Environmental Microbiome

REVIEW

Open Access

A systematic scoping review reveals that geographic and taxonomic patterns influence the scientific and societal interest in urban soil microbial diversity

Simon Masson[1†], Matteo Chialva[1†], Davide Bongiovanni[1], Martino Adamo[1], Irene Stefanini[1] and Luisa Lanfranco[1*]

Abstract
Urban green areas provide multiple ecosystem services in cities, mitigating environmental risks and providing a healthier environment for humans. Even if urban ecology has become popular in the last decade, the soil environment with its microbiota, which sustains many other biodiversity layers, remains overlooked. Here, a comprehensive database of scientific papers published in the last 30 years investigating different aspects of soil microbial diversity was built and systematically reviewed. The aim was to identify the taxa, experimental methods and geographical areas that have been investigated, and to highlight gaps in knowledge and research prospects. Our results show that current knowledge on urban soil microbiota remains incomplete, mainly due to the lack of publications on functional aspects, and is biased, in terms of investigated taxa, with most studies focused on Prokaryotes, and geographic representativeness, with the interest focused on a few large cities in the Northern hemisphere. By coupling bibliometrics with statistical modelling we found that soil microbial traits such as biomass and respiration and omics techniques attract the interest of the scientific community while multi-taxa and time-course studies appeal more to the general public.

Keywords Altmetric, Bibliometrics, GLMM, Scientific attention, Soil microbial diversity, Urbanisation

Introduction

According to recent estimates, nearly 70% of the world's population will live in urban environments by 2050 [1]. A current challenge is therefore to develop urban planning attentive to the needs of citizens and in line with sustainability principles. Urban green areas represent crucial components of modern cities as they can provide many ecosystem services, e.g. contributing to lower heat-island effect [2]. These services largely depend on the microbial life in soil which is one of the planet's greatest reservoirs of biological diversity [3]. Indeed, soil microbial communities contribute to crucial functions such as nutrient cycling, disease suppression and root symbioses, with an impact on plant growth and health [4–6]. Moreover, urban soil microbiota can directly influence human health by suppressing pathogens, stimulating the immune system or decreasing the exposure to pollutants in case of bioremediation [7, 8], revealing its central role in a One Health perspective [9].

Urban environments are often exposed to abiotic stresses (e.g. pollution) that can have a negative impact

[†]Simon Masson and Matteo Chialva contributed equally to this work.

*Correspondence:
Luisa Lanfranco
luisa.lanfranco@unito.it
[1]Department of Life Sciences and Systems Biology (DBIOS), University of Torino, Viale Mattioli, 25, Torino I-10125, Italy

on biological diversity [10]. However, recent surveys showed that urban soils are hotspots of microbial diversity [4, 11, 12], not only from a taxonomic but also from a functional point of view [4, 13], possibly due to intense human driven management practices. Delgado-Baquerizo et al. [13], in a global-scale survey of soil microbiome, found an enrichment of microorganisms involved in denitrification and methanogenesis, human/plant pathogens, and strains carrying antibiotic-resistance genes in urban sites compared to nearby undisturbed ecosystems.

Notwithstanding increasing attention on the importance of soils raised by public awareness campaigns and outreach and educational activities in schools [14], several studies highlighted that social awareness of crucial ecosystem services and potential risks provided by soil remains very low for both citizens [15] and professional workers as gardeners [16]. This is even more true when considering the non-visible biotic components of the soil such as the microbiota [17]. In addition, the limited engagement between soil scientists, stakeholders, and the population often results in the misalignment between research agendas and population needs. As a consequence most of the hidden soil diversity is not yet sufficiently addressed in nature conservation or urban-related policies [18–20]. This phenomenon is coupled to a poor microbiological literacy that is often found in our societies and highlights that microbiota-related topics should be added to school curricula as early as primary school [21, 22].

In this framework, there is a clear need for an improved knowledge of urban soils which also considers their microbial diversity and a more effective way to communicate scientific results to the specialised public as well as citizens and policymakers. However, how the scientific community develops research on urban soil microbiota and communicates research outputs has not been addressed so far. A quick survey through the scientific literature revealed several knowledge gaps: some geographical areas seem to be poorly studied and very few studies applied metagenomics or metatranscriptomics that are the most informative tools to describe the functional biodiversity [23, 24]. Rega-Brodsky et al. [24] advocate that future research in urban environments encompasses a greater diversity of taxonomic groups, including less studied taxa such as microbes that are closely associated with ecosystem functions. To provide an overview of how microbial communities have been studied in urban environments we systematically reviewed the scientific literature on urban soil microbial biodiversity over the last 30 years. In particular, we assessed which taxa, experimental methods, and geographical areas have been investigated and whether there were any biases and we highlighted how these aspects influence scientific and societal attention.

Results & discussion

To identify the parameters investigated in urban soil microbiota studies (i.e. taxa, experimental methods, geographical areas), and to show how these parameters could drive the attention of scientists and the general public, we performed a bibliometric analysis.

Through an automated extensive search on the Web of Sciences database using specific keywords (see methods), we retrieved research publications focusing on urban soil microbiota published from 1987 to 2023, obtaining an initial database of 354 entries. The list was further manually refined by excluding studies out of the scope and a total of 237 studies were kept for further analyses. Our choice was validated by double-checking study eligibility for 50 studies, with a resulting Cohen's k value [25] of 0.83.

Globally, our search revealed that in the last 30 years, a rather limited amount of scientific works aimed to investigate urban soils considering microbiological issues compared to other related research fields such as the study of the plant microbiota (e.g. 343 studies on urban microbiota published over 37 years vs. 382 studies related to rhizosphere microbiota published in a single year, 2018 [26]). Despite early works (around the 2000s) already investigating some aspects of microbial soil diversity in urban environments (Fig. 1), we noticed that the increasing multi-disciplinary interest in urban ecology occurring over the last ten years has also brought to the fore urban microbial ecology (Figure S1).

For each of the selected papers, variables identifying scientific features, including groups of studied taxa and adopted experimental techniques, were manually retrieved (see Material and Methods for further details) and were then related to citation metrics and geographical distributions. This analysis revealed that several different approaches and different areas across the world have been the focus of urban soil microbiologists.

Interest in microbial life forms in urban soils

Soil is likely home to about 59% of the species on Earth and its biotic diversity is still considered largely unexplored [3, 27]. Several pieces of evidence suggest that urban soils host an increased microbial diversity compared to undisturbed ecosystems [4, 13, 28]. This, coupled with the few detailed studies on urban soil microbiota available in the literature, highlights that our current knowledge on urban soil biodiversity remains still overlooked. In the analysed publications we found that the interest within the scientific community (measured as the number of citations) towards microorganisms in urban soils is increasing with time (Fig. 1A), with different trends across the different taxonomic groups investigated.

