



Metals could challenge pollinator conservation in legacy cities

Sarah B. Scott¹ · Frances S. Sivakoff² · Megan E. Meuti¹ · Mary M. Gardiner¹

Received: 11 August 2022 / Accepted: 14 March 2023 / Published online: 8 April 2023
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2023

Abstract

Metal contamination is a worldwide issue that is particularly present and ubiquitous in urban environments. Many pollinators, including species of bees, butterflies, and moths are found in heavily modified landscapes where they may be negatively affected by exposure to metal contamination. Increased efforts to convert vacant urban lands to habitat that benefits such communities necessitates a thorough understanding of the hazard and risks pollinators face in metal contaminated landscapes. This investigation revealed that bees and butterflies have complex species and population specific responses to metals. Exposure to these pollutants can have reproductive, immunological, behavioral, and developmental impacts. These include challenged reproductive efforts, longer developmental times, and elevated brood mortality for pollinators.

Implications for insect conservation This review shows that pollinator conservation efforts are threatened if we fail to recognize the importance of metal exposure within contaminated landscapes. Bees and butterflies are exposed to metal concentrations in legacy cities that can cause reproductive, development, or behavioral impacts.

Keywords Bee · Butterfly moth · Vacant land · Contamination · Post-industrial · Novel habitat · Ecosystem services · Urban · Ecological restoration

Introduction

Over 350 cities worldwide have experienced substantial population loss over the last half century (Luescher & Shetty 2013) largely due to deindustrialization and suburbanization (Lever 1991). A hallmark of these post-industrial ‘legacy cities’ is their large holdings of vacant land resulting from the demolition of abandoned infrastructure (Fig. 1A–D) (Seymour 2020). Legacy cities are characterized by long-term economic disinvestment, shrinking populations, suburbanization, and social and political conflicts (Martinez-Fernandez et al. 2012; Haase et al. 2014). Vacancy shapes the landscape pattern of legacy city by creating dynamic mosaics of occupied and abandoned structures, and patches of formerly occupied vacant land (Gardiner et al. 2013; Sampson et al. 2017). Diverse and abundant bee and butterfly communities

have been documented within urban vacant lots within legacy cities (Sivakoff et al. 2018; Dylewski et al. 2019; Turo et al. 2021), promoting conservation focused investments to manage these reclaimed greenspaces as pollinator habitat (Fig. 1E–F) (Burr et al. 2016; Dylewski et al. 2019). However, vacant lot soils can contain elevated concentrations of metals (Fig. 2) (Sharma et al. 2015a; Perry et al. 2021), and the potential of metal pollution to challenge urban pollinator health cannot be ignored (Harrison & Winfree 2015; Sánchez-Bayo & Wyckhuys 2019; Parreño et al. 2022).

Anthropogenic activities such as transportation, manufacturing, construction, improper disposal of wastes, and demolition have contributed to metal pollution in cities worldwide (Sharma et al. 2015a; Nakajima & Aryal 2018) (Fig. 2). Even following the regulation of some major sources of metal pollution, a legacy of soil metal contamination remains as metals are generally stable and remain in place until remediated. For example, beginning in the 1970s and 1980s lead (Pb) was no longer used in the production of paint and gasoline in the United States (Kerr & Newell 2003). Nonetheless, Pb particles released from car exhaust and paint chips remain in urban soils (Schwarz 2016) and pose a risk to the local biodiversity (Gardiner & Harwood 2017). Likewise, metals such as chromium (Cr), copper

✉ Sarah B. Scott
scott.2094@osu.edu

¹ Department of Entomology, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210, USA

² Department of Evolution, Ecology, and Organismal Biology, The Ohio State University, 1465 Mount Vernon Ave, Marion, OH 43302, USA



Fig. 1 The legacy city of Cleveland, Ohio (USA) has lost over 50% of its peak population, which has resulted in an overabundance of housing infrastructure (A), which is demolished (B) seeded with fescue grasses (C) and mown approximately once per month during the growing season. Monthly mowing supports bloom of urban spontaneous vegetation such as red clover (*Trifolium pratense*), white clover (*Trifolium repens*) and chicory (*Cichorium intybus*) (Perry et al. 2021), which is visited by a high species richness of wild bees (Sivakoff et al. 2018; Turo et al. 2021) (D). The City of Cleveland Land Bank manages over 27,000 vacant lots and has sought out ways

to reimagine these greenspaces to support biodiversity and provide ecosystem services to the community. The addition of pocket prairies containing native Ohio wildflowers (E) and adding ornamental flowering plants to urban farms (F) are management strategies currently employed to provide forage for urban pollinators. Over 100 bee species have been found foraging within Cleveland's vacant lots, thus there is an urgent need to identify the metal exposure risks associated with vacant land as bee habitat and provide recommendations on how to safely implement pollinator focused conservation within legacy cities

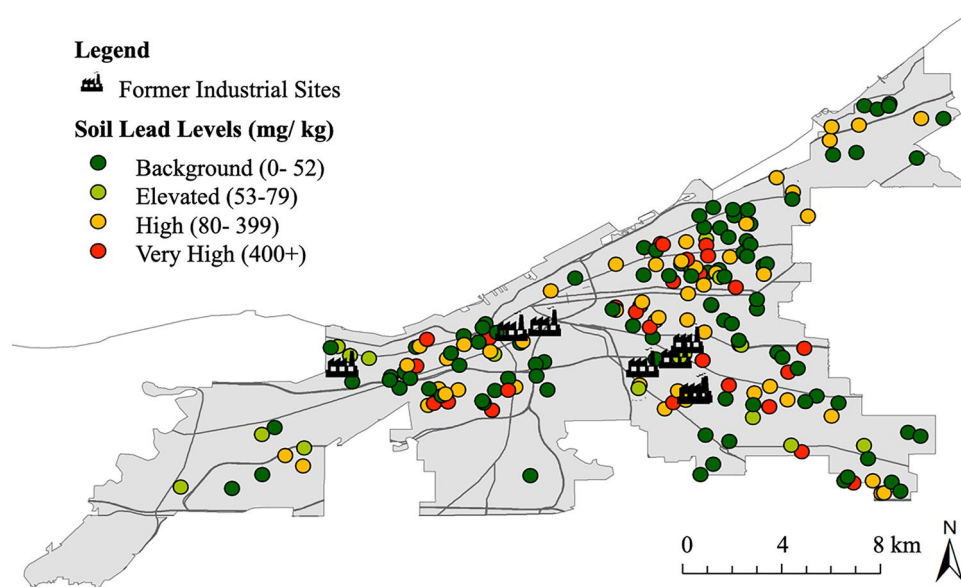


Fig. 2 Soil lead contamination is widespread throughout the city of Cleveland, OH, resulting in large part from historic manufacturing and industrial complexes (Jennings et al. 2002). The map shows locations of historic manufacturing and other industrial sites located in the city of Cleveland, OH, USA, and measured soil lead levels compared to background soil concentrations (51.7 mg/kg) (US EPA 2016). The soil metal data were collected from participants in the Ohio State University Extension's Summer Sprout Program. Vacant

lots under consideration as future garden sites within this program received complementary soil testing, which was completed by the Soil and Plant Tissue Testing Laboratory at the University of Massachusetts Amherst. Soil lead levels from 190 vacant lots are shown, collected from 1997 to 2016. Historic industrial sites were identified using a USA Today investigation from 2012 ("USA TODAY Investigation Reveals Hazardous Levels of Lead in Neighborhoods Across the Country" 2012)

(Cu), and zinc (Zn) are commonly found in urban soils at elevated concentrations (Karim et al. 2014). Due to atmospheric deposition and surface runoff of metals, trace metals are not exclusive to heavily modified urban soils near former industrial, waste disposal, or construction locations and can redistribute across a landscape via erosion, air currents, and water runoff (Li 2018), sometimes several kilometers from a point source (Suvarapu & Baek 2017). Additionally, continuous modern inputs of metals, such as from the demolition of structures, traffic emissions, and improper waste disposal, contribute to elevated soil lead, as well as arsenic, cadmium, zinc, aluminum, and chromium in urban soils (Sharma et al. 2015b). It is difficult to predict where metal contamination is concentrated due to the ability of metal pollution to travel away from point sources, and from continuous modern input of metals from residential sources. Thus, high levels of metal contamination may not be isolated to one area of a legacy city (Fig. 3).

The success of conservation initiatives utilizing vacant land are threatened if we fail to recognize the consequences of metal pollution for pollinator community health (Harrison & Winfree 2015). The goal of our review is to examine potential metal exposure routes for urban bees and butterflies, (hereafter pollinators), summarize known

chronic and acute impacts of metal exposure on pollinator species, including lethal and sublethal effects, and identify hurdles to pollinator conservation using vacant land within cities. We performed literature searches using Google Scholar and Web of Science for articles published between the years of 1980 and 2021 using the keywords 'pollinator, bee, butterfly, moth, caterpillar, Lepidoptera, Apidae AND metals, heavy metals, metalloids, metal pollution, metal contamination'. The resulting articles were screened, and we omitted duplicates, articles for which we were unable to obtain the full text, or articles that did not measure physiological responses, such as immune function, growth and development, and reproduction. Due to the small number of studies assessing metal impacts on pollinators of conservation concern, we also included studies of honey bees, *Apis mellifera*, (Hymenoptera: Apidae) as they are documented bioindicators of metal pollution worldwide (Celli & Maccagnani 2003), and common pestiferous Lepidoptera. We recognize that these species not ideal proxies for all pollinators of conservation concern. Nonetheless, by examining how metals influenced these common flower feeding insects we have formulated a research agenda to advance our understanding of how these pollutants shape conservation investment within legacy cities.

