



# Vacant lot soil degradation and mowing frequency shape communities of belowground invertebrates and urban spontaneous vegetation

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## Abstract

Vacant land in legacy cities is increasingly recognized as a resource to support biodiversity and improve the quality of life for residents. However, the capacity for vacant lot parcels to provide these benefits is influenced by current management practices and landscape legacies of urbanization, which typically results in degraded soil quality. The role of soil quality in supporting urban biodiversity and ecosystem functions is often overlooked when developing sustainable urban planning initiatives. This study investigated how soil physical and chemical properties influenced the community of urban spontaneous vegetation and soil invertebrates found within vacant lots mowed monthly or annually in Cleveland, Ohio, USA. We found that soil chemical and physical properties were strong predictors of soil-dwelling invertebrates, as vacant lots highly contaminated with heavy metals had simplified communities. Moreover, increased mowing frequency resulted in greater biomass and blooms of urban spontaneous forbs. Importantly, vacant lots dominated by urban spontaneous forbs and high bloom abundances also were contaminated with heavy metals, with implications for herbivores and pollinators using these resources. Our findings indicate that conservation initiatives must consider landscape legacies from industrial activity and local habitat management practices in order to support above and belowground habitat quality of greenspaces in urban ecosystems. Understanding how soil degradation impacts habitat quality and the delivery of ecosystem services from vacant land is essential for legacy cities to maximize their environmental benefits.

**Keywords** Arthropod · City · Heavy metals · Insect · Lead · Legacy · Management · Urbanization

## Introduction

Legacy cities are metropolitan areas with less than 20% of their peak population and are larger than 50,000 residents (Mallach and Brachman 2013). Within the United States many factors have contributed to this depopulation, including economic disinvestment, suburbanization, aging populations, diminished property values, and abandonment (Mallach and Brachman 2013; Martinez-Fernandez et al. 2012; Nassauer

and Raskin 2014). This has created a vacancy landscape within legacy cities, consisting of a dynamic mosaic of occupied and abandoned structures and formally occupied vacant land (Herrmann et al. 2016; Odom Green et al. 2016). Vacant land is increasingly recognized as a valuable ecological resource, by provisioning ecosystem services that address environmental degradation (Herrmann et al. 2016; Nassauer and Raskin 2014) and supporting a high richness of flora and fauna (Delgado de la flor et al. 2017, 2020; Perry et al. 2020; Riley et al. 2018a). Yet the important role of soil ecosystems in supporting below and aboveground biodiversity, and ecosystem functions and services such as nutrient cycling, carbon sequestration, food production, and storm-water infiltration (Beniston et al. 2016; Jeffery et al. 2010; Kumar and Hundal 2016) is rarely considered in sustainable urban planning initiatives (Pollak 2006). Understanding how soil degradation might affect biodiversity and the ecosystem services provided by vacant land is vital for legacy cities to minimize risks and achieve environmental benefits (Blanco et al. 2009).

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Vacant lot soils are shaped by both industrialization and deindustrialization processes such as construction and demolition, hydrological changes, deposition of pollutants, and effects of urban heat islands (Guilland et al. 2018; Morel et al. 2015; Schwarz et al. 2016a). These anthropogenic processes can alter soil physical and chemical properties. For instance, vacant lot soils often contain concrete and construction debris, the presence of which can elevate soil pH and reduce stormwater infiltration (Shuster et al. 2014). Furthermore, elevated levels of heavy metals and organic contaminants are common within vacant lot surface soils (Jennings et al. 2002; Sharma et al. 2015a). For example, more than 50% of residential vacant lot soils analyzed in Cleveland, OH, USA exceeded the US EPA lead remediation threshold of 400 mg kg<sup>-1</sup>, with some sites exceeding 1000 mg kg<sup>-1</sup> (Perry et al. 2020). Across United States cities, lead contamination at these levels is common and highly heterogeneous (Clark et al. 2006; Kay et al. 2008; Schwarz 2010), but distance to build structures, historic industrial sources, and major roadways as well as housing age are positive predictors of elevated soil lead (Schwarz et al. 2016b). Residential soil heavy metal contamination has several contributors including the combustion of leaded gasoline, industrial emissions, deterioration of lead-based paint, and demolition of housing containing lead-based paint (Farfel et al. 2003; Mielke and Reagan 1998; Schwarz et al. 2012, 2016b; Walker 2013). This legacy of vacant lot soils can result in an impaired nitrogen cycle, with low concentrations of mineral nitrogen and microbial mineralization (P. L. Phelan, unpublished data). Therefore, the intensity of soil degradation within a vacant parcel could dramatically shape both above and belowground biota and their derived ecosystem functions and services.

Vacant lots are dominated by urban spontaneous vegetation, or plants that colonize naturally without cultivation (Robinson and Lundholm 2012). Although these species are considered tolerant of environmental disturbance (Riley et al. 2018b), soil properties directly influence the ecophysiology of urban plants. For instance, soil compaction can reduce root growth and plant uptake of water and nutrients (Arvidsson 1998; Unger and Kaspar 1994). Likewise, heavy metal contamination can be phytotoxic and reduce plant nutrient uptake as well as bloom abundance and bloom area (Athar and Ahmad 2002; Sivakoff and Gardiner 2017). Therefore, soil properties have the potential to influence the quality of vacant lots as a habitat for plant species and the urban fauna dependent upon them (Robinson and Lundholm 2012; Sivakoff et al. 2018). Further, vacant land soil quality could influence the contributions of urban spontaneous vegetation to ecosystem services such as carbon sequestration and storage, oxygen production, stormwater runoff reduction, and removal of atmospheric pollutants (Day et al. 2010; Riley et al. 2018a).

Soil degradation also threatens belowground invertebrate communities and associated ecosystem functions such as

organic matter dynamics, nutrient cycling, carbon storage, energy flows, and water infiltration and storage (Barrios 2007; Decaëns et al. 2006; Lavelle et al. 2006). For example, food webs within degraded soils can be simplified and lack higher trophic levels (Sharma et al. 2015b). Soils contaminated with heavy metals can also contain reduced earthworm density (Nahmani and Lavelle 2002), affecting soil porosity and aggregation as well as the mixing of soil layers (Edwards 2004). Further, most invertebrates spend at least one life stage within the soil (Decaëns et al. 2006), including many conservation targets. For example, Sivakoff et al. (2018) found that 82% of the bee species occupying vacant land in Cleveland, OH were ground nesting, and the presence of detectable lead within workers of the common Eastern bumble bee (*Bombus impatiens* Cresson) increased within urban Cleveland versus surrounding suburban and rural areas (Sivakoff et al. 2020). Therefore, soil degradation may threaten biodiversity and compromise the invertebrate-based ecosystem services derived from urban vacant land.