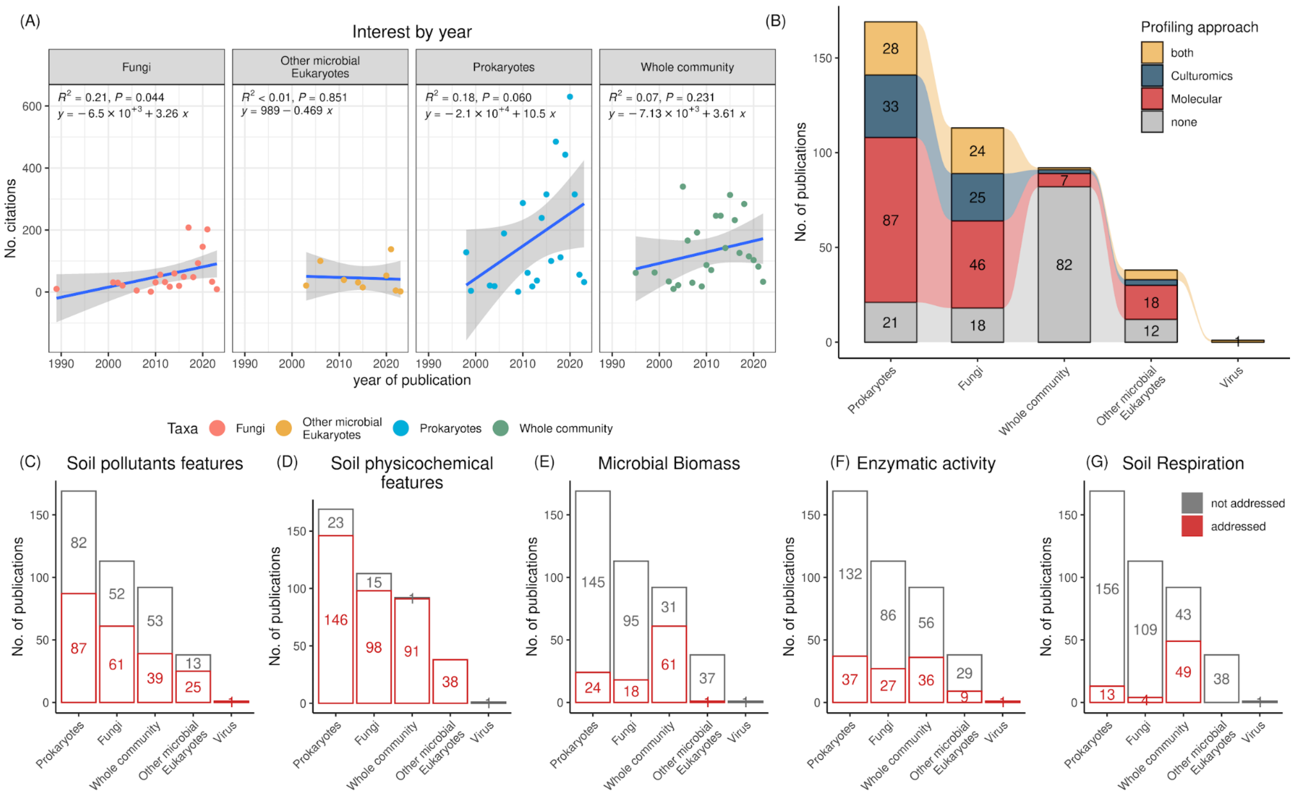

Fig. 1 Microbial domains of life investigated and experimental approaches adopted to unravel urban soil microbiota in the scientific literature over the last 30 years. (**A**) Trend of the scientific interest of the different microbial kingdoms over time using the cumulative numbers of citations of each study included in the dataset as a proxy; blue lines indicate the linear regression fitting the data; determination coefficient (R^2), P-value and model equation are also showed. (**B**) Alluvial plot showing the number of studies for each taxa group and profiling approach adopted to investigate the urban soil microbial diversity. The "molecular" category includes all the profiling approaches based on biological macromolecules (nucleic acids, proteins, fatty acids) while "culturomics" includes all those where the isolation of microorganisms on growth media was performed. (**C**-**G**) Number of articles that considered (addressed) or not (not addressed) soil pollutants (**C**), soil physicochemical characteristics (**D**), microbial biomass (**E**), enzymatic activity (**F**), or soil respiration (**G**) parameters across the different microbial taxa investigated. We categorised as "whole community" all the studies which comprehensively profiled all the domains of microbial life or used respiration- or enzyme-based methods as a proxy for microbiota functionality. See also Table S1 for details on the variables collected

Notably, interest in prokaryotes shows a strong positive trend with time, increasing from the 1990s to the present. This could be related to the observation that prokaryotes are generally more susceptible to environmental changes as pointed out by Grierson and colleagues who explored the diversity of three soil microbial kingdoms across urban green spaces in Tasmania [29]. The authors show that bacterial communities were more susceptible to changes in urban environments than fungal communities, suggesting that bacteria might be a more accurate bioindicator of urban soil quality [29].

Similarly, the interest in fungi is also increasing, although not as much as for prokaryotes. However, fungal communities have an important role sustaining plant growth and stress tolerance as in the case of mycorrhizal fungi [30–32], as bioremediation agents [33] or as human and plant pathogens [34, 35].

Despite the overall number of scientific articles published each year increasing exponentially, for other Microbial Eukaryotes the trend is unchanged [36]. This may be due to a general limited knowledge of the diversity and functions of eukaryotic microbes, with the exception of a few groups. For example, diatoms are used worldwide for water quality monitoring but their application as markers in other environments, such as sea, sediment, and soil quality, is rather recent [37].

Notwithstanding the relevance of Viruses for plant, animal, and human health [38, 39], their impacts on biogeochemical cycles [40], and their use as bioindicators in environmental samples, they are largely underlooked, (only 1 publication, Fig. 1B) and their occurrence in urban soils still remains largely unexplored. This is probably explained by the polyphyletic origin of the viruses, which has made it difficult to attempt to characterize entire viral communities on the basis of a single gene marker using meta-barcoding [41].

We also investigated which are the most frequently used experimental techniques to investigate microbial communities in urban soils. Molecular approaches, including all those techniques analysing biological molecules (nucleic acids, proteins, and fatty acids), are the most widely used, with 51.48% of studies on prokaryotes (87 out of 169) being carried out with these approaches, 40.7% for fungi (46 out of 113), and 47.37% for other microbial eukaryotes (18 out of 38) (Fig. 1B). This trend is fully in line with the increase in popularity of next-generation DNA sequencing techniques [42]. Culturomics approaches lag behind, although a number of papers applied both molecular and culturomics methods. Conversely, considering the studies investigating comprehensively the soil microbiota (all the taxa supergroups, indicated as "whole community") we noticed that the use of indirect quantitative techniques, such those measuring microbial biomass, still overtakes the use of molecular tools (>85% of the studies investigating the whole community). In particular, the microbial biomass is the most studied, followed by soil respiration and enzymatic activity (Fig. 1E-G). This evidence indicates that a large proportion of studies are based on soil biomass-related indicators rather than biota community profiling techniques highlighting that the common interest is still overlooking the relevance of microbial population composition.

Conversely, it has been recently demonstrated that human-driven perturbations, such as land-use changes, reduce not only microbial diversity but also functional potential of soils at a continental scale [43] opening the question of how microbiota functioning is altered in urban environments. Although functional aspects seem crucial in modulating the ecosystem services provided by the soil microbiota, only three publications [13, 44, 45] applied metagenomics and metatranscriptomics, potentially the most appropriate approaches to shed light on these issues. Indeed, Delgado-Baquerizo and colleagues, in their global metagenomic study, revealed that urban ecosystems harbour higher proportions of genes associated with human pathogens, greenhouse gas emissions and nutrient cycling [13]. Metatranscriptome was applied by Scharko et al. [44] to link nitrous acid emissions to ammonia oxidizing bacteria and archaea. Gill et al. [45] surveyed the abundance of seven specific genes that play a role in biogeochemical cycles or the degradation of pollutants (i.e. hydrocarbons, bisphenol and herbicides). The scarcity of this type of studies likely reflects the cost of analysis and the complexity of computational efforts required.

