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A citizen science approach to identifying trace metal contamination risks in urban gardens

Mark Patrick Taylor[a,*], Cynthia F. Isley[a], Kara L. Fry[a], Xiaochi Liu[a,c], Max M. Gillings[a], Marek Rouillon[a], Neda S. Soltani[a], Damian B. Gore[a], Gabriel M. Filippelli[b]

[a] *Department of Earth and Environmental Sciences, Faculty of Science and Engineering, Macquarie University, Sydney, New South Wales 2109, Australia*
[b] *Department of Earth Sciences and Center for Urban Health, Indiana University – Purdue University Indianapolis, Indianapolis, IN, USA*
[c] *School of Information Engineering, China University of Geosciences, Beijing 100083, China*

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ABSTRACT

We launched the *VegeSafe* program in 2013 to assist Australians concerned about exposure to contaminants in their soils and gardens. *VegeSafe* analyses garden soils provided by citizens for trace metals at our laboratory at little to no cost, with easy-to-follow guidance on any intervention required. The response was overwhelming—Australians submitted 17,256 soils from 3,609 homes, and in turn *VegeSafe* researchers now have unparalleled household-scale data, providing new insights into urban trace metal contamination. The results are sobering, with 35% of homes, particularly those that are older, painted and located in inner cities having soils above the Australian residential guideline (300 mg/kg) for the neurotoxic trace metal lead (Pb). Exposure pathway, blood Pb concentration and vegetable uptake modelling showed the communities in these locations were most at risk. *VegeSafe* is transformative: 94% of participants better understood contaminants, 83% felt safer in their home environment and 40% undertook remedial action based on their results. The two-way nature of this program enables education of citizens about environmental contaminants, advances public health, and delivers impactful science.

1. Introduction

Urban gardening has experienced a renaissance, driven by community desire for home-grown produce. Urban croplands represent 5.9% (67.4 Mha) of global cropland (Thebo et al. 2014), with 35% of USA residents (National Gardening Association 2014) and 52% of Australians (Wise 2014) producing some food in their gardens. There are multiple advantages of urban food production (Ives et al. 2018; Winkler et al. 2019), including increased confidence about the source and quality of produce (Chase 2015) and enhanced urban health and sustainability. Urban gardens may have legacy trace metal contamination from building, industry, transport and waste practices (Rouillon et al. 2017a; US EPA 2011a). Urban gardeners typically have little awareness of these problems and little agency in determining whether or not their individual gardening plot is contaminated with trace metals. In 1980, Patterson predicted that urban city landscapes would be rendered uninhabitable due to the “*millions of tons of poisonous industrial lead residues*” (National Research Council 1980). This study examines the legacy risks in Australian garden soils associated, in part, with leaded petrol emissions (Kristensen 2015) and the decay of lead-based paint on older buildings.

The problem of legacy trace metal contamination is concerning, as urban vegetable gardens can contain anthropogenic contamination from toxic trace metals and metalloids (hereafter trace metals), including lead (Pb) (Cheng et al. 2015; Filippelli et al. 2018; Laidlaw et al. 2018; Rouillon et al. 2017a; Spliethoff et al. 2016). Urban environments are also known to be impacted by a suite of non-metal contaminants, all of which present toxic risks, including per- and polyfluoroalkyl chemicals, petroleum hydrocarbons, pesticides, weedicides and asbestos fibres. The spatial heterogeneity of urban soil contamination across cities and individual garden lots is not well understood by the community. This knowledge barrier, coupled with insufficient geochemical testing means there is limited information about specific exposure risks at residential locations or what to do about them (Bechet et al. 2018).

The primary barriers for residents acquiring soil trace metal data are awareness, cost and access. Moreover, commercial laboratories do not

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[*] Corresponding author.
E-mail address: mark.taylor@mq.edu.au (M.P. Taylor).

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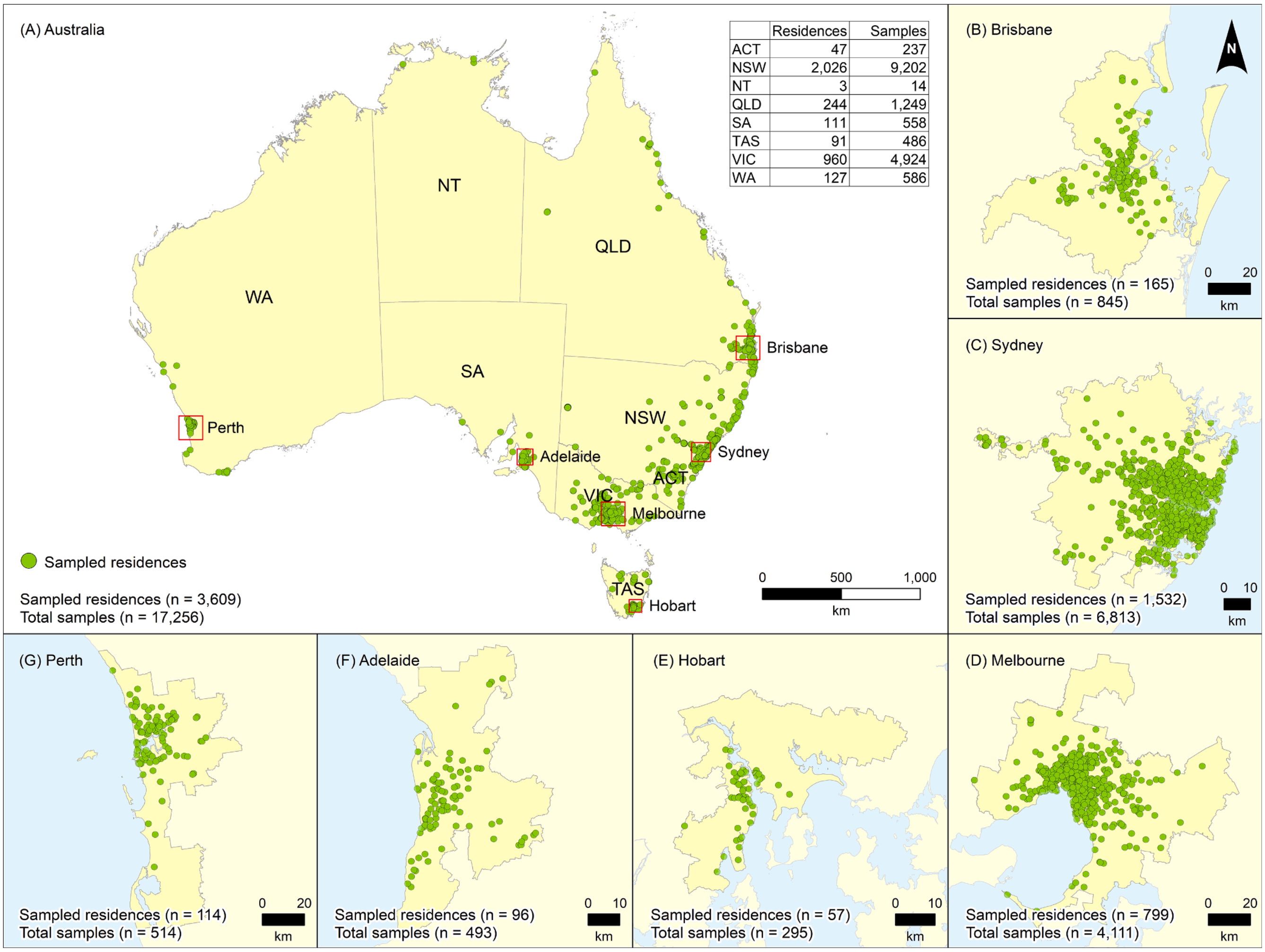
ordinarily provide data interpretation or advice as to appropriate remediation or intervention. Development and access to low-cost portable X-ray fluorescence (pXRF) spectrometry instruments have provided researchers with an affordable opportunity to help homeowners understand trace metal contamination in their gardens and successfully engage citizens in the science of their environment (Filippelli et al. 2018; Rouillon et al. 2017a).

