ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

The role of green roofs as urban habitats for biodiversity modulated by their design: a review

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
7 February 2023

REVISED
2 May 2023

ACCEPTED FOR PUBLICATION
23 May 2023

PUBLISHED
10 July 2023

TOPICAL REVIEW

The role of green roofs as urban habitats for biodiversity modulated by their design: a review

Sékou F M Coulibaly[1,*], Christine Aubry[2], Fanny Provent[2], Sophie Rousset-Rouvière[3] and Sophie Joimel[1]

[1] UMR EcoSys, INRAE, AgroParisTech, Université Paris-Saclay, 91120 Palaiseau, France
[2] UMR SADAPT, INRAE, AgroParisTech, Université Paris-Saclay, 91120 Palaiseau, France
[3] Adivet, Association des toitures et façades végétales, 84 Rue de Grenelle, Paris 75007, France
[*] Author to whom any correspondence should be addressed.

E-mail: sfantamady.c@gmail.com

Keywords: urban habitats, green roofs, biodiversity, fauna, flora

Supplementary material for this article is available online

Abstract

In view of the demographic revolution and the rapid development of urban environments, the installation of green roofs could be a tool to ensure human well-being (e.g. heat island reduction, rainwater management), or to increase urban biodiversity. However, the relationships between biodiversity and green roofs are not yet clear and little research has looked into this. We therefore reviewed studies on the overall biodiversity of green roofs. Our review has shown that there is a lack of knowledge of the biodiversity of green roofs, with recent consideration. We highlighted the importance of green roof contribution, in maintaining urban biodiversity through three lines of research: characterization, modes of use and design. Furthermore, we found that there were very few studies on soil biodiversity on this topic. We concluded that green roof construction guidelines should integrate soil communities into their design and aim to be heterogeneous at roof and landscape level. Future research should focus on the diversification and redundancy of rooftop conditions in the urban matrix. This would increase the area of green habitats and the success of species dispersal in cities.

1. Introduction

Urbanized areas have become the fastest growing environments in the world (Fischer and Lindenmayer 2007, Seto *et al* 2011, Lamb and DiLorenzo 2014), leading to many deleterious effects on climate, natural resources and biodiversity (e.g. Pickett *et al* 2001, Grimm *et al* 2008, McDonald *et al* 2008). For example, the urban biological communities of most taxa (e.g. plants, birds) are often less diverse (McKinney 2002, 2008) and show greater biotic homogenization compared to other environments (e.g. forest, grassland, agriculture) (McKinney and Lockwood 1999, Lockwood *et al* 2000). As the urban human population continues to increase, it thus becomes progressively more necessary to include urbanized areas in biological conservation efforts (Marzluff and Rodewald 2008).

The conservation of biodiversity in cities is a concept aimed at making urban ecosystems more resilient to disturbances due to the major role of biodiversity in the provision of ecosystem services (e.g. Isbell *et al* 2011, Cardinale *et al* 2012, Pickett *et al* 2013). In cities, biodiversity can settle in green spaces, in reduced, fragmented and isolated surfaces (Fuller and Gaston 2009). To provide additional vegetated surfaces, buildings appear as a solution to 're-green the grey' (Jim 2004, Francis and Lorimer 2011). The installation of green roofs could be a tool for increasing urban biodiversity (Oberndorfer *et al* 2007).

Green roofs (such as living roof, eco-roof or garden roofs) are either productive or non-productive, built on flat or sloping surfaces. They consist of an anti-root treated sealing membrane, a drainage layer, a filtering layer, a culture and vegetation medium (Getter and Rowe 2006, Oberndorfer *et al* 2007). According to Adivet (Association des toitures et façades végétales), they are characterized by different types of vegetation depending on the thickness of the growth medium. A distinction is thus made between intensive (>30 cm deep), semi-intensive (12–30 cm) and extensive (4–12 cm) roof types (RP TTV). It should be noted that the distinction between these types of green roofs can also vary according to the types of plants, the frequency of maintenance and the cost of installation (US 2011, Hossain *et al* 2019, Abass *et al* 2020).

Several recent studies have looked at the biodiversity of green roofs by considering a multitude of organisms ranging from microorganisms to vertebrates and including arthropods (Brenneisen 2006, Colla *et al* 2009, Braaker *et al* 2014). Their role as habitat, their integration into the landscape matrix or even their design are all topics covered (Mayrand and Clergeau 2018, Partridge *et al* 2020). However, the relationships between biodiversity and green roofs are not clear yet. If green roofs differ from other urban green spaces located at ground level due to (i) less accessibility for low-dispersal species, (ii) smaller surface area and (iii) specific soil structure, previously manufactured. While some studies have shown that arthropod richness and abundance tends to be lower on green roofs than on ground-level habitats (Tonietto *et al* 2011, Ksiazek *et al* 2012, Braaker *et al* 2017), there is no consensus on these conclusions since Kadas (2006) found an equivalent or an even higher number of species on green roofs compared to those on ground sites. The relationship between green roofs and biodiversity therefore deserves to be systematically examined, as was done within other urban green spaces whose biodiversity was examined (Nielsen *et al* 2014, Clucas *et al* 2018, Joimel *et al* 2022).

The objective of this study is therefore to carry out a systematic review of the scientific literature on the whole of the biodiversity of green roofs to (i) elucidate the role of green roofs in supporting biodiversity in the city by focusing on quantitative data, (ii) and explore the factors influencing green roof biodiversity. For this, we address the following questions which will be treated separately in the corpus of the text: (i) do green roofs play a role of habitat for all biodiversity? (ii) What are the differences between green roofs and other urban or rural uses? Here we consider urban uses to be those located within the city limits (e.g. gardens, parks) and rural uses to be natural (e.g. forest) or pseudo-natural spaces (e.g. agricultural), that can be influenced by human activities. (iii) What is the influence of roof design on biodiversity?

This study will also make it possible to identify future avenues of research to be carried out on green roof biodiversity.

