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The Importance of Urban Green Infrastructures for Realizing Carbon Neutrality in Cities: A Synthesis and Meta-analysis

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Abstract

To evaluate the importance of urban green infrastructure in achieving carbon neutrality. Methods: The relevant articles about urban green infrastructure were searched in foreign language database (Science Direct). The search period was from 2015 to 2023, when the most research results were obtained. Literature screening, using RevMan5.4 software for Meta analysis of data. Results: Finally, 26 literatures were included. According to Meta analysis, compared with other traditional infrastructures, urban green infrastructure can effectively improve urban heat island effect, rainwater treatment, air pollutants and noise pollution. Conclusion: Compared with traditional infrastructure, urban green infrastructure is more conducive to urban sustainable development. Therefore, urban green infrastructure plays a very important role in achieving the goal of carbon neutrality.

Keywords: Urban green infrastructure; conventional infrastructure; carbon neutrality; meta analysis.

1. Introduction

Since the Industrial revolution in the 1760s, with the rapid development of urbanization, a large number of ecological and environmental problems began to emerge. Such as ozone layer destruction, acid rain pollution, water and soil loss, the sustainable development of human society has been seriously threatened, especially the emission of greenhouse gases, which is also one of the main problems leading to global warming. According to the statistics of the World Meteorological Organization (WMO) in the state of the Global Climate 2020 report, 2020 is one of the hottest single years in the history of complete meteorological observation records. The average global temperature in the last five years (2015-2020) and the last ten years (2011-2020) has also reached the highest levels on record, making them the warmest five and ten years on record. Climate changes dramatically over time (IPCC. 2014). The Earth has warmed every decade since 1850. Globally, the evidence of climate change is already clear. In the 20th century, the global mean temperature increased by 0.74°C, the ice sheet decreased by 40%, and the natural sea level rose by 17 cm (Berthold J, 2013).

The global change caused many regional and local impacts which varied significantly between sites (UNFCCC, 2019). These impacts formed real risks to the entire world and especially to the cities where people mainly concentrate. At the same time, many cities around the world suffer from the phenomenon of 'urban heat island'. In general, urbanization processes lead to change the surface's climate within cities and form what is called (urban climate) (Ren G, 2015).

In an effort to combat climate change, 137 countries have pledged to become carbon neutral. As an important part of carbon neutrality, green infrastructure can effectively improve urban heat island effect, regulate urban microclimate, remove air pollutants and improve water quality, thus helping people to achieve carbon neutrality. GI can be defined as all engineered features with natural elements (e.g. vegetation) or natural features, such as remnant habitat, that are within or around urban development and that support ecological services(Tzoulas et al., 2007). We chose to examine GI type that are completely human designed with natural elements (Table 1 in supporting information). The benefits of GI for regulating ecosystem services have been proven and are frequently recommended (Lepczyk et al., 2017; Schilling & Logan, 2008; Tzoulas et al., 2007). For example, vegetation on GI types such as green walls or roofs, reflect and redistribute heat in ways that lead to cooler buildings and cities, both having positive impacts on human health and well-being (Coutts & Hahn, 2015; Miles & Band, 2015; Norton et al., 2015; Sookhan, Margolis, & MacIvor, 2018). GI is also frequently utilized for stormwater regulation and is among the most common reasons for implementation (Jayasooriya & Ng, 2014; Lewis, Simcock, Davidson, & Bull, 2010). Understanding the difference in carbon neutrality between GI and conventional infrastructure or natural counterparts is crucial for improving implementation. Quantifying the benefits of GI on urban environment is a necessary step to find the implications of green infrastructure for carbon neutrality. The materials used in GI construction can be refined in different environments. For instance, Replacing traditional brick roofs with green roofs can help mitigate greenhouse gases since a green roof can reduce the indoor temperature up to 19.9 °C, save 28 % annually in electricity consumption and remove 80 % of rainwater pollutants (Tiago, 2020). The GI case of "tree canopy only" can be a potentially viable choice to reduce particle concentrations on the pathways due to the fact that its better ventilation conditions are more favorable for particle diffusion than other GI configurations (Yue-Ping Jia, 2021). However, there is relatively less quantitative evidence for the contribution of GI to carbon neutrality. Both positive and negative effects of GI on urban environment have been implied and documented, but no comprehensive study has quantified these effects using comparison to conventional counterparts in the urban environment (Table 1). With the expansion of constructed GI research, conducting a synthesis of the available literature can improve GI implementation to optimize contribution to carbon neutrality. In this study, we review the literature and conduct a meta-analysis to improve understanding of GI and its relative contributions to change urban environment compared to natural and conventional counterparts in cities. Meta-analyses are a useful tool to synthesize research findings across studies and quantify estimates of effect sizes for a given hypothesis (Koricheva, Gurevitch, & Mengersen, 2013). Using a systematic review of the literature and extracted datasets from relevant studies, we set out to answer the following objective, and test one hypothesis using a meta-analysis. From our literature review, we describe and highlight research gaps that are present within GI. My hypothesis was that GI will more carbon neutral than conventional counterparts (e.g. green roof vs. bare roof) because GI can provide a higher quality to urban environment. Through Meta analysis, this paper compares green infrastructure with conventional infrastructure to prove that urban green infrastructure can effectively improve urban heat island effect, regulate urban microclimate, remove air pollutants, improve water quality, and explore the importance of urban green space in maintaining urban carbon neutrality. Our systematic review and meta-analysis can identify trends across studies that are generalizable and provide new insight into strategies to support carbon neutrality.

