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Influence of heavy metal contamination on urban natural enemies and biological control

Mary M Gardiner[1] and James D Harwood[2]

Urban agriculture is increasing worldwide. A history of contamination within urban landscapes may negatively impact the biota necessary for sustainable crop production, including arthropod natural enemies. This investigation revealed that heavy metal contamination can influence the composition of natural enemy communities and exposure can have reproductive, developmental, immunological and behavioral impacts on predators and parasitoids. Natural enemies exposed to heavy metals typically live shorter lives, take longer to develop and exhibit a reduced reproductive potential. Further, they may incur significant energy costs though the production of detoxification enzymes. This is a new and relatively unexplored area for biological control research, with important implications for our understanding of urban agricultural food web interactions.

Addresses
[1] Department of Entomology, The Ohio State University, Columbus, OH 43210, USA
[2] Department of Entomology, University of Kentucky, Lexington, KY 40546, USA

Corresponding author: Gardiner, Mary M (gardiner.29@osu.edu)

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Introduction

Agriculture has long been part of the urban landscape, from home gardens to small scale farms [1••] but in recent decades, interest in producing food in cities has grown dramatically [2••]. It is estimated that more than 30% of the global urban population is engaged in some form of urban agriculture (UA) [3]. Furthermore, households with limited access to fresh produce are more likely to engage in UA [4], resulting in greater acquisition of fruits, vegetables, eggs, and other agricultural products within low income communities. Urban greenspaces, including community gardens and farms, have also been demonstrated to reduce human health risks via provision of additional biophysical ecosystem services [5] including filtration of pollutants from the air, reduction of the heat island effect, supplying space for physical activity, and improved neighborhood aesthetics [1••,2••].

UA often occupies vacant land that formerly supported industrial, commercial, or residential land use (Figure 1). These habitats frequently have a history of contamination [6••] by heavy metal (HM) pollutants, with soils serving as the major sink [6••,7•]. HM's include both nonessential elements (arsenic, cadmium, chromium, lead, mercury, and nickel) and elements essential to life that become toxic at higher concentrations (cobalt, copper, manganese, selenium, and zinc) [8•]. There are a multitude of routes to contamination that have facilitated HM pollution including vehicle exhaust, coal combustion, interior and exterior paint, smelting and waste disposal [6••]. HM thresholds for UA sites has focused on lead (Pb) caused by its ubiquity as an urban soil contaminant, correlation with the presence of other HM contaminants, and the documented exposure risks to human health [2••]. Worldwide Pb thresholds vary widely from 85–500 ppm [2••], with differences found between countries, and in some instances even among regions of a country. These thresholds are aimed at limiting human exposure to Pb via the consumption of contaminated produce or accidental soil ingestion or inhalation.

Research and regulations to ensure UA produces food safe for human consumption is paramount, but these contaminants also have important environmental impacts which are less clearly understood or regulated. Key among these is how HM contamination influences the beneficial arthropod fauna that support the ecosystem services necessary for sustainable UA. HMs can impact UA by influencing both top-down and bottom-up processes [9••]. In this article, we examine the impacts of HM contamination on crop plant – pest – natural enemy food webs. In particular, we focus on how HM contamination influences the composition and fitness of natural enemies foraging in contaminated landscapes and identify the potential impacts of HM exposure on biological control within UA.

Heavy metals, crop plants, and herbivores

Production of crops in HM contaminated soils can result in decreased seed germination, reduced growth and development, abnormalities in morphology, altered enzyme activity, disruptions in metabolic pathways, reduced ability to uptake essential nutrients and water, chlorosis, early senescence and phytotoxicity [10•]. Given

Figure 1

(a) Urban agricultural production is growing worldwide, particularly in cities where protracted economic decline and home foreclosure have resulted in a significant amount of vacant land [22•]. (a) When foreclosed or abandoned homes hold little to no property value they are eventually torn down by municipalities. **(b)** Demolition involves removal of debris from the site, but this process could be a source of additional HM soil contamination from materials such as lead-based paints. **(c)** Following demolition, a vacant lot plant community establishes that may contain seeded grasses and/or grasses and forbs from the existing seed bank. Vacant lots are maintained as early-successional habitats with periodic mowing. **(d)** Communities are reimagining a portion of available vacant land as a resource for agricultural production.

the potential human and plant health consequences, urban growers employ several strategies to limit HM uptake by crop plants. These actions can be extensive, including upper level soil removal or 'capping' wherein a barrier is applied to a site and soil for plant production is added above it, although the latter approach is typically cost prohibitive [2••]. More typical recommendations involve the use of raised beds, frequently with HM free potting medium and compost added [11], or amending existing soil to reduce the bioavailability of HMs. Soil properties including pH, cation exchange capacity, oxides and organic matter can affect plant uptake of HMs [6••]. For example, soils with high organic matter content and neutral or alkaline pH generally have a lowered bioavailability of HM to flora and fauna [6••]. Thus, the application of phosphorus-based fertilizers or organic amendments such as biosolids or compost are recommended to reduce the likelihood for uptake of Pb [2••]. Management practices such as soil tillage to mix surface and subsoil can reduce bioavailable HM [6••,12] as can the presence of earthworms and mycorrhizal fungi [13]. Establishing turf or mulching areas between UA plantings can also limit recontamination of managed areas with HM dust from unmanaged areas of an urban farm.

