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REVIEW

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The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis

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Abstract

1. The development of buildings and other infrastructure in cities is viewed as a threat to local biodiversity and ecosystem functioning because natural habitat is replaced. However, there is momentum for implementing green infrastructure (GI), such as green roofs, wetland detention basins and community gardens, that partially offset these impacts and that benefit human health.
2. GI is often designed to explicitly support ecosystem services, including implied benefits to biodiversity. The effects of GI on biodiversity have been rarely quantified, but research on this topic has increased exponentially in the last decade and a synthesis of the literature is needed.
3. Here, we examined 1,883 published manuscripts and conducted a meta-analysis on 33 studies that were relevant. We determined whether GI provides additional benefits to biodiversity over conventional infrastructure or natural counterparts. We also highlighted research gaps and identified opportunities to improve future applications.
4. We determined that GI significantly improves biodiversity over conventional infrastructure equivalents, and that in some cases GI had comparable measures of biodiversity to natural counterparts. Many studies were omitted from these analyses because we found GI research has generally neglected conventional experimental design frameworks, including controls, replication or adequate sampling effort.
5. *Synthesis and applications*. Our synthesis identified that taxa specificity is an important consideration for green infrastructure (GI) design relative to the more common measurements at the community level. We also identified that ignoring multi-trophic interactions and landscape-level patterns can limit our understanding of GI effects on biodiversity. We recommend further examination of species-specific differences among infrastructures (i.e. green, conventional or natural equivalents) or using functional traits to improve the efficacy of GI implementation on urban biodiversity. Furthermore, we encourage policy makers and practitioners to improve the design of GI to benefit urban ecosystems because of the potential benefits for both humans and global biodiversity.

KEYWORDS

ecosystem services, green roof, retention pond, stormwater management, urban ecology, wildlife conservation

1 | INTRODUCTION

Urbanization is occurring globally and threatens the biodiversity of natural systems. Cities support more than 50% of the human population currently and are projected to increase in both extent and density in the future (Grimm et al., 2008; Seto, Fragkias, Güneralp, & Reilly, 2011; UN DESA, 2016). Cities threaten biodiversity because development alters, removes, and replaces natural habitat that supports pre-existing plant or animal species (Aronson et al., 2014). Urban areas are also home to some species of conservation concern (Ives et al., 2016) that may be at risk of extirpation from further human development. This is because impervious development, such as roads, buildings or parking lots, usually increases habitat fragmentation (Aronson et al., 2014), alters nutrient deposition and cycling (McDonnell et al., 1997) and redistributes water (Grimm et al., 2008). As urban environments continue to expand, it becomes increasingly important that efforts to conserve biodiversity include sharing land human needs with natural systems (Lin & Fuller, 2013). There is an opportunity to conserve biodiversity in urban environments by promoting green space that can benefit human populations, for example, stormwater management, urban cooling and air purification (Gómez-Baggethun & Barton, 2013). However, there is still a significant research gap with regard to the measured benefits of incorporating green space into city infrastructure for biodiversity and thus our ability to mitigate the effects of urban development. This is especially the case where traditional protection of natural habitat and restoration opportunities are limited.

Green infrastructure (GI) can support urban biodiversity by providing a more suitable habitat for species relative to conventional, impervious "grey" infrastructure. 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 types that are completely human designed with natural elements (Table 1). Using this definition, we excluded parks because it is challenging to separate human-constructed parks from fragmented remnant habitat in urban centres. We also did not include riparian strips, cemeteries, brownfields or golf courses in our analyses because there is no identified conventional or natural counterpart. We used "wetland detention basin" to encompass many terms of transient of permanent water bodies that are used for stormwater management and surrounded by vegetation including retention ponds, stormwater basins, stormwater wetlands, stormwater management ponds, detention basins and constructed wetlands. 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). However, there is relatively less quantitative evidence for the contribution of GI to biodiversity conservation (Williams, Lundholm, & Scott MacIvor, 2014). GI in cities can provide habitat for species in many ways including providing a substrate for plants and fungi (Fulthorpe, MacIvor, Jia,

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

GI Type	Definition	Conventional infrastructure	Natural counterpart	Key references
Green roof	Roofs with a vegetated surface and substrate that supports the vegetation. The vegetation can be of any type.	Asphalt roof	Natural vegetation (e.g. shrubland, grassland, forest, rocky habitats[a])	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	Natural vegetation on vertical substrates such as cliffs or rock outcrops[b]	Hunter et al., 2014
Wetland detention basin	Human-constructed areas for detaining stormwater that have a soil bottom and are surrounded by a vegetation buffer.	Artificial pond without plants	Natural pond with no stormwater input from human sources	Jayasooriya & Ng, 2014
Vegetated roadsides/bioswales	Edges of vegetation at ground-level or with planters alongside a human development (e.g. road, housing development)	Concrete or asphalt curbs	Natural vegetation (e.g. shrubland, grassland, forest)	Arenas et al., 2017
Yards/gardens	Residential properties and local gardens for growing food, that is, community and allotment gardens	A vacant lot within a city that has vegetation and is unmanaged besides mowing	Natural vegetation (e.g. shrubland, grassland, forest)	Cameron et al., 2012

Note: Comparisons to natural vegetation were study specific. A description of each tested GI type, conventional counterpart and natural counterpart can be found in Table S4.