2. Methods

2.1. Systematic literature review

2.1.1. Retrieval strategy

The literature search was conducted using Science Direct for all peer-reviewed journal articles (i.e. studies) between 2015 and 2023. This time frame was chosen because it captures the majority of the literature on urban green space (see Fig. 1 in supporting information) and included all English-language studies from around the world. We used the following search terms to capture all studies that have documented both the types of GI implementation and Carbon Neutrality: (green infrastructure OR green roof OR rain garden)AND (low carbon OR sustainability). These terms were generated with the assistance of subject matter experts on green infrastructure in academia, government, and industry. The terms returned 2066 results (Fig. 1 in supporting information). All studies were screened for their relevance to the study and 1959 were excluded for reason such as 1) not about green infrastructure, 2) no relationship between green infrastructure and carbon neutrality, 3) presenting a conceptual framework and no data collected (Fig. 2 in supporting information).

2.1.2. Data collection and extraction

Data collection and extraction: Researchers searched the literature independently, read the title, abstract and full text of the articles, and screened the articles according to the inclusion and exclusion criteria. After the inclusion of the literature was determined, the data were extracted, including: article title, author, publication year, research object, research method, data collection period, sample size, outcome index, etc.

2.1.3. Quality evaluation of literature: types of literature included

The 107 selected studies were then reviewed to extract the type of GI, the environmental impact parameters of different types of green infrastructure. We also obtained criteria relating to each city (name, coordinates, current policies of GI, current measures of carbon neutrality). The full list of examined studies and data that were extracted from each can be found in an open-access repository (Filazzola, Maclvor, & Shrestha, 2018). From the review, we identified a multitude of GI types (vegetated roadsides, green roof, rain garden, green wall).

2.2. Green infrastructure definitions

The type we included for comparative analyses included green roofs, green walls, yards/gardens (community & allotment), wetland detention basins, vegetated roadsides (Table 1). Features of GI were defined by the authors of the respective manuscript and we have included a general description of these features in Table 1. Comparisons of GI to conventional and natural counterparts were conducted within an individual study by calculating the Hedge's g effect-size estimate before be compared among studies. Some of the studies had multiple comparisons that would be used in the meta-analysis, such as the role of GI in different climate issues (e.g. heat island effect, air pollution, noise pollution, rainwater treatment).

2.3. Meta- analysis

We conducted a meta-analysis to statistically compare GI to conventional counterparts using data extracted from relevant studies. All analyses and data aggregation was conducted in Revman 5.4. We followed an approach similar to Koricheva et al. (2013) that provides a clear workflow including data aggregation, calculating effect sizes, and conducting statistical models. Studies that were included in the meta-analysis had to include the following criteria: 1) description of the GI and comparable feature (i.e. conventional counterparts), 2) the improvement of environmental problems, and 3) data reported/provided as either means with standard deviation or raw data where means and error could be calculated. The number og replicates in each study was recorded to be used as the n value in analyses. I also extracted any physical characteristics that described the GI including the age post-construction, height (for green roofs and green walls), depth (for vegetated roadsides), pH of soil/water, and area (m^2) of GI. To compare similar metrics within each study, we summarized data to the taxa and measured estimate of environmental improvement. Data was summarized across all sites within a study but separated by the type of GI.

