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Spatio-temporal analysis of knowledge on the linkage between urban green spaces and climate change

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Abstract

This bibliometric analysis explores the temporal and geographical spread of literature on Climate Change and Urban Green Spaces based on the Scopus database. The information was processed with Microsoft Excel 2020, ArcMap, Gephi, and Bibliometrix package using Biblioshiny in R Studio. Findings indicate that there were earliest science papers pertaining to the subject since 2001. There were 1,274 publications, mainly articles, which were processed, and there were 31,135 citations, indicating high research interest. Some of the most highly productive journals are Sustainability, Urban Forestry and Urban Greening, and Science of the Total Environment. Wide international collaboration is also reported, with high productivity from countries such as China, the United States, Italy, Germany, and the United Kingdom, indicating the global reach and growing interest this field of study has gained. However, in spite of this growth, there are still large gaps to be filled particularly in less-represented regions such as Africa and Latin America. Future research should look to include urban green space quality in climate and health impact evaluations, as well as cross-validate remote-sensing-based urban planning software through field-based case deployments. Heightening international collaboration is also recommended in order to facilitate fair knowledge creation and use.

Keywords: Urban green spaces, climate change, bibliometric analysis, international collaboration, scientific publications.

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1. Introduction

The 21st century is marked by a colossal challenge: climate change. With soaring temperatures, extreme weather events, and the relentless rise of sea levels, its damaging impact is already visible and continues to threaten our planet and its future. Given this emergency, the search for sustainable and adaptable solutions to strengthen the resilience of cities became an absolute necessity. To address this challenge, the United Nations' Sustainable Development Goals (UNSDGs) for cities (No. 11) mandates that cities and human settlements be inclusive, safe, resilient, and sustainable (Gelan and Girma, 2021; Singh, 2023). The programmes also call for providing universal access to green spaces to reduce the environmental impact of cities (Gelan and Girma, 2021). It is in this context that cities are transforming into oases, offering a refuge from the climate storm (Addas and Maghrabi, 2021; Nero et al., 2017; Zhao et al., 2023).

To fight back climate change, urban planners are armed with innovative solutions and powerful tools to harness the full potential of green spaces and combat this scourge (Mees and Driessen, 2011). Energy-efficient buildings, smart infrastructure, development and enhancement of green spaces, contribute to climate change mitigation and adaptation (Jones et al., 2024; Lovell and Taylor, 2013; Valença Pinto et al., 2023; Vásquez et al., 2019). These solutions prove to be formidable weapons, making a significant contribution to urban quality of life (Hidalgo-García and Rezapouraghdam, 2023; Kistemann et al., 2023; Pancewicz and Kurianowicz, 2024). They help reduce climate change's harmful effects through measures such as reducing energy consumption, evaporative cooling, and increasing urban albedo (Cheela et al., 2021; Sun et al. 2019). Well-managed and vegetated Urban Green Spaces (UGS) have been shown to absorb and store more carbon and balance CO2 emissions (Dorendorf et al., 2015; Kitha and Lyth, 2011). Moreover, urban vegetation could sequester and absorb a considerable amount of CO2 compared to natural forests. For instance, a scientific study revealed that the average aboveground biomass (AGB) in urban areas in the United States was 89 ± 22 Mg C ha-1, which was higher than the average of 53.5 Mg C ha-1 for all forests in the country (Hutyra et al., 2011).

Therefore, even smaller proportions of UGS in the urban environment could have a significant effect on urban ecosystem services (Dearborn and Kark, 2010). UGS also provide shade, cool temperatures (Baldauf and Reis, 2010; Reis and Lopes, 2019), and considerably reduce urban heat (Dearborn and Kark, 2010). Scientific studies examine and indicate that UGS regulate the climate, purifies
the air, and recycles nutrients. Other studies, on the associations between violent crime, the magnitude of urban heat islands, and UGS in Australia, indicate significantly lower rates of violent crime in areas with a higher percentage of urban vegetation (Stevens et al., 2024).

From New York to Beijing, *via* Milan and Hong Kong, numerous cities have already integrated UGS into their climate management policy. In the United States, for instance, UGS have become a priority in decision-making in New York, Washington DC, Chicago, and Philadelphia (Nowak 2006). In Europe, cities like Milan, Mirandola (Modena), Catania, and Turin are making of UGS a central element of their urban sustainability (Baycan-Levent and Nijkamp, 2009; Donateo et al. 2021; Sanesi et al., 2018). In Asia, UGS projects have been developed in Hong Kong, Beijing, and the Pukou District of Nanjing. Despite the creation of green spaces in densely populated urban areas facing climate challenges, the existence of innovative policies and solutions, the availability of review studies, significant gaps remain. These gaps hinder the development of effective mitigation strategies to combat climate change in cities due to the lack of reliable and accessible data on green spaces and climate change in our cities. For instance, in a systematic review, bibliometric methods were used to analyze and quantitatively examine 276 articles published in the Web of Science and Scopus databases between 1977 and 2023 (Dong et al., 2023). Information on the influencing factors, design methods, and benefits of pocket parks, which are small public green spaces, was provided. The findings indicate the development of an increasing number of these green spaces in various forms in countries like China and the United States. Similarly, other studies solely explore institutional actions to develop green infrastructure as an alternative to combating climate change in Latin American cities (Vásquez et al., 2019). The analysis focused on identifying these institutions, and their objectives, and understanding and using the concept of green infrastructure. Additionally, Zhang and Han (2021) also conducted a review of 32 English and 33 Chinese articles to summarize the definition of pocket parks, research locations, research topics, and trends. They compared the similarities and differences between Chinese and English articles. Kerishnan and Maruthaveeran (2021), on the other hand, examined 15 articles to summarize the factors that drive urban residents to use pocket parks. These studies provide interpretations and analyses of the literature, but the current body of knowledge lacks comprehensive research on the relationships between green spaces and climate change through the lens of bibliometric analysis at a broader scale. This is crucial to enable policymakers, practitioners, and other stakeholders to gain a better understanding of this subject for informed decision-making to mitigate this climate storm on cities.

