Landscape Architecture Solutions to Biodiversity Loss

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In the New York Botanical Garden's Native Plant Meadow, wetland aquatic plants cleanse stormwater at the promenade's edge. Beyond, the Wet Meadow transitions to the Mesic Meadow, where species such as *Asclepias tuberosa* attract pollinators, insects, and birds. The Education Pavilion is seen in the background.

ASLA 2020 Professional General Design Honor Award. The Native Plant Garden at The New York Botanical Garden. New York, USA. OEHME, VAN SWEDEN | OvS / Ivo Vermeulen.

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Abstract

In this review, we synthesize the current literature on landscape architecture intended to enhance biodiversity. There is a large body of literature on planning, assessment, and governance frameworks and proposals for implementing design based on international biodiversity standards, but without – or with very little – empirical data. Additionally, we found a few novel simulating scenarios examining land cover, land use, and landscape connectivity changes that impact biodiversity. The few empirical research studies focusing on existing or experimental green infrastructure (GI), nature-based solutions (NbS), and landscape architecture (LA) projects and their broader biodiversity impacts are summarized in this review study. The review found that landscape architecture strategies are remarkably effective at increasing biodiversity through a) incorporating native plants, supporting pollinators, adopting Integrated Pest Management (IPM) practices in their designs; b) transforming gray urban surfaces to green infrastructure; c), restoring and protecting natural areas; and d) tracking landscape performances through data collection and assessment. In reviewing the results and evidence, we also identified areas of further research and collaboration for researchers, practitioners, policymakers, and community stakeholders.

1. Introduction

According to the IPBES Global Assessment on Biodiversity and Ecosystem Services, about one million of the planet's estimated 8 million species are under threat of extinction. The International Union for Conservation of Nature (IUCN) has assessed 157,190 species for its RedList and found that 44,016 are threatened with extinction. The global community calls for 30% of the world's terrestrial, inland water, and coastal and marine areas to be in effective protection and management by 2030.

In response, the American Society of Landscape Architects (ASLA) has urged governments to make firm commitments to meet the 30 x 2030 goal.

ASLA solicited research on the evidence of the benefits of landscape architecture solutions to the biodiversity crisis. The goals of the research reviews are to: 1) Understand and summarize the current state of knowledge; 2) Synthesize the research literature and provide insights, leveraging key data- and science-based evidence; 3) Create an accessible executive summary in plain language for policymakers, community advocates, and practicing landscape architects. The research review will be used to advance research, advocacy, and communications goals with a range of audiences including policymakers, scientists, design and allied professionals, and community stakeholders.

We embarked on a review of literature on human interventions aimed at increasing and restoring biodiversity to determine what has the potential for real impact on biodiversity, at what scales, and what factors may influence that impact. We also discuss what should be studied further and some novel approaches and opportunities for enhancing researcher-practitioner- community partnerships.

The review's scope focused on intentional designs, using both scientific literature and implemented design case studies, with explicit data on how their features improved biodiversity. What was evident from the peer-reviewed literature is that green infrastructure, nature-based solutions, and landscape architecture projects have the potential to improve as well as impede biodiversity.

While there is a large body of research on planning, assessment, and governance frameworks—and recommendations for implementing these—along with proposals for designs based on international biodiversity standards, there are very few peer-reviewed studies of biodiversity impacts of design projects from pre- to post-completion.

This research review asks the following questions: What landscape architecture and nature-based solutions can effectively address the biodiversity crisis? What lessons can be learned from designs? How can those lessons be scaled up and applied across neighborhoods, cities, regions, and countries?

We discuss how researchers, practitioners, and local and federal governments can learn from these lessons to inform planning, design, policy, public education programs, and future collaboration. We examine planning and design projects at various scales and share results demonstrating biodiversity and other ecological gains, such as sequestered carbon, reduced climate risks, and improved water quality and management.

The synthesized findings provide a basis for developing landscape architecture principles and practices for incorporating biodiversity-friendly design elements and focusing future research. Moreover, we suggest areas researchers and practitioners may work on together:

- Pre- and post-design project biodiversity data collection
- Calls for further research on design implications
- Public awareness campaigns

Studies varied widely in methods of quantifying biodiversity. Most but not all studies measured species count, richness, and abundance—and mainly used indices such as the Shannon-Weiner Diversity Index and Shannon-Wiener Evenness Index. These were often used in combination with other measures and indices. Also, while research methods and design are ultimately at the researcher's discretion, we observed that disparate methods in sampling, measurement, and analysis is a hindrance if trying to use research studies in concert with one another.

Researchers are often eager to explore novel approaches, and of course, there are a number of challenges in replicating environmental variables. However, replication of research design and methods is necessary to build upon each other's research and can contribute to the body of knowledge. Then, we can focus on the variables under investigation and reduce uncertainty regarding whether differences in outcomes are attributable to variables or sampling and analysis methods.

Existing research on biodiversity consists of myriad findings and approaches in site-specific contexts. While results may or may not be replicable in different physical and socio-cultural landscapes, using unified principles, methods, and criteria for the evaluation of biodiversity in human-built landscapes may help identify externalities and variables and new opportunities for practice-based research and testing new ideas in the field.

2. Methodology

This review summarizes the current state of knowledge of landscape architecture planning and design to support biodiversity. It synthesizes current research literature and provides case studies that offer insights, presenting key data- and science-based evidence.

The scope of the research review is design research and projects that include, but are not limited to:

- Blue/green infrastructure and stormwater management
- Ecosystem restoration
- Growth boundaries, green belts
- Native plant communities; forests
- Biodiversity strategies for carbon sequestration
- Pollinator habitats; habitat connections and migration corridors, such as wildlife bridges/crossings
- River, stream, and wetland restoration
- Transportation rights of way
- Living shorelines

This review addresses both scientific literature and implemented design projects with explicit data on how their features improve biodiversity. We employed a three-phased approach to conduct this research:

1. Literature Review
2. Case Study Review
3. Executive Summary and Visualizations

Phase 1: Literature Review

The literature review process started with a scoping review (Tricco et al., 2018) aggregating scientific and peer-reviewed evidence on landscape architecture and nature-based solutions that improve biodiversity. Unlike other literature review techniques, a scoping review provides a comprehensive overview of a large and diverse body of literature pertaining to a broad topic to synthesize and organize findings by field of interest (Arkskey & O'Malley, 2005; Malekpour et al., 2015; Xiao & Watson, 2019).

The search was conducted using Scopus (Figure 1), on September 6, 2023, which is a comprehensive database that covers a wide range of landscape and environment research and is commonly used by review articles in related fields (Cortinovis et al., 2021; Elliot, et al., 2019; Feleki et al., 2018; Rigolon, et al., 2019). We used the keywords ["landscape architecture" OR "nature-based solutions" OR "NBS" OR "green infrastructure" OR "low impact development"] AND ["design" OR "case study" OR "case studies"] AND ["biodiversity"]. We used these Boolean terms and syntax to obtain records that primarily focused on interventions related to biodiversity, searching titles, abstracts, and keyword sections of the articles and returned a list of selected records (Zhang et al., 2023). The review focuses on articles published in English since 2000 to ensure the findings reflect contemporary knowledge. It included peer-reviewed journal articles, book chapters, and conference proceedings from landscape architecture and related disciplines. Following the search, we conducted a three-tier screening process.

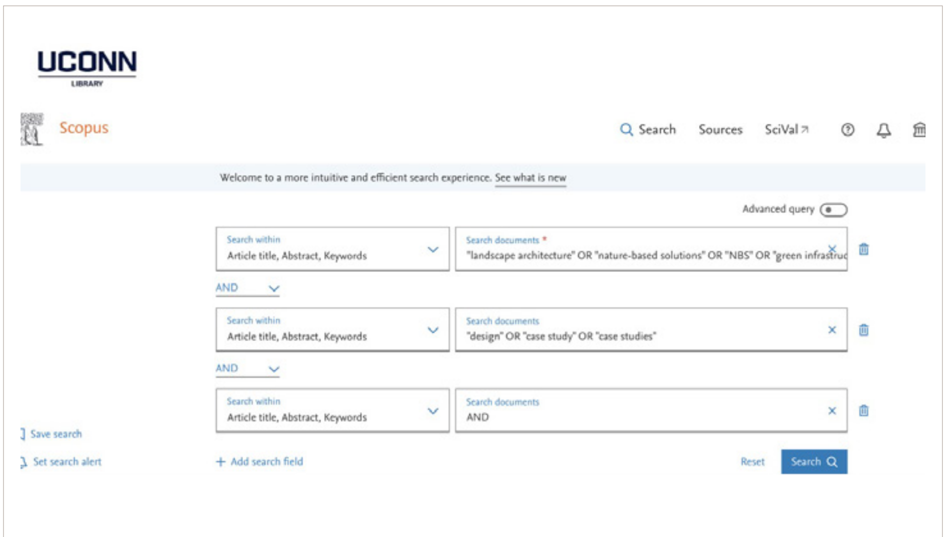

Figure 1. Examples of search window of Scopus, the primary search tool of the literature.

The initial literature search yielded 548 articles. Through the snowball search method, which is a way of tracking down related works by using the bibliography or references list (Nesbitt et al., 2018; Spiliotopoulou & Roseland, 2020), we identified one additional article that meets our inclusion criteria. Of the 549, 2 duplicates and 3 non-English language articles were removed. Therefore, a total of 544 articles were included for the subsequent title-abstract-keyword screening process.

We considered the following criteria to determine whether articles are subject to the scoping review:

1. Whether the article is related to enhancing or evaluating biodiversity as a result of design projects, green infrastructure, nature-based solutions, and restoration projects.

2. Whether the article introduces empirical evidence-based research projects.

3. Whether the article introduces design case studies and evaluates biodiversity before and after project completion.

We included articles that satisfied the first criterion AND either the second OR third criteria. Two graduate research assistants (RA) conducted the screening process. To ensure a consistent understanding of the inclusion criteria, the two RAs reviewed the first 26 title-abstract keywords simultaneously and checked if they could reach a consensus on inclusion. After that, each screened 259 titles, abstracts, and keywords of the articles separately. As a result, 155 articles were selected for full review (see Figure 2 for an illustration of the process).