3. Result

3.1. Green infrastructure research trends

We reviewed 2,512 GI studies, of which 107 provided some qualitative description of the effects of carbon neutrality and sustainable development, and 26 had empirical data available for analysis (*Figure 1*). North America (36%) and Europe (41%) are more frequently studied. Only 33 percent of the studies were conducted outside North America and Europe. The qualitative studies came from 69 different cities in 32 different countries. This study found that the most frequently inspected cities (i.e. more than 5 times) were densely populated cities, such as Melbourne (7), Toronto (7), London (5). The number of studies testing GI has increased significantly over the past 5 years, with 68% (N=1283) using defined search term extraction. Before 2005, the average number of GI studies published per year was about five.

Most of the studies reviewed (91.4%) did not include measures to improve environmental quality and were therefore excluded. These excluded studies mainly focus on the following aspects: 1) the impact of green infrastructure on biodiversity; 2) The impact of green infrastructure on human physical and mental health. In addition, a small number of studies were excluded because they were review literature, conceptual frameworks or policy studies.

3.2. Green infrastructure vs. conventional infrastructure

In the study about the heat-island effect between green infrastructure and traditional infrastructure, a total of 7 studies were included for meta-analysis. The results showed that Heterogeneity: $I^2 = 98\%$. The random effects model (RE) was used to make the forest map. The results showed that green infrastructure and traditional infrastructure had statistical significance in alleviating heat island effect (Fig.2). Among the studies on rainwater treatment by green infrastructure and traditional infrastructure, a total of 6 studies were included for meta-analysis, the test results: Heterogeneity: $I^2 = 94\%$. Among the studies on air pollution from green infrastructure and traditional infrastructure, a total of 7 studies were included in the meta-analysis, and the test results showed that Heterogeneity: $I^2 = 80\%$. Among the studies on noise pollution from green infrastructure and traditional infrastructure, a total of 6 studies were included for meta-analysis, and the Heterogeneity: $I^2 = 96\%$.

Therefore, it is concluded that green infrastructure and traditional infrastructure have statistical significance in alleviating heat island effect, rainwater treatment, air pollution and noise pollution. Through data analysis, it is found that compared with traditional infrastructure, green infrastructure is more conducive to alleviating urban heat island effect, storm water treatment problems, air pollution and noise pollution. So green infrastructure is more conducive to achieving carbon neutrality.

4. Discussion

This study found that compared with traditional infrastructure, green infrastructure can better mitigate urban heat island effect, thus regulating urban temperature and urban microclimate. By ysung ENVI-met, a computer climate simulation program, the temperature of the study area surface was assessd according to four UGI scenarios which involved the use of the cooler materials and the addition of different green and blue assets to the existing grey uses. It was found that UGI has an effective role in reducing the SUHI intensity by 4 to 22℃ in one city (Maryam, 2021). Green infrastructure also improves water quality by filtering pollutants from rainwater.Green infrastructure (GI) revitalizes vegetation and soil, restores hydro-ecological processes destroyed by traditional urbanization, and naturally manages storm water on-site, offering numerous sustainability benefits (Krishna P., 2023). Green infrastructure can better control the amount of water on the ground during the rainy season, thus preventing water accumulation and flooding caused by excessive rainfall. Urban flooding is one of the greatest threats to life and property, further exacerbated by the impacts of a warming climate. A study show that green infrastructure remains effective during more frequent storms (~ 80th percentile) that can occur in warmer climatic conditions and retrofitting or converting a smaller than expected percentage of the urban landscape (up to 5 %) can yield appreciable benefits (Suresh. 2022). Green infrastructure cleans the air by better removing pollutants from it. A study investigated the potential performance of air pollution removal by the green infrastructures and urban forests in the city of Florence, central Italy, with a focus on the two most detrimental pollutants for human health: particulate (PM10) and ozone (O3). The spatial distribution of green infrastructures was mapped using remote sensing data. A spatial modeling approach using vegetation indices, Leaf Area Index, and local pollution concentration data was applied to estimate PM10 and O3 removal. The results are discussed to highlight the role and potential of green infrastructures and urban forests in improving air quality in Southern European cities (Francesca, 2016). To sum up, urban green infrastructure is of great significance for achieving carbon neutrality.

4.1. The limitations of green infrastructure in achieving carbon neutrality

Results show GI is an improvement over conventional infrastructure in most cases, but it still has some limitations for achieving carbon neutrality. The first limitation is that while green infrastructure can mitigate urban heat island effects better than conventional infrastructure, it has a limited effect on carbon neutrality. The second limitation is that because carbon neutrality is a very complex issue, it includes economy, policy, technology and many other areas.