The exposure of herbivores to HM contaminated host plants can alter weight gain, growth, survival, fecundity and eclosion success [9••]. Interestingly, the strength and direction of these relationships are influenced by the concentration of HM contamination. In some cases, predictable negative impacts of HM exposure on herbivore population growth have been documented. For example, the net reproductive rate of the English grain aphid, *Sitobion avenae* (Hemiptera: Aphididae), and the number of offspring per female decreased with increasing cadmium (Cd) concentration [14]. However, at low concentrations, which may be more typical of managed beds within UA, HM contamination can lead to increased growth rates of herbivores. For example, low concentrations of Cd promoted population increase of the beet armyworm, *Spodoptera exigua* (Lepidoptera: Noctuidae), whereas high doses within their diet inhibited growth in population [15]. Exposure to HMs is also highly dependent on host plant selection and feeding strategy. In general, HM concentrations decrease from roots > leaves > stem > inflorescences > seeds, however this can vary by plant species [16]. Furthermore, some plants are considered hyperaccumulators, able to sequester high concentrations of metals in their tissues [17], thus consumption of these plants could result in an increased likelihood of an herbivore ingesting a significant concentration of HM contaminants. Feeding strategy can also influence impacts of HM; for example, feeding on host plants containing nickel (Ni) led to reduced survival of leaf and root chewing herbivores but not phloem feeders [18].

Natural enemies in a contaminated landscape

The composition, configuration, and contamination legacy of the urban landscape is likely to have a significant impact on contamination present within natural enemies supplied to UA [19]. Many of the natural enemies important in the suppression of UA pests immigrate into crop production beds from surrounding greenspaces such as vacant lots [20–23], unlikely to be managed for HM. For example, in Cleveland Ohio, U.S.A. soil Pb concentrations were four times higher in vacant lots than nearby urban farms (Figure 2a, b). Factors, such as neighborhood housing age, concentration of major roadways and proximity to historic sources of HM pollutions such as smelters, could influence the contamination present within these source habitats. Therefore, even if urban farm soils are free of HM contamination, populations of natural enemies may encounter HM via their diet, water consumption and soil contact within source habitats. For example, no difference in Pb concentrations were found within sheet web spiders (Araneae: Linyphiidae) collected from vacant lots and nearby farm sites (Figure 2c). Thus it is important to consider that the biological control function of natural enemies found within UA could be altered by contamination, even if soil testing and management practices are employed to reduce bioavailable HM on-farm.

At the community level, foraging in a contaminated landscape often results in reduced natural enemy richness, abundance and altered community composition [23–26]. However, these community properties can be unaffected, or even positively correlated, with HM contamination [27,28]. Bioindication research demonstrates that HM contamination in natural enemies often correlates with habitat contamination but can vary greatly within and between species. Variables such as life stage, sex and seasonal diet changes influence HM concentrations within a species collected from a contaminated habitat [29,30]. Among species, several traits including capacity for dispersal, prey choice, ability to store or excrete HMs and seasonal occurrence can influence concentrations of HMs found within natural enemies [31–36,37••]. For example, seasonality was found to influence Pb contamination of sheet web spiders (Araneae: Linyphiidae) in vacant lots and urban farms; those collected in early June contained significantly greater concentrations of Pb than those present in July or August (Figure 2d). Although its unknown why this variation occurred, seasonal food web changes could alter exposure risk. Diet variation is known to influence predator contamination, for example, ground beetles (Coleoptera: Carabidae) that fed on larger snails and earthworms accumulated higher concentrations of Cd than species that consumed small snails or a diversity of invertebrates and carrion [37••].

Impacts of HM contamination on natural enemies and biological control

To fully understand the influence of contamination on biological control, it is necessary document how HM exposure alters the physiology and behavior of natural enemies. Studies documenting these impacts have focused predominantly on predatory taxa, with significant focus on a small number of ground beetle and spider species. These studies have revealed reproductive, developmental, immunological and behavioral impacts of contamination on the studied natural enemy fauna (Table 1).