Scoping Review Process

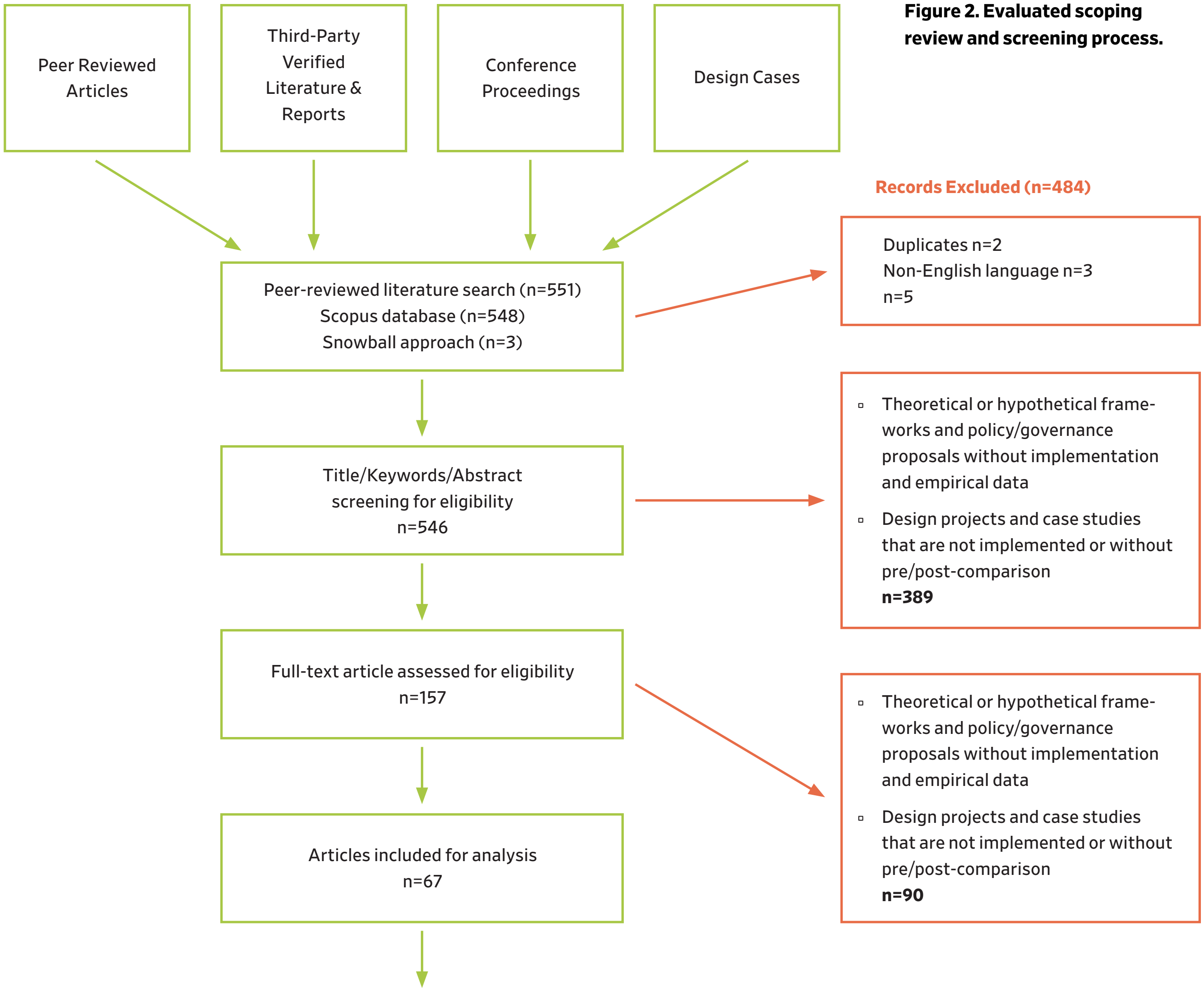

Figure 2. Evaluated scoping review and screening process.

Sumarize Findings, n=67

- Basic citation information
- Study location, which informed city, country, region and continent data.
- Journal discipline
- Spatial scale of study (sites, neighborhood, cities, regions, and countries). However, this review's spatial and temporal scope can be modified depending on the variables
- Design features accounted for biodiversity (e.g., urban parks, green roofs, rain gardens)
- Data type (e.g., animal count data, land cover data, field work data etc.)
- Taxa evaluate
- Research methods (e. g., experiments, quasi-experiments, cross-sectional, case studies)
- Metrics of biodiversity (e.g., species at risk, species restored, species richness, abundance, tree canopy coverage, connectivity, non-native species including noxious weeds (occurrences and % covers), % cover of herbaceous and sub-canopy species, wildlife/animals, soil biodiversity or diversity)

Using these inclusion criteria, we conducted a full-text review of 155 articles from the initial search, plus an additional 2 articles found using the snowball method mentioned above during full-text review (total full-text review of n=157), yielding 67 articles included in the synthesis.

The resulting list of 67 peer-reviewed literature was organized into a spreadsheet for screening and data extraction purposes. The spreadsheet contains distinct columns for authors, titles, publication years, source titles, abstracts, methods, and metrics used for biodiversity evaluation and statistical analyses, taxonomic groups evaluated, geographical focus of study, and spatial scale of the research.

We extracted and summarized the following data from the full-text reviewed articles based on the PRISMA protocol, review articles of related topics, and the research objectives of the review (Nordbø et al., 2018; Xie et al., 2021; Zhang et al., 2023).

- Basic citation information
- Study location, which informed city, country, region, and continent data
- Journal discipline
- Spatial scale of study (sites, neighborhoods, cities, regions, and countries)
- Design features accounted for biodiversity (e.g., urban parks, green roofs, rain gardens)
- Data type (e.g., animal count data, land cover data, field work data)
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To capture a comprehensive understanding of the current scientific fields addressing biodiversity and interventions, the publication outlets of the 155 full-text screened articles were classified based on the Field of Research (FoR) divisions and group classifications for all journals as part of the Australian and New Zealand Standard Research Classification (ANZSRC) by the Australia Bureau of Statistics. While each journal can have up to three research field codes, it still shows the fields and scientific audiences of those 155 selected articles (Appendix 2).

Phase 2: Case Studies

In the second phase, we investigated 11 case studies from the Landscape Architecture Foundation (LAF)'s Landscape Performance Series, the ASLA Professional and Student Awards, and the literature reviewed.

Prior to selecting these 11 cases, we searched design firm websites and other online sources for broad-based projects that have been or are being monitored for biodiversity performance, but data available online regarding biodiversity outcomes was very limited.

3. Research Analysis & Significant Findings

Green infrastructure, nature-based solutions, and landscape architecture projects have the potential to improve as well as impede biodiversity.

Two key findings from the review process:

1. There is a large body of research on planning, assessment, and governance frameworks; proposals for implementing designs based on international biodiversity standards; and novel simulating scenarios of landscape designs examining land cover, land use, and landscape connectivity changes that might improve biodiversity, but without - or with very little - empirical data.

2. There are very few peer-reviewed studies of biodiversity impacts of design projects from pre- to post-completion. The few empirical research studies focusing on existing or experimental green infrastructure (GI), nature based solutions (NbS), or landscape architecture (LA), LA projects and their broader biodiversity impacts are summarized here.

The detailed statistical findings of the literature review pertaining to journal publication outlets, geographic locations of research, research methods, and broadly-classified species examined are demonstrated in the appendices at the end of this article.

Green Infrastructure (GI), Nature-based Solutions (NbS), and Landscape Architecture That Support Biodiversity

Using a meta-synthesis method and leveraging our professional knowledge of landscape architecture, GI, and NbS, we categorized the designs into 15 categories:

- Agroecosystems
- Brownfields, Vacant Lots, and Phytoremediation
- Coastal Restoration,Erosion Control, and Artificial Reefs
- Green Facades
- Green Roofs
- Landscape Connectivity
- Rail Corridors
- Reforestation
- Residential Design & Urban Development
- Riparian Restoration & Erosion Control

- Stormwater GI (Rain Gardens, Bioretention, Bioswales, etc.)
- Trees outside Forests
- Urban Greenspaces (Parks, Gardens, and Meadows)
- Wetland Construction / Restoration
- Other NbS & Blue/Green Infrastructure

Consistent with our expectations, urban greenspaces were the most studied features (n=19), followed by green roofs (n=12), green stormwater infrastructure (n=6), and landscape connectivity enhancement projects (n=5) (see Figure 3).

The synthesized findings of how these designs contributed to biodiversity are discussed in the following sections.

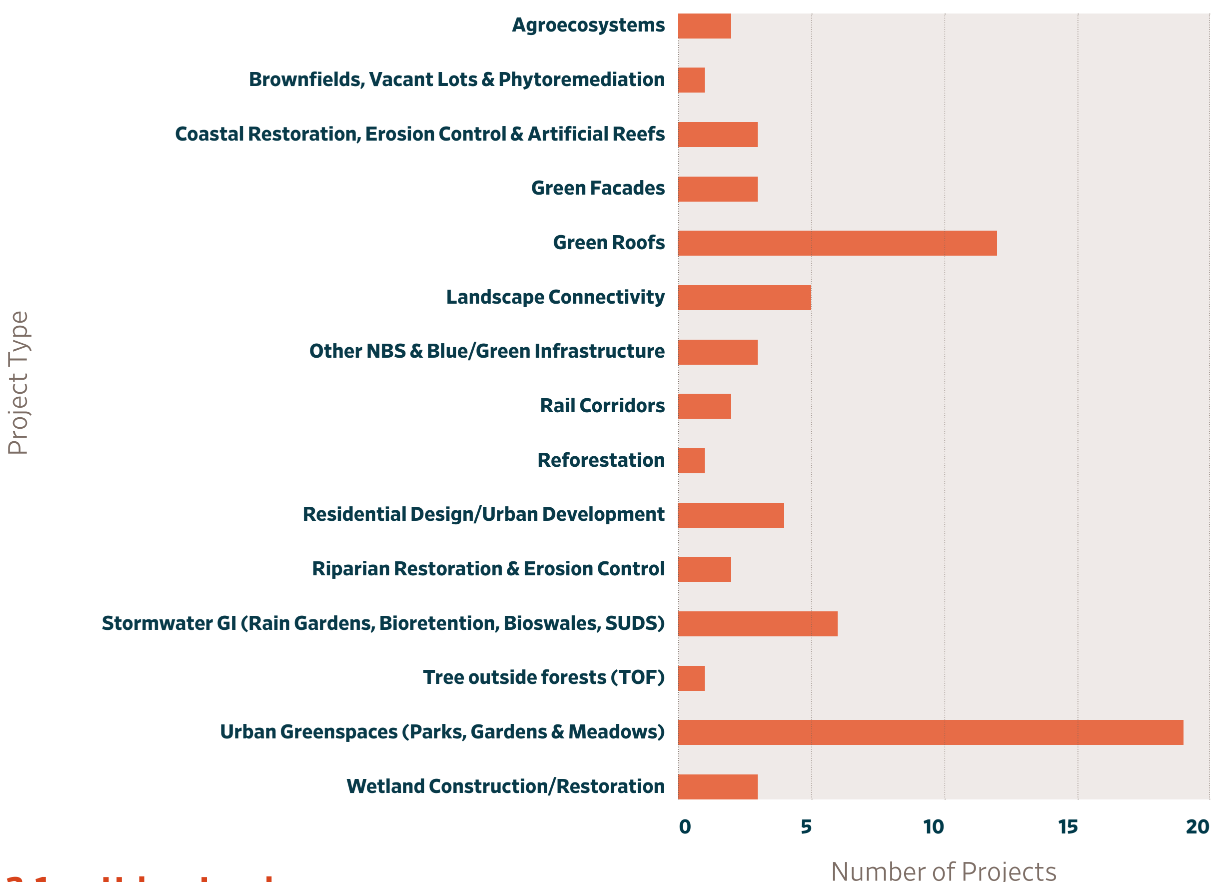


Figure 3. Number of projects by type.

3.1 Urban Landscapes

This category includes general discussion about the characteristics of urban built-up areas, urban form, residential developments, and vacant lots in relation to biodiversity (Plummer et al., 2020; Semerdzhieva & Borisova, 2021; Riley et al., 2022). These studies either involved a city-scale evaluation of ecosystems (Semerdzhieva & Borisova, 2021) or conducted cross-sectional research on sampled urban sites at a country scale (Plummer et al., 2020; Riley et al., 2022). The literature highlighted that urban areas have the capacity for high biodiversity when a balance is struck between the built environment and green space with structurally and functionally complex plant assemblages (Semerdzhieva & Borisova, 2021).