As cities expand and climate challenges intensify, a key question emerges: can Urban Green Spaces significantly mitigate climate change impacts? While local studies suggest a positive role, large-scale bibliometric analysis is needed to validate these findings. Therefore, this study aims to conduct a spatial and temporal analysis of scientific knowledge to visualize the evolution of research and highlight patterns of collaboration. Specifically, this analysis seeks to:

i) understand how research on UGS and climate change has evolved over time;

ii) identify countries or regions leading in this research field;

iii) uncover key international collaborations driving knowledge production; and

iv) reveal geographical disparities in the generation and application of scientific knowledge.

2. Methodology

2.1. Data collection

Bibliometric analysis, depending on its objective, can be conducted using various platforms or repositories that provide access to scientific publications and citation indexes. Among the most widely used databases are Web of Science and Scopus. Given the significant overlap between the two databases and the relatively easier access to Scopus, the current bibliometric analysis was conducted using the Scopus database alone.

The following keywords were used in the search: “urban,” “green,” “space,” and “climate change,” combined as follows: "urban" AND "green" AND "space" AND "climate change". The search was limited to occurrences of these terms in the title, abstract, or keywords of publications. Since most scientific publications are in English—and even those in other languages usually include an English title, abstract, and keywords—the search was conducted using English terms only. The search was performed on 14 February 2024. No subject area restrictions were applied to the search in order to capture a broad and representative sample, given the interdisciplinary nature of the topic.

2.2. Data cleansing

The Scopus search returned 1,311 documents of various types. Initial data cleaning was conducted using Microsoft Excel 2020, where string-matching functions were applied to identify and automatically remove some duplicate entries. To further ensure data quality, a manual review of all documents was carried out to eliminate remaining duplicates and irrelevant records.

In total, 37 documents were removed from the dataset, including 6 duplicates (0.46%), 15 books (1.14%), and 16 conference reviews (1.22%) lacking author information. After cleaning, 1,274 documents remained and were included in the analysis. While it is common in bibliometric studies to restrict the dataset to journal articles and reviews, all remaining documents were retained in this study due to the increasing trend of peer review for book chapters, conference papers, and other formats. The final dataset consisted of 873 journal articles (68.52%), 94 reviews (7.38%), 122 book chapters (9.58%), 170 conference papers (13.34%), and 15 other document types (1.18%)—including data papers (2), editorials (4), letters (1), notes (7), and short surveys (1).

2.3. Data analysis

The temporal distribution of publications and citations over time was analyzed and visualized using Microsoft Excel 2020.

To assess the spatial distribution of research output, authors’ country affiliations were extracted from the dataset. Only documents with complete affiliation information were used for this part of the analysis.

Spatial analysis was conducted in ArcGIS version 10.4, using the global geopolitical boundaries layer from the FAO's Geospatial Data Portal (Geospatial Information for Sustainable Food Systems).

Content analysis was performed using Microsoft Excel 2020 and the Bibliometrix R package (version 4.1.4) via the Biblioshiny interface. This open-source tool enables comprehensive analysis and visualization of scientific literature. Its integration with R provides extensibility and regular updates supported by a large user community (Aria and Cuccurullo, 2017). Its cost-free access also makes it an attractive alternative to more expensive or subscription-based software (Guler et al., 2016). Extensive documentation and learning resources further support its effective use in bibliometric research and data visualization.

Social network analysis was conducted using Gephi version 0.9 to explore research collaboration networks. Gephi was selected for its flexibility in handling network complexity and producing high-quality visualizations. Two main types of collaboration networks were constructed: author-country networks and author-author networks. In these networks, nodes represent either countries or authors, and edges represent co-authored publications. The strength of each edge corresponds to the number of co-authored papers. Following standard bibliometric practice, publications from England, Northern Ireland, Scotland, and Wales were grouped under "United Kingdom" (Liu et al., 2011; Yevide et al., 2016).

The number of authors, institutional affiliations, and countries associated with each publication were also extracted to assess collaboration patterns across individuals, institutions, and national boundaries.

3. Results

3.1. Document types and languages of scientific publications on urban green space and climate change

A total of 1,274 scientific documents constituted the final dataset for analysis. Journal articles dominated the corpus (873; 68.52%), followed by conference papers (170; 13.34%), book chapters (122; 9.58%), and reviews (94; 7.38%). Less common document types included notes (7), editorials (4), data papers (2), and one publication each categorized as a letter and a short survey.

These publications were written in 14 different languages. Articles were available in 13 languages, while non-article documents were published in only 3 languages (Table 1). Czech was exclusively used for conference papers (3), and alongside Czech, only English and Spanish were used for non-article types.

English overwhelmingly dominated the publication language (95.3%), regardless of document type. Chinese (2.04%), German (0.86%), Spanish (0.47%), and French (0.24%) followed but were used far less frequently. While the single Croatian article received no citations, French, Italian, Polish, Russian, and Slovak articles received only one or two citations each. English and Hungarian publications had the highest impact, as measured by average citations per publication and per year.

Notably, conference papers published in Czech and Spanish had received no citations, while those in English amassed 1,244 citations an average of 4.1 citations per conference paper.

Table 1. Number an impact of scientific production per language and document type.

Document types	Languages	Number of publications	Percentages (%)	Total citations	Citations per publication per year	Average citation per publication
Articles and reviews		967	75.9 ; 100	31135	32.2	5.32
	Chinese	26	2 ; 2.7	116	4.5	1.41
	Croatian	1	0.1 ; 0.1	0	0.0	0.00
	English	911	71.5 ; 94.2	30940	34.0	5.59
	French	3	0.2 ; 0.3	2	0.7	0.07
	German	11	0.9 ; 1.1	18	1.6	0.31
	Hungarian	1	0.1 ; 0.1	14	14.0	3.50
	Italian	1	0.1 ; 0.1	1	1.0	1.00
	Persian	2	0.2 ; 0.2	7	3.5	0.44
	Polish	2	0.2 ; 0.2	1	0.5	0.06
	Portuguese	1	0.1 ; 0.1	3	3.0	1.00
	Russian	2	0.2 ; 0.2	1	0.5	0.13
	Slovak	1	0.1 ; 0.1	2	2.0	0.29
	Spanish	5	0.4 ; 0.5	30	6.0	0.63
Others		307	24.1 ; 100	1244	4.1	0.82
	Czech	3	0.2 ; 1.0	0	0.0	0.00
	English	303	23.8 ; 98.7	1244	4.1	0.83
	Spanish	1	0.1 ; 0.3	0	0.0	0.00
Total		1274	100 ; 100	32379	25.4	4.23

NB: For the column on percentage, for each cell, the first number represents the percentage calculated considering the total number of scientific productions (1,274), and the second considers the total number of documents for the corresponding group of document types.