[a]The substrate characteristics and planted vegetation on green roofs most closely resembles alpine communities or other rocky habitats (Lundholm, 2006). However, none of these comparisons were made in the examined studies.

[b]None of these comparisons were observed in the examined studies.

& Yasui, 2018; Thuring & Dunnett, 2014), providing water resources for aquatic animals (Lewis et al., 2010), acting as a refuge from reduced pesticide application (Lepczyk et al., 2017) and providing food resources, such as flowers for pollinators (MacIvor, Ruttan, & Salehi, 2015) or decomposing vegetation for detrivorous insects (Starry et al., 2018). Understanding the difference in habitat between GI and conventional infrastructure or natural counterparts is crucial for improving implementation. Quantifying the benefits of GI on urban biodiversity is a necessary step for city planners to find synergies in supporting ecosystems services and biological conservation.

Materials used in GI construction can be refined for habitat creation in different ecoregions and biodiversity enhancement strategies in cities. For instance, using more diverse assemblages of plants on green roofs can better support arthropod communities (Kadas, 2006; Madre, Vergnes, Machon, & Clergeau, 2013) and bird species (Fernandez-Canero & Gonzalez-Redondo, 2010). Constructing wetland detention basins to more closely resemble wetlands by planting vegetation can provide habitat for amphibians (Hamer, Smith, & McDonnell, 2012). However, there must be consideration of increased salt or pollutants via stormwater run-off from paved areas (Kayhanian, McKenzie, Leatherbarrow, & Young, 2012). To reduce the impacts of urbanization on biodiversity, the design of GI should consider connectivity to nearby natural habitat. For example, on green roofs, building height (MacIvor, 2016) and local landscape composition (Braaker, Ghazoul, Obrist, & Moretti, 2014) were important determinants of biodiversity. Also, microhabitat factors that can increase extreme conditions, such as unique building features like roof depressions or adjacent windows, may affect biodiversity and should be considered (Buckland-Nicks, Heim, & Lundholm, 2016; McIntire & Snodgrass, 2010). Both positive and negative effects of GI on biodiversity have been implied and documented, but no comprehensive study has quantified these effects using comparison to natural or conventional counterparts in the urban environment (Table 1). With the expansion of ecological research of constructed GI, conducting a synthesis of the available literature can improve GI implementation to optimize contribution to biodiversity conversation.

In this study, we review the literature and conduct a meta-analysis to improve understanding of GI and its relative contributions to biodiversity conservation 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 two hypotheses using a meta-analysis. From our literature review, we describe and highlight research gaps that are present within GI. Our first hypothesis was that GI will support higher biodiversity than conventional counterparts (e.g. green roof vs. bare roof) because the constructed vegetation provides a habitat or resources for urban species. Our second hypothesis is that GI will support lower biodiversity than natural counterparts (e.g. wetland detention basins vs. natural pond) because GI is not a replacement for natural systems and does not provide equivalent habitat. Our systematic review and meta-analysis can identify trends across studies that are generalizable and provide new insight into strategies to support biodiversity in cities.

2 | MATERIALS AND METHODS

2.1 | Systematic literature review

The literature search was conducted using Web of Science and Google Scholar for all peer-reviewed journal articles (i.e. studies) between 1980 and March 2019. This time frame was chosen because it captures the majority of the literature on GI (see Figure S1) and included all English language studies from around the world. We used the following search terms to capture all studies that have documented both GI implementation and a measure of biodiversity: (*green infrastructure OR low*impact development OR sustainable drainage system* OR water sensitive urban design OR green*roof OR urban garden OR pollinator garden OR bioretention OR stormwater planter OR raingarden OR tree pit OR wet*swale OR stormwater wetlands OR detention basin* OR infiltration basin*) AND (*diversity OR species OR ecosystem OR ecology OR habitat* OR co-benefit). These terms were generated with the assistance of subject matter experts on GI in academia, government and industry. The terms returned 1,883 results and we collected 28 additional studies from discussion with fellow researchers and identifying citations from the other manuscripts collected (Figure 1). All studies were screened for their relevance to the study and 1,721 were excluded for reasons such as (a) not measuring biodiversity, (b) examining the effects of ecosystem services only (e.g. flood mitigation and reducing solar radiation) or (c) presenting a conceptual framework and no data collected (Figure S2). Lastly, we used Dryad, KnB and Figshare to collect 10 online repositories that measured biodiversity and species occurrences in GI and a natural or conventional counterpart. Our final selection had 33 studies that quantitatively described features of GI in relation to biodiversity and an additional 162 studies that had a qualitative description. An independent researcher validated a small subset of studies to ensure that our criteria for inclusion and exclusion were effective (Koricheva et al., 2013).