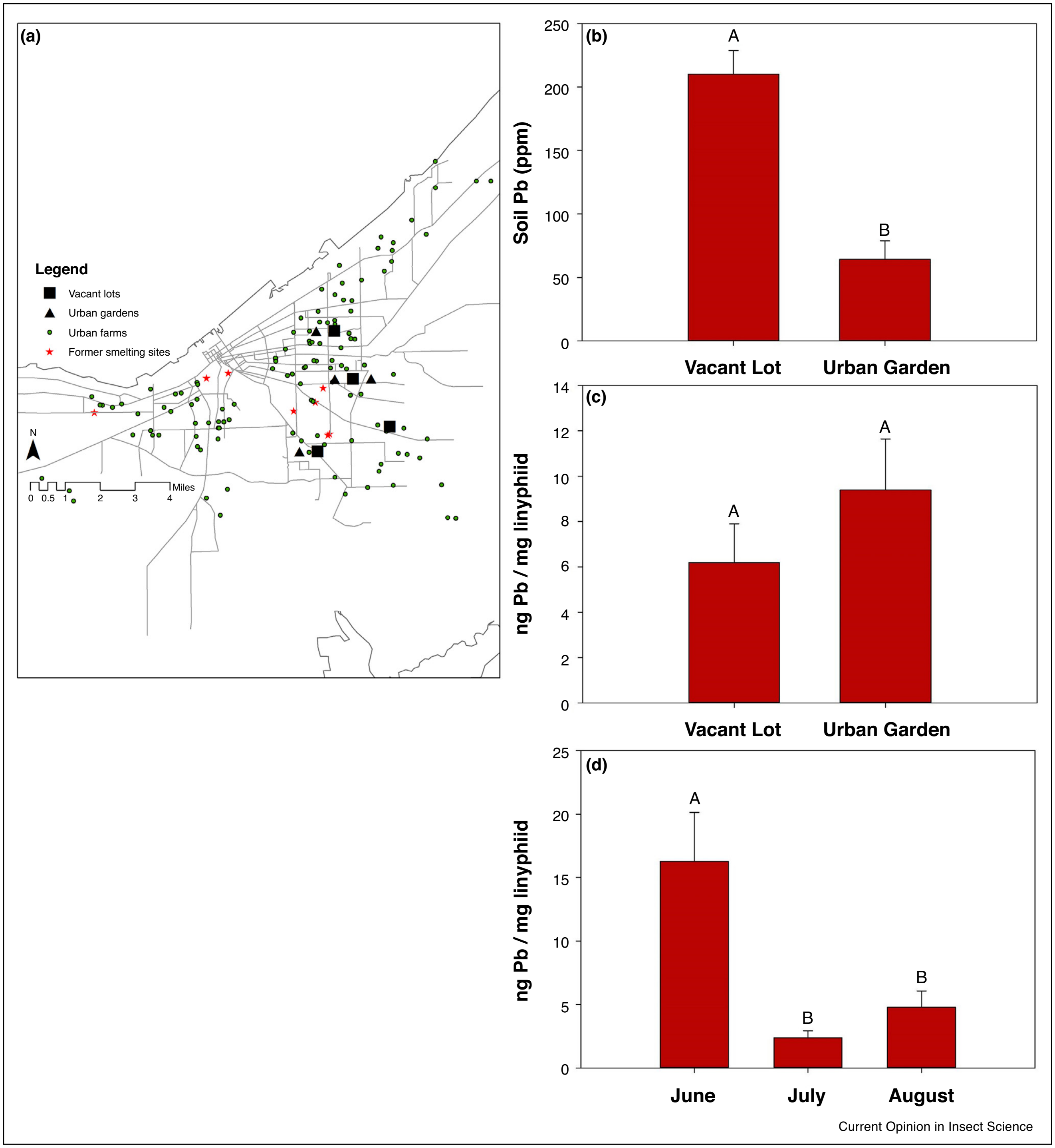
Reproduction

HM exposure can influence the probability of mating, fecundity, and egg hatch among natural enemies [38–43]. For example, females of the wolf spider, *Pirata piraticus* (Araneae: Lycosidae), from uncontaminated sites exhibited a decreased probability of copulation when food deprived, whereas females collected from polluted sites did not [43]. In general, HM contaminated predators produced fewer, larger eggs, with reduced hatching success. One exception was reported by Babczyńska *et al.* [41] who found that funnel web spiders, *Agelena labyrinthica* (Araneae: Agelinidae), collected from contaminated habitats produced a larger number of eggs, albeit smaller ones, and these eggs exhibited reduced hatching success relative to uncontaminated females.

Development time and body size

HM exposure can alter natural enemy development time, adult weight, longevity and starvation tolerance. HM contaminated prey or water sources have been revealed to lengthen development time [44–48]. For example, when feeding on hosts contaminated with copper (Cu), *Nasonia vitripennis* (Hymenoptera: Pteromalidae), exhibited lengthened developmental time and reduced emergence of adult parasitoids from the pupal stage [45]. The adult wasps also had a shortened adult life span and

Figure 2



(a) The city of Cleveland, Ohio U.S.A. has over 100 UA operations occupying formerly-vacant land. These sites vary in distance from historic smelting sites and are embedded within landscapes where factors such as housing age and roadway density can influence HM soil contamination. Within four UA sites and four nearby vacant lots we measured the Pb concentration of soils and sheet-web spiders (Linyphiidae). **(b)** Pb concentrations within vacant lot soils were significantly higher than nearby urban farms ($F = 35.94$, $p < 0.001$). Relative to the Cuyahoga County background soil Pb level of 51.7 ppm [74], vacant lot soils contained nearly four times the Pb, whereas urban farms averaged close to the background Pb concentrations. **(c)** Interestingly, despite the difference in soil contamination we found no difference in Pb concentrations within sheet-web spiders (Araneae: Linyphiidae) collected from urban farm and vacant lot habitats ($F = 1.42$, $p = 0.23$). **(d)** However, variation in linyphiid contamination was detected by month, with greater Pb levels found in spiders collected in June than July or August ($F = 9.65$, $P < 0.001$).

Table 1

Summary of studies examining the reproductive, developmental, behavioral and physiological impacts of HM exposure on predator and parasitoid arthropods. Both laboratory bioassays and analyses of field-contaminated arthropods are included

