A Systematic Review and Characterization of the Major and Most Studied Urban Soil Threats in the European Union

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A Systematic Review and Characterization of the Major and Most Studied *Urban Soil Threats* in the European Union

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Abstract There is an urgent need by the European Union to establish baseline levels for many widespread pollutants and to set out specific levels for these under the Zero pollution action plan. To date, few systematic reviews, superseded by bibliometric analyses, have explored this issue. Even less research has been carried out to compare the efficacy of these two data extraction approaches. This study aims to address these two issues by i) constructing an inventory of the available information on urban soils, highlighting evidence gaps and measuring compliance with the Zero pollution action plan, and by ii) comparing the methods and results of these two data extraction approaches. Through Scopus and Web of Science databases, peer-reviewed articles using the terms urban soil in combination with specific urban soil threats and/or challenges were included. Notably, both approaches retrieved a similar number of initial articles overall, while the bibliometric analysis removed fewer duplicates and excluded fewer articles overall, leaving the total number of articles included

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in each approach as: 603 articles in the systematic review and 2372 articles in the bibliometric analysis. Nevertheless, both approaches identified the two main urban soil threats and/or challenges to be linked to soil organic carbon and/or heavy metals. This study gives timely input into the Zero pollution action plan and makes recommendations to stakeholders within the urban context.

Keywords PTEs · Soil organic carbon · Soil compaction · Excess nutrient · Pesticides · Hydrocarbons

1 Introduction

As stated by the European Green deal, soils are expected to provide the means of life and well-being for nearly 10 billion people by 2050; a crucial challenge that requires planning-ahead to mitigate effects which may further compromise the ecological limits of our planet (Gardi et al., 2021; Toth et al., 2016). The European Union recognizes the paramount importance of cities and the vulnerability of the urban and peri-urban environments to cope with the effects of climate change (https://urban.jrc.ec.europa.eu/thefutureofcities/climate-action#the-chapter). In the last few decades, anthropogenic activities, such as increasing greenhouse emissions (Luqman et al., 2023), land use changes (Ferreira et al., 2022), and urban densification (Decoville & Feltgen, 2023), have transformed the urban and peri-urban environments (Antrop, 2004), often degrading highly productive soils (Schillaci et al., 2022). The consequential soil degradation has irreversible consequences for nutrient cycling in soils (Novák et al., 2020; Smith et al., 2016). Minimizing the surface area of soils that are sealed by urban environments could mitigate the effects of future anthropogenic activities, such as climate change (Piero et al., 2017). Quantifying urban soil pollution can help to generate baseline diffuse pollution levels (Ballabio et al., 2018; Panagos et al., 2021; Van Eynde et al., 2023) and provide guidance on the safe use and re-use of soils (Evans et al., 2022) (e.g., for urban agriculture). However, a lack of harmonized laboratory methods and definition of contamination thresholds together with geographic bias in urban soil data makes it difficult to compare between countries and climatic zones (Binner et al., 2023). Consequently, to monitor soil properties in the urban environment, the year of sampling, number of samples, the spatial extent, and the current land use must be defined to provide reliable information about EU urban soil threats and to assess their status. Thus, there is a need to assess whether urban soils in the EU are under threat, and a primary step is to summarize case studies among peer reviewed articles that analysed urban environments. In Europe, several case studies highlighted the legacy of metal industries (Kicińska, 2016; Kicińska & Wikar, 2021; Skorbiłowicz et al., 2021) and heavy metal anthropogenic pollution (Ajmone-Marsan et al., 2019; Cetin et al., 2022a, b; Cicchella et al., 2020). A few studies on the effect of urbanisation on different parent materials (Delbecque et al., 2022; Minolfi et al., 2017; Sándor & Szabó, 2014) and the effects of wildfires (Francos et al., 2020) have shown significantly lower values in bonfire soils of soil water repellence aggregate stability, total nitrogen, soil organic matter, Al, Mn, Fe, Cr, S and SPAR comparing to control soils. For their carcinogenic effects on humans, several studies have analysed the concentration of arsenic and antimony exposure (De Miguel et al., 2017), copper, lead and

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zinc (Davidson et al., 2019; Panagos et al., 2018; Pastor-Jáuregui et al., 2022; Silva et al., 2021), as well as iron (Grembecka & Szefer, 2013; Kypritidou & Argyraki, 2021) pollution due to chemicals (Pavlović et al., 2021). Several studies have directly analysed the potential harmful effects of urbanisation on edible plants (Martini et al., 2023; Medvedeva et al., 2021; Nicola & Paraschiv, 2021; Vanni et al., 2015). To fulfil the objective of this paper to provide a larger-scale overview, a detailed bibliometric analysis was conducted that included all published literature on urban soil in Europe, including main soil threats, from articles that were identified through a systematic sampling protocol. Bibliometric analysis brings to the audience a gross inventory and classification of the research carried out in a specific domain; it provides publication trends and highlights author collaboration networks (Bettoni et al., 2022; Bezak et al., 2021; Liu et al., 2023). Despite the fact that bibliometric analyses are growing in number, the data extraction and supervised analysis of the items is sometimes difficult and requires collaborative efforts to be carried out to identify specific research gaps (Borrelli et al., 2021). Furthermore, there is often a lack of database harmonization (SCOPUS and Web of Science) and, although there is a substantial overlap (Mongeon & Paul-Hus, 2016), the exclusion of one of the two can led to the exclusion of a reasonable amount of studies (Schillaci et al., 2018). The goal of this work was to: (i) identify the existence and abundance of data on urban soil threats in the EU, (ii) identify the data sources and (iii) build a database for the scientific community as well as for the general public.

2 Methods

The bibliometric searches for the systematic review and the bibliometric analysis were carried out in May 2023 and aimed at collating evidence on urban soil threats, such as heavy metals, microplastics, hydrocarbons, antibiotics, excess of nutrients, herbicides and/or pesticides in the EU from peer-review scientific articles, published in the fields of soil science, material science, hydrology, land and urban planning, geology, agricultural sciences, ecology and other related disciplines.

