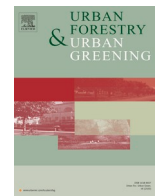


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Review article

## Global approaches for ecological restoration in urban environments: A PRISMA review

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## ABSTRACT

Since the Industrial Revolution, global urbanization has expanded rapidly, leading to serious implications for human well-being and biodiversity. The rapid construction of cities has resulted in significant habitat loss, especially in the context of anticipated climate changes. Identifying trends in forest restoration in urban areas can contribute to implementing adaptive and mitigating measures that support future public policies. Using the PRISMA method, this study aimed to identify scientific articles describing restoration approaches in urban forests, focusing on trends that facilitate model development in urban regions facing rising temperatures and droughts. Our results show that, despite convergence favoring ecological restoration in urban areas, the scientific knowledge supporting model development is still in progress. Most reviewed articles focused on countries with temperate forests, while none addressed the tropics. Our results highlight that restoration requires a strategic approach, prioritizing native species and combining local knowledge with scientific expertise. Community involvement and continuous monitoring are crucial to maintaining ecological functions and adapting to rapid climate-related changes occurring globally, especially in the tropical zone. We also emphasize that forest restoration strategies in cities should be incorporated into long-term urban policies and not remain solely within the scope of compensatory actions. This work highlights a gap in forest restoration in urban areas and highlights the importance of countries in tropical regions developing more research with these approaches.

## 1. Introduction

In the first decade of the 21st century, the human population living in cities surpassed the rural population for the first time in history. The trend of urbanization is accelerating and by 2035, 62 % of the global population is expected to live in cities (UN-Habitat, 2022). This has severe implications for human well-being and health, as well as threats to biodiversity and the provision of ecosystem services due to rapid and unplanned urbanization (IPBES, 2021; Rodrigues et al., 2022). Urban lifestyles generally distance humans from direct contact with nature as most medium-sized, large, and megacities predominantly comprise a gray infrastructure matrix. While some municipalities intensively promote green infrastructure (Lafortezza and Sanesi et al., 2019), large cities in tropical regions have limited capacity to improve human

well-being and face significant challenges in providing ecosystem services and supporting biodiversity (Oliveira et al., 2020).

Rapid urban growth in countries in Africa, Asia, and Latin America has transformed natural landscapes leading to significant habitat losses, especially in areas designated as biodiversity hotspots (Weller et al., 2019). Tropical forests, in particular, continue to be converted to other land uses mainly due to peri-urbanization, which can reduce and isolate forest remnants (Oliveira et al., 2020). This trend is particularly evident in the deforestation arc prevalent in countries with high socioeconomic inequality and socioenvironmental vulnerability, including those in South and Central America, Africa, and Southeast Asia (Achard et al., 2014; Furumo and Aide, 2017; Houghton & Nassikas, 2017).

Countries transitioning from predominantly agricultural to industrial activities have a high potential to convert degraded land into forest

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systems. However, urban land rarely reverts to natural or agricultural systems (Grau et al., 2003), emphasizing the importance of maintaining and restoring green ecosystems in cities. Knowledge on the dynamics of native and planted forests is essential for proper restoration, especially in highly anthropized environments. Restoring degraded forest fragments and even deforested lands is essential to reestablish ecological balance. In this sense, urban forest restoration plays a key role in biodiversity maintenance and in promoting more resilient cities. One example is the increased possibility of gene flow in the urban environment and a wider range of niches for urban species (Santos et al., 2024). However, such restoration programs must not remain solely within the scope of compensatory actions but strategically incorporated into urban planning (Yirga et al., 2023). This involves the creation of strong public policies encouraging the protection and recovery of green areas, conservation of water bodies, and places for health promotion.

Despite urban forest fragments contributing significantly to people's overall well-being and quality of life (Laforteza et al., 2018; Giannico et al., 2021), they have received less attention in ecological restoration programs than natural environments. It is worth highlighting that urban forests provide numerous ecosystem services for cities and humans (i.e., nutrient cycling, food supply, and climate regulation), especially from the perspective of physical and mental health benefits (Endreny et al., 2017; Jungman et al., 2023).

Considering the models of urban ecological restoration to guide effective practices in different biomes (Hobbs and Harris, 2001), specific challenges such as heat islands, air pollution, and the introduction of exotic and invasive species are often overlooked. These challenges have been underreported in urban restoration papers (Ribeiro et al., 2021a, 2021b; Ramon et al., 2023). The scarcity of studies outlining protocols for restoring urban forests with high biological diversity limits their implementation, especially in urban territories within important biogeographic domains (e.g., Cerrado, Atlantic Forest, and Amazon). Furthermore, few papers published in important databases like Web of Science are in languages other than English, which limits understanding and information synthesis.

This premise aligns with the urgent need to develop city adaptation models capable of addressing projections of extreme climatic events in the coming decades, such as ecological droughts or extreme precipitation events in Latin America (Nunes et al., 2023). Therefore, reviewing previous studies on the topic could guide the generation of protocols considering similar and divergent characteristics of each region where the urban restoration model is applied.

In the ecological context, urban green spaces have gained prominence in recent years due to their crucial role in supporting biodiversity and ecosystem services (Douglas et al., 2020). However, the lack of applicable guidelines based on scientific knowledge complicates decision-making in urban restoration projects and hinders the acquisition of resources and the achievement of effective and sustainable results. Furthermore, the absence of a consolidated set of best practices can lead to failed attempts, resource wastage, and additional biodiversity loss.

