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Three Decades of Evolution in Approaches and Methods in Urban Soil Research (1995–2024). A Bibliometric Perspective

Trzy dekady ewolucji podejścia i metod w badaniach gleb miejskich (1995–2024). Perspektywa bibliometryczna

Abstract: The article presents the results of a study on the formation and evolution of the global research field devoted to urban soils between 1995 and 2024. A database comprising 961 scientific articles published during this period was compiled and subjected to a detailed bibliometric analysis. The analysis included an assessment of the temporal dynamics of publication output, the identification of the most frequently publishing journals and countries with the highest research activity, an examination of international collaboration patterns, and the distribution of publication languages. The core part of the study involved an analysis of keyword co-occurrence in the collected literature. Based on these data, a network model was constructed to represent the variability and interconnections among keywords. Analytical methods derived from mathematical graph theory were applied to characterize complex network structures in terms of their coherence, vertex degree distribution, and the extraction of so-called *p*-layers. To isolate these layers, an original graph-layering technique was proposed, enabling a multilevel interpretation of relationships and hierarchies within the analysed network. The keyword co-occurrence analysis revealed that the development of urban soil research can be divided into two distinct phases. The first phase (1995–2010) represents the emergence of research awareness, while the second (2011–2024) corresponds to a "developmental" stage charac-

terized by the expansion and deepening of knowledge about urban soils. Furthermore, the results indicate that research in this field has revolved around a limited number of central concepts (Urban Soil, Heavy Metals, Biochar), which serve as semantic reference points within the scientific discourse. The established prominence of these keywords positions them as enduring thematic anchors in a still relatively young yet dynamically developing research domain, which continues to evolve in parallel with growing public awareness of the importance of the urban environment.

Keywords: urban soils; bibliometric analysis; soil survey; complex networks; network analysis

Abstrakt: W artykule zaprezentowano wyniki badań dotyczących kształtowania się i rozwoju nurtu badawczego związanego z glebami miejskimi na świecie w latach 1995–2024. W ramach analizy opracowano bazę danych obejmującą 961 artykułów naukowych opublikowanych w badanym okresie, które następnie poddano szczegółowej analizie bibliometrycznej. Analiza ta objęła ocenę dynamiki liczby publikacji w czasie, identyfikację najczęściej publikujących czasopism i krajów o najwyższej aktywności badawczej, charakterystykę współpracy międzynarodowej oraz dystrybucję języków publikacji. Zasadniczą część pracy stanowiła analiza współwystępujących w artykułach słów kluczowych. Na ich podstawie skonstruowano sieciowy model ich zmienności oraz powiązań między nimi. W badaniach zastosowano metody analityczne oparte na matematycznej teorii grafów, umożliwiające konstrukcję oraz charakterystykę złożonych struktur sieciowych pod względem ich spójności, rozkładu stopni wierzchołków oraz analizy tzw. *p*-warstw. W celu wyodrębnienia tych warstw zaproponowano autorską technikę warstwowania grafu, pozwalającą na wielopoziomową interpretację powiązań i hierarchii w obrębie badanej sieci. Analiza współwystępowania słów kluczowych wykazała, że rozwój badań nad glebami miejskimi można podzielić na dwa etapy. Pierwszy z nich (1995–2010) dotyczy formowania się świadomości badawczej, a drugi (2011–2024) obejmuje etap „rozwojowy", w którym pogłębiano wiedzę o glebach miejskich. Ponadto wykazano, że badania opierały się na ograniczonej liczbie centralnych pojęć (*urban soil*, *heavy metals*, *biochar*), które stanowią „semantyczne punkty odniesienia" w dyskusji naukowej. Utrwalone pozycje tych słów kluczowych czynią z nich semantyczne punkty odniesienia w dyskusji naukowej, mimo że jest to wciąż stosunkowo młody trend badawczy, rozwijający się dynamicznie wraz ze wzrostem społecznej świadomości znaczenia środowiska miejskiego.

Słowa kluczowe: gleby miejskie; analiza bibliometryczna; badania gleb; sieci złożone; analiza sieci

1. INTRODUCTION

Understandably, there is a growing interest among researchers in the field of urban ecology, particularly urban soils (US). The expansion of urbanized areas and their increasing population have been recognized over the past decades as major factors contributing negatively to the natural environment (Poumanyvong & Kaneko, 2010; Zhang, 2005). Despite urban areas occupying less than 1% of the land surface (Zhou et al., 2015), it is estimated that their area could triple by 2030 compared to 2000, covering an additional 1.2 million km² (Seto et al., 2012).

A frequently cited report (United Nations, 2018) indicated that by 2016, there were 512 cities with populations of at least 1 million inhabitants, with projections suggesting an increase to 662 by 2030. This underscores that urban issues are already a significant research challenge, with their importance expected to grow in the coming years and decades.

It is therefore pertinent to inquire about the current state of the literature on urban soils, the historical dynamics of its development, and, in particular, the shared approaches and frameworks used by researchers in this field. Analysing and assessing these issues would not only allow an evaluation of the current state of the topic but also aid in identifying potential "white spots" on the map of urban soil research. Consequently, it may suggest new and promising research directions.