We also found that a vast majority of studies in our dataset consider physico-chemical features (total carbon, total nitrogen, organic/inorganic carbon, percentage of clay, silt or sand, etc.) regardless of the type of taxa investigated (Fig. 1D). It is well known that these soil characteristics contribute to shaping microbial biodiversity and, as a consequence, biogeochemical cycles, fertility, and soil "health" [46]. Soil pollutants were also often considered, regardless of the taxa being investigated (Fig. 1C). Urban soils are often contaminated with heavy metals, hydrocarbons, pesticides, or solvents [47, 48]. Pollutants affect the soil microbial community and interfere not only with the health and functionality of microbial communities and plants but also with animal and human health [49, 50]. In light of this, the large number of studies exploring both microbiota and pollutants in soil may reflect the recognition of microorganisms as relevant soil quality indicators. In our database, 29% of the studies also considered plant communities (data not shown), but vegetation parameters often simply accompany the characterization of the sampling site. Few studies considered the effect of selected plant species on urban soil microbiota in the context of afforestation [51] or food production [52]. Only a few works analysed the effect of management practices and socio-economic factors (see as examples Xie et al. [53] or Fang et al. [54]), which makes the data too fragmentary and uninformative. This may be explained by the difficulty to retrieve exhaustive information on management practices in urban environments [55].

Taken as a whole, our analysis shows that multiple soil microbiota-related characteristics are often monitored: general features such as microbial biomass and respiration or community diversity using molecular methods, which are low-cost and easily accessible techniques, are commonly measured while functional aspects remain unexplored. This leads to a fragmented view of urban soil biology, being limited to soil features and to a still partial microbial census, with a limited insight on functioning.

Influence of studies variables on scientific interest and popularity

It is known that scientific research across many disciplines, including ecology, suffers from cognitive biases introduced by the researchers [56]. We therefore investigated which are the factors that drive scientific and public interest in the urban soil microbial ecology field. By applying a bibliometric approach coupled with statistical modelling we searched for effects of the different aspects previously reviewed (general scientific variables, non scientific variables, techniques used and investigated taxa; Fig. 2) in predicting citations number (CrossRef database) and the Altmetric Attention Score considered as a proxy for scientific and societal interest, respectively. The Altmetric Attention Score is specifically an indicator of potential downstream impact of research. We included in the model one well-acknowledged non-scientific factor affecting citational metrics, i.e. open-access variable. Publishing in 'gold' open-access journals does not have an impact on societal attention while it significantly

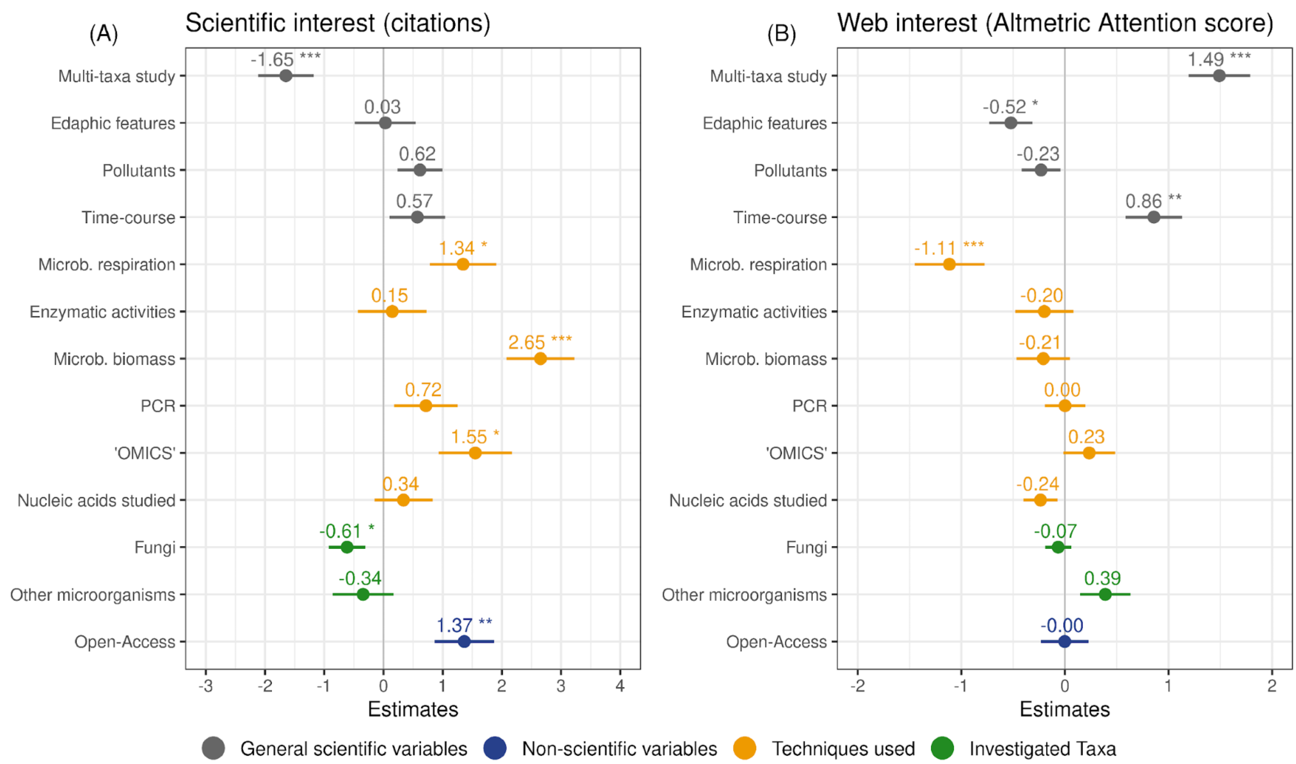

Fig. 2 Influence of urban soil studies variables on scientific interest (CrossRef citations, panel **A**) and web popularity (Altmetric Attention Score, panel **B**). Forest plots summarise the variable effects based on Gaussian linear mixed models (GLMMs). Positive residuals indicate higher effect of the variable compared with its baseline level (see Table S1). Colours indicate different categories of the independent variables. Error bars show 95% confidence intervals while asterisks (*) the significance of the effects ($\alpha = 0.05$). Estimated regression parameters are provided in Table S2; see also Figure S3 and Figure S4 for model validation parameters

increases scientific interest, as already demonstrated [57]. It should be noted that these two metrics (citations and Altmetric Attention Score) show a very weak correlation (Figure S2), confirming what has been previously demonstrated [58].

Our results show that the two different modelled metrics are affected by different factors. Scientific attention seems to be mainly driven by the use of omics tools and classical microbial features such as biomass and respiration, while studies reporting microbial respiration or focusing on edaphic features negatively influenced the attention on the web (Fig. 2). Unexpectedly, multi taxa-focused studies (i.e. those which considered other layers of biodiversity, including animals and plants, besides microorganisms) do not meet the interest of the scientific community while increasing the attention score on the web. Popularity on the web can be explained by the fact that these publications often consider animals such as earthworms [59, 60], which are normally better known to any citizen. In addition, studies also focusing on plants may be more attractive due to their potential applications in afforestation [51, 61] or food production [52] programs.

In general, the specific microbial taxa investigated do not influence public attention. This evidence could be explained by the fact that a non-scientific public often has a general interest in biodiversity but is less interested in the details of the taxonomic group investigated and in the experimental techniques adopted. The lack of interest in experimental techniques is expected since it requires specialised knowledge, as pointed out by a systematic analysis of the literature in the field of omics techniques [62].