This confluence of public need and our scientific curiosity led to the creation of the Australia-wide program *VegeSafe* in 2013 (Macquarie University 2019), based at Macquarie University, Sydney, which is ongoing in 2021. The *VegeSafe* program supports emerging public interest in the nexus between environmental trace metal contamination and food safety while providing public awareness, as well as management solutions to homeowners, where required. Participants mail up to five samples from their yards to Macquarie University for analysis and receive a report containing their results (Supplementary Fig. S1), Australian soil guidelines (NEPM 1999, updated 2013) and information on management options. Data are displayed on the publicly available web platform MapMyEnvironment (2020) (Supplementary Text S2). *VegeSafe* has the added benefit of facilitating authentic community engagement and building a genuine social licence (Lubchenco 1998); providing tools to reduce risk and increase confidence in the safety of gardens and the quality of home grown produce. The program has yielded unique and unrivalled datasets for scientists and citizens, providing insights into the extent and pattern of residential anthropogenic trace metal contamination. As well as collecting data, citizen scientists have also supported this work financially, contributing approximately AU$100,000 over seven years in donations to the program. Their questions to us have been (i) is our soil trace metal contaminated, and (ii) are our vegetables and fruit produce safe to eat? *VegeSafe* has enabled and supported thousands of Australians to carry on gardening in a more sustainable way, with reduced contaminant exposure risks and safer food produce. While the program is overseen by senior researchers, junior scientists (pre- and post-graduate students) manage sample analyses, reporting, and community engagement, providing invaluable real-world experience in communicating science effectively to a broad audience.

This study addresses the following research questions: (1) What is the distribution of soil trace metal concentrations in gardens across Australian cities? (2) What factors control spatial trends of trace metal contamination across cities and within gardens? (3) Do trace metal concentrations exceed relevant guidelines, and if so, where? (4) How effective is a citizen-science program such as *VegeSafe* at facilitating authentic community engagement, decision making and remedial action to inform and mitigate exposure risk to toxic trace metal contaminants?



	Residences	Samples
ACT	47	237
NSW	2,026	9,202
NT	3	14
QLD	244	1,249
SA	111	558
TAS	91	486
VIC	960	4,924
WA	127	586

Fig. 1. Location of sampled residences across the states and territories of Australia (A) and the Significant Urban Areas (SUAs) of state capital cities: Brisbane (B), Sydney (C), Melbourne (D), Hobart (E), Adelaide (F) and Perth (G) (Australian Bureau of Statistics 2018a). The selected SUAs represent approximately 65% of Australia's population and account for >75% of sampled residences. ACT – Australian Capital Territory; NSW – New South Wales; NT – Northern Territory; QLD – Queensland; SA – South Australia; VIC – Victoria; WA – Western Australia.

2. Methods

As of May 2020, *VegeSafe* had received 17,256 soil samples from 3,609 homes (Fig. 1). Soil trace metal concentrations (arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), manganese (Mn), nickel (Ni), Pb and zinc (Zn)) and associated metadata were interrogated using spatial and temporal variables to establish the factors influencing concentration, potential vegetable uptake and human health risk. Recruitment for the program was via our website, social media pages, word of mouth, Macquarie University and community events and media. Participants were invited to collect five soil samples from four areas around their homes including front yard, back yard, gutter drip line (adjacent to homes) and vegetable garden areas to capture variation across the outdoor area and indicate possible sources. Exposure risks, particularly to young children, are present not only from soils intended for vegetable gardening, but from any areas where they play, hence samples from across the entire yard must be considered.

Participants were provided with sampling instructions that requested each soil sample be the size of a cricket ball (∼300 g of soil), sampled at 0–2 cm depth, placed into sealable polyethylene bags and mailed to the University (Supplementary Fig. S3). The depth interval was stipulated to ensure that sampling was consistent and required minimal effort for gardeners. Further, it aligned with the relevant Australian Standards (Standards Australia 2000) and contains the components of soil most likely to be accessed by children or mobilised as dust. Surface soil represents the most common part of the soil profile impacted by anthropogenic trace metal contamination from atmospheric depositions (e.g. industry, transport, leaded gasoline emissions) and inputs from paint and building materials, which may also be a source of contamination in adjoining soil (Birch et al. 2011; Gulson et al. 1995; Rouillon et al. 2017a). All samples received were processed when accompanied by a consent form containing relevant metadata including sample locations, home age, building materials and painted/unpainted status (Supplementary Fig. S4). *VegeSafe* trace metal data were compared to Australian soil guidelines (NEPM 2013) for residential properties with exposed soil (Australian HIL A). The Australian guidelines do not designate a 'safe' maximum concentration threshold, but instead are the point at which further investigation is warranted to establish risks to human health according to particular land use types.

2.1. *Trace metal analysis using portable X-ray fluorescence (pXRF) spectrometry*

Two Olympus Delta Premium pXRF analysers, both with 40 kV, 4 W rhodium anode tubes, were used to generate screening level data for As, Cd, Cr, Cu, Mn, Ni, Pb and Zn concentrations in soils. These metals were reported because they are commonly known to be present in urban soils at potentially toxic concentrations, especially Pb, for which there is no accepted safe level of exposure and whose effects are cumulative and systemic on the human body (Abadin et al. 2020; National Toxicology Program 2012). A detector calibration check, a milled quartz (SiO_2) blank to assess instrument cleanliness and two Standard Reference Materials (SRM; NIST 2710a and NIST 2711a) were measured routinely. Soils and SRMs were measured for 60 s (20 s for each of three tube power measurement conditions) using the instrument's bundled soil calibration. Analytical precision and accuracy were typically better than 20% where concentrations exceeded 100 mg/kg (Supplementary Table S5). Analytes reporting below the instrument limit of quantification (LoQ) were recorded at 0.5 × LoQ, and this value was used for all calculations (Table 1).

Soil samples were analysed through polyethylene bags to reduce sample preparation time, and operator exposure to unknown concentrations of urban contaminants. Large sticks, rocks and leaves were first removed to maintain consistency across samples. Polyethylene bags were typically 20–30 μm thickness, which is acceptable for the metals measured here, with the exception of Cd which may suffer from 12 to 17% attenuation of the X-ray intensity (Supplementary Text S6a-c). This approach differs from that used by many laboratories that dry, sieve and subsample soil prior to analysis. However, our objective was to screen and analyse a large number of soils quickly, safely and at low cost to provide a reliable estimate of trace metals in garden soils (Rouillon et al. 2017b). These data allow residents to make informed decisions about whether or not to complete more standard but costly laboratory analyses of their soils.

In order to understand data quality, raw *VegeSafe* analyses were compared to matched samples that had been dried, sieved to <500 μm, cupped and analysed using pXRF (i.e the sieved data published in Rouillon et al. (2017a)). Correlations between the two values for trace metals As, Cr, Cu, Ni, Mn, Pb and Zn were statistically significant, with $p < 0.0001$ in all cases (Supplementary Fig. S7). Assessment of the Cd

Table 1

Summary data for n = 17,256 samples analysed from the *VegeSafe* program database. As – arsenic; Cd – cadmium; Cr – chromium, Cu – copper; Mn – manganese; Ni – nickel; Pb – lead; Zn – zinc. Guideline values are based on the Australian Health Investigation Level – A (HIL A), which are designed for 'Residential with garden/accessible soil (home grown produce <10% fruit and vegetable intake (no poultry)), also includes childcare centres, preschools and primary schools.'(NEPM 2013).

n = 17,256 samples (3,609 homes)	As (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
LoQ[a]	1	4	2	2	3	4	1	1
n > LoQ	9,829	537	15,883	16,538	17,190	8,049	17,069	17,221
Minimum	<1	<4	<2	<2	<3	<4	<1	<1
5th percentile[b]	0.5	2	1	6	65	2	7	30.4
10th percentile[b]	0.5	2	10	10	89	2	11	45.7
25th percentile[b]	0.5	2	22	18	136	2	22	84
50th percentile[b]	4	2	35	31	207	2	66	171
75th percentile[b]	9.4	2	50	54	319	20	228	373
90th percentile[b]	21	2	70	91	496	31	570	725
95th percentile[b]	32.2	2	91	126	712	41	879	1,038.5
Maximum	3,096	88	7,853	8,152	23,309	2,657	12,400	29,400
Australian geogenic value[c]	2	0.03	26	11.85	246	11.6	7.36	26.1
Australian guideline value	100	20	100[d]	6000	3,800	400	300	7,400
Number (%) of samples with value >guideline	137 (0.79)	206 (1.19)	692 (4.01)	1 (0.01)	29 (0.17)	6 (0.03)	3,464 (20.07)	11 (0.06)
Number (%) of homes with at least one sample value >guideline	96 (2.66)	186 (5.15)	397 (11.00)	1 (0.03)	15 (0.42)	6 (0.17)	1267 (35.11)	11 (0.30)

[a] Where the sample reported below the instrument limit of quantification (LoQ), values were recorded as 0.5 × LoQ.