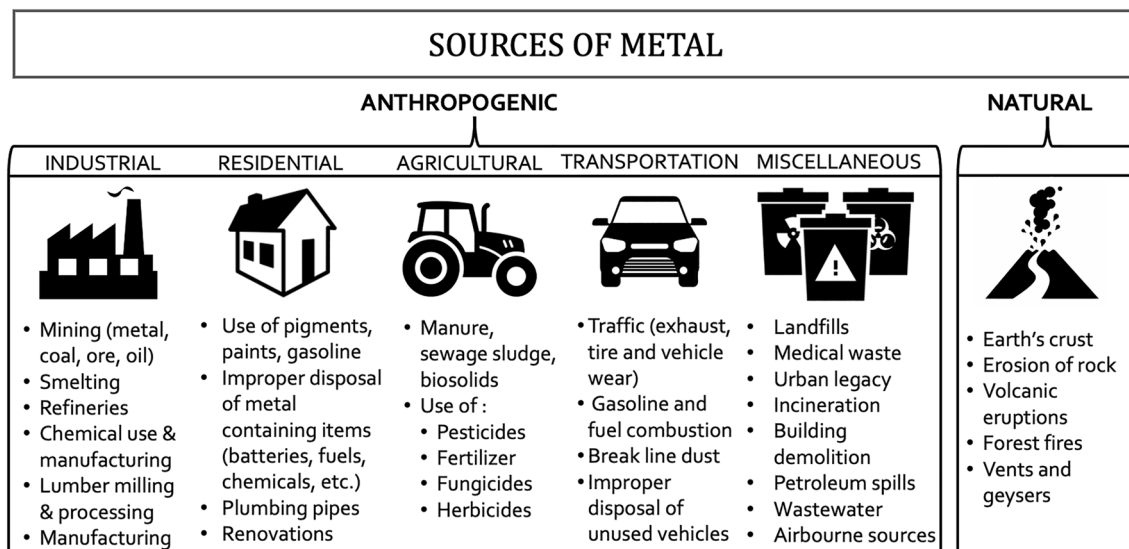


Fig. 3 Metals are byproducts of both natural and anthropogenic activities. Certain metals, such as iron, aluminum, and calcium make up large portions of the earth's crust and are released during erosion or volcanic eruption events. Anthropogenic sources of metals include pollution, traffic emission (tire and automobile wear particles, vehicle exhaust fumes, break line dust), the weathering of buildings and

machinery, industrial runoff, smelting, mining, fertilizers, domestic emission from the use of metal containing products, such as lead-based paint and leaded gasoline, and byproducts of urban legacy-materials that result from activities related to urban development and growth (Jennings et al. 2002; Wuana and Okieimen 2011a, b)

Possible metal exposure pathways

Within a contaminated habitat, pollinators could be exposed to metals through direct dermal contact with polluted water, air, or soil, and/or indirectly from ingesting contaminated resources or during grooming behaviors (Fig. 4). While the relative importance of these possible metal exposure pathways has not been identified, below we highlight possible metal exposure routes for urban pollinators.

Direct metal exposure pathways

Metal-contaminated dust, resulting from traffic emissions, fuel combustion, and construction and demolition processes is common within city landscapes (Aguilera et al. 2021). Metal-contaminated dust has been detected on tree leaves and other surfaces near roadways and industrial areas (Norouzi et al. 2015). Metal deposition on foliage surfaces represents a hazard to foliar feeding caterpillars that travel across and consume plant materials. Further, butterflies, moths, and bees could consume metal dust that settles on floral heads and within floral nectar and pollen provisions (Courtney et al. 1982; Clarke et al. 2017). Scanning electron microscope coupled with X-ray spectroscopy images revealed that metal particles concentrate on the head, wing margins, and corbiculae regions of honey bees (Negri et al. 2015). Thus, self-grooming and social bee allogrooming behaviors increase the possibility of ingesting metals (dust

particles with metals sorbed to the surface and/or metal dust) affixed to hairs and body surfaces and incorporating metals into collected resources. Further, particles that gather on the corbiculae, structures involved in pollen collection, are likely to be incorporated into pollen loads that will be fed to developing bees, as it has been demonstrated that anthropogenic dust can adhere to pollen grain surfaces (Okuyama et al. 2007; Negri et al. 2015).

Urban stormwater runoff often contains both dissolved and particulate-bound fractions of metals (Sansalone & Buchberger 1997; Turer et al. 2001), in addition to other pollutants (Song et al. 2019). Bees drink and collect water for nest construction from contaminated puddles (Antoine & Forrest 2021), and puddling behavior may expose butterflies to nonessential metals (Inoue et al. 2015). Surface soils (approximately 15 cm depth from surface) store the bulk of metals from stormwater runoff (Turer et al. 2001; Suvarapu & Baek 2017) and settled airborne particulates (Yang et al. 2016). Ground nesting and mason bees are commonly found in cities (Camilo et al. 2017; Sivakoff et al. 2018) and regularly contact and ingest soil during nest construction. For example, metal concentrations in pollen (Cd: 0.89–9.31 mg/kg), lead (Pb: 42.05–356.16 mg/kg), and zinc (Zn: 55.90–592.42 mg/kg) collected by *Osmia bicornis* (Hymenoptera: Megachilidae, previously *Osmia rufa*) near smelting sites in Poland were positively correlated with metal concentrations measured in surface soils at foraging sites, even though specific exposure routes were

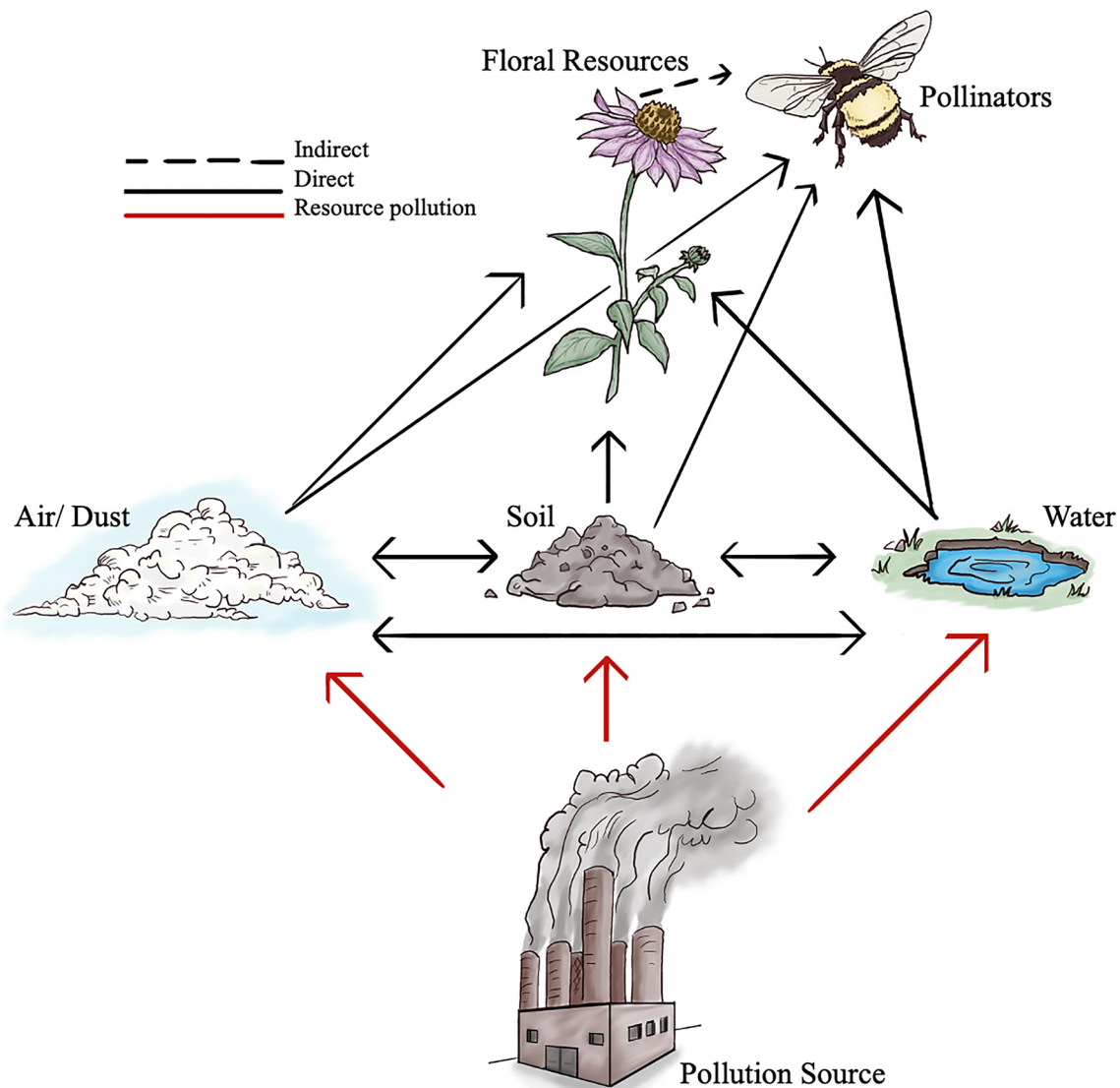


Fig. 4 Heavy metal exposure routes. Resources are directly contaminated from pollution sources, such as smelting operations, industrial manufacturing, and domestic use of metal containing items. Once resources are contaminated (air, soil, water), contamination can be transferred between resources; air and soil (dust erosion and deposition), air and water (evaporation and precipitation), soil and water (runoff). Additionally, plants can become contaminated from dust particulate landing on foliar surfaces as well as metal uptake from soil and water. Pollinators may be exposed to metals in the environ-

ment either directly or indirectly. Direct exposure routes may include consuming contaminated water, directly contacting contaminated soil during nest construction or travel, or contacting dust particulate while foraging on floral resources. Indirect exposure routes include consuming contaminated food resources, such as nectar or plant materials, taken up by the plant from the soil. Many unknowns remain surrounding pollinator metal exposure routes and impacts of metals on pollinator species

not confirmed (Moroń et al. 2012). Metal contamination of surface soils also presents a hazard to foliar feeding caterpillars, which travel across and consume soils to enhance their intestinal microbiota (Hannula et al. 2019).