2. Methodology: data acquisition

2.1. Research criteria

The research on green roof biodiversity was conducted on 15 November 2021 in Web of Sciences (WoS) using all the databases suggested. Different keywords were chosen from a sample of 34 articles dealing with both biodiversity and green roofs. The keywords selected were as follows: (« green roof* » or rooftop* or greenroof*) and (biodiversity* or plant* or fauna or wildlife). In total, 2392 articles were retrieved as search results. A first selection was made based on the titles and abstracts, or even the whole article, in order to identify the articles that really fall within the topic i.e. the study of biodiversity on green roofs. In addition, we considered ten articles which were not included in WoS, they were found using Google Scholar on the same subject. In total, 154 articles were found to be relevant for our study.

2.2. Data collection

For each of the 154 articles selected, the following data were extracted based on titles and abstracts:

- Title of the result
- Authors, year, and journal of publication
- Type of article (research, journal, book, book chapter)
- Geographical location of the study, classified by country and continent
- Species/Taxa examined, status of taxa (fauna, flora)
- Compartment of species examined (above ground, below ground)
- Quantified biodiversity (yes, no, cannot be determined)
- Main conclusion of the study.

3. Bibliometric analysis

Our bibliometric analysis revealed an increase in the consideration of urban biodiversity in scientific studies from 1995 (figure 1). This is all the more true for the biodiversity of green roofs, since 99% of the publications on this subject only appeared after 1995, with a notable increase in the 2010s. Representing less than 1% of the publications on urban biodiversity, studies on roofs developed especially after 2013. However, the share of studies on green roof biodiversity remains rare and represents less than 2.5% of the total number of publications on urban biodiversity, illustrating a relative lack of knowledge on this subject. This fits in with the evolutionary history of green roofs. Since it was only during the 20th century that the creators of modern architecture (Le Corbusier, Alvar Aalto and Frank Lloyd) began to implement green roofs in their design to integrate the natural within the construction (Abass *et al* 2020). The development in Germany, some thirty years ago, of very light substrates (or growing media), mixing mineral matter and organic matter (Jim 2017), allowed green roofs to develop significantly. This technology then spread to Europe, especially in Germanic and Scandinavian countries, then to North America and to some Asian countries.

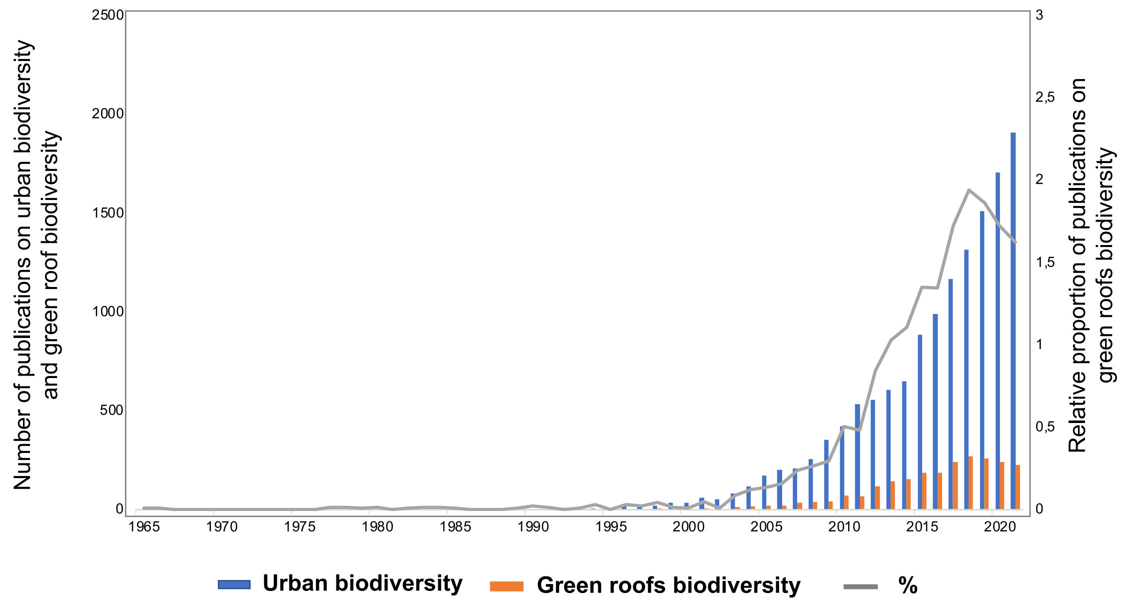

Figure 1. Evolution of the number of scientific publications on urban biodiversity (blue histogram) and on green roofs biodiversity (orange histogram) published annually in the international scientific literature for the period 1965–2021. The gray line represents the relative proportion of publications on green roof biodiversity compared to those on urban biodiversity.