The term "urban soils" has long been descriptive rather than classificatory (Uzarowicz et al., 2020). Only recently has there been recognition of the need for a detailed definition and systematic classification similar to those established for natural soils (Kopel et al., 2016). Craul (1985) stated that "urban soils constitute a distinct category of pedogenic units shaped by the processes of urbanization. For this reason, they cannot be considered independently of the spatial and geographical boundaries of the urbanization process itself" (p. 330). He also defined urban soils as "a soil material having a non-agricultural, manmade surface layer more than 50 cm thick that has been produced by mixing, filling, or by contamination of land surface in urban and suburban areas" (Craul, 1992, p. 396). This, in turn, has led to the evolution of methodologies and research directions, collectively contributing to the ongoing development of the subject. Many researchers delivered insight into relations between the development of urban soils and land use, as well as the impact of industry on the chemical and physical properties of soils (Burghardt, 1994; Burghardt et al., 2015; Effland & Pouyat, 1997; Lehmann & Stahr, 2007).

The aim of this review is to examine the evolution of research approaches and methodological frameworks in urban soil studies between 1995 and 2024. Specifically, the study seeks to identify key thematic trends, methodological shifts, and emerging research directions that have shaped the development of this field over the past three decades.

Bibliometric analysis was employed to reconstruct the geographical structure of the research community, with a focus on authors' affiliations. Based on the results obtained, areas that have been intensively researched and gaps in current knowledge were identified.

Bibliometric analysis has proven to be a valuable tool for mapping the evolution of scientific fields and identifying emerging research directions. By quantitatively examining publication trends, citation patterns, and keyword networks, it allows for a systematic assessment of how research topics and methodologies have

developed over time (Araújo et al., 2023; Pesta et al., 2018; Wang et al., 2018). Despite its limitations – such as reliance on available metadata and potential biases in database indexing – this approach provides a robust framework for exploring the intellectual structure and dynamics of urban soil research.

2. MATERIALS AND METHODS

This review will analyse how researchers' approaches to the topic of urban soils have evolved over the past 30 years, identifying the aspects that have garnered the most attention and how the catalog of these topics has developed. It will also consider the participation of researchers from various parts of the world. The year 1995 is chosen as the starting point due to the rapid development of literature on the subject since then (Liu & Chu, 2008). To address these questions, network analysis methods and bibliometric methods were employed. Regarding the former, a network model of keyword co-occurrence frequencies in 961 thematic articles was constructed, analysed based on node degrees, and decomposed into subsequent *p*-layers. This approach examined the popularity of declared keywords and the frequency of their mutual co-occurrence in research papers.

In April 2025, a literature search was conducted to identify publications on urban soils released between 1995 and 2024. The search was carried out in the Scopus database using the phrase "URBAN SOIL" in the title field. To ensure thematic consistency, only entries containing the words as a single term in the title were considered, thereby excluding articles with divergent subject matter. Book chapters, reviews, abstracts, and editorial materials were excluded from the dataset, retaining only articles that contributed new knowledge to the state of research.

From the resulting collection, further exclusions were made: articles unrelated to the urban soil topic, those lacking complete bibliometric metadata, and those with erroneous metadata were removed. The final dataset comprised 961 scientific articles, encompassing a total of 3,384 unique keywords. The structured database was exported in CSV format and included the following fields: authors, title, year of publication, journal name, author affiliations, citation count, language of publication, and keywords.

It should be noted that authors-supplied keywords may not always precisely reflect the actual content of a publication. Keyword selection can be influenced by various factors, including editorial guidelines, database indexing practices, and individual author preferences – such as the inclusion or omission of geographical names, soil-specific terminology, or methodological terms. Consequently, the results of keyword-based analyses should be interpreted with some caution. Nevertheless,

previous studies have shown that aggregated keyword data provide a reliable approximation of conceptual and thematic trends within a research field.

A series of bibliometric analyses was conducted to identify trends and patterns in: the temporal dynamics of publication volume, most frequently publishing journals, countries with the highest publication output, international collaboration based on co-authorship, languages of publication, and the most commonly used keywords. To avoid redundancy in keyword data, plural forms were reduced to singular (soils – soil), abbreviations were expanded (PAH – polycyclic aromatic hydrocarbon), and terms were normalized criteria – criterion). In cases where articles listed authors from multiple countries, these affiliations were disaggregated into separate entries. All data processing and analyses were performed using the Python programming language.

The applied network methodology was based on a graph-based model of keyword co-occurrence. This model was constructed as a series of consecutive temporal graphs, each representing the co-occurrence of keywords over a five-year period. The set of vertices for each graph consisted of the keywords listed in the articles published within the corresponding time interval. A pair of keywords (vertices) was connected by an edge if, and only if, they co-occurred in at least one article. The number of such articles in the given period was assigned to each edge as its weight. Each temporal graph can be interpreted as a "snapshot" of the evolving structure of the studied network. Comparative analysis of these snapshots enables insight into the dynamics of change within the network – a mental map of urban soil research as it developed over time. The temporal graphs forming this model were comparatively analysed in terms of three main dimensions: connectivity, degree, and *p*-layers.

From this construction, it follows that a single article assumes the form of a complete graph in which every vertex is connected to every other. Such graphs are referred to as cliques, especially when considered as subgraphs within a larger network. Each clique containing n vertices contains exactly $\frac{n\,(n\text{-}1)}{2}$ edges (Wilson, 1998). The whole model is thus the union of all such cliques. Accordingly, the weight of any given edge can be equivalently defined as the number of cliques (i.e. articles) in which that edge (keyword pair) appears.