The 33 selected studies were then reviewed to extract the type of taxa examined (e.g. birds, arthropods, plants), the response variable measured (e.g. abundance, richness, diversity), the type of GI and the comparison habitat (conventional or natural counterparts). We also obtained criteria relating to each city (name, coordinates, current population estimate and current population density). The full list of examined studies and data that were extracted from each can be found in an open-access repository (Filazzola, MacIvor, & Shrestha, 2018). From the review, we identified a multitude of GI types (vegetated roadsides/bioswales, cemetery, green roofs, green wall, golf course, public/community gardens, wetland detention basins, urban tree canopy, urban park and yards/home gardens), conventional infrastructure counterparts (artificial water, conventional roadsides, conventional roof, conventional wall, agriculture/farm and urban ground) and natural

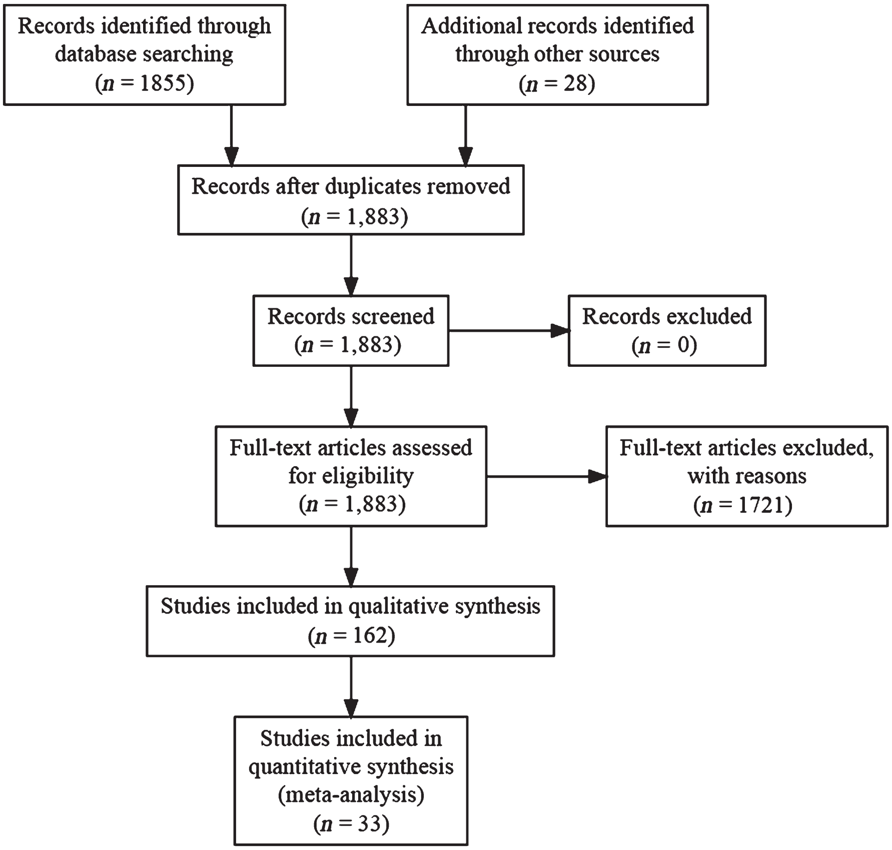

FIGURE 1 PRISMA report on the number of studies examined and retained through the systematic review

counterparts (natural pond, grassland and forest; Table 1). The relative frequency of each GI type was tested per study using a Pearson's Chi-squared test.

2.2 | GI definitions

The types we included for comparative analyses included green roofs, green walls, yards/gardens (community and allotment), wetland detention basins, bioswales/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 if they used different taxa (e.g. birds, arthropods, reptiles) or if they used a different measure (e.g. richness, biomass, abundance).

2.3 | Meta-analysis

We conducted a meta-analysis to statistically compare GI to conventional and natural counterparts using data extracted from relevant studies. All analyses and data aggregation were conducted in R Version 3.4.3 and a transparent workflow can be found online (https://afilazzola.github.io/GreenInfrastructureMeta). 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: (a) description of the GI and comparable feature (i.e. conventional or natural counterparts), (b) a measure of biodiversity (e.g. richness, abundance, Shannon Diversity) and (c) data reported/provided as either means with standard deviation or raw data where means and error could be calculated. The number of replicates in each study was recorded to be used as the *n* value in analyses. We also extracted any physical characteristics that described the GI including the age post-construction, height (for green roofs), depth (for wetland detention basins or vegetated roadsides/bioswales), 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 biodiversity. Data were summarized across all sites within a study but separated by the type of GI.

To contrast the two groups (GI vs. conventional, and GI vs. natural), we calculated effect sizes using the mean, standard deviation and n from each possible comparison (function *escalc*, package *metafor*; Viechtbauer, 2010). To correct for positive bias when comparing the mean difference between two groups, we used Hedge's *g* for the calculation of the effect size (Hedges, 1982). The meta-analysis was then conducted using a mixed-effects model (function *rma*, package *metafor*). A mixed-effects model was used because it accounts for differences in study methodologies and assumes the selected comparisons are a random subset of a large population of studies conducting similar comparisons

TABLE 2 The frequency of studies that were examined for each green infrastructure (GI) type and the taxa that were explored

GI type	Number of studies	Amphibians, reptiles and fish[a] (%)	Invertebrates (%)	Birds and bats (%)	Plants and trees (%)
Constructed wetland					
Wetland detention basin	28	44	36	8	12
Constructed terrestrial					
Green roof	24	0	46	25	29
Green wall	2	0	50	50	0
Public/community gardens	26	0	38	10	52
Vegetated roadsides/ bioswales	9	0	45	0	55
Yards/home gardens	28	0	42	21	37
Other GI					
Cemetery	1	0	0	0	100
Golf course	3	0	66.7	33.3	0
Urban tree canopy	16	0	0	0	100

[a]Fish and reptiles were only present in studies with wetland detention basins.