Assessing how soil quality influences above and belowground biota is essential if legacy cities aim to take advantage of any environmental benefits associated with their increasing vacant land holdings (Herrmann et al. 2016; Odom Green et al. 2016). Vacant lot ecosystems are shaped by regular management via mowing, a practice that has the potential to alter the biotic, chemical, and physical properties of soils and also has proved detrimental to the conservation of some arthropod species (Watson et al. 2019). Therefore, this study investigated the relationships among soil properties, urban spontaneous vegetation, and soil invertebrate communities under two mowing regimes: monthly and annually. Our objective was to examine management frequency and soil physical and chemical properties as drivers of aboveground urban spontaneous vegetation and belowground invertebrates found within vacant lots in Cleveland, Ohio, USA, a legacy city that contains large holdings of vacant land. We predicted that: 1) increased severity of soil degradation from heavy metal contamination and compaction would reduce the dominance of urban spontaneous flowering forbs and the abundance of soil invertebrates; and 2) reduced mowing frequency would enhance the dominance of forbs and the abundance of their blooms, improving resource availability and habitat quality for arthropods in vacant lots.

## Materials and methods

### Study site

Research was conducted in Cleveland, Ohio, USA (41.4993° N, 81.6944° W), a Midwestern city that has lost 42% of its peak

population since 1950. Historically, the primary vegetation type of this area was temperate deciduous forest consisting of beech (*Fagus*), maple (*Acer*), and basswood (*Tilia*) (Dyer 2006). In 1800, forests covered approximately 94% of Cuyahoga County but have decreased to 19.6% as of 2014 (Flinn et al. 2018). Northeast Ohio has a humid continental climate with an average annual precipitation of 111.5 cm and an average annual temperature of 10.2 °C from 2010 to 2019 (Midwestern Regional Climate Center 2020).

The city of Cleveland contains over 27,000 vacant lots totaling more than 1600 ha of land (Western Reserve Land Conservancy 2015). Abandoned residential properties continue to be demolished by the city (Fig. 1a–b). The resulting vacant land parcels are seeded with a fescue grass mixture following demolition of residential properties and managed by the City of Cleveland Land Bank via monthly mowing from April to September (Western Reserve Land Conservancy 2015) (Fig. 1c). Vacant lots used in this study were leased from the City of Cleveland Land Bank who worked with our research team to select replicate lots across inner-city Cleveland neighborhoods.

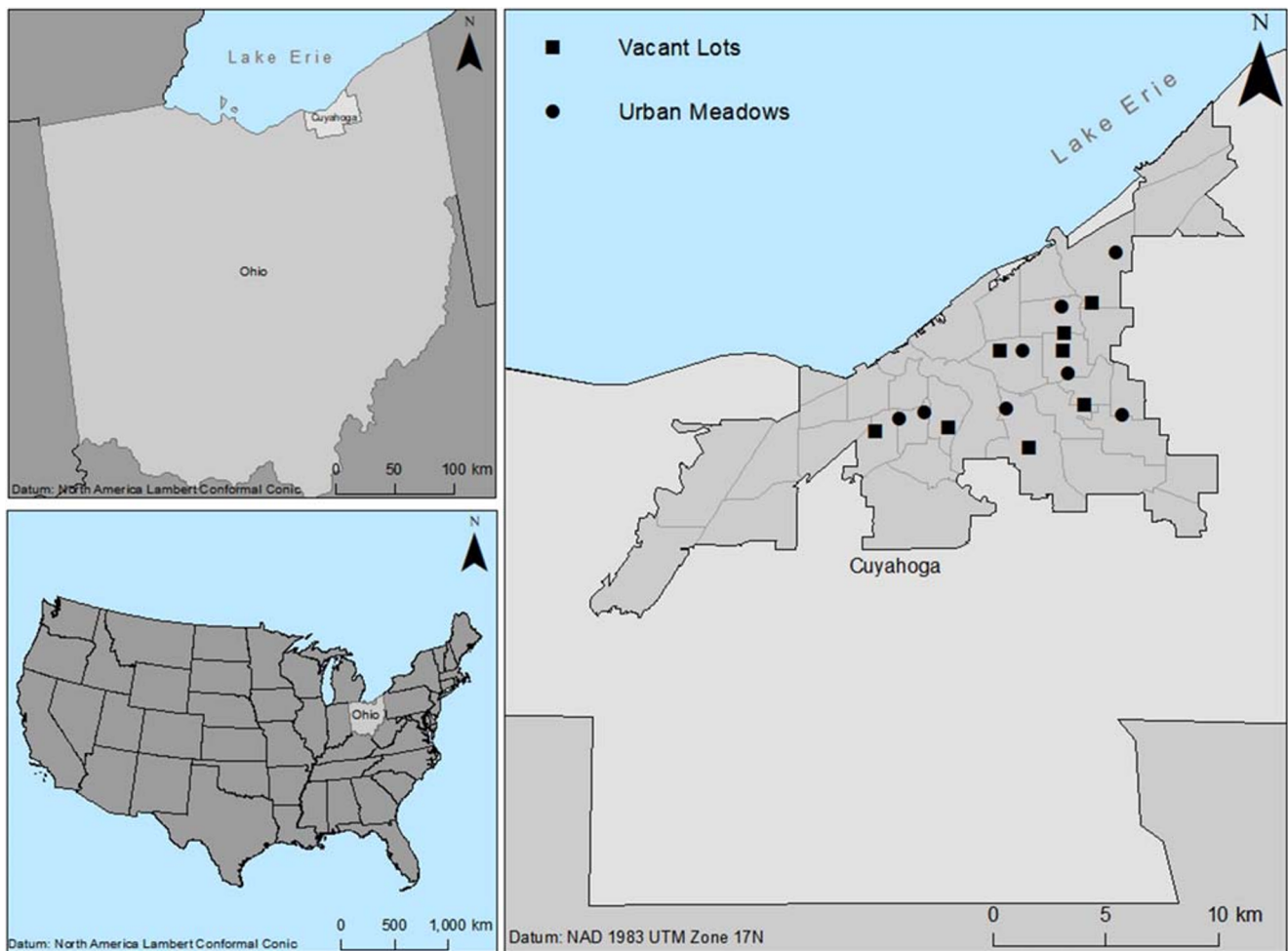
## Experimental design

This project was part of a city-wide manipulative field experiment, the Cleveland Pocket Prairie Project (Delgado de la flor et al. 2020; Perry et al. 2020), which aimed to enhance the beauty of city neighborhoods while providing valuable habitat for wildlife such as insects. For this study, two habitat management treatments based on mowing regime were established in 14 vacant lot sites (each 12 × 30 m) across seven inner-city Cleveland neighborhoods (Fig. 2). Each neighborhood contained two sites that had one of the following imposed mowing treatments: 1) Vacant Lots (Control) mowed monthly to a height of 15–20 cm from April to September, representing the current management employed by the City of Cleveland Land Bank (Fig. 1d–e) and 2) Urban Meadows, which consisted of existing vegetation but managed with a reduced mowing regime (Fig. 1f). The Urban Meadow treatment was originally seeded with a fescue grass mixture by the city and cut regularly by the City of Cleveland Land Bank prior to 2014 when this study was initiated, and annually in October during data collection. The grass and forb mulch resulting from each mowing event remained on site; it was not bagged