Local soil conditions such as pH, soil type and texture, and organic matter content influence metal toxicity through changing metal bioavailability and movement through the environment (Rieuwerts et al. 1998; Turner & Mawji 2004). The reactive fraction of metals in the soils,

not the total concentration, dictates overall risk to flora and fauna (Liu et al. 2018). For example, pH influences metal solubility with generally high solubility under low pH conditions, while high organic carbon content in soil can adsorb certain metals and reduce bioavailability (Hou et al. 2020). Generally, water soluble and exchangeable forms of metals are more bioavailable to organisms than precipitated or particle bound species (Kim et al. 2015). Therefore, it is difficult to predict metal toxicity and risk

to pollinators by quantifying soil total metal concentrations alone.

Plant uptake and translocation of heavy metals

Certain plants are capable of translocating metals from contaminated soil or water to aboveground structures, including leaves and shoots, and pollen and nectar provisions (Meindl & Ashman 2015; Xun et al. 2017, 2018). Plants have evolved complex and efficient mechanisms for obtaining essential nutrients from the environment, even if present in extremely low concentrations. These mechanisms are also involved with the uptake, translocation, and sequestration of toxic elements (Tangahu et al. 2011; Singh et al. 2016). Plants can be classified into three major groups: metal excluder, indicators, and metallophytes/ hyper-accumulators (Bhalerao et al. 2013). Metal excluder species limit the translocation of metals from substrate and can maintain a low level of contaminant in their tissue over a wide range of metal concentrations. Indicator plant species accumulate metals in their biomass to levels that are usually reflective of soil metal concentrations (Cole & Smith 1984). Metallophytes, or hyper-accumulator plants, can take up metals from the roots and accumulate them in above ground tissues at concentrations 100–1000 fold higher than observed in non-hyperaccumulating species, all without experiencing any negative toxic effects (Singh et al. 2016). To date, over 450 metal hyper-accumulator species have been identified across 45 angiosperm families (Suman et al. 2018), with a majority of species in the *Brassicaceae* family, followed by *Asteraceae*, *Rubiaceae*, and *Fabaceae* (Morel et al. 2006), many of which contain important pollinator forage species.

Unfortunately, there is some evidence that urban plants commonly utilized by pollinators for foraging and nesting can accumulate metals (Simon et al. 1996; Zhu et al. 2001; Eskov et al. 2015; Pietrelli et al. 2022). Most plant metal uptake studies focus on metal concentrations in vegetative plant parts such as roots, shoots, and leaves (Shahid et al. 2017). Many crops commonly produced in urban agroecosystems (Mirecki et al. 2015), as well as urban spontaneous vegetation found within vacant lots, can accumulate metals in these plant parts, such as chicory (*Cichorium intybus*), dandelion (*Taraxacum officinale*), common milkweed (*Asclepias syriaca*), and clovers (*Trifolium*) (Simon et al. 1996; Zhu et al. 2001). Foliar metals represent a risk to developing caterpillars (Li et al. 2010; Pietrelli et al. 2022), as caterpillars have similar body metal profiles and metal concentrations as found in plant foliage after feeding on metal contaminated host plants (Wong & Cheung 1986; Ooik & Rantala 2010; Mitchell et al. 2020). Some genera of native plants recommended for pollinators in the Midwestern US (Xerxes Society 2017) can also accumulate metals in their above ground vegetative tissues including blazing star

(*Liatris*), black-eyed Susan (*Rudbeckia*), and wild bergamot (*Monarda*) (Miles & Parker 1979). Other pollinators, such as leaf cutting bees (*Megachilidae*), use leaf fragments to partition their nests for developing brood and may collect metal contaminated foliar resources within contaminated regions (Pitts-Singer & Cane 2011). For instance, in Toronto, Canada three species of leaf cutting bees utilized multiflora rose within nests (MacIvor 2016); this invasive plant can sequester Pb and other metals within aboveground plant tissues (Antonkiewicz et al. 2017). While the risk and toxicity of metal contaminated nest leaf fragments for adult female bees and their developing larva has not been identified, it is important to note this hazard to solitary stem nesting bees.

Fewer studies have examined the ability of plants to accumulate metals in flowers (Simon et al. 1996; Zhu et al. 2001; Xun et al. 2017; Pietrelli et al. 2022), nonetheless there is evidence that contaminated nectar and pollen could represent an exposure route for foraging pollinators, as demonstrated by metal content in honey bee honey (Conti & Botrè 2001). For instance, several bee visited plants within urban lots can accumulate metals within their flowers, including red clover (*Trifolium pratense*), chicory (*Cichorium intybus*), Queen Anne's lace (*Daucus carota*), and narrowleaf plantain (*Plantago lanceolata*) (Simon et al. 1996; Zhu et al. 2001; Eskov et al. 2015; Pietrelli et al. 2022). The nectar of common crops from urban agroecosystems such as sunflowers (*Helianthus*) (McCutcheon & Schnoor 2003), mustards (*Brassica*) (Bennet et al. 2003), radish (*Raphanus sativus*) and summer squash (*Cucurbita pepo*) (Hladun et al. 2015; Xun et al. 2017) have also been shown to contain metals. However, even closely related plants can vary in their translocation abilities of different metal species, which complicates identifying bioavailability and exposure. For example, the goldenrod species *Solidago canadensis* bioaccumulates Pb and Zn in its leaves, inflorescences, and roots (Bielecka & Królak 2019), while *Solidago gigantea* has high bioaccumulation but low translocation ability to move cadmium (Cd), Cu, Cr, iron (Fe), and nickel (Ni) from below ground to foliar tissues (Dambiec et al. 2022). Therefore, limiting pollinator exposure to metals when creating habitat will require testing of specific plants and metals as information from related species may not be representative.

Secondary effects of metals on resource availability and quality

Metal contamination in soils can influence plant physiology, community composition, and cause shifts in host plant range, which in turn alters available pollinator forage resources (Pandey et al. 2014; Chowdhury & Maiti 2016). Soil metal contamination can cause reduced seed production and germination, decreased seedling height, stunted growth, reduced fruit production, decreased root and shoot growth,

and morphological deformities (Kabata-Pendias 2011; Ahmad et al. 2012). These effects vary depending on the metal properties, concentration, and plant species (Cheng 2003). Metal pollution can significantly impact pollen germination and tube length, decrease pollen vitality and negatively impact plant reproductive biology (Mulder et al. 2005; Muradoğlu et al. 2017). Deformed flowers and plants receive fewer pollinator visits than normal flowers (Ohashi & Yahara 1998), resulting in lower pollination, genetic diversity, and reduced seed set.

Within contaminated sites, metal-tolerant genotypes dominate plant communities within a short timespan (Ryser & Sauder 2006). Physiological stress from metal exposure slows down succession in grasslands, which benefits early successional plants such as the fritillary butterflies host plant, *Viola calaminaria* (Salz & Fartmann 2017). Some critical nectar plants of butterflies are sensitive to metals and have reduced vigor in response to metal pollution. For instance, certain early spring host plants, annuals, and highly producing nectar plants are highly sensitive to metal pollution (Mulder et al. 2005). Butterfly population shifts in metal contaminated habitats may be a secondary effect of metal stress on host plant vigor, reduced nectar or pollen availability, and changes in species presence (Mulder et al. 2005). Interestingly, certain plants preferred by moths are almost twice as tolerant of metals compared to plants visited mainly by butterfly species (Mulder et al. 2005) which may lead to shifts in plant community structure and subsequent changes in lepidopteran population dynamics from shifting host plant ranges.

Metals and pollinator health

Metal pollution has direct negative impacts on pollinator survivorship (Di et al. 2016; Ali et al. 2019), reproduction and fitness (Morón et al. 2014; Scott et al. 2022), morphology (Szentgyörgyi et al. 2017), and behavior (Burden et al. 2016, 2019) (Fig. 5). Clearly, mortality from metal exposure negatively impacts pollinator populations (Sgolastra et al. 2018a, b), however, the sublethal effects of metal exposure are more nuanced.

Reproductive success

Pollinators exposed to metals can experience reduced reproductive success (Morón et al. 2014; Sivakoff et al. 2020; Scott et al. 2022). For instance, the fecundity of the solitary, stem nesting red mason bee, *Osmia bicornis* (Hymenoptera: Megachilidae), declined with proximity to two smelters in Poland and the UK that contaminated the soil with Cd, Pb, and Zn (Morón et al. 2014). Females foraging near the smelters collected provisions with elevated Zn concentrations and

constructed fewer brood cells; their offspring sustained twice the larval mortality as individuals in uncontaminated sites with 50–60% overall brood mortality (Morón et al. 2014). Within the legacy city of Cleveland, Ohio (USA), colonies of the common eastern bumble bee, *Bombus impatiens* (Hymenoptera: Apidae) were more likely to contain measurable concentrations of Cr (0.39 mg/kg), Cu (23.9 mg/kg), Fe (119.5 mg/kg), Ni (0.63 mg/kg) and Zn (93.2 mg/kg) within forager bodies and collected provisions compared to colonies located outside the city (Sivakoff et al. 2020). Chronic consumption of provisions contaminated with As, Cd, Cr, or Pb caused 40 to 90% bumble bee brood mortality, three times that of unexposed colonies (Scott et al. 2022). Additionally, honey bee fitness is negatively affected when jointly exposed to Cd and Cu in the laboratory, causing an increase in larval development duration and mortality (Di et al. 2020). A larger impact of metals on immature insects compared to adults could be because developing brood express fewer detoxification genes than adult females (Xu et al. 2013; Di et al. 2016). For instance, Hunt's bumble bee, *Bombus huntii* (Hymenoptera: Apidae) express varying levels of genes associated with immune response and detoxification across life stages, and to a greater extent than other genes (Xu et al. 2013).