[b] Parameters including 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentile calculated including 0.5 × LoQ.

[c] Based on the median value from Reimann and de Caritat (2017) sub-surface samples (60–80 cm depth).

[d] Guideline is for hexavalent chromium (CrVI); pXRF reports total Cr.

relationship was not possible because sieved Cd values were below the LoQ. The veracity of pXRF data *versus* SRMs and analyses of acid digested soil using inductively coupled plasma mass spectrometry for a range of trace metals has been demonstrated elsewhere (Rouillon and Taylor 2016; Rouillon et al. 2017b). Further, the equivalence of in-field pXRF analyses (similar to *VegeSafe* sample analysis) *versus* laboratory prepared samples for Mn, Zn and Pb was evaluated by Rouillon et al. (2017b), who showed good consistency between the two sets of values. Analysis of soil Pb concentrations, the main target trace metal in this study because of the frequent exceedances of the Australian guideline value (300 mg/kg), was shown to be particularly robust with an R value of 0.81 (Supplementary Fig. S7; (Rouillon et al. 2017b)).

2.2. Participant metadata cleaning and processing

Household trace metal concentrations were examined alongside residential characteristics including home age, painted/unpainted status, building material and sample location in each garden. Of the 17,343 measurements in the *VegeSafe* program database, 87 were discarded due to address match error, superfluous data entry, or having no trace metal data recorded for the sample, leaving 17,256 samples from 3,609 homes. Metadata were provided by participants in the form of descriptive text regarding home construction, whether the external walls were painted or unpainted, and where the samples were collected. To encode this information into analysable variables, we applied regular expressions, based on the questions asked on the consent form, to establish three categorical variables: building material, paint, and sample location. To improve matching accuracy, a list of synonyms was used for each variable based on entries in the whole dataset, and this list was refined iteratively as extraction progressed. Taking the “sample location” variable as an example, participants used different descriptors, such as “veggie”, “vege”, “vegy”, “vegetable”, “veggiepatch” and so on, to describe samples collected from a vegetable garden. Therefore, we iteratively built a list of synonym recognition patterns to match all possible words for vegetable gardens in the dataset. As a result, the levels of three categorical variables are: (a) building material: brick, fibro (fibrous cement sheet), metal, stone and timber; (b) paint: painted and unpainted; (c) sample location: front yard, drip line, side, back yard, vegetable garden, chicken coop and compost. Data cleaning was completed using R (R Core Team 2020).

Metadata on property age (year of construction), painted/unpainted status and distance to the central business district (CBD; the distance in km to the city town hall) were assessed using smoothed conditional means, fitted using a general additive model and 95% confidence intervals. The CBD was chosen as a central, standard comparative feature that encapsulates a composite of factors in each city e.g. greater population density, more concentrated vehicle emissions per unit area and a prevalence of older homes. Property age data were available for 78% of all samples received (n = 13,455). Most samples (68%; n = 11,769 samples) were from Australia’s three largest state capital cities, which comprise ~50% of the national population: Sydney, n = 6,813, population 5.3 M; Melbourne, n = 4,111, population 5.1 M; Brisbane, n = 845, population 2.5 M (Australian Bureau of Statistics 2020). Trace metal concentrations were evaluated with respect to distance from the CBD to the maximum outer edge of each respective significant urban area (SUA) (Australian Bureau of Statistics 2018a).

Metadata provided by participants also contained information on building materials and soil sample locations at each property. After data cleaning, we identified specific sample locations, including front yard (n = 3,668), back yard (n = 3,431), vegetable garden (n = 6,777) and drip line (n = 1,744) that comprised 90% of the total samples. Dominant building materials (brick, timber, fibrous cement, metal, stone) used at the participant’s property were assigned to 84% (n = 14,420) of samples. Significant differences ($p < 0.05$) between each building material category were determined using a Kruskal-Wallis test followed by Dunn’s multiple comparison. Figures showing relationships between trace metal concentrations and explanatory variables, such as sample location, building material, and property age, were generated using the package ggplot2 (Wickham 2016).

2.3. Principal component analysis

Principal component analysis (PCA) was applied to the eight trace metals (As, Cd, Cr, Cu, Mn, Pb, Ni, Zn) measured in the *VegeSafe* soils to examine the variation between individual sample concentrations and across geographic locations (i.e. the SUA of the capital cities of Brisbane, Sydney, Melbourne). PCA analysis expressed the critical dimensions of the total data set as eight principal components, which correspond to a linear combination of the original trace metals. The first and second dimensions explain most of the variance in the data and are expressed as two-dimensional plots. PCA was conducted using FactoMineR (Lê et al. 2008) and visualized with the factoextra (Kassambara and Mundt 2020) package.

2.4. Geospatial analysis

Trace metal concentrations were assessed across multiple scales: individual gardens, and within and between Australia’s three main cities (Sydney, Melbourne, Brisbane). Analysis of spatial data was performed using ESRI ArcGIS 10.15. Data analysis was delineated using Australian Bureau of Statistics (ABS) geographic structures. Residential soil trace metal concentrations and associated health risk variables were assessed using the ABS Statistical Area Level 3 (SA3) boundaries. Statistical areas are nested sets of defined geographic area that are used by the ABS for the delivery of official Australian Government spatial statistical economic, social, population and environmental data (Australian Bureau of Statistics 2018a). The SA3s comprise areas of regional towns and cities with populations >20,000 or related clusters associated with urban commercial and transport centres. For visualisation, selected SA3s were confined to the greater capital city areas of Sydney, Melbourne and Brisbane (Australian Bureau of Statistics 2018a) where sample density and population are greatest.

Soil trace metal concentrations from front yard, back yard, drip line and vegetable garden sample locations were averaged for each residence. Total residential trace metal concentrations were then calculated for each SA3 within the three major capital city areas. This process was repeated to calculate mean trace metal concentrations from vegetable garden samples at each residence. Trace metal concentration data were classified according to the Australian National Environmental Protection Measure (NEPM 2013) Health Investigation Levels (HIL A, residential land with accessible gardens).

The percentage of residences with soil Pb concentrations exceeding the Australian investigation level for residential soil Pb concentrations (300 mg/kg) (NEPM 2013), and the percentage of vegetable gardens exceeding Australian standards for trace metal uptake by edible plants was determined for each SA3. Exceedances of non-carcinogenic and carcinogenic US EPA (2002) health risk factors were calculated for young children (0–2 years old) in each SA3 area. To support health risk interpretation, population densities (km^2) of children (0–2 years) were calculated for each SA3 using 2016 ABS census data (Australian Bureau of Statistics 2017) to provide a relative comparison of risk geospatially.

Relationships between community involvement in the *VegeSafe* program and socioeconomic status were mapped for each SA3 using the ABS Socio-Economic Indexes for Areas (SEIFA) (Australian Bureau of Statistics 2018b). The combined indexes are based on data from the Census of Population and Housing and rank districts in Australia according to a relative assessment of socio-economic disadvantage. SEIFA scores derived for each SA3 were compared to the percentage of households within that area that contributed *VegeSafe* samples to ascertain sample density relative to population.

2.5. Vegetable uptake of trace metals

In order to address the basic food safety concerns posed by the public, while retaining scientific quality, we used the standard method as detailed in the National Environmental Protection Measure legislation (NEPM 2013) to estimate vegetable uptake of trace metals. While it would be preferable to collect actual vegetable samples and analyse those for trace metals and to further examine soil chemistry, this was beyond the scope of the program and not possible across the 2,631 vegetable gardens for which 6,777 soil samples were submitted. Thus, the next best alternative was to estimate the potential uptake using the NEPM (2013) legislation. The Australian soil guidelines (NEPM 2013) were developed in 1999 in consideration of contemporary literature on plant uptake from soils (Schedule B7, Appendix A1). In order to determine if these Australian Guidelines remain adequately protective in terms of food safety considerations, more recent literature regarding uptake of trace metals by vegetables was considered, with detail of the method provided in Isley et al. (in press). Briefly, literature values for uptake of trace metals by different types of fruits and vegetables were collated. Those based on soil trace metal concentrations that differed significantly from *VegeSafe* concentrations, or on non-edible parts of the plant were excluded. Using this method, we estimated the upper maximum soil trace metal concentrations suitable for safe food production. This was based on Australian Government (2017) and WHO/FAO Codex Alimentarius Commission (2011) food standards for Pb and Cd and European Union (2015) and Food Standards Australia New Zealand (2019) for As.