**Fig. 1** Cleveland, OH is a legacy city that has lost over 42% of its peak population. Across the city unoccupied homes (a) are eventually demolished by the City of Cleveland Land Bank (b). These sites are then graded and seeded with fescue grass and cut to a height of 15–20 cm monthly throughout the growing season with a brush mower (c). Our study compared plant and soil arthropod communities found within a Vacant Lot treatment cut monthly following standard city management practices (d and e show vacant lots before and after mowing) versus a Meadow treatment cut annually in October (f). Both habitats contain seeded fescue grasses and a diversity of urban spontaneous vegetation, many of which are non-native species. We found that bloom abundance was greater under a monthly versus annual mowing regime. Meadow sites were grass dominated and dried down earlier in the season as compared to vacant lots cut monthly







**Fig. 2** Vacant lot (square) and urban meadow (circle) sites established across seven inner-city neighborhoods in Cleveland, Ohio, USA (right). Maps on the left show the locations of Cuyahoga County in Ohio (top) and Ohio in the USA (bottom)

or raked and removed. Within the center of each vacant lot, a  $7 \times 15$  m grid with 105  $1 \text{ m}^2$  plots was established wherein vegetation and invertebrate data collection occurred.

### Belowground soil measurements

Soils were collected in April 2014. Vacant lot sites were divided into quadrants and five soil cores (3 cm in diameter  $\times$  20 cm in depth) were collected from random locations within each quadrant using a push probe, totaling 20 soil cores per site. Soil cores were stored at  $4^\circ\text{C}$  until processed, wherein cores were air-dried at  $23^\circ\text{C}$ , passed through a 2 mm sieve, and pooled by site. Pooled soil samples were analyzed for pH, cation exchange capacity ( $\text{cmol}_c \text{ kg}^{-1}$ ), phosphorus (Bray P1), ammonium acetate potassium, and heavy metals by the Service Testing and Research Laboratory (<https://u.osu.edu/starlab/>) (Table S1). Total heavy metal concentrations ( $\text{mg/kg}$ ) were determined using inductively coupled plasma-mass spectrometry with perchloric acid digestion. Metals included: arsenic (As), aluminum (Al), antimony (Sb), barium (Ba),

cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), vanadium (V), and zinc (Zn). Additionally, pooled soil samples were used to quantify the active pool of organic matter.

Site-level heavy metal contamination was assessed using the Contamination Factor (*CF*) Index (Weissmannová and Pavlovský 2017) for each heavy metal by calculating the ratio of the observed concentration to the average background level determined for the eastern USA (US EPA 2007). Background concentrations ( $\mu\text{g/g}$ ) used were 5.0 (As), 71,000.0 (Al), 1.0 (Sb), 350.0 (Ba), 0.23 (Cd), 45.0 (Cr), 9.0 (Co), 18.0 (Cu), 21,000.0 (Fe), 19.0 (Pb), 430.0 (Mn), 15.0 (Ni), 60.0 (V), and 45.0 (Zn) (US EPA 2007). Next, the *CF* indices were used to calculate the Pollution Load Index (*PLI*) (Liu et al. 2005; Tomlinson et al. 1980; Weissmannová and Pavlovský 2017) for each site (Table S2), which is an integrated measure of heavy metal contamination. Four *PLI* classes were used to evaluate contamination levels of heavy metals: 1) low contamination ( $PLI < 1$ ); 2) moderate contamination ( $1 \leq PLI < 2$ );

3) considerable contamination ( $2 \leq PLI < 3$ ); and 4) very high contamination ( $3 \leq PLI$ ) (Demková et al. 2017).

The active pool of organic matter was assessed using three soil quality indicators: 1) soil mineralizable carbon or respiration, a measure of microbial activity and nutrient mineralization; (2) permanganate-oxidizable carbon, a measure of the labile carbon pool; and (3) soil protein pool, a measure of available organic nitrogen (Table S1). Mineralizable carbon was based on the methods of Franzluebbers et al. (2000). Briefly, 10 g of air-dried soil was measured into 50-mL polypropylene screw-top centrifuge tubes. Soils were then rewetted with deionized water to 50% water-filled pore space which was previously determined gravimetrically. The tubes were then tightly sealed with caps fitted with septa and kept in the dark at 25 °C for 24 h. After incubation, a 1 mL syringe was used to sample 0.5 mL of air from the tube through the septa. CO<sub>2</sub> concentrations were determined by injecting the sampled air into a Li-Cor LI-820 infrared gas analyzer (LI-COR, Biosciences, Lincoln, NE). Permanganate-oxidizable carbon (POXC, mg kg<sup>-1</sup> soil) was measured based on the methods of Weil et al. (2003) adapted by Culman et al. (2012). In brief, 20 mL of 0.02 mol L<sup>-1</sup> KMnO<sub>4</sub> was added to 50 mL tubes containing 2.5 g air-dried soil. The tubes were shaken for 2 min at 240 oscillations min<sup>-1</sup> then allowed to settle for 10 min. After settling, 0.5 mL of the supernatant was diluted with 49.5 mL of deionized water and sample absorbance was read at 550 nm on a spectrophotometer. Soil protein was determined following the protocol described in Hurisso et al. (2018). In brief, 24 mL of 0.02 M sodium citrate was added to 3 g of air-dried pooled soil. After shaking for 5 min at 180 oscillations per minute, samples were autoclaved at 121 °C (15 psi) for 30 min. Soil particles were resuspended by shaking for 3 min at 180 oscillations per minute, and then 1.75 mL of the sample slurry was removed and centrifuged (10,000×g for 3 min). Next, 10 µL of the sample supernatant was combined with 200 µL of Bicinchoninic acid working reagent (Thermo Scientific, Pierce™, Rockford, IL) and incubated on a block heater at 60 °C for 60 min. The absorbance was determined at 562 nm using a spectrophotometer, and the amount of soil protein in each sample was calculated using the equation in Hurisso et al. (2018).

Soil compaction was measured via bulk density (g/cm<sup>3</sup>) (Table S1). Four additional soil cores (5 cm in diameter × 20 cm in depth) were collected using a hammer probe fitted with plastic sleeves (159 cm<sup>3</sup>). Soil cores were dried at 120 °C for 48 h. Bulk density was calculated for each soil core by dividing the dry weight (g) by the volume (cm<sup>3</sup>) of the plastic collection sleeve. The volume of the sleeve was adjusted for cores containing large rocks by determining the volume of the rock and subtracting it from the container volume. Bulk

density measurements were averaged by site. Soil cores were collected in July 2015.