Fitness consequences likely result from physiological trade-offs between metal detoxification and reproduction in insects (Bashir-Tanoli & Tinsley 2014; Schwenke et al. 2016). This has been demonstrated in honey bees whereby queens stressed by pesticide exposure produce fewer eggs than unstressed queens in similarly sized colonies (Wu-Smart & Spivak 2016). Similarly, exposure to a mix of pesticides and fungicides reduced ovarian maturation and shortened the lifespan of *Osmia bicornis* (Sgolastra et al. 2018a). It is highly likely that detoxifying metals would activate similar physiological pathways in solitary bees and therefore may result in decreased reproduction, but this requires further investigation. Yet, species vary in their tolerance of metals, for instance, metal exposure has different impacts on pestiferous lepidopteran species. The tobacco cutworm, *Spodoptera litura* (Lepidoptera: Noctuidae), fed artificial diet with 300–750 mg/kg of Zn have a shortened egg laying period and reduced oviposition rate compared to individuals not fed metals (Shu et al. 2009). Similarly, the beet armyworm, *Spodoptera exigua* (Lepidoptera: Noctuidae) copulate less and produce fewer eggs when fed artificial diet containing 51.2 mg/kg of Cd-spiked food (Su et al. 2021). Conversely, Zn tolerant female cabbage white butterflies, *Pieris rapae* (Lepidoptera: Pieridae), produce more eggs and have higher reproductive efforts under nonpolluted conditions (Shephard et al. 2021). Physiological responses to metal exposure are complex, and species and population specific, thus potential risks should be assessed at the species level.

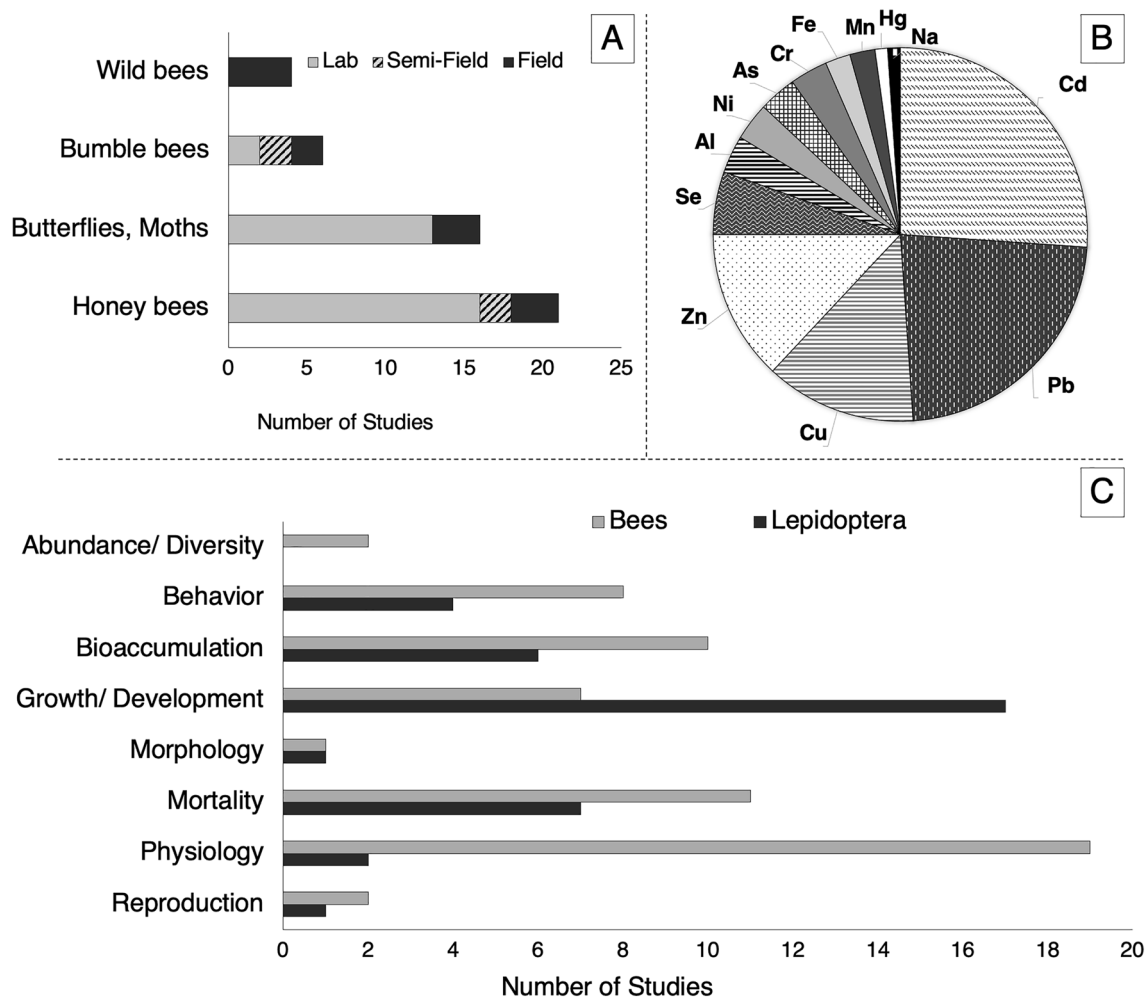


Fig. 5 Summary of studies measuring the impact of metals on pollinators. Summary graphs of literature search using Web of Science and Google Scholar from years 1980–2021, using search terms: pollinator; bee; solitary bee; butterfly; bumble bee; honey bee; Lepidoptera; AND heavy metal; metal; metal pollution; metal contamination resulted in 48 articles that fit our search criteria. **A** Research articles were classified as field based, semi-field (outdoors with manipulation), or lab based per group. **B** Pie chart sections represent the most common metals tested in bee and butterfly literature combined **C** Major effects of metal exposure on pollinators that were identified

Growth and development

Metal exposure at toxic levels can result in pollinator morphological abnormalities, such as reduced eye (Philips et al. 2017), head (Monchanin et al. 2021) and wing size (Szentgyörgyi et al. 2017; Shephard et al. 2020), which have clear implications for dispersal and foraging success. Increased incidence of morphological deformities such as deformities of pupal body and improper molting in Cd-exposed northern armyworm, *Mythimna separate*, moths have also been noted (Wei et al. 2020).

within each study. Some articles addressed multiple topics within the study. All bee groups (honey bees, bumble bees, solitary bees) were combined into ‘bees’ (n=32), and ‘butterflies and moths’ include some common pestiferous lepidopteran species (n=16). ‘Physiology’ category contains the following topics combined: cellular physiology (Bees: 1; Leps: 0), gene expression (Bees: 6; Leps: 0), immune function (Bees: 1; Leps: 0), metabolomics (Bees: 2; Leps: 0), microbiomics (Bees: 2; Leps: 0), physiology (Bees: 7; Leps: 1) and tolerance (Bees: 0; Leps: 1)

Butterflies reared on food containing field realistic concentrations of Cd, Cu, Fe, Pb and Zn can exhibit reduced consumption and growth rates, lower pupation weight and a smaller adult body size (Nieminen et al. 2001; Fred & Brommer 2005; Ali et al. 2019; Shephard et al. 2020). For instance, autumnal moth, *Epirrita autumnata* (Lepidoptera: Geometridae) caterpillars reared on metal polluted bilberry leaves (As: 1.02 mg/kg; Ni: 12.9 mg/kg; Pb: 0.85 mg/kg) grown near smelting locations in Finland exhibited reduced body mass and growth rates compared to caterpillars fed uncontaminated bilberry leaves and had significantly higher levels of metals in their bodies compared to caterpillars

reared on uncontaminated leaves (Eeva et al. 2018). Importantly, these developmental effects vary among pollinator species. Non-native pest species often exhibit a greater tolerance to metal exposure and may have enhanced detoxification ability due to recent selection from targeted insecticide management (Shephard et al. 2020), compared with species of conservation concern which are usually protected from such management techniques. For example, monarch caterpillars, *Danaus plexippus* (Lepidoptera: Nymphalidae) have reduced survivorship to pupation when reared on diets containing 344 mg/kgZn in the laboratory, whereas cabbage white butterfly caterpillars fed the same diet exhibited increased survival (Shephard et al. 2020). The cabbage white butterflies that consumed Zn did, however, experience a tradeoff through prolonged developmental time and a smaller adult body size (Shephard et al. 2020).

Response to stressors

Metal exposure impacts insect immune function (van Ooik et al. 2008), gene expression (Johnson et al. 2012), stress response (Martinek & Hedb 2020), and survival when exposed to multiple environmental stressors (Rothman et al. 2020; Jiang et al. 2021). Investing in immune responses to parasites, diseases, or pathogens may reduce a pollinator's ability to detoxify other contaminants (Goulson et al. 2015; Gong & Diao 2017). For example, honey bees exposed to 1.0 mg/kgCd demonstrate severe cellular damage of fat bodies and reduced immunocompetence, resulting in decreased ability to combat bacterial infection (Polykretis et al. 2016). Conversely, sometimes a mild stressor can upregulate a conserved metabolic pathway and thereby synergistically enhance an organism's ability to combat another environmental threat. Honey bees that are orally exposed to sublethal doses of pesticide and fed ad libitum have increased survivorship when challenged with an additional stressor, possibly through hormesis (Dickel et al. 2018). Similarly, pollution exposure enhances immune function of female autumnal moths, but not in males (Ooik & Rantala 2010).

Metal exposure alters honey bee microbiome composition, metabolite profile, detoxification compounds (Rothman et al. 2019b), and alters gut microbial community composition and relative abundance of specific core biota in bumble bees (Rothman et al. 2019a). Insect detoxification and microbiota symbiosis influence the severity of metal exposure and cause multigenerational impacts of these contaminants for pollinator health. Gut microbiota contribute to digestion, development, pathogen resistance, and other physiological processes including detoxification (Jing et al. 2020), as well as influence the survival, size, and egg production in some insects (Coon et al. 2016), so a disruption to the microbiome can negatively impact metabolism, immune function, and health (Raymann & Moran 2018; Rothman et al. 2019b).