	HM[a]	Effects of HM exposure	Ref.
Araneae: Agelenidae			
Agelena labyrinthica	M	Increased detoxifying enzyme (CarE) activity	[57]
Agelena labyrinthica	M	Increased activity of detoxifying enzymes (GPOX and GSTPX) in females	[58]
Agelena labyrinthica	M	Increased metallothionein protein concentrations, reduced mitochondrial potential, higher ADP/ATP ratio	[59]
Agelena labyrinthica	M	Increased metallothionein protein concentrations correlated with concentrations of Zn, but not Cd, Cu, or Pb	[36]
Agelena labyrinthica	M	Enhanced egg production, reduced hatching success	[41]
Agelena labyrinthica	Mg	Lengthened developmental time, reduced survivorship, similar web construction but greater variation in placement	[60]
Araneae: Araneidae			
Araneus diadematus	M	Increased metallothionein protein concentrations correlated with concentrations of Cd, Pb, and Zn but not Cu	[36]
Araneae: Linyphiidae			
Linyphia triangularis	M	Increased metallothionein protein concentrations correlated with concentrations of Pb and Zn, but not Cd or Cu	[36]
Araneae: Lycosidae			
Pardosa astrigera	Pb, Zn	Increased developmental time, reduction in body weight at high metal concentrations, production of fewer eggs	[65]
Pardosa lugubris	M	Increased detoxifying enzyme (CarE) activity	[57]
Pardosa saltans		Reduced body size, delayed reproductive period for females, production of fewer, larger eggs	[66]
Pirata piraticus	M	Negative relationship between fluctuating asymmetry and clutch size	[61]
Pirata piraticus	M	Reduced fecundity and clutch size, production of larger eggs	[39]
Pirata piraticus	M	Production of larger eggs, decreased growth rate	[62]
Pirata piraticus	M	More likely to reproduce under food stress than females collected from uncontaminated habitat	[43]
Pirata subpiraticus	Cd	Lengthened developmental time and reduced starvation tolerance	[46]
Pirata subpiraticus	Cd	Increased metallothionein protein concentrations, decreased growth rate, decreased survival	[63]
Pirata subpiraticus	Mg	Increased activity of detoxification enzyme GSH, reduced activity of SOD, CAT, and GST	[64]
Xerolycosa nemoralis	M	Reduced egg production, similar hatching success compared with females from uncontaminated sites	[41]
Coleoptera: Carabidae			
Carabus splendens	Cd	No effect on prey consumption, increased mortality	[53]
Poecilus cupreus	Zn	No difference in body mass at pupal emergence, decreased body mass following overwintering	[67]
Pterostichus melanarius	M	Reduced fat content in adults	[68]
Pterostichus oblongopunctatus	M	Reduced tolerance to food deprivation, increased susceptibility to pesticide exposure	[55]
Pterostichus oblongopunctatus	Zn	Reduced egg production, increased development time and body size of laboratory-reared F1 generation	[40]
Pterostichus oblongopunctatus	M	Higher detoxification enzyme activity (GST and CarE) in female beetles within some contaminated sites relative to reference site, no difference in enzyme activity among male beetles	[50]
Pterostichus oblongopunctatus	M	Decreased detoxification enzyme activity when exposed to Cd (GPOX), Pb (SOD), or Zn (GST), increased activity when exposed to Pb (GSTPX, GR) Cu (GPOX), and Cd (GSTP, GR)	[69]
Pterostichus oblongopunctatus	M	Larger body mass	[49]
Pterostichus oblongopunctatus	M	No difference in laboratory-reared F2 generation in susceptibility to starvation or insecticide exposure	[40]
Pterostichus oblongopunctatus	Zn	Reduced elytra length	[70]
Pterostichus oblongopunctatus	Zn	Greater egg production, reduced egg hatch, no effect on laboratory-reared F1 generation survivorship or developmental rate	[40]
Pterostichus oblongopunctatus	Cd, Zn	Increased whole-organism respiration rate	[52]
Coleoptera: Curculionidae			
Phyllobius betalae	M	Reduced detoxification enzyme activity when exposed to Cu (GPOX), Pb (GSTP), or Zn (GSTP)	[69]

f-

Table 1 (*Continued*)

	HM[a]	Effects of HM exposure	Ref.
Coleoptera: Scarabaeidae			
Geotrupes stercorosus	M	Increased detoxification enzyme activity when exposed to Cd (GSTP, GR), Cu (GSTP, GST), Pb (SOD, GSTP, GPOX, GR), and Zn (GPOX, GR), reduced activity when exposed to Cd (GST)	[69]
Coleoptera: Staphylinidae			
Staphylinus caesareus	M	Increased detoxification enzyme activity when exposed to Cd (SOD, GSTP, GPOX), Cu (SOD, GPOX, GST), Pb (SOD, GPOX), Zn (GST), reduced activity when exposed to Pb (GST, GR), and Cd (GST, GR)	[69]
Hemiptera: Pentatomidae			
Podisus maculiventris	Se	Longer developmental time, reduced adult weight, increased mortality	[48]
Podisus maculiventris	M	Longer developmental time, reduced adult weight, no effect on survivorship	[47•]
Hymenoptera: Formicidae			
Formica aquilonia	M	Increased encapsulation at moderate and decreased encapsulation at high levels of HM exposure	[51•]
Formica aquilonia	M	Reduced mound volume (indicative of reduced colony size), no difference in worker morphological characteristics	[71]
Formica aquilonia	Cu	Reduced intraspecific aggression	[54]
Parasitoids			
Hymenoptera: Braconidae			
Aphidius ervi	Cd	Cd alone and in combination with imidacloprid insecticide reduced adult emergence from host	[56]
Glyptapanteles liparidis	M	No effect on parasitization success	[72]
Hymenoptera: Diapriidae			
Coptera occidentalis	M	No effect on parasitoid fecundity or percentage of females produced in laboratory-reared F1 generation	[38]
Coptera occidentalis	Cd, Cu	Equal parasitism of control and HM contaminated hosts, reduced emergence of females from contaminated hosts, no effect on developmental rate, life span, or fecundity	[44]
Hymenoptera: Ichneumonidae			
Pimpla turionellae	Cd, Pb	Reduced life span	[73]
Hymenoptera: Pteromalidae			
Nasonia vitripennis	Cu	Reduced growth and increased developmental time, reduced emergence of adults, shortened adult life span, reduced fecundity in females	[45]

[a] M = multiple heavy metals (more than 2) studied.

emales exhibited reduced fecundity [45]. Interestingly, exposure to HMs results in reduced body mass in some predators [48] and greater body mass in others [49]. For example, the ground beetle, *Pterostichus oblongopunctatus* (Coleoptera: Carabidae), collected from HM contaminated sites had a greater body mass [49]; the authors speculated this pattern may be caused by reduced competition with other predators.