### Aboveground vegetation measurements

Total vegetation biomass (g/m<sup>2</sup>), estimated dry weight of dominant forbs (%), vegetation height (cm), and bloom abundance (blooms/m<sup>2</sup>) were quantified in 20 random plots twice during the growing season each year. Vegetation measurements were collected during 1–16 July and 13 August–3 September in 2014 and during 22 June–1 July and 17–24 August in 2015. Measurements were collected within a 0.5 m<sup>2</sup> quadrat placed in the center of each 1 m<sup>2</sup> plot.

Total vegetation biomass was quantified using the comparative yield method (Haydock and Shaw 1975). A five-point-yield scale based on visual and tactile estimates of dry biomass for the overall site vegetation was established by identifying five plots representing the lowest estimated biomass (1) to the highest estimated biomass (5). Using the five-point-yield scale, a comparative yield score (using 0.25 increments) based on visual and tactile assessments was assigned for 20 random plots. Following assessment, vegetation in the five-point-yield scale plots was harvested, dried at 75 °C for 36–48 h, and weighed to the nearest 0.1 g. These weight measurements were used to create a linear equation for each site in which the assigned comparative yields were inserted into the equation to calculate an estimated biomass for each of the 20 plots. These estimated measurements were averaged to get site-level mean vegetation biomass per sampling interval, and then averaged across the two sampling intervals of each year.

Estimated dry weight of dominant forbs (represented as a percentage) was quantified using the dry-weight-rank method (Mannetje and Haydock 1963). Within 20 random plots, plants were identified to species (Uva 1997), or to genus in cases where the species could not be determined with confidence. Species identifications were particularly challenging for some plants after vacant lots were mowed. Next, the top three dominant forb species were identified based on visually and tactilely estimated dry weight. Ties were allowed. Using the calculations provided in Mannetje and Haydock (1963), each species' percentage of biomass was determined for each vacant lot site. The forb biomass percentages were totaled for each vacant lot site and then averaged across the two sampling intervals of each year.

Vegetation height (cm) and bloom abundance (blooms/m<sup>2</sup>) were quantified in each site. In 2014, 25 height measurements were collected throughout the grid for all plant species found within six random plots. Height measurements were averaged per species, and then averaged across all species to get mean plant height per site for each sampling interval. In 2015, three plant height measurements were collected within six plots. Height measurements were averaged for each plot, and then averaged across the six plots to get a mean plant height per site

for each sampling interval. Bloom abundance was quantified by counting all blooms within the same six plots. Bloom abundance was averaged across plots to get a mean bloom abundance per site for each sampling interval.

### Soil invertebrate collection

Soil invertebrates were sampled via soil cores (5 cm in diameter  $\times$  10 cm in depth) collected from random plots within the grid. Soil cores were stored at 4 °C until processed using Berlese funnels (Macfadyen 1953). All cores were processed within seven days of collection. Macrofauna were removed using forceps while transferring the soil to the funnels. Soil was heated from above using lamps until dried, which occurred within 3 days. Soil invertebrates were collected in 70% ethanol and adults were identified to class, order, or family (Triplehorn and Johnson 2005) using a dissecting microscope. Invertebrate sampling via soil cores is biased towards mesofauna such as Acari and Collembola, and therefore, counts of macrofauna should be interpreted with caution. In 2014, six soil cores were collected twice from each vacant lot site during 17–28 July and 8–15 September, totaling 12 soil cores per site. In 2015, four soil cores were collected twice from each site during 22 June–1 July and 17–24 August, totaling 8 soil cores per site.

### Statistical analysis

Abundances of soil invertebrate taxa were pooled across years for each vacant lot site due to low counts. Soil and vegetation variables were averaged across years for each site. Generalized linear models (GLMs) were used to compare soil, vegetation, and invertebrate response variables between vacant lot management treatments using the ‘stats’ package in R version 3.6.0 (R Core Team 2020). Soil, vegetation, and invertebrate response variables were checked for normality and variance, and those variables that did not meet these assumptions were rank transformed (Quinn and Keough 2002). Predictor variables for the GLMs were management treatment (monthly mow or annual mow) as a fixed factor and neighborhood as a random factor.

Partial Least Squares Canonical Analysis (PLSCA) and relevance network analysis were used to evaluate the relationships between belowground soil variables, aboveground vegetation variables, and soil invertebrates. PLSCA is similar to PLS regression, but all variables are considered dependent and compared as a canonical correlation (i.e. variables are not identified as responses or predictors a priori). There are several advantages of PLS methods, including the ability to incorporate multiple response variables, use many predictors that may be collinear, and have small sample sizes relative to the number of dependent variables (Carrascal et al. 2009). PLSCA

analyzes the linear relationships between variables in two matrices by deriving a latent variable from each matrix to maximize the covariance explained between them (Abdi and Williams 2013). PLSCA was conducted with the complete set of soil, vegetation, and invertebrate variables. Variables were scaled to have a mean of zero and variance of one. PLSCA was performed using the package ‘plsdepot’ (Sanchez 2012) in R version 3.6.0 (R Core Team 2020). Variables with correlation coefficients higher than 0.5 or lower than  $-0.5$  on either axis were considered significant and retained for the relevance network analysis. Relevance network analysis calculates a pairwise similarity matrix using the latent variables from the PLSCA, simultaneously representing positive and negative correlations within the data. The similarity values are calculated by summing the correlations between the individual pairs of variables and each of the latent variables from the PLSCA and approximate a Pearson correlation (González et al. 2012). A 0.5 threshold was used to evaluate the strength of variable associations for the relevance network analysis. Relevance network analysis was performed in R using the package ‘mixOmics’ (Rohart et al. 2017).

### Results

Vacant lots were characterized by grasses and volunteer forbs, the majority of which were non-native species (Table 1). Vacant lots mowed monthly were dominated by white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), broadleaf plantain (*Plantago major* L.), and narrowleaf plantain (*Plantago lanceolata* L.). Urban meadows were grass dominated, but still contained similar plant species as well as common milkweed (*Asclepias syriaca* L.), daisy fleabane (*Erigeron annuus* L.), and white heath aster (*Symphyotrichum ericoides* L.). A total of 7180 soil invertebrates were collected from vacant lots representing seven taxonomic groups: Oligochaeta, Acari, Araneae, Myriapoda, Collembola, Coleoptera, and Formicidae (Table 2). Of these seven taxa, Acari (40.6% of total individuals collected), Formicidae (32.4%), and Collembola (16.7%) were the most abundant, while Myriapoda (1.9%) and Araneae (1.3%) were the least abundant.

Reduced management of vacant lot sites decreased dominant forbs ( $F_{1,6} = 32.39$ ;  $P = 0.002$ ) and the abundance of blooms ( $F_{1,6} = 12.37$ ;  $P = 0.017$ ) (Table 3). Estimated dry weight of dominant forbs was lower ( $43.1 \pm 4.3\%$ ) in meadow vacant lots mowed annually than in urban vacant lots ( $79.8 \pm 6.3\%$ ) mowed monthly. Abundance of blooms also was lower ( $4.2 \pm 1.3$  blooms/m<sup>2</sup>) in meadow vacant lots than in urban vacant lots ( $12.2 \pm 2.7$  blooms/m<sup>2</sup>). Mowing frequency did not impact the abundances of soil invertebrates or belowground soil variables (Table 3).

