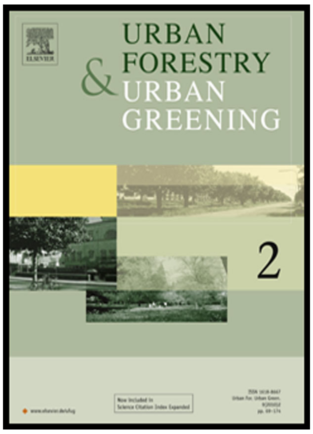

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Biodiversity-friendly practices to support urban nature across ecosystem levels in green areas at different scales

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Abstract

Biodiversity is pivotal for delivering ecosystem services to the human society, but lack of nesting, shortages of trophic resources and disharmonic biological communities are common problems in urban areas. In this review, we aimed to understand how to transform urban green areas into biodiversity-friendly spaces. We surveyed studies by targeting several trophic levels: from plants and their soil symbionts to pollinators, birds and mammals in order to find ways of reactivating ecosystem functioning and redundancy. Specifically, here we focused on three key ecological pillars: establishment (*i.e.*, planting/nesting), resources acquisition (*i.e.*, feeding) and the multiplicity of ecosystem levels. We also propose to integrate the actions used on broad surfaces and big parks with micro-injections for local scales and small green areas to increase habitat suitability, and we detailed a set of best and bad practices to streamline the enhancement of multi-taxa urban biodiversity by applying a combination of appropriate management of existing urban features and targeted installation of supporting elements. We also plea for a systematic incorporation of post-operam monitoring to test action efficacy and highlight the crucial role of a cooperative attitude among society participants, and we also highlight three main topics for urgent future research. In this review, we show that restoring urban nature could be based on an ensemble of simple, yet effective, supporting actions targeting different ecological levels to sustain ecosystem functioning and services at different spatial scales.

Keywords:
Green area management; urban sustainability; Supporting biodiversity; urban; ecosystem services

1. Introduction

Biodiversity is fundamental to the provisioning of ecosystem services of various types. Species richness assures ecosystem functionality, the stability of ecological communities and ecosystem services over time and against perturbations (Duncan et al., 2015; Ross et al., 2021). Moreover, many of the ecosystem services are guaranteed by species interactions (Hines et al., 2015; Luck et al., 2009). As single individuals need to collect resources, they interact with a number of other organisms, thus contributing to ecosystem functionality (Klaus and Kiehl, 2021). Therefore, to achieve effective biodiversity restoration and enhancement, it is crucial to establish, restore and/or maintain species rich areas also in human-dominated landscapes whenever and wherever possible (Behm, 2020), especially by targeting all aspects of an organism's life cycle. In other words, providing both food resources and appropriate breeding sites is of fundamental importance to ensure a high species diversity over time.

Given that urban green spaces are important for biodiversity but also to society for social and cultural reasons, the management of these green areas should take into account both the human perception and the ecological requirements of animals, plants and soil organisms (Silvert et al., 2023; Smith et al., 2018). In fact, a significant factor to a successful intervention for biodiversity and its medium-long term maintenance is the acceptance by the society. Coordinated management of green areas that engages stakeholders from different social, cultural, and scientific backgrounds, alongside effective communication of the benefits of keeping biodiversity, are essential aspects for successfully enhancing urban biodiversity (Aronson et al., 2017).

In this review, we aim to overview and analyse measures to increase biodiversity applied in urban green areas, highlighting positive and negative experiences, unwanted side-effects and particularly successful cases; We highlighted key aspects of life histories of plant, soil microbiota and some animal groups regarding establishment, shelter and trophic resources acquisition that could restart or fuel ecosystem dynamics, while encompassing the importance of biodiversity friendly actions considering multi-taxa approaches and different geographic scales.

2. Methods

For all groups, search keywords and different combinations were used for literature retrieval, the most important ones are listed. Group name (*i.e.*, “plant”, “microbiota”/ “fungi”, “pollinator”, “bird”, “ground mammal”, “bat”) and words “community”, “urban”, “species interaction”, “green area”, “city”, “management” and their combination were mostly used. For the animals also “nesting”, “nutritional”, “flower”, “nest-box”, “ornamental plant”, “supplemental feeding” were mostly used in combination with the above ones. For the microbiota section, “microbial inocula application in urban soil” was also used. For the pollinator section “flowering mix”, “bee hotel” and “bee pathogen” were also used. For bats, “artificial light”, “noise”/ “soundscape”, “water”/ “pond” were also used. Literature of the last 5 years was preferred; older literature was used at need.

3. Results

This review included a total of 184 published studies. Although the initial literature search identified 246 studies, some were excluded from this review because they did not focus on urban areas, or used data already included in other studies, or lacked technical details on biodiversity enhancement applications, or failed to present complete results directly related to the intervention for biodiveristy enhancement.

This review focused on three key ecological pillars, the establishment (*i.e.*, planting/nesting), the resources acquisition (*i.e.*, feeding) and the multiplicity of ecosystem levels, to solve the problems of lack of nesting, trophic resources shortages and disharmonic biological communities. The literature review resulted in a number of best practices that could be applied to the context of green areas of different sizes for all biodiversity groups analysed: plants, soil microbiota, pollinators, birds, ground mammals and bats.

The organisms targeted in this review represent different ecosystem levels from primary producers (plants and their soil symbionts, see sections “Supporting woody and herbaceous plants” and “Supporting soil microbial diversity”) to several kinds of consumers like pollinators (see section “Supporting urban pollinators”), birds (see section “Supporting urban birds”) and mammals (see section “Supporting small ground and flying mammals”). For instance, fruit eating birds and mammals boost seed dispersal, pollinators support plant reproduction, while plants provide shelter, nests and biomass to the other organisms, often supported by soil microbiota. In so doing, these groups contribute to ecosystem functioning and services. As an example of the benefit of the interconnectedness across ecosystem levels, cities around the world are experiencing an increasing abundance of species thanks to reintroduction actions of native plants followed by the creation of suitable habitats for animals (Moxon et al., 2023).

In detail, the biodiversity groups chosen here are based on their renown ecological importance. Plant diversity supports a number of ecosystem services and is often used in Nature Based Solution for city sustainability, including the reduction of temperatures and stormwater run-off effects, the decrease of air pollution and noise problems, the provision of ecological benefits by supporting urban flora and fauna biodiversity (Bellini et al., 2024; Bretzel et al., 2016; Wooster et al., 2022). Plant-associated microorganisms have been shown to boost plant diversity and development and also have positive effects on human health and wellbeing (Banerjee and van der Heijden, 2023). Pollinators mainly contribute to plant reproduction (Biella et al., 2021), and evidences highlight their role for human well-being and sustainable development (Patel et al., 2020; Potts et al., 2016). A diversified small mammal community provides multiple ecosystem services (*e.g.*, seed dispersal, contribution to soil structure and composition, pest control; Pearce, 2017) making its conservation in functional urban ecosystems pivotal. Birds are acknowledged as sensitive indicators of ecosystem health, play the roles of flagship and umbrella species (De Groot et al., 2021) and are crucial for ecosystem services like pollination, pest control, seed dispersal and the promotion of mental well-being (Hedblom et al., 2014; Yang et al., 2015).

The review found several effective actions that can be grouped into those artificial ones (*i.e.*, element produced by humans) and management of already existing resources. Those ones to contribute to population establishment (Table 1), most are applicable both at small and large scales and focusing on artificial solutions provided by humans and appropriate management of existing natural resources. As for trophic resource acquisition, a number of solutions are found regarding the nutritional needs of the local biodiversity (Table 2). However, most of these solutions are artificially provided by humans and only part of them are applicable at both small and big scales. Specific measures and key points for each ecosystem level are presented below. These enhancing actions can be interconnected in a framework, useful to guide restoration measures in urban contexts (Fig. 3)

3.1 From large green areas to micro-injections of supporting actions

In urban areas, nature conservation actions cannot overlook adequate landscape planning. A crucial role for biodiversity maintenance in urban green areas is played by green area isolation: As urban expansion and habitat loss persist, there is a need for green infrastructure planning to ensure habitat maintenance and connectivity (MacKinnon et al., 2023). This is a crucial aspect of urban planning for biodiversity, because the nature conservation value of green spaces depends on both their ability to provide access to key resources (food, shelter, and nesting sites), and to promote dispersal flow to the surroundings (App et al., 2022; Nelli et al., 2022). Moreover, green spaces (*i.e.*, vegetated areas) intersecting blue surfaces (*i.e.*, water bodies) are key landscape features that create blue-green corridors to support biodiversity and connectivity (Dietz et al., 2020; Krauel and LeBuhn, 2016; Lehrer et al., 2021). Although isolation is subjective depending on the organism mobility and the biological needs, connecting habitats among the urban green spaces is essential (Biella et al., 2022; Pioltelli et al., 2024). This aim can be achieved by designing large habitat fragments intermixed with small green areas or green roofs in the urban matrix (Ries and Sisk, 2008) and by assuring corridors between urban parks and non-urban lands (Breitbart et al., 2023).