Therefore, this study aimed to revise and discuss scientific approaches of urban ecological restoration worldwide to propose guidelines for urban fragments, primarily focusing on the effects of anticipated climate changes. This synthesis will facilitate the understanding of how diverse strategies can be effectively implemented in complex urban environments, supporting the development of particular practices for each territory considering its ecological and socio-environmental aspects.

## 2. Method

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, 2023) guidelines. An exploratory analysis was performed to identify descriptors for ecological restoration in urban environments using the terms

"restoration ecology," "ecological restoration," "urban," "urban forest," and "cities". The term "climate change" was further included to ensure that only studies within this perspective were selected. During the screening process, books, book chapters, and articles in languages other than English were excluded. The search for publications was not limited to a specific time frame.

The search was carried out in the Web of Science (WoS) database, which contains approximately 75 million academic data points, 1.5 billion cited references in 254 disciplines, and around 34,000 journals. WoS has a small number of journals exclusively covered (Singh et al., 2021) and a low proportion of absence of highly cited documents (Martín-Martín, 2018). Given the importance of local and regional scientific journals that meet social needs, in 2015 WoS expanded its scope to a more comprehensive representation of the most influential research, while maintaining a balance between subjects and regions (Birkle et al., 2020). In addition to providing a variety of search resources and data downloads (Birkle et al., 2020), WoS is considered an effective academic research system for synthesizing evidence in the form of systematic reviews (Gusenbauer and Haddaway, 2020). In addition, 44.5 % of WoS publication records are in the Life Sciences (Singh et al., 2021), which is particularly relevant to this study.

Once we identified the publications (195), titles and abstracts were read to first recognize the ones unrelated to our topic (30). Analytical reading of the abstracts led to a second exclusion. Out of 165 studies, 37 were excluded as book chapters and 73 for not being in English.

The remaining 55 articles underwent a full manuscript reading. Twenty-one were not strictly related to the main search topic, and six were excluded for not focusing on the objectives of this review, even though they were initially selected after abstract reading. Finally, 34 articles were considered and technically analyzed within the scope of the PRISMA Systematic Review (PRISMA, 2023) (Fig. 1).

The 34 selected publications were compiled using the "market list" feature on the WoS and the complete metadata was exported to an Excel file. A detailed analysis of the articles and their metadata was conducted using inductive coding techniques to structure categories of analysis by breaking down the text and grouping it into registration units. These units included the following elements: authors, article title, year source, title, DOI link, country of study, city, main topic, and potential outcomes for public policies, as well as possibilities, difficulties, and challenges.

After re-reading the 34 manuscripts, textual analyses were conducted using the Iramuteq software (R 4.1.3) to identify word clusters, trends, and correlations. The abstracts of all manuscripts were formatted, resulting in summaries primarily composed of verbs and nouns. This method aimed to prevent the clustering of manuscripts due to non-technical words (i.e., pronouns and articles).

Using the formatted text, the software processed the data to create a co-occurrence matrix, which records how often words appear together in the text. We focused on words having a minimum occurrence of '10' (Ratinaud, 2009). Subsequently, a similarity analysis was performed, generating a co-occurrence tree to visualize the strength of the connections between terms determined by the frequency with which words co-occur in the text (Salviati, 2017). This analysis results in clusters of words that often appear together, revealing patterns and semantic connections within the texts.

## 3. Results and discussion

### 3.1. Restoration models in urban forests worldwide

A chronological analysis of the manuscripts evaluated reveals that between 2008 and 2020, the number of articles that fell within the scope of this systematic review was relatively low. However, in recent years (2021–2023), the number of manuscripts on the restoration of urban ecosystems has doubled in comparison to the sum of the previous period (Fig. 2). This growing trend of articles from 2021 onwards has been driven especially by China, most likely due to its unprecedented