**Table 1** Plant species found in the vacant lots only, urban meadows only, and in both treatments in Cleveland, Ohio, USA. For plants identified to species, asterisks denote those native to eastern North America

Vacant Lot	Urban Meadow	Present in Both Treatments
<i>Daucus carota</i>	<i>Asclepias syriaca</i> *	<i>Hedera helix</i>
<i>Achillea millefolium</i> *	<i>Erigeron annuus</i> *	<i>Artemisia</i> spp.
<i>Ambrosia</i> spp.	<i>Symphytotrichum ericoides</i> *	<i>Cichorium intybus</i>
<i>Arctium</i> spp.	<i>Trifolium hybridum</i>	<i>Erigeron canadensis</i> *
<i>Cirsium arvense</i>	<i>Hibiscus</i> spp.	<i>Solidago</i> spp.
<i>Cerastium vulgatum</i>	<i>Malva neglecta</i>	<i>Sonchus</i> spp.
<i>Securigera varia</i>	<i>Agrostis stolonifera</i>	<i>Taraxacum</i> spp.
<i>Juncus tenuis</i> *	<i>Potentilla norvegica</i> *	<i>Thlaspi arvense</i>
<i>Lamium purpureum</i>	<i>Parthenocissus quinquefolia</i> *	<i>Convolvulus arvensis</i>
<i>Veronica serpyllifolia</i> *		<i>Medicago lupulina</i>
<i>Digitaria sanguinalis</i>		<i>Melilotus officinalis</i>
<i>Festuca</i> spp.		<i>Trifolium pratense</i>
<i>Poa annua</i>		<i>Trifolium repens</i>
<i>Setaria viridis</i>		<i>Glechoma microcarpa</i>
<i>Rumex obtusifolius</i>		<i>Prunella vulgaris</i> *
<i>Solanum carolinense</i> *		<i>Oxalis stricta</i> *
		<i>Plantago lanceolata</i>
		<i>Plantago major</i>
		<i>Agrostis gigantea</i>
		<i>Dactylis glomerata</i>
		<i>Elymus repens</i>
		<i>Festuca arundinacea</i>
		<i>Lolium perenne</i>
		<i>Muhlenbergia schreberi</i> *
		<i>Poa pratensis</i>
		<i>Reynoutria japonica</i>
		<i>Rumex crispus</i>
		<i>Viola sororia</i> *

Soil physical and chemical properties were important predictors of invertebrates, and to a lesser extent, urban

spontaneous vegetation (Fig. 3; Table 4, S3). Moreover, two relevance networks were identified, with one

**Table 2** Abundance of soil invertebrates sampled via soil cores in vacant lots and urban meadows in Cleveland, Ohio, USA. Cores were collected twice during the summers of 2014 and 2015. Abundances are

pooled by treatment to reflect all sampling efforts. Primary feeding guilds for members of each soil invertebrate taxon follows Coleman et al. (2004)

Soil Invertebrate Taxa						
Class	Order	Family	Feeding Guild	Vacant Lot	Urban Meadow	Total
Oligochaeta			Detritivores	127	100	227
Arachnida	Acari		Detritivores/Fungivores/Predators	1725	1188	2913
	Araneae		Predators	64	31	95
Myriapoda			Detritivores/Predators	72	65	137
Collembola			Detritivores/Fungivores	711	488	1199
Insecta	Coleoptera		Detritivores/Herbivores/Predators	219	67	286
	Hymenoptera	Formicidae	Herbivores/Predators	1591	732	2323
Total				4509	2671	7180

**Table 3** Main effects of management treatment on vegetation, soil, and invertebrate variables in vacant lots and urban meadows in Cleveland, Ohio, USA. Vacant lots were mowed once per month during the growing season based on current city management practices. Urban Meadows

were mowed annually in October. Averages ( $\pm$  SE) for each variable are provided for Vacant Lot ( $n = 7$ ) and Urban Meadow ( $n = 7$ ) treatments. Results are from GLMs

Variables	Vacant Lot	Urban Meadow	<i>F</i>	<i>P</i>
<b>Vegetation</b>				
Total Vegetation Biomass (TB)	51.9 (6.1)	65.9 (15.6)	0.83	0.405
Dominant Forbs (DF)	79.8 (6.3)	43.1 (4.3)	32.39	0.002
Vegetation Height (VH)	17.2 (1.0)	26.8 (5.4)	1.25	0.332
Bloom Abundance (BA)	12.2 (2.7)	4.2 (1.3)	12.37	0.017
<b>Soil</b>				
Soil Bulk Density (BD)	1.9 (0.1)	1.7 (0.1)	3.48	0.126
Soil pH (PH)	7.2 (0.1)	7.4 (0.1)	5.28	0.069
Cation Exchange Capacity (CEC)	11.8 (1.3)	13.2 (1.6)	0.78	0.415
Heavy Metal Pollution Load Index (PLI)	2.1 (0.2)	2.0 (0.2)	0.02	0.882
Phosphorus (P)	87.2 (19.2)	84.3 (21.0)	0.01	0.915
Potassium (K)	118.1 (21.6)	106.7 (14.0)	0.43	0.558
Mineralizable Carbon (MC)	87.4 (15.5)	78.4 (7.4)	0.24	0.643
Permanganate-oxidizable Carbon (POXC)	587.4 (90.1)	602.4 (29.3)	0.22	0.649
Protein (PR)	6.9 (1.0)	6.4 (0.2)	0.02	0.893
<b>Invertebrates</b>				
Oligochaeta	16.7 (6.6)	12.8 (3.4)	0.42	0.542
Acari	269.2 (67.5)	191.3 (92.0)	4.96	0.077
Collembola	94.7 (36.8)	64.7 (30.9)	1.34	0.310
Myriapoda	9.8 (3.4)	6.8 (2.5)	0.28	0.620
Araneae	10.5 (3.3)	4.7 (1.1)	3.06	0.145
Formicidae	212.3 (117.8)	107.2 (47.6)	0.84	0.423
Coleoptera	34.5 (13.5)	10.3 (3.1)	6.18	0.057

dominated by the soil variables permanganate-oxidizable carbon, mineralizable carbon, and soil protein, and the other network driven by cation exchange capacity and the Pollution Load Index (Fig. 4). Oligochaeta, Araneae, Myriapoda, Coleoptera, and Formicidae were positively associated with mineralizable carbon, permanganate-oxidizable carbon, soil protein, and potassium (Fig. 3; PLSCA axis 1; 39.6% variance explained). These soil variables were strongly, positively correlated to the abundance of Oligochaeta, followed by Formicidae and Coleoptera (Fig. 3; Table 5). Acari, Collembola, dominant forbs, and bloom abundance were positively associated with cation exchange capacity, soil pH, and the Pollution Load Index, and negatively associated with phosphorus (Fig. 3; PLSCA axis 2; 36.9% variance explained). In particular, heavy metal contamination and cation exchange capacity were strongly, positively correlated with the abundance of Acari and Collembola (Fig. 4; Table 5). Vacant lots with greater heavy metal contamination also had a higher abundance of blooms and the urban spontaneous vegetation was dominated by forbs rather than grasses, however these relationships were not

strong enough to meet the 0.5 association threshold for the relevance network analysis.