To reach this scenario of an interconnected matrix of green areas, it is necessary to apply several types of biodiversity-friendly measures aimed at providing or managing resources at various scales, from the landscape level to the local ones. On one hand, large green areas could host enhancement interventions for biodiversity by having extended patches of natural or artificial trophic and nesting resources, while on the other hand small areas should host dedicated measures too (Fig. 1). Specifically, we also propose here an effective solution to the isolation problem, that is to distribute “micro-injections” of supporting measures, such as “micro-installation” of elements to enhance biodiversity applied at very small scale, which could progressively transform otherwise inhospitable land into habitat useful for urban biodiversity. Furthermore, at any scale of intervention, several essential features are to be carefully considered for the effectiveness of enhancing habitat biodiversity, as summarized in Figure 2. That figure clarifies the essential elements for designing measures to enhance multi-taxa biodiversity, based on nesting and trophic resource availability. In this review, sections dedicated to each animal or plant group studied in this review detail strategies for urban biodiversity.

3.2 Supporting woody and herbaceous plants

3.2.1 Afforestation for urban areas

Despite the multiple benefits, most urban areas around the world have scarce native forest cover (Clarkson et al., 2007). In recent years, efforts have been mainly directed to implement afforestation programs within and around cities and find NBS (*e.g.*, restoration of vacant lots, environmental compensation, green roofs, improve novel ecosystems, restore remnant patches, etc.) for increasing green areas and habitat opportunities for plant and animal species. Overall, to pair traditional restoration actions and architectural solutions would promote interaction between human and natural elements in the urban landscape (Standish et al., 2013).

Urban afforestation is aimed at providing refugia to multiple species sustaining native biodiversity (Gentili et al., 2024), reducing fragmentation of landscapes (Clarkson et al., 2007), halting the establishment and pressure of invasive alien species (Trammell et al., 2020) and providing ecosystem services to reduce the heat island effect (Zipper et al., 2016). However, due to human pressure and harsh conditions extant in urban environments, newly afforested areas are time and funding demanding because of the need to implement management actions, that are required to favour and accelerate natural processes and restore functional ecosystems (Ruiz-Jaén and Aide, 2006). To further help plants in their crucial function, management practices of lands dedicated to afforestation typically include soil amelioration, removal of weeds and alien invasive species (*e.g.*, eradication, herbicide application, and competitive vegetation), followed by re-introduction of native plant species (*e.g.*, native tree and shrub plantlets, herbaceous strips) (Johnson and Handel, 2019). Urban afforestation often takes place nearby existing native forest patches and/or directly on the forest edges, by planting woody and shrub species in the adjacent open areas (Chávez-García and Mendoza, 2017). Therefore, contrasting urbanization by increasing afforestation could help the transformation of small-size greenspaces into larger patches (Jin et al., 2021). In fact, afforestation is also crucial for ecological resilience, as maintaining urban vegetation and performing mitigation actions have been predicted to minimize the potential of plant extinctions in future (Hahs et al., 2009).

In all afforestation actions, we advocate that identifying in advance the most suitable plant species to be used and the sites where they have to be planted is crucial to increase the chances of survival and the likelihood to persist in a new habitat and to decrease time and funding investment for management and post-planting care. This strategic thinking should guide the choice of plants for urban afforestation programs, which are usually based on a reference ecosystem (Rivière et al., 2022); however, we also point out that the identification of the suitable species to be planted should be pursued by considering also other aspects like social preferences and landscape characteristics (Chechina and Hamann, 2015), possibly programming the supply of plants of local and wild provenance for each intervention (Rivière et al., 2022).

As an alternative to afforestation and traditional forest plantings, the opportunities associated with passive restoration, based on natural ecological succession, have to be considered by city planners and biodiversity practitioners as a new frontier of urban restoration. This means to leave some areas available to the spontaneous colonization of vegetation that does not need frequent and intense management actions, but can finally evolve in new emerging urban forests (Riley et al., 2018). These spontaneous vegetation patches can provide habitats to many organisms and are an interesting future avenue for urban afforestation, despite likely being often dominated by alien plant species (Kowarik et al., 2019).

3.2.2 Increasing vegetation outside urban forests

Urban greening and restoration of ecological functions also envisage re-establishing native plant communities of mostly herbaceous species either on the ground or on green roofs. Although native grassland patches are rare in urban contexts (Gentili et al., 2024), intensive seed bombing and sowing have been described as a promising technique to produce diverse grassland habitats rich in plant species, in turn supporting different animal communities (Anderson and Minor, 2021). Among interventions on urban vegetation, green roofs are widely used techniques for establishing different vegetation types (*e.g.*, grasses or succulents, or small dwarf-shrubs) on the top of buildings. Despite the importance and application of green roofs, criteria to be used for plant choice are understudied and scarcely documented across the literature (Bellini et al., 2024). At present, the succulent species like those belonging to the genus *Sedum* seem to be widely used since these species are particularly resistant to high temperature, high solar radiation and water deficit (Pérez et al., 2020).

Urban vegetation thrives in areas such as gardens and urban farms. Restoration and nature amelioration of community gardens, urban farms and orchards has been described as a high potential application for producing multifunctional areas and habitat diversification in cities (Horák et al., 2018), . especially when managed according to an ecosystem based-agriculture. Under ecological conditions, community gardens, urban farms and orchards can become sites with conservation potential and high biodiversity (Horák et al., 2018; Royer et al., 2023). Structurally diverse gardens and yards with native vegetation and green built-up areas (Snep et al., 2016) offer practical and easy solutions also for animal biodiversity, such as for bird habitat quality and quantity inside cities. However, high plant diversity is also usually recorded in residential areas, thanks to private gardens, where factors related to human management (*e.g.*, fertilizing frequency) and economic wealth (*e.g.*, housing price) are positively related with cultivated plant richness (Guo et al., 2024), a clear indication of the key role of the luxury effect in keeping a high urban plant biodiversity (Zhang et al., 2022). Therefore, greening and ecological restoration initiatives may be directed towards economically disadvantaged and otherwise vegetation-poor areas in order to reach environmental justice across urban wealth gradients and rescue the luxury effect (Chamberlain et al., 2019; Leong et al., 2018).

3.3 Supporting soil microbial diversity

3.3.1 Perspectives on soil microbiota for urban restoration

Although the advantages of green spaces in urban environments are well acknowledged by the scientific community, citizens and policy makers, the vital ecological services of the soil life that underlies urban green areas are rarely taken into consideration even by urban greening projects that have a solid scientific background (Fan et al., 2023). This "underground blindness" is in surprising contrast with the widespread and growing sensitivity for the role of plant-associated microbiota in natural and agricultural contexts, where the growing attention of stakeholders, farmers and policy makers for food quality and its relation with soil health, ecological sustainability of agricultural production and landscape and environment conservation (Giovannetti et al., 2023), feed a number of local, national and international initiatives (Panagos et al., 2022). The subterranean communities of bacteria and fungi also play critical functions when planning an artificial ecosystem, such as storing carbon, cycling nutrients, altering soil structure and improving plant mineral nutrition and protecting them plants from pathogens and abiotic stress (*i.e.*, drought) (S. Liu et al., 2022). For these reasons, and for being major actors in plant mineral nutrition and health, underground plant interactions represent a key element in the establishment of nature-based, robust, resilient artificial ecosystems such as agroecosystems and urban green areas.

Rethinking green infrastructure design from a soil microbiological perspective holds promise for enhancing plant diversity and development. Indeed, urban soils of bad quality can reduce the establishment of native trees and their health, also decreasing the long-term success of afforestation programs (Pregitzer et al., 2016). In such cases, the use of soil improvers such as the compost addition can ameliorate site conditions and plant growth over time (Oldfield et al., 2015). In order to apply such beneficial effects to the advantage of urban greening projects, it is imperative to promote and integrate plant-microbe symbioses for greener and healthier cities (Stewart et al., 2021). Given the overwhelming complexity of natural plant-associated microbiota, it appears difficult to understand, manage and functionalize it to support biodiversity in urban green areas that often lack pristine conditions. Two main ways could be feasible for boosting plant-microbe symbioses in urban areas. On one hand, it could be feasible to recreate a nature-like community of plants and wait for the spontaneous and progressive recovery of microbial partners already occurring in the surrounding peri urban areas, in analogy with similar strategies for reintroducing animal biodiversity (Liu et al., 2024). However, this process may take decades and it is still to be demonstrated as a successful approach under urbanized conditions. On the other hand, managers could inoculate a few well-known beneficial soil microbes since the initial setup of the green areas (Delgado-Baquerizo et al., 2016; Huot et al., 2017; Korneykova et al., 2021). On this line, an increasing number of studies is highlighting the advantages of inoculating synthetic microbial communities, or SynCom, in natural and agricultural ecosystems (H. Liu et al., 2022; Yin et al., 2022). Microbial inoculation has several advantages: commercial inocula containing a mix of beneficial bacteria and fungi are available on the market for sustainable agricultural practices; furthermore, while the complexity of natural plant-associated microbiota remains beyond our current reach, several studies have demonstrated the positive effect of individual microbes on several cultivated plants, strongly suggesting that these microbial strains can be as efficient in supporting plant health in urban green areas (Fan et al., 2023).