A common theme is a strong positive correlation between landscape heterogeneity and biodiversity. This heterogeneity is inclusive of human-built structures as well as topography (Kowarik et al., 2016; Huang et al., 2019; Korányi et al., 2021; Bornschlegl et al., 2023; Bruner et al., 2023;). Furthermore, high woody plant diversity demonstrated promising results in suppressing phytophagous arthropods on residential properties and are considered a more sustainable pest management practice than using pesticides (Riley et al., 2022).

There is a need to plan urban landscapes that are sensitive to the needs of biodiversity. Several articles examined the characteristics of urban landscapes that support diverse species, such as birds (Plummer et al., 2020; Korányi et al., 2021; Breed et al., 2022) and moles (Fellows et al., 2020).

Plummer et al. (2020) found that contiguous areas of greenspace with high woody density and grass cover within urban sites are preferential for accommodating breeding birds, compared to a more fragmented arrangement of multiple, small greenspace patches. Korányi et al. (2021) found a variation of bird species between types of green space due to differing nesting and feeding habits, as well as the ability to hide from predators.

In addition, Plummer et al. (2020) revealed that the density of 70% of bird species decreased in response to the higher proportion of buildings, roads, and built surfaces in their observed urban sites. Yet, Korányi et al. (2021) found that increased urbanization did not have an impact on species richness, and instead, there was greater diversity within the city than in surrounding agricultural and rural areas. They note that this could be due to Göttingen, Germany being unique. It has a vast amount of green space in comparison to other cities. The city's architecture provides crevices for nesting. And differences in green spaces within the city lend themselves to creating habitat variety that attracts different species (Korányi et al., 2021). These incongruous results provide opportunities for further research on the relationship of different variables to the correlation of urbanization, green space, and species richness.

Of particular interest in the body of biodiversity literature are vacant lots and their contribution to biodiversity. They can harbor spontaneous plant communities that provide habitat for fauna species.

Vacant lots and wastelands in urban environments were recognized as opportunities for GI and biodiversity conservation. One case study in Barking Riverside, UK demonstrated that incorporating "eco-mimicry" in repurposing brownfields and restoring ecosystem services successfully outperformed traditional residential landscapes in floral diversity and overall invertebrate diversity (Connop et al., 2016).

3.2 Green Roofs

This rooftop at Sonoma Academy High School incorporates photovoltaic panels and a meadow creating a biosolar roof. Buildings at this school are designed to teach students to engage their environments, to be critical thinkers, and to observe and collect data, including this green roof.

ASLA 2021 Professional Research Honor Award. Ecoregional Green Roofs: Theory and Application in the Western USA and Canada. Bruce Dvorak, ASLA. Sonoma Academy High School, Sonoma, California. Janet Durgan Guild & Commons. WRNS Studio / Bruce Dvorak

Twelve studies focused on green roofs. The study area is spread across the globe, including both the Southern and Northern Hemispheres and across continents. Only three of the 12 studies studied green roofs in the U.S., including one in New York City, NY (Yee et al., 2022), one in Harrison, OH (Johnson et al., 2016), and one in Puerto Rico (Grullón-Penkova, 2020).

There was considerable evidence showing the ability of green roofs to support diverse species, such as 91 ground beetle species found in Europe (Pétremand et al., 2018), birds, arthropods, and gastropods (Fabián et al., 2022; Wooster et al., 2022), and diverse plant species (Yee at al., 2022). Studies on the impacts of green roofs also demonstrate that roof height can affect nesting patterns (MacIvor, 2016), and native, well-adapted species may spontaneously replace introduced species (Grullón-Penkova et al., 2020).

Photovoltaic (PV) arrays can create microhabitats that lead to greater biodiversity (Nash et al., 2016). However, further study is needed on the density of PV arrays and their potential inimical nature to certain invertebrates such as bees (Nash et al., 2016).

Furthermore, several key characteristics of green roofs were considered in the studies that demonstrated effective support of mostly faunal biodiversity. Intentionally introducing diverse plant species in green roofs showed a significant positive correlation to supporting a high diversity of arthropods (Fabian et al., 2021) and enhancing the retention capacity for reactive nitrogen (Johnson et al., 2016).

Native species supported more species diversity of insect communities than exotic species, as evident in an experimental study of green roofs in Córdoba City, central Argentina (Fenoglio et al., 2023). In addition, both vertical and horizontal connectivity with other green roofs and surrounding ground-level greenspaces improves biodiversity, although high density plantings may lead to increased parasitism (MacIvor, 2016), support a wide range of arthropod species (Fabian et al., 2021), and enhance insect abundance (Fenoglio et al., 2023).

On the other hand, building heights of the rooftops were found to be negatively associated with the number of bee and wasp nests in Toronto, Canada (MacIvor, 2016), indicating green roof construction should prioritize short buildings first if providing pollinator nesting habitats is a priority.

Spontaneous plant species (Fabian et al., 2021) on green roofs were also found to significantly support higher numbers of arthropod species (Fabian et al., 2021) and insect abundance (Fenoglio et al., 2023) in Argentina.

However, there is a question regarding the correlation of vegetation intensity and diversity to higher abundance of insect nesting patterns to observed insect visits. Results from other studies differ, which may be due to different collection and sampling methods. MacIvor (2016) used nest traps—thus only capturing bees and wasps that nest on the roof. In Fenoglio et al. (2023), though, native plants supported substantially higher insect abundance, regardless of the trap type used.

Soil depth and substrate composition also matter (Molineux et al., 2017; Bruner et al. 2023; Fabián et al., 2021; Pétremand et al., 2018; Johnson et al. 2016; Yee et al., 2022). One study focused on the enhancement of substrate performance on green roofs via soil microbial inoculations in order to increase plant diversity, suggesting that brick-based substrate blends are most effective for vegetation performance as are deeper depths (8cm v.s. 5.5cm) (Molineux et al., 2017).

As interest in installing rooftop solar panels grows, the study by Nash et al. (2016) in London demonstrates the potential synergies of having substantial bio-solar roofs that support vegetation and invertebrate communities, delivering co-benefits in terms of energy efficiency and biodiversity.

Green roofs, however, have been beset by a longstanding preconception that they attract urban pests like mosquitoes. However, according to a group of scholars, extensive green roofs were not favored by vector mosquitoes, compared with positive and negative control sites using open water bodies in Hong Kong (Wong and Jim, 2016).

Despite the small scale of green roofs, researchers were able to influence designs and apply rigorous scientific research design. Five of twelve studies were experimental, with observed pre- and –post- design conditions (e.g., Fenoglio et al., 2023)

3.3 Urban Forests

While only addressed in one study, small tree patches outside forests (with a size between 0.05 and 0.5 hectares or 0.12 and 1.24 acres), mostly occurring in a human-altered landscape, demonstrated support for a wide range of plant diversity and naturalness, though such effects were associated with the surrounding matrix type (urban, agricultural, natural and semi-natural, and mixed land-use) and landscape configuration and topographic factors, especially when considering native species within such plant communities (Bazzato et al., 2021).

These results highlight the potential of small wood lots as “pillars” to build and extend green infrastructure networks in both natural and human-altered environments, providing nature-based solutions to hamper ecosystem fragmentation effects (Bazzato et al., 2021).

Brunbjerg et al., (2018) found that spatial scales of vegetation cover matter in relation to bees, hoverflies, and bird species response. For instance, vegetation cover at small scales (100–250 m or 328-820 ft radius) was most important for bees and hoverflies, while intermediate scales (250–500 m or 820-1640 ft) mattered most to bats. Bird species richness increased with greater variation in tree canopy height at a large spatial extent (1,000 m or 3,281 ft) but increased with higher tree cover at a small scale (100 m or 328 ft) differently (Brunbjerg et al., 2018).

3.4 Urban Public Green Spaces

Nineteen articles examined urban green spaces and their contribution to biodiversity. This category includes public parks, meadows, cemeteries, and other municipally defined urban green spaces.

Empirical evidence confirmed the role of urban green spaces, parks, and squares in supporting diverse fauna communities, such as birds (Shwartz et al., 2023; Sultana et al.,2022; Yarnvudhi et al., 2022), butterflies (Shwartz et al., 2023), and beetles (Fattorini & Galassi, 2016). Several articles further proved that the characteristics of those green spaces matter (Fattorini & Galassi, 2016; Muhlbauer et al., 2021; Zhao et al., 2022).

For example, an examination of 103 city squares in Munich found that the proportion of grass cover, tree density, and the abundance and proportion of old trees (i.e., trees with a diameter at breast height > 60 cm or 23.6 in) had a positive correlation to bird abundance and diversity. (Muhlbauer et al., 2021). Landscape heterogeneity of the greenspace and size also plays an important role in supporting bird diversity, as evident in a Thailand urban park (Yarnvudhi et al., 2022) and parks in Germany (Sultana et al., 2022).

Fellows et al. (2020) claimed that a minimum greenspace of approximately 10 hectares (24.7 acres) was required for the abundance and diversity of European mole. Evidence also supports the influence of greenspace connectivity: distance to the nearest green area and proximity to waterbody on bird diversity in small-sized urban green areas as found in Germany (Sultana et al., 2022) and on mole abundance and diversity in London (Fellows et al., 2020).

In addition, park type also matters—according to Talal and Santelmann (2019), natural, passive-use parks with larger sizes yielded more plant species richness and diversity and more native species compared with active-use parks and multi-use parks in Portland, Oregon.

This finding implies that park managers and land-use planners should limit recreational development, land-use change, and other human disturbances in natural, passive-use parks and promote the creation of native habitat patches in multi-use and active-use parks for the purposes of increasing native biodiversity and its associated benefits (Talal & Santelmann, 2019).

3.5 Green Facades

Alternative Future 2 - Home to Stone Wall Tree. This approach looks at the active building of communities around trees and public engagement. Understanding Stone Wall Tree typology is the first step towards reconsidering the design of the urban environment to truly embrace the existence of Stone Wall Trees in the neighborhood.

ASLA 2019 Student Honor Award, Communications. Stone Wall Trees 2040: A Critical Discussion of their Alternative Futures. SAR China. Anson Ting Fung Wong, Student, Harvard University Graduate School of Design Student

In an unusual research approach to green facades, Huang et al. (2019) study the spontaneous vegetation growth on masonry walls in Chongqing, China. While not the first study of its kind, they had an interesting recommendation to "embrace and integrate with existing masonry walls to achieve sustainable ecological urban design." (p.10).

The researchers observed 20 native herbaceous species, which were nearly non-existent in ground plantings in the vicinity, thriving on walls, indicating their low tolerance for disturbance. Further, they found that *ficus virens*, a native strangler fig species, was well adapted to the vertical landscape and dominated over other tree species on the wall.

Kowarik et al. (2016) studied an old cemetery in Berlin, left relatively undisturbed, that had been overtaken by natural growth in parts and served as a conservation haven. They found critically endangered, threatened, and protected plants, bryophyte, lichen, bat, bird, and arthropod species, including some that had been considered extinct.