## Discussion

Vacant land has become an abundant form of greenspace in post-industrial legacy cities and could be a valuable conservation resource for biodiversity in urban ecosystems (Gardiner et al. 2013). However, the conservation potential of these habitats is shaped by current management practices as well as landscape legacies of urbanization, housing demolition processes, and industrial activities that have degraded soil quality. In this study, we examined how management frequency and soil physical and chemical properties influenced the community of urban spontaneous vegetation and soil invertebrates found within vacant lots in Cleveland, Ohio, USA, a legacy city with over 1600 ha of vacant land (Western Reserve Land Conservancy 2015). Our results revealed that increased mowing frequency resulted in greater biomass and blooms of early successional forbs, while soil chemical and physical properties were strong predictors of soil invertebrate communities.



**Table 4** Partial Least Square Canonical Analysis (PLSCA) correlation coefficients for belowground soil variables, aboveground vegetation variables, and soil invertebrates from vacant lot and urban meadow sites in Cleveland, Ohio, USA. Coefficients are obtained by calculating the correlation between each variable and the associated latent variable. Only variables with a correlation coefficient higher than 0.50 or lower than -0.50 on either axis were considered significant

Variables	Axis 1 (t1)	Axis 2 (t2)
<b>Soil</b>		
Soil Bulk Density (BD)	-0.40	0.48
Soil pH (PH)	-0.29	0.66
Cation Exchange Capacity (CEC)	0.17	0.82
Heavy Metal Pollution Load Index (PLI)	-0.17	0.83
Phosphorus (P)	-0.12	-0.77
Potassium (K)	0.73	0.25
Mineralizable carbon (MC)	0.87	0.26
Permanganate-oxidizable carbon (POXC)	0.86	0.12
Protein (PR)	0.96	-0.22
<b>Vegetation</b>		
Total Vegetation Biomass (TB)	-0.17	-0.02
Dominant Forbs (DF)	-0.01	0.56
Vegetation Height (VH)	-0.28	-0.22
Bloom Abundance (BA)	0.07	0.54
<b>Invertebrates</b>		
Oligochaeta	0.93	0.13
Acari	0.27	0.84
Collembola	0.07	0.90
Myriapoda	0.56	0.32
Araneae	0.50	0.45
Formicidae	0.63	-0.20
Coleoptera	0.71	0.13

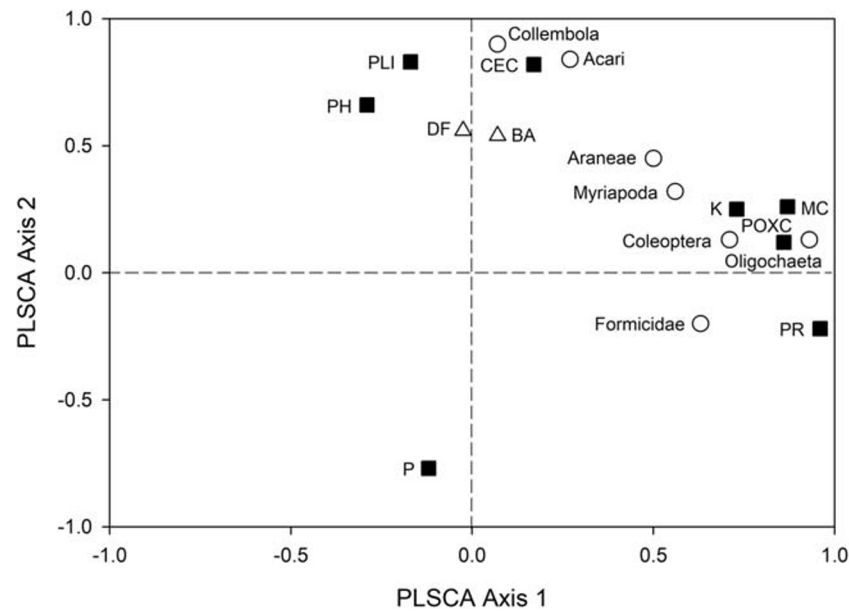
## Soil properties

Urban soils have experienced long-term anthropogenic degradation through compaction and contamination and may be a significant barrier to urban biodiversity conservation. We predicted that increased severity of soil degradation from heavy metal contamination and compaction would reduce the dominance of urban spontaneous flowering forbs and the abundance of soil invertebrates. Soil properties were important predictors of invertebrate communities in urban vacant lots, and to a lesser degree flowering plants. Relevance network analysis identified two distinct networks that can be characterized as vacant lots with ‘low quality’ and ‘higher quality’ soils. Vacant lots with low soil quality were characterized by elevated levels of heavy metal contamination, greater cation exchange capacity, and higher pH levels, whereas vacant lots with higher quality soils had enhanced microbial activity and nutrient mineralization as well as larger pools of labile carbon and available nitrogen. These soil quality distinctions were not influenced by mowing frequency, as neither soil properties nor invertebrate communities varied among treatments. This could be due to the short-term implementation of these mowing regimes. Therefore, other local and landscape factors not assessed in this study may explain the observed differences in soil quality among vacant lots, such as past management history, length of vacancy, age of demolished housing stock, and/or distance to historic smelting sites. Land-use legacies and site history have been identified as important drivers of soil development and soil-based ecosystem services and contribute to the high variability of soil properties within and among urban greenspaces (Pavao-Zuckerman 2008; Ziter and Turner 2018). Due to the highly heterogeneous nature of urban landscapes and their legacy, understanding the relative importance of site history on urban soil quality warrants further study to inform vacant land management (Ziter et al. 2017).