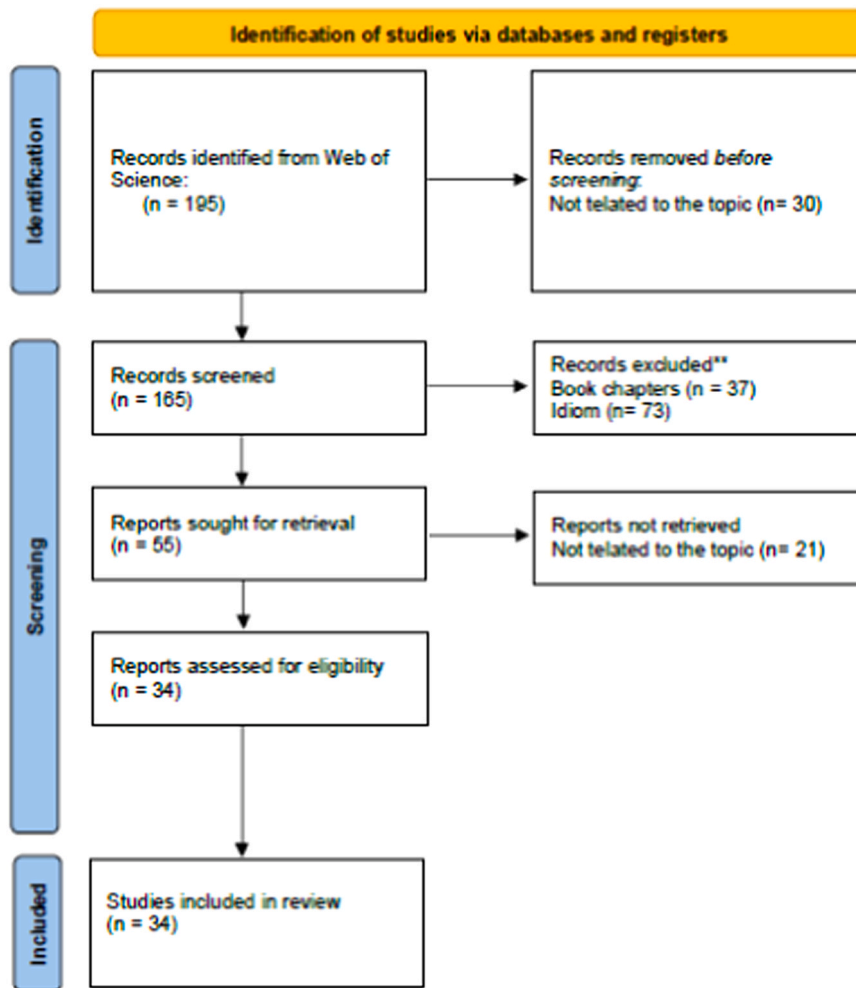


Fig. 1. Study flowchart.

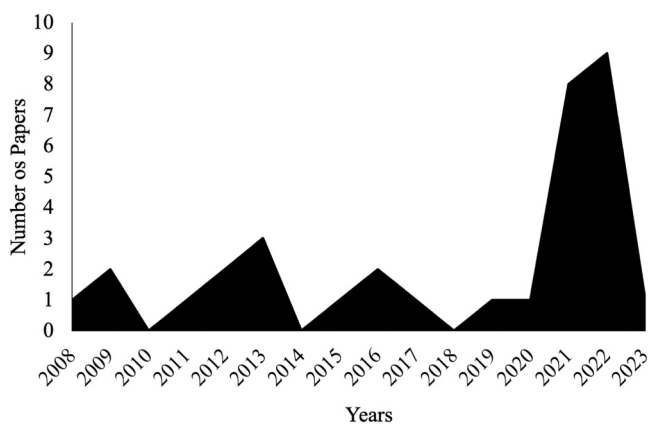


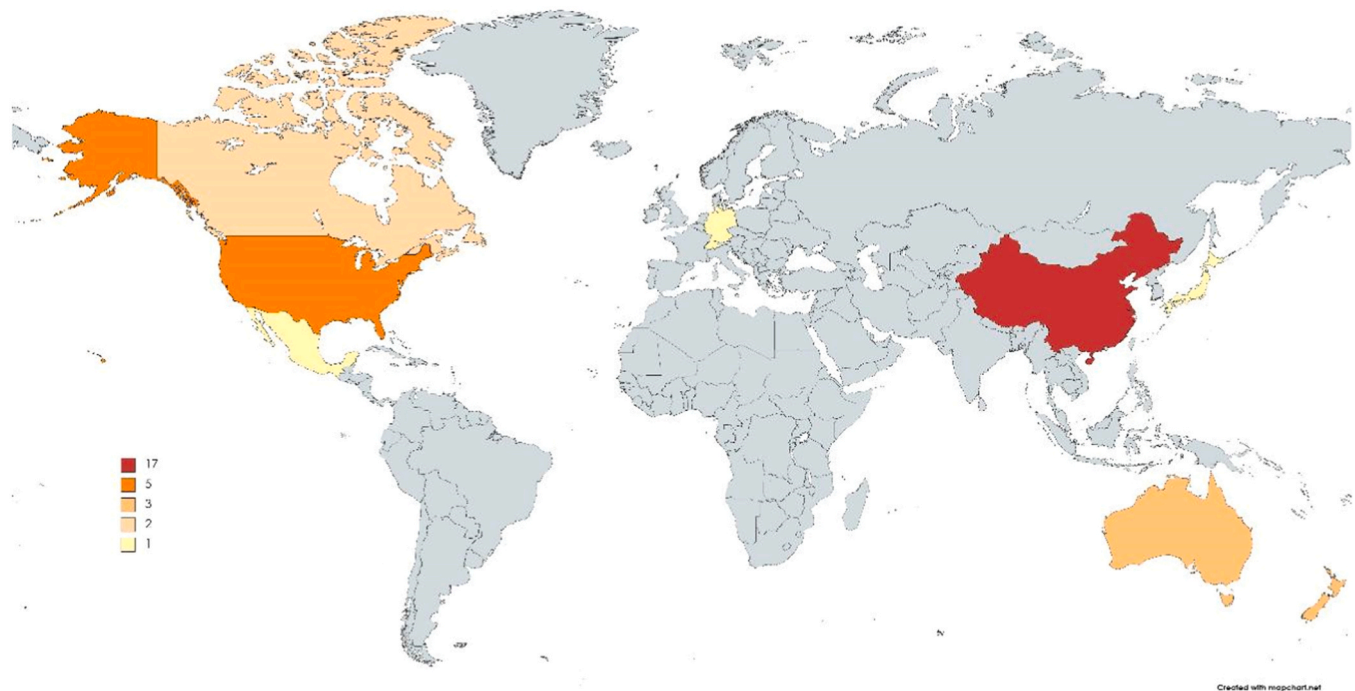
Fig. 2. Scientific publication trend from 2008 to 2023 encompassing ecological restorations in urban fragments.

urbanization process (Hou et al., 2023). The advancement of remote sensing technologies, the accumulation of metadata, and the development of modeling have also contributed to this increase in scientific production. These resources have enabled the creation of integrated approaches for identifying priority areas and formulating ecological restoration policies based on long-term land use changes (Cao et al., 2022; Hou et al., 2023; Hu et al., 2022; Huang et al., 2022).