2.1 Data Sources

The research was carried out on the two most widespread bibliographic online databases: i) “Scopus” (Elsevier), and ii) “Web of Science Core Collection” on the Web of Science (WoS) platform (Clarivate) core collections. Both searches are conducted with no restriction on the publication year and include research spanning 1968 to May 2023. This allows the cover of most publications available to the scientific community and particularly to identify those which are most relevant. The.bibtext file was automatically extracted from Scopus with all the relevant information useful for the bibliometric analysis. To avoid conflicts, the data extracted from Web of Science were merged in the same.bibtext file following the Scopus formatting.

2.2 Search for Articles

The search was performed only for scientific articles written in English. This ensures that the publications considered have a significant relevance to the scientific community and are globally disseminated and recognized. To carry out the search, the Boolean operators OR and AND were used, allowing combinations of several different terms within a single search string. Since the keyword terms are made up of several words, the symbols "*" were used to combine multiple words within the same terms to identify specifically those publications in which these terms are used completely and written in the correct order.

For this study, the following keywords in association with the Boolean operator term “OR” were used: “urban soil*” OR “urban chemistry” OR “urban geochemistry” OR “soil chemistry” OR “soil geochemistry” OR “urban green” OR “urban park” OR “urban agri*” OR “urban forest” AND “heavy metal*” OR "metal*" OR “trace metal*” OR “soil carbon” OR “soil organic carbon” OR "SOC" OR "hydrocarbon*" OR "microplastic*" OR "antibiotic*" OR "antimicrob*" OR “soil compact*” OR "pesticide*" OR "herbicide*" OR "nutrient*" OR “soil sealing” OR “soil biodivers*” OR “soil reuse” OR “soil remediation" OR “heavy metal*” OR metal* OR “trace metal*” OR “soil carbon” OR “soil organic carbon” OR SOC OR hydrocarbon* OR microplastic* OR antibiotic* OR antimicrob* OR “soil compact*” OR pesticide* OR herbicide* OR nutrient*

OR “soil sealing” OR “soil biodivers*” OR “soil reuse” OR “soil remediation” AND "EU" OR "Austria" OR "Belgium" OR "Bulgaria" OR "Croatia" OR "Cyprus" OR “Czech Republic” OR "Denmark" OR "Estonia" OR "Finland" OR "France" OR "Germany" OR "Greece" OR "Hungary" OR "Ireland" OR "Italy" OR "Latvia" OR "Lithuania" OR "Luxembourg" OR "Malta" OR "Netherlands" OR "Poland" OR "Portugal" OR "Romania" OR "Slovakia" OR "Slovenia" OR "Spain" OR "Sweden" OR "England" or “Great Britain” OR “United Kingdom” OR "Scotland" OR "Wales" OR “Northern Ireland” OR "Switzerland" OR "Norway" OR "Liechtenstein" OR "Iceland".

Please note that the UK, Denmark and Switzerland, although not in the EU, were included in the search terms of this study because of their regional relevance.

Since the two bibliographic databases do not allow the same search parameters in terms of the categories, we defined the categories separately for each database to include all relevant articles. In Scopus, the search was limited to article title, abstract and keywords, while in Web of Science the search was limited to the ‘topic’ command. In both searches, only research articles and reviews were included. The results of the two separate searches were imported to the free reference manager Zotero.

2.3 Data Analysis

2.3.1 *Bibliometric Analysis Workflow*

Articles were extracted from the SCOPUS and Web of Science in.bibtext format, subsequently loaded into the R environment (version 4.0.2, (R Core Team, 2021)) where the bibliometric analysis was carried out using the bibliometrix package (Aria & Cuccurullo, 2017). The bibliometric analysis is a technique that allows analysis of the distribution models of publications using mathematical and statistical techniques (Pritchard, 1969) where a comprehensive science mapping analysis can be performed. Before carrying out the analyses, a thorough check of the database for errors was performed. Publication trends were carried out using the R bibliometrix package (timespan, sources, and average years from publication, average citations per documents and per year). No co-citation plots were prepared as this was outside the scope of this work.

The workflow of the two approaches is illustrated in Figs. 1 and 2.

2.3.2 *Systematic Review Workflow*

This database includes the following information for each article: bibliographic information (authors,