Kowarik et al. (2016) note: "From the perspective of monument preservation, it is important that the colonization of built structures by plants and animals not be negatively perceived as the destruction of important artifacts." (p.75) This notion of undisturbed human-built structures and spaces serving as natural conservatories—along with Huang et al.'s (2019) recommendations and findings—suggests an interesting possibility and avenue for future research questions into the structural tolerance of existing masonry structures to accommodate various types of vegetal growth, including trees, and the potential for vertical phytoremediation, while also preserving function, heritage, and safety.

As Bornschlegl et al. (2023) suggest, "in order to function as revolutionary infrastructure, green infrastructure must prioritize the creation of heterogeneity for non-human species, balance nature–culture relations, incorporate ecological perspectives into human infrastructure design, and embrace the uncertainty and openness of urban naturecultures." (p.2)

This embrace of wildlife and the uncertainty they may bring to design, as well as the need for adaptive management, is also highlighted in a study by Bailey et al. (2019) of wetland restoration sites in Seattle, WA. The anticipation of ecosystem engineers – beavers in this case – into the design and adaptive management was not only favorable for the ecosystem but necessary from a maintenance cost perspective (Bailey et al., 2019).

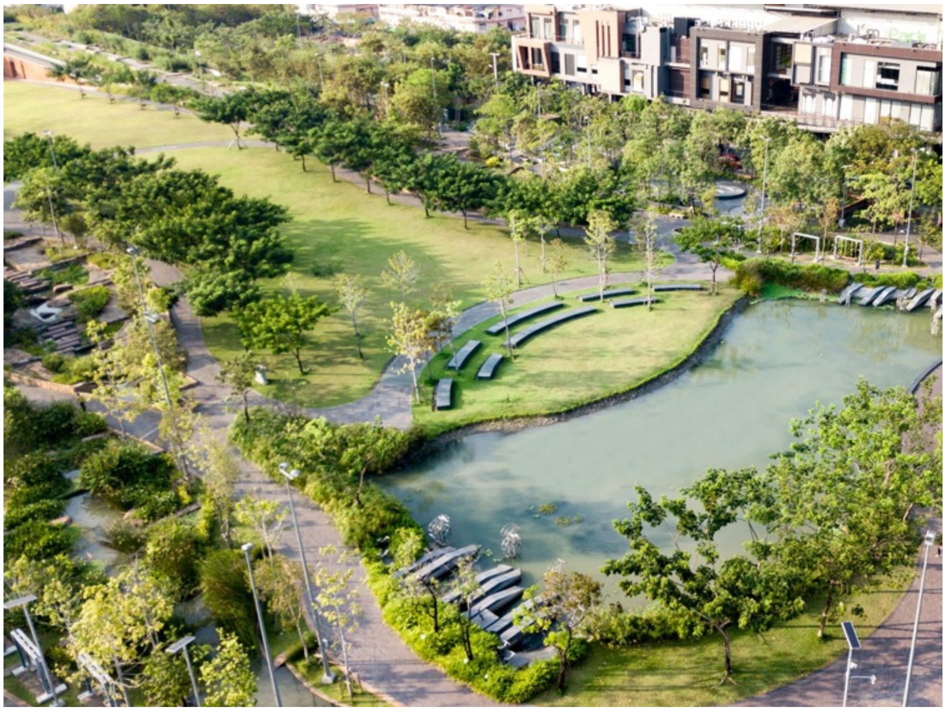
3.6 Habitat Network Restoration and Improving Landscape Connectivity as a Proxy of Biodiversity

These articles followed a similar flow: identify existing habitat, use least-cost path analysis to reconstruct or restore a habitat network using greenspaces, and target specific species to put parameters on the dispersal distance or probability of moving within the network (MacKinnon et al., 2023; Nguyen et al., 2021; Thomas et al., 2022; Van Teeffelen et al., 2015; Zhang et al., 2019).

More specific work involved simulations of different development scenarios and evaluated impacts on landscape connectivity, such as Thomas et al.'s work (2022) on the Couesnon watershed in France. A closer look at the interaction between landscape network restoration and climate change further sheds light on the need to satisfy particular spatial configurations and abiotic factors in mitigating the negative effects of climate change on the habitat of a climate-sensitive species—the great crested newt (Van Teeffelen et al., 2015).

Other design features: railway corridors that supported faunal movement. Braschler et al (2020) found that 1,200 animals used the bridge, including small mammals, reptiles, and amphibians, as well as numerous invertebrates.

3.7 Stormwater GI and Water Sensitive Urban Design



The size and degree of heterogeneity of urban green spaces contribute to the amount of biodiversity it can sustain. The Chulalongkorn University Centenary Park has distinct biomes, including a wetland, forest patches, and grassland integrated with the built form and multiple levels and gradients. These features create unique habitats that attract 59 bird species.

ASLA 2019 Professional General Design Honor Award. Chulalongkorn University Centenary Park. Bangkok, Thailand. LANDPROCESS

Kazemi et al. (2011) demonstrate that bioretention swales used in streetscapes outperformed traditional "garden-bed" and "lawn-type" streets in the number of species, species richness, and diversity of the invertebrate communities in Australia. Vegetation structural complexity, floral diversity, pH, and slope also factored in the success of bioswale in supporting biodiversity (Kazemi et al., 2011).

Bioretention, which is one type of green infrastructure for stormwater management, was frequently explored by researchers. Krivtisov et al. (2023, 2020) studied water quality in introduced control sustainable drainage systems (SuDS) ponds, which control run-off, and conducted ecological surveys in the surrounding vicinity to understand the ecological impacts of the infrastructure better.

They observed relatively high plant species richness at these sites, although not as much as that of natural ponds, and noted variation between sites, suggesting size, design, pond area, and plant communities could be influential factors. Sagrelius et al. (2023) compared twelve design configurations from the four major types, to ascertain their co-benefits of social, ecological, and economic impacts and found evidence that Type A was most preferential for flora biodiversity and robustness, even though this type was not most cost-effective nor adaptive to climate variability.

Moreover, when diverse plant assemblages are introduced as part of GI, they were more efficient in water retention for stormwater management than monocultures. But how this efficiency is determined by plant community composition may differ according to the type of green infrastructure, planting medium, retention area, plant cover, and climate (Bruner et al., 2023; Johnson et al., 2016; Kasprzyk et al., 2023). For instance, while plant assemblages with complementary traits are more efficient for rain gardens (Bruner et al., 2023), this may not be as important for green roofs so long as monocultures are avoided (Johnson et al., 2016).

3.8 Agroecosystems

Several types of agricultural landscapes were also examined in their capacities to support biodiversity, such as vineyard landscapes (Rosas-Ramos et al., 2018) and agricultural crops (Zina et al., 2022).

Echoing the findings in urban landscapes and greenspaces (Plummer et al., 2022), the vegetation structural complexity and diversity of green infrastructure also played a key role in agroecosystems, as exemplified by the linear ecological infrastructure (e.g., woodland hedges, rosaceous hedges, grass strips, and flower strips) in support of spider assemblages (Rosas-Ramos et al., 2018).

The interactions between ecological infrastructure and crop type matrix also played a key role in supporting biodiversity, as exemplified by ant richness in Mediterranean floodplain agricultural crops (Zina et al., 2022).

3.9 Ocean and Coastal Ecosystems

Reef-building bivalves such as oysters and mussels are increasingly used for coastal restoration, shoreline protection, and erosion control. They provide additional biodiversity benefits by supporting valuable habitats, such as intertidal flats, seagrasses, salt marshes, and mangroves (Ysebaert et al., 2018).

Hickling et al. (2023) found that replacing conventional human-made marine structures or enhancing them with patented reef cubes could improve the diversity of benthic invertebrate communities. Furthermore, through DNA metabarcoding, researchers found coastal defense structures had varying levels of impact on species count and diversity of benthic communities, which can further inform practices of coastal zone management (Tagliabue et al., 2023).

3.10 River, Stream, and Wetland Restoration

In the Suining South Riverfront Park, a resilient wetland lagoon phytoremediation system filters water at the upper level of Fujiang River and directs it through three ponds for filtration, absorption, and assimilation.

ASLA 2020 Professional General Design Honor Award. From a Concrete Bulkhead Riverbank to a Vibrant Shoreline Park—Suining South Riverfront Park. Sichuan, China. ECOLAND Planning and Design Corp./Sichuan Provincial Architectural Design and Research Institute Co., Ltd. / Arch-Exist Photography.

While wetland restoration projects are not new, Semeraro et al. (2015) evaluated a wetland that was constructed in Southern Italy for the specific purpose of treating wastewater with biodiversity as a co-benefit.

Not only were there significant biodiversity gains, but the site's multifunctionality went beyond wastewater treatment and biodiversity to include recreational, educational, and research uses. Likewise, Greenway (2017) also revealed the success of stormwater wetlands in providing habitats for a wide range of macroinvertebrates compared with concrete channels and natural wetlands.

3.11 Co-Benefits of GI

It was beyond our expectations to find only one article focused on comparing the cost and benefits of implementing various types of GI and its response to the biodiversity of other ecosystem services.

Epelde et al. (2022) incorporated seven types of GI and simulated three scenarios to adapt those GI with varying intensity. They found that compared with flood control and temperature reduction, biodiversity and carbon storage required more intense installation of GI, such as intensive and extensive green roofs and big courtyards (Epelde et al. ,2022).

3.12 Biodiversity and Social Impacts

In the New York Botanical Garden's Native Plant Meadow, wetland aquatic plants cleanse stormwater at the promenade's edge. Beyond, the Wet Meadow transitions to the Mesic Meadow, where species such as *Asclepias tuberosa* attract pollinators, insects, and birds. The Education Pavilion is seen in the background.

ASLA 2020 Professional General Design Honor Award. The Native Plant Garden at The New York Botanical Garden. New York, USA. OEHME, VAN SWEDEN | OvS / Ivo Vermeulen.

Perceived vs. Real Biodiversity

Another novel research direction involved a comparison of perceived and real biodiversity in parks, aesthetic value, and their restorative effects, with a focus on a social-ecological lens (Hoyle et al., 2017; Hoyle et al., 2018; Palliwoda et al., 2017; Shwartz et al., 2023).

The authors note the differences in aesthetic preference in different countries, notably the changing aesthetic perception of a public educated on the ecological benefits of certain landscapes. The researchers found that meadows once perceived as messy were earning favor in the United Kingdom (Hoyle et al., 2017; Hoyle et al., 2018).
Both studies found that while people's aesthetic experience was better with colorful flowers—and even provoked perceptions of biodiversity—the greenery and more "natural" planting design had a more restorative effect.

Hoyle et al. (2018) found that there was less invertebrate diversity in plots with both high plant species diversity and high color diversity, although the invertebrates that favored these plots tended to be pollinators or "seen" species. As a result, they recommended low plant diversity and high color diversity to satisfy human aesthetic and pollinator preference. Hoyle et al. (2018) recommended lower plant species diversity, which conflicts with the other studies mentioned above that recommended plant assemblages with greater structural and functional diversity for the ecosystem services and habitat function they provide for fauna.

Shwartz et al. (2023) further delved into the difference between perceived versus actual diversity and linked it with the psychological well-being effects that those biodiversity indicators have on greenspace users. In their study, perceptions of bird, butterfly, and plant richness were seldom consistent with actual species richness.