China leads the publications (n = 17). The concept of eco-

civilization (ecological civilization) was adopted by the country in the 2010s as a national strategy for sustainable development and is the main public policy driving these studies (Chen et al., 2017; Chen et al., 2022; Lv et al., 2022; Hong et al., 2022; Ran et al., 2022; Wang et al., 2022a, 2022b; Cao et al., 2022; Wang et al., 2021). Fig. 3 shows the distribution of works by countries and continents, highlighting the places that most contribute to this field of knowledge. The level of concern regarding ecological restoration in urban areas was low in the United States of America (n = 4) (Johnson & Handel, 2019; McLain et al., 2012; Pavao-Zuckerman, 2008; Watkins et al., 2013); New Zealand (n = 3) (Busbridge et al., 2021; Clarkson & Kirby, 2016; Wallace et al., 2022) and Australia (n = 3) (O’Meara & Darcovich, 2015; Sinclair and HOBBS, 2009; Standish et al., 2013). Canada had two publications (Schaefer, 2009; 2011), while other countries, such as Germany (Schröder and KIEHL, 2020); Japan (Takeuchi et al., 2014); Mexico (Bonilla-Rodríguez et al., 2021); Switzerland (González Molina, et al., 2022), and Taiwan (Lin et al., 2022) published only one article (Fig. 3). These numbers reveal concerning scenarios. For example, only two studies were performed in Europe (González Molina, et al., 2022; Schröder and KIEHL, 2020), renowned for its ancient cities, and one study in Japan (Takeuchi et al., 2014), a country with a small area and one of the largest populations among the world’s major cities.

Although only China represents the global South in this review, 51 % of the studies are from this part of the world. These studies address the identification of key sites for green infrastructure based on the establishment of ecological networks (Hou et al., 2023; Yu et al., 2012; Zhai and Huang, 2022); the importance of ecosystem services (Wang et al.,



**Fig. 3.** Global distribution of the number of publications on ecological restoration in urban environments according to the PRISMA search (keywords: "restoration ecology," "ecological restoration", "urban," "urban forest," and "cities") between 2008 and 2023.

2022a, 2022b; Sun et al., 2021) and the landscape quality (Huang et al., 2022; Hu et al., 2022). Furthermore, Chinese research has examined the impact of climate change and land use on local carbon dynamics (Liu et al., 2021); the function of natural vegetation in maintaining water quality (Yu et al., 2013), and the role of local ecological knowledge in urban restoration (Chen et al., 2016).

Of the 41 sites evaluated in ten territories (including Taiwan), 17 are considered large, mega, and metacities with a population expected to surpass 230 million by 2030 (UN, 2019). The largest agglomerations studied were Sydney (Australia), Beijing, Chongqing, Hangzhou, Hefei, Jinan, Nanjing, Qingdao, Shanghai, Shenzhen, Suzhou, Tianjin, Wuhan, and Zhenjiang (China), Mexico City (Mexico), and Chicago and New York (United States) (Bonilla-Rodríguez et al., 2021; Cao et al., 2022; Chen et al., 2016; Hou et al., 2023; Hu et al., 2022; Huang et al., 2022; Johnson & Handel, 2019; Liu et al., 2021; Lv et al., 2022; O'Meara and Darcovich, 2015; Sun et al., 2021; Yang et al., 2019; Yu et al., 2012; 2013; Watkins et al., 2013; Wang et al., 2022a, 2022b; Zhai and Huang, 2022).

We found no articles from South America and Africa with an urban restoration approach, despite the enormous demand in these continents for methodologies that adapt cities to climate change. Their territories are socioeconomically vulnerable and consequently face greater socio-ecological challenges (Nadir et al., 2020). This may indicate a research gap in restoration studies of urban forests in developing countries, even considering studies involving other perspectives on urban forests that were recently published (Pereira et al., 2022; Ramon et al., 2023; Ferreira, 2024).

Specifically in the case of Brazil, which is a country with continental dimensions in South America and with numerous biodiversity hotspots, this research gap represents a threat amid current challenges in environmental and climate policies. The Atlantic Forest, for example, the second-largest South American tropical forest, hosts about 70 % of the Brazilian population (Tabarelli et al., 2010). Although there is a robust regulatory system for maintaining and recovering this biome, its implementation still requires more effort. The Federal Law of the Atlantic Forest, published in 2006, includes the implementation of the Municipal Plan of the Atlantic Forest, an instrument aimed at restoring

degraded areas to expand the forest continuum. However, by 2023, only 12 % of municipalities located in the biome had taken measures to implement the policy (Ferreira et al., 2023; PMMA, 2024).

This scenario further increases the need to know, compile, and adapt ecological restoration models in urban forests. In this review, approaches focused on the urban environment bring different perspectives depending on the context in which the restoration is embedded, considering regional aspects, as shown in Table 1. The articles found present a variety of proposals for urban restorations in different political, social, and economic contexts and it is possible to note from the description of the main topics the reasons and relevance that each manuscript highlights. While some authors emphasize the ecological value of urban forest restoration, others point out methods that have been relatively successful in restoration, such as the work of Chen et al., (2016) who consider Local Ecological Knowledge as a source of solutions for modern landscaping, promoting its interaction with nature.