3.2 Evolution and impacts of scientific productions on Urban Green Space and Climate Change

The analysis of the evolution of scientific literature on Urban Green Spaces (UGS) and climate change reveals a generally upward trend in publications since the first two appeared in 2001. However, growth was uneven in the early years, with no articles published in 2002, 2003, and 2008. Between 2001 and 2008, a total of 14 publications including 9 articles were produced, generating 786 citations, which corresponds to an average of 87.33 citations per publication.

The first non-article document (a conference paper) was published in 2003, followed by two more in 2007, including one book chapter that received 20 citations. Two additional book chapters were published in 2008, one of which was cited nine times.

After 2008, there was consistent and steady growth in the number of scientific publications across all document types, continuing until 2018. For journal articles specifically, growth was relatively modest during the four-year period from 2015 to 2018. Two publication peaks occurred during this phase first in 2011, and again in 2017 both marked by a significant number of conference papers and book chapters.

Following 2018, publication outputs increased exponentially, averaging 153 publications per year for all document types combined, and 117 articles per year. The highest number of publications was recorded in 2023.

Citation trends showed considerable fluctuations up to 2020 with six notable peaks, the most significant of which occurred in 2015. Over the 23-year period, articles accumulated a total of 31,135 citations, averaging 32.2 citations per year and 5.32 citations per publication per year.

In contrast, the 307 documents classified as other types (conference papers, book chapters, editorials, etc.) received a total of 1,244 citations resulting in a lower impact: an average of 4.1 citations per publication and less than one citation per publication per year (0.82).

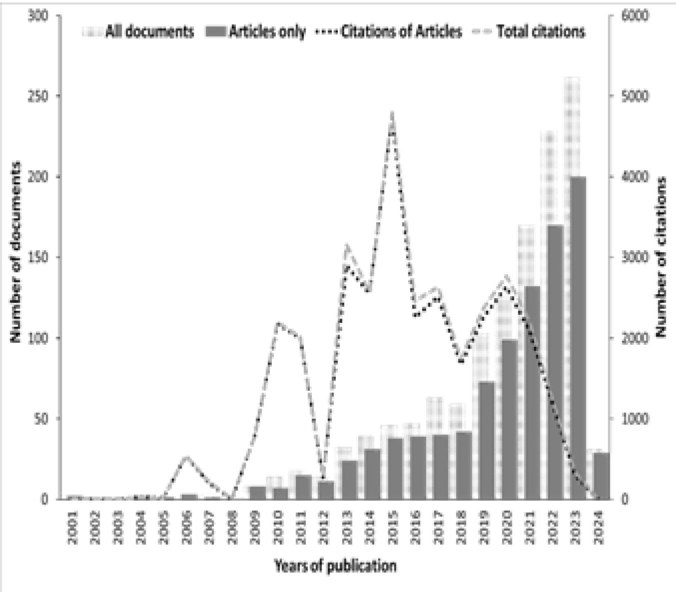

Figure 1. Evolution of scientific productions and total citation count from 2001 to 2024.

3.3. The most productive and influential journals

The total of 967 articles and reviews published on the studied topic encompass 401 journals out of which, 282 have published a single publication, 56, 23, 8, and 32 journals have published 2, 3, 4, and more than 4 publications respectively. The lattest group has published 472 publications representing 48.81% of the total published articles. Among this group of journals that published more than 4 articles, *Sustainability*, having an impact factor of 3.9 was the most productive journal with 74 publications, followed by *Urban Forestry and Urban Greening* and *Science of the Total Environment* which recorded 49 and 35 publications respectively (Table 2). The most productive and most influential journal was *Landscape and Urban Planning* with an impact factor of 9.1. Indeed, apart from being among the top 5 most productive journals, *Landscape and Urban Planning* has a good impact factor, the highest number of citations (4,906), and is ranked eighth in terms of number of citations per publication, but first in terms of number of citations per publication per year. The highest number of citations per publication (1,454) was recorded by *Lancet* which has the highest impact factor (168.9) in the list of the sources that published articles on UGS and climate change.

Table 2. List of the most active sources and their impacts

Sources	Number of publications	Percentage of publication	Total citations	TC/P	TC/P/Y	Impact factors
Sustainability (Switzerland)	74	7.65	971	13.12	225.92	3.9
Urban Forestry and Urban Greening	49	5.07	1685	34.39	344.33	-
Science of the Total Environment	35	3.62	1830	52.29	354.01	9.8
Land	28	2.90	158	5.64	68.95	-
Landscape and Urban Planning	24	2.48	4906	204.42	522.25	9.1
Sustainable Cities and Society	23	2.38	891	38.74	282.68	11.7
International Journal of Environmental Research and Public Health	20	2.07	245	12.25	61.22	-
Remote Sensing	16	1.65	188	11.75	51.09	5
Journal of Environmental Management	15	1.55	858	57.20	155.80	8.7
Forests	14	1.45	167	11.93	37.48	2.9
Cities	12	1.24	404	33.67	59.43	-
Shengtai Xuebao	12	1.24	116	9.67	19.02	-
Journal of Cleaner Production	11	1.14	422	38.36	106.73	11.1
Environment International	10	1.03	583	58.30	113.71	11.8
Frontiers in Sustainable Cities	10	1.03	38	3.80	15.00	-
Urban Climate	10	1.03	286	28.60	50.16	6.4
Building and Environment	9	0.93	723	80.33	87.19	7.4
Urban Planning	9	0.93	46	5.11	14.18	-
Atmosphere	8	0.83	57	7.13	18.36	2.9
Ecological Indicators	8	0.83	449	56.13	71.21	6.9
Environmental Science and Policy	7	0.72	105	15.00	26.58	-
Frontiers in Environmental Science	7	0.72	37	5.29	17.75	4.6
Land Use Policy	7	0.72	510	72.86	104.28	-
Water (Switzerland)	7	0.72	26	3.71	16.50	3.4
WIT Transactions on Ecology and the Environment	7	0.72	10	1.43	1.53	-
Energies	6	0.62	51	8.50	11.73	3.2
Environment, Development and Sustainability	6	0.62	79	13.17	16.21	-
Environmental Research	6	0.62	715	119.17	112.25	8.3
Environmental Research Letters	6	0.62	228	38.00	48.80	6.7
Urban Ecosystems	6	0.62	140	23.33	26.85	2.9
Journal of Hydrology	5	0.52	131	26.20	43.33	6.4
Sustainable Mediterranean Construction	5	0.52	0	0.00	0.00	-