Employing bird, butterfly, and plant species field surveys and in-situ questionnaires, they found that perceptions of biodiversity were closely linked to users' level of connection to nature, ecological knowledge level, and demographics. Notably, they found a high association between perceived species richness and psychological well-being, attachment, sense of identity, and continuity with the past—and these associations were largely strengthened by garden size. Those findings confirmed the social and health benefits of biodiversity to human beings.

Human interaction and color preference

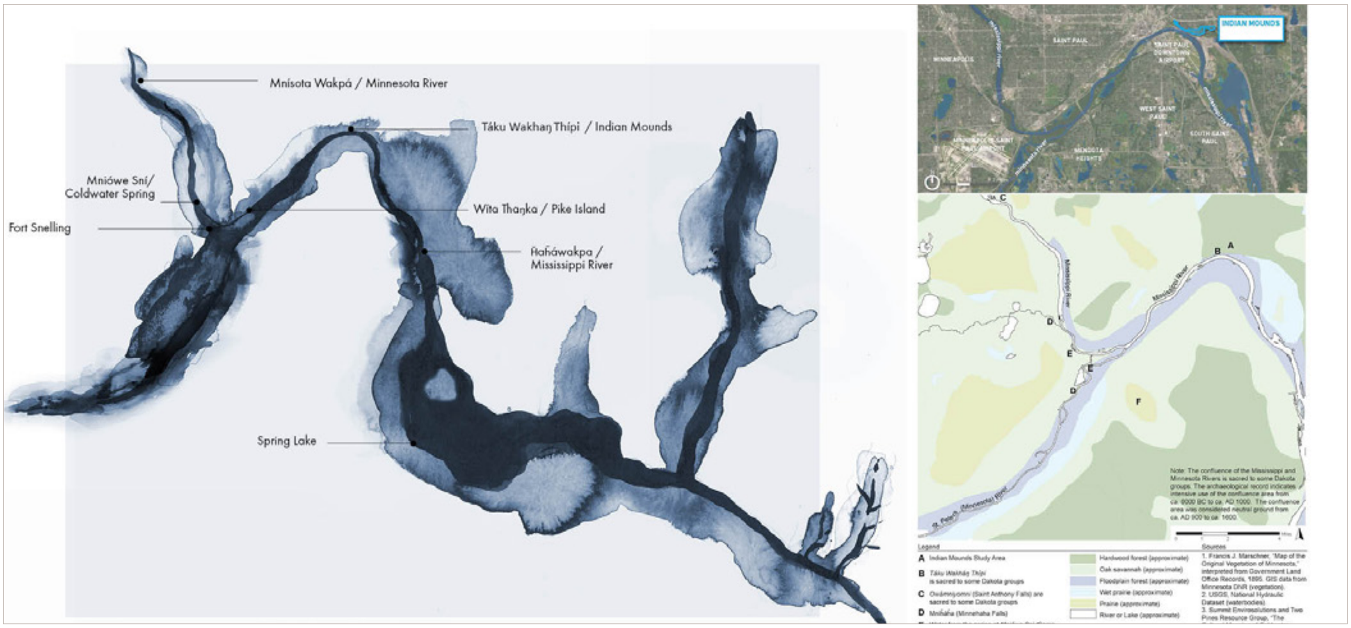
Thorpert et al. (2022) created a simulation based on human preference for high color contrast and pollinator preference for plant species and posited that green facade designs could potentially be "based on color theory without compromising with biodiversity outcomes, namely species richness, pollination, and the nativeness of the species." (p.1) Of course, this was a simulation based on literature studying human color preference for meadow design and pollinator observations in meadows—a very different landscape. The researchers acknowledged these limitations and significant others to their simulation study, such as climate and socio-cultural aesthetics (Thorpert et al., 2022).

What is more interesting is that Palliwoda et al. (2017) found a substantial proportion of park user activities related to biodiversity interaction with specific plant species (12%), compared with other activities like passing through and resting, which were observed in two Berlin parks. They found 26 species were observed as being specifically used by people for consumption, decoration, and biodiversity experiences, among which many were native and spontaneous species (Palliwoda et al., 2017).

The authors provided an exhaustive list of biodiversity-friendly plant species and encouraged park design paradigms. These findings shed light on how park design should focus on social-ecological communities and consider biocultural heritage, integrating both biodiversity and cultural inclusiveness.

Indigenous vs. colonized landscapes

Immigration and colonization have challenged the indigenous knowledge systems, traditional garden designs, and the native species biodiversity, as evident in communities inhabited by both the Batswana indigenous population and European descendants in South Africa (Davoren et al., 2016).



The Bdóte area of the Mississippi River Valley contains many sites significant to the Dakota. Western culture applies edges as cues communicating the end of one thing and the beginning of another. Rigid boundaries also indicate land ownership, another concept not aligned with Dakota worldviews. Cross-cultural expressions are essential tools to communicate alternative perspectives.

ASLA 2021 Professional Analysis and Planning Honor Award. Indian Mounds Cultural Landscape Study and Messaging Plan. Saint Paul, Minnesota. Quinn Evans, Ten x Ten, Allies, Inc. / Watercolor - Ten x Ten, Google Maps with Quinn Evans overlay

Davoren et al. (2016) found that while indigenous Tshimo gardens harbored more total, indigenous-cultivated, and native species, colonized gardens and the new Westernized Batswana gardens favored by an emerging African middle class that is abandoning cultural practices introduced more alien species and spontaneous non-native species. This indicated not only biodiversity challenges but also risks of losing indigenous, traditional, and local knowledge systems due to globalization.

Notably, a few studies considered adapting Indigenous nature-based solutions to reintroduce indigenous ecosystems (Buckley et al.,2023; Gooden & Pritzlaff, 2021). For example, the reintroduction of indigenous methods has led to the recolonization of native fish populations and an increase in endangered species in the southern United States (Gooden & Pritzlaff, 2021).

A partnership with Māori tribes is discussed under the “restoration in process” section below (Buckley et al., 2023). Such cases require researchers and practitioners to build relationships and partnerships based on respect and reciprocity with Indigenous groups.

3.13 Human Conflicts with Biodiversity

Human activity could negatively impact bird diversity and abundance in urban spaces, possibly due to both direct human disturbance and noise related to human activity interrupting birds' foraging activities (Muhlbauer et al., 2021). However, other species, such as moles, may be able to adapt to human disturbance and human-altered landscapes. An even greater abundance of moles was found in areas with higher urban intensity constructed areas (Fellows et al., 2020).

And while urban areas provide landscape heterogeneity that might be preferable for bird nesting (Korányi et al., 2021), there is also a clear correlation between undisturbed landscapes and species conservation and regeneration (Huang et al., 2019; Kowarik et al., 2016).

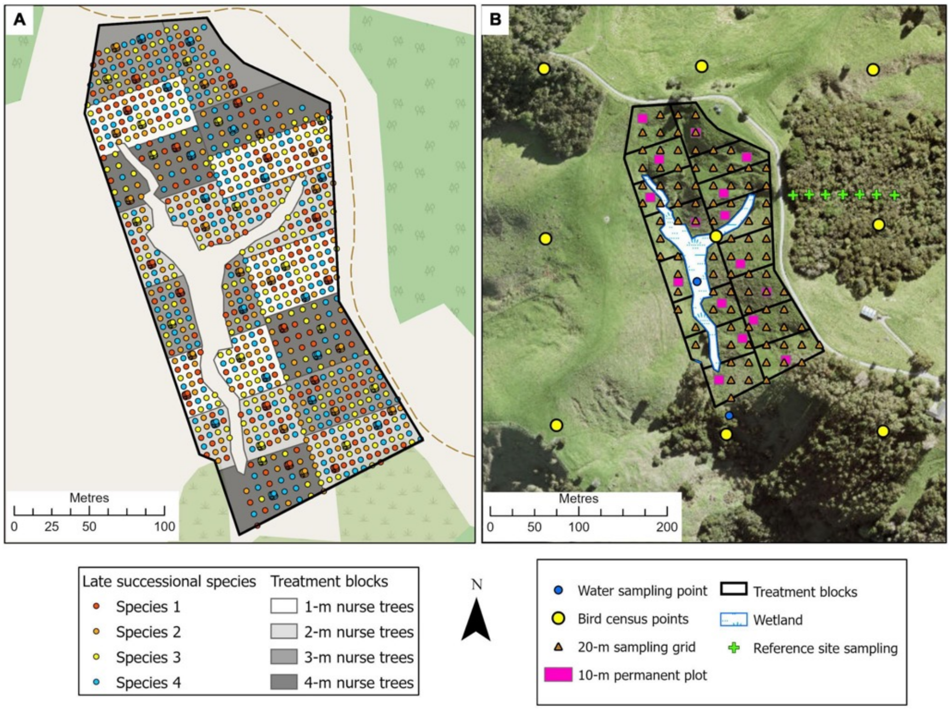
A common thread we noticed was that changing aesthetic inclinations are shifting to more "natural" looking landscapes, such as meadows replacing lawns. Once viewed as unkept and messy, they have become acceptable and even preferred due to public education on the importance of pollinators for our food supply and meadows to pollinators.

We recommend expanding public awareness programs regarding human-non-human species interactions within ecosystems, starting with those that are of greatest conservation concern, such as amphibians and arthropods other than bees and butterflies.

Moreover, researchers must make their findings more accessible to the broader public. This should not only be done through media and social media, but also consider partnerships among practitioners, schools, governments, and non-governmental organizations. Partnerships can create avenues for interaction, such as applied research, experiential learning opportunities, demonstrations, and community discussion.

4. Discussion

4.1 Ecological Restoration Efforts in Process



An illustration of the tree planting, treatment block, and site monitoring design for the AUT Living Laboratories program forest restoration Te Muri experimental site in New Zealand.

Buckley HL, Hall D, Jarvis RM, Smith V, Walker LA, Silby J, Hinchliffe G, Stanley MC, Sweeney AP and Case BS (2023) Using long-term experimental restoration of agroecosystems in Aotearoa New Zealand to improve implementation of Nature-based Solutions for climate change mitigation. Frontiers for Global Change 5:950041. / Creative Commons Attribution License (CC BY)

There were a few interesting studies in process that have yet to collect post-project data but were intentional about documenting and collecting pre-project biodiversity data through various methods, with plans for post-project data collection (Buckley et al., 2023; Kirk et al., 2021; Ito et al., 2021).