4.2. The research prospect of urban green infrastructure

Existing studies show that urban green space plays a prominent role in social, environmental, biological and economic aspects. It is an important place to relieve pressure, enhance communication, cultivate emotions and exercise the body in modern society, and it is irreplaceable in the future urban development. In addition, the dense population and crowded buildings lead to constant contradictions and conflicts in modern cities. The existence of urban GI is not only an ideal way to realize the construction of an ecological city, but also an effective way to alleviate various contradictions and conflicts in the process of urban development. As an important part of urban landscape, urban green space is the “glue” between urban buildings. It connects isolated buildings organically. It not only forms the “face” of the city, but also serves as the lubricant for each building unit (Wilson et al, 2011). From the perspective of research content, geographical knowledge plays a special role in the cognition of urban green space location and regional differences, so urban green space should be one of the main research contents of urban geography. Based on the scale, size and landscape characteristics of green space, this paper makes a comprehensive analysis of its ecological, social and economic functions, understands and measures the contribution and role of green space to the social, economic and environmental aspects of the city in combination with the distribution characteristics of urban residential and economic activities, and analyzes the interaction between the natural and social economic aspects of the city. So as to optimize the urban layout and enhance the sustainability of urban development (Zhenshan Yang, 2015) (Figure 3).

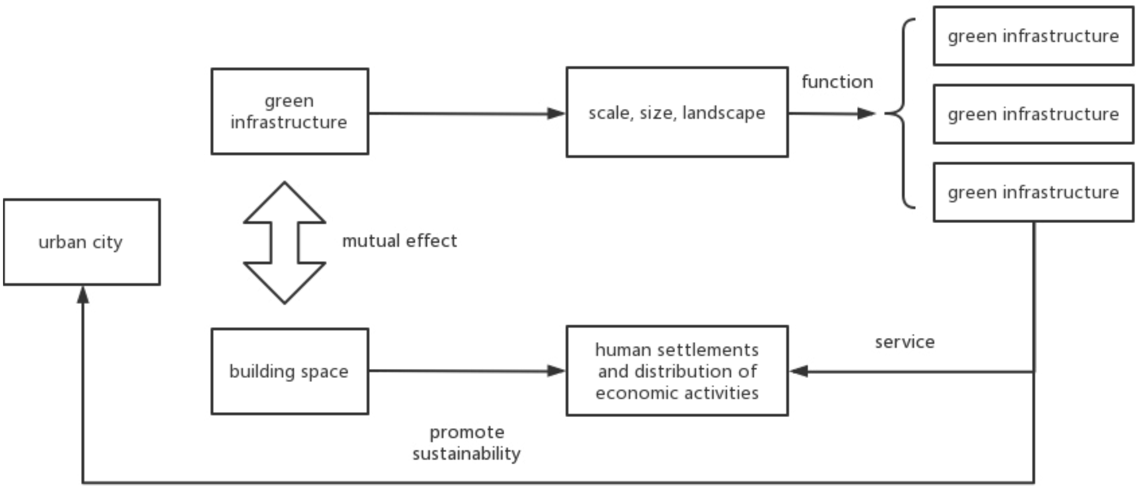

Figure 3. Role of urban green space in sustainable urban development

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Support Information

Table 1: Definitions of constructed green infrastructure (GI) types used for comparisons with conventional and natural counterparts.

GI Type	Definition	Conventional Infrastructure	Key reference
Green roof	Roofs with a vegetated surface and substrate that supports the vegetation. The vegetation can be of any type.	Asphalt roof	(Oberndorfer et al., 2007)
Green wall	Vegetation that grows on the side of a building and relies on support structures (e.g. trellises)	Concrete or brick wall	(Hunter et al., 2014)
Rain garden	Rain gardens are shallow, vegetated depressions that are decentralized micro-scale control measures for rainwater management.	The rain collection system or the drain	(Ewa, 2023)
Yards/gardens	Residential properties and local gardens for growing food, i.e. community and allotment gardens	A vacant lot within a city that has vegetation and is unmanaged besides mowing	(Cameron et al., 2017)

Table 2: The frequency of studies that were examined for each green infrastructure (GI) type and the urban environmental problems that were explored

GI Type	Number of Studies	Heat Island Effect (%)	Rainwater Treatment (%)	Air Pollution (%)	Noise Pollution (%)
Green roof	151	40%	28%	30%	2%
Green wall	41	46%	0%	32%	22%
Rain garden	10	0	100%	0	0
Yards/ gardens	16	31%	62%	0	7%
Vegetated roadsides	16	19%	0	81%	0