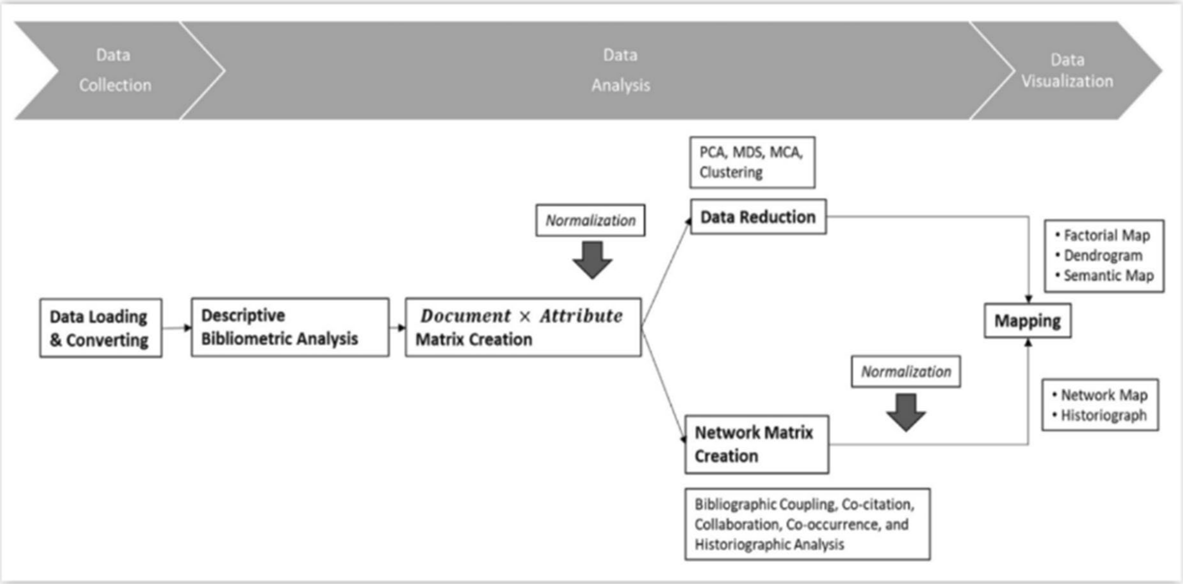

Fig. 1 General workflow of the bibliometric analysis

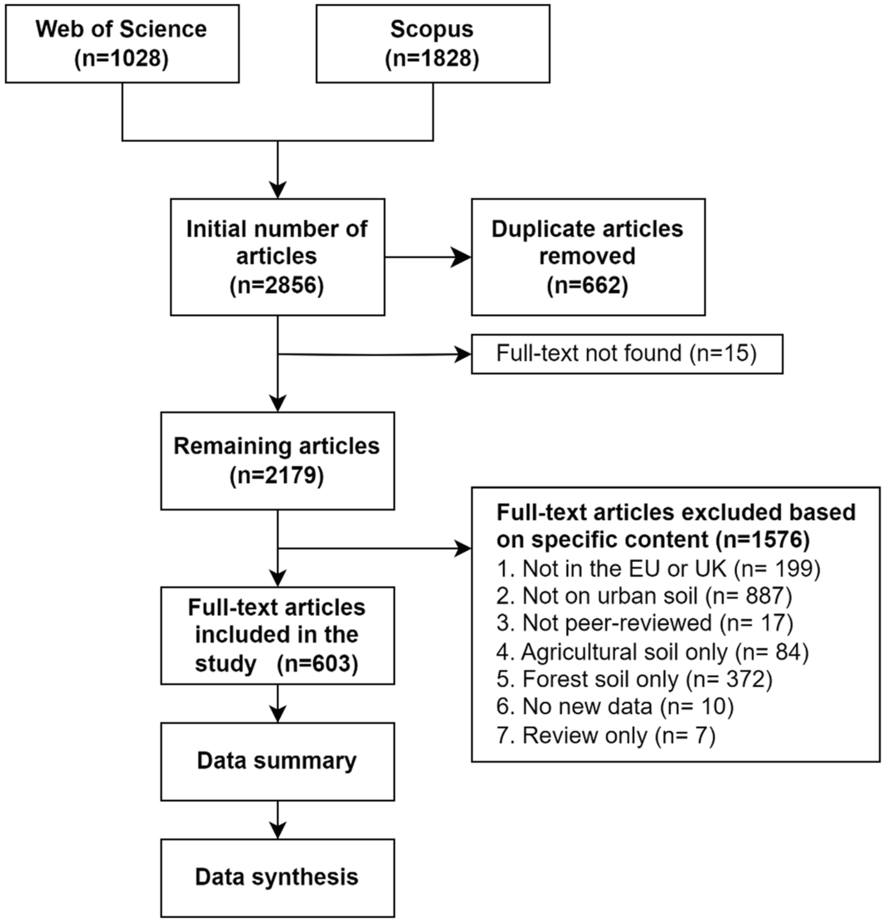

Fig. 2 Flow diagram of the systematic review approach; the final database was divided into chunks and each co-author carried out the database compilation

publication title, affiliation, keywords, corresponding author's country, journal, year, references, citations, abstract, DOI), type of soil data used, regional information (country, urban area, population size, area size, mean annual rainfall and temperature), number of samples, the setting (urban park, private garden, roadside, urban agricultural plot, urban forest), the soil classification and the specific soil threat were extracted.

For the systematic screening process, all articles were included in a spreadsheet comprising all relevant information on the articles, such as authors, journal name, title, DOI, year of publication, and type of the article. All articles were screened following a two-stage process. At the first stage, only article titles and abstracts were screened, in the second stage the dataset was shared among co-authors and full text screening was conducted using rigorous exclusion criteria, which are shown in Fig. 2.

Several of the publications conducted research in more than one setting and/or on more than one urban area and special attention was needed when conducting data analyses on these entries so that no errors occur (Table 1).

2.4 Data Extraction

For the soil threat analysis and characterisation, multiple entry tables were set up (Fig. 3) with dropdown menus including the main subject matter of each of the articles, the outcomes of the analysis in terms of country, urban area, land use type, soil threat analysed, and the potential data availability at the selected level of analysis.

Table 1 Result comparison of the systematic review and the bibliometric approach

	Bibliometric approach	Systematic review
Timespan for included articles	1968—2023	1968—2023
Total number of articles before exclusion	2848	2856
Duplicates removed	476	662
Number of articles removed based on exclusion criteria	/	1576
Final number of articles included in each respective analysis approach	2372	617

3 Results

3.1 Comparison of the Bibliometric and Systematic Review Approaches

The two approaches yielded similar numbers of articles initially, with 2848 articles retrieved by the bibliometric analysis and 2856 articles retrieved by the systematic review. For duplicate removal, the bibliometric analysis removed 476 articles and the systematic review approach led to the removal of 662 articles and revealed that full-text records were not available for 15 publications (older papers which only existed in hard copy).