(Viechtbauer, 2010). We treated the features of GI as fixed effects to account for differences in the response of biodiversity. A mixed-effects model was fit for comparisons of GI to conventional counterparts (studies*comparisons = 15) and to natural counterparts (studies*comparisons = 40). We also fitted random-effect models for each GI type to describe the effect sizes within each sub-group.

3 | RESULTS

3.1 | GI research trends

We reviewed 1,883 studies on GI, with 162 that had some qualitative description of the effects for biodiversity and 33 that had empirical data available for analysis (Figure 1). A high frequency of studies were identified in North America (36%) and Europe (41%; Figure S3). Only 33% of studies were found outside of North America and Europe. The qualitative studies were described from 69 different cities in 32 different countries. We found cities that were examined frequently (i.e. greater than five times) were heavily populated such as New York (7), Melbourne (7), Toronto (7), Hong Kong (5) and London (5). The number of studies testing GI has increased significantly in the last 5 years with 68% of studies (N = 1,283) extracted using the defined search terms. Prior to 2005 the average number of studies on GI published per year was approximately five.

The majority of studies reviewed (91.4%) did not include measures of biodiversity and were excluded (Figure S2). These excluded studies focused on the effects of GI for (a) providing ecosystem services, such as flood management or reducing urban heat (22.8%), (b) human well-being (6.7%), or (c) green space planning for aesthetics (7.9%). Also, a small proportion of studies were excluded because they were reviews (6.2%), conceptual frameworks (3.2%) or policy studies (3.6%).

Each GI type had a significantly different number of associated studies (χ^2 = 91.5, p < .001; Table 2). Among the most frequently studied were green roofs, public/community gardens and residential yards (Table 2). Invertebrates and plants were most represented in the literature (Table 2). The most common community estimates in all studies were species richness (18.7%) and total abundance of individuals (35.9%). In a few cases, there were specific ecological variables of communities or species including: number of bird nests found (n = 1), pollen limitation (n = 1), total leaf area (n = 1) and survivorship (n = 1).

The physical characteristics of the measured GI were infrequently reported. In the 162 studies that had some qualitative description of GI effects for biodiversity, less than half of the studies included some measurement of size (20.3%), height/depth (11.7%) or pH of soil/water (8.1%). In the studies that provided some quantitative measures of GI effects for biodiversity, the year since the GI was constructed was reported in 32.5% of the studies. In the studies where age was reported, the average age of GI was 9.2 ± 2.03 years.

3.2 | Green versus conventional infrastructure

We found that GI significantly increased biodiversity relative to the conventional counterpart (mean effect ± SE = 1.00 ± 0.33; Z_{14} = 2.98, p = .0029; Figure 2), although responses among each type significantly varied (Q_W = 84.11, p < .001). Separating the type of GI explained some of this variability (Q_E = 49.9, p < .001) because there were significant differences among each group (Q_M = 19.9, p = .0013). The effect of GI significantly increased biodiversity for bioswales versus conventional roadsides (p = .0043; Figure 2), and green roofs versus bare roofs (p = .0093; Figure 2), but green walls versus building walls were not significantly different (p = .15; Figure 2). Wetland detention basins and urban gardens also did not have a significant effect on urban biodiversity relative to their