Bumble bee queens' gut microbiome changes across key life stages from eclosion to egg laying, and likely play important roles in egg development and fecundity (Wang et al. 2019). Furthermore, microbiota inoculation increases survival for bumble bees exposed to field realistic doses of selenate (0.75 mg/L) compared to uninoculated bees (Rothman et al. 2019a). The microbiome increases survival for bees exposed to metalloids (Rothman et al. 2019b), therefore, may play a significant role in bee fecundity and success or failure in contaminated landscapes.

Foraging behavior

Some bee species do not avoid foraging on metal contaminated flowers, as they are unable to detect nectar qualities until inspection (Hladun et al. 2015; Sivakoff & Gardiner 2017; Xun et al. 2017). For example, honey bees do not avoid Ni-contaminated resources when presented with a choice (Meindl & Ashman 2014, 2015), and bumblebees are not able to detect naturally occurring concentrations of nectar toxicants within choice feeding assays (Tiedeken et al. 2014). However, pollinators have been found to alter their foraging activity at contaminated resources with certain compounds after resource inspection. For instance, honey bees and wasps take fewer and shorter visits to nectar feeders containing concentrations of metals commonly found in roadside soils (Cd: 0–0.8 mg/kg; Cu: 0–50 mg/kg; Pb: 0–3 mg/kg; Sb: 0–0.8 mg/kg; Zn: 0–100 mg/kg) (Phillips et al. 2021). Bumble bees and honey bees forage for shorter durations at sunflowers (*Helianthus*) grown in Pb contaminated soil (Sivakoff & Gardiner 2017), *Impatiens capensis* (Balsaminaceae) flowers contaminated with aluminum (Al) (Meindl & Ashman 2013) and at *Hosta* flowers where metal contaminated nectar was added (Zn: 80 mg/L; Cu: 55 mg/L; Ni: 50 mg/L; Pb: 55 mg/L) (Xun et al. 2018). The inability of pollinators to detect and avoid metal contaminated food until consumption suggests contaminated nectar can be a direct exposure route (Meindl & Ashman 2015; Burden et al. 2019).

Oral metal exposure can impair pollinator memory, cognition, long-term recall, and learning (Burden et al. 2016; Monchanin et al. 2021), which can also influence their foraging behavior. For example, manganese (Mn) exposure alters honey bee brain biogenic amine levels that causes premature transition from in-hive functions to foraging behaviors and results in poor foraging by these precocious and inexperienced workers (Søvik et al. 2015). Chronic oral exposure to trace amounts of Pb results in impaired cognition and reduced olfactory learning performance (Monchanin et al. 2021), critical for successful foraging bouts. Any reduction in foraging efficiency can reduce food resources that are available for developing brood, and poor pollination services

for the plant, ultimately leading to a decline in seed set (Stefan-Dewenter & Tscharrntke 1999; Webber et al. 2020).

Hurdles to urban pollinator conservation

Metal contamination remains a ubiquitous, yet largely under investigated challenge to urban pollinator conservation (Fig. 5A–C). To date, the majority of studies that have assessed the lethal or sub-lethal impacts of metal exposure on wild pollinators have been conducted in the laboratory, with metal concentrations that may or may not be field relevant (Fig. 5A). Further, most studies have targeted honey bees and pestiferous Lepidoptera—few have focused on species of conservation concern (Fig. 5A). Likewise, not all common metal contaminants have received equal focus, with most studies examining how exposure to Cd, Pb, Cu and Zn influence pollinator health (Fig. 5B). Although these are common soil contaminants within many legacy cities (Sharma et al. 2015a) other metals, such as As, Cr, Ni, and Fe, are also frequently found at elevated concentrations (Sharma et al. 2015a, b; Pietrelli et al. 2022) and could represent a significant risk to pollinators. There is a major need to invest in assessing the physiological effects of metal exposure on pollinators of conservation concern. Fewer than 20 studies have examined physiological effects of metals on pollinator health, with growth and development, survivorship, and bioaccumulation being the most studied to date (Fig. 5C).

Field-relevant metal toxicity and multiple stressors

Focusing on field-relevant doses of metals is fundamental for determining realistic risks in contaminated environments. Specifically, soils contaminated with the metal byproducts of industrial activity, both biologically available and unavailable, often contain elevated concentrations of several pollutants and the additive or synergistic effects of exposure to these toxins warrants further study. Further, presence of a metal in the environment does not necessarily mean toxicity, so understanding the risk posed by environmentally relevant metal concentrations is paramount. Likewise, the frequent use of indicator species such as honey bees is unlikely to accurately illustrate mortality risks of acute metal exposure for all pollinators (Arena & Sgolastra 2014; Franklin 2019). For example, a meta-analysis comparing sensitivities of honey bees versus non-honey bee Apiformes to pesticides found high variability of sensitivities between species, with certain species having ten-fold higher sensitivity than honey bees to chemicals (Arena & Sgolastra 2014). Metal toxicity can also vary by life stage, sex, feeding behaviors, and genetic background (Tchounwou et al. 2012) as well as functional traits such as nesting substrate, floral specialization,

and capacity for dispersal, necessitating studies accounting for these differences. In fact, the importance of soil metal contamination as a driver of pollinator distributions is virtually unknown with just two studies measuring bee species diversity and abundance across a contamination gradient (Morón et al. 2012, 2014). To our knowledge no studies have examined butterfly diversity across a contamination gradient, or the influence of environmental metal contamination on the distribution of pollinator functional diversity in legacy cities.

Sublethal effects and tolerance

To date, just 17 studies have measured the effects of chronic exposure to sublethal metal concentrations on wild pollinator behavior, physiology, and morphology (Fig. 5C, see Appendix S1). Metal exposure is known to alter gut microbiota which in turn can impact nutrient availability, immune function and detoxification across an insect's lifecycle (Jing et al. 2020). Understanding how metals, in combination with other urban stressors such as elevated temperatures, reduced habitat quality, and the presence of additional pollutants influence pollinator health is challenging but necessary to advance conservation planning. A pollinator's physiological condition, such as their nutritional status, is likely to vary across urban landscape contexts and this could influence the severity of health impacts resulting from metal exposure (Tchounwou et al. 2012). For example, bumble bee queen development in reproductive colonies is impacted by available nutrition (dos Santos et al. 2016), and exposure to metals may differentially influence queen production in colonies with suboptimal versus optimal nutrition.

Animals found in stressed environments can develop a tolerance to metals (Singh 2005; Merritt & Bewick 2017), but to our knowledge the capacity of pollinators to do so is not known. Certainly, a high species richness of bees and butterflies are found in contaminated sites (Sivakoff et al. 2018; Turo et al. 2021), but as highly mobile insects, differentiating between populations that have experienced chronic metal exposure versus individuals that have recently emigrated from outside of the contaminated region is difficult. Life history traits may influence a pollinators' likelihood to adapt, specifically if the nesting habits of certain species are more likely to expose them to stressors and/or if their host plants hyperaccumulate metals.

Identifying exposure routes

Understanding metal exposure routes and bioavailability for pollinators is critical to advancing urban conservation planning and implementation. Assessments of metals' risks to pollinators by airborne particulates, soil, and water are needed to develop best management practices to minimize

harmful exposure. Pollinators may also be exposed to metals via plant uptake from contaminated soil. The accumulator status of urban spontaneous vegetation growing in ruderal locations, which represents a major source of urban pollinator forage, is largely unknown. This information could guide best practices for urban pollinator habitat establishment and management. For instance, if plant uptake is a major exposure route, frequent mowing of urban vegetation to prevent bloom could be practiced within contaminated vacant land to limit pollinators' dietary exposure (Rascio & Navari-Izzo 2011). Additionally, plant exposure to metals may negatively influence the quality of the nectar and pollen and further harm bees by providing poor quality food (Muradoğlu et al. 2017).

Low-cost remediation strategies

Metals represent a hazard to humans and wildlife living in human dominated areas, as metal contamination is present where large proportions of human populations live. The objective of any soil remediation effort is to be protective of and reduce overall risk to human, plant, and animal health (Wuana and Okieimen 2011a, b). Several options for in situ and ex situ remediation techniques that use chemical, physical, or biological methods are available, including phytoremediation, soil amendments, immobilization and soil washing (Wuana and Okieimen 2011a, b; Li et al. 2019). Additional cost-efficient methods to reduce the chances of metal exposure include frequent mowing of blooming species in contaminated areas, and sowing plant species that do not uptake metals into the biomass. However, we need to understand exposure routes, metal speciation, and bioavailability to appropriately design a successful remediation strategy. Soil contamination needs to be characterized to establish type, distribution, and amount of metal in the soil and the desired end concentration must be established (Wuana and Okieimen 2011a, b). Therefore, to identify a metal remediation goal, we first need to determine environmental quality guidelines for pollinator metal exposure levels that can be used to inform remediation efforts.

Conclusions

This review was motivated by the enthusiasm that community leaders within legacy cities demonstrate for urban pollinators and their willingness to establish bee habitat utilizing reclaimed vacant land. These individuals recognize the risk metals may pose to their conservation plans and seek low-cost tactics to reduce or eliminate pollinator exposure within urban habitats. For example, Bee City USA is a national program that encourages local communities to implement pollinator focused plantings and make commitments to conserve

native pollinators through conscious action. Cities, towns, and counties are encouraged to "...create and enhance pollinator habitat on public and private land by increasing the abundance of native plants and providing nesting sites" ("Bee Campus USA Commitments" 2020). These plantings could include vacant lots or border highways, where metal exposure could be a concern. For instance, the Bee City USA volunteers in the city of Lynchburg, Virginia, USA collaborated with the city Buildings and Grounds department to reduce mowing and herbicide use in vacant lots and on local roadways in an effort to provide food and habitat for pollinators ("Affiliate Spotlight" 2021). Such dedication to aiding urban pollinator communities deserves research-based guidelines for the selection of sites, plant communities and management practices to diminish the risks posed by metals.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10841-023-00474-y>.