Detoxification, immunity and energy costs

HM exposure can influence the production of metallothioneins and enzymes involved in detoxification, including carboxyesterases (CarE), catalases (CAT), glutathiones (GSH), glutathione-*S*-transferases (GST), gluthione reductase (GR), superoxide dismutases (SOD), and selenium-dependent (GPOX) and selenium-independent (GSTPX) glutathione peroxidases [36,50,57–59,63,64,69]. HM exposure frequently leads to greater detoxification enzyme activity; however, variation exists both within and between species, often varying by sex [36,50]. Induction of detoxification enzymes above normal levels may have fitness consequences for arthropods as energetic demands shift from maintenance and reproduction. In ants, for example, encapsulation rates (a measure of immunity) actually increased with moderate HM contamination but decreased in heavily contaminated ants [51•]. Whole-organism respiration rates have also been shown to increase with HM concentration, suggesting that natural enemies can incur energy costs with toxicity [52].

Biocontrol services

Few studies have focused on the impact of HM contamination on predator–prey interactions and biological control. However, we can infer some potential impacts from studies examining how predator fitness and behavior are altered by HM contamination. For example, feeding on contaminated prey is likely to reduce the longevity of biocontrol services provided by an individual natural enemy. Although the predation rate of the ground beetle, *Carabus splendens* (Coleoptera: Carabidae), was not affected by consuming Cd contaminated snails, the beetles experienced significantly greater mortality [53]. In some cases, HM contamination has been demonstrated to reduce the aggressiveness of natural enemies, which could alter their efficiency as a predator [54]. For example, ants exposed to contamination from a Cu smelter were less likely to demonstrate aggressiveness to foreign colonies, a behavior hypothesized to be either a result of direct toxicity or changes in resource availability [54]. Exposure to HM may also make natural enemies less able to tolerate cyclic prey populations common in UA. The ground beetle, *Pterostichus oblongopunctatus* (Coleoptera: Carabidae), collected from HM polluted sites exhibited increased susceptibility to food depravation [55]. HM exposure may also alter outcomes of integrated pest management programs by causing greater sensitivity of natural enemies to pesticides [55,56]. For example, the parasitoid, *Aphidius ervi* (Hymenoptera: Braconidae), exposed to aphids feeding on plants grown in soil contaminated with Cd exhibited reduced adult emergence, an effect that was magnified when imidacloprid was applied to the soil [56].

Future research directions

Herein, we identify HM as a factor that could influence biological control, a key ecosystem service provided to UA. The data presented here illustrate reduced survivorship, altered developmental time and reproductive output, and energetic investment into the production of detoxification enzymes. However, will these impacts translate into measureable reductions in biological control? Testing this hypothesis is complex, as the likelihood and extent of natural enemy contamination by HM is dependent on identifying contamination risk within multiple dimensions of niche space. For example, factors such as the extent of surface soil contact, use of alternative prey and non-prey foods, overwintering strategies, and capacity for dispersal vary extensively among common natural enemies. Such factors could all influence HM contamination and the biological control services afforded by different species, and thus should be investigated. Further, the field studies reviewed here are predominately gradient analyses wherein natural enemies were collected within semi-natural habitats at successive distances from a point source of contamination such as a former mining site or smelter. Within an UA context, however, focal habitats are embedded in a landscape with varying sources and levels of contamination, not necessarily one identifiable source of HM pollution. Therefore, identifying how a species niche influences contamination risk and its potential to provide biological control services should be studied within the content of the surrounding urban landscape matrix.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cois.2017.03.007.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. •• Mok HF, Williamson VG, Grove JR, Burry K, Barker SF, Hamilton AJ: **Strawberry fields forever? Urban agriculture in developed countries: a review**. *Agron. Sustain. Dev.* 2014, **34**:21-43.
This review examines the risks, benefits and challenges posed by urban agriculture in the developed world.

2. •• Wortman SE, Lovell ST: **Environmental challenges threatening the growth of urban agriculture in the United States**. *J. Environ. Qual.* 2013, **42**:1283-1294.
This paper reviews the abiotic factors that influence urban agriculture, including soil contamiation.

3. Badami MG, Ramankutty N: **Urban agriculture and food security: a critique based on an assessment of urban land constraints**. *Glob. Food Secur.* 2014, **4**:1-8.

4. Warren E, Hawkesworth S, Knai C: **Investigating the association between urban agriculture and food security, dietary diversity, and nutritional status: a systematic literature review**. *Food Policy* 2015, **53**:54-66.

5. Shanahan DF, Fuller RA, Bush R, Lin BB, Gaston KJ: **The health benefits of urban nature: how much do we need?** *Bioscience* 2015, **65**:476-485.

6. •• Pouyat R, Szlavecz K, Yesilonis ID, Groffman PM, Schwarz K: **Chemical, physical, and biological characteristics of urban soils**. In *Urban Ecosystem Ecology*. Edited by Aitkenhead-Peterson J, Volder A. American Socieity of Agronomy, Crop Science Society of America, Soil Science Society of America; 2010:119-152.
This chapter examines the direct and indirect impacts of urbanization on soil chemical, physical and biological properties.

7. • Clark HF, Hausladen DM, Brabander DJ: **Urban gardens: lead exposure, recontamination mechanisms, and implications for remediation design**. *Environ. Res.* 2008, **107**:312-319.
This study measured Pb concentrations in soils sampled from raised planting beds within a network of backyard gardens and discusses routes of re-contamination.