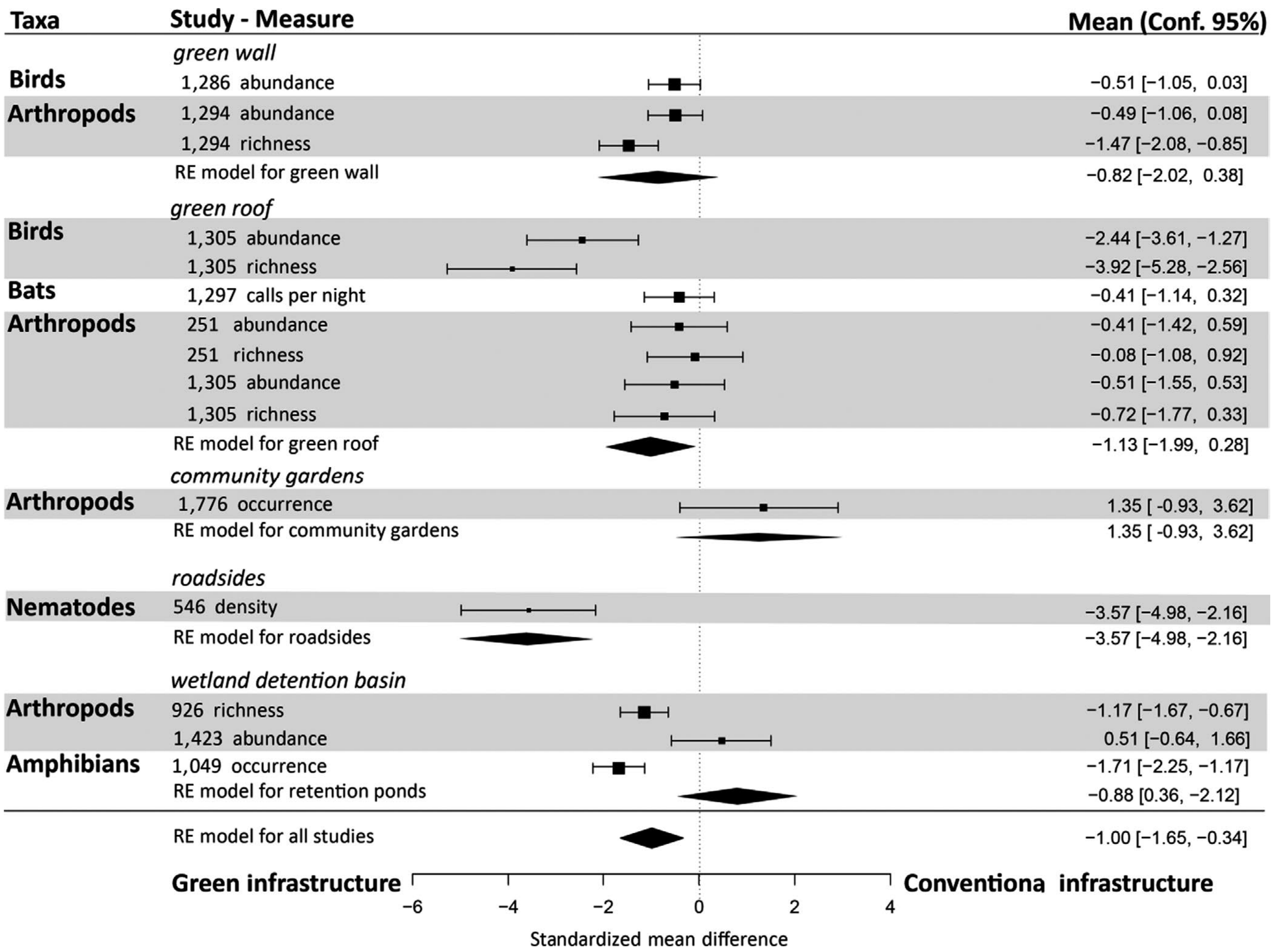

FIGURE 2 Mean effect sizes (Hedges' *d*) of green infrastructure (GI) on biodiversity relative to conventional counterpart separated by taxa and GI type. The study number represents a unique identifier from the list of manuscripts that were systematically reviewed (Filazzola et al., 2018). The measure is the estimate of urban biodiversity used in 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

conventional counterparts (Figure 2). Invertebrates were found to have an inconsistent response to GI with 50% of studies having no significant difference relative to a conventional counterpart (Figure 2). Measures of vertebrate species, with the exception of bats, almost always increased on GI compared to conventional counterparts (Figure 2).

3.3 | GI versus natural counterpart

We found that GI was not significantly different from its natural equivalents (Z_{40} = 0.17, p = .22; Figure 3). There were significant amounts of unexplained variability in this model (Q_W = 361.1, p < .001) that can be explained by separating the GI type (Q_E = 259.7, p < .001). There were significant differences among GI types (Q_M = 15.4, p = .017) with mixed responses among certain comparisons. GI did not improve biodiversity relative to its natural counterparts for green roofs, wetland detention basins, vegetated roadsides or urban gardens when compared to forests (p > .05 for all comparisons). However, vegetated roadsides/bioswales were observed to have significantly higher abundance and richness of mosquitoes when compared to a natural wetland (p < .001; Figure 3). Another study also found higher densities of bumblebee nests in urban gardens when compared to natural areas (p = .012). There was no observable pattern among the taxa and number of studies that were significantly different between GI and the natural equivalent (Figure 3).

4 | DISCUSSION

GI is frequently suggested to benefit urban biodiversity, but these effects have not been effectively quantified (Williams et al., 2014). Using a systematic review and meta-analysis we identified that the majority of the research on GI has been focused on ecosystem services and human health, and many utilize conceptual frameworks or reviews, rather than data-driven experiments. As a result,