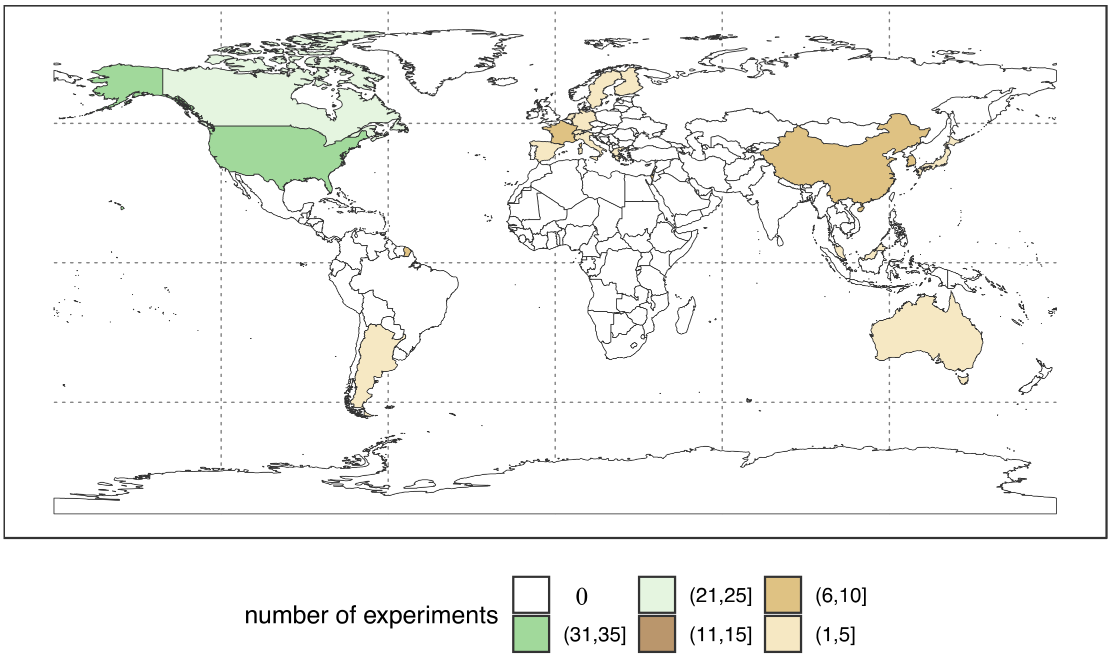

Figure 2. Geographical representation of the number of studies on green roof biodiversity according to the 154 articles selected.

Focusing on the 154 articles selected for our study, we noted 137 studies in simple search, 15 reviews and 2 meta-analyses. From a geographical point of view, the majority of these studies were carried out in the countries of the northern hemisphere (figure 2) with about 36% in North America and Europe, followed by 23% in Asia. Only four studies described roofs in different countries; all being located in Europe (Bubnova *et al* 2012, Van Mechelen *et al* 2015, Nicolaisen *et al* 2017, Lönnqvist *et al* 2021). Moreover, no study on this subject was referenced in Africa. This is quite common, since according to previous reviews (e.g. Guilland *et al* 2018, Joimel *et al* 2022), there are few, if any, studies concerning urban biodiversity on this continent either for lack of laboratories or of financing. Furthermore, with its moderately developed urban environments compared to those of other continents (Europe, North America, Asia) (Appolloni *et al* 2021), it is not surprising to see the lack of studies on green roofs in Africa.

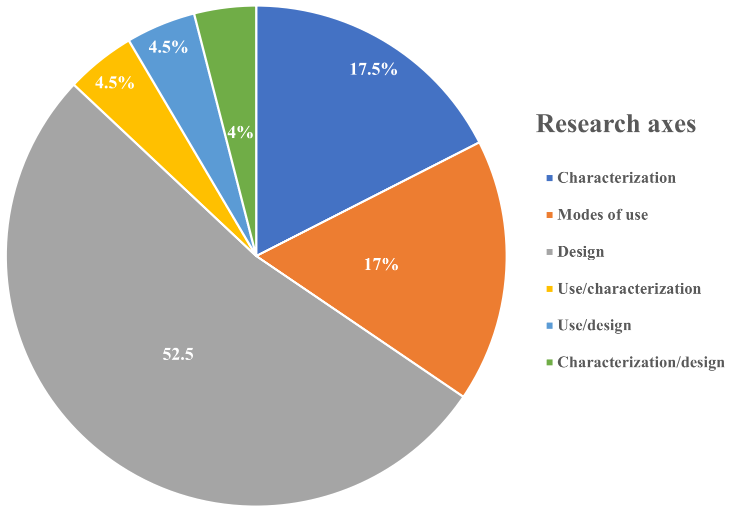

Figure 3. Percentage of publications (out of the 154) according to research axes.

4. Research axes on the biodiversity of green roofs

The 154 articles were classified according to three main categories: characterization, modes of use and design. Examination of these various publications on green roof biodiversity revealed that 17.5% of scientific articles focused on characterization, 17% on modes of use and 52.5% on the various aspects linked to design. Some items found themselves in two categories simultaneously, i.e. 4.5% for use/characterization as well as for use/design and approximately 4% for characterization/design (figure 3).

4.1. Characterization of the biodiversity by green roofs: biodiversity support

Many studies ($n = 27$) have characterized the biodiversity of green roofs, focusing for more than half on extensive roofs (59%). The other studies did not consider it useful to provide information on the type of green roof (41%).

In general, studies mainly use taxonomic diversity and abundance as metrics to quantify biodiversity. For example, in their study, Partridge *et al* (2020) collected over 15 000 arthropod individuals from 16 different taxa and one dominant bat species (*Lasirus borealis*), all living on a green roof in New York City. Other authors studying bees visiting a green roof in downtown Toronto, showed a differentiation in the number of individuals according to the taxonomic groups (e.g. *Lasioglossum sp., Apis sp., Bombus sp.*) identified (MacIvor *et al* 2015). Only a few studies ($n = 3$) focused on functional diversity and these also investigated taxonomic diversity. Finally, two studies assessed the survival or presence/absence index (Dvorak and Volder 2013, Marttinen *et al* 2020). Furthermore, it is important to note that 37% of the studies ($n = 10$) do not use an index (table 1).

Regarding the biodiversity studied on green roofs (table 2), it is mainly the aerial compartment (81%), and more specifically plants (55%) (e.g. Bubnova *et al* 2012, Lundholm and Williams 2015, Chow *et al* 2019), followed by aerial invertebrates (11% on butterflies, bees, wasps, flies) (e.g. MacIvor *et al* 2015, Passaseo *et al* 2020) and on vertebrates (4% on birds and bats) (Fernández Cañero and González Redondo 2010, Partridge *et al* 2020). Soil biodiversity is studied in only 7% of the studies (e.g. arthropods, micro-organisms, soil microarthropods) (Rumble and Gange 2013, Marttinen *et al* 2020) whereas it represents 25% of terrestrial species (Decaëns *et al* 2006). Multi-taxa studies remain infrequent with about 11% of the studies analyzing at least two taxa simultaneously (Ko and Lee 2010, Partridge *et al* 2020); plants being most often one of the groups represented in these multi-taxa studies (67% of papers).