**Table 5** Pairwise similarity matrix calculated from a relevance associations network analysis following the Partial Least Square Canonical Analysis (PLSCA). The similarity values are calculated by summing the correlations between the individual variables and each of

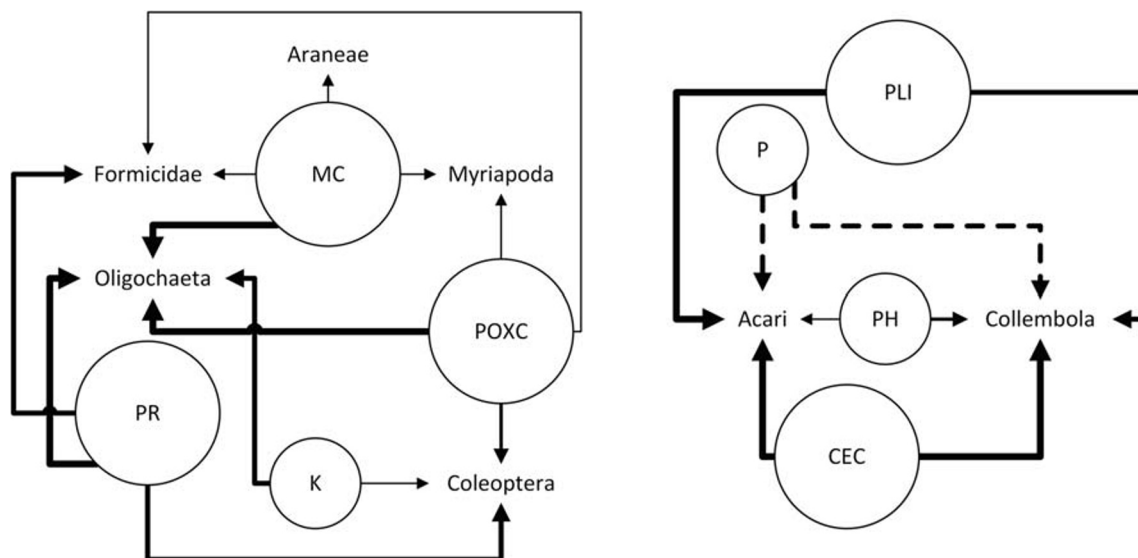
the latent components from the PLSCA model. These similarity values approximate a Pearson correlation coefficient. A 0.5 threshold value was used for the relevance network analysis, and associations that met this threshold are shown below

Predictor Variable	Oligochaeta	Acari	Araneae	Myriapoda	Collembola	Coleoptera	Formicidae
Soil pH (PH)		0.56			0.62		
Cation Exchange Capacity (CEC)		0.85			0.84		
Pollution Load Index (PLI)		0.76			0.81		
Phosphorus (P)		-0.72			-0.71		
Potassium (K)	0.71					0.58	
Mineralizable carbon (MC)	0.83		0.56	0.58		0.67	0.50
Permanganate-oxidizable carbon (POXC)	0.81			0.52		0.67	0.55
Protein (PR)	0.84					0.72	0.71



**Fig. 3** Partial Least Square Canonical Analysis (PLSCA) plot for belowground soil variables, soil invertebrates, and aboveground vegetation variables from vacant lot and urban meadow sites in Cleveland, Ohio, USA. Total variance explained by axes 1 and 2 was 39.6% and 36.9% respectively. Variables with correlation coefficients higher than 0.5 or lower than  $-0.5$  on either axis are shown below. The strength and direction of relationships in PLSCA are determined by relative distance, with closer variables being positively correlated to one another. *Soil variables* are squares and labeled as follows: pH (PH), heavy metal Pollution Load

Index (PLI), cation exchange capacity (CEC), potassium (K), mineralizable carbon (MC), permanganate-oxidizable carbon (POXC), soil protein (PR), and phosphorus (P). *Soil invertebrate variables* are circles. *Vegetation variables* are triangles and labeled as follows: estimated dry weight of dominant forbs (DF) and bloom abundance (BA). PLSCA correlation coefficients for all variables are provided in Table 4. The explained variance contributed by each variable to the latent variables is provided in Table S3



**Fig. 4** Relevance network plot for belowground soil variables, soil invertebrates, and aboveground vegetation variables from vacant lot and urban meadow sites in Cleveland, Ohio, USA. Soil variables are labeled as follows: pH (PH), heavy metal Pollution Load Index (PLI), cation exchange capacity (CEC), phosphorus (P), potassium (K), mineralizable carbon (MC), permanganate-oxidizable carbon (POXC), and soil protein (PR). Variables with PLSCA correlation coefficients higher than 0.5 or lower than  $-0.5$  on either axis were retained for the relevance network analysis (Table 5). A 0.5 correlation threshold was used to evaluate the

strength of variable associations. No aboveground vegetation variables met this threshold. Solid lines indicate positive associations, whereas dashed lines are negative associations. Thickness of the lines indicate the strength of the association between the two variables, with thicker lines having a stronger similarity value. Size of the circles for the soil variables is related to their PLSCA correlation coefficient, with variables in larger circles loading more strongly in the PLSCA. PLSCA correlation coefficients and relevance network similarity values for the soil and invertebrate variables are provided in Tables 4 and 5, respectively

Heavy metal contamination may limit some ecosystem services desired from vacant land. Considerable heavy metal contamination was observed in 36% of vacant lot sites, with these patterns driven by elevated levels of lead, cadmium, zinc, copper, arsenic, and antimony. In particular, vacant lots were highly contaminated with lead compared to background levels determined for the eastern US (US EPA 2007), and over 50% of sites had lead levels above the  $400 \text{ mg kg}^{-1}$  health threshold designated by the US Environmental Protection Agency (US EPA 2019). These findings are consistent with other studies that have measured vacant lot soil quality in Cleveland, OH, USA (Jennings et al. 2002; Perry et al. 2020; Sharma et al. 2015a). Heavy metal contamination can reduce microbial biomass and the activity of soil enzymes involved in the cycling of nutrients such as nitrogen and phosphorus (Kandeler et al. 1996), impairing essential services required by terrestrial ecosystems. Mobility and bioavailability of heavy metals in soil is influenced by a suite of chemical properties, including pH, organic matter content, concentrations of phosphorus, and cation exchange capacity (Pouyat et al. 2010). For example, low pH reduces cation exchange capacity for lead cations in the soil due to high affinity of hydrogen protons to binding sites (Wortman and Lovell 2013). Moreover, the presence of organic matter and phosphate in soils can aid in heavy metal stabilization through the formation of precipitates (Pouyat et al. 2010; Wortman and Lovell 2013). Because vacant lot sites with elevated concentrations of total heavy metals also had greater cation exchange capacity and high pH levels, lead and other metals may have reduced mobility and bioavailability in these soils. However, further analyses are required to quantify bioavailable levels of metals within urban vacant lots.