8. • Feleafel M, Mirdad Z: **Hazard and effects of pollution by lead on vegetable crops**. *J. Agric. Environ. Ethics* 2013, **26**:547-567.
This study reviewed factors influencing Pb update by crop plants, how Pb concentrations vary within plant parts, and how to reduce exposure through agricultural management and food safety practices.

9. •• Butler CD, Trumble JT: **Effects of pollutants on bottom-up and top-down processes in insect–plant interactions**. *Environ. Pollut.* 2008, **156**:1-10.
This review highlights the importance of understanding how pollution influences the bottom-up and top-down forces driving herbivore populations. A small number of studies were found to examine HM impacts on these interactions, illustrating a need for research in this area.

10. • Nagajyoti PC, Lee KD, Sreekanth TVM: **Heavy metals, occurrence and toxicity for plants: a review**. *Environ. Chem. Lett.* 2010, **8**:199-216.
This review examines how exposure to HM contamination influences plant physiological and biochemical processes.

11. Mitchell RG, Spliethoff HM, Ribaudo LN, Lopp DM, Shayler HA, Marquez-Bravo LG, Lambert VT, Ferenz GS, Russell-Anelli JM, Stone EB, McBride MB: **Lead (Pb) and other metals in New York City community garden soils: factors influencing contaminant distributions**. *Environ. Pollut.* 2014, **187**:162-169.

12. Farfel M, Orlova A, Lees P: **A study of urban housing demolition as a source of lead in ambient dust on sidewalks, streets, and alleys**. *Environ. Res.* 2005, **99**:204-213.

13. Aghababaei F, Raiesi F, Hosseinpur A: **The combined effects of earthworms and arbuscular mycorrhizal fungi on microbial biomass and enzyme activities in a calcareous soil spiked with cadmium**. *Appl. Soil Ecol.* 2014, **75**:33-42.

14. Gao H-H, Zhao H-Y, Du C, Deng M-M, Du E-X, Hu Z-Q, Hu X-S: **Life table evaluation of survival and reproduction of the aphid Sitobion avenae, exposed to cadmium**. *J. Insect Sci.* 2012, **12**:44.

15. Su H-H, Hu M-M, Harvey-Samuel T, Yang Y-Z: **Accumulation and excretion of cadmium in three successive generations of *Spodoptera exigua* (Lepidoptera: Noctuidae) and impact on the population increase**. *J. Econ. Entomol.* 2014, **107**:223-229.

16. Antosiewicz D: **Adaptation of plants to an environment polluted with heavy metals**. *Acta Soc. Bot. Pol.* 1992, **61**:281-299.

17. Cheruiyot DJ, Boyd RS, Moar WJ: **Exploring lower limits of plant elemental defense by cobalt, copper, nickel, and zinc**. *J. Chem. Ecol.* 2013, **39**:666-674.

18. Jhee EM, Boyd RS, Eubanks MD: **Nickel hyperaccumulation as an elemental defense of *Streptanthus polygaloides* (Brassicaceae): influence of herbivore feeding mode**. *New Phytol.* 2005, **168**:331-344.

19. Burkman CE, Gardiner MM: **Urban greenspace composition and landscape context influence natural enemy community composition and function**. *Biol. Control.* 2014, **75**:58-67.

20. Gardiner MM, Prajzner SP, Burkman CE, Albro S, Grewal PS: **Vacant land conversion to community gardens: influences on generalist arthropod predators and biocontrol services in urban greenspaces**. *Urban Ecosyst.* 2014, **17**:101-122.

21. Burkman CE, Gardiner MM: **Spider assemblages within greenspaces of a deindustrialized urban landscape**. *Urban Ecosyst.* 2015, **18**:793-818.

22. • Gardiner MM, Burkman CE, Prajzner SP: **The value of urban vacant land to support arthropod biodiversity and ecosystem services**. *Environ. Entomol.* 2013, **42**:1123-1136.
This study reviews the value of vacant land for arthropods and examines the ability of urban arthropods to support needed ecosystem services within community gardens and farms.

23. Diehl E, Sanhudo CE, Diehl-Fleig E: **Ground-dwelling ant fauna of sites with high levels of copper**. *Braz. J. Biol.* 2004, **64**:33-39.

24. Skalski T: **Ground beetle community responses to heavy metal contamination**. *Balt. J. Coleopterol.* 2010, **10**:1-12.

25. Zmudzki S, Laskowski R: **Biodiversity and structure of spider communities along a metal pollution gradient**. *Ecotoxicology* 2012, **21**:1523-1532.

26. Vorobeichik EL: **Changes in diversity of soil macrofauna in industrial pollution gradient**. *Russ. Entomol. J.* 2012, **21**:203-218.

27. Lock K, Desender K, Jassen CR: **Effects of metal contamination on the activity and diversity of carabid beetles in an anciety Pb-Zn mining area at Plombières (Belgium)**. *Entomol. Exp. Appl.* 2001, **99**:355-360.

28. Grześ IM: **Cadmium regulation by *Lasius niger*: a contribution to understanding high metal levels in ants**. *Insect Sci.* 2009, **16**:89-92.

29. Wilczek G, Babczyńska A, Wilczek P, Dolezych B, Migula P, Młyńska H: **Cellular stress reactions assessed by gender and species in spiders from areas variously polluted with heavy metals**. *Ecotoxicol. Environ. Saf.* 2008, **70**:127-137.

30. Urbini A, Sparvoli E, Turillazzi S: **Social paper wasps as bioindicators: a preliminary research with *Polistes dominulus* (Hymenoptera Vespidae) as a trace metal accumulator**. *Chemosphere* 2006, **64**:697-703.