3.3.2 Features of urban soil plant symbionts and microbiota

It is essential to note that biological features of soil microbes is most often context-dependent when it comes to compare urban and rural areas (Li et al., 2023). Consequently, the results obtained in agricultural environments are challenging to infer to urban contexts and broad-scale studies are needed to characterize native microbiota and specific plant-microbe partnerships in urban environments (Fan et al., 2023). As an example, Delgado-Baquerizo et al. (2021) conducted a global field survey in urban greenspaces and adjacent natural ecosystems across 56 cities on six continents. Their study emphasized the significance of urban soils as hotspots for bacterial, protist, and functional gene diversity but observed that soil microbiomes are more similar among urban soils globally than between urban and nearby natural ecosystems. Moreover, urban greenspaces often lack microbial symbionts, such as mycorrhizal fungi, while exhibiting a higher proportion of fast-growing bacteria, algae, amoebae, and fungal pathogens compared to natural ecosystems.

The collective body of research focusing on microbial communities in various urban environments has focused on the identification of microbial mutualisms, particularly symbionts, given their potential to enhance plant health and growth. AM fungi, for instance, are frequently identified in urban parks and gardens, forming associations with a variety of grasses such as switchgrass (*Panicum virgatum*), as this association aids the host plants in acquiring 20–60 times more phosphorus and can result in up to 50% greater biomass production (Clark et al., 1999).

Investigating the impact of urban land uses on soil microbiota, (Christel et al., 2023) studied microbial communities (archaea/bacteria and fungi) in 78 urban soils in Dijon, France, categorized into three main land uses: public leisure, traffic, and urban agriculture. Results indicated that the stable habitats of leisure sites favoured the establishment of specialized microbial groups, including plant symbionts like arbuscular mycorrhizal (AM) fungi. On the contrary, within the diverse urban areas studied, urban agriculture sites emerged as the most disturbed land parcels. This perturbation might be the consequence of various agricultural practices, including the application of fertilizers, soil tillage, watering, and the absence of ground cover grass, which contributed to an overall reduction in microbial biomass levels (Christel et al. 2023).

Additionally, Whitehead et al. (2022) explored how intrinsic urban variables (such as urbanity and soil chemistry) influence microbial community richness and composition across 53 grassland sites in Berlin, Germany. They found that urbanity distinctly impacted fungal richness, particularly affecting AM fungal fungi. Specifically, urbanity led to increased richness in drought-sensitive Archeosporales (Canarini et al., 2021), while soil chemical features drove increased richness in Diversisporales and Glomerales. The study highlighted that many microbial species are well-adapted to urban soils, as evidenced by an increase in diversity.

3.3.3 Using soil microbial plant inoculants in urban contexts

At present, few publications discuss the application of bioinoculants in urban contexts, albeit with contrasting results. (Leonard and Lyons, 2015) employed commercial soil inoculants for grassland restoration in a 126-hectare park in San Antonio, Texas. In that study, half of the native grass plants received treatment with a soil bacteria inoculant along with additional nutrients, while the other half served as controls. However, no statistically significant effects of the treatment were observed in that study concerning overall native species abundance, soil resources, or the presence of soil microbes.

Bioinoculants have also been applied to green roofs with the aim of enhancing establishment success rates. Investigating the impact of mycorrhizas, *Trichoderma* spp., and soil bacteria on the abundance and biodiversity of higher trophic species, such as microarthropods, and examining potential effects on plant growth on a mature green roof, Rumble and Gange (2017) explored the efficacy of bioinoculants. Their findings revealed that certain microbial inoculants were more effective than others in remediating soil nutrient webs. Additionally, the study highlighted that commercial bioinoculants are recalcitrant in altering the microbial communities in mature green roofs, possibly due to the presence of stable native microbiota. By contrast, the concurrent application of biochar with either organic nitrogen sources or plant growth promoting microbes (PGPMs) as biofertilizers resulted in a notable enhancement of the growth of *Acer saccharinum L*. (silver maple) saplings cultivated in urban soil (Sifton et al., 2023).

Urban areas are also particularly prone to abiotic stresses, namely drought and heavy metal contamination. Under these conditions, positive examples of the effects of microbial inoculants can be found in literature. (Mahdavi et al., 2020) considered inoculation with PGPM in turfgrass for improving drought tolerance. This work demonstrated that *Pseudomonas fluorescens* inoculation increased turf quality, plant fresh weight, chlorophyll content, relative water and phosphorus contents. Schröder et al. (2019) used AM fungal inoculation into standard green roof substrate to enhance plant performance and drought resistance, with significantly positive results under moderate drought conditions. Overall, the studies presented here reveal that applying soil plant symbionts in urban contexts are an interesting avenue for supporting plant diversity.

3.4 Supporting urban pollinators

3.4.1 Urban existing resources for pollinators

Studies demonstrate that in urban environments some existing elements may help creating refuge areas for pollinators. First of all, the local availability of food resources plays a fundamental role on pollinators, especially in terms of flower diversity (Ayers and Rehan, 2023; Schmack and Egerer, 2023). Exotic ornamental plants can Also serve as suitable trophic resources as alternatives to native species, especially during periods of otherwise lack of flowering (Mata et al., 2021; Zaninotto et al., 2023). Regarding nesting, cracks in buildings and crevices make excellent nesting sites for cavity-nesting bees (Dar et al., 2020) or existing bare soil (Fortel et al., 2016). In addition, rooftops hosting flower beds or covered with soil and vegetation can provide valuable habitats (Jacobs et al., 2023).

3.4.2 Adding resources for pollinator nesting

Common actions to enhance biodiversity typically involve the installation of artificial nests. However, it is sometimes essential to understand pollinator biology to implement effective interventions for different taxonomic groups. In face of the heterogeneity of nesting and growing substrates of pollinators, it is particularly challenging to comprehend many species in a handful of nest types. A significant urban intervention for several bee kinds consisted in creating both ground surfaces for soil nesters and elevated artificial tubes for cavity nesting ones (Fortel et al., 2016). The following monitoring demonstrated that these feasible interventions combining different nesting surfaces involved 20% of the species pool in the area, thus revealing the success of the intervention. The success of bee hotels in an urban environment has also been reported for private gardens using cavity-nesting bees within an urban area (Prendergast, 2023). In this study, the nesting rate in wood blocks drilled with three measures for holes (*i.e.*, 4, 7, and 10 mm, 15 cm depth) showed that small diameters were preferred by native bees. An interesting result also regards the timing: it was found that bees took approximately 1 month to locate the nests regardless of the period in which they are installed. Moreover, other studies tested materials for creating bee hotels in urban areas (González-Zamora et al., 2021), comparing bamboo canes, *Arundo* canes, grooved boards, and drilled logs, with the latter being the most preferred by bees. Furthermore, different hole sizes were preferred in different substrates: intermediate hole sizes were preferred in drilled logs (*i.e.*, 4.9 - 6.5 mm and 7 - 9.2 mm), while smaller diameter holes (2.6/2.7 – 4.9/5.0 mm) were chosen for canes, and diameters of 5 mm were favoured for grooved boards. In the United Kingdom, 5-floor bee hotels have also been installed in urban meadows, and it has been demonstrated that these are excellent nesting sites for other taxa as well (Gardiner and Fargeaud, 2018): bee hotels create an ideal habitat at their base for grasshopper nesting because of the unmown grass underneath, and provide a good vertical platform for adult stridulation.

Despite the well-documented success of bee hotels, several challenges emerge once they are installed. The aggregation of many individuals in a confined space could lead to negative side-effects on wild bees: common are the increase and spread of parasites, predators, and occasional unwanted colonisers (MacIvor and Packer, 2015). It is well known the potential for parasite and disease spread within bee hotels due the close proximity of occupied cells and the diversity of bee species (Straffon-Díaz et al., 2021). Leaving spaces between cavities and using tubes of thick material to prevent cross-spread of pathogens and parasites is therefore recommended (MacIvor and Packer, 2015). Moreover, bee hotels can also attract other Hymenoptera such as wasps (MacIvor and Packer, 2015), which undoubtedly play a valuable role in green areas by acting as natural predators of pests but they could also displace native bees. If only bees are targeted for the hotel, a recommended solution would be to place the bee hotels in direct sunlight, thus creating an ideal condition for most bees that is less preferred by most wasps that typically prefer shaded nesting sites (Taki et al., 2004). Furthermore, bee hotels can be vulnerable to colonisation by non-native cavity nesting bee species. This is exemplified by the case of the *Megachile sculpturalis*, a large Asian bee, exotic in Europe and North America, with aggressive nesting habits that tend to occupy bee hotel cavities in significant numbers often preventing or even removing native bees (Geslin et al., 2020). To mitigate this, it is suggested to avoid using large cavities in bee hotels, *i.e.*, no larger than 8-10mm as *M. sculpturalis* is larger than many European cavity-nesting native bees and thus it avoids narrow tubes. However, the prevention of invasive co-nesting species is more challenging in cases where the cavity sizes and material are shared with native bees.

