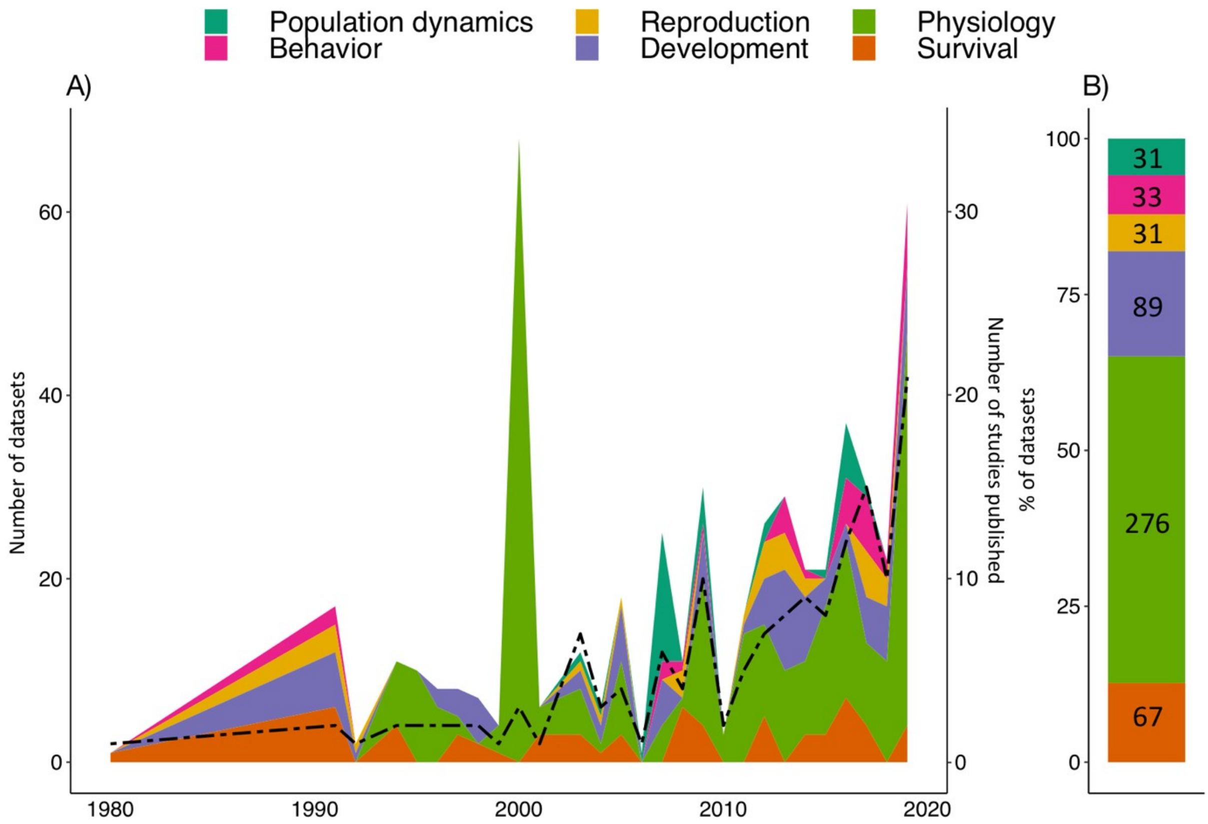

Figure 3: Biological variables measured. A) Area chart of the number of experiments per biological variable (year 2020 was omitted). The peak in 2000 is due to three large studies studying physiological effects in the field (38 experiments). The black dashed line represents the number of studies published yearly. **B)** Overall proportions of experiments per biological variable (numbers of datasets in black).

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SUPPLEMENTARY MATERIALS

Table S1: Raw data. Excel file detailing all parameters took into account for the analyses and the bibliographic sources of the 154 published articles.

Table S2: Permissible limits (ppm) for heavy metals in food, water and soil according to international and local standards. International standards used are displayed in bold.

Matrices	Area of application	Arsenic (As)	Cadmium (Cd)	Mercury (Hg)	Lead (Pb)	Source
Food	**International**	**0.1-0.2**	**0.05-2**	**0.5-1**	**0.01-3**	**(Codex Alimentarius 2015)**[1]
	European Union	0.1-0.2	0.05-3	0.1-1	0.02-3	Commission Regulation (EC) No 1881/2006 2006[2]; Commission Regulation (EU) 2015/1006 2015
	USA	NA	NA	NA	NA	The U.S. Food and Drug Administration has not established regulatory limits for trace metals in finished food products other than bottled water.
	China	0.5	0.05	0.01	0.2	Retrieved from (Li *et al.* 2006)[3]
Drinking water	**International**	**0.01**	**0.003**	**0.001**	**0.01**	**(Codex Alimentarius 2015)**[1]
	European Union	0.01	0.005	0.01	0.001	(European Commission 2019)[4]