2.6. Health risk assessment

The US EPA (2002) health risk model estimates potential non-carcinogenic and carcinogenic adverse outcomes associated with exposure to environmental trace metal contaminants in soil. The model was applied to estimate potential health risk for children (aged 0–2 years) exposed to *VegeSafe* soil via three exposure routes (ingestion, inhalation and dermal contact), following methods outlined in Doyi et al. (2019). Children aged 0–2 years are sensitive receptors of trace metal contamination due to their normal, habitual hand-to-mouth behaviours, lower body mass, less-developed and thus less discriminate gastric uptake mechanism and rapidly developing neural capacities, making them a recommended demographic for health risk assessment in this context (EnHealth 2011).

Health risk was calculated for each SA3 in the capital city areas of Sydney, Melbourne and Brisbane (Australian Bureau of Statistics 2018a). Health risk estimates were calculated only for SA3s with a minimum of 30 samples. Non-carcinogenic health risk estimates were calculated for As, Cu, Mn, Ni, Pb and Zn soil concentrations. Cadmium was not included in the calculation of health risk due to the large number of samples reporting values below the LoQ (97%; Table 1). Carcinogenic health risks were assessed for As and Pb; the only applicable elements for which there are chronic slope factors and reference doses required to calculate incremental lifetime cancer risks. These are also available for CrVI (hexavalent chromium) but not total Cr. The difference between CrVI and total Cr was not determined in our analyses, and thus modelling based on available reference doses for CrVI could not be calculated.

In order to supplement health risk assessment, potential blood Pb increments from exposure to soil were calculated because this was the trace metal that most commonly exceeded Australian soil concentration guidelines at residential homes (Table 1). The influence of soil Pb only on blood Pb (excluding all other sources) has been examined in the Australian context in two recent studies: Gulson and Taylor (2017) and Dong et al. (2020), who showed that a soil Pb increase of 100 mg/kg is associated with a 0.17 μg/dL and 0.12 μg/dL increase in blood Pb, respectively. Here we use the Dong et al. (2020) value because it provides a minimum estimate of risk and it is derived from an analysis of 6,265 individually matched blood Pb to soil Pb observations, the outcome of which is similar to Gulson and Taylor's (2017) smaller study sample of 108 children.

2.7. VegeSafe engagement and impact assessment

The *VegeSafe* program sought to ascertain the efficacy of its work and value to the community and so between August to October 2020, participants were invited via email and social media posts to complete a short questionnaire (Macquarie University ethics project number 2446). The aim of the questionnaire was to assess participant engagement, knowledge and understanding of contaminants and actions taken to mitigate soil trace metal contamination risks. Questions are listed in Supplementary Text S8. A total of 393 responses were received from *VegeSafe* participants, with 32 being partially complete. Survey data were analysed and compared to the findings above to better understand the efficacy of *VegeSafe's* engagement. The impact of participation on the awareness of trace metal contamination risks alongside measures undertaken by participants to improve community health was also evaluated.

3. Results

The results examine the influence of residential characteristics on trace metal soil concentrations — garden sample location, house building materials, geospatial variations across cities and exposure risks. Data analyses focus on trace metals that exceed guideline values or present an identifiable exposure risk. Participant motivation for involvement with the *VegeSafe* program, subsequent engagement with the program data and changes in gardening practice and understanding of environmental trace metal contamination are considered in the discussion section.

3.1. Residential characteristics and trace metals concentrations

Summary statistics for *VegeSafe* samples are in Table 1. For Pb, 20% ($n = 3{,}464$) of samples ($n = 17{,}256$) exceeded the Australian soil guideline (HIL A of 300 mg/kg). Of the other trace metals, only Cd and Cr exceeded guidelines. Cadmium values were above LoQ (4 mg/kg) in only 3% ($n = 537$) of samples, with 1% ($n = 206$) exceeding the guideline of 20 mg/kg. For Cr, 8% of samples ($n = 1{,}373$) returned concentrations below LoQ (2 mg/kg); with 4% ($n = 692$) exceeding guidelines (100 mg/kg). Australian Cr guidelines are based on CrVI health risk, whereas *VegeSafe* measured total Cr, yet it is unlikely that CrVI:total Cr is close to 100% in *VegeSafe* samples (Bartlett 1991). Moreover, given that the soils analysed are from residential gardens and not from industry contaminated sites there is limited likelihood of CrVI being present at harmful concentrations (Broadway et al. 2010).

Age of home was a determinant of soil Pb concentration. Mean soil Pb for homes ≥80 years (leaded-paint era) was higher whether painted (447 mg/kg, 95% CI: 423–469 mg/kg) or unpainted (288 mg/kg, 95% CI: 264–316 mg/kg) compared to homes ≤50 years of age (post-lead paint era), which had mean values of 136 mg/kg (painted 95% CI: 124–150 mg/kg) and 80 mg/kg (unpainted 95% CI: 72–88 mg/kg).

Average front yard soil Pb concentrations (272 mg/kg) were significantly ($p = 0.025$) higher than back yard samples (221 mg/kg) (Fig. 4A). Lead concentrations in vegetable garden soils were significantly lower than soils from front yards ($p < 0.0001$, 97 mg/kg lower), roof drip line ($p < 0.0001$, 139 mg/kg lower) and back yard ($p < 0.0001$, 48 mg/kg lower) (Fig. 4A; Supplementary Fig. S9A). In order of soil Pb concentrations, timber homes were significantly higher ($p < 0.0001$) than other building material types, followed by brick, stone, fibrous cement and metal homes (Fig. 4B; Supplementary Fig. S9B).

3.2. Spatial distribution of trace metals

Samples collected from SUAs in Sydney (n = 6,813), Melbourne (n = 4,111) and Brisbane (n = 845) encompassed 40%, 24% and 5% of total samples. Mean soil Pb concentrations >10 km from each city's CBD (Fig. 2) were well below the Australian guideline, at 82 mg/kg (95% CI: 75–90 mg/kg) for Sydney, 73 mg/kg (95% CI: 63–87 mg/kg) for Melbourne and 74 mg/kg (95% CI: 53–103 mg/kg) for Brisbane. Other industrially sourced anthropogenic contaminants, As, Cu and Zn (Supplementary Fig. S10A–B), exhibited similar spatial and temporal patterns. Homes within 10 km of each city's CBD demonstrate the relevance of home age and painted status on soil Pb concentrations (Fig. 2B–D).

3.3. Principal component analysis

For samples from the Sydney, Melbourne and Brisbane SUAs, the first and second PCA dimensions (principal components) accounted for 39% of total variability. The largest contributions to these two dimensions were Zn (22%), Pb (21%), Mn (14%) and Ni (13%) (Fig. 3A). Copper, Zn, As and Pb were positively correlated, as were Cr, Mn and Ni (Fig. 3A). Geographic origins of the samples were unable to be differentiated in these first two dimensions; no boundary differentiated the samples from different SUAs (Fig. 3B). PCA analyses for nation-wide samples (n = 17,256) are in Supplementary Fig. S11.

3.4. Community risk characterisation

Each city area (SUA) was mapped using local (SA3) demographic boundaries to depict sample distribution and calculate the intersection between trace metal concentrations, population density of children and exposure risk from soil and homegrown vegetables (Fig. 5; Supplementary Fig. S12A-B). The data indicate intersections between trace metal concentration, population density and established inner-city areas across Sydney, Melbourne and Brisbane (Fig. 5, Supplementary Fig. S12A-B).