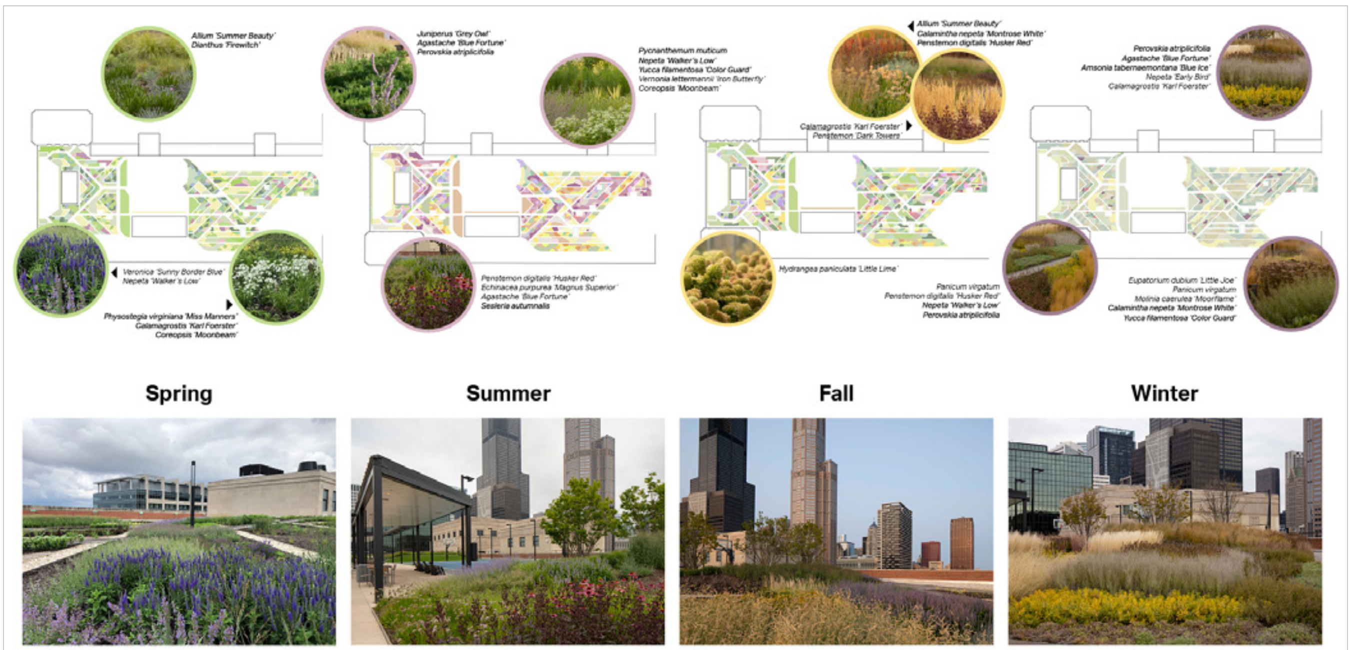
Buckley et al. (2023) are attempting a groundbreaking longitudinal experimental living lab in Aotearoa New Zealand, in partnership with indigenous Māori tribes. They provide extensive protocols on how experiments, monitoring, and evaluation will take place and allow for sub-experiments. While there is no impact evidence on biodiversity yet, this is an interesting model for universities to follow—creating living labs in partnership with communities with biodiversity restoration in mind.

Kirk et al. (2021) applied the Biodiversity Sensitive Urban Design Framework (BSUD) to a redevelopment project in Australia through a participatory engagement process, with conservation efforts focused on key species selected by stakeholders. The project is due to be completed in 2050; an empirical study of post-completion biodiversity is yet to come. Also, since a full pre-project assessment could not be conducted due to the project timeline, the researchers constructed existing and baseline data from a combination of the team's existing data and citizen science resources.

4.2 Implications for Landscape Architecture Practice

Across the literature, it was clear that landscape heterogeneity and native species are key to supporting biodiversity. It is important to highlight that in order to facilitate research on biodiversity impacts of LA, GI, and NbS, practicing landscape architects should consider implementing projects that include:

Planting Design



With four perennial plant palettes, bloom times at The Meadow at the Old Chicago Post Office was carefully choreographed to provide seasonal interest year-round.

ASLA 2023 Professional General Design Award. The Meadow at Old Chicago Post Office. Chicago Illinois. Hoerr Schaudt / Image Credit: Scott Shigley.

- **Incorporating Native Plants**
  Native plants are important but so are structural and functional diversity that complements each other. The goal should be reaching 80-100% endemic heterogeneous plantings that translates into a diversity of ecosystem services the plant community provides, from stormwater retention, phytoremediation and soil-nutrient restoration to serving as a food source for a larger variety of insect and animal species.

- **Supporting Pollinators**
  Landscape architects can consider the timing of when plants flower, types of flowers produced, pollination mechanisms, and other characteristics, traits, or behaviors related to the flowering process. They can stagger

flowering phases by using different individuals or populations of the same flower species at different times. These strategies also support faunal diversity. The landscape architects that designed the South Eveleigh Community Rooftop Garden intentionally curated native plant communities to address functional diversity and flowering timing and colors to attract pollinators.

- **Enabling Integrated Pest Management**
  Landscape architects can design plant communities that facilitate integrated pest management, such as planting certain plant species that attract beneficial species and keep destructive species in check. The High Line in New York City is an example of a successful integrated pest management scheme.

The Highline in NYC integrates the cityscape of an old rail line with native grasses, pollinator meadows, and trees. The public space is also used for education and workshops to raise awareness about biodiversity.

ASLA 2010 Professional Award. The High Line, Section 1. New York City, New York, USA. Field Operations / Iwan Bann

- **Allelopathic & Companion Plants**
  When the objective is to minimize maintenance and the use of synthetic herbicides, landscape architects should determine if aggressive plant species that present challenges on a site are known to secrete allelopathic compounds, such as juglone, and consider planting dense native species that have a higher tolerance to these natural biochemical compounds and can outcompete the "weeds." Moreover, certain plants are inherently beneficial to one another, and this should be a consideration when designing plant communities. The South Eveleigh Community Rooftop Garden demonstrates the use of plants to inhibit weeds while enhancing the garden. The team planted Warrigal greens (*Tetragonia tetragonioides*) to serve as a food source and control invasive weeds.

- **Protected Areas**
  Landscape architects can include designated areas to be left undisturbed by humans and pets in projects to create space for species that thrive when there is no human disturbance. The Dune Peninsula at Defiance Point Park is an example where signage was used to keep people on paths and out of meadows to minimize disturbance in order to allow the meadow to establish itself. Research studies in Berlin, Germany (Kowarik et al., 2016) and Chongqing, China (Huang et al., 2019) demonstrated a spontaneous return of endangered native plants, as well as animal species in undisturbed areas.

Transforming Grey to Green

- **Retrofitting**
  Urban greening initiatives should consider how existing buildings and walls can be retrofitted with green roofs and green facades. Vegetation can be allowed to naturally overtake walls without compromising their structure, or walls and roofs can be retrofitted with appropriate technology. Green roofs and walls improve energy efficiency, enhance air quality, mitigate the urban heat island effect, manage stormwater, and promote biodiversity.

- **Slope and Pitch**
  Planting design should be specific to place and slope. Pitch roofs might benefit from moss plantings while flat roofs can accommodate plants with deeper roots that can provide stormwater retention capabilities.

- **Building Height and Architecture**
  Landscape architects should consider building height and architectural details when installing green roofs to enhance insect or bird diversity or provide nesting habitats. For instance, research indicates that high buildings are potentially less likely to be conducive to pollinator nesting (MacIvor, 2016), but high buildings with architectural details could possibly be more conducive for birds prone to cavity nesting. Objectives will vary by project and location and should take these factors into account.

- **Bio-solar Roofs**
  Landscape architects can explore integrating photovoltaics into planting design. Bio-solar roofs may deliver co-benefits in terms of energy efficiency and supporting vegetation and invertebrate communities. An important factor to plan for it is the density of photovoltaic arrays (Nash et al., 2016), which can affect certain invertebrates, as well as high density plantings that can lead to increased parasitism (MacIvor, 2016).

Tracking Performance

- **Data Collection**
  Landscape architects can integrate pre- and post-project data collection and internalize rigorous and systematic monitoring of the projects post-completion for five years to obtain longitudinal data for researchers to work with. This may be done through engaging citizen science, public-private partnerships, and academic research collaborations.

- **Assessment**
  Consider using the IUCN Global Standard for Nature-based Solutions Self-Assessment tool or the Sustainable Sites Initiative (SITES) monitoring framework.

4.3 Future Research Agenda

Here, we summarize some areas for future research mentioned throughout the review:

- Can landscape heterogeneity paired with native plant diversity and abundance in urban areas lead to greater faunal species abundance within urbanized areas than peri-urban, rural, and agricultural? How would adding patches of "undisturbed zones" change the outcome?

- What are the impacts of vegetation density and diversity on arthropods' nesting and feeding patterns, and what variables contribute to divergent outcomes? (MacIvor, 2016)

- How does the density of photovoltaic arrays affect certain invertebrates (Nash et al., 2016)? How would this differ by topography and climate (urban green roof, peri-urban residential neighborhood, meadow, arid, humid, sunny, rainy, etc.)?

- What is the structural tolerance and stability of existing (maintained and neglected) masonry structures to accommodate various types of vegetal growth, including trees? What is the potential for vertical phytoremediation while preserving function, heritage, and safety?

- What is the feasibility and impacts of retrofitting flat and pitched roofs in urban and suburban areas? Which types of green roofs are suitable for different roof types (e.g. sod roofs on pitched roofs)?

- How can we build upon existing research by replicating designs and methods, but change scale, geography, and other variables to enhance existing knowledge by focusing on the variables under investigation, rather than the methods used? How can we reduce uncertainty on whether differences in outcomes are attributable to variables or research and sampling methods?

4.4 Opportunities for Stakeholder Collaboration

Community Partnerships

Increasingly, landscape architects understand the need for community voices and buy-in for large projects. Community partnerships should be real and deep connections, not superficial. Participatory design processes should focus on social-ecological communities, with consideration for bio-cultural heritage, integrating both biodiversity and cultural inclusion. This not only adds capacity to the project but also serves as a means for public education and outreach. It is integral that Indigenous groups and other community stakeholders are involved in the design, biodiversity monitoring, stewardship and decision-making processes. Relationships and partnerships must be built on respect and reciprocity. This is also where researchers come in.

Connecting Research and Practice

Practitioners and researchers also have an opportunity to expand their collaboration. Similar to the Landscape Architecture Foundation's Landscape Performance Series, design firms and researchers should consider teaming up to conduct more quasi-experimental pre- and post-project research to evaluate the real-world biodiversity impacts of large-scale projects. While universities often conduct experimental research with controls that are useful in narrowing down cause and effect, these research sites are often plots or greenhouses that are only accessible to the researchers and small insects or animals that can get through fences (e.g. no deer), therefore creating an unrealistic environment that lacks key variables—societal interaction and disturbance. Developments on Buckley et al. (2023) longitudinal experimental living lab in Aotearoa, New Zealand in partnership with indigenous Māori tribes will be a key research design to follow as it progresses.

Public Awareness Campaigns

Another key area for multi-sector collaboration is public education. Practitioners, researchers, community stakeholders, and policymakers should work in tandem to expand educational biodiversity awareness campaigns. Changing perceptions around meadows and pollinators are evident in the United States, but it is time to expand awareness beyond bees and butterflies to other life forms that might not be as endearing or obviously important to the public.

What of the salamanders, frogs, snakes, moths, and various beetles, flies, and ants that our ecosystems rely on? It is important that the public begin drawing connections to how integral other species are to planetary systems we all rely on—such as the decomposition of organic matter or being pivotal to the food chain as both predator and prey.

4.5 Limits of this Review

While our review aims to examine a full range of landscape architectural and GI strategies in improving biodiversity, a series of other review articles could supplement the knowledge of specific design interventions and techniques that quantitatively improve biodiversity: see Filazzola et al. (2019) for green infrastructure; Williams et al. (2014) and Butler et al. (2012) regarding green roofs and the use of native species in support of biodiversity; and McKinney (2021) on wastelands and biodiversity.