3.4. Spatial characteristics of knowledge distribution on UGS and climate change

The results of the spatial analysis suggest that 87 countries worldwide were involved in scientific productions in regard to UGS and climate change regardless of the type of document. Among them, 40 countries including 4 from Africa (Benin, Egypt, Ghana, and Nigeria) contributed both for the publication of articles and non-article type of documents. Among the remaining 47 countries 4, all non-African countries (Barbados, Ecuador, Mongolia, and Nepal), were involved only in the production of non-article documents while 43, with 10 from the African continent, published only articles. Germany (102, 6.5%) in Europe, China (176, 11.1%) in Asia, Australia (216, 13.7%) in Oceania, United States (146, 9.2%) in North America, and South Africa (14, 0.9%) in Africa, were the most productive countries per continent as regard to publication of articles (Figure 2). While similarly for Australia in Oceania, and United States in North America, Italy in Europe and India in Asia were the countries that published most of the non-article documents. From 2001 to the first months of 2024, all document types combined, United States, China, Germany, Italy, and the United Kingdom were the most productive countries with more than 100 published scientific productions. They were followed by Australia, India, and Spain with scientific productions ranging from 51 to 100. Most of the contributions from African countries were below 25 and almost two third of the countries did not contribute to UGS and climate change publications with no country from Central Africa (Figure 3).

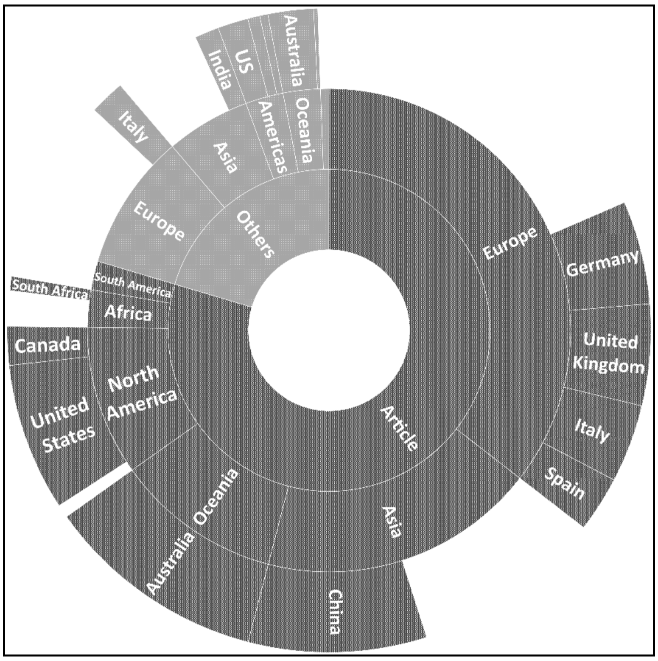

Figure 2. Contribution of continents and their most productive countries in publication on UGS and CC per types of documents.

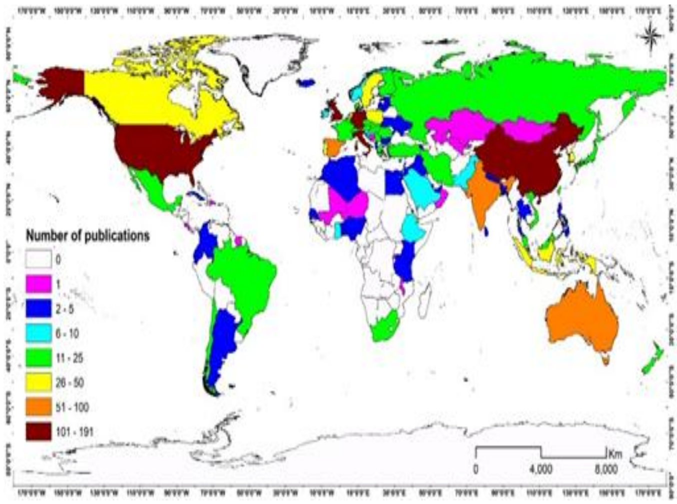

Figure 3. Spatial distribution of scientific productions worldwide.

3.5. Analysis of collaboration between authors, authors' countries, and institutions

From the first publication on UGS and climate change in 2001 through early 2024, 4,312 authors contributed to 1,120 co-authored publications. In addition, 154 publications (12.09%) were authored by a single individual, including 27 book chapters and 34 conference papers.

Across all co-authored works, a total of 18,510 collaboration links (edges) were identified, forming a network composed of numerous isolated sub-networks (Figure 4a). When limiting the analysis to journal articles only, 3,556 authors were involved, generating 16,539 collaboration links (Figure 4d).

To analyze the strength of collaboration, edges formed by a single co-authored publication were removed. This filtering left 738 edges among 404 authors across all document types (Figure 4b) and 656 edges among 333 authors for articles only (Figure 4e). Further narrowing to collaborations with at least three co-authored publications produced a final network of 52 authors for all document types. The strongest and most prominent collaboration cluster was formed by Zhang S, Liu Z, Dong W, and Liu X (Figure 4c).

For journal articles alone, the final network included 42 authors and 32 edges, distributed across 16 smaller, isolated networks (Figure 4f). Compared to the article-only network, the full-document-type network contained five additional two-author clusters. Four of these clusters involved authors who had published both articles and non-article documents, allowing them to meet the inclusion threshold of three publications. One cluster involved a pair who had co-authored three conference papers exclusively (Figure 4c, red-colored nodes).

Regarding collaboration among authors' countries, 930 publications (73.0%) were produced by authors affiliated with a single country. China (123), the United States (89), Italy (83), Germany (60), and the United Kingdom (55) led in single-country publications across both articles and non-article types.