Hubs – vertices with significantly higher degrees (i.e. a greater number of connecting edges, hence more neighbours) than others – correspond to keywords that appear in the most significant number of studies. These represent concepts that attract the most attention from researchers and serve as leading themes in the scientific discourse on urban soils. Analysis of changes in hub nodes across successive temporal graphs provides deeper insight into the evolving core categories that shape thinking about urban soils over time.

In this study, a *p*-layer of a graph is defined as a subgraph composed of edges with weights equal to or greater than *p*, along with the vertices to which these edges

are connected. To obtain precise and conceptually relevant subgraphs, the value of the parameter p – and thus the number of layers – was incrementally increased for each temporal graph. As a result, progressively smaller subgraphs were extracted, composed of edges with increasingly higher weights (represented visually by thicker lines). This is authors' original analysis based on a graph-theoretical approach specifically designed for this study, illustrated in Fig. 1.

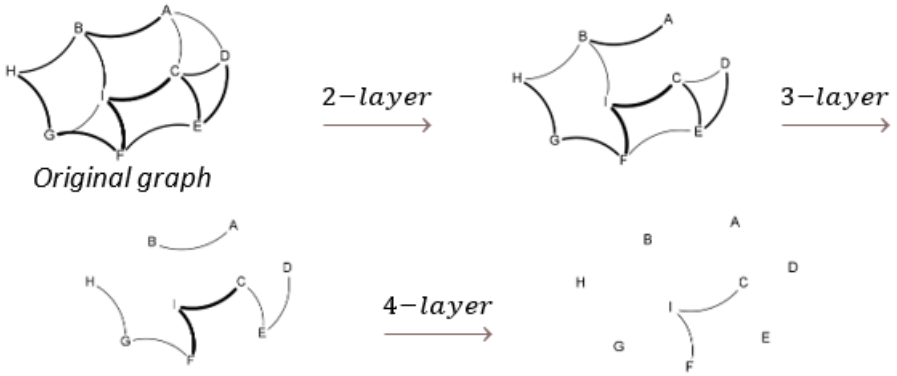

Fig. 1. Steps in graph layering (Source: Authors' own study)

From the initial graph, the 2-, 3-, and 4-layer were successively extracted. Since the edges in the original graph have weights ranging from a minimum of 1 to a maximum of 4, the 1-layer is equivalent to the complete graph itself, while the 5-layer would be a null graph, containing no edges and no vertices. By definition, each p-layer also includes all edges belonging to layers with higher p values. Therefore, each subsequent layer is a subgraph that is smaller than or equal to the preceding one. The described procedure is referred to in this study as the graph peeling method. The graphs were processed and visualized using Gephi version 0.10.1.

3. RESULTS AND DISCUSSION

3.1. Bibliometric analysis

The distribution of publications over time containing "US" in the title indicates a steady increase (Fig. 2a). This trend confirms the growing research activity in the field of soil science and is closely linked to global concerns regarding climate change, food security, sustainable development (Demir, 2024; Jia et al., 2024). Related studies are also conducted within urban ecology, environmental chemistry,

geography, and landscape planning, reflecting the interdisciplinary character of this field. The distribution of articles can be divided into three significant periods: 1995–2004 (4.8%), 2005–2014 (31.1%), and 2015–2024 (64.1%), with a notable peak in 2024, when 80 articles were published. Since 2005, the number of publications has grown dynamically, albeit irregularly.

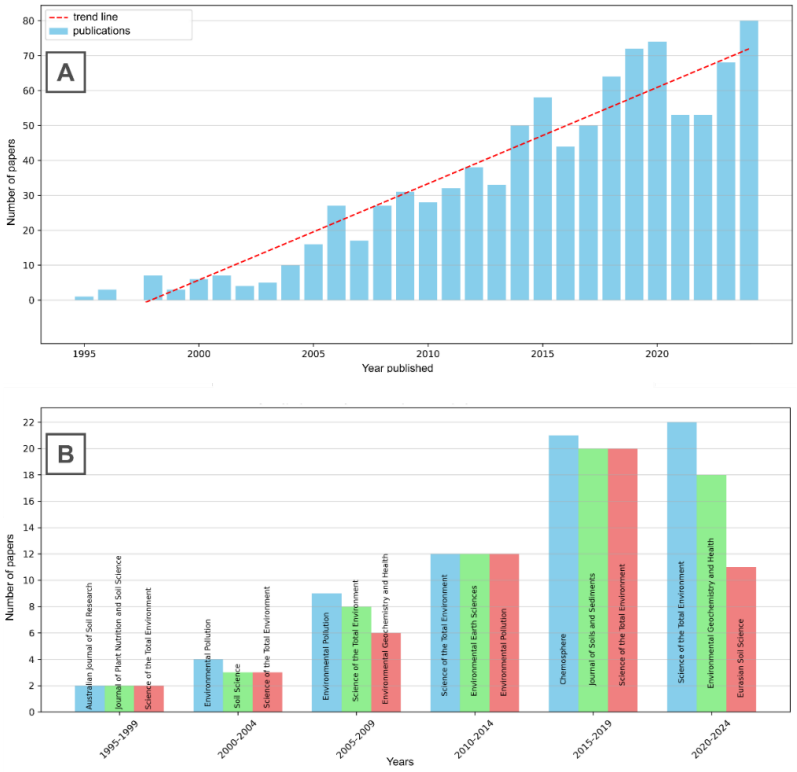

Fig. 2a. Number of scientific articles published between 1995 and 2024 containing the term "urban soil" in the title. 2b. Journals publishing the most articles on "urban soil" over the past five years (Source: Authors' own study)