Considering the scientific community, studies investigating fungi were significantly less-cited compared to the Prokaryotes baseline and those including all the other microbial groups (Other microorganisms, Fig. 2) followed the same trend. The lesser scientific interest in fungi, and even with a weak effect on all the other microorganisms, compared to prokaryotes could be explained by the fact that these taxa may constitute a fairly specific field of study, for example yeasts [63], mycorrhizal fungi [30] or algae [64], limiting the interest to specific niches of the scientific community. In the case of fungi, we anticipate a change of route, given that recent large international initiatives, such as SPUN (https://www.spun.earth/), are having success in involving the public and giving impulse to scientific research. Moreover, the study of some groups of microbial eukaryotes (i.e. Excavata, Amoebozoa, Cercozoa, Ciliophora, Apicomplexa) is fairly

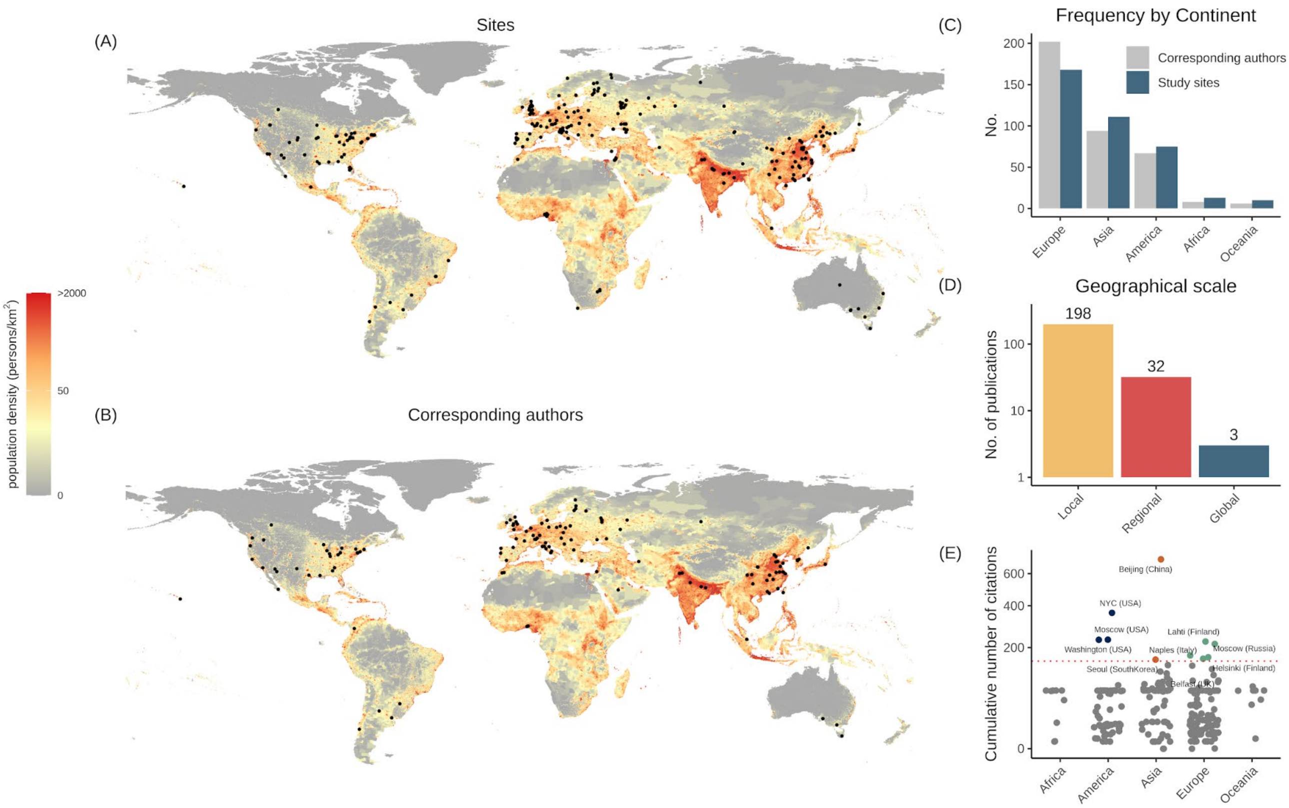

Fig. 3 Geographic distribution of the studies and their main features. (**A**) Overall distribution of sites where soil samples were taken in the various studies. (**B**) Worldwide distribution of the corresponding authors of the articles included in the study. Both maps show the log-scaled population density (Gridded Population of the World, GPWv4). (**C**) Frequency of corresponding authors and study sites by continent. (**D**) Frequency of articles by geographical scale (local means that the sampling took place in the same town and its surroundings; regional means that the sampling took place in the same country or on the same continent; global means that the sampling took place on at least two continents). (**E**) Cumulative number of citations by continent (each point corresponds to a city)

recent [64] and more time is needed to include these domains of life in routine analyses.

Is the microbial diversity of urban soils being studied comprehensively worldwide?

We further reconstructed the spatial distribution of the study sites investigated and that of the corresponding author institutions from the collected papers (see methods). At first glance, we highlighted a fairly clear overlap between the studied cities and corresponding authors' countries with the global population density (Fig. 3A, B). The most studied continents were Europe, Asia, and America (Fig. 3C). Notably, many low-income and densely populated countries are underrepresented in our dataset, including Central America, Africa, and South Asia (India, Indonesia, the Philippines), recalling citational biases already known for researchers working in the Southern hemisphere [65]. In these countries, scientific research in different disciplines is limited, possibly due to a scarcity of funding [66]. Also, the political instability of some of these countries can lead to a less efficient allocation of resources and a reduction in research and development efforts by companies and governments [67]. In addition, a systematic study of urban ecology in Africa [68] revealed that, beside the economic reasons, there may also be a lack of local experts in this field, a situation further aggravated by the brain drain phenomenon [69, 70]. Moreover, here we systematically reviewed only articles written in English; the inclusion of articles in other languages or from minor journals (referred to as "peripheral publishing" [71]) would have better represented these regions.

The scarcity of collaboration between Northern and Southern Hemisphere countries [72] should also be taken into account in explaining these results. It is indicative that the most comprehensive study among the few conducted on a global scale [13] looked at only a few cities in the Southern Hemisphere. In any case, these areas deserve further investigation since the knowledge obtained from researches in the North Globe will not be sufficient to implement effective urban developmental policies in these countries [73]. The extremely fast growth of some of these urban areas offers the opportunity to study the ongoing effect of urbanisation; moreover, these cases would represent a possible model for what happened in North America and Europe between the mid-19th and mid-20th century in terms of environmental and social impact. For the future, it is hoped that there may be more interactions and more fruitful collaborations between research groups of the two hemispheres [74]. Diversifying the academic publication space by authorising non-English versions of articles or encouraging the use of citations from studies carried out in Southern countries could be another way of ensuring that these countries are not left on the periphery [75].

The spatial distribution of the corresponding author's institution indicates that scientists mostly investigate cities in which they work [76] (bias in favour of the 'home' university city) probably because of easy sampling and/or since several funding agencies mostly promote research in local territories. Considering the geographical scale of the investigation, we observed that the majority of studies (85%) explored the urban soil microbiota at the local scale (same city). These data may be not representative of the different urban areas of the same country limiting the implementation of soil biodiversity protection legislation or urban greening planning at a national scale. The large scale study of microbial community composition across Europe by Labouyrie et al. [43], although referring to natural forests and agricultural systems, is undoubtedly an example to follow. Within our dataset, only three studies were conducted on a global scale [13, 77, 78] (sites across different continents). It is likely that increasing the geographical scale makes search for funding, collaboration and sampling more difficult, limiting this type of approach, even if their contribution to knowledge is often more important [79] (Fig. 3D).