We would also like to draw attention to a few articles that were excluded from the review as they were not based on empirical studies that showed the correlation between human-designed, constructed, and/or restored landscapes and biodiversity outcomes. Although they did not fit the selection criteria, the information provided can inform project design for the aim of enhancing biodiversity with additional co-benefits. The reviews already conducted in this area, along with other studies, produced useful considerations for designing to enhance biodiversity with co-benefits: Jacklin et al. (2021) review with list of phytoremediators; Li et al. (2023a; 2023b) effects of land use on spontaneous plant life along river corridors.

Le Gouvello et al. (2023) produced a report focused on the use of the IUCN Global Standard for NBS Self-Assessment tool and applied it to two case studies (Zanzibar and Indonesia). The authors used information provided by the community partners including unpublished data to score the various criteria including biodiversity. In the case of Zanzibar, there wasn't much biodiversity data collected, and in the case of Indonesia, an increase in biodiversity was assumed based on wetland restoration but researchers noted that further study and assessment was necessary. Since the report was not an empirical study on the impacts of human-made landscape interventions, it was not within the scope of this review. However, it may be a useful framework for practitioners and communities to conduct self-assessments.

Appendix 1: Geographical Breakdown of Research Focus

Country	# Articles focus*
Aotearoa New Zealand	4
Argentina	2
Australia	5
Bulgaria	1
Canada	1
China	2
France	1
Germany	6
Israel	1
Italy	4
Japan	1
Mexico	1
Other/Unknown	4
Poland	1
Portugal	1
South Africa	2
Spain	4
Sweden	1
Switzerland	2
Thailand	1
The Netherlands	2
United Kingdom	12
United States of America	11
Grand Total	70

US State	# Articles focus*
AL	1
AZ	1
MI	1
NY	3
OH	1
OR	1
PR	1
TX	1
WA	1
Grand Total	11

Country	# Articles focus*
2011	1
2015	2
2016	8
2017	5
2018	5
2019	6
2020	6
2021	11
2022	14
2023	9
Grand Total	67

Global Region	# Articles focus*
Asia	4
Europe	33
Middle East/North Africa	1
North America	12
Oceania	9
Other/Unknown	4
South America	2
Sub-Saharan Africa	2
Grand Total	67

US Region	# Articles focus*
Midwest	2
Northeast	3
South	2
U.S. Caribbean	1
West	3
Grand Total	11

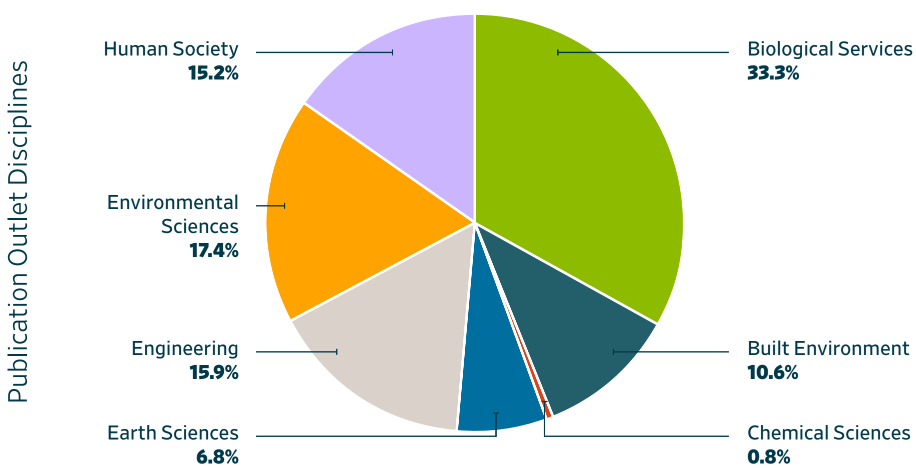
Appendix 2: Publication Outlets

The 155 full-text reviewed articles were from 87 publications, reflecting the diverse and multidisciplinary nature of current research on biodiversity, green infrastructure, and landscape architecture.

Biological sciences, environmental sciences, and human society (i.e., human geography subdivision specifically) are the top three research fields that publications belong to. The fact that 27 articles were published in a journal specifically categorized as multidisciplinary also reflects this insight.

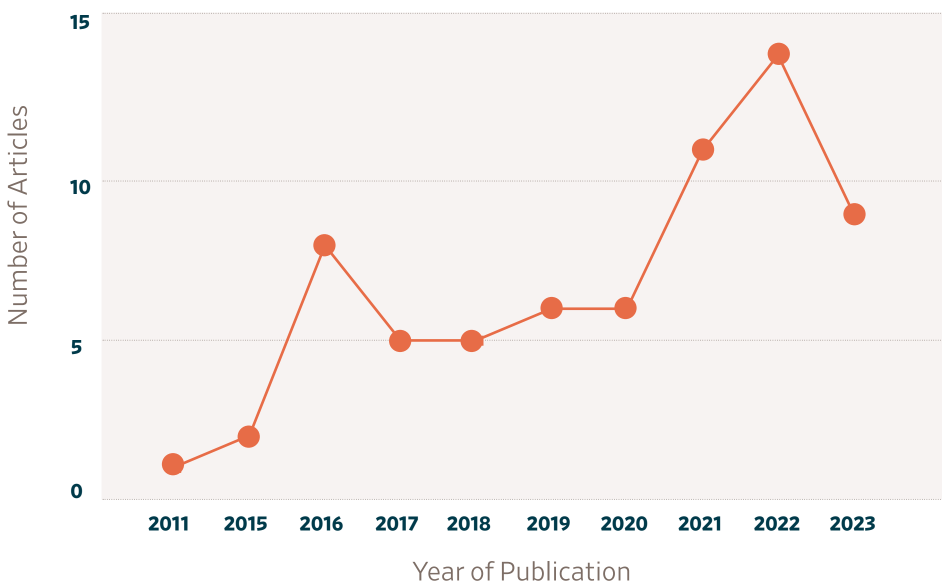
The top ten publication outlets with selected articles include:

- Urban Forestry and Urban Greening (n=14)
- Sustainability (n=13)
- Landscape and Urban Planning (n=7)
- Acta Horticulture (n=6)
- Science of the Total Environment (n=6)
- Land (n=6)
- Ecological Engineering (n=4)
- Cities and Nature (n=3)
- Ecological Applications(n=3)
- IOP Conference Series: Earth and Environmental Science (n=3)



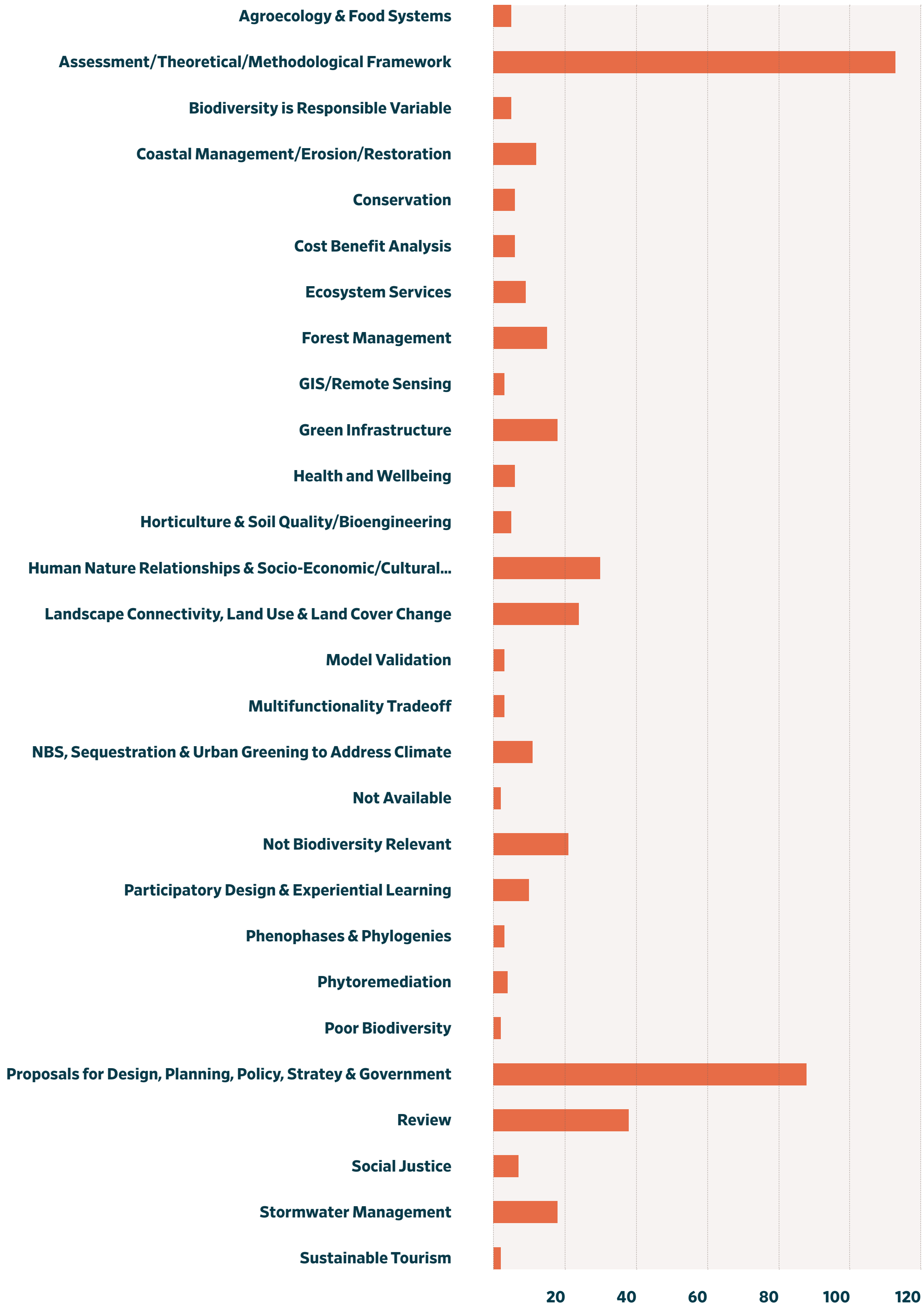
The 155 selected articles were published between 2000 and 2023, with the majority published since 2015.

We categorized 386 excluded articles for additional analysis to demonstrate that types of research being conducted related to biodiversity but not specifically to the empirical evaluation of biodiversity impacts of human-built landscapes, nature-based solutions, or restoration projects.



A large body of the searched literature was theoretical and introduced frameworks for GI assessment, priority, and spatial planning, with or without case studies application. However, these studies lacked empirical evidence on how proposed measures could improve biodiversity. Another focus of the existing literature that falls outside of our scope is the socio-cultural and economic aspects of GI and ecosystem services. For example, people's perceptions, aesthetic values, cost-benefit analysis, etc.