31. Marc P, Canard A, Ysnel F: **Spiders (Araneae) useful for pest limitation and bioindication**. *Agric. Ecosyst. Environ.* 1999, **74**:229-273.

32. Purchart L, Kula E: **Content of heavy metals in bodies of field ground beetles (Coleoptera, Carabidae) with respect to selected ecological factors**. *Polish J. Ecol.* 2007, **55**:305-314.

33. Rabitsch WB: **Seasonal metal accumulation patterns in the red wood ant *Formica pratensis* (Hymenoptera) at contaminated and reference sites**. *J. Appl. Ecol.* 1977, **34**:1455-1461.

34. Butovsky RO: **Heavy metals in carabids (Coleoptera, Carabidae)**. *Zookeys* 2011, **100**:215-222.

35. Koivula MJ: **Useful model organisms, indicators, or both? Ground beetles (Coleoptera, Carabidae) reflecting environmental conditions**. *Zookeys* 2011, **100**:287-317.

36. Babczyńska A, Wilczek G, Szulińska E, Franiel I: **Quantitative immunodetection of metallothioneins in relation to metals concentration in spiders from variously polluted areas**. *Ecotoxicol. Environ. Saf.* 2011, **74**:1498-1503.

37. •• Jelaska L, Jurasović J, Brown DS, Vaughan IP, Symondson WOC: **Molecular field analysis of trophic relationships in soil-dwelling invertebrates to identify mercury, lead and cadmium transmission through forest ecosystems**. *Mol. Ecol.* 2014, **23**:3755-3766.
This study is the first to use molecular gut content analysis to uncover the trophic interactions that explain HM movement through food webs.

38. Kazimirova M, Ortel J: **Metal accumulation by *Ceratitis capitata* (Diptera) and transfer to the parasitic wasp *Coptera occidentalis* (Hymenoptera)**. *Environ. Toxicol. Chem.* 2000, **19**:1822-1829.

39. Hendrickx F, Maelfait J-P, Speelmans M, Van Straalen NM: **Adaptive reproductive variation along a pollution gradient in a wolf spider**. *Oecologia* 2003, **134**:189-194.

40. Lagisz M, Laskowski R: **Evidence for between-generation effects in carabids exposed to heavy metals pollution**. *Ecotoxicology* 2008, **17**:59-66.

41. Babczyńska A, Wilczek G, Szulińska E, Kedziorski A, Franiel I, Migula P: **The reproductive potential of the spiders *Agelena labyrinthica* and *Xerolycosa nemoralis* from areas contaminated with metals**. *Sci. Total Environ.* 2012, **435–436**:374-379.

42. Eraly D, Hendrickx F, Bervoets L, Lens L: **Experimental exposure to cadmium affects metallothionein-like protein levels but not survival and growth in wolf spiders from polluted and reference populations**. *Environ. Pollut.* 2010, **158**:2124-2131.

43. Eraly D, Hendrickx F, Lens L: **Condition-dependent mate choice and its implications for population differentiation in the wolf spider *Pirata piraticus***. *Behav. Ecol.* 2009, **20**:856-863.

44. Kazimírová M, Slovák M, Manová A: **Host-parasitoid relationship of *Ceratitis capitata* (Diptera: Tephritidae) and *Captera occidentalis* (Hymenoptera: Proctotrupoidea: Diapriidae) under host heavy metal stress**. *Eur. J. Entomol.* 1997, **94**:409-420.

45. Ye GY, Dong SZ, Dong H, Hu C, Shen ZC, Cheng JA: **Effects of host (*Boettcherisca peregrina*) copper exposure on development, reproduction and vitellogenesis of the ectoparasitic wasp, *Nasonia vitripennis***. *Insect Sci.* 2009, **16**:43-50.

46. Zhang Z-T, Zhang H-C, Wang Q-L, Pang Z-L, Liang Z-A, Xia M, Du R-Q: **Changes in developmental duration, starvation tolerance and cadmium**. *Acta Entomol. Sin.* 2011, **54**:997-1002.

47. • Cheruiyot D, Boyd R: **Biotransfer, bioaccumulation and effects of herbivore dietary Co, Cu, Ni, and Zn on growth and development of the insect predator *Podisus maculiventris* (Say)**. *J. Chem. Ecol.* 2013, **39**:764-772.
This study examined HM contamination of an agricultural predator via contaminated prey.

48. Vickerman DB, Trumble JT: **Biotransfer of selenium: effects on an insect predator, *Podisus maculiventris***. *Ecotoxicology* 2003, **12**:497-504.

49. Zygmunt PMS, Maryański M, Laskowski R: **Body mass and caloric value of the ground beetle (*Pterostichus oblongopunctatus*) (Coleoptera, Carabidae) along a gradient of heavy metal pollution**. *Environ. Toxicol. Chem.* 2006, **25**:2709-2714.

50. Stone D, Jepson P, Laskowski R: **Trends in detoxification enzymes and heavy metal accumulation in ground beetles (Coleoptera: Carabidae) inhabiting a gradient of pollution**. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 2002, **132**:105-112.

51. • Sorvari J, Rantala LM, Rantala MJ, Hakkarainen H, Eeva T: **Heavy metal pollution disturbs immune response in wild ant populations**. *Environ. Pollut.* 2007, **145**:324-328.
This study examined immune function in HM contaminated ant populations using an encapsulation response experiment.

52. Bednarska AJ, Stachowicz I: **Costs of living in metal polluted areas: respiration rate of the ground beetle *Pterostichus oblongopunctatus* from two gradients of metal pollution**. *Ecotoxicology* 2013, **22**:118-124.