3.5. Vegetable uptake of trace metals

Uptake of trace metals in home-grown produce is an important consideration for Australian gardeners (Fig. 5) and is a concern for *VegeSafe* participants. Estimated uptake varied across vegetables (Supplementary Fig. S13) with the highest As and Cu concentrations in plants of the genus brassica, consistent with phytoextraction literature (Bazan and Galizia 2018). Predicted Cr uptake values were highest for citrus, with Ni, Pb and Zn being highest in leafy vegetables. The soil metal concentration threshold at which foods may exceed food standards was based on the geometric mean uptake of all foods (Isley et al., in press). The Australian residential soil guideline for As (100 mg/kg) is well below the modelled food standard exceedance, being 9,956 mg/kg (Australian food standards) or 1,991 mg/kg (WHO/FAO food standards). Exceedance of food standards may occur in soils with Cd concentrations >4 mg/kg. This is of some concern as Cd uptake by edible produce was previously determined (NEPM 2013) to account for 67% of overall Cd exposure. In the *VegeSafe* data, however, Cd concentrations exceed 4 mg/kg Cd in only 1.8% of vegetable gardens sampled (Isley et al., in press). Food safety concerns can arise where soil Pb exceeds 270 mg/kg (Australian food standards (Australian Government 2017)) to 319 mg/kg (WHO/FAO food standards (Codex Alimentarius Commission 2011)). Given that the *VegeSafe* program has applied consistently the Australian soil Pb guideline (NEPM 2013) of 300 mg/kg in its advice to participants, this means that its guidance is consistent with global risk assessments and minimises human health exposure via vegetable uptake.

VegeSafe data indicate that most food produced from vegetable gardens is likely to comply with Australian and WHO/FAO food standards (Supplementary Fig. S13). Nevertheless, the data indicate that soil Pb concentrations are the main concern for garden produce and vigilance is needed. Data modelling indicates that 20% of vegetable gardens Australia-wide (31%, 19% and 19% of all vegetable gardens from Sydney, Melbourne, Brisbane, respectively) are likely to produce food exceeding Australian Government (2017) Pb standards. Application of

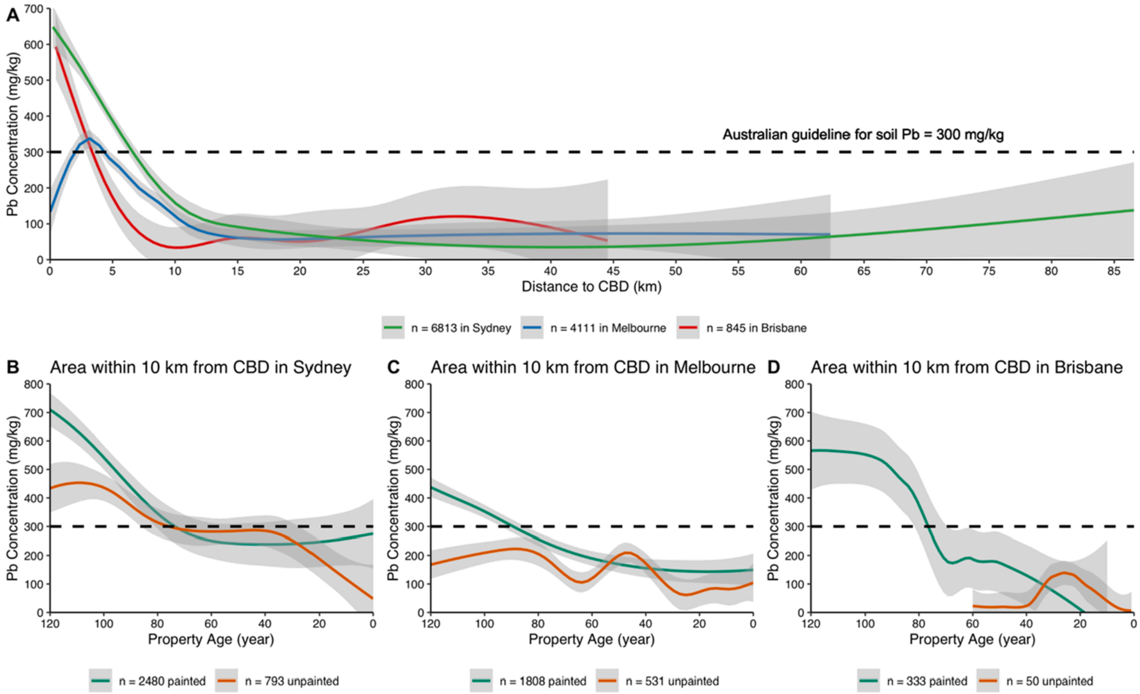


Fig. 2. Relationships between soil Pb concentration and temporal and spatial factors associated with residential gardens in Sydney, Melbourne and Brisbane: plot (A) shows the relationship between Pb concentration and distance from each city's CBD; plot (B, C, D) show the relationship between Pb concentration and property age for painted and unpainted homes within 10 km of each city's CBD. Curves were fitted by the generalised additive model and the grey shading represents the 95% confidence interval (data for additional trace metals are in Supplementary Fig. S10A-B).

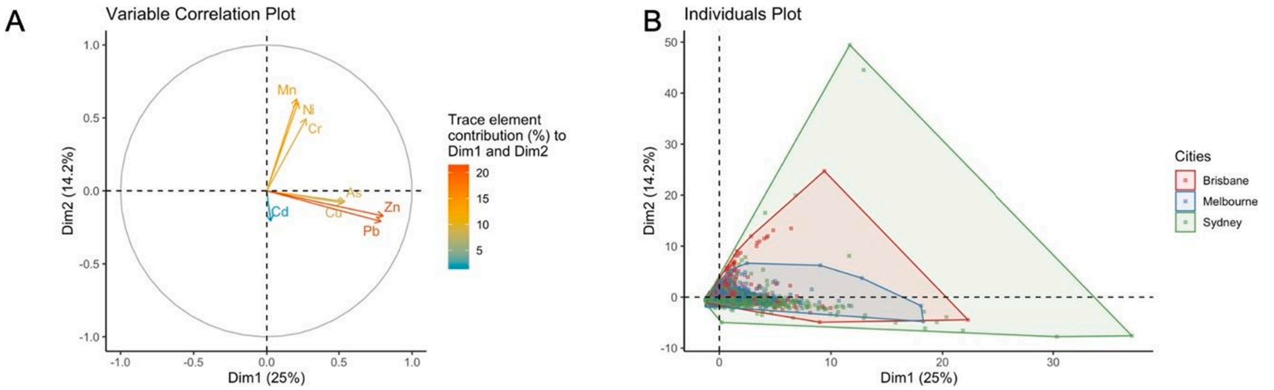


Fig. 3. PCA analysis on 11,769 samples from Sydney (n = 6,813), Melbourne (n = 4,111) and Brisbane (n = 845). (A) The Variable Correlation Plot shows: (i) the relationship between eight trace metals, indicated by directions of the arrows; (ii) the quality of the representation (how much Dim1 and Dim2 can represent the original trace metal), indicated by the lengths of arrows; and (iii) the contribution of each trace metal to Dim1 and Dim2, indicated by the colours of the arrows. (B) The Individuals Plot shows where similar samples are grouped together on the graph.

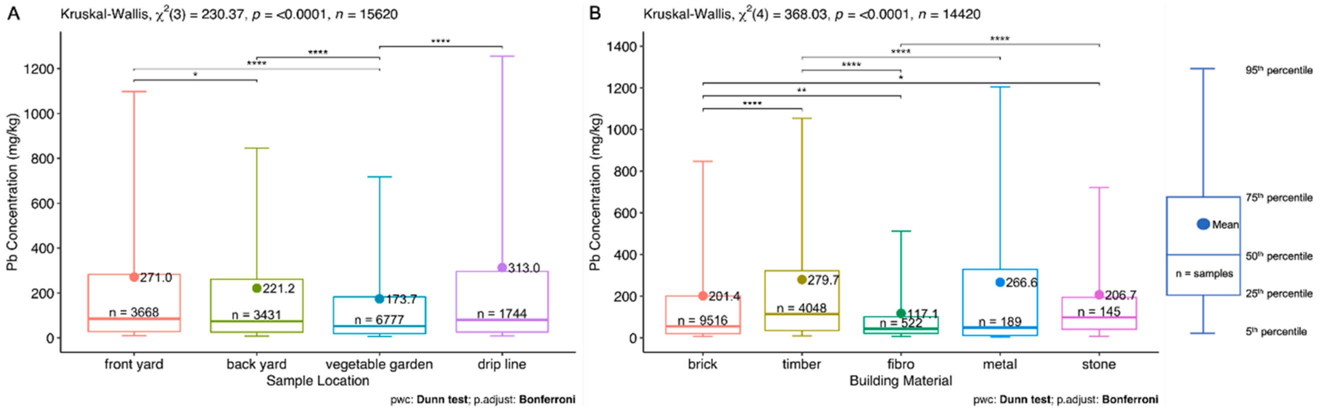


Fig. 4. Boxplots depicting the influence of sample location (A) and building material (B) on Pb soil trace metal concentrations. Statistical differences were determined using a Kruskal-Wallis test with Dunn's multiple comparison test: **** ($p < 0.0001$), *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.05$) levels. Data for additional trace metals are provided in Supplementary Fig. S9A-B.

the less stringent WHO/FAO (Codex Alimentarius Commission 2011) standards, revealed that an estimated 17% of gardens Australia-wide (27%, 17% and 14% from Sydney, Melbourne and Brisbane, respectively) could produce food that exceeds acceptable Pb concentrations (Isley et al., in press).