In stark contrast, the systematic review allowed for the application of exclusion criteria, which the bibliometric analysis did not allow for. This led to the further exclusion of 1576 articles in the systematic review approach, which excluded articles that were beyond the intended scope of this paper and excluded articles that (1) did not conduct research in the EU, the UK, Denmark or Switzerland, (2) did not conduct research on urban soils, (3) were not peer-reviewed, (4) focussed on agricultural soil only, (5) focussed on forest soil only, (6) did not provide new data, such as summary papers and (7) review papers, which in effect also did not provide new data (for details on the number of articles excluded for each criterion see Fig. 2). Therefore, after exclusion and duplicate removal, the bibliometric analysis included a total of 2372 articles and the systematic review included a total of 603 articles. The overlap between the bibliometric and the systematic database is 60% (Figs. 4, 5 and 6).

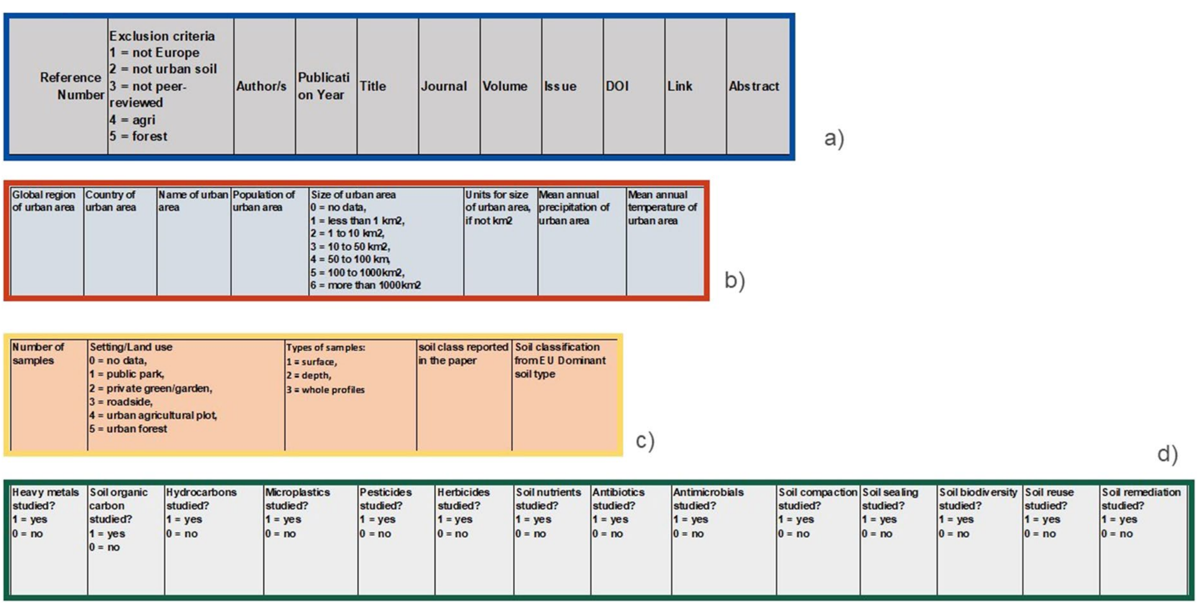

Fig. 3 Structure of the database: a) Reference identifier, exclusion criteria and bibliographic details derived by the database, b) Region characterization, urban area features, average annual temperature and precipitation, c) Land cover type, d) Soil threat

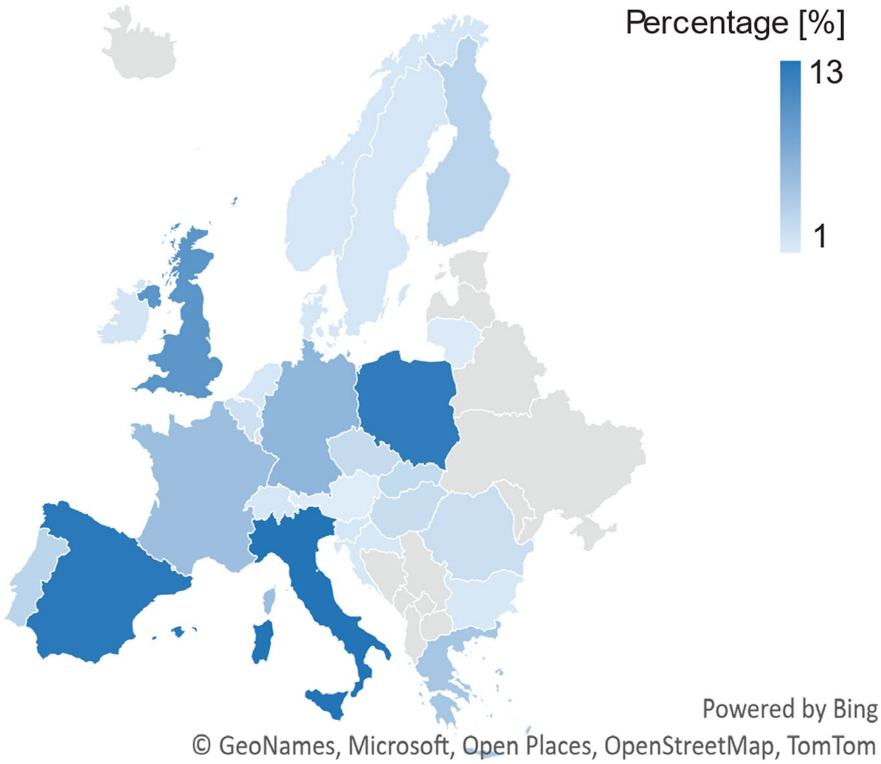

Fig. 4 Percentage of articles available for countries in the EU, the UK, Denmark and Switzerland included in this study (grey indicates that zero articles were available for that country; n = 603)