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	USA	0.01	0.005	0.002	0.015	(US EPA 2017)[5]
	China	0.01	0.005	0.001	0.01	(Ministry of Health, China 2006)[6]
Irrigation water	**International**	**0.1**	**0.01**	**NA**	**5**	**(Ayers & Westcot 1994)**[7]
	USA	NA	0.005-0.01	NA	5	(US EPA 1978)[8]
	China	0.05	NA	0.01	NA	Retrieved from (Zhao *et al.* 2018)[9]
Soil	**International**	**20**	**0.9-3**	**0.03-2**	**30-50**	(WHO/FAO 2001; de Vries *et al.* 2003)[10,11]
	European Union	NA	NA	NA	NA	The European Union has not established limits for heavy metals in soils. There is however on-going policy to manage contamination, see (Council Directive 86/278/EEC 1986)[12] which states limit values in sludge for use in agriculture (Cd: 1-3 ppm; Hg:1-1.5 ppm; Pb:50-300 ppm)
	Finland	5-100	1-20	0.5-5	60-750	(Ministry of the Environment, Finland 2007)[13]. The Finnish standard values represent a good approximation of different national systems in Europe have been applied in an international context for

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						agricultural soils as well.
	UK	32-640	10-230	1-3600	450-750	(UK Environment Agency 2009)[14]
	USA	0.11	0.48	1	200	(US EPA 2002)[15] (US EPA 1993)[16] stated limit values in sludge for use in agriculture (As: 75 ppm; Cd: 85 ppm; Hg: 420 ppm; Pb: 840 ppm)
	China	20-40	0.3-0.6	0.3-1	80	(Environmental Protection Ministry of China 2015)[17]

References:

[1] Codex Alimentarius. (2015). Codex general standard for contaminants and toxins in food and feed - CODEX STAN 193-1995. Joint FAO/WHO.

[2] Commission Regulation (EC) No 1881/2006. (2006). Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs (OJ L364). EU.

[3] Li, J., Xie, Z.M., Xu, J.M. & Sun, Y.F. (2006). Risk assessment for safety of soils and vegetables around a lead/zinc mine. Environ. Geochem. Health, 28, 37–44.

[4] European Commission. (2019). Proposal for a Directive of the European Parliament and of the Council on the quality of water intended for human consumption (COM/2017/0753). EU.

[5] US EPA. (2017). Drinking water regulations (Safe Drinking Water Act).

[6] Ministry of Health, China. (2006). Standards for drinking water quality (GB 5749-2006).

[7]Ayers, R.S. & Westcot, D.W. (1994). Water quality for agriculture. FAO irrigation and drainage paper. Food and Agriculture Organization of the United Nations, Rome.

[8] US EPA. (1978). Aircraft industry waste water recycling (EPA-600/2-78-130).

[9] Zhao, X., Wang, H., Tang, Z., Zhao, T., Qin, N., Li, H., et al. (2018). Amendment of water quality standards in China: viewpoint on strategic considerations. Environ. Sci. Pollut. Res., 25, 3078–3092.

[10] WHO/FAO. (2001). Codex alimentarius commission. Food additives and contaminants. Food Standards Programme, ALINORM 10/12A. Joint FAO/WHO.

[11] de Vries, W., Schütze, G., Lots, S., Meili, M., Römkens, P., de Temmerman, L., et al. (2003). Critical limits for cadmium, lead and mercury related to ecotoxicological effects on soil organisms, aquatic organisms, plants, animals and humans. In: Proceedings of the expert meeting on critical limits for heavy metals and methods for their application, Berlin, 2–4 December 2002. Held under the UN/ECE Convention on Long- Range Transboundary Air Pollution UBA-Texte 47/03 (eds. Schütze, G., Lorent, U. & Spranger, T.). Umweltbundesamt, Berlin, pp. 29–78.

[12] Council Directive 86/278/EEC. (1986). Council Directive of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (OJ L181). EU.

[13] Ministry of the Environment, Finland. (2007). Government Decree on the assessment of soil contamination and remediation needs (214/2007).

[14] UK Environment Agency. (2009). Soil guideline values for arsenic, cadmium, mercury and lead in soil (SC050021).

[15] US EPA. (2002). Supplemental guidance for developing soil screening levels for superfund sites. Office of Solid Waste and Emergency Response, Washington, D.C.

[16] US EPA. (1993). Clean Water Act (Sec. 503, vol. 58, no. 32).

[17] Environmental Protection Ministry of China. (2015). Standards of soil environmental quality of agricultural land. Huangbanhang 69: Office of Environmental Protection Ministry of China, Beijing, China.

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