The remaining publications involved international collaborations and formed a network of 88 countries connected by 549 edges (Figure 5a). The United Kingdom occupied a central position in the collaboration network, with strong links with Spain, Germany, and Italy (Figure 5c). However, the United States and China had the single strongest bilateral collaboration, with 25 co-authored publications.

The largest collaboration networks were led by the United Kingdom (connected to 30 countries), Germany (26), the United States (25), and China (21) (Figures 6a–6d). South Africa was the only African country integrated into multiple large networks, maintaining collaborations with at least two of these global leaders (Figure 6e).

Other African countries such as Ghana, Nigeria, Kenya, and Egypt were connected to either the United States, Germany, or Japan. In contrast, Benin and Togo appeared isolated from the main international network (Figure 6f).

To assess collaboration between institutions, a summary table was created showing the number of authors, institutions, and countries per publication. It revealed that only about 10% of all publications were authored without collaboration across individuals, institutions, or national borders (Table 3).

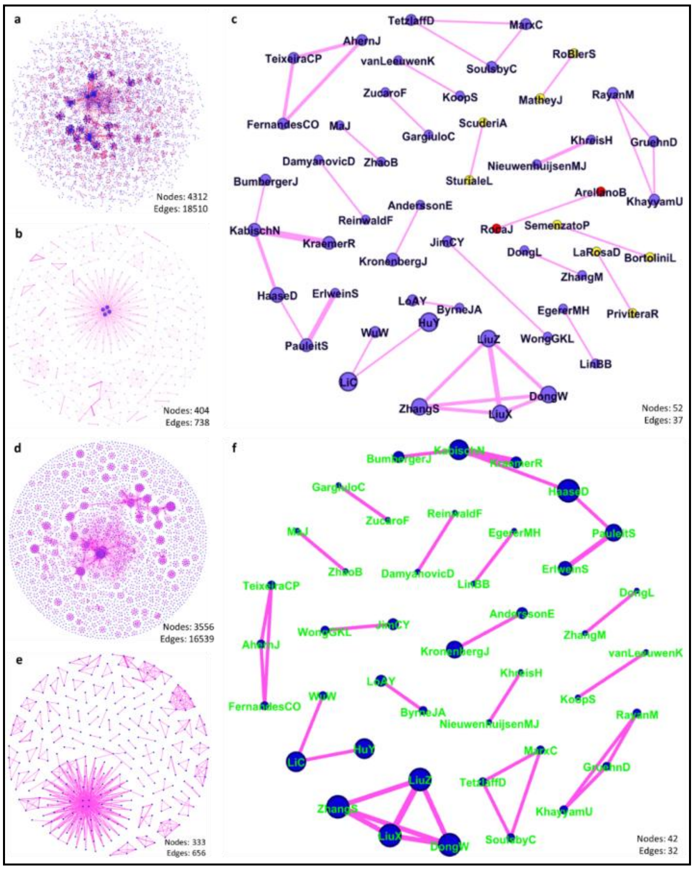

Figure 4. Social networks of collaboration between authors regardless of the number of scientific productions published together (a), with a minimum of two scientific productions published together (b), with a minimum of three scientific productions published together (c), regardless of the number of articles published together (d), with a minimum of two articles published together (e), with a minimum of three articles published together (f).

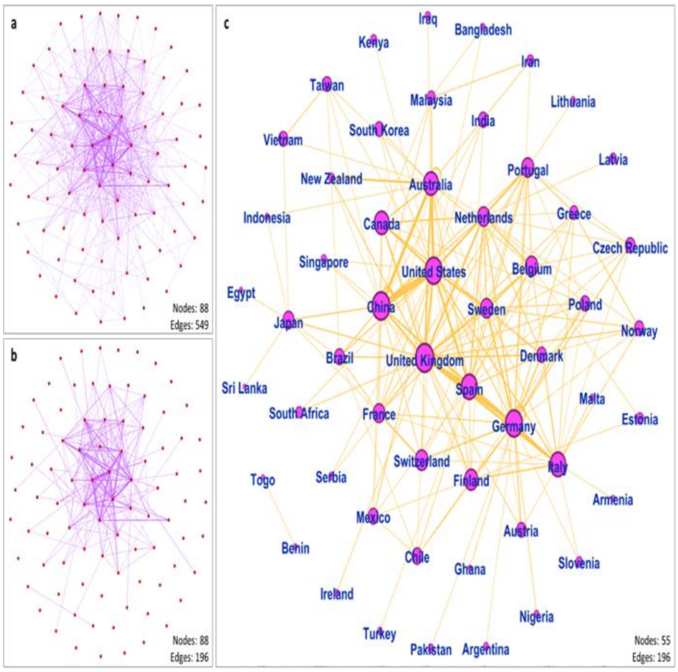

Figure 5. Social networks of collaboration between authors' countries regardless of the number of publications published together (a), with only one publication edges removed (b), with a minimum of two publications published together (c).

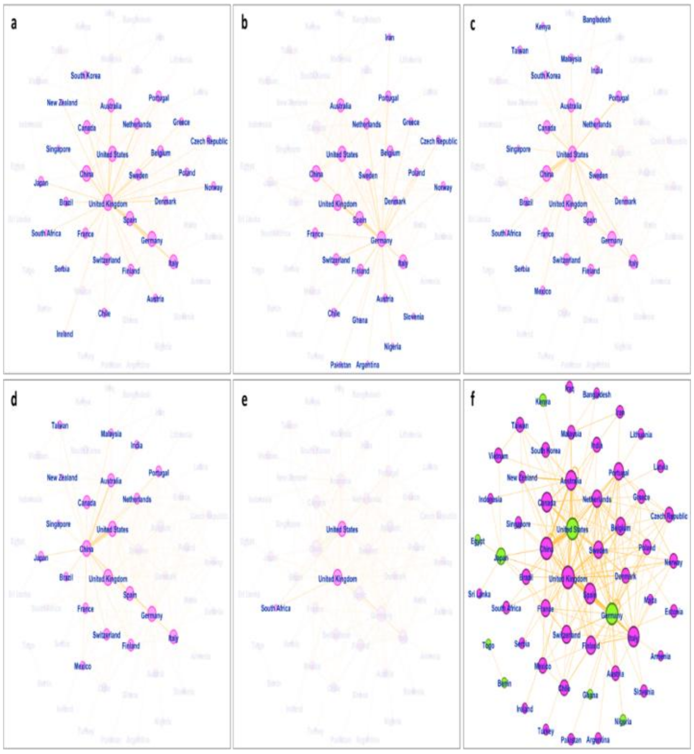

Figure 6. Collaborative authors' countries network with United Kingdom at the center (a), with Germany at the center (b), with United States at the center (c), with China at the center (d), with South Africa at the center (d), with different green color nodes for African countries and their Foreign associated countries (f)

To investigate collaboration between authors' affiliations, a table presenting the number of authors, authors' affiliations, and authors' countries was produced and revealed that only one-tenth of the publications produced on UGS and climate change were published without collaboration between neither authors, institutions, and countries (Table 3).