Acknowledgements We thank R. Lanno for providing feedback and edits on this article. S.B.S. was supported by a fellowship from the United States National Science Foundation Graduate Research Fellowship Program.

Author contributions S.B.S. conducted the literature search. S.B.S. and M.M.G wrote the main manuscript text. M.M.G prepared figure 1. F.S.S prepared figure 2. S.B.S. prepared figures 3-5 and table 1 in the appendix. All authors reviewed the manuscript.

Declarations

Competing interest The authors declare no conflict of interest.

References

- Affiliate Spotlight: Lynchburg, Virginia (2021) <https://beecityusa.org/affiliate-spotlight-lynchburg-virginia/>. Accessed 23 June 2022
- Aguilera A, Bautista F, Gutiérrez-Ruiz M, Cenicer-Gómez AE, Cejudo R, Goguitchaichvili A (2021) Heavy metal pollution of street dust in the largest city of Mexico, sources and health risk assessment. *Environ Monit Assess* 193:193
- Ahmad I, Akhtar MJ, Zahir ZA, Jamil A (2012) Effect of cadmium on seed germination and seedling growth of four wheat (*Triticum aestivum* L.) cultivars. *Pak J Bot* 44:1569–1574
- Ali S, Ullah MI, Saeed MF, Khalid S, Saqib M, Arshad M, Afzal M, Damalas CA (2019) Heavy metal exposure through artificial diet reduces growth and survival of *Spodoptera litura* (Lepidoptera: Noctuidae). *Environ Sci Pollut Res* 26:14426–14434
- Antoine CM, Forrest JRK (2021) Nesting habitat of ground-nesting bees: a review. *Ecol Entomol* 46:143–159
- Antonkiewicz J, Kołodziej B, Bielińska EJ (2017) Phytoextraction of heavy metals from municipal sewage sludge by *Rosa multiflora* and *Sida hermaphrodita*. *Int J Phytorem* 19:309–318
- Arena M, Sgolastra F (2014) A meta-analysis comparing the sensitivity of bees to pesticides. *Ecotoxicology* 23:324–334
- Bashir-Tanolli S, Tinsley MC (2014) Immune response costs are associated with changes in resource acquisition and not resource reallocation. *Funct Ecol* 28:1011–1019

- Bee Campus USA Commitments (2020) <https://beecityusa.org/bee-campus-usa-commitments/>. Accessed 26 Jan 2022
- Bennet L, Burkhead J, Hale K, Terry N, Pilon M, Pilon-Smits E (2003) Analysis of transgenic Indian Mustard plants for phytoremediation of metal-contaminated mine tailings—Bennett et al. 32 (2): 432—Journal of Environmental Quality. J Environ Qual 32:432–440
- Bhalerao DSA, Dalvi AA, Bhalerao SA (2013) Response of plants towards heavy metal toxicity: an overview of avoidance, tolerance and uptake mechanism
- Bielecka A, Królak E (2019) *Solidago canadensis* as a bioaccumulator and phytoremediator of Pb and Zn. Environ Sci Pollut Res 26:36942–36951
- Burden CM, Elmore C, Hladun KR, Trumble JT, Smith BH (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 CM, Morgan MO, Hladun KR, Amdam GV, Trumble JJ, Smith BH (2019) Acute sublethal exposure to toxic heavy metals alters honey bee (*Apis mellifera*) feeding behavior. Sci Rep 9:1–10
- Burr A, Schaeg N, Muñiz P, Camilo GR, Hall DM (2016) Wild bees in the city: reimagining urban spaces for native bee health. Cons J Sustain Dev 16:96–121
- Camilo GR, Muñiz PA, Arduser MS, Spevak EM (2017) A Checklist of the Bees (Hymenoptera: Apoidea) of St. Louis, Missouri, USA. J Kansas Entomol Soc 90:175–188
- Celli G, Maccagnani B (2003) Honey bees as bioindicators of environmental pollution. Bull Insectol 2003:137–139
- Cheng S (2003) Effects of Heavy metals on plants and resistance mechanisms. Environ Sci Pollut Res 10:256–264
- Chowdhury A, Maiti SK (2016) Identification of metal tolerant plant species in mangrove ecosystem by using community study and multivariate analysis: a case study from Indian Sunderban. Environ Earth Sci 75:744
- Clarke D, Morley E, Robert D (2017) The bee, the flower, and the electric field: electric ecology and aerial electroreception. J Comp Physiol A 203:737–748
- Cole MM, Smith RF (1984) Vegetation as indicator of environmental pollution. Trans Inst Br Geograph 9:477–493
- Conti ME, Botrè F (2001) Honeybees and their products as potential bioindicators of heavy metals contamination. Environ Monit Assess 69:267–282
- Coon KL, Brown MR, Strand MR (2016) Gut bacteria differentially affect egg production in the anautogenous mosquito *Aedes aegypti* and facultatively autogenous mosquito *Aedes atropalpus* (Diptera: Culicidae). Parasit Vectors 9:375
- Cooper AM et al (2020) Monitoring and mitigation of toxic heavy metals and arsenic accumulation in food crops: a case study of an urban community garden. Plant Direct 4:e00198
- Courtney SP, Hill CJ, Westerman A (1982) Pollen carried for long periods by butterflies. Oikos 38:260–263
- Dambiec M, Klink A, Polechońska L (2022) Concentration and translocation of trace metals in *Solidago gigantea* in urban areas: a potential bioindicator. Int J Environ Sci Technol. <https://doi.org/10.1007/s13762-022-03932-3>
- Di N, Hladun KR, Zhang K, Liu TX, Trumble JT (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 KR, Rust M, Chen Y-F, Zhu Z-Y, Liu T-X, Trumble JT (2020) Joint effects of cadmium and copper on *Apis mellifera* forgers and larvae. Comp Biochem Physiol c: Toxicol Pharmacol 237:108839
- Dickel F, Münch D, Amdam GV, Mappes J, Freitak D (2018) Increased survival of honeybees in the laboratory after simultaneous exposure to low doses of pesticides and bacteria. PLoS ONE 13:e0191256
- dos Santos CF, Acosta AL, Dorneles AL, dos Santos PDS, Blochtein B (2016) Queens become workers: pesticides alter caste differentiation in bees. Sci Rep 6:31605
- Dylewski Ł, Maćkowiak Ł, Banaszak-Cibicka W (2019) Are all urban green spaces a favourable habitat for pollinator communities? Bees, butterflies and hoverflies in different urban green areas. Ecol Entomol 44:678–689
- Eeva T, Holmström H, Espín S, Sánchez-Virosta P, Klemola T (2018) Leaves, berries and herbivorous larvae of bilberry *Vaccinium myrtillus* as sources of metals in food chains at a Cu-Ni smelter site. Chemosphere 210:859–866
- Eskov EK, Eskova MD, Dubovik VA, Vyrodov IV (2015) Content of heavy metals in melliferous vegetation, bee bodies, and beekeeping production. Russ Agric Sci 41:396–398
- Franklin EL, Raine NE (2019) Moving beyond honeybee-centric pesticide risk assessments to protect all pollinators. Nat Ecol Evol 3:1373–1375
- Fred MS, Brommer JE (2005) The decline and current distribution of *Parnassius apollo* (Linnaeus) in Finland; the role of Cd. Ann Zool Fenn 42:69–79
- Gardiner MM, Harwood JD (2017) Influence of heavy metal contamination on urban natural enemies and biological control. Curr Opin Insect Sci 20:45–53
- Gardiner MM, Burkman CE, Prajzner SP (2013) The value of urban vacant land to support arthropod biodiversity and ecosystem services. Environ Entomol 42:1123–1136
- Gong Y, Diao Q (2017) Current knowledge of detoxification mechanisms of xenobiotic in honey bees. Ecotoxicology 26:1–12
- Goulson D, Nicholls E, Botías C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science. <https://doi.org/10.1126/science.1255957>
- Haase A, Rink D, Grossmann K, Bernt M, Mykhnenko V (2014) Conceptualizing urban shrinkage. Environ Plan A Econ Sp 46:1519–1534
- Harrison T, Winfree R (2015) Urban drivers of plant-pollinator interactions. Funct Ecol 29:879–888
- Hannula SE, Zhu F, Heinen R, Bezemer TM (2019) Foliar-feeding insects acquire microbiomes from the soil rather than the host plant. Nature Commun 10:1254
- Hladun KR, Parker DR, Trumble JT (2015) Cadmium, copper, and lead accumulation and bioconcentration in the vegetative and reproductive organs of *Raphanus sativus*: implications for plant performance and pollination. J Chem Ecol 41:386–395
- Hou D, O'Connor D, Igalavithana AD, Alessi DS, Luo J, Tsang DCW, Sparks DL, Yamauchi Y, Rinklebe J, Ok YS (2020) Metal contamination and bioremediation of agricultural soils for food safety and sustainability. Nat Rev Earth Environ 1:366–381
- Inoue TA, Ito T, Hagiya H, Hata T, Asaoka K, Yokohari F, Niihara K (2015) K+ Excretion: the other purpose for puddling behavior in Japanese *Papilio butterflies*. PLoS ONE 10:e0126632
- Jennings AA, Cox AN, Hise SJ, Petersen EJ (2002) Heavy metal contamination in the brownfield soils of Cleveland. Soil Sedim Contam Int J 11:719–750
- Jiang D, Tan M, Guo Q, Yan S (2021) Transfer of heavy metal along food chain: a mini-review on insect susceptibility to entomopathogenic microorganisms under heavy metal stress. Pest Manag Sci 77:1115–1120
- Jing T-Z, Qi F-H, Wang Z-Y (2020) Most dominant roles of insect gut bacteria: digestion, detoxification, or essential nutrient provision? Microbiome 8:38
- Johnson RM, Mao W, Pollock HS, Niu G, Schuler MA, Berenbaum MR (2012) Ecologically appropriate xenobiotics induce cytochrome P450s in *Apis mellifera*. PLoS ONE 7:e31051