The interest of the scientific community is directed towards studies analysing the soil microbiota of a few and larger cities (Fig. 3E): among them, Beijing and Seoul emerged for Asia, New York, Washington, and Moscow (Idaho) in America, Naples, Belfast and two Finnish cities (Helsinki and Lahti) for Europe. This might be due to the fact that those cities have been investigated across different studies, as in the case of Beijing ($n = 18$), New York ($n = 12$). It is worth noting that only a few cases of single studies gathered a high scientific recognition (number of citations). For example, the work by Scharenbroch et al., investigating the city of Moscow [80] (Idaho, USA), was cited 222 times, probably because it describes different physical, chemical, and biological properties of urban soils that may be of interest to a wider audience. Similarly, a work carried out in Belfast [81] has gathered 136 citations, possibly because it investigates the hot topic of the occurrence of antibiotic resistance genes.

Overall we noticed that a small number of very large cities worldwide have attracted considerable attention from researchers, resulting in a city size-related bias that has been already described with large cities being much better represented in the literature than smaller ones [76] also when considering urban ecosystem services [82]. Focusing only on large cities can distort our understanding of urban microbial diversity, as many stressors reach extreme and harsh values in these areas (e.g. pollution, human and animal densities, soil sealing, temperature, etc.). This may skew the research only towards organisms with multi resistant traits. In addition it is worth noting that almost 50% of the world's urban population lives in cities of less than 500,000 inhabitants [83]. This observation underlines the importance of the spatial scale when conducting urban ecology studies, and emphasises the need to investigate both large and small cities [84] to explore how eco-evolutionary processes scale to shape urban biodiversity [85, 86].

Conclusions

Concluding remarks

In this work we reviewed the scientific literature on urban soil microbial diversity encompassing the last 30 years of research which was dominated by a growing interest in urban ecology paralleled by the increasing availability of powerful molecular tools that allow an efficient description of the diversity of microscopic organisms. Our results highlighted that current knowledge and attention on urban soil microbiota remains incomplete, mainly due to the lack of studies on functional aspects, and is biased, in terms of investigated taxa and geographic representativeness. Prokaryotes are the most studied organisms while other taxa, such as microbial eukaryotes and viruses, seem to be neglected. Even considering fungi, which play an acknowledged ecological role, the collected bibliometric data clearly show that they still do not warrant enough attention by scientists also in urban environments, as already underlined in other contexts [19, 20]. We also envisage that viromes of urban environments will also be the focus of future investigations, due to their implications on human health and ecosystems [39].

By coupling bibliometrics with statistical modelling we defined factors driving the interest of scientists and general public: the scientific community gave more attention to general microbial traits such as biomass and respiration and omics techniques while multi-taxa and time-course studies attracted the interest of the general public.

Our analysis also revealed the occurrence of a geographic pattern in the study of urban soil microbial diversity. The interest of researchers focused on a few large cities in the Northern hemisphere. We highlight the need to extend investigations to poorly explored geographical locations, such as Central America and Africa. They could provide an unprecedented opportunity for delving into the impact of human activities on soil microbiota in the context of different models of urban development.

Our data suggest the urgent need to promote an integrated view of the urban soil environment, which simultaneously considers different soil traits, from microbial diversity and functioning to chemical-physical features, and, possibly, other layers of biological diversity [87] (e.g. including macroorganisms).

Limitations of the study

Our approach intentionally excluded the elaboration and interpretation of the data included in the retrieved publications, as a meta-analysis was out of the scope of this work and would have required a different methodological approach. Rather, we focused on the general breadth of the most relevant studies and systematically captured which factors, considered by authors when planning research and analysing results, influence the scientific impact and the society's interest. We are aware that the metrics considered in this study may provide a distorted view, especially for the public interest that has been measured only using a web-based score (Altmetric Attention Score), that is however a quantitative score easy to retrieve at a global scale.

Methods

Data mining and variable selection

This study is based on studies retrieved through the Web of Science (WoS) advanced search including all the available databases (last access 03/21/2023) following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) and using the following query:

QUERY = (((((TS=("urban soil*" AND microb*)) OR TI=("urban soil*" AND microb*)) OR AB=("urban soil*" AND microb*)) OR AK=("urban soil*" AND microb*)) NOT (DT==("REVIEW") OR DT==("PROCEEDINGS PAPER" OR "BOOK CHAPTER" OR "EDITORIAL MATERIAL"))) AND ((LA==("ENGLISH")) NOT (SILOID==("PPRN") OR DT==("OTHER" OR "MEETING" OR "DATA SET" OR "ABSTRACT" OR "PATENT" OR "UNSPECIFIED" OR "LETTER"))).

The query already excluded studies not focused on soil microbial diversity in urban environments, review papers, documents not written in English and data papers. The obtained list of papers was further manually refined by excluding studies not fitting the topic or not available/retrievable. We measured the degree of agreement between authors by means of the Cohen's K approach [25], using the online cohen's K free calculator resource (https://idostatistics.com/cohen-kappa-free-calculator/#calculator).

Data belonging to the categories described in Table S1 were manually extracted from each study. The data-entry operations were performed on a spreadsheet, while the subsequent data-analysis operations were done in the R v4.3.3 [88] The only exception concerns the data-entry of the dependent variables: we extracted the number of citations using the 'rcrossref' package (last update: 04/12/2023), and the Altmetric Attention Score was obtained directly from Altmetric using the Altmetric Explorer tool (https://www.altmetric.com/explorer/) with a custom API key. Two of the most important non-scientific factors potentially affecting the impact of a study on science and society were included in the analysis: the open access (OA) status and the name of the journal where the study was published [89].

The coordinates of the cities of the study sites and the corresponding authors were extracted with an automatic R script on openstreetmap (https://www.openstreetmap.org) by using the manually-collected locations names (see Table S1) and the ISO 3166 country code (to avoid homonyms and clarify the search) with the help of RJSONIO package v1.3-1.9 [90]. If the city was not specified in the article, the country coordinates were entered manually instead.

Visualisation

All the graphical elaborations were performed in R v4.3.3 [88] using 'ggplot2' v3.5.0 [91] and 'ggalluvial' v0.12.5 [92] libraries. Global distributions of the study sites and corresponding author institutions were visualised using ggplot2 package with extended functionality from the 'tidyterra' v0.5.1 [93] package and using the $\log(1+x)$-scaled Gridded Population of the World (GPWv4) global population density raster obtained from the 'geodata' v0.5-9 [94].

Modelling and statistical analysis

We used regression analyses [95] to assess relationships between scientific (number of citations in CrossRef database) and societal (Altmetric Attention Score) interest in urban soil microbial diversity. Collinearity between the independent variables (Figure S2) and regressions reported in Fig. 1A were obtained using a linear model and by calculating the R-squared, P-value and the Pearson's correlation coefficient using the 'ggpmisc' v0.5.5 library in R [96].

We used the package 'glmmTMB' v1.1.1 for modelling [97] and 'tidyverse' version 2.0.0 [98] for data wrangling and visualisations.

We followed the approach described by Zuur et al. for data exploration, model fitting, and validations [95]. We visually inspected data distribution, checked the presence of outliers, and verified multicollinearity by using the VIF (Variance Inflation Factor) for independent factorial variables and pairwise Pearson's correlations for the two dependent variables. We balanced factor levels, as much as possible [99] as described in Table S1. We created two separate models, one for citation number and a second for Altmetric Attention Score. In both models we included the same variables (see below formula).