The distribution of publications among the journals with the highest number of analysed articles is notably uneven (Fig. 2b). Among all journals, the most frequently represented are *Science of the Total Environment* – 67 articles (7.0%), *Environmental Pollution* – 41 articles (4.3%), and *Journal of Soils and Sediments* – 38 articles (3.6%). The chart showing the top three publishing journals in five-year intervals indicates that, although their ranking changes over time, *Science of the Total Environment* appears in every period. This is further confirmed by the total number of citations (Tab. 1), which exceeds 5,700 for this journal alone –

representing 14.2% of all citations. Impact metrics (Impact Factor and CiteScore) indicate that leading positions among the most influential journals are occupied by titles published by Elsevier.

Tab. 1. Number of citations for the most popular journals (Source: Authors' own study)

Journal	Publisher	Citation count	Impact factor	Cite store
Science of the Total Environment	Elsevier	5,772	8.2	17.6
Environmental Pollution	Elsevier	4,904	7.6	16.0
Chemosphere	Elsevier	2,739	-	18.1
Journal of Hazardous Materials	Elsevier	1,841	12.2	25.4
Journal of Soils and Sediment	Springer	1,649	2.8 (2023)	–
Ecotoxicology and Environmental Safety	Elsevier	1,627	6.2	12.3
Geoderma	Elsevier	1,590	5.6	12.9
Environmental Geochemistry and Health	Springer	1,261	3.2 (2023)	–
Journal of Geochemical Exploration	Elsevier	1,186	3.4	7.0
Environmental Monitoring and Assessment	Springer	1,023	2.9 (2023)	–

When considering the countries with the highest number of publications between 1995 and 2024, China clearly leads with 237 publications, accounting for nearly one-quarter of all articles (Fig. 3). The United States also contributes significantly, with 90 publications, followed by Russia (80), Germany (42), Italy (39), and Poland (36). These countries exhibit an upward trend in publication output, and researchers from these regions increasingly prioritize urban soil studies as part of broader regional and global research strategies (Demir, 2024; Hartemink, 2019).

Notably, many countries have not published any research articles on urban soils to date – for example, Venezuela, Uruguay, and Thailand. These examples illustrate regional disparities and the uneven global distribution of research activity on urban soils. The majority of the analysed literature focuses on studies conducted in Europe (including Russia), accounting for 43.4%, and in Asia, which contributes 37.0%. In contrast, the lowest number of studies was found in South America, Africa, and Australia/Oceania, with respective shares of 2.9%, 2.9%, and 1.7%. The overwhelming majority of publications were written in English (91.2%), significantly facilitating international accessibility and knowledge exchange (Fig. 3).

The strongest international research collaborations have formed between China and the United States, as well as between China and Germany (Fig. 4). Notable partnerships are also observed among Western European countries, including Italy–Spain, Italy–United Kingdom, Italy–Slovenia, and Portugal–United Kingdom, as well as within East Asia, particularly China–Japan, China–India, and China–Hong Kong.

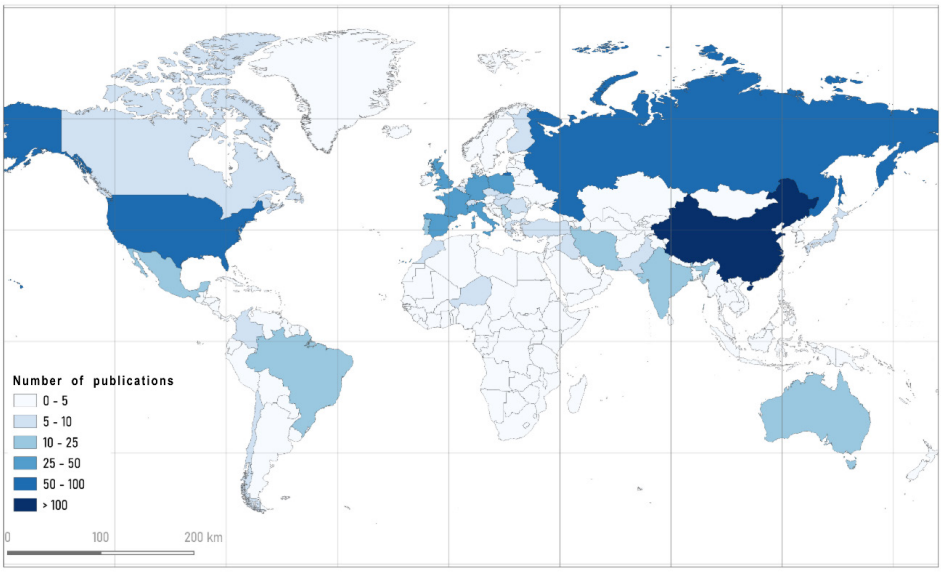

Fig. 3. Distribution of publications across countries (Source: Authors' own study)