The articles in this review provide some guidelines that can be grouped according to their respective urban-ecological similarities: i) Urban Ecological Restoration & Ecological Memory, ii) Land Use, Vegetation, and Environmental Interaction, iii) Methodology & Planning For Restoration Strategies, iv) Water Resources and Edible Landscapes, and v) Disaster-Affected Urban Environments.

The possibilities in urban restoration are numerous and encompass a sequence of measures. Initially, the environment needs to be assessed regarding the spatial distribution of green areas and ecological corridors (Hou et al., 2023; Sun et al., 2021). This enables the identification of key areas to be protected and degraded areas for restoration (Wang et al., 2021; Wang et al., 2022), which can be done through the Morphological Spatial Pattern Analysis technique (Zhai and Huang, 2022), soil analysis (Pavao-Zuckerman, 2008), and understanding the region's challenges (Hong et al., 2022).

Beyond these ecological actions, ecological restoration should be understood as a multifactorial process involving ecological, social, and economic aspects that advances in parallel with the city's development (Bonilla-Rodríguez et al., 2021; Hu et al., 2022; Yu et al., 2012).

Adapted strategies are also needed for urban centers and peripheries, as each reality may present specific restoration needs (Clarkson and

**Table 1**  
Ecological restoration approaches identified in this PRISMA review.

Authors	Year	Source title	Country of study	City	Main topic
Pavao-Zuckerman, MA	2008	Restoration Ecology	United States	Tucson	Detect the impacts of cities on soil and their implications for urban ecological restoration.
Sinclair, EA; Hobbs, RJ	2009	Restoration Ecology	Australia	Perth	Examine the effects of sample size of species in an urban ecological restoration.
Schaefer, V	2009	Restoration Ecology	Canada	Victoria	Analyze the importance of ecological memory for urban ecological restoration.
Schaefer, VH	2011	Urban Ecosystems	Canada	Victoria	Analyze the importance of ecological memory and invasive species for restoration.
Yu, DY; Xun, B; Shi, PJ; Shao, HB; Liu, YP	2012	Ecological Engineering	China	Shenzhen-Guangdong province	Develop a methodology for planning a conservation network based on remote sensing data.
McLain, R; Poe, M; Hurley, PT; Lecompte-Mastenbrook, J; Emery, MR	2012	Urban Forestry & Urban Greening	United States	Seattle	Analyze the benefits of producing and using edible landscapes in cities.
Standish, RJ; Hobbs, RJ; Miller, JR	2013	Landscape Ecology	Australia	Crawley	Understand how urban ecological restorations influence interactions between humans and nature.
Yu, DY; Shi, PJ; Liu, YP; Xun, B	2013	Ecological Engineering	China	Shenzhen-Guangdong province	Design a comprehensive water quality indicator to understand the impact of ecological restoration on water resources.
Watkins, C; Massey, D; Brooks, J; Ross, K; Zellner, ML	2013	Ecology and Society	United States	Chicago	Investigate how structural and behavioral mechanisms influence decision-making in urban ecological restorations.
Takeuchi, K; Elmqvist, T; Hatakeyama, M; Kauffman, J; Turner, N; Zhou, D	2014	Sustainability Science	Japan	Kesenuma	Identify key points for urban restoration of environments affected by disasters.
O'Meara, J; Darcovich, K	2015	Ecological Management & Restoration	Australia	Sydney	Monitor 12 years of restoration of an urban park.
Chen, CD; Meurk, CD; Cheng, H; Lv, MQ; Chen, RY; Wu, SJ	2016	Urban Forestry & Urban Greening	China	Chongqing	Suggest an urban restoration model that considers Local Ecological Knowledge as a source of solutions for modern landscaping, promoting its interaction with nature.
Clarkson, BD; Kirby, CL	2016	Ecological Management & Restoration	New Zealand	Hamilton	Review the history and current state of restoration ecology in urban fragments.
Johnson, LR; Handel, SN	2019	Urban Forestry & Urban Greening	United States	New York	Analyze the vegetation structure and community composition in 3 urban parks to understand the impact of management intensity on the long-term success of restoration.
Yang, YY; Zheng, H; Xu, WH; Zhang, L; Ouyang, ZY	2019	Sustainability	China	Beijing-Tianjin-Hebei	Evaluate land use policies and examine changes in vegetation distribution and its interaction with the environment.
Schröder, R; Kiehl, K	2020	Urban Forestry & Urban Greening	Germany	Osnabrück	Develop and test different measures for the ecological restoration of an urban fragment to increase native plant species richness.
Liu, C; Liang, Y; Zhao, YJ; Liu, SS; Huang, CB	2021	International Journal of Environmental Research And Public Health	China	Wuhan	Estimate spatial changes in response to land use changes and climate change.
Sun, H; Liu, CH; Wei, JX	2021	Land	China	Nanjing, Suzhou, Wuxi, Changzhou, and Zhenjiang	Identify key locations to provide a cost-effective method for the restoration and development of an ecological network in urban clusters.
Wang, ZY; Shi, PJ; Zhang, XB; Tong, HL; Zhang, WP; Liu, Y	2021	Sustainability	China	Jiuquan	Analyze spatial principal components to assess the ecological security of the regional landscape.
Busbridge, S; Clarkson, BD; Wallace, KJ	2021	Urban Forestry & Urban Greening	New Zealand	Hamilton	Understand the drivers behind the planning, implementation, and management of urban restoration projects.
Bonilla-Rodríguez, M; Arroyo-Lambaer, D; Castillo, A; Zambrano, L; Cano-Santana, Z	2021	Frontiers In Sustainable Cities	Mexico	Mexico City	Assess the feasibility of restoring vegetation on a university campus.
Hu, XW; Xu, WW; Li, FY	2022	Land	China	Hangzhou	Identify degraded landscapes in urban fragments and coordinate socio-ecological needs to determine restoration.
Lv, L; Zhang, SH; Zhu, J; Wang, ZM; Wang, Z; Li, GQ; Yang, C	2022	International Journal Of Environmental Research And Public Health	China	Chongqing	Combine the construction of ecological security patterns with circuit theory to identify key points of sources and ecological corridors.
Hong, L; Pang, SL; Zhu, CF; Li, YH; Guo, YX; Lei, TT; Wang, K	2022	Discrete Dynamics In Nature And Society	China	Jiaozuo	Propose a green and diverse strategy for sustainable urban restoration planning to meet citizens' needs for a natural ecosystem experience.
Ran, YJ; Lei, DM; Li, J; Gao, LP; Mo, JX; Liu, X	2022	Ecological Indicators	China	Yunnan	Build an Ecological Security Pattern by identifying sources and ecological corridors to determine crucial areas for restoration.
Wang, ZF; Liu, Y; Xie, XQ; Wang, XK; Lin, H; Xie, HL; Liu, XZ	2022	Land	China	Fujian	Assess the importance of ecological service functions and ecological sensitivity.
Cao, XF; Liu, ZS; Li, SJ; Gao, ZJ	2022	International Journal of Environmental Research and Public Health	China	Hefei	Propose a framework to evaluate the expected effects of ecological restoration based on land use changes and ecological security.