3.4.3 Adding resources for pollinator feeding

Two ways can be pursued regarding providing food for pollinators: keep unmown surfaces and/or planting flower strips. Regarding the former, managing existing floral resources is the first step toward conserving pollinator biodiversity, and mowing practices emerge as crucial actions (Süle et al., 2023). Johansen et al. (2019), specifically studying hay meadows, found that mowing regimes significantly influences the resources for pollinators. They demonstrated that the composition of flowers for pollinators varies following mowing timing and the diversification of mowing across different areas guarantees local flower resources across the season. Even in urban environments, it is possible to organize effective mowing management: in urban parks, leaving unmown areas rich in flowers increases insect biodiversity (Biella et al., 2025) and suspending mowing during the peak flowering period significantly contributes to maintaining pollinators (Brom et al., 2022). To ensure floral diversity and staggered flowering times, the novel "Three-strip management" has been proposed and tested on flower margins in semi-natural environments (Parmentier, 2023). The methodology involves dividing the grass margin into 3 strips and mowing them in a curved line rather than longitudinally. This allows for spatial-temporal variation in mowing and ensures diversity in structure and composition. This strategy seems very promising for urban green areas as well and it will ensure the availability of trophic resources for pollinators by the local wild flora.

Flower strips are commonly planted to enhance trophic resources to pollinators, and even if their floral composition is usually targeting domesticated bees, their effectiveness in supporting pollinator communities has been well-established in agricultural contexts (Sanchez et al., 2020). Flower strips are commonly used within agricultural ecosystems, and their dimensions can vary significantly, typically spanning from a few meters in width (2-8m) to several hundred meters in length (Amy et al., 2018; Bommarco et al., 2021; Kowalska et al., 2023). However, in urban areas smaller strips are usually applied as it is often unlikely to have large areas available for planting. A problem could arise if strips cause too high individual pollinator aggregation as it could result in a high pathogen transmission, as flowers can facilitate sharing viruses and pathogens between pollinators (Najberek et al., 2023) and flower strips with high pathogen occurrence may affect bumblebee infection intensity (Adler et al., 2000). Nevertheless, while it's true that in areas with high pollinator densities there is an increased risk of disease transmission, a variety of plant species in the flower strip serves to dilute pollinators with different feeding strategies and flower morphological preferences that, in turn, lowers the infection rate (Figueroa et al., 2019). In other words, it is crucial to sown flower strips with high plant diversity for the optimal nutrition of pollinators.

Regarding the plant composition of flower strips, several factors come into play when selecting the flower species to be sown there. In order to ensure a wide array of trophic resources to various pollinator requirements it is crucial to maintain an ample variety of different floral species covering morphological and nutritional diversity (Amy et al., 2018). Moreover, the long-term stability of flower strips is of utmost importance and hence both annual and perennial plants should be located. To provide resources continuously throughout the season, plants alternating their flowering time should be chosen. This strategy of ensuring the continuous availability of flowering resources correlates well with promoting the stability and diversity of pollinators (Buhk et al., 2018). However, commercially available seed mixes raised concerns among pollinator experts as those plants often attract large bees as the honeybees and their suitability to other pollinators is doubted. For example, a study from the U.K. showed that it would be sufficient to add representative species of Apiaceae, Asteraceae and Geraniaceae plant families to the mixes to support most wild bee species (Nichols et al., 2019). Furthermore, the plants included in commercially available mixes often disregard the local ecosystem in terms of plant origin and ecology, resulting in the introduction of non-native species or selected varieties or in the colonization by invasive species. However, we believe that the need of using non-native flora for flower strips should be carefully evaluated before sowing them.

3.5 Supporting urban birds

3.5.1 The role of existing urban features for birds

The conditions of urban green spaces has a profound impact on avian life, a taxonomic group renowned for its exceptional mobility, navigating diverse landscapes and bridging ecosystems (Gaston, 2022). Strategic keeping and improvement of urban greenery, therefore, becomes a pivotal factor in shaping the habitat and sustenance for these highly mobile species.

Central to surviving in urban habitats is the ability of birds to meet nutritional requirements in the face of altered or novel nutritional environments (Coogan et al., 2018). In cities, birds have access to a multitude of anthropogenic food sources –including food waste– and vegetation types (*e.g.*, planted native and non-native food-bearing plants; Burgin and Saunders, 2007). In urban areas, ornamental plants are able to offer basic bird habitat elements, especially providing food resources (fruits, nectars, grain and insects), shelter and cover (Idilfitri et al., 2014; Magre et al., 2019). Alien birds and urban adapter birds can utilize these resources (Idilfitri et al., 2014), allowing some species to thrive and causing changes in bird community composition.

In areas with intense human presence, landscapes may not provide enough resources for birds. The scarcity of key resources contributes to the loss of forest birds and insectivores while favouring generalists (*i.e.*, widespread and broadly tolerant species) and exotic species

(Chace and Walsh, 2006; Threlfall et al., 2016). Invasive alien species often emerge as winners in these contexts, disrupting native communities through competition, predation, and hybridization (Blackburn et al., 2014). This leads to increased genetic, taxonomic, and functional similarities in regional biotas over time (Olden and Rooney, 2006), resulting in reduced species diversity across urban areas (Colléony and Shwartz, 2020).

3.5.2 Increasing trophic and nesting resources for birds

In urban landscape design, incorporating building-integrated vegetation, such as green roofs and walls, stands out as a well-established strategy to enhance wildlife habitat (MacKinnon et al., 2023; Partridge and Clark, 2022) and connect urban greens. For optimal effectiveness, green roofs should be meticulously designed to mimic the surrounding green space and be sufficiently large to host birds (*e.g.*, 27,316 m2, see Partridge and Clark, 2022), with an ideal height lower than 50 meters from the ground (MacKinnon et al., 2023). Strategic planning, guided by least-cost path models, can create ecological corridors on rooftops, fostering native bird dispersal and breeding—illustrated by a study showing that adding 0.7 km2 of green roofs (5% of the total study area) reduced dispersal costs and enhanced corridor quality on four endemic keystone species in New Zealand (MacKinnon et al., 2023).

To counteract habitat fragmentation, green patches with improved vegetation structure are essential for both human and bird ecosystem services (Snep et al., 2016). A proper vegetation structure, featuring a multi-layer canopy of native plants, significantly boosts bird abundance, diversity, and native species richness, biomass, and breeding pairs of native species (Magre et al., 2019; Snep et al., 2016). Specific vegetation management is crucial for maintaining plant heterogeneity and sufficient understory vegetation, positively impacting insectivorous bird species (Threlfall et al., 2016). Wildlife oriented vegetation planting and management must maintain a diverse and complex array of vegetation habitat elements (De Groot et al., 2021; Hedblom et al., 2014; Magre et al., 2019; Partridge and Clark, 2022; Sanllorente et al., 2023): for example, a multi-layer canopy of plants and trees (Chace and Walsh, 2006; Partridge and Clark, 2022), medium-sized trees to favour bird nesting (Magre et al., 2019), retention of large and old trees (De Groot et al., 2021; Sandström et al., 2006), along with trees with cavities (Strohbach et al., 2013), and a well-designed water systems (Yang et al., 2015). Native or ornamental trees should be considered in the urban landscape as this vegetation would provide fruits and berries to frugivorous birds, promoting bird diversity and the pleasantness of urban environments for citizens (*e.g.*, Rowanberry tree; Suhonen and Jokimäki, 2015). Moreover, citizens often embrace artificial feeding, using bird feeders as a tool to improve the overwinter survival of certain species (Chace and Walsh, 2006); however, negative effects may be present and should be taken into consideration before bird feeding is widely adopted in urban areas (Wilcoxen et al., 2015). Bird feeding, either artificially or by means of specific vegetation, should be carefully evaluated and scientifically assessed in future studies for a more careful adoption.