Widespread soil contamination poses a significant threat to invertebrate populations and the ecosystem services they provide in urban areas. Direct or indirect exposure of invertebrates to elevated levels of heavy metals in the soil can result in developmental (Cheruiyot et al. 2013; Lagisz 2008; Scheifler et al. 2002), reproductive (Hendrickx et al. 2003; Lagisz and Laskowski 2008), immunological (Migula et al. 2004; Sorvari et al. 2007; Stone et al. 2002), and behavioral (Eraly et al. 2009; Sorvari and Eeva 2010) consequences that can increase their susceptibility to other environmental stressors (Stone et al. 2001) and impact ecosystem services such as pest suppression (Gardiner and Harwood 2017). Vacant lots with low soil quality were characterized by simplified arthropod communities with greater abundances of small, soil-dwelling species such as Acari and Collembola that primarily graze on fungi, bacteria, and nematodes (Coleman et al. 2004). Some species of Acari and Collembola are shown to be tolerant of urbanization (Santorufu et al. 2012b, 2014), and thus, tend to be abundant in contaminated soils (Bengtsson and Rundgren 1988; Fountain and Hopkin 2004; Migliorini et al. 2004). In contrast, large ground-dwelling

predators and detritivores such as Araneae, Coleoptera, Formicidae, Myriapoda, and Oligochaeta were more abundant in vacant lots with higher soil quality. These arthropod taxa live or burrow in the soil, contributing to the mixing of soil layers and maintenance of soil structure, porosity, and infiltration of water and air (Brussaard 1997). Detritivores such as Myriapoda and Oligochaeta influence decomposition and nutrient cycling processes in soils through comminution of organic matter such as vegetation, leaf litter, and carrion (Coleman et al. 2004; Nielsen 2019).

Bioavailability, bioaccumulation, and toxicity of heavy metals for soil invertebrates are complex and dynamic processes influenced by soil chemical and physical properties (Bruus Pedersen et al. 1997; Sandifer and Hopkin 1997; Spurgeon and Hopkin 1996b; van Gestel 2008), as well as species-specific rates and modes of uptake (van Straalen et al. 2005), sequestration, detoxification, and excretion (Lanno et al. 2004; Santorufu et al. 2012a; van Gestel 2012). Although studies have reported accumulation of heavy metals in the bodies of soil invertebrates representing multiple trophic levels (Butovsky 2011; Hunter et al. 1987; Larsen et al. 1994; Migliorini et al. 2004; Spurgeon and Hopkin 1996a), the complexities of these processes result in context dependencies where findings cannot be generalized across locations or invertebrate taxa (van Gestel 2008). Future research should use a biodynamic approach (Luoma and Rainbow 2005) to improve mechanistic understanding of the risks associated with urban contamination for soil invertebrates, including potential additive and synergistic effects of multiple heavy metals.

### Mowing frequency

Frequent and intensive greenspace management is commonly employed in urban areas by public and private landowners to maintain socially accepted manicured lawns, but generally contradicts biodiversity conservation goals (Shwartz et al. 2014; Watson et al. 2019). In this study, we predicted that reduced mowing frequency would enhance the dominance of forbs and the abundance of their blooms, improving resource availability and habitat quality for arthropods in vacant lots. Contrary to our prediction, monthly mowing of vacant lots enhanced the dominance of early successional, primarily non-native forbs and the abundance of blooms from these species compared to vacant lots mowed annually in the fall, which were dominated by grasses. Common flowering species included red clover (*Trifolium pratense* L.), white clover (*T. repens* L.), chicory (*Cicorium intybus* L.), and Queen Anne's lace (*Daucus carota* L.), which represent common forage for wild bees within neighborhoods where vacant land is prevalent (Sivakoff et al. 2018). Importantly, our monthly mowing treatment was less frequent and less intense (i.e. cut to a height of 15–20 cm) than typical residential lawn management and perhaps was able to maintain a dense layer of

vegetation in which these forbs thrived. Studies from North America and Europe that have examined the impacts of lawn management on flora and fauna largely reported negative impacts of mowing weekly or removing a greater proportion of vegetation biomass (i.e. shorter height) (Lerman et al. 2018; Smith et al. 2015; Watson et al. 2019). For example, a meta-analysis of studies conducted in North America and Europe revealed that increased mowing intensity (cut to 2–5 cm) and frequency (once per week) of urban lawns supported lower overall insect and plant diversity, but higher occurrences of pest species than lawns managed less intensively (Watson et al. 2019). Although monthly mowing supported early successional forbs, many of which were exotic species, and enhanced the number of blooms, these changes in habitat quality did not affect invertebrate communities, likely due to their soil-dwelling lifestyle. Highly managed turf habitats can support high abundances of soil-dwelling arthropods with some taxa showing resiliency to varying lawn management regimes (Kunkel et al. 1999; Rochefort et al. 2013; Venn and Kotze 2014).

Our findings corroborate the idea that reducing management frequency to a “lazy lawnmower” approach would contribute to urban biodiversity conservation (Lerman et al. 2018). Monthly mowing is the current vacant land management strategy employed by the City of Cleveland Land Bank to maintain over 27,000 vacant parcels throughout the city, and based on our findings, this strategy is compatible with insect pollinator conservation goals within legacy cities (Hall et al. 2017). Nevertheless, previous studies have highlighted the detrimental effects of mowing for biodiversity (Wastian et al. 2016; Watson et al. 2019) when employed at greater frequencies within residential landscapes where regular lawn management is desired by citizens that prioritize a traditional lawn aesthetic over enhancing native biodiversity (Larson et al. 2016). For example, 68–70% of homeowners in Edina, MN, USA mowed their lawn once per week (Carpenter and Meyer 1999), and these behaviors can be difficult to change due to attitude, social, and monetary barriers (Eisenhauer et al. 2016; Nassauer et al. 2009). The quality of urban greenspaces for native plants, insects, and the ecosystem services they provide could be enhanced by reducing lawn management (e.g. the “lazy lawnmower” approach, *sensu* Lerman et al. 2018). Willingness to adopt environmentally friendly lawn management strategies has been observed in some populations of homeowners in the USA (Eisenhauer et al. 2016). Development of alternative management approaches such as reduced mowing regimes must consider the perceptions and values of local citizens and stakeholders in order to be successful (Turo and Gardiner 2019), but these initiatives could be fostered with neighborhood involvement rather than an individual-based strategy (Nassauer et al. 2009).

## Conclusions

Minimally managed vacant land in post-industrial legacy cities provides an opportunity to foster natural habitat and biodiversity in urban ecosystems (Gardiner et al. 2013). In this study, we found that soil chemical and physical properties were strong predictors of soil-dwelling invertebrate populations, with sites highly contaminated with heavy metals resulting in simplified invertebrate communities. Moreover, monthly mowing of vacant lots resulted in urban spontaneous, flowering forbs, which suggests that a reduction in lawn management could support the conservation value of these greenspaces for plant diversity, herbivorous insects, and pollinators. Importantly, vacant lots dominated by early successional forbs and high bloom abundances also were contaminated with heavy metals, indicating that conservation initiatives that only focus on aboveground flowering plant diversity may be negligible if belowground soil quality remains poor. Conservation initiatives that aim to improve aboveground habitat quality must consider the possibility of creating attractive sinks wherein colonizing insect species fail to survive and/or reproduce due to unmanaged soil contamination. Our findings indicate that landscape legacies from industrial activity and local habitat management practices must be considered together to support above- and belowground habitat quality of greenspaces in urban ecosystems.

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**Author contributions** MMG and NCH developed the study; NCH collected the field data; NCH, SWC, and KIP collected the laboratory data; KIP analyzed the data; KIP, MMG, and NCH wrote the first draft of the manuscript; all authors reviewed and edited the manuscript.

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