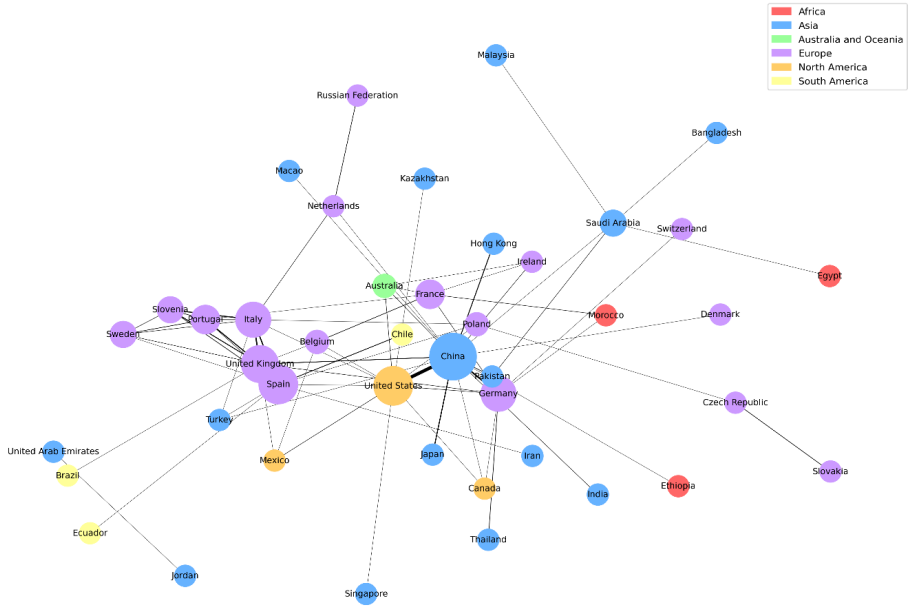

Fig. 4. International cooperation network (Source: Authors' own study)

3.2. Keyword co-occurrence analysis

3.2.1. CONSISTENCY

In the first decade of the study period, the keywords provided in articles did not form a coherent thematic structure (Tab. 2). It is also worth noting that not all papers containing the term "Urban Soils" in their title listed it among their keywords. Some used entirely original keyword sets, which is reflected in the presence of isolated clusters. Nevertheless, in both the 1995–2004 and 2005–2009 temporal graphs, we observe the emergence of significant connected components, distinguished by their size. These components are organized around two central terms – hubs: "Soils" and "Urban Soils". Interestingly, these hubs are not directly linked, but are connected via an intermediary subset of nodes such as "Trace elements", "Pb isotopes", "Soil pollution", and "Geostatistics". All of these are clearly associated with the study of soil contamination, suggesting that while "Soils", as a general term, appeared earlier in the keyword network, the category of "Urban Soils" emerged specifically from concerns related to soils contaminated by industrial sediments. This is important because it reflects the early stage of conceptual evolution in this field, when urban areas were mainly associated with soil pollution and environmental degradation. Similar observations have been made in previous reviews (Burghardt, 2025; O'Riordan et al., 2021; Paltseva et al., 2022), which emphasised that such perceptions, while historically justified, may oversimplify the complex functions of urban soils.

This interpretation is further supported by the presence of other central keywords such as "Lead", "Metal", and "Soil Contamination". It indicates that the motivation behind research on urban soils stemmed not merely from academic curiosity, but from the fact that many urban environments contain soils that are among the most contaminated due to industrial activity and long-term anthropogenic pressure, although contamination levels vary substantially across regions. This is confirmed by the size of the clusters surrounding both hubs. While in the first temporal graph, the neighbourhood of the keyword "Soils" is significantly larger than that of "Urban Soils", this relationship reverses in the subsequent period. Furthermore, the urban soil cluster becomes notably more extensive and more structurally complex. All of this suggests that during the years 2000–2004, a distinct research awareness had emerged – one grounded in the recognition that urban soils constitute a qualitatively different type of substrate, meriting focused and independent investigation.

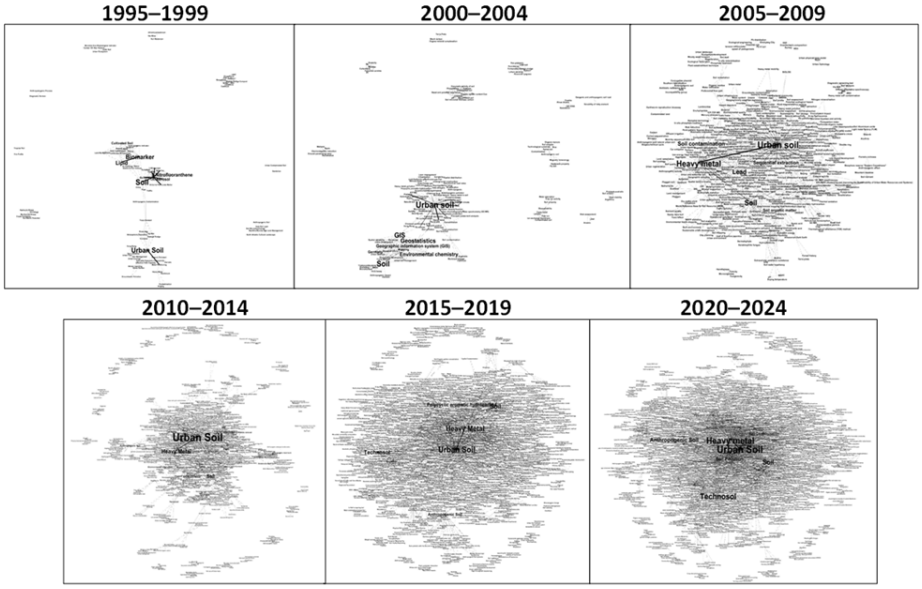

Fig. 5. Instantaneous graphs of keywords in the years 1995–2024, in a proportional Yifan-Hu representation (Source: Authors' own study)