3.6. Health risk assessment

Non-carcinogenic health risk hazard quotients (HQ) were calculated for ingestion, inhalation and dermal contact for each SA3 (Supplementary Table S14). The summation of HQs provides a hazard index (HI), with values exceeding unity (>1.0) representing a potential health concern (US EPA, 2011b), with greater values denoting higher risk (Asante-Duah 2002). Only nine Brisbane SA3s, representing 100 homes, met the minimum criteria for health risk analysis i.e. 30 samples per SA3. In Sydney and Melbourne, 37 and 30 SA3 areas had sufficient sample numbers, encompassing 1,515 and 772 homes, respectively (Supplementary Table S14).

Fourteen SA3 areas exceeded tolerable risk (HQ) for Mn or Pb. Tolerable risk (HQ) for children exposed to garden soil was exceeded in the following areas of Sydney (Fig. 5): Canada Bay (Pb = 1.21), Leichhardt (Pb = 1.77), Liverpool (Pb = 1.41), Marrickville (Pb = 1.61), Merrylands (Mn = 1.34), Strathfield (Pb = 1.61), Sydney Inner City (Pb = 2.33); Melbourne (Supplementary Fig. S12A): Brunswick/Coburg (Pb = 1.01), Dandenong (Pb = 2.05), Port Phillip (Pb = 1.20), Stonnington East (Pb = 1.30), Yarra (Pb = 1.30); and Brisbane (Supplementary Fig. S12B): Brisbane Inner (Pb = 2.48) and Holland Park/Yeronga (Pb = 1.39). Carcinogenic risk is defined when values exceeded the upper risk threshold of 1×10^{-4} (US EPA 2001). All assessed areas reported carcinogenic risks within acceptable limits (Supplementary Table S14).

The blood Pb risk from soil Pb concentrations *only* was also modelled according to SA3 areas and is based on Dong et al.'s (2020) estimate that an additional 0.12 µg/dL of blood Pb is associated with each 100 mg/kg Pb in soil. As expected, the data mirror the distribution of soil Pb concentrations, with elevated levels of risk in the older, inner-city areas of Sydney, Melbourne and Brisbane (Fig. 5; Supplementary Fig. S12A-B). Additional exposure risks from soil only to blood Pb is relatively low, but should be contextualised in the absence of other potential sources of Pb exposure such as air, dust, food, water, etc., which are not included in this estimate of risk.

4. Discussion

4.1. Community impact and engagement

Participant accessibility, motivation and engagement were evaluated to understand program reach, efficacy and value. Socio-economic barriers to accessing *VegeSafe* were determined by assessment of the distribution of participating homes and population density (Supplementary Fig. S15A–C). The majority (76% and 86%) of samples from New South Wales and Victoria were received from the SUAs of Sydney and Melbourne, accounting for 65% and 70% of state population, respectively

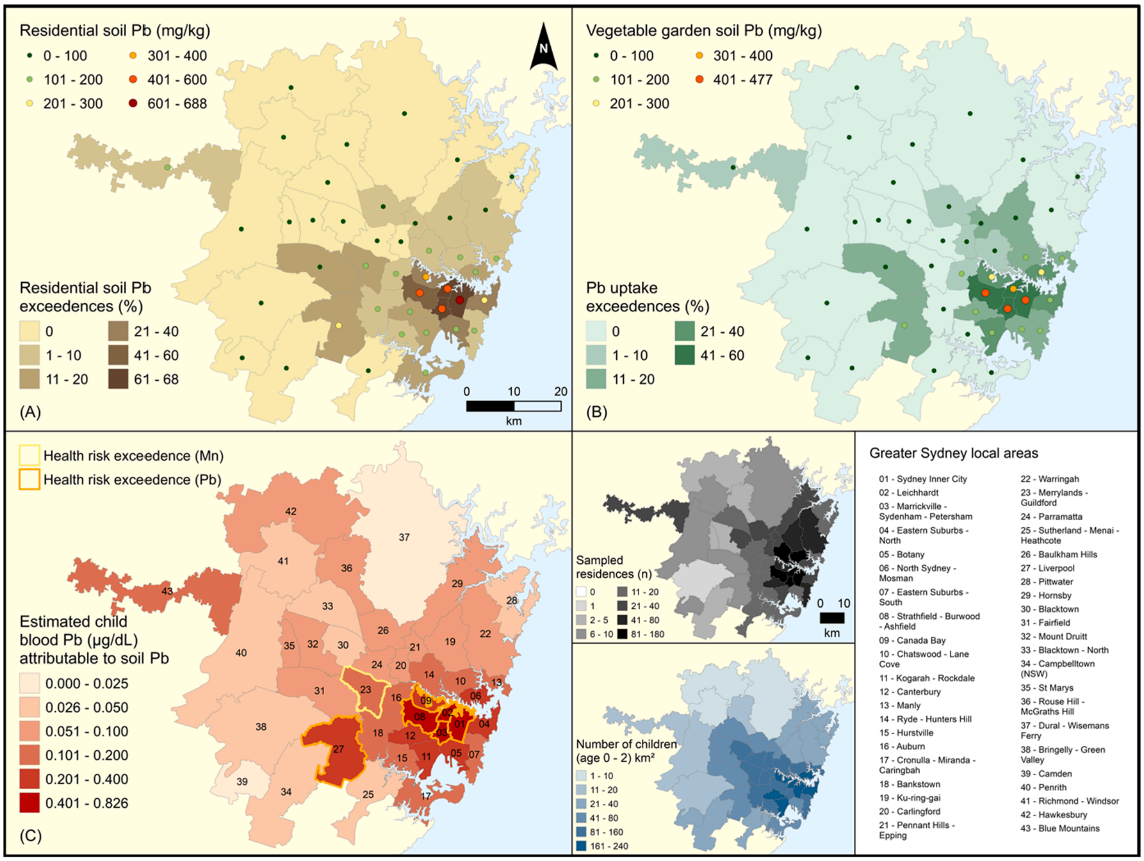


Fig. 5. Map of health risks associated with residential soil Pb and other trace metal concentrations across SA3 locations within the SUA of Sydney. Sampled residences and also the population density of children between the ages of 0 – 2 years for each SA3 (Australian Bureau of Statistics 2017) are shown in the two maps in the lower right panel of the figure. Panels A–C show: (A) Percent of sampled residences with an average Pb concentration (using all samples from a single residence) exceeding the Australian soil guideline of 300 mg/kg Pb for residential areas with gardens or accessible soil (NEPM 2013). Centroid points represent the average residential soil Pb concentration for sampled residences within each SA3. (B) Percent of vegetable gardens from which produce is likely to exceed Australian food standards due to the uptake of Pb from soil by edible plants. Centroid points indicate the average Pb concentration for sampled vegetable gardens within each SA3. (C) Highlighted SA3 boundaries indicate where a non-carcinogenic health risk threshold has been exceeded, and that elevated trace metals within the residential soil of that SA3 pose a health risk to children between the ages of 0 – 2 years (US EPA 2011b). The blood Pb risk from soil *only* is also modelled according to SA3 areas and is based on Dong et al.'s (2020) estimate that 0.12 µg/dL of blood Pb is associated with each 100 mg/kg of soil. Other possible sources such as water, air, food etc are not included in this estimate of risk. Numbers in panel (C) accompanying each SA3 correspond to the listed SA3 designations. Corresponding maps for the SUAs of Melbourne and Brisbane are in Supplementary Fig. S12A-B. The categories used in all the panels are capped at their respective maximum values.