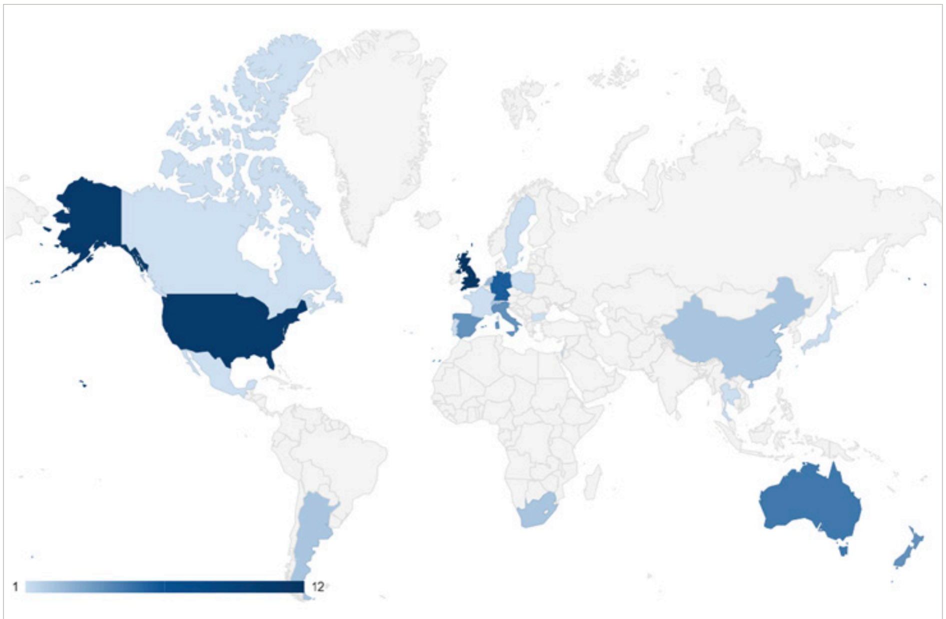
Reason for Exclusion (Abstract Review & Full Article Review)



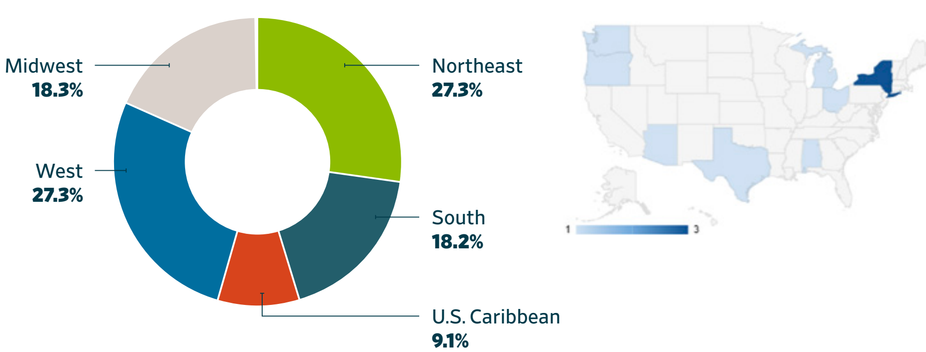
We also excluded review articles with empirical research. There are a few articles focusing on synthesizing current knowledge and empirical evidence of biodiversity and green infrastructure, which could be a great reference for this research project. For example, focusing on different types of green infrastructure, Filazzola et al. (2019) conducted a meta-analysis of 33 articles and proved that green infrastructure significantly improves biodiversity over conventional infrastructure and that, in some cases, green infrastructure had comparable effects on biodiversity to natural counterparts. While some articles did not fit neatly into one category, the best category was chosen based on information provided in abstracts.

Appendix 3: Geographic Focus Of Research

Most research in the peer-reviewed literature focused on Europe (n=33) and North America (n=12), with the United Kingdom (n=12) and the United States (n=11) having the highest count. However, we recognize that unbalanced and inequitable processes in academic publishing are likely to contribute significantly to this, and research published in languages other than English may also be available.

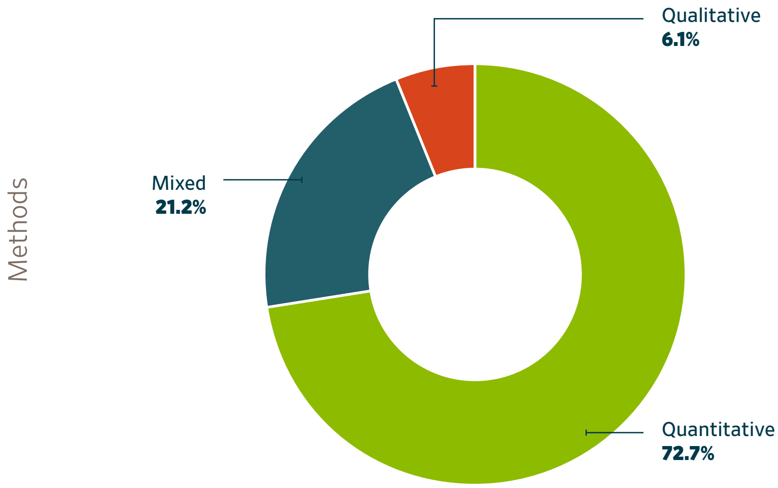


Number of Articles Research Focus by US Region



Appendix 4: Research Methods Snapshot

Of the 67 articles reviewed, 49 used quantitative methods, 4 used qualitative, and 14 were mixed (Figure 8). The research design was more distributed (Figure 9) with Case Studies (10), Experimental (6), Quasi-experimental (11), Simulation (7), and Sampling/Cross-sectional (33).



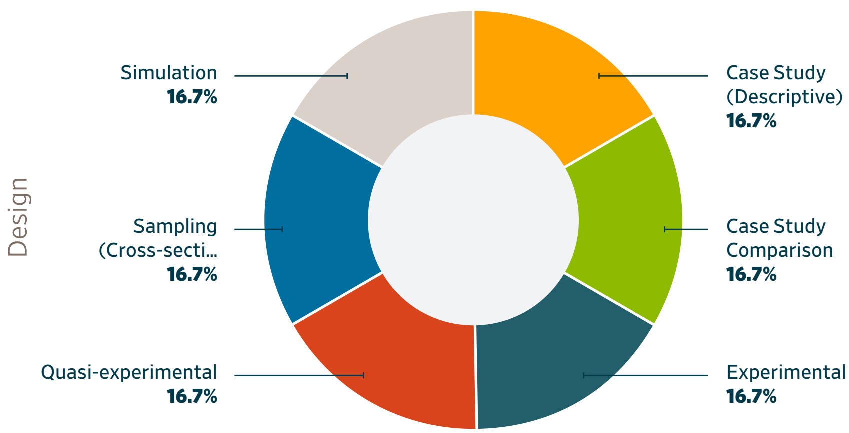
Studies varied in methods of quantifying biodiversity, most measuring species count, richness, and abundance. Some accounted for native versus non-native; relative density and relative frequency; taxonomic composition and richness; guild composition; alpha and beta diversity. While the most commonly used indices were Shannon-Weiner Diversity Index and Shannon-Wiener Evenness Index, many times in combination with others, not all studies used these indices.

Other indices included: Simpson Diversity Index; Exponential of Shannon Entropy; Inverse of Simpson Concentration; Normalized Difference Vegetation Index (NDVI); Normalized Difference Infrared Index (NDII); Jaccard Similarity Index (J); Relative Basal Area (RBA); Relative Volume Equivalent Value (RVEV); Basal Area (BA) calculated from diameter at breast height (DBH); Buzas and Gibson's Evenness Index; Bray-Curtis Similarity Index; Patrick Index; Duncan's new multiple range test; IBMWP index; Pielou Index; Braun–Blanquet Species Abundance Scale; Nuorteva Synanthropic Index; Mehniks and Margalefs Diversity Index; Species Vulnerability Score Kattan Index; Fragmentation Index; Leaf-Area-Index (LAI); Hemeroby Index; and Nuorteva Synanthropic Index.

Additionally, experimental models and statistical analysis methods included the Circumplex Model of Affect; ANOVA (one-way); ANOVA (multi-factor); Sidak

Correction; Pearson Correlation; Principal Components Analysis; Shapiro-Wilk Test; Generalized Linear Models (GLMs); General Linear Mixed-effects Models (GLMMs); Permutational Multivariate Analysis of Variance; Simper Analysis; and Mann-Whitney U (1-tailed) Exact tests.

While research methods and design are ultimately at researchers' discretion, we have observed that the multitude of sampling, measurement, and analysis methods hinders comparison of research studies.



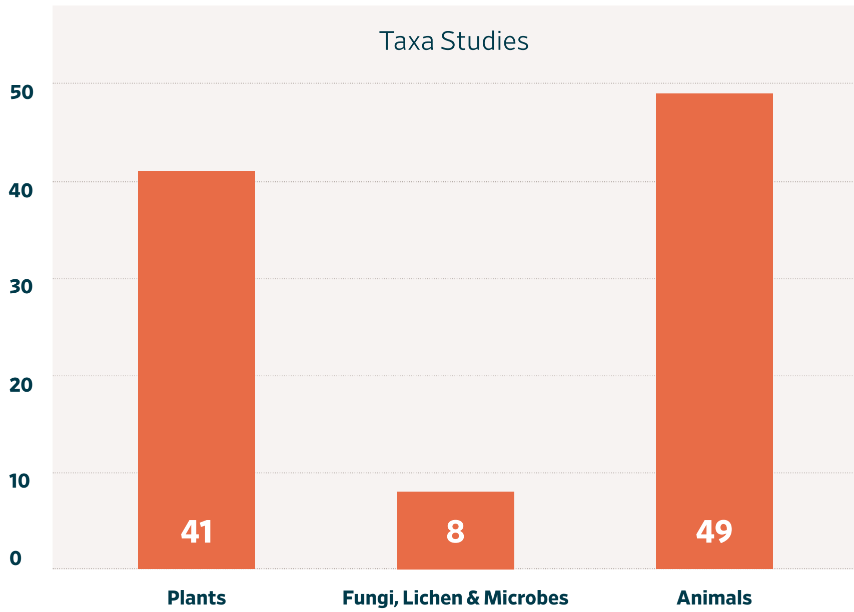
We understand that researchers are often eager to explore novel approaches and recognize the challenges of replicating environmental variables. However, building upon other's research by replicating designs and methods can contribute to the body of knowledge by focusing on the variables under investigation. This approach can enhance our understanding of the complexities within ecosystems and their intricate relationships with human-built landscapes, all while reducing uncertainty regarding whether differences in outcomes are attributable to variables or research and sampling methods.

It is improbable that experiments from the reviewed literature would yield identical results when replicated in different physical and socio-cultural landscapes. Nevertheless, these variations in results could offer additional insights into previously unconsidered variables and generate new hypotheses.

Appendix 5: Species Examined

There are a total of 41 articles exploring flora biodiversity as a desired outcome of green infrastructure and design, and 49 articles focused on fauna biodiversity.

Birds and insects were the most frequently studied fauna, and native plants were most often the focus of flora studies. In addition, 8 out of the 67 articles studied fungi, lichen, or microbes.



Interestingly, while we anticipated the empirical studies involving biodiversity contribution and improvement would treat biodiversity as a desirable outcome, several studies examined flora biodiversity as a precondition or introduced measures to explore its impacts on fauna biodiversity further (Belaire et al., 2022), ecosystem services provision (Belaire et al., 2022; Blair et al., 2017), social perception, interaction, and aesthetic values (Palliwoda et al., 2021). This yields a result of 25 articles focusing on both flora and fauna species richness or abundance.

While the majority focused on vascular plants, insects, and birds, several articles focused on benthic communities and macroinvertebrates species (Greenway, 2017; Hickling et al., 2023; Tagliabue et al., 2019; Ramírez-Agudelo et al., 2021; Ysebaert, 2018) as well as bacterial communities present in different types of GI (Joyner et al., 2019) as an indicator of habitat quality and precursor to further biodiversity enhancement.

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