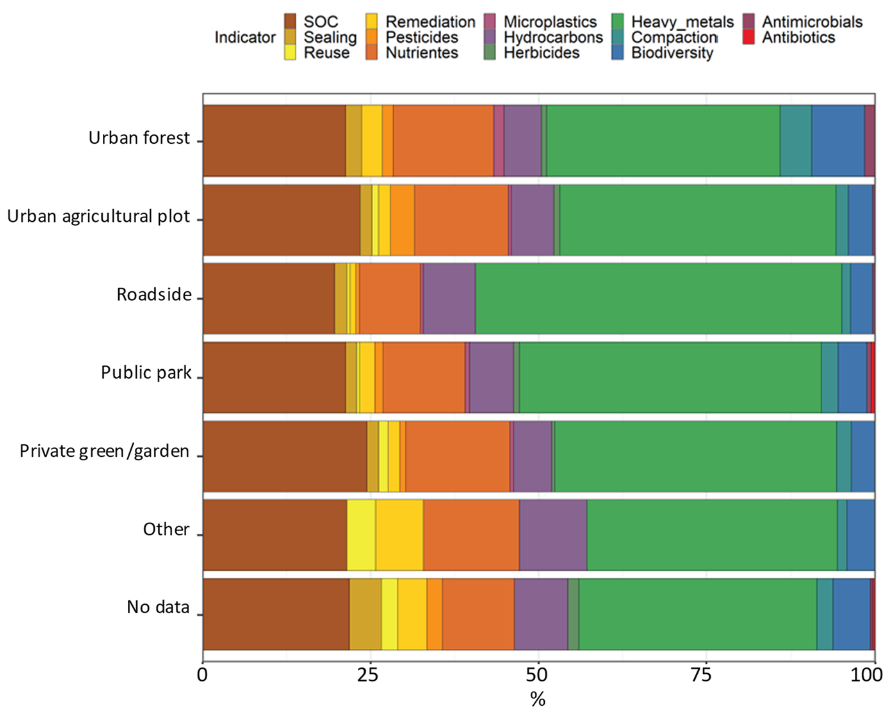

Fig. 5 Percentage of soil threats identified per land cover during this study (n = 603)

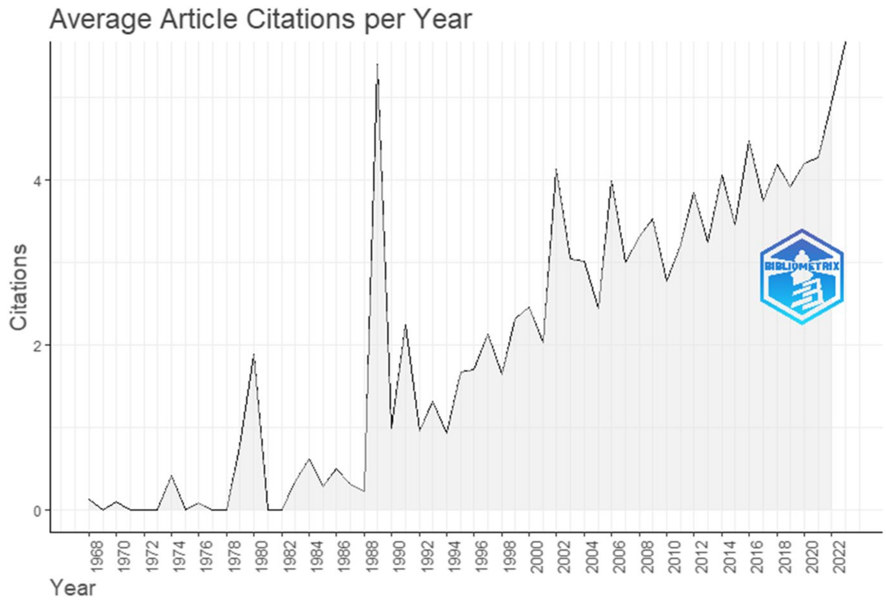

Fig. 6 Number of articles published between 1968 and 2023 (n = 2372)

3.2 Soil Threat and Data Stocktake

3.2.1 Data Availability per Country

The availability of the 603 identified articles is uneven across Europe (Fig. 7): The systematic review reveals that the majority of urban soil data is available for Italy, Spain and Poland (13% of the data; 83, 81 and 79 publications, respectively) and the UK (including Northern Ireland, Scotland and Wales; 10% of the data; 62 publications). Less than 10% of data is available for the following countries: Germany

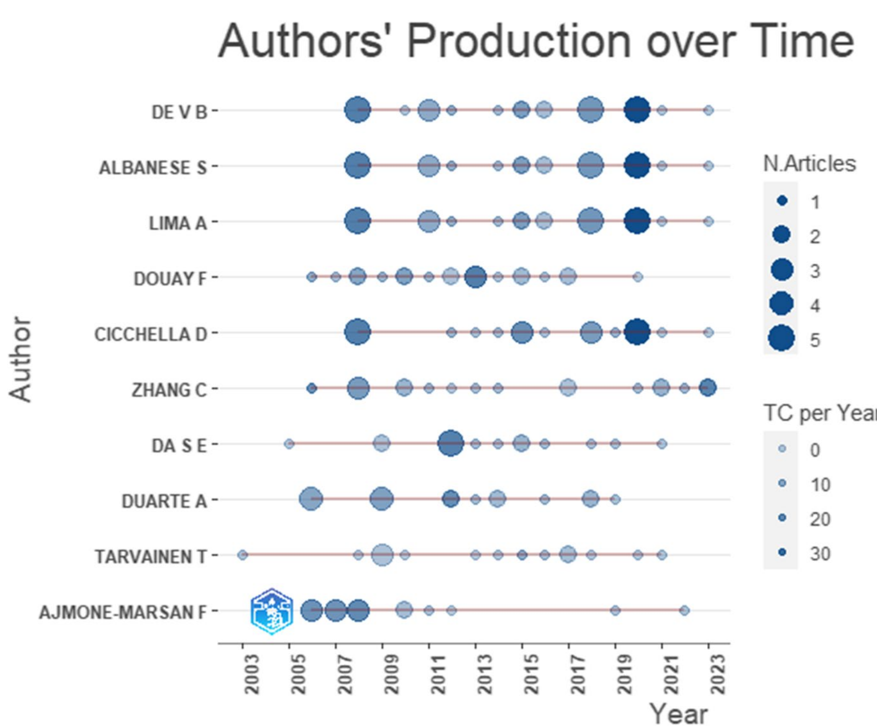

Fig. 7 Productivity of the top 10 authors identified in this study, shown over time (n = 2372; TC: Average citations per year)