(Australian Bureau of Statistics 2018c). In Queensland, 68% of samples were received from the SUA of Brisbane, which comprises 48% of the state's population. The distribution of participants across different socio-economic areas indicates that this factor was not a major barrier to accessing *VegeSafe* (Supplementary Fig. S15B–C), an inherent goal of the program. Nevertheless, greater engagement from inner-city homes (higher socio-economic areas) means that those most at risk have participated (Australian Bureau of Statistics 2018b).

In order to assess motivation, impact and engagement with *VegeSafe*, survey data (n = 31 questions) were collected from 393 participants, with a subset of the most relevant survey questions provided in Supplementary Text S8. More than two thirds (67.2%, n = 264/393) of respondents indicated their primary reason for participating was concern about garden food production. Following receipt of their results, 40.1% (n = 146/364) implemented strategies to reduce trace metal contaminants in their garden environment. Reported interventions included installing raised garden beds, mulching exposed soil, replacing soil, removing Pb paint and moving produce planting to areas uncontaminated by trace metals. The proportion of respondents who undertook some form of intervention corresponds closely with this study's finding that 35.1% of homes had at least one soil sample that exceeded the Australian soil Pb guideline of 300 mg/kg. Of the respondents, 96.1% (n = 347/361) were '*likely*' to recommend the program to others, 94.2% (n = 340/361) stated the program had increased their understanding of trace metal contaminants in gardens and 83.4% (n = 301/361) felt safer in their home environment. The program's impact has extended beyond individuals with *VegeSafe* being promoted by local and state governments as a community resource to help gardeners ensure their soil is fit for purpose (Inner West Council 2020; Victoria State Government 2020; Wollongong City Council 2020). Internationally, we have engaged New Zealand researchers from the University of Auckland and their national Crown Science research organisation GNS, who launched *SoilSafe: Aotearoa* in early 2021. The program also collaborates with USA researchers from Indiana University who began a *Safe Urban Gardening* initiative at about the same time as *VegeSafe* was launched, also sharing their data via MapMyEnvironment (2020).

People are generally conscious about potential contamination risks in residential garden soils (Kaiser et al. 2015), but until now have had very few resources to determine if their concerns are valid. With the large scope of *VegeSafe* we were able to determine risk in an individual garden and on a regional basis—we found that trace metal contamination is a reasonable and fair concern, particularly in older inner-city neighbourhoods.

4.2. Data outcomes

The large dataset acquired by the *VegeSafe* program has enabled a more robust spatial assessment of soil trace metal contamination and association with house age and building materials than was previously possible (Cheng et al. 2015; Filippelli et al. 2018; Laidlaw et al. 2018). Our analysis shows that in soils from inner-city gardens (i.e. near to the CBD, Table 2), elevated Pb concentrations present the most common trace metal hazard (Fig. 2). This is particularly evident in older homes that have had their exteriors painted (Fig. 2). Overall, samples immediately adjacent to homes (gutter drip lines) had the greatest soil mean Pb concentrations: 313 mg/kg (95% CI: 277–352 mg/kg; Fig. 4). This trend is evident even when the data are disaggregated according to distance from the CBD and garden sample location (see 50th percentile value, Table 2), concurring with US data (Fig. 4; Supplementary Fig. S9A-B (Filippelli et al. 2018)).

The overall data reveal that timber homes were associated with significantly higher mean soil Pb (280 mg/kg; 95% CI: 264–297 mg/kg; Fig. 4) than all other structures, which is a function of their age and painted/unpainted status. Vegetable garden soils returned the lowest mean Pb concentrations: 174 mg/kg (95% CI: 165–183 mg/kg), but were significantly elevated relative to Australian (Reimann and de Caritat 2017) and Sydney (Wu et al. 2017) geogenic values, being <30 mg/kg (Fig. 5). Elevated Pb concentrations in vegetable gardens also pose greater risk than other trace metals in terms of vegetable uptake modelling with regard to acceptable food standards (Supplementary Fig. S13). Front yard soil Pb was statistically greater than back yard samples, possibly reflecting the influence of remobilised roadside emissions from the leaded gasoline era (Laidlaw et al. 2012). Leaded petrol combustion caused significant adulteration of natural soils where the fuel was used in high volumes (Mielke et al. 2011). Over the seven decades of leaded petrol use in Australia, emissions amounted to 240,510 t (Kristensen 2015). Emissions were greatest in Sydney (67,893 t), followed by Melbourne (49,443 t) and Brisbane (41,859 t) (Kristensen 2015), the order of which corresponds to city size, traffic volume and soil Pb concentrations (Table 2).

The large quantity of data from the *VegeSafe* program has enabled unparalleled, robust multi-city modelling of exposure risk from ingestion, inhalation or dermal contact with trace metal contaminants. Inner city homes present the greatest risk from elevated Pb levels, though unexpectedly, there are outlying suburbs that are also impacted, including one for Mn in Sydney. Of the 14 SA3s exceeding non-carcinogenic health risk across Sydney, Melbourne and Brisbane, 11 occurred in older, inner-city suburbs (Fig. 5, Supplementary Fig. S12A-B). Within the outer suburbs, carcinogenic and non-carcinogenic health risks are predominantly low. Thus, the following variables are critical determinants for elevated soil Pb risk: proximity to city centre, home age, painted status and timber wall construction and are useful for future guidance of potential residential trace metal hazards.

The risk of raising blood Pb levels solely from exposure to soil is relatively low, but the areas that present the most concern are inner-city locations that are characterised by older homes (and thus potentially more likely to have lead paint) that have been more greatly impacted by deposition from leaded petrol combustion and other aerosol sources (Fig. 2, Fig. 4, Fig. 5A-B; Supplementary Figs. S12A-B). Modelled Australian risk factors of soil Pb on blood Pb exposures (Gulson and Taylor, 2017; Dong et al., 2020) are similar to those determined by von Lindern et al. (2003) for Bunker Hill (Idaho, USA), but are different to some USA studies, which indicate its influence is more significant (Johnson and Bretsch 2002; Mielke et al. 1999).

4.3. Spatial distribution across cities

Spatial trace metal concentrations display a ‘bullseye’ pattern with highest Pb concentrations located around city centres, consistent with global trace metal contaminant studies (British Geological Society 2020; Reimann et al. 2012). The primary factors that contribute to this are: historical concentration of industry in city centres; higher population density; associated leaded gasoline emissions from vehicles (during 1932–2002 in Australia (Kristensen 2015)) and a greater number of older homes where Pb-based paint was used (Fig. 5A-B, Table 2). Nearly a century of Pb pollution has been concentrated in surface soils due to its low transport mobility (Semlali et al. 2004), leading to potential exposure via ingestion of produce grown in contaminated soil

Table 2
Sample trace metal concentrations across Sydney, Melbourne and Brisbane cities, summarised according to distance (near or far) from their respective CBDs according to garden sample location

City	Distance threshold (km)[a]	City sector	Sample location	n	Percentiles of soil Pb (mg/kg)						
					5th	10th	25th	50th	75th	90th	95th
Sydney	6.4	Near to CBD	front yard	716	21	38	99	292	687	1,382	2,085
		(samples < 6.4 km from CBD)	back yard	760	21	30	86	258	576	975	1,252
			vegetable garden	1,319	16	27	71	226	506	877	1,146
			drip line	278	25	46	128	336	792	1,565	2,213
		Far from CBD	front yard	697	10	14	24	52	134	314	547
		(samples > 6.4 km from CBD)	back yard	690	9	15	24	48	137	340	560
			vegetable garden	1,370	8	12	19	40	110	271	482
			drip line	347	9	14	25	55	158	450	759
Melbourne	7.6	Near to CBD	front yard	415	17	25	57	151	325	667	969
		(samples < 7.6 km from CBD)	back yard	445	16	26	66	189	414	711	960
			vegetable garden	807	14	20	51	139	352	587	787
			drip line	206	25	38	87	178	394	755	1,045
		Far from CBD	front yard	407	8	11	22	45	86	172	256
		(samples > 7.6 km from CBD)	back yard	422	9	13	26	51	119	293	462
			vegetable garden	858	7	10	18	38	96	201	275
			drip line	223	7	12	22	52	128	302	500
Brisbane	9	Near to CBD	front yard	81	8	10	29	62	260	829	1,015
		(samples < 9.0 km from CBD)	back yard	87	12	17	38	121	300	635	823
			vegetable garden	166	5	6	13	47	204	578	1,015
			drip line	47	12	17	40	121	540	1,559	1,842
		Far from CBD	front yard	79	5	7	9	17	29	125	227
		(samples > 9.0 km from CBD)	back yard	87	4	7	10	17	50	107	187
			vegetable garden	174	3	5	8	15	34	80	263
			drip line	51	6	8	13	29	71	325	736

[a] The distance threshold is the median distance of all samples to their respective CBD.