Urban green areas often exhibit unsuitable vegetation structures for birds: Clearance of the shrub layer results in the loss of an important habitat layer for bird and arthropods, diminishing feeding and shelter opportunities (Magre et al., 2019; Yang et al., 2015). Urban planners might hesitate to introduce more plants in public areas, yet research indicates that moderately dense vegetation is appreciated by city residents (Bjerke et al., 2006; Threlfall et al., 2016). Human presence can disrupt bird occurrence, especially by affecting their feeding (Snep et al., 2016) and nesting habits (Magre et al., 2019). Intensive pruning poses a risk to urban wildlife, particularly during nesting, leading to a decline in bird diversity and richness due to low canopy density in the breeding season (Bassett et al., 2022; Magre et al., 2019). While in some cases it fostered passerine nesting, this was observed in only two tree species and was dependent on winter pruning and a subsequent large foliar mass in spring (Magre et al., 2019). This emphasizes the need to carefully schedule tree care activities to prevent disturbance to nesting birds. Furthermore, the prevalence of man-made sounds may impact bioacoustics, contributing to habitat fragmentation (Hedblom et al., 2014). Consequently, human presence significantly influences bird populations.

Insectivorous birds are commonly primary users of nest boxes, and integration into urban green areas and buildings enhance bird occupancy and survival (Chace and Walsh, 2006; Thompson et al., 2023). Research emphasizes crucial factors influencing nest box occupancy: the significance of well-designed and soundly constructed nest boxes for thermal stability (Griffiths et al., 2018), their strategic placement accounting for exposure to weather, climate and predation (Ardia et al., 2006; Bailey and Bonter, 2017; Schwartz et al., 2020), density of nest boxes in an area (Lima and Garcia, 2016), proximity to remnant vegetation and vegetation structure (Holt and Martin, 1997; Kavanagh et al., 2009), nest box design as depth and entrance hole size, wall thickness, construction materials and height (Carstens et al., 2019; Goldingay et al., 2015; Lambrechts et al., 2012), the potential attraction of non-target species and parasites (Charter et al., 2016; Goldingay et al., 2020; Stojanovic et al., 2021). Recognizing the pivotal role of birds in nurturing urban ecosystems poses a clear challenge to developing sustainable cities worldwide. The interconnectedness of bird biodiversity, bird songs, and human well-being underscores the importance of reconciling urban development with biodiversity conservation (Hedblom et al., 2014).

3.6 Supporting small ground and flying mammals

3.6.1 Plant and artificial refuges for small ground mammals

For small ground mammals, design and management measures should support the habitat diversity of green spaces by planting hard and soft mast plants that provide food resources throughout the year (*e.g.,* in Europe: *Fagus sylvatica, Quercus spp., Corylus avellana, Rosa spp., Sambucus nigra*) and low growing trees in the shrub layer (*e.g.*, *Carpinus betulus, Prunus avium*) to ensure a complex vertical structure of vegetation (Pearce, 2017). Preserving contiguity between tree canopies would be beneficial for arboreal and semi-arboreal species with low dispersal abilities (*e.g.*, *Sciurus* sp., hazel dormouse *Muscardinus avellanarius*) (Ofori and Ackon, 2023; Pearce, 2017) and maintaining climbing plants (*e.g*., *Hedera helix*) and bramble (*Rubus* sp.) can provide safe movement paths (*e.g.*, for yellow-necked mouse *Apodemus flavicollis*), and nesting material (Pearce, 2017). The spatial configuration of green space is also crucial for the conservation of small mammals. Recently, App et al. (2022) showed that the habitat area and the overall landscape permeability to West European hedgehog (*Erinaceus europaeus*) movements would decrease by 63% and 75% without private and gardens, respectively, in the city of Braunschweig (Germany).

In a well-connected network of green spaces, artificial refugees/nest boxes can support the conservation of small ground mammal communities, but studies on this guild in urban areas are still limited and evidence of the positive effect of these measures are rather scarce (Cowan et al., 2021). In the UK, Gazzard and Baker (2022) showed that the West European hedgehog systematically uses nest boxes in residential gardens throughout the year and life cycle. However, the physical design, positioning, and management of artificial refugees/nest boxes are critical factors for their success (Gazzard and Baker, 2022; McComb et al., 2019). Good practices for boxes design, management, and positioning include: adopting anti-predation precautions (*e.g.*, presence of a divider between the entrance tunnel and the main nest-box chamber), providing leaf litter to help preserving suitable temperatures and air circulation (Morris, 2018), favouring locations with a low level of human disturbance and predation risk (Bearman-Brown et al., 2020), choosing sheltered locations, such as log pile or scrub cover (Gazzard and Baker, 2022), deploying boxes for a long time to avoid neophobic behaviours (Stryjek et al., 2019). Eventually, supplementary feeding close to artificial boxes can increase the occupation rate (Gazzard and Baker, 2022).

3.6.2 Plant and artificial trophic resources for small ground mammals

Food provisioning practices for ground mammals can include planting native berry plants (Jokimäki et al., 2017). Supplemental feeding (*i.e.*, food intentionally provided by humans to wildlife), significantly affects the presence/abundance of multiple small mammal species (Gazzard and Baker, 2022; Williams et al., 2018; Wist and Dausmann, 2023), particularly in winter (Jokimäki et al., 2017). For example, Wist and Dausmann (2023) found that Eurasian red squirrel (*Sciurus vulgaris*) abundance in urban parks in Hamburg (Germany) where supplemental feeding was provided was higher than in parks where this does not occur.

Implementing measures for the conservation of small ground mammals could have side or detrimental effects. Alien or pest species could be inadvertently favored by actions targeted to native species (Bonnington et al., 2014). Higher risk of pathogen transmission and predation risk, also due to domestic animals (Fardell et al., 2023), alteration of nutritional intake or individual behaviour could arise from supplemental feeding and use of artificial refugees and nest boxes (Gimmel et al., 2021; Rosli et al., 2023). In urban environments, individuals might even perceive site-specific cues as misleading indicators of good habitat quality, turning urban green areas into ecological traps (Zuñiga-Palacios et al., 2021).

3.6.3 Supporting urban bat nesting

Bats are sensitive to urbanisation, and urban tolerance seems being linked to specific life-history and ecological traits and predictable across bioregions (Jung and Threlfall, 2018). To support viable populations and biodiversity in bat communities, urban environments must be capable of supplying roosting sites, food sources, and foraging habitats (Rowse et al., 2016; Russo and Ancillotto, 2015). However, bats being nocturnal, artificial lights and soundscape features can be significant factors affecting bat behaviours in urban areas: a growing attention is now given to the potential effects of anthropogenic noise in disrupting bat behaviour (Bunkley and Barber, 2015; Lehrer et al., 2021). To mitigate potential negative effects of noise, urban planners and policy makers should pay attention to reduce noisy human activities (*e.g.*, industrial development, music festival, road traffic) in the surrounding of known roosts and around potential foraging areas, also considering that anthropogenic noise could impair the benefits that bats have received by conservation-oriented measures (Lehrer et al., 2021).
Features of roosts, which are used for reproduction and hibernacula, are often species-specific and should guarantee suitable structure, microclimate, and protection from predators (Voigt et al., 2015). In urban areas, bats usually use buildings and trees as roosts, and when suitable roosting sites are lacking, artificial roost (*i.e.*, bat houses and bat boxes) may represent a mitigation tool. Practical measures to preserve natural roosts functionalities should aim at keeping a low level of human disturbance, avoiding eviction of roosts or, if it is needed, intervening when roosts are not used by bats (*i.e.*, outside reproduction or hibernation

periods). Large roosts, such as those in buildings, should be preserved as possible because a decrease in size and structural complexity of the roost space may lead to decline or even loss of the colony (Voigt et al., 2015). Buildings are successfully and mainly used by synanthropic species (*e.g.*, *Pipistrellus pipistrellus*), as they act as surrogates for cliffs, caves, or trees (Russo and Ancillotto, 2015; Voigt et al., 2015). Bats can exploit vertical cracks, fissures, small holes of buildings as well as interior spaces (Voigt et al., 2015). Therefore, roof eaves, gables, chimney joints, roof voids, wall cavities, and cellars which have gaps that bats can use or through which they can entry to other part of the building and that have the suitable microclimate conditions (*e.g.*, humidity, stable temperature, darkness) can favour the selection of buildings as roost (Howard and Richardson, 2009). Guidelines to promote bat-friendly buildings are available in several countries worldwide (*e.g.*, https://www.eurobats.org/sites/default/files/documents/publications/other_available_publications/VleermuisbouwenEN%202012.pdf) and should keep in mind by householders, architects, and policy makers in building and renovating projects. For example, bat roosts can be integrated post-construction in buildings through structure in the wall cavity or outer wall. Such integrated roosts remain isolated from the rest of the building occupied by humans, while assuring stable temperature and thus more suitable as hibernacula or nursery roosts. Additionally, preserving older buildings and promoting heterogeneity in architectonic features can reduce environmental filtering and foster bat species richness (Printz and Jung, 2023).