6% (40 publications), France and Greece 5% each (34 and 29 publications, respectively), Finland, Portugal, Slovakia and the Czech Republic 3% (21, 20, 17 and 16 publications, respectively), Hungary, Romania, Belgium and Ireland 2% each (15, 14, 12 and 10 publications, respectively), and concerning Denmark, Norway, Slovenia, Sweden, Switzerland, the Netherlands, Bulgaria, Croatia, Lithuania, Austria and Serbia 1% each (each less than 10 publications). All other countries have zero publications on urban soils (namely Cyprus, Estonia, Bosnia and Herzegovina, Latvia, Luxemburg Macedonia and Ukraine).

In contrast, the bibliometric analysis identified Spain as the country with the majority of urban soil data and Italy as the second most (Table 2). The same eight countries feature in each of the analysis approaches, namely: Italy, Spain, Poland, the UK, Germany, France, Greece and Finland. However, the bibliometric analysis lists the Czech Republic and Sweden in the ten most frequently studied countries, while these two countries feature further down the list in the systematic review approach.

3.2.2 Data Availability per Urban Area/City

There are a total of 310 individual urban areas in the dataset with a combined urban population of ca. 200 million. Most research has been carried out in large cities/areas with an area of 100–1000 km^2 (51%; 159 publications). Next are small towns/areas with areas of 10–50 km^2 (19%; 58 publications), medium towns/areas with areas 50–100 km^2 (16%; 51 publications), very large cities/areas with areas > 1000 km^2 (7%; 23 publications), minor towns/areas with areas of 1–10 km^2 (4%; 11 publications) and villages < 1 km^2 in size (2%; 6 publications).

3.2.3 Data Availability Number of Samples

Between 1 and 64000 samples were tested per article, with a median of 34.5 samples per article. The samples were taken from the following areas: 33% in public parks (317 publications), 16% on roadsides (151 publications), 14% in urban agricultural plots (139 publications), 13% in private gardens (128 publications) and 7% in urban forests (66 publications). Additionally, 18% of publications (173 publications) did not specify the function of the sampled area.

3.2.4 Data Availability per Soil Depth

Surface samples (Topsoil) were the most popular and were conducted in 81% of publications (491 publications).Research materials taken from depth (subsoil) and whole soil profiles were present in 11% and 14% of publications (64 and 84 publications, respectively).

3.2.5 Data Availability per Urban Soil Threat and Land Cover

We define soil threat as a topic of emerging interest for soil quality and therefore the word ‘threat’ may mean the term is the subject of the threat (i.e. pollution), or that the threat emerges from the lack of research or importance given to the term (i.e. soil organic carbon, remediation).The main soil traits identified in the 603 articles are: soil organic carbon (81%; 494 publications), PTEs (72%; 435 publications), soil nutrients (23%; 137 publications),

Table 2 Corresponding Author’s Countries

Country	No. of articles	Frequency	SCP	MCP	% of articles
Spain	204	0.099	183	21	9
Italy	187	0.091	166	21	8
Poland	186	0.09	173	13	8
Germany	152	0.074	146	6	6
United Kingdom	145	0.07	129	16	6
Sweden	115	0.056	97	18	5
France	114	0.055	105	9	5
Czech Republic	94	0.046	88	6	4
Finland	67	0.033	58	9	3
Greece	67	0.325	61	6	3

SCP: Single Country Publications, MCP: Multiple Country Publications, the rate of self-citation by people on the author list is not considered (n = 2372)

Polycyclic Aromatic Hydrocarbons (PAHs) (11%; 69 publications), soil biodiversity (7%; 44 publications), soil remediation (5%; 30 publications), soil sealing & soil compaction (4% each; 22 and 26 publications, respectively), soil reuse & pesticides (3% each, 16 and 20 publications, respectively) and herbicides, antibiotics, microbials and microplastics (1% each; 7, 4, 3 and 3 publications, respectively); please note that some articles identified more than one soil threat.

When comparing land cover and soil threats across the database clear trends can be observed: SOC and heavy metals feature most frequently across all land cover types (Fig. 5).

3.3 Bibliometric Analysis Findings

The bibliometric analysis allowed for further analyses to be carried out on author productivity, top journals and keywords used. Figure 6 shows the number of articles published for each year from 1968 to 2023. There are some years without relevant publications up to 1989, 2003, 2007, 2014, 2016. The highest number of relevant articles registered is after 2002.

Furthermore, the bibliometric analysis was able to identify the top 10 authors within urban soil threat research identified during this study and to show these author's productivity over time (Fig. 7). These trends show that productivity fluctuates year on year, however, many of these authors frequently publish three to five articles per year, which are widely cited.

Comparing articles of the top ten most productive countries (Table 3) with the most frequently used journals (Table 4) shows that the journal *Science Of The Total Environment* is in first place on both lists. The most cited article is authored by Manta, with 783 total citations and an average citation rate of 35 per year. Together the first 10 authors contribution appears substantial, but they are 3 groups of co-authors, and the total amount of articles that have passed the screening process is rather small.