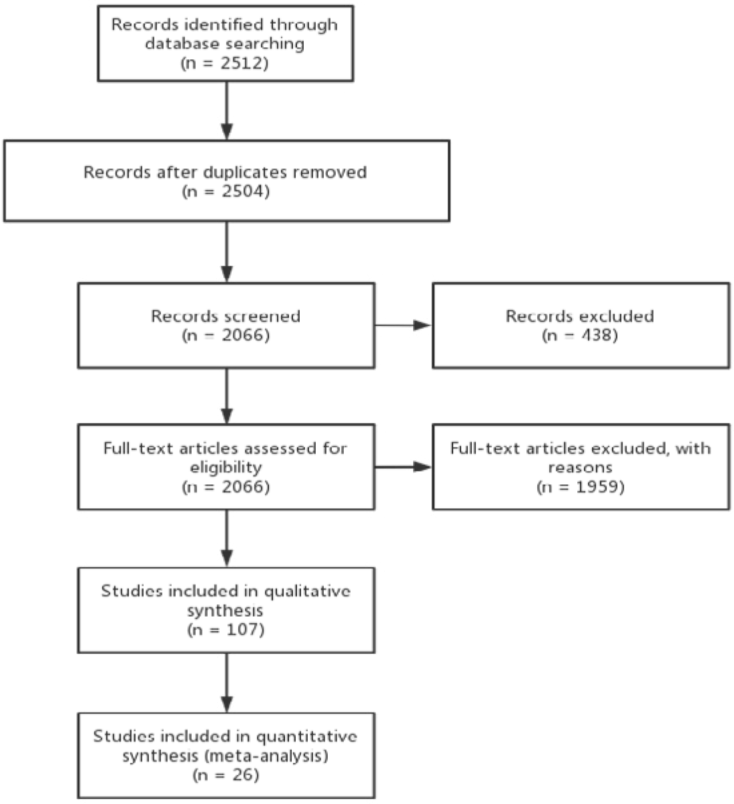

Figure 1. report on the number of studies examined and retained through the systematic review