		Number of authors						Total
		1	2	3	4	5 to 9	> 9	
One Country	1 institution	131	132	92	43	38		436
	2 institutions	10	74	58	49	52	2	245
	3 institutions	1	9	30	21	58	4	123
	>3 institutions		1	9	22	74	11	117
	Sub total	142	216	189	135	222	17	921
Two countries	2 institutions	2	26	19	14	12	1	74
	3 institutions		11	12	29	23		75
	>3 institutions	1	6	9	9	57	9	91
	Sub total	3	43	40	52	92	10	240
Three countries	3 institutions			7	8	2		17
	>3 institutions		1	3	7	25	11	47
	Sub total	0	1	10	15	27	11	64
> Three countries	>3 institutions			1	4	13	20	38
	Sub total	0	0	1	4	13	20	38
Total		145	260	240	206	354	58	1263

Table 3. Collaboration between authors' institutions

3.6. Content analysis through word cloud and thematic mapping

The word cloud is a content analysis tool used to identify the most frequent terms in publication titles, abstracts, keywords, or any specified corpus within a dataset. For the current study, a word cloud was generated based on the titles of the retrieved publications on Urban Green Spaces (UGS) and climate change to highlight the key themes and areas of research foci.

To refine the results and ensure meaningful insights, common bigrams related to the search terms such as "climate change," "urban green," "green space," "green spaces," and "green infrastructure" were excluded from the word cloud. The top 50 resulting terms were visualized (Figure 7). In the word cloud, the size of each word is proportional to its frequency in publication titles. The prominence of terms such as "urban heat," "heat island," "ecosystem services," and "nature-based solutions" suggests that key research themes focus on the warming characteristics of urban environments and the role of green infrastructure as nature-based solutions to mitigate these effects and enhance ecosystem services.

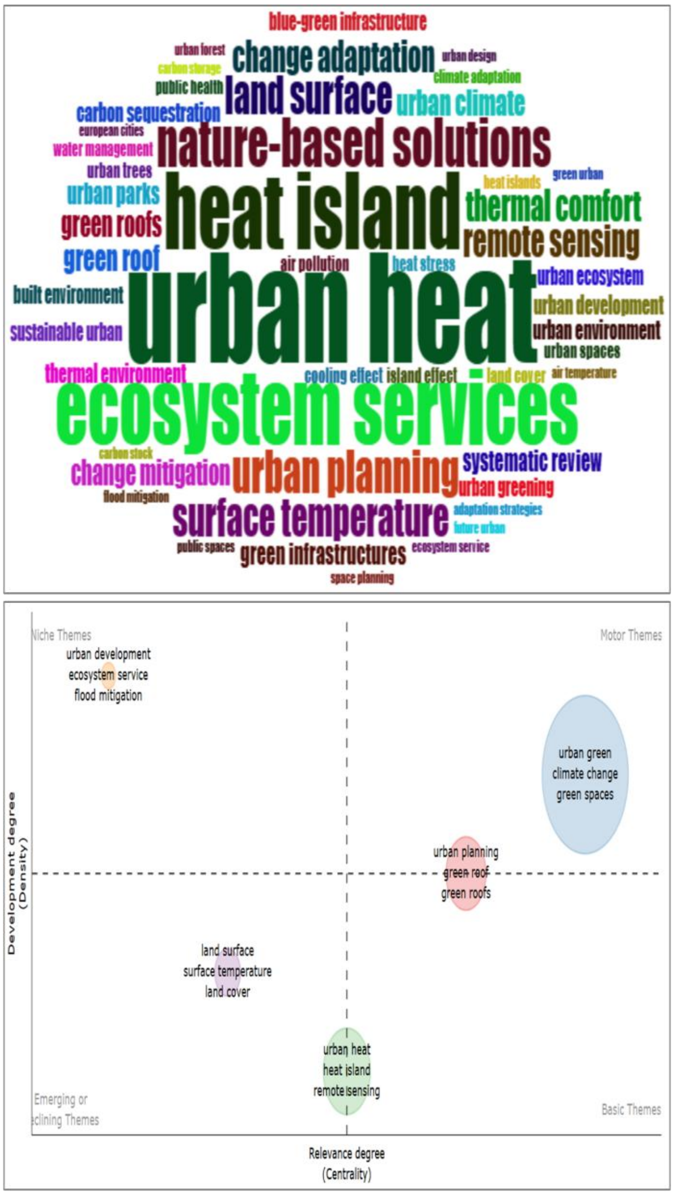

Figure 7. Word cloud outcome of the 50 meaningful themes (up), and thematic map of the most relevant topics (down) from the publications' titles of scientific productions on urban green spaces and climate change.

The thematic mapping (Figure 7) provides a comprehensive overview of the various themes within the field of UGS and climate change. Organized into four categories, this mapping allows for the identification and visualization of the evolution of the research field. The map is organized into four categories: niche topics, driving or motivating topics, emerging or declining topics, and core topics covered by scientific researchers. Note that degrees of relevance (centrality) are on the horizontal axis and degrees of development (density) are on the vertical axis, where circle sizes are related to the number of publications associated with each keyword. In the analysis, niche topics such as "urban development," "ecosystem service," and "flood migration" appear in the lower-right quadrant. These themes are moderately important but not yet well-developed, indicating potential for growth.

Driving or motor themes, including "urban green," "climate change," and "green spaces," are both well-developed and central to the field. They form the theoretical backbone of the research domain.

Emerging or declining themes like "land surface," "surface temperature," and "land cover" show lower centrality and varying levels of development, suggesting either a fading interest or topics that are still in early stages of exploration.