In the subsequent years, a clear expansion and consolidation of the urban soil literature can be observed. Although the number of isolated clusters increases proportionally over time, they remain marginal in comparison to the size of the largest connected components. This indicates the presence of a well-established and commonly shared framework that reflects how the majority of authors in the analysed literature conceptualize urban soils. While keywords are not a perfect proxy for conceptual understanding, their aggregated use across large datasets is widely interpreted in bibliometric research as indicative of prevailing thematic and conceptual orientations (Demir, 2024).

3.2.2. DEGREES OF VERTICES

Tab. 2 presents the degrees of the eight nodes with the highest values in each temporal graph. Given that the analysed network is contextual in nature-meaning that not only the hierarchy of nodes but also their relative positions in the ranking are essential-it was decided to provide a broader context and a more comprehensive view of the situation, rather than focusing on a specific criterion for selecting hubs. Instead, for each graph, the eight most interconnected vertices were identified, i.e. the eight most frequently cited keywords within a given time period.

Tab. 2. The most frequent keywords (Source: Authors' own study)

1995–2000		2000–2004		2005–2009		2010–2014		2015–2019		2020–2024	
Keyword	Deg.	Keyword	Deg.	Keyword	Deg.	Keyword	Deg.	Keyword	Deg.	Keyword	Deg.
Soil	19	Urban Soil	61	Urban Soil	189	Urban Soil	209	Urban Soil	398	Urban Soil	414
Urban Soil	18	Soil	21	Heavy Metal	92	Heavy Metal	95	Heavy Metal	135	Heavy Metal	211
Biomarker	14	GIS	17	Soil	63	Soil	74	Soil	106	Technosol	111
Lipid	14	Geostatistics	16	Lead	24	Polycyclic Aromatic Hydro-carbon	37	Technosol	86	Soil	108
3-Nitrofluor-anthene	10	Environ-mental Chemistry	14	Soil Contami-nation	20	Lead	35	Polycyclic Aromatic Hydro-carbon	64	Anthropo-genic Soil	92
Aerosol	10	Germany	14	Sequential extraction	20	Land Use	28	Anthropo-genic Soil	50	Soil Pollution	77
Cultivated Soil	10	Mapping	14	Soil Organic Matter	19	Antrhropo-genic Soil	27	Soil Contami-nation	48	Soil Contami-nation	66
Gc/Ms/Ms	10	Research Article	14	Contami-nated Soil	18	Metal	27	Metal	47	Polycyclic Aromatic Hydrocarbon	63

The hub-keywords serve as focal points for scientific discussion. Their distribution reveals a consistent direction in which the research effort has evolved, namely an emphasis on the anthropogenic character of urban soils. These soils acquire their specific qualitative features, distinguishing them from natural soils, as a result of the accumulation of toxic industrial materials, particularly heavy metals (especially lead) and polycyclic aromatic hydrocarbons. This contamination leaves a distinct imprint on the biological characteristics of urban soils, marking them as heavily polluted environments, as confirmed by numerous studies (Alloway, 2013; Plak, 2018; Wieczorek et al., 2020; Yang & Zhang, 2015). This perspective invites us to view urban soils as a degraded form of natural soils, representing, in a sense, a subsequent stage in their anthropogenic and technogenic evolution.

3.2.3. P-LAYERS

Fig. 6 presents the results of successive p-layer extraction from the temporal graphs in the model. To indicate which layer is represented in each cell of the table, the corresponding *p*-layer is abbreviated in parentheses in the header (e.g. 3-L denotes the 3-layer).

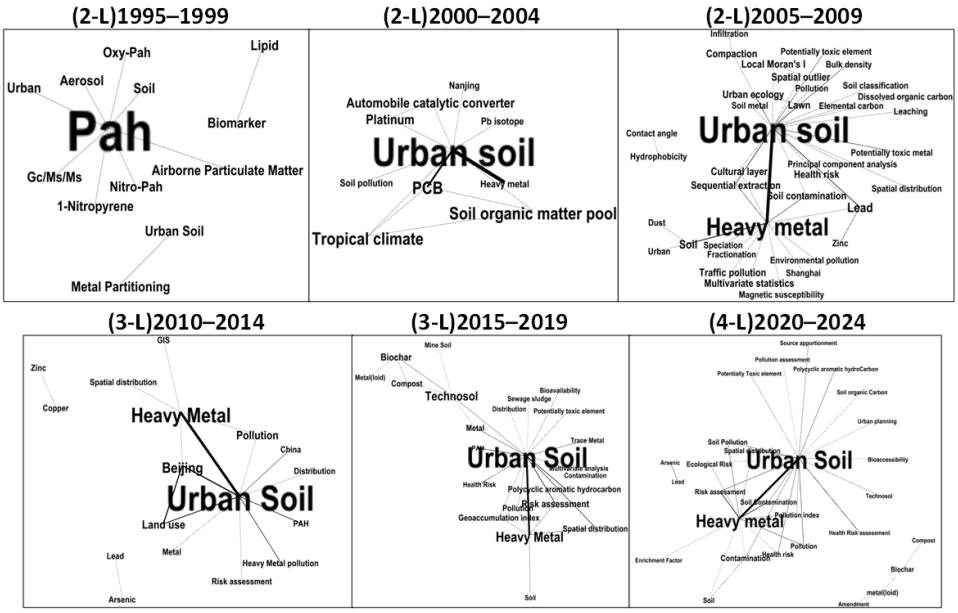

Fig. 6. Subsequent significant *p*-layers of moment graphs (Source: Authors' own study)