The presence of trees as roosting sites in urban areas is particularly important for bat species that do not usually roost in buildings (Laux et al., 2022). Fissured barks and hollows represent essential features in supporting roosting selection in trees. Such characteristics are commonly found in old and large trees, therefore their retention in parks or along streets is pivotal (Laux et al., 2022; Threlfall et al., 2017). When roosting sites are not available, or original roosts have been destroyed, artificial roosts (*i.e.*, bat houses and bat boxes) could represent an alternative (Rueegger, 2016). For example, in the campus of University of Florida, bat houses successfully host around 500,000 bats mostly belonging to three native species (https://www.floridamuseum.ufl.edu/bats/). Effective bat boxes require targeting and understanding species-specific roost preferences. Boxes should be made from durable materials, be unattractive to non-target species to avoid interspecific competition and be, to some extent, self-cleaning (Rueegger, 2016). However, considering that some species tend to avoid artificial boxes (Robinson et al., 2024), protection of existing roosts and potential roosting sites (*e.g.*, old trees) should be considered a paramount action to preserve bat communities (Rueegger, 2016; Voigt et al., 2015).

3.6.4 Providing urban bat nutrition

In urban areas, trees, other than being important for roosting as discussed above, are important site-level factors proving nutrition and protection (Threlfall et al., 2017, 2016).

Therefore, site-level tree management should aim at preserving and favouring trees with higher diversity of microhabitats and complexity structure (*e.g.*, fissured bark, fork splits, hollows, reduction of pruning) that can promote a higher diversity and abundance of insects (Laux et al., 2022; Threlfall et al., 2017), to act as grounds for foraging activities and to supply protection from artificial light at night especially for sensitive bat species (Straka et al., 2019). Moreover, high densities of large trees and the volume of understory are important to foster bat diversity in general and for clutter-adapted species (Threlfall et al., 2017, 2016).

Artificial light at night is a significant factor that can affect bats in urban areas as this may interfere with their foraging behaviour, disrupt their resting cycles, and influence physiological and behavioural processes crucial for reproduction. The commonly used Light Emitting Diode (LED) lamps can interfere with the hunting and orientation patterns of both fast- and slow-flying bats (Haddock et al., 2019). The colour spectrum of LED lamps plays a crucial role in affecting bat behaviour: Warm-tones (red and amber) lights are less disruptive to bats, while cool-toned (white or blue) lights can interfere with bats' ability to detect prey and navigate effectively, albeit the latter are capable of attracting a larger biomass of insects. Further studies are currently needed to delve deeper into what could be the best strategies to adopt to reconcile the needs of limiting artificial light at night disturbance towards bats (*e.g.*, include using low-intensity lighting, directing lights to reduce direct glare, implementing low-light zones, implementing tree belts to mitigate light spill and glare, opting for warm-tones light spectrum) and the needs of citizens' activities and safety at night in urban areas (Bolliger et al., 2022; Haddock et al., 2019; Straka et al., 2019).

The presence of blue-green ecological corridors enhances the availability of suitable foraging habitats, where water sources are essential for drinking, foraging, and navigating in the environment (Li and Wilkins, 2014; Russo and Ancillotto, 2015; Straka et al., 2019). For example, bat activity and species richness increased in the campus of University of North Carolina Greensboro after the construction of wetland sites (Parker et al., 2019). Providing riparian vegetation around ponds and linear waterways that increase the availability of invertebrate preys and shelters is also pivotal (Lintott et al., 2015; Straka et al., 2019).

3.7 Priorities for future studies: identifying bad practices, the crucial role of monitoring and of society acceptance

Several research topics need urgent attention in the context of this review. Among them, at least three stand out as particular relevant and worth mentioning in this review. First, future research should prioritize identifying bad practices and understanding failures that hinder the enhancement of urban biodiversity. Such failures, often unrecorded or omitted from the literature, hold valuable insights that could inform more effective strategies: alongside interventions for biodiversity, monitoring the success of supporting actions over time is crucial, to measure the effectiveness of the applied measures. In fact, here we highlighted those bad practices to avoid when the aim is to support biodiversity in effective ways (Table 3), but only by means of future researches aimed at systematically monitor the interventions, it will be possible to discover what exactly needs to be changed or tailored according to the context, towards a spiral of progressively more effective interventions.

Secondly, future researches could systematically incorporate and test modern monitoring methods in relation to actions aimed at increasing urban biodiversity. In addition to traditional approaches like direct observation or sampling, monitoring could use video/audio recording or sensor systems, which are efficient in terms of time and field skills, but they may sometimes lack taxonomic precision. For pollinators, videos can also be used to retrieve information on nesting performance, behaviour, inquilinism and foraging rates (Knauer et al., 2022). Promising tools for an effective mammal community monitoring are camera traps with motion-detection triggers, low-latency and high signal-to-noise ratio (Klemens et al., 2021), or tunnel footprints for monitoring the effectiveness of artificial refuges and nest boxes (Gazzard and Baker, 2022). For bats, smart bat sensors may be installed in cities and, using machine learning and edge computing, can process real-time data also during period which traditionally would not be monitored (Gallacher et al., 2021). To cope with the high amount of data produced by some of these systems, artificial intelligence is being employed for instance to identify individual species and calculate nesting and foraging times (Knauer et al., 2022). Furthermore, environmental DNA metabarcoding can be an eligible tool for effective detections, especially for species that are elusive or challenging to be identified (Kim et al., 2022; Zhang et al., 2023).

Thirdly, another important research question for the near future regards assessing the acceptance by the society. Among the various methods to measure society acceptance, we suggest that in urban and peri- urban areas, citizen science platforms could be utilized both to involve citizens and to monitor the effectiveness of interventions. Even dedicated events for rapid data collection by Bio Blitzes or events that engage the general public could help in retrieving useful data while also serving as effective tools for measuring societal engagement in efforts to enhance urban nature: for example, in Brussels, the nesting habits of wild bees species between sidewalk tiles were assessed with the active involvement of the public (Noël et al., 2024), and user observations have contributed to data collection regarding butterflies in Italian national parks (van Tongeren et al., 2023). Alternatively, urban biodiversity can be quantified by utilising data already uploaded by citizens to web platforms, resulting in the creation of extensive datasets (Callaghan et al., 2020). These openly collaborative ways may be extremely useful for providing fundamental insights on the efficacy of interventions aimed at enhancing biodiversity in urban areas, while also involving and educating citizens towards urban nature.

4. Conclusions

This review presented ways to realize measures for supporting biodiversity of several trophic levels within the urban areas, also accounting different landscape scales: from small to big green areas and their interconnection. We advocate that biodiversity support should be based on three pillars: establishment (*i.e.*, planting/nesting), resources consumption (*i.e.*, feeding) and multiplicity of ecosystem levels. Additional precious information on the solutions applied can be acquired by monitoring by experts or citizen science, in order to assess success rate or possibly outline correcting measures. Achieving a balance between recreational spaces and biodiversity-friendly environments requires collaboration among diverse stakeholders. This integrated approach contributes not only to biodiversity conservation but also to fostering human well-being in the evolving urban landscape. We strongly suggest that in urban areas, biodiversity experts, conservationists, biodiversity-oriented associations, administrators, private citizens, companies and stakeholders should cooperate for welcoming species diversity and their interactions within ecosystems, in order to reactivate and reinforce ecosystem service provisioning and ecosystem functioning in all kinds of urban areas.

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Declaration of Competing Interest

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

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FIGURE 1

Figure 1 - In the urban matrix, each landscape type (ranging from intensive urbanized areas to large urban parks) could contribute to enhancing urban biodiversity by providing, managing and improving nesting and trophic resources. It is essential that these elements are spatially interconnected and properly managed. Here, only aspects common across more than one taxonomic group (symbols) are depicted, see Table 1-3 for more specific information for each group.

FIGURE 2

Figure 2 - It is possible to support and increase biodiversity by integrating trophic resources and nesting sites into the urban matrix. Here only aspects common across taxonomic groups are depicted, see Table 1-3 for more specific information for each group.

FIGURE 3

Figure 3- The actions for enhancing urban biodiversity can be interconnected in a framework, useful to guide the efforts for enhancing habitat quality and the restoration measures in urban contexts

TABLES

TABLE 1 - Selected best practices for supporting implanting/nesting of biodiversity in urban green areas: the organism groups targeted here represent different ecosystem levels from primary producers to several kinds of consumers. The suggested actions are detailed in the main text, here information is given regarding landscape scale, whether they are artificial or existing local resources, possible critical aspects and proposed remedies, and the main references.