- Kabata-Pendias A (2011) Trace elements in soils and plants. Page CRC Press, Boca Raton
- Karim Z, Qureshi BA, Mumtaz M, Qureshi S (2014) Heavy metal content in urban soils as an indicator of anthropogenic and natural influences on landscape of Karachi—a multivariate spatio-temporal analysis. *Ecol Ind* 42:20–31
- Kerr S, Newell RG (2003) Policy-induced technology adoption: evidence from the U.S. lead phasedown. *J Ind Econ* 51:317–343
- Kim R-Y, Yoon J-K, Kim T-S, Yang JE, Owens G, Kim K-R (2015) Bioavailability of heavy metals in soils: definitions and practical implementation—a critical review. *Environ Geochem Health* 37:1041–1061
- Lever WF (1991) Deindustrialisation and the reality of the post-industrial city. *Urban Stud* 28:983–999
- Li F (2018) Heavy metal in urban soil: health risk assessment and management. *Heavy Metals*. <https://doi.org/10.5772/intechopen.73256>
- Li Q, Cai S, Mo C, Chu B, Peng L, Yang F (2010) Toxic effects of heavy metals and their accumulation in vegetables grown in a saline soil. *Ecotoxicol Environ Saf* 73:84–88
- Li C, Zhou K, Qin W, Tian C, Qi M, Yan X, Han W (2019) A review on heavy metals contamination in soil: effects, sources, and remediation techniques. *Soil Sedim Contam Int J* 28:380–394
- Liu L, Li W, Song W, Guo M (2018) Remediation techniques for heavy metal-contaminated soils: principles and applicability. *Sci Total Environ* 633:206–219
- Luescher A, Shetty S (2013) An introductory review to the special issue: shrinking cities and towns: challenge and responses. *Urban Des International* 18:1–5
- MacIvor JS (2016) DNA barcoding to identify leaf preference of leafcutting bees. *R Soc Open Sci* 3:150623
- Martinek P, Hedb J (2020) Adverse responses of *Cabera pusaria* caterpillars to high dietary manganese concentration. *Entomol Exp Appl* 168:635–643
- Martinez-Fernandez C, Audirac I, Fol S, Cunningham-Sabot E (2012) Shrinking cities: urban challenges of globalization. *Int J Urban Reg Res* 36:213–225
- McCutcheon S, Schnoor J (2003) Phytoremediation: transformation and control of contaminants. Wiley, Hoboken
- Meindl GA, Ashman T-L (2013) The effects of aluminum and nickel in nectar on the foraging behavior of bumblebees. *Environ Pollut* 177:78–81
- Meindl GA, Ashman TL (2014) Nickel accumulation by *Streptanthus polygaloides* (Brassicaceae) Reduces Floral Visitation Rate. *J Chem Ecol* 40:128–135
- Meindl GA, Ashman TL (2015) Effects of floral metal accumulation on floral visitor communities: introducing the elemental filter hypothesis. *Am J Bot* 102:379–389
- Merritt TJS, Bewick AJ (2017) Genetic diversity in insect metal tolerance. *Front Genet*. <https://doi.org/10.3389/fgene.2017.00172>
- Miles LJ, Parker GR (1979) DTPA soil extractable and plant heavy metal concentrations with soil-added Cd treatments. *Plant Soil* 51:59–68
- Mirecki N, Agic R, Šunić L, Milenkovic L, Ilic Z (2015) Transfer factor as indicator of heavy metals content in plants. *Fresenius Environ Bull* 24:4212–4219
- Mitchell TS, Agnew L, Meyer R, Sikkink KL, Oberhauser KS, Borer ET, Snell-Rood EC (2020) Traffic influences nutritional quality of roadside plants for monarch caterpillars. *Sci Total Environ* 724:138045
- Monchanin C et al (2021) Chronic exposure to trace lead impairs honey bee learning. *Ecotoxicol Environ Saf* 212:112008
- Morel J-L, Echevarria G, Goncharova N, Organization NAT (eds) (2006). Springer, Dordrecht
- Moroń D, Grześ IM, Skórka P, Szentgyörgyi H, Laskowski R, Potts SG, Woyciechowski M (2012) Abundance and diversity of wild bees along gradients of heavy metal pollution. *J Appl Ecol* 49:118–125
- Moroń D, Szentgyörgyi H, Skórka P, Potts SG, Woyciechowski M (2014) Survival, reproduction and population growth of the bee pollinator, *Osmia rufa* (Hymenoptera: Megachilidae), along gradients of heavy metal pollution. *Insect Conserv Divers* 7:113–121
- Mulder C, Aldenberg T, Zwart D, Wijnen H, Breure A (2005) Evaluating the impact of pollution on plant-Lepidoptera relations. *Environmetrics* 16:357–373
- Muradoğlu F, Beyhan Ö, Sönmez F (2017) Response to heavy metals on pollen viability, germination & tube growth of some apple cultivars. *Fresenius Environ Bull* 26:4456–4461
- Nakajima F, Aryal R (2018) Heavy metals in urban dust. *Heavy Metals*. <https://doi.org/10.5772/intechopen.74205>
- Negri I, Mavris C, Di Prisco G, Caprio E, Pellicchia M (2015) Honey bees (*Apis mellifera*, L.) as active samplers of airborne particulate matter. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0132491>
- 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
- Norouzi S, Khademi H, Faz Cano A, Acosta JA (2015) Using plane tree leaves for biomonitoring of dust borne heavy metals: a case study from Isfahan, Central Iran. *Ecol Ind* 57:64–73
- Ohashi K, Yahara T (1998) Effects of variation in flower number on pollinator visits in *Cirsium purpuratum* (Asteraceae). *Am J Bot* 85:219–224
- Okuyama Y, Matsumoto K, Okochi H, Igawa M (2007) Adsorption of air pollutants on the grain surface of Japanese cedar pollen. *Atmos Environ* 41:253–260
- Pandey B, Agrawal M, Singh S (2014) Coal mining activities change plant community structure due to air pollution and soil degradation. *Ecotoxicology* 23:1474–1483
- Parreño MA et al (2022) Critical links between biodiversity and health in wild bee conservation. *Trends Ecol Evol* 37:309–321
- Perry KI, Hoekstra NC, Culman SW, Gardiner MM (2021) Vacant lot soil degradation and mowing frequency shape communities of belowground invertebrates and urban spontaneous vegetation. *Urban Ecosyst* 24:737–752
- Perugini M, Manera M, Grotta L, Abete MC, Tarasco R, Amorena M (2011) Heavy metal (Hg, Cr, Cd, and Pb) contamination in urban areas and wildlife reserves: honeybees as bioindicators. *Biol Trace Elem Res* 140:170–176
- Philips KH, Kobiela ME, Snell-Rood EC (2017) Developmental lead exposure has mixed effects on butterfly cognitive processes. *Anim Cogn* 20:87–96
- Phillips BB, Bullock JM, Gaston KJ, Hudson-Edwards KA, Bamford M, Cruse D, Dicks LV, Falagan C, Wallace C, Osborne JL (2021) Impacts of multiple pollutants on pollinator activity in road verges. *J Appl Ecol* 58:1017–1029
- Pietrelli L, Menegoni P, Papetti P (2022) Bioaccumulation of heavy metals by herbaceous species grown in urban and rural sites. *Water Air Soil Pollut* 233:141
- Pitts-Singer TL, Cane JH (2011) The alfalfa leafcutting bee, *Megachile rotundata*: the world's most intensively managed solitary bee. *Annu Rev Entomol* 56:221–237
- Polykretis P, Delfino G, Petrocelli I, Cervo R, Tanteri G, Montori G, Perito B, Branca JJV, Morucci G, Gulisano M (2016) Evidence of immunocompetence reduction induced by cadmium exposure in honey bees (*Apis mellifera*). *Environ Pollut* 218:826–834
- Rascio N, Navari-Izzo F (2011) Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? *Plant Sci Int J Exp Plant Biol* 180:169–181