(continued on next page)

Table 1 (continued)

Authors	Year	Source title	Country of study	City	Main topic
Lin, CY; Liao, MC; Wang, W; Tzeng, Y	2022	Sustainability	Taiwan	Dadu District	Understand the soil composition characteristics of urban forests and the use of seed banks for urban ecological restoration.
Zhai, TL; Huang, LY	2022	Frontiers In Ecology and Evolution	China	Shandong Peninsula	Analyze the morphological spatial pattern and evaluate habitat quality.
Wallace, KJ; Clarkson, BD; Farnworth, B	2022	Forests	New Zealand	Aotearoa	Present results of an urban forest restoration project.
Wang, F; Yuan, XZ; Zhou, LL; Zhang, MJ	2022	Environmental Science and Pollution Research	China	Chongqing	Identify ecological sources by integrating ecosystem services and landscape connectivity through the Ecological Security Pattern.
González-Molina, HZ; Trilleras, JM; Pyszczyk, OL; Romero-Duque, LP	2022	Acta Botanica Mexicana	Switzerland	Zurich	Analyze the role of cultural ecosystem services associated with participatory ecological restoration.
Huang, JD; Wang, YC; Zhang, L	2022	Land	China	Shanghai	Identify the most degraded areas of landscape quality and classify the types of ecological restoration at different levels of degradation.
Hou, W; Zhai, L; Walz, U	2023	Ecological Engineering	China	Pequim	Spatial analysis for identifying priority areas for the restoration and conservation of ecological networks.

Kirby, 2016), especially urban centers that are more affected by the effects of climate change (Liu et al., 2021). These actions promote a more efficient practice, ensuring targeted efforts with the least possible investment (Lv et al., 2022).

For the restoration itself, the paths point to a common goal: the use of native species and removal of invasive species, thus restoring the local ecological memory (Schröder and Kiehl, 2020; Schaefer, 2009; Schaefer, 2011). The knowledge of the local population is a key component in this process (Chen et al., 2016) and combining it with scientific data indicates safe paths for restoration (Busbridge et al., 2021; Takeuchi et al., 2014). Moreover, restoration can benefit from natural resources by

using the Ecological Security Pattern to map routes (Wang et al., 2022).

Community involvement, not only during restoration but also throughout the process of establishing the urban forest, is essential for success because it brings meaning to the population strengthening the interaction between humans and nature (González Molina, et al., 2022; Lin et al., 2022; McLain et al., 2012). Regular monitoring of restoration by local inhabitants, the scientific community, and decision-makers ensure the continuity of the process and guarantee the maintenance of ecological functions (Huang et al., 2022), especially in rapidly changing urban environments (Johnson & Handel, 2019).