Animal or plant groups	Description of the application	Application scale (microinjection to small areas, applicable to broad green areas)	Natural or artificial resources	Drawbacks of the intervention	Solutions for such drawbacks	References
Plants	Planting young plants or seeds	Applicable to large areas	Artificial	- To identify the target ecosystem and the right species also considering climatic issues - To consider human preference and social aspects	- Testing new plant assemblages and resilient plants - Management activities also involving citizens	(Chechina and Hamann, 2015; Trammell et al., 2020; Zipper et al., 2016)
Plants	Self colonization	Applicable to large areas	Natural	Invasion by alien species	Manual control; eradication	(Kowarik et al., 2019; Riley et al., 2018)
Soil microbiota	Use of commercial inocula containing arbuscular mycorrhizal fungi and plant growth-promoting bacteria and fungi	Microinjection, applicable also to large areas	Natural / artificial			(Leonard and Lyons, 2015)
Pollinators	Bee-hotels with holes of different diameters and from various materials (*e.g.,* empty stems, pity stems, holes in wood)	Microinjection, applicable also to large areas	Artificial	- Spread of viruses and pathogens - colonization by alien species	- Cleaning periodically (*e.g.*, every 3-5 years) - Large alien bees can be excluded by using smaller holes	(Fortel et al., 2016; Gardiner and Fargeaud, 2018; González-Zamora et al., 2021; Prendergast, 2023)

	Leave or create bare soil surfaces or small hills	Microinjection, applicable also to large areas	Natural	Easily colonized by vegetation	Careful removal of covering plants	(Fortel et al., 2016; Neumüller et al., 2022)
Birds	Leave and/or increase patches or strips of wild-native shrubs and large/old trees	Microinjection, applicable also to large areas	Natural / artificial	- Might be perceived as unpleasant in urban parks. - Intense pruning might affect colonization	- Correctly inform and educate people; - Delineate recreational areas through zoning; - Avoid intense pruning.	(De Groot et al., 2021; Magre et al., 2019)
Birds	Positioning artificial nest boxes	Microinjection, applicable also to large areas	Artificial	- Inappropriate location; - Lack of cooperation between stakeholders.	- Identify optimal locations; - Design artificial nests to meet species-specific needs; - Implement cooperation between, researchers, ornithologists and the different stakeholders.	(Thompson et al., 2023)
Ground mammals	Artificial nest boxes	Microinjection, applicable also to large areas	Artificial	- Spread of pathogens - Risk of predation - Human/pets disturbance - Unsuitable microclimate (*e.g.,* thermal profile) and physical features (*e.g.*, entrance dimension)	- Clean periodically - Position boxes in sheltered sites (*e.g.*, log piles, scrubs) - Use boxes specifically designed for the targeted species or follow specific guidelines for home-made boxes	(Cowan et al., 2021; Gazzard and Baker, 2022; McComb et al., 2019)
	Preserve/plant shrubs and trees providing suitable refuges and nesting habitat (*e.g.*, large old trees with holes and covered cracks, dead wood, leaf litter, bramble)	Microinjection, applicable also to large areas	Natural			(Dondina et al., 2016; Pearce, 2017)
Bats	Bat-boxes	Microinjection, applicable also to large areas	Artificial	Potential colonization of nests by hornets. This can represent a problem in the case of bat boxes		(Gunnell et al., 2012)

				placed near areas used by people		
	Conserve old or dead trees in urban green areas	Microinjection, applicable also to large areas	Natural	Old trees, snags or lags may cause public safety problems	Consider preventing access to areas with unsafe trees	(Gunnell et al., 2012)

TABLE 2 - Selected best practices for supporting trophic resource acquisition by biodiversity in urban green areas: the organism groups targeted here represent different ecosystem levels from primary producers to several kinds of consumers and follows the groups covered in Table 1. The suggested actions are detailed in the main text, here information is given regarding landscape scale, whether they are artificial of existing local resources, possible critical aspects and proposed remedies, and main references.

Animal or plant groups	Description of the application	Application scale (microinjection to small areas, applicable to broad green areas)	Natural or artificial resources	Drawbacks of the intervention	Solutions for such drawbacks	References
Plants	Soil improvers (*e.g.*, compost)	Microinjection, applicable also to large areas	Artificial	Cost of the intervention	Circular economy: recovery of waste products	(Oldfield et al., 2015)
	Selection of plants adapted to local present and expected future climate	Applicable to large areas	Artificial	Plant supply chain issues	Structuring supply chains of native plant material of wild and local provenance	(Rivière et al., 2022)
Soil microbiota	Implementation of commercial microbial inocula with biostimulants promoting mycorrhizal symbiosis	Microinjection, applicable also to large areas	Artificial			(Oddi et al., 2024; Volpe et al., 2023, 2020)
Pollinators	Sown flower strips or patches	Microinjection, applicable also to large areas	Artificial	- Lack of local flora in the seed mix - Short flowering phenologies not covering the entire season - Fragile to human and	- Careful selection of seed mixes - High plant diversity and knowledge on flowering timing	(Hofmann and Renner, 2020; Nichols et al., 2019; Süle et al., 2023)

				pet disturbance (trampling etc)	- Signal the presence of the intervention, or exclusion fence	
	Leave patches or strips of pre-existing plants free to grow by unmowing	Applicable to large areas	Natural	- Frequent mowing for recreational or human-centred reasons - Challenging selection of patches, based on distribution of flower diversity; - Disturbance by people or pets	- mowing only rarely - Careful previous study of flower diversity in the area - Area fencing	(Biella et al., 2025; Johansen et al., 2019; Parmentier, 2023)
Birds	Allow patches or strips of pre-existing plants to grow freely (*i.e.*, unmown areas)	Applicable to large areas	Natural	- Citizens perceive unmown areas as unpleasant in urban parks.	- Correctly inform and educate people. - Mowing only rarely (once or maximum twice per year). - Fencing of unmown areas.	(Lovell and Johnston, 2009; Sandström et al., 2006; Snep et al., 2016)
Birds	Artificial bird feeders	Microinjection	Artificial	- Inappropriate location. - Feeders increase generalists or invasive species.	- Correctly inform and educate people - Design feeders to meet species-specific needs	(Coogan et al., 2018; Snep et al., 2016; Strohbach et al., 2013)
Ground mammals	Provide food into artificial boxes	Microinjection	Artificial	- Poor quality food and alteration of energy intake - Disruption of hibernation patterns		(Gazzard and Baker, 2022; Gimmel et al., 2021)
	Preserve plant species (or add novel ones) providing edible seeds and fruits (*e.g.*, bramble, *Prunus, Corylus avellana*)	Microinjection, applicable also to large areas	Natural			(Dondina et al., 2016; Pearce, 2017)
Bats	Promote the distribution of Asteraceae, Graminaceae, Leguminosae and Polygonaceae in open habitats	Microinjection, applicable also to large areas	Natural			(Arrizabalaga-Escudero et al., 2015)

	and along ecotones. These taxa include a large amount of host plants of moth larvae, prey of several bat species.					
	Within urban areas with low prey abundance, the use of UV light could be a strategy to concentrate food availability near hibernacula, both in the pre-hibernation period and after spring arousal.					(Frick et al., 2023)

Table 3 - List of some commonly applied bad practices that should be avoided for urban biodiversity support. The organism groups targeted here represent different ecosystem levels from primary producers to several kinds of consumers and follows the groups covered in Table 1 and in Table 2.

Animal or plant groups	Bad practice	Justification	Reference
Plants	Frequent management activities of green spaces (*e.g.*, mowing lawns and flowerbeds)	Reduction of plant and animal diversity since continuous mowing stops plant succession	(Jakobsson et al., 2018)
Soil microbiota	Use of fungicides	Fungicides affect the beneficial fungal community in the soil.	(Hage-Ahmed et al., 2019)
Pollinators (bees)	Using very large holes in bee hotels	Large holes will be ignored or occupied with difficulty by native species (*e.g.*, > 1 cm). Large diameters (> 0.8 cm) will be likely occupied by large-body invasive species.	(Geslin et al., 2020)
Bird	Intensive pruning	Intense pruning during breeding and nesting periods may reduce bird diversity and richness of nesting birds	(Bassett et al., 2022)
Ground	Clearing the	Grass, shrubs, leaf litter and	(Pearce, 2017)

mammals	understorey	deadwood in the understorey provide important resources to small ground mammals that inhabit/exploit wood patches	
Bats	Interventions (*i.e.*, building restoration, tree management) in the event of a bat colony during lactation and hibernation periods	Bat disturbances during pregnancy, lactation and weaning are potentially highly detrimental to recruitment in bat populations.	(Voigt and Kingston, 2016)