We normalised the y variables (citations and Altmetric Attention Score) by the study publication year, hypothesising that older studies should be more cited than recent studies. To this aim, we first fitted a GAM (Generalised Additive Model) to predict the over- or the under-citation of each study and we used the residuals as a dependent variable [89] in the subsequent GLMM models according to the following formula (see Table S1 for variables IDs:

$$y \sim MolTech + Targets + MolStudied + MBiomass + PhChCharact + Pollutants + TempSampling + OA. + (1|SO)$$

We introduced random factors to remove the journal prestige (1|SO), in view of the fact that its influence should smooth out most of the trends produced by the scientific approach itself. Model results were visualised in 'sjPlot' v2.8.15 [100]. To validate models we used the 'performance' package v 0.10.8 [101]. Results of model validation are reported in Figure S3 and Figure S4.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40793-025-00677-7.

Supplementary Material 1

Supplementary Material 2

Acknowledgements
The Authors thank Stefano Mammola and Paola Bonfante for useful comments and discussions.

Author contributions
SM contributed to the methodology, investigation, data curation, writing of the original draft and writing - review and editing. MC contributed to the conceptualization, methodology, investigation, data curation, formal analysis, visualisation, writing of the original draft, and writing - review and editing. DB contributed to the investigation, data curation, and writing of the original draft. MA contributed to the conceptualization, methodology, investigation, data curation, formal analysis, visualisation, writing of the original draft, and writing - review and editing. IS was responsible for writing - review and editing, and funding acquisition. LL contributed to conceptualization, writing the original draft, writing - review and editing, and funding acquisition. All authors read and approved the final manuscript.

Funding
The work was supported by the project CN_00000033 funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n. 3175 of 18 December 2021 of the Italian Ministry of University and Research funded by the European Union– NextGenerationEU. Funders had no role in the design of the study and collection, analysis, and interpretation of data and in writing the manuscript.

Data availability
Data and code generated in this study are publicly available in FigShare, (https://doi.org/10.6084/m9.figshare.25360240).

Declarations

Competing interests
The authors declare no competing interests.

Received: 10 July 2024 / Accepted: 23 January 2025
Published online: 04 February 2025

References

1. United Nations, Department of Economic and Social Affairs. World Urbanization Prospects 2018: Highlights [Internet]. United Nations; 2019 [cited 2024 Mar 11]. Available from: https://www.un-ilibrary.org/content/books/9789210043137
2. Vasenev V, Varentsov M, Konstantinov P, Romzaykina O, Kanareykina I, Dvornikov Y, et al. Projecting urban heat island effect on the spatial-temporal variation of microbial respiration in urban soils of Moscow megalopolis. Sci Total Environ. 2021;786:147457.
3. Anthony MA, Bender SF, van der Heijden MGA. Enumerating soil biodiversity. Proc Natl Acad Sci USA. 2023;120:e2304663120.
4. Fan K, Chu H, Eldridge DJ, Gaitan JJ, Liu Y-R, Sokoya B, et al. Soil biodiversity supports the delivery of multiple ecosystem functions in urban greenspaces. Nat Ecol Evol. 2023;7:113–26.
5. Barrios E. Soil biota, ecosystem services and land productivity. Ecol Econ. 2007;64:269–85.
6. Bardgett RD, van der Putten WH. Belowground biodiversity and ecosystem functioning. Nature. 2014;515:505–11.
7. Sun X, Liddicoat C, Tiunov A, Wang B, Zhang Y, Lu C, et al. Harnessing soil biodiversity to promote human health in cities. Npj Urban Sustain. 2023;3:1–8.
8. Grönroos M, Parajuli A, Laitinen OH, Roslund MI, Vari HK, Hyöty H, et al. Short-term direct contact with soil and plant materials leads to an immediate increase in diversity of skin microbiota. MicrobiologyOpen. 2019;8:e00645.
9. Banerjee S, van der Heijden MGA. Soil microbiomes and one health. Nat Rev Microbiol. 2023;21:6–20.
10. Rillig MC, van der Heijden MGA, Berdugo M, Liu Y-R, Riedo J, Sanz-Lazaro C, et al. Increasing the number of stressors reduces soil ecosystem services worldwide. Nat Clim Chang. 2023;13:478–83.
11. Wang H, Cheng M, Dsouza M, Weisenhorn P, Zheng T, Gilbert JA. Soil bacterial diversity is Associated with Human Population Density in Urban Greenspaces. Environ Sci Technol. 2018;52:5115–24.
12. Whitehead J, Roy J, Hempel S, Rillig MC. Soil microbial communities shift along an urban gradient in Berlin, Germany. Front Microbiol. 2022;13.
13. Delgado-Baquerizo M, Eldridge DJ, Liu Y-R, Sokoya B, Wang J-T, Hu H-W, et al. Global homogenization of the structure and function in the soil microbiome of urban greenspaces. Sci Adv. 2021;7:eabg5809.
14. Fatton M, Schneiter A, Allisiardi M, Hänni L, Hauser G, Gonçalves-Fernandes Y et al. Microbes go to School: using Microbiology and Service-Learning to increase Science Awareness and fostering the relationship between universities and the General Public. Front Educ. 2021;6.
15. Schwarz K, Wohldmann EL, Chen Y, Pouyat RV, Gonzalez A, Mao S et al. Community knowledge and concerns about urban Soil Science, Practice, and process: perspectives from the Healthy Soils for Healthy Communities Initiative in Los Angeles, CA, United States. Front Ecol Evol. 2022;9.
16. Kim BF, Poulsen MN, Margulies JD, Dix KL, Palmer AM, Nachman KE. Urban Community gardeners' knowledge and perceptions of Soil Contaminant risks. PLoS ONE. 2014;9:e87913.
17. Vanermen I, Kessels R, Verheyen K, Muys B, Vranken L. The effect of information transfer related to soil biodiversity on flemish citizens' preferences for forest management. Sci Total Environ. 2021;776:145791.
18. Newbound M, Mccarthy MA, Lebel T. Fungi and the urban environment: a review. Landsc Urban Plan. 2010;96:138–45.
19. Gonçalves SC, Haelewaters D, Furci G, Mueller GM. Include all fungi in biodiversity goals. Science. 2021;373:403–403.
20. Guerra CA, Bardgett RD, Caon L, Crowther TW, Delgado-Baquerizo M, Montanarella L, et al. Tracking, targeting, and conserving soil biodiversity. Science. 2021;371:239–41.
21. Timmis K, Cavicchioli R, Garcia JL, Nogales B, Chavarría M, Stein L, et al. The urgent need for microbiology literacy in society. Environ Microbiol. 2019;21:1513–28.
22. Timmis K, Timmis J, Jebok F. The urgent need for microbiology literacy in society: children as educators. Microb Biotechnol. 2020;13:1300–3.