Study or Subgroup	Experimental Events	Experimental Total	Control Events	Control Total	Weight	Risk Ratio M-H, Random, 95% CI
2.1.1 heat island effect						
Carlos Ba 2020	72	253	116	120	4.1%	0.29 [0.24, 0.36]
Carlos Ba 2021	86	160	123	160	4.2%	0.70 [0.59, 0.83]
Federica 2022	144	150	150	208	4.3%	1.33 [1.22, 1.46]
H. M. P. I. K. Herath 2018	63	280	43	280	3.7%	1.47 [1.03, 2.08]
L. Zardo 2017	58	60	60	135	4.1%	2.17 [1.79, 2.64]
Maryam F 2021	30	93	30	107	3.4%	1.15 [0.75, 1.76]
Richard Le 2022	60	85	100	120	4.2%	0.85 [0.72, 0.99]
Subtotal (95% CI)		**1081**		**1130**	**28.1%**	**0.97 [0.61, 1.55]**
Total events	513		622			
Heterogeneity: Tau² = 0.38; Chi² = 287.08, df = 6 (P < 0.00001); I² = 98%						
Test for overall effect: Z = 0.12 (P = 0.91)						
2.1.2 rain water treatment						
Cary Co 2021	60	05	100	120	4.2%	0.05 [0.72, 0.99]
Jingming Hou 2020	68	196	68	271	3.9%	1.38 [1.04, 1.83]
Josefina Herrera 2017	52	165	165	240	4.0%	0.46 [0.36, 0.58]
Kyoung Jin An 2015	342	415	342	445	4.4%	1.07 [1.00, 1.15]
Newton Célio 2017	100	121	100	196	4.2%	1.62 [1.38, 1.90]
Sara Perales-Momparler 2017	179	316	183	398	4.3%	1.23 [1.07, 1.42]
Subtotal (95% CI)		**1298**		**1670**	**25.0%**	**1.03 [0.80, 1.33]**
Total events	801		958			
Heterogeneity: Tau² = 0.09; Chi² = 89.51, df = 5 (P < 0.00001); I² = 94%						
Test for overall effect: Z = 0.22 (P = 0.83)						
2.1.3 air problem						
Ashutosh Kumar Pandey 2015	35	235	34	120	3.4%	0.53 [0.35, 0.80]
Ashutosh Kumar Pandey 2016	37	160	54	160	3.6%	0.69 [0.48, 0.98]
Mare Orbinovska 2020	33	342	40	342	3.3%	0.02 [0.53, 1.20]
Margareth Viecco 2021	59	150	60	150	3.9%	0.98 [0.74, 1.30]
Naomi J. Paull 2018	37	280	67	280	3.6%	0.55 [0.38, 0.80]
Nathalie Tomson 2021	46	60	60	60	4.3%	0.77 [0.67, 0.89]
V. M. Jayasooriya 2017	28	30	30	38	4.2%	1.18 [0.98, 1.43]
Subtotal (95% CI)		**1257**		**1150**	**26.3%**	**0.78 [0.62, 0.99]**
Total events	275		345			
Heterogeneity: Tau² = 0.07; Chi² = 30.72, df = 6 (P < 0.0001); I² = 80%						
Test for overall effect: Z = 2.07 (P = 0.04)						
2.1.4 noice problem						
Chang Liu 2022	60	85	100	120	4.2%	0.85 [0.72, 0.99]
Lan-Ting Chang 2022	68	196	68	271	3.9%	1.38 [1.04, 1.83]
M. Connelly 2015	52	165	165	240	4.0%	0.46 [0.36, 0.58]
Myung-Jun Kim 2014	100	121	100	196	4.2%	1.62 [1.30, 1.90]
Z. Azkorra 2015	46	60	60	60	4.3%	0.77 [0.67, 0.89]
Subtotal (95% CI)		**627**		**887**	**20.6%**	**0.92 [0.62, 1.38]**
Total events	326		493			
Heterogeneity: Tau² = 0.20; Chi² = 95.57, df = 4 (P < 0.00001); I² = 96%						
Test for overall effect: Z = 0.39 (P = 0.69)						
Total (95% CI)		**4263**		**4837**	**100.0%**	**0.92 [0.78, 1.08]**
Total events	1915		2418			
Heterogeneity: Tau² = 0.16; Chi² = 522.33, df = 24 (P < 0.00001); I² = 95%						
Test for overall effect: Z = 1.05 (P = 0.29)						
Test for subgroup differences: Chi² = 2.58, df = 3 (P = 0.46), I² = 0%						

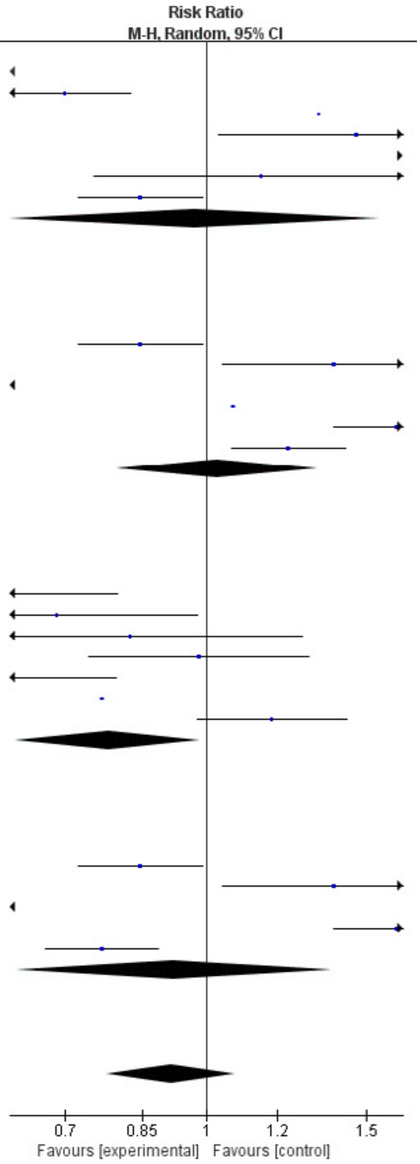

Figure 2. Mean effect sizes (Hedges'd) of green infrastructure (GI) on biodiversity relative to conventional counterpart separated by GI type

The study number represents a unique identifier from the list of manuscripts that were systematically reviewed (Filazzola et al., 2018). The measure is the estimate of carbon neutrality used that study. Error bars represent 95% confidence intervals and bars not overlapping zero (dashed line) are considered significant. To assess bias in the selection of studies, we calculated the Rosenthal's fail-safe number to be 432, suggesting there would need to be a significant number of unpublished studies to reduce these findings to insignificant.