Fig1

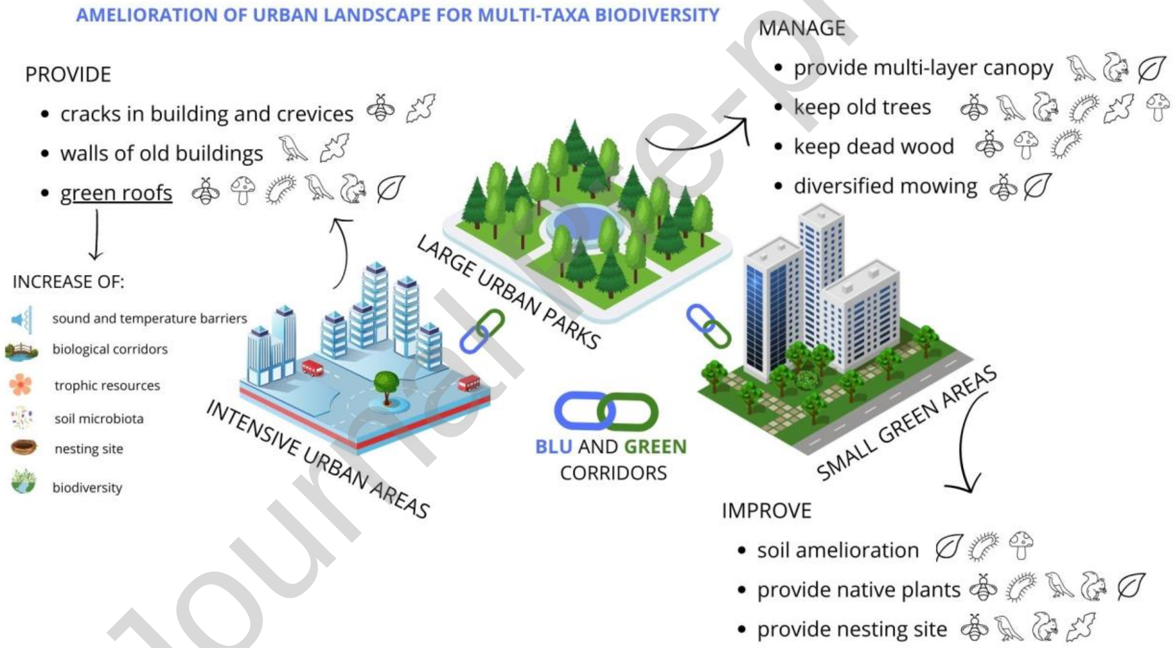


Fig2

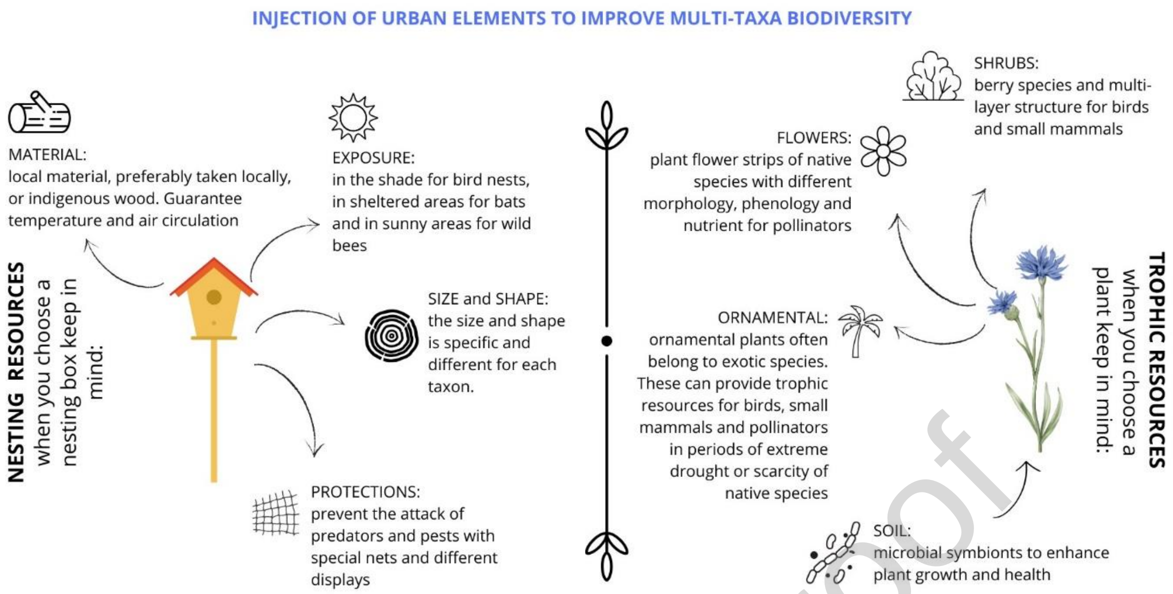
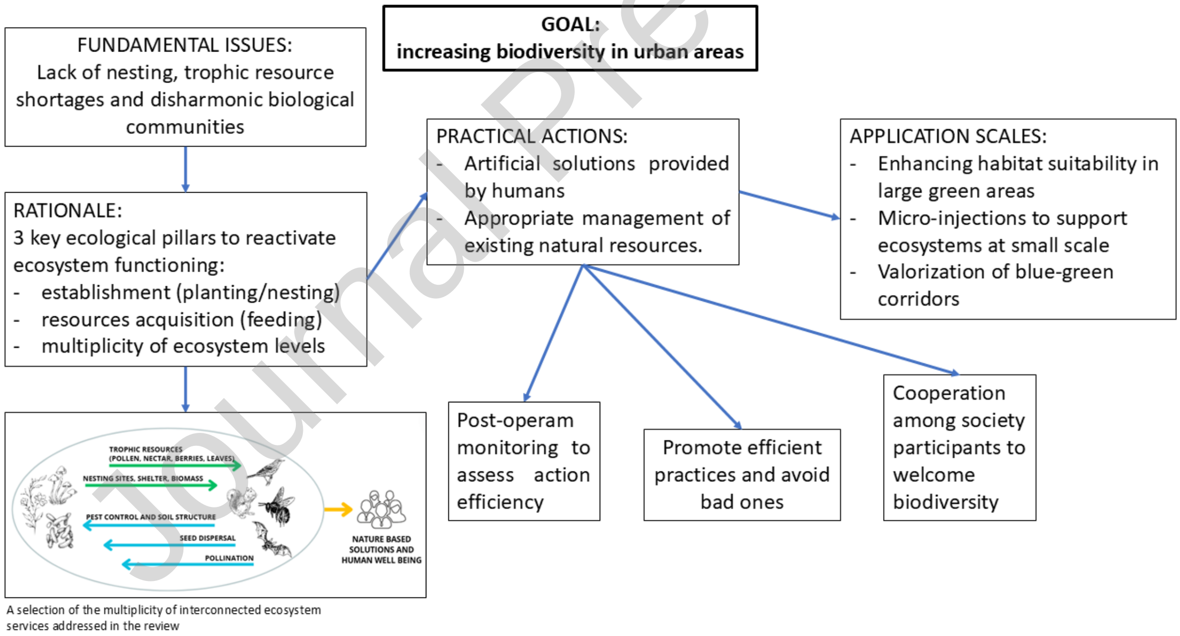

INJECTION OF URBAN ELEMENTS TO IMPROVE MULTI-TAXA BIODIVERSITY
NESTING RESOURCES when you choose a nesting box keep in mind:
MATERIAL: local material, preferably taken locally, or indigenous wood. Guarantee temperature and air circulation
EXPOSURE: in the shade for bird nests, in sheltered areas for bats and in sunny areas for wild bees
SIZE and SHAPE: the size and shape is specific and different for each taxon.
PROTECTIONS: prevent the attack of predators and pests with special nets and different displays
TROPHIC RESOURCES when you choose a plant keep in mind:
SHRUBS: berry species and multi-layer structure for birds and small mammals
FLOWERS: plant flower strips of native species with different morphology, phenology and nutrient for pollinators
ORNAMENTAL: ornamental plants often belong to exotic species. These can provide trophic resources for birds, small mammals and pollinators in periods of extreme drought or scarcity of native species
SOIL: microbial symbionts to enhance plant growth and health

Fig3


GOAL: increasing biodiversity in urban areas
FUNDAMENTAL ISSUES: Lack of nesting, trophic resource shortages and disharmonic biological communities
RATIONALE: 3 key ecological pillars to reactivate ecosystem functioning:
- establishment (planting/nesting)
- resources acquisition (feeding)
- multiplicity of ecosystem levels
TROPHIC RESOURCES (POLLEN, NECTAR, BERRIES, LEAVES)
NESTING SITES, SHELTER, BIOMASS
PEST CONTROL AND SOIL STRUCTURE
SEED DISPERSAL
POLLINATION
NATURE BASED SOLUTIONS AND HUMAN WELL BEING
A selection of the multiplicity of interconnected ecosystem services addressed in the review
PRACTICAL ACTIONS:
- Artificial solutions provided by humans
- Appropriate management of existing natural resources.
APPLICATION SCALES:
- Enhancing habitat suitability in large green areas
- Micro-injections to support ecosystems at small scale
- Valorization of blue-green corridors
Post-operam monitoring to assess action efficiency
Promote efficient practices and avoid bad ones
Cooperation among society participants to welcome biodiversity