To verify the quality of publications as well as the general scientific productivity, the total number of global (total number of citations identified in Scopus and Web of Science of the articles present in this database) and local citations (how many times a document included in this collection have been cited

Table 3 Number of publications and citations of the 10 most productive countries

First Author Name	Publication Year	Journal Abbreviation	First Author Country	DOI	TC	TC/Year	NTC
Manta Ds	2002	Sci Total Environ	Italy	10.1016/S0048-697(02)00273–5	783	35.6	9.02
Smith Sr	2009	Environ Int	UK	10.1016/j.envint.2008.06.009	721	48.1	14.56
Tyler G	2004	Plant Soil	Sweden	10.1007/s11104-005–4888-2	708	35.4	12.37
Schulze E-D	1989	Science	Germany	10.1126/science.244.4906.776	644	18.4	3.51
Komárek M	2010	Environ Int	Czech Republic	10.1016/j.envint.2009.10.005	572	40.9	15.76
Imperato M	2003	Environ Pollut	Italy	10.1016/S0269-7491(02)00478–5	462	22	7.57
Ball Bc	1999	Soil Tillage Res	UK	10.1016/S0167-1987(99)00074–4	423	16.9	7.62
Christoforidis A	2009	Geoderma	Greece	10.1016/j.geoderma.2009.04.016	384	25.6	7.76
Bucheli Td	2004	Chemosphere	Switzerland	10.1016/j.chemosphere.2004.06.002	324	16.2	5.66
Franco-Uria A	2009	J Hazard Mater	Spain	10.1016/j.jhazmat.2008.10.118	322	21.5	6.50

SCP Number of country's individual publication, *MCP* Number of articles for the country collaborated with other countries, *TC* Total number of citations

Table 4 Most frequently used peer-reviewed journals to publish articles on urban soil threat, as identified by this study (n = 2372)

Journal	Number of articles
Science Of The Total Environment	208
Environmental Pollution	96
Geoderma	72
Journal Of Geochemical Exploration	72
Water Air And Soil Pollution	68
Environmental Geochemistry And Health	59
Environmental Monitoring And Assessment	48
Plant And Soil	46
Environmental Science And Pollution Research	43
Chemosphere	42

by other paper also in the collection) was used as an indicator.

The keyword search within the bibliometric analysis revealed that heavy metals are the most frequently referred to urban soil threat.

4 Discussion

The overall availability of publications on urban soil threats is low, especially considering the number of urban areas and the land area covered within Europe, the current extent of research does not sufficiently provide an overview of the status of urban soils. Nevertheless, this review casts a light on the trends and gaps in the current best knowledge of urban soil threats.

4.1 Bibliometric Analysis on the Merged Dataset (*Scopus* and Web of Science)

The aim of this study was to collect and summarize the present knowledge about urban soil threats, including heavy metals, excess of nutrients, herbicides, pesticides, microplastics, antibiotic, etc. Relevant articles, the availability of data associated with the articles, and fields of research that have had the greatest impact on the topic were analysed with a bibliometric inventory produced (Supplementary material). Since the authorship includes researchers from several countries, several authors also reported the wealth of data published in the national soil or geological surveys, (e.g. the Irish case reported a low number of articles and this was surprising as there is a lot of published soil data available, as well as datasets by the Geological Surveys, which the literature search isn't finding this sort of dataset. Bibliometric analysis identified the most frequent types of publication, most productive countries (according with the corresponding author affiliation), most productive authors, the amount of research produced through time, and the journals that were mainly chosen to publish these results. The authors keywords used to identify the main areas of the articles (Fig. 8) showed that the vast majority of articles were dealing with heavy metals, as confirmed in several recent publications (López-Rayo et al., 2016; Mónok et al., 2021; Mosquera-Losada et al., 2017; Skorbiłowicz et al., 2021). The number of articles published, related to soil threat increased in

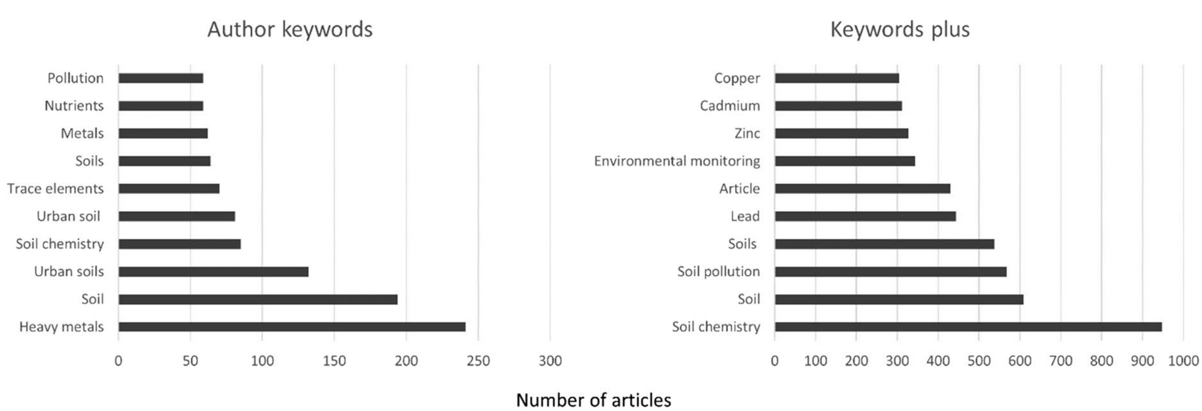

Fig. 8 Authors Keywords and Keywords plus derived from the indexation of the items in the databases

time, as well as the perception of the public opinion and the increase in the R&I investment (Arias-Navarro et al., 2023), having a peak in 1989, 2003, 2007, 2014, and 2016. Analysis of scientific production, as illustrated in Fig. 7, emphasizes that the majority of authors publish 1 to 3 articles per year. Analysing the scientific production of different countries, we observe the greatest contribution from Spain, Italy and Poland (affiliation of the corresponding author), followed by Germany. The top ten authors produced almost one third of the total available data, which shows not only the importance of specialized research groups, but also the skew of the data based on the geographic location in which these research groups are based. Furthermore, there may be increased pressure on these researchers to continue their efforts, which is subject to a range of factors, and analysis of the production over time has shown that the relationship between author productivity and the number of citations is not straightforward. A further limitation of this type of analysis is that only first author names were considered, but many researchers may have been involved in additional publications as second, third, etc. or last author, which this analysis does not include, And the likelihood of them slipping down the author list increases with career stage as they supervise other students and postdocs.