Restoration solutions are diverse, given that the urban environment

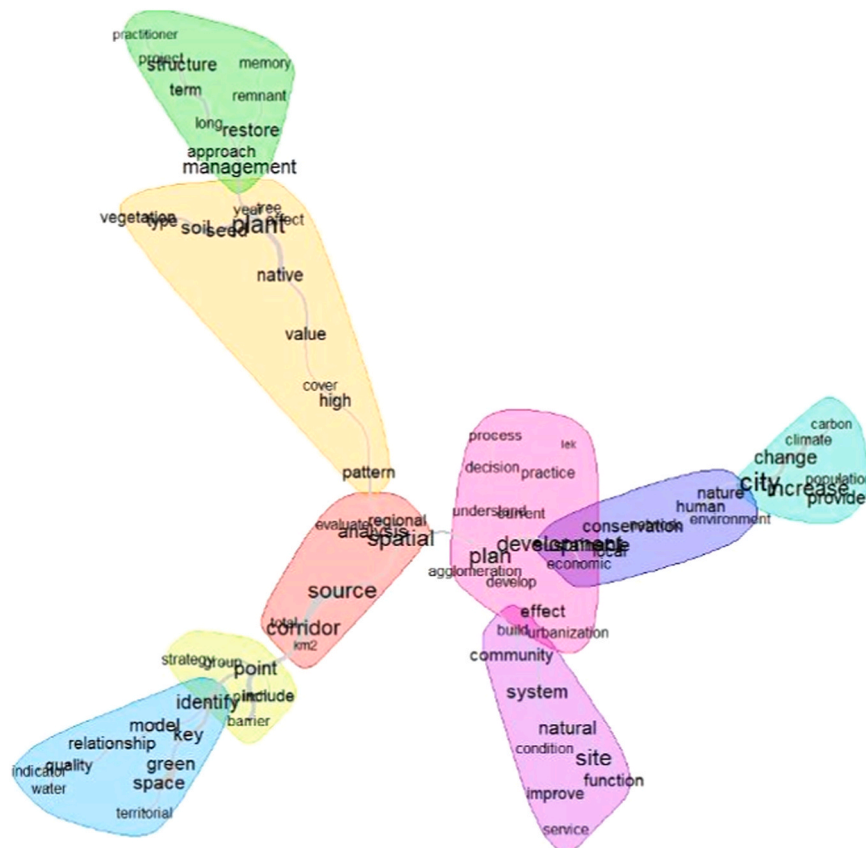


Figure 4. Word similarity analysis with a frequency equal to or greater than '10'. create a green area that is meaningful to society and aligned with the region's native flora."

is a heterogeneous and complex landscape. An integrated approach is necessary to evaluate the entire context of where the urban environment is located, from the environment to be restored, the surrounding population, the management, and the restoration objectives.

### 3.2. Textual analysis of restoration models in urban forests

The compilation of summaries of the articles selected in this review (corpus) resulted in nine clusters (Figure 4), showing low information similarity. This graphic representation, marked by branches and words with different sizes, helps to understand common occurrences of words and favors potential associations (or distance) in certain terms.

We observed that the larger the sphere, the greater the frequency of word occurrences in the ecological restoration models. The clusters are interconnected by branches, representing the connection strength. The thicker the branch (gray color), the stronger the connection (Figure 4).

The words within the green grouping indicate that many articles on restoration consider the management of remaining areas, ecological memory, and the structure of the site's vegetation. This cluster of words demonstrates the importance of identifying Local Ecological Knowledge and meeting the needs of citizens in urban ecological restorations to create green areas meaningful to society and aligned with the region's native flora (Chen et al., 2016; Hong et al., 2022; González Molina, et al., 2022). Understanding the local ecological memory is crucial for identifying species that best adapt to the location, promoting stability and resilience for the restored system (Schaefer, 2009), and reinforcing the interaction between the local community and nature (Standish et al., 2013).

'Plant', in the orange grouping, is the largest cluster in the corpus and the most used term in the articles, associated mainly with words like 'native,' 'value,' 'pattern,' and 'soil.' These co-occurrences indicate the authors' attention to the choice of species for restoration and the importance of native species over alien species, generating ecological value for the restored area according to the natural vegetation cover and following a pattern that promotes greater balance for the area (Sinclair and HOBBS, 2009; Schaefer, 2009; Schaefer, 2011; Chen et al., 2016; Hong et al., 2022). Choosing native species also brings other benefits and favors fundamental ecosystem processes in forest productivity (e.g., nutrient cycling) (Ferreira et al., 2021). Lin et al. (2022) and Schröder and KIEHL (2020) highlight the feasibility of using native herbaceous plants for restoration of some green areas, ensuring rapid revegetation of the fragment. This strategy seems suitable for promoting pollinator habitats while enhancing the scenic value of the urban landscape (Banhara et al., 2003).

On the other hand, the red grouping below 'Plants' suggests that connecting natural and urban environments through ecological corridors is a suitable strategy for restoring urban forests. Identifying and understanding crucial areas for ecological restoration is essential to promoting targeted practice (Ran et al., 2022), connecting internal and external city parts, and creating an ecological network (Zhai and Huang, 2022). Ecological Security Patterns play a role in this context, as reported by Cao et al. (2022), Lv et al. (2022), Ran et al. (2022), Wang et al., (2022a,b).

On the right side of the corpus, four intersecting clusters stand out, whose main co-occurrences were 'development', 'conservation', 'plan', 'site', 'natural', 'city', and 'change'. These words suggest that restoration models for urban forests should align their practices with sustainable development perspectives. One way is through municipal policies (e.g., urban forestry plans) that must take into consideration other urban challenges, especially those related to climate change.

Liu et al. (2021), Hou et al. (2023), and Yang et al. (2019) emphasize the relevance of including the restoration of urban forests in important Agendas (e.g., 2030 Agenda, New Urban Agenda, Climate Agenda), where the positive impact of carbon sequestration from reforestation might neutralize, in parts, the negative effects of urbanization. Moreover, Yu et al. (2013) report that vital economic indicators in restored

urban environments showed an annual growth of 1.5 %, reinforcing the viability and importance of restoring nature in urban areas for economic development. Additionally, Yurui et al. (2021) show that restoration of native forests in urban areas significantly controlled environmental problems related to urban water resources, reducing soil erosion processes, and preventing flood incidence in the city. This information highlights the importance of ecological restoration to adapt cities to the effects of extreme climatic events.