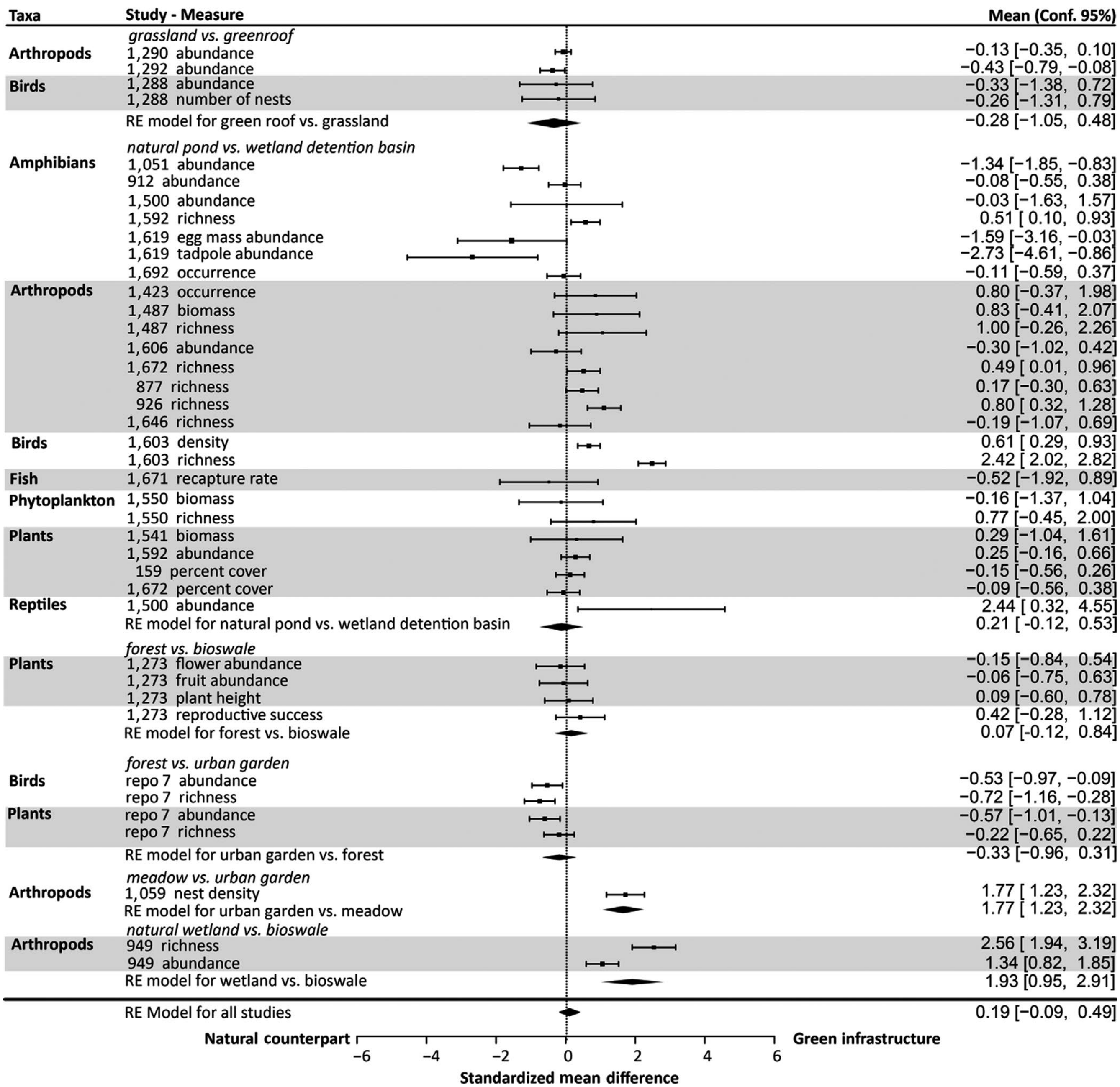

FIGURE 3 Mean effect sizes (Hedges' *d*) of green infrastructure on biodiversity relative to a natural counterpart separated by taxa and GI type. The study number represents a unique identifier from the list of manuscripts that were systematically reviewed (Filazzola et al., 2018). The measure is the estimate of urban biodiversity used in that study. Error bars represent 95% confidence intervals and bars not overlapping zero (dashed line) are considered significant. This comparison was not significantly different thus no bias criterion was calculated

contributions of GI to urban biodiversity have generally been neglected. In studies that measured biodiversity, we found support for our first hypothesis that GI provides a greater benefit to biodiversity relative to conventional counterparts when compared within the same city. We did not find support for our second hypothesis and instead found that, in some cases, GI had equivalent measures of biodiversity to natural counterparts. However, most of the natural counterparts were remnant habitat in city centres that are generally lower in biodiversity relative to more protected areas outside of urban areas. Additionally, we found differences in the effect of GI on biodiversity that is dependent on the GI type and is taxa specific. Below we identify nuanced considerations of the effects of GI on biodiversity, including opportunities for future research, taxa-specific considerations and management implications.

4.1 | Opportunities for future research

Research on GI is increasing, and our examined studies indicated that GI supports urban biodiversity. However, many studies that we reviewed lack a basic experimental framework, including appropriate controls (i.e. positive or negative). In the context of GI, a negative control is represented by the conventional counterpart and is used to evaluate the effect of GI implementation. A positive control is represented by the natural counterpart and is used to assess the validity of GI relative to environments that are known to be effective for supporting biodiversity. Within our review of 162 studies, we were only able to extract data from 10 studies that included negative controls and 25 that included positive controls. We believe the bias against using controls could be because of the inherent comparison between infrastructures that can appear obvious. For example, comparing the abundance of plants on a bare roof relative to a green roof or comparing bird richness on vegetated roadsides relative to native grasslands. However, there are notable studies that have identified species in association with conventional infrastructure (Wong & Jim, 2016) and natural habitat (McCarthy & Lathrop, 2011; Tonietto, Fant, Ascher, Ellis, & Larkin, 2011) relative to GI that needs to be quantified. Comparing GI to conventional infrastructure allows one to quantify the contribution of the "green" (e.g. vegetation or substrate) to biodiversity. Similarly, if remnant habitat is the targeted goal for restoration then natural counterparts can be used as a reference site to assess an appropriate level of implementation efficacy (Maron et al., 2010). When comparing among GI types the location can be important because urban landscapes are heterogeneous (Cadenasso, Pickett, & Schwarz, 2007) and thus the effects on urban species are variable. Using paired comparisons with the same regional characteristics can improve estimates of the efficacy of implementation rather than comparing GI measures between cities. There is also an easy opportunity to include controls and improve our measurements of GI on biodiversity because conventional infrastructures are abundant and often natural counterparts are the targeted goal or template for design (Lundholm & Walker, 2018). Future research on GI should execute more careful study designs so that we can more concretely determine the benefits of GI to biodiversity to better integrate them into existing or future management strategies for urban conservation.