23. Kumar A, Yadav A. Next generation sequencing in Metagenomics and Metatranscriptomics. In: Mani I, Singh V, editors. Multi-omics Analysis of the human microbiome: from technology to clinical applications. Singapore: Springer Nature; 2024. pp. 49–75.
24. Rega-Brodsky CC, Aronson MFJ, Piana MR, Carpenter E-S, Hahs AK, Herrera-Montes A, et al. Urban biodiversity: state of the science and future directions. Urban Ecosyst. 2022;25:1083–96.
25. Landis JR, Koch GG. The measurement of Observer Agreement for Categorical Data. Biometrics. 1977;33:159–74.
26. Brunel C, Pouteau R, Dawson W, Pester M, Ramirez KS, van Kleunen M. Towards unraveling macroecological patterns in Rhizosphere Microbiomes. Trends Plant Sci. 2020;25:1017–29.
27. Guerra CA, Heintz-Buschart A, Sikorski J, Chatzinotas A, Guerrero-Ramírez N, Cesarz S, et al. Blind spots in global soil biodiversity and ecosystem function research. Nat Commun. 2020;11:3870.
28. Scholier T, Lavrinienko A, Brila I, Tukalenko E, Hindström R, Vasylenko A, et al. Urban forest soils harbour distinct and more diverse communities of bacteria and fungi compared to less disturbed forest soils. Mol Ecol. 2023;32:504–17.
29. Grierson J, Flies EJ, Bissett A, Ammitzboll H, Jones P. Which soil microbiome? Bacteria, fungi, and protozoa communities show different relationships with urban green space type and use-intensity. Sci Total Environ. 2023;863:160468.
30. Buil PA, Renison D, Becerra AG. Soil infectivity and arbuscular mycorrhizal fungi communities in four urban green sites in central Argentina. Urban Urban Green. 2021;64:127285.
31. Balacco JR, Vaidya BP, Hagmann DF, Goodey NM, Krumins JA. Mycorrhizal Infection Can Ameliorate Abiotic Factors in urban soils. Microb Ecol. 2023;85:100–7.
32. Zwiazek JJ, Equiza MA, Karst J, Senorans J, Wartenbe M, Calvo-Polanco M. Role of urban ectomycorrhizal fungi in improving the tolerance of lodgepole pine (Pinus contorta) seedlings to salt stress. Mycorrhiza. 2019;29:303–12.
33. Radić DS, Pavlović VP, Lazović MM, Jovičić-Petrović JP, Karličić VM, Lalević BT, et al. Copper-tolerant yeasts: Raman spectroscopy in determination of bioaccumulation mechanism. Environ Sci Pollut Res. 2017;24:21885–93.
34. Ali-Shtayeh MS. Keratinophilic fungi of school playgrounds in the Nablus area, West Bank of Jordan. Mycopathologia. 1989;106:103–8.
35. Marfenina OE, Danilogorskaya AA. Effect of elevated temperatures on composition and diversity of microfungal communities in natural and urban boreal soils, with emphasis on potentially pathogenic species. Pedobiologia. 2017;60:11–9.
36. Thelwall M, Sud P. Scopus 1900–2020: growth in articles, abstracts, countries, fields, and journals. Quant Sci Stud. 2022;3:37–50.
37. Minaoui F, Hakkoum Z, Douma M, Mouhri K, Loudiki M. Diatom communities as Bioindicators of Human disturbances on Suburban Soil Quality in Arid Marrakesh Area (Morocco). Water Air Soil Pollut. 2021;232:146.
38. Cobián Güemes AG, Youle M, Cantú VA, Felts B, Nulton J, Rohwer F. Viruses as winners in the game of life. Annu Rev Virol. 2016;3:197–214.
39. Schoelz JE, Stewart LR. The role of viruses in the Phytobiome. Ann Rev Virol. 2018;5:93–111.
40. Braga LPP, Spor A, Kot W, Breuil M-C, Hansen LH, Setubal JC, et al. Impact of phages on soil bacterial communities and nitrogen availability under different assembly scenarios. Microbiome. 2020;8:52.
41. Wommack KE, Nasko DJ, Chopyk J, Sakowski EG. Counts and sequences, observations that continue to change our understanding of viruses in nature. J Microbiol. 2015;53:181–92.
42. Satam H, Joshi K, Mangrolia U, Waghoo S, Zaidi G, Rawool S, et al. Next-generation sequencing technology: current trends and advancements. Biology. 2023;12:997.
43. Labouyrie M, Ballabio C, Romero F, Panagos P, Jones A, Schmid MW, et al. Patterns in soil microbial diversity across Europe. Nat Commun. 2023;14:3311.
44. Scharko NK, Schütte UME, Berke AE, Banina L, Peel HR, Donaldson MA, et al. Combined Flux Chamber and Genomics Approach Links Nitrous Acid Emissions To Ammonia Oxidizing Bacteria and Archaea in Urban and Agricultural Soil. Environ Sci Technol. 2015;49:13825–34.
45. Gill AS, Lee A, McGuire KL. Phylogenetic and Functional Diversity of Total (DNA) and expressed (RNA) bacterial communities in Urban Green infrastructure Bioswale Soils. Appl Environ Microbiol. 2017;83:e00287–17.
46. Gąsiorek M, Halecki W. Soil microbial biomass carbon and nitrogen in historic convent gardens under long-term horticultural cultivation in Krakow, Poland. Soil Use Manag. 2022;38:1004–14.
47. Adewumi AJ, Ogundele OD. editor Gail Villaseñor M 2024 Hidden hazards in urban soils: a meta-analysis review of global heavy metal contamination (2010–2022), sources and its ecological and health consequences. Sustain Environ Res 10 2293239.
48. Cachada A, Pato P, Rocha-Santos T, da Silva EF, Duarte AC. Levels, sources and potential human health risks of organic pollutants in urban soils. Sci Total Environ. 2012;430:184–92.
49. van Gestel CA, Mommer L, Montanarella L, Pieper S, Coulson M, Toschki A, et al. Soil biodiversity: state-of-the-art and possible implementation in Chemical Risk Assessment. Integr Environ Assess Manag. 2021;17:541–51.
50. Global assessment of soil pollution: Report [Internet]. FAO and UNEP. 2021 [cited 2024 Mar 11]. Available from: http://www.fao.org/documents/card/en/c/cb4894en
51. Pierre S, Groffman PM, Killilea ME, Oldfield EE. Soil microbial nitrogen cycling and nitrous oxide emissions from urban afforestation in the New York City Afforestation Project. Urban Urban Green. 2016;15:149–54.
52. Reeves J, Cheng Z, Kovach J, Kleinhenz MD, Grewal PS. Quantifying soil health and tomato crop productivity in urban community and market gardens. Urban Ecosyst. 2014;17:221–38.
53. Xie T, Wang M, Su C, Chen W. Evaluation of the natural attenuation capacity of urban residential soils with ecosystem-service performance index (EPX) and entropy-weight methods. Environ Pollut. 2018;238:222–9.
54. Fang Z, Zhou S, Zhang S, Xing W, Feng X, Yang Q, et al. Spatial distribution and influencing factors of urban soil organic carbon stocks in Xi'an City, China. Urban Ecosyst. 2023;26:677–88.
55. Feng X, Sun X, Li S, Zhang J, Hu N. Relationship study among soils physicochemical properties and bacterial communities in urban green space and promotion of its composition and network analysis. Agron J. 2021;113:515–26.
56. Mammola S, Adamo M, Antić D, Calevo J, Cancellario T, Cardoso P et al. Drivers of species knowledge across the tree of life. Donoso DA, Perry GH, editors. eLife. 2023;12:RP88251.
57. Craig ID, Plume AM, McVeigh ME, Pringle J, Amin M. Do open access articles have greater citation impact? A critical review of the literature. J Informetr. 2007;1:239–48.
58. Akella AP, Alhoori H, Kondamudi PR, Freeman C, Zhou H. Early indicators of scientific impact: Predicting citations with altmetrics. J Informetr. 2021;15:101128.
59. Amossé J, Dózsa-Farkas K, Boros G, Rochat G, Sandoz G, Fournier B, et al. Patterns of earthworm, enchytraeid and nematode diversity and community structure in urban soils of different ages. Eur J Soil Biol. 2016;73:46–58.
60. Tresch S, Frey D, Le Bayon R-C, Zanetta A, Rasche F, Fliessbach A, et al. Litter decomposition driven by soil fauna, plant diversity and soil management in urban gardens. Sci Total Environ. 2019;658:1614–29.
61. Oldfield EE, Felson AJ, Wood SA, Hallett RA, Strickland MS, Bradford MA. Positive effects of afforestation efforts on the health of urban soils. Ecol Manag. 2014;313:266–73.
62. Calabrò GE, Sassano M, Tognetto A, Boccia S. Citizens' attitudes, knowledge, and Educational needs in the field of Omics Sciences: a systematic literature review. Front Genet. 2020;11.
63. Tepeeva AN, Glushakova AM, Kachalkin AV. Yeast communities of the Moscow City soils. Microbiology. 2018;87:407–15.
64. Geisen S, Mitchell EAD, Adl S, Bonkowski M, Dunthorn M, Ekelund F, et al. Soil protists: a fertile frontier in soil biology research. FEMS Microbiol Rev. 2018;42:293–323.
65. Nakamura G, Soares BE, Pillar VD, Diniz-Filho JAF, Duarte L. Three pathways to better recognize the expertise of Global South researchers. Npj Biodivers. 2023;2:1–4.
66. Man JP, Weinkauf JG, Tsang M, Sin JHDD. Why do some countries Publish more than others? An International Comparison of Research Funding, English proficiency and publication output in highly ranked General Medical journals. Eur J Epidemiol. 2004;19:811–7.
67. Aisen A, Veiga FJ. How does political instability affect economic growth? Eur J Political Econ. 2013;29:151–67.
68. Awoyemi AG, Ibáñez-Álamo JD. Status of urban ecology in Africa: a systematic review. Landsc Urban Plan. 2023;233:104707.
69. Herman A, Andersen JP, Nielsen MW. Brain drain outweighs brain circulation between the Global North and South. OSF; 2024.
70. Vasiliadis G, Panagiotakis C, Stenaki I, Fanourgiakis J. The impact of brain-drain in country ranking: the case of computer science. Scientometrics. 2023;128:1441–50.
71. Salager-Meyer F. Scientific publishing in developing countries: challenges for the future. J Engl Acad Purp. 2008;7:121–32.