These different studies have made it possible to assess the capacity of green roofs to serve as potential habitats for some organisms (e.g. plants, bees, birds, arthropods) of biodiversity. In order to be a viable habitat, green roofs must correspond to a place or location where an organism lives, with sufficient resources allowing it to feed and reproduce. Davis (1960) exploring the formal distinctions between the concepts of habitat and environment also concluded that the emphasis is on the location as well as on the conditions. The notion of resources, defined as 'various forms of energy and matter potentially or actively useful to organisms' is central to, but often neglected or omitted from, the concept of habitat (Davis 1960). These resources must be available to the organism beyond its minimum needs (Davis 1960). The habitat therefore constitutes an ecological entity including species and communities, as well as their biotic and abiotic environment.

Table 1. Number of studies measuring biodiversity as well as measurement indices, considering the characterization category. NA = no information was found on the study.

Biodiversity measured	Number of studies			
	Total	Index		
		Taxonomic diversity/Abundance	Functional diversity	Presence/Absence
Yes	16	14	3	2
No	10			
NA	1			

Table 2. Number of studies on the taxa studied, considering the characterization category. NA = no indication on the taxon group studied.

Taxa studied	Number of studies
Microorganisms	1
Soil microarthropods	1
Arthropods	5, including 1 with bats and 1 with plants
Plants	17, including 2 with arthropods and 1 with birds
Bees	2
Birds	2 including 1 with plants
NA	3

Across the 27 articles, it appears that roofs form a viable habitat for many species such as plants (e.g. sedum), arthropods (e.g. moths, springtails), or vertebrates (e.g. bats). It is specifically by providing a viable habitat for arthropods or for plants that other organisms such as bats can find food resources in the context of urbanized environments (Pearce and Walters 2012, Partridge *et al* 2020). It sometimes seems that some species, especially bees, favor vegetation (Hofmann and Renner 2018). Conversely, when these plant and invertebrate communities are depleted, the role of green roofs for other species is no longer ensured (Rumble and Gange 2013). Several authors have concluded that promoting soil communities in green roofs would create sustainable habitats and maximize gains in urban biodiversity (e.g. Rumble and Gange 2013, Williams *et al* 2014).

If green roofs seem to be a viable habitat, the majority of species present on green roofs are often generalist species (e.g. mosses, insects), which are able to withstand difficult environmental conditions (e.g. sun, wind).

4.2. Modes of use

Studies comparing modes of use mainly focused on the differences between: (i) types of roofs (green vs. bare, $n = 8$), (ii) types of green roofs (extensive, productive, intensive, and various plant structures, $n = 5$), (iii) green roofs vs. urban habitats (at ground level, $n = 23$) or natural habitats (retention basin, $n = 1$) or pseudo-natural habitats (agricultural environment, $n = 1$).

4.2.1. Comparison between 'types of roofs'

The studies ($n = 8$) that compared the effects of green roofs on biodiversity came to different conclusions, including for the same taxonomic group (e.g. birds, bats) (table 3). (i) The majority (62.5%) of the studies demonstrated higher biodiversity on green roofs than on bare roofs for a diversity of taxonomic groups (e.g. arthropods, gastropods, birds). For example, Wooster *et al* (2022) found that green roofs supported four times more birds, over seven times more arthropods, and twice as many gastropods than non-green roofs. The same trends were shown for bat activity (Pearce and Walters 2012). (ii) Twenty-five percent of the studies did not however observe any differences between a green roof and a bare roof (table 3). This is the case, for example, of the similar avian use of green roofs to that of bare roofs in Chicago (Washburn *et al* 2016). (iii) Finally, only 12.5% of the studies demonstrated a higher biodiversity on non-green roofs (see Wong and Jim 2016).

4.2.2. Comparison between 'types of green roofs'

Comparing the different typologies of green roofs, the majority of the studies found that the biodiversity was lower on roofs with extensive vegetation (plants in Droz *et al* (2021); arthropods in Madre *et al* (2013)) (table 4).

In general, a high diversity of plant species on roofs increases the biological diversity of other species (Kyrö *et al* 2020). This observation is also demonstrated in the literature in natural areas (e.g. Perez et al 2013, Henneron *et al* 2016, Salmon 2018). Madre *et al* (2013) confirmed this for green roofs by demonstrating a significantly higher richness and abundance of most arthropod taxa on roofs with a more complex vegetation. However, on extensive roofs, often highlighted for their lower biodiversity, the vegetation is generally composed solely of succulent plant species (e.g. moss and sedum). Therefore, plant communities are more diverse on intensive roofs than on extensive roofs (Droz *et al* 2021).

Table 3. Representation of the studies comparing the biodiversity between green roofs and other habitats (non-green roofs, urban green spaces on the ground, natural green spaces, agricultural environments). The signs ‘+’, ‘−’ or ‘ = ’ which precede the letters mean that the biodiversity (taxa) of green roofs is ‘higher’, ‘lower’ or ‘similar’ compared to that of other habitats. The letters are associated with the corresponding studies. Multi-taxa = invertebrates, birds, bats, plants.

	Others				
Green roofs vs.	Non-green roofs	Green space on the ground	Natural habitats	Agricultural habitats	References
Microorganisms		+a		+b	Molineux *et al* (2015)[a], Nicolaisen *et al* (2017)[b]
Arthropods	+a	−b			Wooster *et al* (2022)[a,] Parkins and Clark (2015)[a]; Schindler *et al* (2018)[a], Braaker *et al* (2017)[b]; Domínguez *et al* (2020)[b]
Gastéropods	+a				Wooster *et al* (2022)[a]
Snails		−a			McKinney *et al* (2019)[a]
Birds	+a, =b	−c			Partridge and Clark (2018)[a], Wooster *et al* 2022 [a;] Washburn *et al* (2016)[b], Eakin *et al* (2015)[c]
Bats	+a, =b				Parkins and Clark (2015)[a]; Pearce and Walters (2012)[a,b]
Bees	=a	−b, +c			Maclvor (2016)[a], Ksiazek *et al* (2012)[b], Hofmann and Renner (2018)[c]
Wasps	=a				Maclvor (2016)[a]
Gnat	-a	−b			Wong and Jim (2016)[a,b]
ulti-taxa			+a, =b		Filazzola *et al* (2019)[a,b]

Table 4. Representation of the studies comparing the biodiversity between types of green roofs (extensive vs. productive, intensive and complex plant structures). The signs ‘<’, ‘>’ or ‘ = ’ mean that the biodiversity (taxa) of extensive roofs is ‘lower’, ‘higher’ or ‘similar’ compared to that of other types of green roofs.