The analysis of keyword co-occurrence frequency using the *p*-layer extraction method from temporal graphs yields equally insightful conclusions. Its dynamics align closely with the results presented above. In the first three temporal graphs, the extraction of the 2-layer network – by removing one-time, and thus incidental, keyword co-occurrences – led to a radical simplification of the network structures. The extraction of 3- and 4-layer graphs became analytically meaningful only for graphs from the 2010–2024 period, clearly indicating that with the emergence of new hubs, traditional connections between keywords were also intensifying. This suggests not a revolutionary shift, but rather a continuous and systematic development along already established lines of inquiry.

For instance, within the 3-layer structures of the fourth and fifth temporal graphs, we observe core chains of keywords that were also identified during the comprehensive analysis stage. These include: Urban Soil, Soil, Heavy Metal, Biochar, and Technosol. The consistency between results obtained through two different analytical techniques highlights the prominent role of these terms in the scholarly discourse. It strongly supports the argument that they function as "semantic reference points" – concepts to which other research efforts must relate, either directly or by intentionally excluding them, as is often the case in isolated clusters.

The internal coherence of these findings also allows the development of urban soil research to be divided into two fifteen-year periods. The first may be termed the "formative phase", during which the research community gradually developed a shared awareness of the field and converged on a central focus: the analysis of urban soils in terms of their heavy metal content, which significantly influences their physicochemical properties. Between 2010 and 2014, this phase transitioned smoothly into a "developmental phase", characterized by an expansion of research directions. These new directions aimed to deepen the understanding of the origins and transformation of urban soils as both anthropogenic and technogenic phenomena. During this phase, attention also increasingly turned toward the well-being of urban organisms – humans, plants, and animals – whose health and functioning depend, in part, on the condition of surrounding soils.

What stands out most in the conclusions presented above is that the emerging portrait of the discipline – by necessity broad in scope – remains fully aligned with the current scientific understanding of soil formation, classification, and function. This analysis was conducted independently of the substantive content of the articles, based only on the keywords they declared. Although public awareness and scientific knowledge of urban soils continue to grow steadily, scholarly interest in this topic remains a relatively recent phenomenon. The historical research gap is primarily because, in the past, only a small proportion of the global population resided in cities, and urban areas occupied a relatively small portion of the Earth's surface

(Eisinger, 2006). Although high levels of contamination and limited space have often restricted the use of urban soils for agriculture, in many regions such soils have nonetheless been cultivated for food production, particularly in peri-urban and community gardens.

CONCLUSIONS

This study examined the formation and development of the research field on urban soils between 1995 and 2024. A bibliometric analysis of 961 scientific articles revealed a consistent growth of interest in this topic. *Science of the Total Environment* was identified as the most active journal in this area, with the highest number of citations. Among the most productive countries, China, the USA, Russia, and Germany dominate, with the strongest international collaborations established between China and the United States as well as between China and Germany.

The keyword co-occurrence analysis based on graph theory revealed significant transformations in the conceptual structure of the field. During the initial decade (1995–2004), the literature was fragmented and lacked a cohesive framework, reflected by numerous disconnected keyword clusters. Over time, consolidation processes emerged around key hubs – Soils and Urban Soils – connected through terms related to soil contamination. After 2004, research became more consistent and interconnected, forming a shared conceptual context focused on the anthropogenic origins and contamination of urban soils, primarily with heavy metals and industrial compounds.

The evolution of urban soil research can be divided into two main phases: 1995–2010: the formative phase, characterized by the emergence of research awareness and the definition of foundational concepts; 2011–2024: the developmental phase, marked by the expansion and deepening of studies on the genesis, transformations, and environmental implications of urban soils.

The consistency of results across temporal graph analyses confirms that research in this field is centred around a limited set of core concepts – Urban Soil, Heavy Metal, and Biochar – which serve as semantic reference points in the scientific discourse. Although still relatively young, this research domain is dynamically evolving in parallel with growing public awareness of the importance of urban environments.

Conflict of interest: The authors declare that no potential conflicts of interest were reported.

REFERENCES

Alloway, B.J. (2013). Sources of heavy metals and metalloids in soils. In B.J. Alloway (Ed.), *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (pp. 12–50). Springer. https://doi.org/10.1007/978-94-007-4470-7

Araújo, T., Abreu, A., & Louçã, F. (2023). The evolution of complexity co-occurring keywords: Bibliometric analysis and network approach. *arXiv preprint arXiv:2308.00992*. https://doi.org/10.48550/arXiv.2308.00992

Burghardt, W. (1994). Soils in urban and industrial environments. *Zeitschrift für Pflanzenernährung und Bodenkunde*, *157*(3), 205–214. https://doi.org/10.1002/jpln.19941570308

Burghardt, W. (2025). 25 years of SUITMAs: Urban soils-a new research field in soil science. What makes these soils and the interest in these soils so special? *Journal of Soils and Sediments*, *25*(2), 374–389. https://doi.org/10.1007/s11368-024-03826-6

Burghardt, W., Morel, J.L., & Zhang, G.L. (2015). Development of the soil research about urban, industrial, traffic, mining and military areas (SUITMA). *Soil Science and Plant Nutrition*, *61*(sup1), 3–21. https://doi.org/10.1080/00380768.2015.1046136

Craul, P.J. (1985). A description of urban soils and their desired characteristics. *Arboriculture & Urban Forestry*, *11*(11), 330–339.