Basic and transversal themes such as “urban planning,” “green roof,” and “green roofs” are relevant but still in the process of deeper development.

Additionally, “urban heat,” “heat island,” and “remote sensing” stand out as the most mature and well-developed research topics, indicating their dominant role in the scientific discourse on the relationship between UGS and climate change.

3.7. Urban climate change issues and contributions of UGS research to improving urban dwellers’ wellbeing

As highlighted in the content analysis, heat is one of the most critical climate-related threats facing urban environments. The relatively higher temperatures experienced in cities compared to surrounding non-urban areas result from factors such as building configuration and density, heat-retaining materials, reduced ventilation, and heat emissions from human activity. This phenomenon is commonly referred to as the Urban Heat Island (UHI) effect (Shaw, 2017). In addition to heat, cities are increasingly vulnerable to frequent and intense flooding events, which pose serious risks to public health, safety, and infrastructure (Alves et al., 2024).

Although climate change is not the direct cause of UHI, it exacerbates the effect, creating major challenges for city planners and residents alike (Shaw, 2017). Recognizing the urgent need to redesign urban areas for future environmental and social conditions, many cities have turned to the “re-naturalization” of public spaces through Nature-Based Solutions (NBS) (Shaw, 2017; Panno et al., 2017; Nóblega-Carriquiry et al., 2023; Pancewicz et al., 2023).

NBS refer to actions inspired by, supported by, or copied from nature, designed to address a range of environmental and societal challenges. It includes the restoration of floodplains, the rewetting of peatlands, the maintenance of high nature value grassland, and the promotion of urban green spaces that in a city can mitigate UHI effect by reducing surface heat absorption, increasing solar energy reflection and water retention, as well as cooling warm spaces nearby through heat diffusion (Schlegelmilch et al., 2018). NBS do not only serve to reduce the risk of flooding and drought, but they also provide additional sustainability values, such as strengthening ecosystem services through increased biodiversity and recreation opportunities (Ternell et al., 2020). NBS are supported by nature and mimic natural processes. They serve as an umbrella concept for multiple sustainability-oriented approaches, including green infrastructure and ecosystem-based adaptation (Shilky et al., 2024), and can function as carbon sinks that reduce greenhouse gas emissions (Nassary et al., 2022).

Studies of establishment and implementation of various NBS strategies in cities to identify NBS strategies that are most beneficial for cities inhabitants and for environment led to a full-scale implementation of different NBS strategies including installing green roofs, de-sealing parking areas, enhancing vegetation in urban parks, and planting street trees, and a combination of them in Barcelona (Spain), Malmö (Sweden), and Utrecht (the Netherlands). Most scenari provide multiple benefits, but each one is characterized by a specific mix. In all cities, a full-scale deployment of green roofs shows the greatest potential to reduce runoff and increase biodiversity, while tree planting either along streets or in urban parks, produces the greatest impact on heat mitigation and greenness (Cortinovis et al., 2022). Implementation of NBS in public spaces such as street trees, and rain gardens is preferred over measures implemented on public buildings like green roofs and facades. A method to support urban NBS planning processes while addressing multiple climate adaptation objectives using a three-step GIS-based multi-criteria approach (priority areas identification, site-specific NBS allocation, and multifunctional performance evaluation) has been applied as a strategy to mitigate the UHI effect in vulnerable urban environments (Alves et al., 2024). In Poznań, a major Polish city, an urban green cover model and a 3D tree model were generated by integrating airborne laser scanning (ALS), Copernicus Land Monitoring Service (CLMS), topographic data, and ortho-imagery to complement a smart city model with comprehensive statistics (Uciechowska-Grakowicz et al., 2023). These computer algorithms generated reports on forest cover volume, CO2 reduction, air pollutants, and the effect of greenery on mean temperature, interception, precipitation absorption, and biomass changes. This methodology provides insights into the potential of modifying UGS locations and their impacts on ecosystem services, aiding urban planners in their decision-making processes. In the realm of urban planning, researchers have proposed a remote-sensing-based urban planning tool to identify and optimize UGS locations in cities, considering various ecosystem services provided by UGS, such as CO2 reduction and air quality improvement. Additionally, researchers have explored the combined effects of UGS on multiple air quality concerns, including carbon emissions (Van Ryswyk et al., 2019), urban heat islands (Ghazalli et al., 2018; Van Ryswyk et al., 2019; Ye and Qiu, 2021), and ozone pollution (Sun et al. 2019). By addressing these various pollutants and their combined effects, the research underscores the multifaceted benefits of UGS in promoting cleaner air within urban environments.

Despite their advantages, remote-sensing methods also had certain limitations. The spatial resolution of remote-sensing data can limit the ability to identify and characterize small landscape features, such as individual trees. In addition, cloud cover can obscure land surfaces and prevent the acquisition of usable remotely sensed images (Yevide et al., 2023), and the integration of remotely sensed data with other data sources, such as cadastral data or household surveys, can be complex and require specialized skills. The other problem with these studies is that they don't present validations of the planning tool, and don't show how it has been used to make real urban planning decisions. Also, these studies focus on specific cities and, therefore, cannot be generalized to other countries or regions.

Other studies demonstrate the role of UGS in improving the health of urban populations, notably by reducing exposure to air pollution and the effects of greenhouse gases (Pessoa et al., 2022; Tate et al., 2024). More specifically, research shows that UGS contribute to reducing the risk of respiratory diseases by acting as a barrier against air pollution (Jaafari et al., 2020; Sun et al., 2019), reducing cardiovascular diseases (Heo and Bell, 2019; Hu et al., 2022) and limiting premature births (Asta et al., 2019). These studies show that UGS play a crucial role in protecting urban populations from one of the main environmental hazards associated with urbanization, air pollution, and thus help reduce the risk of non-communicable diseases. In addition, a significant number of studies focus on the positive impact of UGS on cardiovascular disease risk (Astell-Burt and Feng, 2020; Kondo et al., 2018; Seo et al., 2019).