72. Potter RWK, Pearson BC. Assessing the global ocean science community: understanding international collaboration, concerns and the current state of ocean basin research. Npj Ocean Sustain. 2023;2:1–12.
73. Karlsson S, Srebotnjak T, Gonzales P. Understanding the north–south knowledge divide and its implications for policy: a quantitative analysis of the generation of scientific knowledge in the environmental sciences. Environ Sci Policy. 2007;10:668–84.
74. Csomós G, Lengyel B. Mapping the efficiency of international scientific collaboration between cities worldwide. J Inf Sci. 2020;46:575–8.
75. Bol JA, Sheffel A, Zia N, Meghani A. How to address the geographical bias in academic publishing. BMJ Glob Health. 2023;8.
76. Kendal D, Egerer M, Byrne JA, Jones PJ, Marsh P, Threlfall CG, et al. City-size bias in knowledge on the effects of urban nature on people and biodiversity. Environ Res Lett. 2020;15:124035.
77. Beroigui M, Naylo A, Walczak M, Hafidi M, Charzyński P, Świtoniak M, et al. Physicochemical and microbial properties of urban park soils of the cities of Marrakech, Morocco and Toruń, Poland: human health risk assessment of fecal coliforms and trace elements. CATENA. 2020;194:104673.
78. Epp Schmidt DJ, Pouyat R, Szlavecz K, Setälä H, Kotze DJ, Yesilonis I, et al. Urbanization erodes ectomycorrhizal fungal diversity and may cause microbial communities to converge. Nat Ecol Evol. 2017;1:1–9.
79. Guerra CA, Delgado-Baquerizo M, Duarte E, Marigliano O, Görgen C, Maestre FT, et al. Global projections of the soil microbiome in the Anthropocene. Glob Ecol Biogeogr. 2021;30:987–99.
80. Scharenbroch BC, Lloyd JE, Johnson-Maynard JL. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia. 2005;49:283–96.
81. Zhao Y, Cocerva T, Cox S, Tardif S, Su J-Q, Zhu Y-G, et al. Evidence for co-selection of antibiotic resistance genes and mobile genetic elements in metal polluted urban soils. Sci Total Environ. 2019;656:512–20.
82. Luederitz C, Brink E, Gralla F, Hermelingmeier V, Meyer M, Niven L, et al. A review of urban ecosystem services: six key challenges for future research. Ecosyst Serv. 2015;14:98–112.
83. Bolay J-C. Urban facts. In: Bolay J-C, editor. Urban Planning against Poverty: how to think and do Better Cities in the Global South. Cham: Springer International Publishing; 2020. pp. 7–55.
84. Bell D, Jayne M. Small cities? Towards a Research Agenda. Int J Urban Reg Res. 2009;33:683–99.
85. Johnson MTJ, Munshi-South J. Evolution of life in urban environments. Science. 2017;358:eaam8327.
86. Uchida K, Blakey RV, Burger JR, Cooper DS, Niesner CA, Blumstein DT. Urban Biodiversity and the importance of Scale. Trends Ecol Evol. 2021;36:123–31.
87. Jing X, Sanders NJ, Shi Y, Chu H, Classen AT, Zhao K et al. The links between ecosystem multifunctionality and above- and belowground biodiversity are mediated by climate. Nat Commun. 2015;6.
88. R Core Team. R: A Language and Environment for Statistical Computing [Internet]. Vienna, Austria: R Foundation for Statistical Computing. 2024. Available from: https://www.R-project.org/
89. Mammola S, Piano E, Doretto A, Caprio E, Chamberlain D. Measuring the influence of non-scientific features on citations. Scientometrics. 2022;127:4123–37.
90. Lang DT, Wallace J. RJSONIO: Serialize R Objects to JSON, JavaScript Object Notation [Internet]. 2023. Available from: https://CRAN.R-project.org/package=RJSONIO
91. Wickham H. ggplot2: elegant graphics for data analysis. 2nd ed. Springer International Publishing; 2016.
92. Brunson JC. Ggalluvial: layered grammar for alluvial plots. J Open Source Softw. 2020;5:2017.
93. Hernangómez D. Using the tidyverse with terra objects: the tidyterra package. J Open Source Softw. 2023;8:5751.
94. Hijmans RJ, Barbosa M, Ghosh A, Mandel A. geodata: Download Geographic Data [Internet]. 2023. Available from: https://CRAN.R-project.org/package=geodata
95. Zuur AF, Ieno EN. A protocol for conducting and presenting results of regression-type analyses. Methods Ecol Evol. 2016;7:636–45.
96. Aphalo PJ. ggpmisc: Miscellaneous Extensions to ggplot2 [Internet]. 2023. Available from: https://CRAN.R-project.org/package=ggpmisc
97. Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, et al. glmmTMB balances speed and flexibility among packages for zero-inflated generalized Linear mixed modeling. R J. 2017;9:378–400.
98. Wickham H, Averick M, Bryan J, Chang W, McGowan LD, François R, et al. Welcome to the Tidyverse. J Open Source Softw. 2019;4:1686.
99. Zuur AF, Ieno EN, Elphick CS. A protocol for data exploration to avoid common statistical problems. Methods Ecol Evol. 2010;1:3–14.
100. Lüdecke D, sjPlot. Data Visualization for Statistics in Social Science [Internet]. 2023. Available from: https://CRAN.R-project.org/package=sjPlot
101. Lüdecke D, Ben-Shachar MS, Patil I, Waggoner P, Makowski D. Performance: an R Package for Assessment, comparison and testing of statistical models. J Open Source Softw. 2021;6:3139.

Publisher's note