Craul, P.J. (1992). *Urban Soil in Landscape Design*. Wiley

Demir, S. (2024). Bibliometric analysis of soil classification research in soil science from 1980 to 2023. *Selcuk Journal of Agriculture and Food Sciences*, *38*(3), 542–552. https://doi.org/10.15316/SJAFS.2024.048

Effland, W.R., & Pouyat, R.V. (1997). The genesis, classification, and mapping of soils in urban areas. *Urban Ecosystems*, *1*(4), 217–228. https://doi.org/10.1023/A:1018535813797

Eisinger, A. (2006). Urbanization. In P. Oswalt & T. Rieniets (Eds.), *Atlas of Shrinking Cities* (pp. 28–29). Hatje Cantz Verlag.

Hartemink, A.E. (2019). Open access publishing and soil science – trends and developments. *Geoderma Regional*, *18*, e00231. https://doi.org/10.1016/j.geodrs.2019.e00231

Jia, L., Wang, W., Zvomuya, F., & He, H. (2024). Trends in soil science over the past three decades (1992–2022) based on the scientometric analysis of 39 soil science journals. *Agriculture*, *14*(3), 445. https://doi.org/10.3390/agriculture14030445

Kopel, D., Brook, A., Wittenberg, L., & Malkinson, D. (2016). Spectroscopy application for soil differentiation in urban landscape. *Journal of Soils and Sediments*, *16*, 2557–2567.

Lehmann, A., & Stahr, K. (2007). Nature and significance of anthropogenic urban soils. *Journal of Soils and Sediments*, *7*(4), 247–260. https://doi.org/10.1065/jss2007.06.235

Liu, J., & Chu, C. (2008). Discussion of the extension and division of research stage of urban soil. *Journal of Pingdingshan University*, 23(5), 106–109.

O'Riordan, R., Davies, J., Stevens, C., & Quinton, J.N. (2021). The effects of sealing on urban soil carbon and nutrients. *Soil*, *7*(2), 661–675. https://doi.org/10.5194/soil-7-661-2021

Paltseva, A.A., Cheng, Z., McBride, M., Deeb, M., Egendorf, S.P., & Groffman, P.M. (2022). Legacy lead in urban garden soils: Communicating risk and limiting exposure. *Frontiers in Ecology and Evolution*, *10*, 873542. https://doi.org/10.3389/fevo.2022.873542

Pesta, B., Fuerst, J., & Kirkegaard, E.O. (2018). Bibliometric keyword analysis across seventeen years (2000–2016) of intelligence articles. *Journal of Intelligence*, *6*(4), 46. https://doi.org/10.3390/jintelligence6040046

Plak, A. (2018). *Funkcje miasta a zawartość i rozmieszczenie metali ciężkich, metaloidów i pierwiastków ziem rzadkich w glebach miejskich*. Wyd. UMCS.

Poumanyvong, P., & Kaneko, S. (2010). Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis. *Ecological Economics*, *70*(2), 434–444.

Seto, K.C., Güneralp, B., & Hutyra, L.R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083–16088.

United Nations. (2018). *Revision of world urbanization prospects*. Department of Economic and Social Affairs, Population Division.

Uzarowicz, Ł., Greinert, A., Kwasowski, W., Jankowski, M., & Charzyński, P. (2020). Studies of technogenic soils in Poland: Past, present, and future perspectives. *Soil Science Annual*, *71*(4), 281–299. https://doi.org/10.37501/soilsa/131615

Wang, M., & Chai, L. (2018). Three new bibliometric indicators/approaches derived from keyword analysis. *Scientometrics*, *116*(2), 721–750. https://doi.org/10.1007/s11192-018-2768-9

Wieczorek, K., Turska, A., Słowik-Borowiec, M., & Wolf, W.M. (2020). Comprehensive evaluation of metal pollution in urban soils of a post-industrial city – a case of Łódź, Poland. *Molecules*, *25*(18), 4350. https://doi.org/10.3390/molecules25184350

Wilson, R. (1998). *Wprowadzenie do teorii grafów*. PWN.

Yang, J.L., & Zhang, G.L. (2015). Formation, characteristics and eco-environmental implications of urban soils – a review. *Soil Science and Plant Nutrition*, *61*(supl), 30–46. https://doi.org/10.1080/00380768.2015.1035622

Zhang, G.L. (2005). Ecological services of urban soils in relation to urban ecosystem and environmental quality. *Science and Technology Review*, *25*(3), 16–19. (In Chinese with English summary).

Zhou, Y., Smith, S.J., Elvidge, C.D., Zhao, K., Thomson, A., & Imhoff, M. (2015). A global map of urban extent from nightlights. *Environmental Research Letters*, *10*(5), 054011. https://doi.org/10.1088/1748-9326/10/5/054011

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