The intersection between two clusters (pink and lilac) in the lower left part of Figure 4 highlights the co-occurrences of 'identification', 'model', 'key', 'point', and 'strategy', expressing the need to identify not just a fundamental model, which is a strategy for the recovery of urban environments, but also critical locations for restoration in large centers such as in several articles from China (Yu et al., 2012; Wang et al., 2022a, 2022b; Hou et al., 2023). Likewise, a study carried out in Mexico highlighted the importance of choosing key locations to promote restoration (Bonilla-Rodríguez et al., 2021). Such a strategy can be a strong ally of public management in territories with wide social inequality and spatial heterogeneity of urban forests, as these spaces bring benefits to physical and mental health (Carrus et al., 2015; Spano et al., 2023). In the context of the socio-environmental crisis, Wang et al. (2021) and McLain et al. (2012) propose the feasibility of restoring urban fragments through edible landscapes, i.e., restorations with plants commonly consumed by the local community so that these fragments can be more significant for the population. This increases contact between society and nature, also highlighted by Chen et al. (2016) and Hong et al. (2022).

In this same trend of prioritizing ecological restoration areas, the only Japanese article included in this review also focused on natural hazards and disaster risk reduction through strategic ecological restoration sites. Areas with low urban suitability can be used to maintain biodiversity and promote ecosystem services (Takeuchi et al., 2014).

Hu et al. (2022) and Huang et al. (2022) emphasize the importance of identifying key areas to incorporate green infrastructure in cities and highlight that a target location should be degraded and highly anthropized areas. This identification of target locations can reestablish ecological patterns and processes inherent to biodiversity, increase gene flow, and facilitate fauna movement and seed dispersal, making the restoration process more economically and ecologically viable (Hou et al., 2023).

Six authors of this review highlighted that one way to identify key areas for urban forest restoration is through Morphological Spatial Pattern Analysis, which diagnoses patches and habitat corridors that connect the landscape (Cao et al., 2022; Huang et al., 2022; Lv et al., 2022; Sun et al., 2021; Zhai and Huang, 2022). This method uses land use data to extract natural ecological elements and other land use types through various means of image processing, emphasizing structural connection to identify landscape types crucial to maintaining connectivity and supporting the selection of ecological corridors (Ye et al., 2020).

Although the location of the fragment to be restored is a very important point, monitoring the restoration process is equally necessary. Johnson & Handel (2019) emphasize that fragments restored with greater monitoring have greater ecological balance. This highlights the importance of continuous management of restored areas given the rapid changes occurring in urban centers (Wallace et al., 2022; O'Meara and Darcovich, 2015). Monitoring the ecological restoration process can be done with the involvement of different actors, through formal and lasting meetings, increasing the gains of the process and making decisions more assertive (Clarkson and Kirby, 2016).

The term 'pollution' was absent in our similarity analyses. However, this is an essential aspect to be considered in ecological restoration processes, as the species chosen should be tolerant to particulate and/or gaseous pollutants. When well managed and positioned, tree density can serve as an action to mitigate atmospheric pollution by reducing the dispersion of particulate matter over long distances (Martins et al.,

2021). In this review, only Yu et al. (2013) addressed this aspect when investigating water quality indicators to measure the effects of diffuse pollution in urban areas. These authors showed that restored areas promoted better water quality in the region analyzed.

However, there is still a lack of significant investment in restoring urban areas to facilitate temperature reduction through evapotranspiration. This highlights a weak connection between scientific research and the planning, implementation, and management of ecological restoration, as noted by Busbridge et al. (2021). Watkins et al. (2013) also emphasized the need for formal meetings to consolidate information and develop urban ecological restoration approaches. To ensure the success of this convergence, a strong link among research, planning, implementation, and management is essential.

#### 4. Conclusion

Ecological restoration in urban environments is still at an embryonic stage, although models have gained prominence over the years. The articles in this review point to heterogeneity of interests in the subject across the globe, with a massive emphasis on China. Countries from the global North were also well represented in this review, while South America, Africa, the Middle East, and Europe were underrepresented. Interest in ecological restoration in urban environments has generally become more pronounced after the COVID-19 pandemic, likely driven by a greater need to expand well-designed urban green areas.

Restoration is not an individual action and requires a strategic and comprehensive approach to be effective. Among the steps, the most crucial is analyzing the environment to be restored, identifying and prioritizing degraded areas, and planning urban restoration to enhance ecological connectivity between sources and corridors. The use of native species should be prioritized, combining local community knowledge with scientific expertise as the involvement of the community is essential for the success of the process. Once restored, the work is not complete and monitoring remains a vital step to maintain ecological functions in parallel to adaptations to the rapid changes in urban environments, especially considering climate changes in the tropical zone that is still largely neglected.

In a socio-environmental context, restoration could incorporate edible species (e.g., fruit trees) and urban gardens, thus improving food security and increasing community engagement with green spaces. Despite these insights, we recommend that ecological restoration in urban environments should be widely investigated by the scientific community so that urban planners and stakeholders can have more tools for decision-making, especially concerning city adaptation strategies for extreme events.

#### CRedit authorship contribution statement

**Catarina Carvalho Nievola:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **MAURÍCIO Lamano FERREIRA:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Elaine Aparecida Rodrigues:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Eduardo Pereira Cabral Gomes:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Isabella Aparecida Fonseca Bertoleti:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

#### Declaration of Competing Interest

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

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