4.2 | GI type and taxa-specific considerations

There were no significant differences in the effect of GI type on biodiversity, but studies selected represent types that differ greatly in application and design. Interestingly, the effects of roadsides and wetland detention basins relative to conventional counterparts were infrequently studied when compared to other GI types despite their high frequency and importance in urban environments. Road ecology has been a field of study for several decades and previously research has highlighted that when managed, can be rich in both native and planted species (Arenas, Escudero, Mola, & Casado, 2017; Arifin & Nakagoshi, 2011). Further exploration of the potential to vegetate roadsides could have significant effects on biodiversity because of the large area they occupy in cities and high degree of connectivity roadways share to natural habitat or other GI types (von der Lippe & Kowarik, 2008). Although there can be negative impacts of roadways, such as increased collisions with vehicles, these effects can be mitigated using appropriate measures and our understanding of road ecology (Angelstam et al., 2017). Examining wetland detention basins also presents an important opportunity because the presence of water provides an inherent resource that is not shared by the other GI types allowing for amphibious and aquatic wildlife to seek refuge in cities. Additionally, both wetland detention basins and bioswales can help mitigate the negative impacts of urbanization on riparian habitats that are sensitive to disturbance (Pennington, Hansel, & Gorchov, 2010; Wang, Lyons, Kanehl, & Bannerman, 2001), but care must be applied in design to prevent the creation of ecological traps (Hale, Coleman, Pettigrove, & Swearer, 2015). For instance, a wetland detention basin built to resemble a natural wetland, if left unmaintained, can quickly accumulate toxic pollutants that will negatively impact amphibian populations (Hale et al., 2015). Examining the biodiversity conservation potential of all types of GI is currently needed, but vegetated roadsides and wetland detention basins are low-hanging fruit as each is understudied despite having some benefit for urban biodiversity.

The contribution of GI to urban conservation strategies can be species specific. Vertebrate species more consistently benefited from the implementation of GI while invertebrates, especially insects, had a more varied response. Invertebrates can occupy a larger range of environmental conditions than vertebrate species and this could explain why natural counterparts were not significantly different in biodiversity relative to GI. The studies in our meta-analysis used general measures of community composition (i.e. abundance and species richness) that are not sensitive to changes in relative abundances of species. For instance, mosquito abundance and richness has been found to be greater on conventional infrastructure relative to GI because mosquitoes have low requirements for development and predators are less abundant, such as birds and bats (Wong & Jim, 2016). Similarly, we observed that natural counterparts had lower mosquito abundance and richness relative to GI (Medlock & Vaux, 2014). The use of more complex measures, such as the diversity of functional traits, can more effectively inform the resilience of communities to environmental change and for the delivery of ecosystem services (Petchey & Gaston, 2002). For example, the absence of detrivores that are critical for nutrient cycling can suggest that an intervention, such as the addition of coarse woody debris with suitable moisture content, can support colonization (Rumble & Gange, 2013). Functional traits provide a more mechanistic understanding of how species respond to environmental conditions (McGill, Enquist, Weiher, & Westoby, 2006) and can be more informative when monitoring impacts of land-use on biodiversity (Vandewalle et al., 2010; Williams et al., 2009). These measures of community composition can better identify species-specific differences and therefore improve GI design urban biodiversity (MacIvor, Cadotte, Livingstone, Lundholm, & Yasui, 2016).

4.3 | Limitations of GI

Results show GI is an improvement over conventional infrastructure in most cases, but it is not a replacement for natural systems.

Natural systems provide a higher level of function for biodiversity habitat and should be prioritized for protection in conservation planning or policies. However, where opportunities are limited for such management actions, constructed GI should be strongly considered over conventional grey infrastructures. The observed difference between GI and conventional infrastructure is driven by strong effect sizes (e.g. there is little biodiversity on a concrete curb relative to a vegetated roadside), but the non-significant comparison with natural systems is more nuanced. The conservation benefits delivered by GIs should not be overstated, even for biodiversity of urban associated species (Williams, Lundholm, & MacIvor, 2014, 2014). There are risks in relying on GI to maintain biodiversity relative to natural environments outside of an urban environment because cities have greater stressors/disturbances, such as road kill or fragmentation (Andersson, Koffman, Sjödin, & Johansson, 2017; Coffin, 2007), building strikes for birds (Machtans, Wedeles, & Bayne, 2013), pet-caused mortality (Bonnington, Gaston, & Evans, 2013), light pollution (Dominoni, Quetting, & Partecke, 2013), noise pollution (Francis, Ortega, & Cruz, 2011) and increased disease risk (Galbraith et al., 2014). GI biodiversity benefits will be greatest where planning ensures connectivity between GI and the natural environment (Braaker et al., 2014). Ecological corridors have increased arthropod diversity where species are negatively affected by fragmentation (Vergnes, Viol, & Clergeau, 2012). Alternatively, there may be instances where deliberate disconnection of GI is necessary to prevent the establishment of pest species, such as rats or weeds, or to prevent predation of urban species by house pets (Bonnington et al., 2013). The inclusion of buffers around GI or natural remnant habitat could limit these impacts and provide additional habitat for urban species. For instance, large (100 to 1,000 meters) terrestrial buffers surrounding wetland detention basins can provide necessary habitat for semi-aquatic species, such as amphibians or water fowl, as well as terrestrial species (Blackwell, Schafer, Helon, & Linnell, 2008; Hamer et al., 2012; Semlitsch, Bodie, Hamer, Smith, & McDonnell, 2003). Further consideration of community composition and, in response to GI, can be more informative to evaluate where traditionally 'non-urban' species may find cities valuable habitat.