	Between types of green roofs			
Taxa	Extensive vs. Productive	Extensive vs. Intensive	Extensive vs. Diverse plant structures	References
Collembola	=			Joimel *et al* (2018)
Arthropods			<	Madre *et al* (2013), Kyrö *et al* (2020)
Plants		<		Droz *et al* (2021)

These variations in the structure of biodiversity within green roofs are also observed at the level of species composition, including in studies that show no effect on the richness or abundance between the two types of roofs (Joimel *et al* 2018). Extensive roofs thus tend to host generalist species, tolerant to xerothermophilic conditions, which are favored by these types of green roofs (Madre *et al* 2013, Joimel *et al* 2018). Conversely, on intensive roofs, the species are rather specialists with requirements in relation to the microclimatic conditions which must be favorable to their development.

Besides, in comparison to extensive roofs, the plant diversity on intensive roofs can be more sensitive to local environment variables (soil texture, size and fertilizer use) (Droz *et al* 2021). We also notice there can be differences in colonisation depending on the different roof types due to design/uses. Joimel *et al* (2018) showed that a way for colonising these urban habitats for collembola could be wind dispersion.

A new type of classification of green roofs could help to: (i) bridge the gap between practitioner knowledge and ecological knowledge and (ii) predict patterns which favor biodiversity installation focusing on the surrounding landscape green roofs built rather than on the thickness of their substrates.

4.2.3. Comparison ‘green roofs vs. urban habitats and/or natural or pseudo-natural habitats’

Publications on the comparison between green roofs and other urban habitats show that: (i) 75% of the studies showed a lower biodiversity on green roofs than that of urban habitats (at ground level) (table 3). For example, recently, Domínguez *et al*

(2020) showed that species richness, abundance, and arthropod predation rates were significantly higher in ground-level habitats than on green roofs. In addition, plant-pollinator relationships may be satisfactory on green roofs, even though bee numbers and diversity are lower on green roofs compared to ground habitats (Ksiazek *et al* 2012). (ii) Only 25% of studies demonstrated a higher biodiversity on green roofs. Thus, it was shown that the root zones of green roofs can have an abundant soil microbial community which, in some cases, may be more diverse and numerous than the communities found in brownfield areas (Molineux *et al* 2015). Also in their review, Hofmann and Renner (2018) showed that the percentage of cavity-nesting bees on rooftops was higher than in the surrounding soils.

Indeed, the conditions on green roofs are very distinct from those of ground habitats. For example, urban parks contain both managed and unmanaged vegetation zones, leading to diverse ecological niches and community differentiation (Li *et al* 2006, Shwartz *et al* 2008, Bertoncini *et al* 2012). Old urban parks exhibit mature successional stages, while non-mature successional stages are observed on rooftops (Ksiazek-Mikenas *et al* 2018), and rooftop communities may vary depending on their age (Madre *et al* 2014, Kyrö *et al* 2018). The absence of direct solar radiation on the ground, less trampling, and the addition of litter or compost lead to more organic matter and higher moisture content in the soil of the parks than on the roofs (Sarah *et al* 2015).

Regarding the comparison with natural and pseudo-natural (agricultural) environments, the two rare studies on the subject have different conclusions. If Filazzola *et al* (2019) demonstrated a green roof biodiversity comparable to that of natural habitats; Nicolaisen *et al* (2017) demonstrated a higher biodiversity on green roofs than on agricultural habitats. Indeed, rooftop fungal communities were more diverse than in rapeseed fields, likely reflecting greater mixing of air from a range of microenvironments for rooftop sites.

Green roofs, like other urban green spaces, can have ecological significance in cities by attracting and supporting a greater taxonomic diversity which can then add important functional capacities to previously impoverished spaces (Parkins and Clark 2015, Wooster *et al* 2022).

4.3. Design

The effects that the design has on green roof were widely studied in extensive roofs (90% of publications). Biodiversity can be influenced by different factors relating to the design of green roofs: a mix of plant species, plant cover, substrates, irrigation, age (or aging of the roofs), surface area, height, maintenance and surrounding landscape (table 5). Some studies have simultaneously crossed some of these factors. Almost all of the studies describe plants (table 5).

4.3.1. Effects of plant species

The vegetation, whether in terms of diversity, as we have already discussed, percentage cover or flowering, will affect other species. First, an increase in the area of vegetation cover seems to favorably affect other species, such as arthropods (Salman and Blaustein 2018). Several studies ($n = 9$) found a positive effect on the biodiversity when there was a mix of plant diversity (e.g. fungi, arthropods, plants) (table 5). Hoch *et al* (2019) thus demonstrated that the relative abundance of mycorrhizal fungi was higher on roofs with a mixed vegetation and observed higher pathogen loads on roofs with sedum. Some effects may be linked to flowering times (Benvenuti 2014).

Overall, incorporating functional diversity, particularly varied growth forms, increases the diversity of green roofs, potentially improving the resilience and performance of green roof systems over the long term (Heim and Lundholm 2014, van Mechelen *et al* 2015).

4.3.2. Effects of substrates

Publications on substrates have highlighted their effects on biodiversity depending on their (i) composition and/or their (ii) thickness (table 5).