Several studies have revealed that the implementation of NBS especially the development of green spaces infrastructures, is an innovative approach to mitigate UHI effect and improve life qualities in cities. However, despite the positive effect of NBS implementation on humans and environment, it comes with some downsides especially contributing to inequitable distribution of urban ecosystem services, benefiting wealthier areas while excluding marginalized communities (Thompson et al., 2023). Furthermore, NBS do not guarantee uniform benefits for people and nature, and can exacerbate urban tensions tied to conflicting visions of re-naturalization (Nóblega-Carriquiry et al., 2023). Research in the Global North shows that green agendas, if aligned with neoliberal urban development, can lead to displacement and rising housing costs, ultimately harming vulnerable populations (Torres et al., 2023).

4. Discussion

This review provides a comprehensive overview of Urban Green Spaces (UGS) and climate change through a spatiotemporal lens, highlighting the global scientific effort to address urban climate challenges. The analysis covered 1,274 scientific publications, primarily journal articles (873) and conference proceedings (170). English proved to be by far the dominant language of publication, accounting for 95.29% of the documents. This suggests that the majority of research in this field is disseminated and accessible to an international English-speaking audience. This dominance of English could limit the accessibility of research to non-English speaking audiences and hinder the global dissemination of knowledge. Indeed, by addressing language barriers and promoting inclusive research communication, findings of research on this critical topic could be accessible to a wider global audience and contribute to more informed decision-making and effective actions. Contributions of non-English speaking researchers to research on this topic may have been underrepresented despite the diversity of publication languages due to the search pattern used to retrieve scientific productions and the platform used. However, despite the importance of the topic covered by bibliometric analysis, several authors have pointed out that English was the dominant publication language (Liu et al., 2011; Yevide et al., 2016; Guerrero-Moreno et al., 2024).

Research on UGS and climate change developed slowly after 2000 with a low growth rate and years of non-production till 2008. From 2008 onwards, there was a marked increase in the number of publications that continued exponentially from 2017 until 2023. This noticeable increase reflects the growing interest in research on UGS and climate change. It also reflects the rising recognition of the importance of UGS in mitigating climate change and promoting sustainable urban development. This trend could also be explained by the growing awareness of the impacts of climate change on urban areas such as heat island issues and the development of new methodologies as well as the urgency to act.

Furthermore, China and the USA have led the way in research into urban green spaces, while Germany has the third-highest number of publications in the world, well ahead of Australia. China's surge in publications stems from a growing interest in urban green spaces and heightened environmental awareness. As the country shifts from break-neck urban expansion to a model focused on high-quality development, green spaces have become an essential counterbalance to high-density construction in its major cities (Dong et al., 2023). The surge in research in these countries can be explained by several factors: awareness of the impacts of climate change on cities, recognition of the crucial role of urban green spaces in climate resilience, public health and general well-being, rapid urbanization, biodiversity concerns and the search for sustainable solutions for cities. Thus, since research on this subject has been carried out in China and the USA, it has developed rapidly. In-depth analyses of the Chinese CNKI database have revealed that research on "pocket parks", a type of urban green space in China, has mainly focused on planning and designing strategies for mitigating the heat island effect. Despite the progress made, it is important to note that research into UGS and climate change remains concentrated in a limited number of countries, especially developed ones. Entire regions, particularly in Africa, are lagging far behind. Nevertheless, the lack of information and research in Africa and Latin America can hamper evidence-based decision-making and planning (Du Toit et al., 2018). This also widens disparities in knowledge or knowledge gaps and limits the implementation of appropriate solutions on a global scale.

A global network of collaborations involving 4,312 authors from 87 countries worldwide contributed to research on UGS and climate change from 2001 to 2024. This network highlights the international nature of this research and the need for global cooperation to meet the challenges of climate change. South Africa's position as the only African country connected to the major networks is encouraging, but it also highlights Africa's limited contribution. Intense collaboration between China and the United States suggests that they are major players in this field of research. However, some countries' leadership in single-country publications may reflect national priorities in UGS and climate change research. The UK as the center of collaboration and the USA with the strongest collaboration, particularly with China, indicate strategic partnerships. The preponderance of the keywords "urban heat" and "heat islands" in publication titles highlights the growing impact of urbanization on urban microclimates. Urban concentration, characterized by increasing densification and population growth, contributes to rising temperatures and the formation of heat islands in cities (Padon et al., 2020). This trend is particularly noticeable in rapidly developing areas, where land use is changing at an accelerating pace. Studies reveal that increased urban density leads to higher temperatures in the urban environment compared to surrounding rural areas (Iamtrakul et al., 2024). Since understanding this complex phenomenon is essential to developing effective climate change mitigation and adaptation strategies in urban contexts, it is imperative to recognize the undeniable effectiveness of local climate data in quantifying the extent of the urban heat island effects. The increasing access to detailed climate data and the use of rigorous remote-sensing methods are opening up new perspectives for research into UGS and climate change (Best et al., 2023; Borna et al., 2023; Duan et al., 2022; Guo et al., 2022; Murtaza, et al., 2023). These data enable researchers to analyze long-term trends and understand spatial variations in the impacts of climate change on UGS in different urban contexts (Pudar and Plavšić, 2022). This enables informed decision-making and effective strategies to mitigate the effects of heat islands in cities. Rather than focusing solely on one-off urban heat events in specific areas, studies are turning to the analysis of time series of temperature data over several years. This approach provides a better understanding of local climate trends and enables us to assess the effectiveness of adaptation and mitigation strategies. These studies suggest the need to take into account the diversity of urban contexts for a thorough understanding of the interactions between UGS, urbanization and climate change (Barbierato et al., 2019; Pudar and Plavšić, 2022; Srivanit and Iamtrakul, 2019). Each city has its own natural and built environmental characteristics, which uniquely influences the impact of UGS on the urban microclimate.

5. Conclusion

This study illustrates the need for further research into UGS and climate change in Africa, Latin America and other under-represented regions of the world, and for comparative studies in several cities to identify general trends and regional variations. Given the current methodological gaps in the field of climate change and urban green spaces (UGS), future research should account for the quality of UGS when evaluating their impacts on both climate change and human health. It is also essential to validate urban planning tools based on remote sensing technologies and to illustrate their application through concrete case studies. This may help to better understand the state of facts and propose effective and sustainable strategies to mitigate the effects of climate change in our cities. In addition to these gaps and recommendations, it is important to strengthen international collaborations in UGS and climate change research, especially in under-represented countries. Pooling the knowledge and resources of researchers from all over the world is essential to developing effective and sustainable solutions to the challenges of climate change and urbanization.

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