- Raymann K, Moran NA (2018) The role of the gut microbiome in health and disease of adult honey bee workers. *Curr Opin Insect Sci* 26:97–104
- Rieuwerts JS, Thornton I, Farago ME, Ashmore MR (1998) Factors influencing metal bioavailability in soils: preliminary investigations for the development of a critical loads approach for metals. *Chem Speciat Bioavailab* 10:61–75
- Rothman JA, Leger L, Graystock P, Russell K, McFrederick QS (2019a) The bumble bee microbiome increases survival of bees exposed to selenate toxicity. *Environ Microbiol* 21:3417–3429
- Rothman JA, Leger L, Kirkwood JS, McFrederick QS (2019b) Cadmium and Selenate exposure affects the honey bee microbiome and metabolome, and bee-associated bacteria show potential for bioaccumulation. *Appl Environ Microbiol* 85:e01411-19
- Rothman JA, Russell KA, Leger L, McFrederick QS, Graystock P (2020) The direct and indirect effects of environmental toxicants on the health of bumblebees and their microbiomes. *Proc R Soc B Biol Sci* 287:20200980
- Ryser P, Sauder WR (2006) Effects of heavy-metal-contaminated soil on growth, phenology and biomass turnover of *Hieracium piloselloides*. *Environ Pollut* 140:52–61
- Salz A, Fartmann T (2017) Larval habitat preferences of a threatened butterfly species in heavy-metal grasslands. *J Insect Conserv* 21:129–136
- Sampson N, Nassauer J, Schulz A, Hurd K, Dorman C, Ligon K (2017) Landscape care of urban vacant properties and implications for health and safety: lessons from photovoice. *Health Place* 46:219–228
- Sánchez-Bayo F, Wyckhuys KAG (2019) Worldwide decline of the entomofauna: a review of its drivers. *Biol Conserv* 232:8–27
- Sansalone JJ, Buchberger SG (1997) Partitioning and first flush of metals in urban roadway storm water. *J Environ Eng* 123:134–143
- Schwarz K (2016) Modeling to predict high Pb areas. In: Hodges Snyder E, McIvor K, Brown S (eds) *Sowing seeds in the city: human dimensions*. Springer, Dordrecht, pp 135–145
- Schwenke RA, Lazzaro BP, Wolfner MF (2016) Reproduction-immunity trade-offs in insects. *Annu Rev Entomol* 61:239–256
- Scott SB, Sivakoff FS, Gardiner MM (2022) Exposure to urban heavy metal contamination diminishes bumble bee colony growth. *Urban Ecosyst*. <https://doi.org/10.1007/s11252-022-01206-x>
- Seymour E (2020) Tighe & Ryberg-Webster: legacy cities: continuity and change amid decline and revival. *J Am Plan Assoc* 86:520–522
- Sgolastra F, Arnán X, Cabbri R, Isani G, Medrzycki P, Teper D, Bosch J (2018a) Combined exposure to sublethal concentrations of an insecticide and a fungicide affect feeding, ovary development and longevity in a solitary bee. *Proc R Soc B Biol Sci* 285:20180887
- Sgolastra F, Blasioli S, Renzi T, Tosi S, Medrzycki P, Molowny-Horas R, Porrini C, Braschi I (2018b) Lethal effects of Cr(III) alone and in combination with propiconazole and clothianidin in honey bees. *Chemosphere* 191:365–372
- Shahid M, Dumat C, Khalid S, Schreck E, Xiong T, Niazi NK (2017) Foliar heavy metal uptake, toxicity and detoxification in plants: a comparison of foliar and root metal uptake. *J Hazard Mater* 325:36–58
- Sharma K, Basta NT, Grewal PS (2015a) Soil heavy metal contamination in residential neighborhoods in post-industrial cities and its potential human exposure risk. *Urban Ecosyst* 18:115–132
- Sharma K, Cheng Z, Grewal PS (2015b) Relationship between soil heavy metal contamination and soil food web health in vacant lots slated for urban agriculture in two post-industrial cities. *Urban Ecosyst* 18:835–855
- Shephard AM, Mitchell TS, Henry SB, Oberhauser KS, Kobiela ME, Snell-Rood EC (2020) Assessing zinc tolerance in two butterfly species: consequences for conservation in polluted environments. *Insect Conserv Divers* 13:201–210
- Shephard AM, Zambre AM, Snell-Rood EC (2021) Evaluating costs of heavy metal tolerance in a widely distributed, invasive butterfly. *Evol Appl* 14:1390–1402
- Shu Y, Gao Y, Sun H, Zou Z, Zhou Q, Zhang G (2009) Effects of zinc exposure on the reproduction of *Spodoptera litura* Fabricius (Lepidoptera: Noctuidae). *Ecotoxicol Environ Saf* 72:2130–2136
- Simon L, Martin HW, Adriano DC (1996) Chicory (*Cichorium intybus* L.) and dandelion (*Taraxacum officinale* Web.) as phytoindicators of cadmium contamination. *Water Air Soil Pollut* 91:351–362
- Singh VP (2005) *Metal toxicity and tolerance in plants and animals*. Sarup & Sons, Delhi
- Singh S, Parihar P, Singh R, Singh VP, Prasad SM (2016) Heavy metal tolerance in plants: role of transcriptomics, proteomics, metabolomics, and ionomics. *Front Plant Sci*. <https://doi.org/10.3389/fpls.2015.01143/full>
- Sivakoff FS, Gardiner MM (2017) Soil lead contamination decreases bee visit duration at sunflowers. *Urban Ecosyst* 20:1221–1228
- Sivakoff FS, Prajzner SP, Gardiner MM (2018) Unique bee communities within vacant lots and urban farms result from variation in surrounding urbanization intensity. *Sustainability* 10:1926
- Sivakoff FS, Prajzner SP, Gardiner MM (2020) Urban heavy metal contamination limits bumble bee colony growth. *J Appl Ecol*. <https://doi.org/10.1111/1365-2664.13651>
- Song Y, Du X, Ye X (2019) Analysis of potential risks associated with urban stormwater quality for managed aquifer recharge. *Int J Environ Res Public Health* 16:3121
- Søvik E, Perry C, Lamora A, Barron A, Ben-Shahar Y (2015) Negative impact of manganese on honeybee foraging. *Biol Lett* 11:20140989
- Steffan-Dewenter I, Tscharnkte T (1999) Effects of habitat isolation on pollinator communities and seed set. *Oecologia* 121:432–440
- Su H, Wu J, Zhang Z, Ye Z, Chen Y, Yang Y (2021) Effects of cadmium stress at different concentrations on the reproductive behaviors of beet armyworm *Spodoptera exigua* (Hübner). *Ecotoxicology* 30:402–410
- Suman J, Uhlik O, Viktorova J, Macek T (2018) Phytoextraction of heavy metals: a promising tool for clean-up of polluted environment? *Front Plant Sci*. <https://doi.org/10.3389/fpls.2018.01476/full>
- Suvarapu LN, Baek S-O (2017) Determination of heavy metals in the ambient atmosphere: a review. *Toxicol Ind Health* 33:79–96
- Szentgyörgyi H, Morón D, Nawrocka A, Tofilski A, Woyciechowski M (2017) Forewing structure of the solitary bee *Osmia bicornis* developing on heavy metal pollution gradient. *Ecotoxicology* 26:1031–1040
- Tangahu BV, Sheikh Abdullah SR, Basri H, Idris M, Anuar N, Mukhlisin M (2011) A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *Int J Chem Eng* 2011:1–31
- Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ (2012) Heavy metals toxicity and the environment. In *Molecular, clinical and environmental toxicology* p 133–164
- Tiedeken EJ, Stout JC, Stevenson PC, Wright GA (2014) Bumblebees are not deterred by ecologically relevant concentrations of nectar toxins. *J Exp Biol* 217:1620–1625
- US EPA O (2016) USGS background soil-lead survey: state data. <https://www.epa.gov/superfund/usgs-background-soil-lead-survey-state-data>. Accessed 14 June 2022
- USA TODAY Investigation Reveals Hazardous Levels of Lead in Neighborhoods Across the Country (2012) PR Newswire. PR Newswire Association LLC. <https://go.gale.com/ps/i.do?p=AONE&sw=w&issn=&v=2.1&it=r&id=GALE%7CA328188032&sid=googleScholar&linkaccess=abs>. Accessed 14 June 2022

- Turer D, Maynard JB, Sansalone JJ (2001) Heavy metal contamination in soils of urban highways comparison between runoff and soil concentrations at Cincinnati, Ohio. *Water Air Soil Pollut* 132:293–314
- Turner A, Mawji E (2004) Hydrophobicity and octanol–water partitioning of trace metals in natural waters. *Environ Sci Technol* 38:3081–3091
- Turo KJ, Spring MR, Sivakoff FS, de la Flor YAD, Gardiner MM (2021) Conservation in post-industrial cities: how does vacant land management and landscape configuration influence urban bees? *J Appl Ecol* 58:58–69
- van Ooik T, Rantala MJ (2010) Local adaptation of an insect herbivore to a heavy metal contaminated environment. *Ann Zool Fenn* 47:215–222
- van Ooik T, Pausio S, Rantala MJ (2008) Direct effects of heavy metal pollution on the immune function of a geometrid moth, *Epirrita autumnata*. *Chemosphere* 71:1840–1844
- Wang L et al (2019) Dynamic changes of gut microbial communities of bumble bee queens through important life stages. *mSystems* 4:e00631-19
- Webber SM, Garratt MPD, Lukac M, Bailey AP, Huxley T, Potts SG (2020) Quantifying crop pollinator-dependence and pollination deficits: the effects of experimental scale on yield and quality assessments. *Agric Ecosyst Environ* 304:107106
- Wei Z-H, Wang X-Q, Li P-R, Tan X, Yang X (2020) Diet-mediated effects of cadmium on the fitness-related traits and detoxification and antioxidative enzymes in the oriental armyworm, *Mythimna separata*. *Entomologia Generalis* 40:407–419
- Wong MH, Cheung YH (1986) Heavy metal concentrations in caterpillars fed with waste-grown vegetables. *Agric Wastes* 18:61–68
- Wuana RA, Okieimen FE (2011a) Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. <https://www.hindawi.com/journals/isrn/2011a/402647/>. Accessed 22 Aug 2019
- Wuana RA, Okieimen FE (2011b) Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. *ISRN Ecol* 2011:e402647
- Wu-Smart J, Spivak M (2016) Sub-lethal effects of dietary neonicotinoid insecticide exposure on honey bee queen fecundity and colony development. *Sci Rep* 6:32108
- Xerxes Society (2017) Pollinator plants midwest region. https://xerxes.org/sites/default/files/2018-05/17-050_03_XerxesSoc_Pollinator_Plants_Midwest-Region_web-3page.pdf
- Xu J, Strange JP, Welker DL, James RR (2013) Detoxification and stress response genes expressed in a western North American bumble bee, *Bombus huntii* (Hymenoptera: Apidae). *BMC Genom* 14
- Xun E, Zhang Y, Zhao J, Guo J (2017) Translocation of heavy metals from soils into floral organs and rewards of *Cucurbita pepo*: implications for plant reproductive fitness. *Ecotoxicol Environ Saf* 145:235–243
- 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
- Yang J, Teng Y, Song L, Zuo R (2016) Tracing sources and contamination assessments of heavy metals in road and foliar dusts in a typical mining city, China. *PLoS ONE* 11:e0168528
- Zhu Y, Christie P, Scott LA (2001) Uptake of Zn by arbuscular mycorrhizal white clover from Zn-contaminated soil. *Chemosphere* 42:193–199

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.