(Supplementary Fig. S13). Our results indicate that inner-city vegetable gardens are more likely to contain soil above Australian Pb guidelines, thus potentially producing food above Pb standards and posing some exposure risk. This is a particular concern in highly populated areas of inner-city Sydney (Fig. 5) but it is also apparent in Melbourne and Brisbane (Supplementary Fig. S12A-B).

Even though some vegetable gardens contain elevated Pb concentrations (Entwistle et al. 2019; Laidlaw et al. 2018), other studies examining the uptake of toxic metals into food suggest the actual risk is lower than the hazard that the contaminated soil presents. For example, where total soil Pb bioaccessibility was very low (1–4.3%, compared with 77% in Sydney (Laidlaw et al. 2017), only carrots exceeded Pb food standards, and vegetable cleaning is effective at reducing food chain transfer (Attanayake et al. 2015). Even where bioaccumulation factors were high in vegetables, it was uncertain that Pb would be absorbed after consumption (Brown et al. 2016). Other studies have indicated that urban gardeners' blood Pb was statistically indistinguishable from their non-gardening neighbours (Entwistle et al. 2019). Nevertheless, a precautionary approach and best practice would be to ensure soils are suitable for food production given that Pb and other industrial trace metal contaminants are pervasive in older cities and there are no identifiable safe lower limits for exposure (Lanphear 2017).

4.4. Connecting citizens to science

This study presents data that are more comprehensive than any existing available dataset examining the sources of trace metal contamination found in residential gardens. Moreover, these data and related information are available to the public in an accessible and easily interpretable format (Map My Environment 2020). Researchers rarely achieve such a close-up view of environmental quality at the household scale, a perspective provided by the citizen-science nature of data collection. Other studies of garden trace metal contamination are comprised of much smaller datasets (Kandic et al. 2019; Rouillon et al. 2017a), have less or no detailed metadata incorporating residential dwelling characteristics and often focus on local communities or single cities, limiting their geographic relevance (Cheng et al. 2015; Entwistle et al. 2019; Masri et al. 2020). This citizen science study sets itself apart from other more spatially and temporally limited efforts because for the first time, residential trace metal contaminant levels have been analysed across a country incorporating geospatial variables, individual building characteristics, garden sample location, socio-economic factors and health risk modelling have been examined as a whole and over a 7-year period. *Post hoc* analysis of the program indicates that *VegeSafe* is meeting the needs of the community that it is intended to serve. Our analysis indicates that the program enables participants to better understand their environment, and their exposome. Our new and individualised data have provided thousands of Australians with invaluable information on their environment, alongside advice on how to protect their health.

Unlike most scientific studies that work 'on' communities by way of an investigation or epidemiology-type of analysis, *VegeSafe* flipped the standard approach and worked *with* and *for* communities. The development of our outward facing program has produced new and important home-level garden exposure data expressly for the community, whose interest in using their yards for food production is growing rapidly (Wright 2017).

Benefits of urban gardening significantly outweigh potential risks caused by trace metal contamination (Brown et al. 2016; Kaiser et al. 2015). In a rapidly urbanising world, urban gardening creates opportunities for children to connect to nature and understand food production (Dillon et al. 2003). Nonetheless, given that many chemicals are toxic to human systems at low levels, and trace metal contaminant exposure effects display a supralinear dose–response curve (Lanphear 2017), it would be prudent for gardeners to remain alert to risks and know how to address them.

4.5. Data challenges and recommendations

This study has a number of limitations related to sampling and analysis that are common with a citizen-science program that utilises a screening approach for trace metal contaminants. Sampling is participant driven, not randomised and hence is likely skewed toward people who are engaged in gardening and have concerns about environmental trace metal contamination.

Being an Australian program, it is appropriate that we have applied the Australian residential soil guideline for trace metals (NEPM 2013). However, regulatory guidance for soil trace metal contaminants can differ markedly across jurisdictions (Jennings 2013). Local guidance must therefore be considered when using these data. Further, particularly with respect Pb, there is no level of exposure that is considered truly 'safe' (Abadin et al. 2020).

Although participants are provided with instructions on sampling depth and preferred sampling locations the accuracy of this information across the sample pool cannot be ascertained. *Ad hoc* conversations with participants indicate that sample information aligns well with actual sample locations. Other metadata rely on accurate participant reporting and, given the nature of this program, acceptance of participant data is taken at face value. The use of pXRF and analysis of *VegeSafe* samples as received (equivalent to *in situ* analysis) means that the data are likely to differ from values acquired via *ex situ* laboratory methods. Indeed, often *in situ* and *ex situ* methods do not measure precisely the same sample. Portable XRF measures the total bulk *in situ* soil trace metal concentration, whereas laboratory *ex situ* approaches typically analyse a small fraction (~0.5 g) of soil that has been dried, sieved and analysed using a strong acid digestion to measure pseudo-total elemental concentrations. Neither measurement method is incorrect, they are simply different, but are clearly related as shown in Supplementary Fig. S7. Further, analysis of the difference between these approaches indicated that pXRF can have significant benefits over laboratory methods, relating to increased sampling frequency and lower costs, reducing uncertainties relating to mean concentrations and small sample sizes (Rouillon et al. 2017b).

Due to the nature of the *VegeSafe* program we were unable to directly determine the actual metal concentration in the home-grown produce of participants. Estimated trace metal uptake by vegetables does not account for the full complexity of transfer of soil contaminants to produce at different locations. Transfer factors and bioavailability depend on trace metal concentration, pH, organic matter content and interaction with other metals (Intawongse and Dean 2006; Kachenko and Singh 2006). Further, *VegeSafe* requests participants supply only topsoil, however deep-rooted plants may access underlying soils with different metal concentrations. However, for consistency, trace metal transfer from soil to produce was assessed using the method applied in development of the Australian Pb soil guidelines (NEPM 2013).

The *VegeSafe* program is ongoing. Future research should also examine the efficacy of interventions addressing trace metals and organic contaminant risks. Despite extensive literature regarding trace metal uptake into vegetables, variables influencing nutrient and contaminant absorption vary markedly between locations. Site-specific studies would be informative given that reliance on generic uptake values may not adequately address risk management pursuant to regulatory guidelines (NEPM 2013). Furthermore, exposure pathway health risk modelling of additional media, such as dust, may provide more insight into household level exposure and refine risk characterisation. Given that older cities remain a risk for blood Pb exposure from a number of pathways, future surveillance programs should target these locations to ensure any unidentified exposures and their inherent harms (Lanphear 2017) are addressed.

5. Conclusions

The *VegeSafe* citizen-science program has transformed thousands of Australians' understanding of trace metal risks in their gardens and provided them with the knowledge and tools to reduce toxic exposure via soil and home-produced food. Answering our research questions, in terms of Question 1, the distribution of trace metal concentrations, the data show that inner city homes have a greater tendency to have garden soil that is Pb contaminated. Health risk modelling of exposure pathways, blood Pb concentration and vegetable uptake indicates the communities in these locations are most vulnerable. The factors (Question 2) most contributing to this spatial trend are that older and painted homes are more likely to be contaminated by Pb. Trace metal Pb concentrations exceed the Australian guideline (Question 3) at 35% of homes. The *VegeSafe* program has been demonstrated to be effective (Question 4), with a survey of participants showing that engagement with *VegeSafe* resulted in participants better understanding contaminants, feeling safe in their home environment and undertaking remedial intervention where necessary. The program has also produced and made available to the public and research community the largest and most detailed dataset covering home garden environments. It has promulgated new scientific findings and has driven authentic engagement with citizens to promote safer urban gardening practices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106582.

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