Generally, the soils which develop on green roofs are referred to as Technosols (e.g. World Reference Base for Soil Resources-WRBSR, Group I.W 2006, Lehmann 2006). They are composed of various technogenic materials, i.e. artifacts, generally marked in their composition by human activity (e.g. urban waste, building materials, industrial by-products) (Hiller 2000, El Khalil *et al* 2008, Grard *et al* 2020).

Regarding the composition of substrates, several authors have highlighted the major role of organic matter, which has positive effects on biodiversity (Nagase and Dunnett 2011, Chen *et al* 2018, 2021). It is not only about increasing the substrate OM content but also about reaching the optimal level. Some authors mention adding values of 10% OM (Nagase and Dunnett 2011) especially thanks to the application of biochar (Chen *et al* 2018) in order to obtain an optimal growth of cultivated plant species and a significant increase in microbial biomass.

Structure also plays a role. Coarse particle substrates induce higher mortality rates in most introduced plant species, as well as lower vegetation cover compared to treatments with fine particles (Toland *et al* 2014).

As for the effects of substrate depth on biodiversity, Molineux *et al* (2015) suggested that increasing substrate depth improved plant establishment, but this effect was not consistent across substrates.

Once established, technosols will undergo much faster pedogenesis than natural soils. They are above

Table 5. Representation of the studies on the effects of design parameters of green roofs influencing biodiversity. The signs '+', '−' or '0' mean the 'positive', 'negative' or 'neutral' effect of a design parameter on the biodiversity (taxa) considered.

		Conception										
		Plant species		Substrate								
References	Taxa	Diversity/ coverage	Flowering	Addition of O.M.	Depth	Structure	Irrigation	Age	Area	Height	Maintenance	Landscape around
Hoch *et al* (2019)	Microorganisms	+/0										
Salman and Blaustein (2018)	Arthropods	+										
Benvenuti (2014)	Pollinators (Bees)		+									
Aguiar *et al* (2019)	Plants	+										
Heim and Lundholm (2014)	Plants	+										
van Mechelen *et al* (2015)	Plants	+										
Chen *et al* (2018, 2021)	Microorganisms, plants			+								
Nagase and Dunnett (2011)	Plants			+			0					
Toland *et al* (2014)	Plants			0		− coarse particles						
Moulineux *et al* (2015)	Plants				+/0	+ type of aggregates						
Schindler *et al* (2019)	Arthropods					0 heterogeneous structure						
Paraskevopoulou *et al* (2020)	Plants						− low					

(Continued.)

Table 5. (Continued.)

		Conception										
		Plant species		Substrate								
References	Taxa	Diversity/ coverage	Flowering	Addition of O.M.	Depth	Structure	Irrigation	Age	Area	Height	Maintenance	Landscape around
Kokkinou *et al* (2016)	Plants						+ low					
Schrader and Boening (2006)	Collembola							− young roof				
Dusza *et al* (2020)	Plants—pollinators	+ monculture	+		+ high							
Nagase and Dunnett (2010)	Plants	+					+ low					
MacIvor *et al* (2013)	Plants			+			0					
Solodar *et al* (2018)	Plants			0			0					
van der Kolk *et al* (2020)	Plants				+ high					+ shady		
Madre *et al* (2014)	Plants				+ high				+ high	+ high	+ high	0
Fabian *et al* (2021)	Arthropods	+	+					+ high	+ high	+ low		+ high

all conditioned by the vegetation (root penetration, exudation of organic compounds, water withdrawal) (Scalenghe and Ferraris 2009, Scholtus *et al* 2009). This evolution will induce a strong evolution of the profiles over 3 years, with rapid changes in the number and characteristics of the horizons (Séré *et al* 2010). Chemical (decarbonation) and physical (aggregation) weathering occur through processes similar to those that occur in natural soils. We can expect that these rapid modifications in the structure and composition of the constructed technosols will affect the local pedoclimatic conditions, which depend on the future of biodiversity in these environments.

4.3.3. Effects of irrigation

Roofs, with their impermeable surfaces, are simple and unobtrusive hydrological compartments in which water inflows and outflows can be monitored precisely. Ideally, precision water management would use irrigation to maintain soils at higher average moisture levels for satisfactory vegetation development. During storms, this higher antecedent moisture causes irrigated soils to shed more water than they would otherwise (Harada *et al* 2018).

For example, regarding the effects of irrigation on green roof biodiversity, studies have shown that a low irrigation regime is enough to see satisfactory plant growth (Kokkinou *et al* 2016, Paraskevopoulou *et al* 2020). However, it is clear that these results were observed on roofs with extensive vegetation and that the plants that live there are adapted to xerothermophilic conditions (Madre *et al* 2014), a low irrigation regime is enough for their growth.

4.3.4. Effects of roof ageing

The effects of roof aging on the biodiversity of green roofs are difficult to measure because the study of roofs is an emerging research subject.

However, a study evaluating the effect of roof age on biodiversity indicated that Collembola density was slightly higher on old roofs (built between 1990 and 1994) compared to young roofs (built between 1998 and 1999) (Schrader and Böning 2006).

On the dynamics, studies are often confined to limited time stages: 1 year (summer 2002) for Schrader and Böning (2006), while Bubnova *et al* (2012) conducted their study over 2 years (2011 and 2012). They noticed a dynamic evolution in species composition and in projective vegetation cover surface, in the absence of maintenance. Thus, over time, plants of the sedum genus are oppressed and replaced by moss. These studies indicate that over time, the environment is probably more stable in the substrates due to the advanced formation of the soil, the improvement of Collembola niche occupation and to the establishment of undemanding plants. However, studies on the evolution of soils/technosols are rare and it is difficult to really conclude on the orientation of their pedogenesis. Grard *et al* (2020) thus showed a high fertility in technosols with nutrient stocks after five years of cultivation. Maintaining this fertility would potentially lead to positive effects on biodiversity support.