4.4 | Management implications

The physical characteristics of GI were infrequently reported in the reviewed studies despite the importance of these variables for characterizing habitat for urban species. In less than half of the reviewed studies, the age of GI was reported and studies varied from being conducted immediately post-construction (e.g. Buffam, Mitchell, & Durtsche, 2016; Medlock & Vaux, 2014) to more than 20 years later (Guderyahn, Smithers, & Mims, 2016). Some GI are unmanaged and vegetation communities follow successional processes through time, such as an abandoned rooftop that over time is colonized by lichens, mosses and forbs (Baumann & Kasthen, 2010; Drake, Grimshaw-Surette, Heim, & Lundholm, 2018). Many of the surveyed GI types are relatively young (<10 years) and thus the effects on urban biodiversity may not yet be fully realized. We also noted that properties of GI, such as area, pH and height, were missing from the majority of reviewed studies. These variables are of particular interest for the implementation of GI because of the major limitations for different taxa associated with each. For example, water quality, including pH, is a major limitation of amphibian richness in urban environments (Scheffers & Paszkowski, 2013) and habitat size is highly relevant for strategies of biological conservation in cities (Donnelly & Marzluff, 2004; Prugh, Hodges, Sinclair, & Brashares, 2008). Studies and monitoring programs that assess the effects of GI on biodiversity should recorded these variables to provide information that can lead to better construction or management practices. There is an opportunity for researchers to expand their surveys to consider more diverse taxa (Fulthorpe et al., 2018). Estimates of plant community composition, both planted and spontaneous, could be particularly informative for characterizing GI habitat, and allow for future improvements to design and maintenance. The species planted with GI are typically limited due to extreme environments, for example, single genera (*Sedum*) on extensive green roofs, cedars in roadside planters, grass on golf courses, but there are strategies of managing plant composition to be more complex that can be used to promote biodiversity (e.g. Aronson et al., 2017; Chong et al., 2014; Fontana, Sattler, Bontadina, & Moretti, 2011; Threlfall et al., 2017). The design and implementation of GI in cities is a relatively young industry that is continuing to develop in practice. Reporting dimensions or characteristics of each feature by practitioners and researchers will significantly improve its support for biodiversity conservation.

GI can be designed and maintained to support urban biodiversity, especially where the opportunities for the traditional habitat restoration is limited. A multi-trophic approach helps in understanding the complexity of urban ecosystems and define conservation goals (Seibold, Cadotte, MacIvor, Thorn, & Müller, 2018). GI design using a 'bottom-up' approach would focus on the growing media for plants (e.g. soil composition, mycorrhizal inoculum) or selecting specific plant species that attract target invertebrate species (Pocock, Evans, & Memmot, 2012). For example, increased plant abundance can provide resources for herbivorous insects, such as caterpillars, or flowers for pollinators, such as bumblebees (Goulson, Nicholls, Botías, & Rotheray, 2015; Hülsmann, von Wehrden, Klein, & Leonhardt, 2015). Identifying these fundamental ecological interactions can inform GI design to concurrently support multiple trophic levels. Diversity (Benvenuti, 2014; Lundholm, 2015; Madre et al., 2013) and total cover (Schindler, Griffith, & Jones, 2011) are key parameters in developing the structural complexity of these ecosystems. Designing GI to support multiple trophic levels and considering the landscape can significantly increase efficacy and the benefit to urban ecosystems.

GI is usually designed to deliver an ecosystem service, such as stormwater management and human well-being, while biodiversity conservation often comes second. However, these objectives do not need to be mutually exclusive. For instance, designing green roofs with plant communities that lead to long bloom periods is both aesthetically pleasing and provides a longer foraging window for pollinators (Benvenuti, 2014; Dunnett & Hitchmough, 2004). High plant diversity, especially diversity that delivers structure and different trait sets, can provide a more heterogeneous environment for arthropods (Madre et al., 2013), and is linked to improved regulations of building temperature and stormwater management (Lundholm, MacIvor, MacDougall, & Ranalli, 2010). Policy and planning documents that promote GI for multifunctionality that includes biodiversity (e.g. Torrance, Bass, MacIvor, & McGlade, 2013) can simultaneously benefit humans and urban ecosystems. It is necessary to continue to identify areas where these goals are considered conflicted to help implement better management strategies. For instance, there is a belief that decaying wood and standing water are not aesthetically pleasing and could encourage pest species despite their capacity to promote detrivorous or aquatic invertebrates (Medlock & Vaux, 2014). However, decaying wood is considered similar in aesthetic appeal and acceptability in urban green spaces (Hauru et al., 2014) and managed GI typically has a lower abundance of pest species relative to conventional counterparts (Wong & Jim, 2016). Policymakers and urban planners should promote GI with the goal of increasing the effects for biodiversity that will benefit all residences within the urban environment. Additionally, future research should continue to explore incorporating GI for habitat function. GI implementation and design needs to include promotion of high functional diversity among planted communities, the inclusion of adequate buffer areas, and maximizing habitat connectivity with other green spaces.

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AUTHORS' CONTRIBUTIONS

A.F., N.S., and J.S.M. each conceived the ideas, determined the search terms, and participated in the data extraction from published manuscripts. A.F. synthesized the data together and conducted the meta-analysis. A.F. also led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available from knb ecoinformatics repository at https://doi.org/10.5063/F1S180S8 (Filazzola et al., 2018).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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