53. Scheifler R, Gomot-de Vaufleury A, Toussaint ML, Badot P: **Transfer and effects of cadmium in an experimental food chain involving the snail *Helix aspersa* and the predatory carabid beetle *Chrysocarabus splendens***. *Chemosphere* 2002, **48**:571-579.

54. Sorvari J, Eeva T: **Pollution diminishes intra-specific aggressiveness between wood ant colonies**. *Sci. Total Environ.* 2010, **408**:3189-3192.

55. Stone D, Jepson P, Kramarz P, Laskowski R: **Time to death response in carabid beetles exposed to multiple stressors along a gradient of heavy metal pollution**. *Environ. Pollut.* 2001, **113**:239-244.

56. Kramarz P, Stark JD: **Population level effects of cadmium and the insecticide imidacloprid to the parasitoid, *Aphidius ervi* after exposure through its host, the pea aphid, *Acyrthosiphon pisum* (Harris)**. *Biol. Control.* 2003, **27**:310-314.

57. Wilczek G, Babczyńska A, Migula P, Wencelis B: **Activity of esterases as biomarkers of metal exposure in spiders from the metal pollution gradient**. *Polish J. Environ. Stud.* 2003, **12**:765-771.

58. Wilczek G, Babczyńska A, Augustyniak M, Migula P: **Relations between metals (Zn, Pb, Cd and Cu) and glutathione-dependent detoxifying enzymes in spiders from a heavy metal pollution gradient**. *Environ. Pollut.* 2004, **132**:453-461.

59. Babczyńska A, Wilczek G, Wilczek P, Szulińska E, Witas I: **Metallothioneins and energy budget indices in cadmium and copper exposed spiders *Agelena labyrinthica* in relation to their developmental stage, gender and origin**. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 2011, **154**:161-171.

60. Liu J, Gao J, Yun Y, Hu Z, Peng Y: **Bioaccumulation of mercury and its effects on survival, development and web-weaving in the funnel-web spider *Agelena labyrinthica* (Araneae: Agelenidae)**. *Bull. Environ. Contam. Toxicol.* 2013, **90**:558-562.

61. Hendrickx F, Maelfait JP, Lens L: **Relationship between fluctuating asymmetry and fitness within and between stressed and unstressed populations of the wolf spider *Pirata piraticus***. *J. Evol. Biol.* 2003, **16**:1270-1279.

62. Hendrickx F, Maelfait JP, Lens L: **Effect of metal stress on life history divergence and quantitative genetic architecture in a wolf spider**. *J. Evol. Biol.* 2008, **21**:183-193.

63. Zhang Z-T, Yu M-Y, Pang Z-L, Xia M, Du R-Q, Yang F-F, Peng Y: **Effects of cadmium on metallothionein content in *Pirata subpiraticus* (Araneae: Lycosidae) and its growth and development**. *Acta Entomol. Sin.* 2011, **54**:293-298.

64. Zhang Z-T, Zhang H-C, Liang Z-A, Xia M, Du R-Q: **Effects of mercury on activities of antioxidant enzymes in *Pirata subpiraticus* from different habitats**. *Sichuan J. Zool.* 2011, **30**:552-555.

65. Chen X, Zhang Z, Liu R, Zhang X, Chen J: **Effects of the metals lead and zinc on the growth, development, and reproduction of *Pardosa astrigera* (Araneae: Lycosidae)**. *Bull. Environ.* 2011, **86**:203-207.

66. Eraly D, Hendrickx F, Backeljau T, Bervoets L, Lens L: **Direct and indirect effects of metal stress on physiology and life history variation in field populations of a lycosid spider**. *Ecotoxicol. Environ. Saf.* 2011, **74**:1489-1497.

67. Kramarz P, Laskowski R: **Effect of zinc contamination on life history parameters of a ground beetle, *Poecilus cupreus***. *Bull. Environ. Contam.* 1997, **59**:525-530.

68. Lindqvist L, Block M: **Metal pollution and fat accumulation in the carabid beetle *Pterostichus melanarius* (Coleoptera, Carabidae)**. *Bull. Environ. Contam.* 2001, **66**:184-188.

69. Migula P, Laszczyca P, Augustyniak M, Wilczek G, Rozpedek K, Kafel A, Woloszyn M: **Antioxidative defence enzymes, in beetles, from a metal pollution, gradient**. *Biologia (Bratisl)* 2004, **59**:645-654.

70. Lagisz M: **Changes in morphology of the ground beetle *Pterostichus oblongopunctatus* f. (Coleoptera; Carabidae) from vicinities of a zinc and lead smelter**. *Environ. Toxicol. Chem.* 2008, **27**:1744-1747.

71. Eeva T, Sorvari J, Koivunen V: **Effects of heavy metal pollution on red wood ant (*Formica* s. str.) populations**. *Environ. Pollut.* 2004, **132**:533-539.

72. Ortel J, Gintenreiter S, Nopp H: **The effects of host metal stress on a parasitoid in an insect/insect relationship (*Lymantria dispar* L., Lymantriidae lepid.—*Glyptapanteles liparidis* Bouchè, Braconidae hym.)**. *Arch. Environ. Contam.* 1993, **24**:421-426.

73. Ortel J, Vogel W: **Effects of lead and cadmium on oxygen consumption and life expectancy of the pupal parasitoid, *Pimpla turionellae***. *Entomol. Exp. Appl.* 1989, **52**:83-88.

74. Ohio EPA: **Evaluation of background metal soil concentrations in Cuyahoga County—Cleveland area**. *Summary Report for Ohio EPA's Voluntary Action Program* 2013. 134 pages.