4.3.5. Combined effects of different layouts and practices

Studies on the modulation of several design features (e.g. plant species, surface area and roof age) to promote biodiversity show positive effects.

Fabian *et al* (2021) showed that plant species richness, roof canopy cover, substrate depth, roof area and age, and isolation in terms of height and canopy cover at the landscape scale, have beneficial effects on arthropod communities. More specifically, these authors indicate that: (i) the composition of arthropod community on green roofs was affected by their area and by the vegetation cover in the landscape. (ii) Green roof area was positively correlated to total species richness, species richness of most functional feeding groups, and total arthropod abundance. (iii) Green roofs with greater plant richness, mostly spontaneous, and less isolated (both vertically and horizontally) favored entomophagous arthropods. (iv) Other variables, such as age and ground cover of green roofs, were also important for herbivores, predators, parasitoids and detritivores.

In addition, other design features (e.g. substrates, irrigation, height of buildings) put forward by some studies to promote biodiversity showed divergent effects. For example, in a study by MacIvor *et al* (2013), ground cover and biomass of grasses and herbaceous plants were significantly higher in organic-based growing media, with no effect of additional irrigation. Surprisingly, other studies showed that plant growth was not dependent on water type or substrate type (Solodar *et al* 2018). On the other hand, the mixture of diversified plants could be more advantageous than a monoculture in terms of greater survivability and higher visual index in dry conditions (Nagase and Dunnett 2010). Thus, planting extensive green roofs with a mix of plant species can ensure the survival of certain species and maintain cover and biomass when additional irrigation is stopped to save water, or during extreme drought (MacIvor *et al* 2013).

Other design features involving the interaction of substrate depth and building height showed positive effects on the biodiversity of green roofs. Indeed, increasing the depth of the substrate and the amount of shade (coming from a taller building) can promote the richness and diversity of plant species (van der Kolk *et al* 2020). Shade probably works by reducing water stress, while, increasing substrate depth improves plant diversity due to the addition of native nutrients and seeds. These authors recommend taking these two aspects into account when designing green roofs.

5. Discussion/conclusion on the research axes

We reviewed the data available in the scientific literature on the biodiversity of green roofs. These data allowed us to show three main axes evaluating the biodiversity of green roofs: characterization, modes of use and design.

Characterization studies have provided information on the ability of green roofs to serve as habitat for some groups of organisms (e.g. plants, bees, birds, arthropods). However, to our knowledge there are not enough data on other organisms (e.g. soil invertebrates) to generalize the ecological role of green roofs in maintaining urban biodiversity.

The studies regarding modes of use have contributed to our ability to assess the categories of roofs that are more biodiversity friendly. Green roofs or types of green roofs with deeper substrates (e.g. intensive roofs) and those with more complex plant structures seem to be the most suitable.

The design studies allowed us to assess several factors (e.g. height, surface area depth of substrate) influencing biodiversity. Taking these factors into account when designing green roofs makes it possible to quantify its biodiversity. Overall, studies advocate installing green roofs more and more in cities to mitigate the negative effects of urbanization and preserve one of the many ecosystem services, such as biodiversity.

6. Biodiversity services

Currently, the interest for studies on biodiversity lies mainly because of its key role in the provision of a range of ecosystem services. These services range from aesthetic, cultural and recreational values to goods that have direct use value and enhance many other ecosystem services on which humans depend (Bulte *et al* 2005, Mertz *et al* 2007). Beyond the characterization of biodiversity, it is interesting to evaluate the services offered by biodiversity to green roofs. Only few studies have shown an interest in plant species as the main factor.

For example, in a study conducted in Shanghai (China), the presence of *Poa pratensis, Lolium perenne* and *Agrostis stolonifera* on roofs led to a reduction in runoff (Li *et al* 2018). In general, incorporating annuals into Sedum-based green roofs reduces not only CO_2 concentrations (Klein *et al* 2017) but also heat island effects (Chow *et al* 2019). In addition, other studies highlighted the services provided by living invertebrates on green roofs (MacIvor and Ksiazek 2015). This is the case for example of (i) pollination for plant reproduction and yield of cultivated crops, (ii) pest control to reduce damage to green roof vegetation, (iii) decomposition to retain the organic matter and nutrient cycling in the substrate, and (iv) contribution to food webs of species such as birds which visit green roofs.

7. Research perspectives

We analyzed the scientific literature available on green roof biodiversity. Green roofs seem to serve as habitat for some organisms and this depended on the taxonomic groups but also on the design of the green roofs. Thus, it would be necessary to prioritize the actions to be carried out in favor of biodiversity thanks to green roofs. A point of attention must be made on the risk of biotic homogenization by favoring only a few specific species.

Today's cities, designed for the well-being of city dwellers, must adapt and take into account the needs of biodiversity. For this, the development of roof bio-urbanisms requires a better knowledge of both the characteristics of roofs influencing biodiversity and of their landscape integration to ensure ecological continuities.

Regarding the knowledge acquired on green roof biodiversity, we have identified several factors which influence biodiversity and which are poorly taken into account in the literature: (i) taking into account the surface. A large disparity in size is observed between the different roofs. This may explain the variability in the results obtained on the capacity of the roofs to serve as habitats. (ii) Integrating both aboveground and belowground biodiversity indicators. Soil biodiversity is often understudied even though it is highly sensitive to different types of soil. Plants are the most studied taxon. (iii) Considering time. Currently, there is very little data on green roof population dynamics. However, the soils of green roofs are subject to very rapid pedogenesis which can potentially influence their role in supporting biodiversity depending on the age of the roof. (iv) Studying new roofs which combine different functions. For example, the combination of green roofs with photovoltaic or solar (PV) panels is believed to provide synergistic benefits. The panel is cooled down by the presence of vegetation, and thus produces more electricity, while PV improves the conditions for vegetation growth and increases abiotic heterogeneity, resulting in greater plant diversity.