The top cited publications, and therefore most relevant publications for the field or urban soil threats, arise from a range of environmental science journals, however, articles published in the journal Science of the Total Environment are among the most frequently cited. This shows not only the relevance of the journal for the subject area (urban soil threats), but also the resource that this database offers for future research, very interestingly that the most prolific cross-disciplinary journals (i.e. Nature and Science) do not have a large share of soil research at least in urban and peri-urban environments, this indicates that the scientific community, or at least the large publishers, are not considering seeing/understanding soil threats as a major risk, which is in contrast with these journals frequently publishing articles on climate threats.

4.2 Soil Threat and Data Stocktake from the Subset of Urban Soil Publications

While the overall number of publications on urban soil threats is low, since the appearance of the first publication in 1968 until 2023, the number of publications has increased year on year, with spikes in 1988 and thereon that might be related to major soil conferences and policy interest, with the most recent spike showing in 2022. This indicates a clear shift in the research landscape, which is in line with policy placing increased importance on urban soils through the development of policies such as the European Soil Strategy, the European Missions: a soil deal for Europe and the Zero Pollution Action Plan (European Commission 2021, COM(2021) 400 final). Interestingly, while the author keywords would indicate that heavy metals and soil chemistry are among the most frequently studied, our review on the relevant articles shows that soil organic carbon is the most frequently studied, closely followed by heavy metals and soil nutrients.

Data availability for different countries clearly indicate a geographic disparity in urban soil research within the European Union, with Italy, Spain, Poland, and the UK contributing to more than a third of the available data. This uneven distribution suggests that urban soil pollution research may be influenced by national research priorities, funding availability, and possibly the presence of active research groups specializing in this area. The lack of data from certain countries could impede EU-wide policy development and enforcement. It is imperative for future initiatives to incentivize research in underrepresented regions to obtain a more balanced view of the EU's urban soil health.

Data availability for urban area size is concentrated in large urban areas (>10 km^2), which could be due to the greater impact of pollution in densely populated regions or the easier access to research infrastructure. However, this focus may overlook the unique challenges faced by smaller urban areas and villages or non-urban agricultural areas/habitats, potentially leading to a one-size-fits-all approach in policy that may not be effective across different urban scales. A more equitable distribution of research efforts, including small and medium towns, would provide a better-informed foundation for localized urban soil management strategies.

There is a considerable variation in the number of samples per article (from 1 to 64,000) indicating a broad methodological diversity in urban soil studies, which may affect the comparability of results. The predominance of surface samples suggests a focus on recent pollution events, but to fully understand urban soil's role in long-term environmental health, deeper soil profiles should also be examined. This aspect is critical for assessing historical contamination and for planning soil remediation.

Data availability for soil depths suggest that the majority of these publications obtain surface soil samples, which aids the analysis of recent soil changes, but to address historic soil threats the depth and whole soil profiles require more study in the future (Batjes et al., 2020).

Regarding data availability for soil threat areas in general, we can state that in the vast majority of cases urban EU soils have been investigated for PTEs. Concurrently, soils were analysed for their Soil Organic Carbon content and its stock, PAHs and soil biodiversity which are under the lens of EU soil scientists. There is also a steady increase in emerging pollution threats such as microplastics and antimicrobials. From the current limited data, SOC dynamics with emphasis on SOC losses has been identified as the main threat area based on the crucial role carbon capture plays in helping to combat climate change, closely followed by PTEs diffuse pollution, based on historic anthropogenic activities. To address these urban soil threat areas, data from across Europe is needed to identify trends linked to spatial variation, climatic conditions, historic land use and industrialisation, as well as urban sprawl. Urban soils tend to be soils that remain untouched for several decades and may offer an ideal target for longer-term carbon storage, but to utilise this potential we require information on the current status of these soils (Cambou et al., 2023; Dynarski et al., 2020). The soil threat surrounding heavy metals also touches on environmental and human health factors: on the one hand, many studies on urban soils across Europe have already indicated widespread presence of elements such as Pb, but also Hg and As, due to their extensive historic use, which not only concerns environmental health, but also human health where these concentrations are elevated in park-settings or even urban private gardens that may cultivate vegetables (Ajmone-Marsan et al., 2019; Biasioli & Ajmone-Marsan, 2007; Cachada et al., 2012; Madrid et al., 2006). Data availability for land cover was primarily available for public parks, several roadside sampling and a few urban agriculture plots. The challenge to address various land cover remains, as does the need for better mapping and classification of urban soils (Ajmone-Marsan et al., 2016).

5 Conclusions

With this work, we provided a systematic review of emerging urban soil threats in the European Union. Data mapping from literature analysis was carried out based on the peer-review literature published in journals and other types of publication indexed in the Web of Science and Scopus bibliographic databases to collate the research done in urban soils and, especially, to capture their status and potential threats. There is an uneven data availability for urban soil studies across Europe: only a few countries (Italy, Spain, Poland) make up half of the available data, while there are seven countries with no urban soil publications to date. The current dataset shows that primarily very large cities and small to medium size towns are the target of urban soil studies, which is certainly needed, but most cities and towns across Europe are still unexplored. Another crucial issue emerging from our data analysis is the wide range of sample sizes, which may further hinder a true reflection of the amount of available data, when considering that one urban area may have been sampled multiple times through small sampling campaigns, while another urban area may have been covered with a single extensive sampling campaign. There is a need to harmonize for soil depth, land cover nomenclature and laboratory measurement. Standardised procedures are required to identify and compare potential threat areas and to enable local authorities to carry out effective monitoring and sampling campaigns that address the current knowledge gaps and unexplored areas in many urban centres across the European Union.

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Data Availability The raw data is provided in the supplementary material.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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