Concerning bio-urbanism, our research proposal focuses mainly on the integration of green roofs, at the landscape scale, in the ecological continuities of the city. The distance between rooftops and other urban or peri-urban green spaces is therefore a major research issue. In addition, in the case of green roofs, the height is another criterion to be taken into account. Indeed, the height of buildings strongly influences the diversity of species regardless of their degree of mobility (Braaker *et al* 2014, Maclvor 2016, Kyrö *et al* 2018).

Finally, the links between green walls and green roofs could act in concert for the movement of organisms in the city and the synergies between these two habitats remain unresolved.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This study was conducted as part of a research project led by the Urban Agriculture Chair of AgroParisTech and funded by the Paris Habitat Foundation. The authors would like to thank the Chaire Vinci-lab Recherche Environnement for their partnership. The authors report that there are no conflicts of interest associated with this work.

References

Abass F, Ismail L H, Wahab I A and Elgadi A A 2020 A review of green roof: definition, history, evolution and functions *IOP Conf. Ser.: Mater. Sci. Eng.* **713** 12048

Aguiar A C, Robinson S A and French K 2019 Friends with benefits: the effects of vegetative shading on plant survival in a green roof environment *PLoS One* **14** e0225078

Appolloni E, Orsini F, Specht K, Thomaier S, Sanye-Mengual E, Pennisi G and Gianquinto G 2021 The global rise of urban rooftop agriculture: a review of worldwide cases *J. Clean. Prod.* **296** 126556

Benvenuti S 2014 Wildflower green roofs for urban landscaping, ecological sustainability and biodiversity *Landsc. Urban Plan.* **124** 151–61

Bertoncini A P, Machon N, Pavoine S and Muratet A 2012 Local gardening practices shape urban lawn floristic communities *Landsc. Urban Plan.* **105** 53–61

Braaker S, Ghazoul J, Obrist M K and Moretti M 2014 Habitat connectivity shapes urban arthropod communities: the key role of green roofs *Ecology* **95** 1010–21

Braaker S, Obrist M K, Ghazoul J, Moretti M and Cuddington K 2017 Habitat connectivity and local conditions shape taxonomic and functional diversity of arthropods on green roofs *J. Anim. Ecol.* **86** 521–31

Brenneisen S 2006 Space for urban wildlife: designing green roofs as habitats in Switzerland *Urban Habitats* **4** 27–36 (available at: www.eaglehill.us/urban-habitats/Vol%204/wildlife_pdf.pdf)

Bubnova A B, Melnichuk I A and Ignatieva M E 2012 Sedum plant communities, applying on green roofs and dynamic of development *Rudn J. Agron. Anim. Ind.* 5–12 (available at: https://agrojournal.rudn.ru/agronomy/article/view/1431)

Bulte E, Hector A and Larigauderie A 2005 ecoSERVICES: assessing the impacts of biodiversity changes on ecosystem functioning and services *Divers. Rep.* **3** 40

Cardinale B J *et al* 2012 Biodiversity loss and its impact on humanity *Nature* **486** 59–67

Chen H, Du X, Lai M, Nazhafati M, Li C and Qi W 2021 Biochar improves sustainability of green roofs via regulate of soil microbial communities *Agriculture* **11** 620

Chen H, Ma J, Wei J, Gong X, Yu X, Guo H and Zhao Y 2018 Biochar increases plant growth and alters microbial communities via regulating the moisture and temperature of green roof substrates *Sci. Total Environ.* **635** 333–42

Chow M F, Bakar M F A and Arenanda V 2019 Influence of native plant species on substrate moisture content behaviour within extensive green roof system *AIP Conf. Proc.* **2129** 020020 (available at: https://pubs.aip.org/aip/acp/article-abstract/2129/1/020020/1007190/Influence-of-native-plant-species-on-substrate?redirectedFrom=fulltext)

Clucas B, Parker I D and Feldpausch-Parker A M 2018 A systematic review of the relationship between urban agriculture and biodiversity *Urban Ecosyst.* **21** 635–43

Colla S R, Willis E and Packer L 2009 Can green roofs provide habitat for urban bees (Hymenoptera: Apidae)? *Cities Environ.* **2** 4

Davis J H 1960 Proposals concerning the concept of habitat and a classification of types *Ecology* **41** 537–41

Decaëns T, Jiménez J J, Gioia C, Measey G J and Lavelle P 2006 The values of soil animals for conservation biology *Eur. J. Soil Biol.* **42** S23–38

Domínguez M V S, González E, Fabián D, Salvo A and Fenoglio M S 2020 Arthropod diversity and ecological processes on green roofs in a semi-rural area of Argentina: similarity to neighbor ground habitats and landscape effects *Landsc. Urban Plan.* **199** 103816

Droz A G, Coffman R R and Blackwood C B 2021 Plant diversity on green roofs in the wild: testing practitioner and ecological predictions in three midwestern (USA) cities *Urban For. Urban Green* **60** 127079

Dusza Y, Kraepiel Y, Abbadie L, Barot S, Carmignac D, Dajoz I and Raynaud X 2020 Plant-pollinator interactions on green roofs are mediated by substrate characteristics and plant community composition *Acta Oecol.* **105** 103559

Dvorak B D and Volder A 2013 Plant establishment on unirrigated green roof modules in a subtropical climate *AoB Plants* **5** pls049

Eakin C J, Campa III H, Linden D W, Roloff G J, Rowe D B and Westphal J 2015 Avian response to green roofs in urban landscapes in the Midwestern USA *Wildl. Soc. Bull.* **39** 574–82

El Khalil H, Schwartz C, Elhamiani O, Kubiniok J, Morel J L and Boularbah A 2008 Contribution of technic materials to the mobile fraction of metals in urban soils in Marrakech (Morocco) *J. Soils Sediments* **8** 17–22

Fabian D, González E, Domínguez M V S, Salvo A and Fenoglio M S 2021 Towards the design of biodiverse green roofs in Argentina: assessing key elements for different functional groups of arthropods *Urban For. Urban Green* **61** 127107

Fernández Cañero R and González Redondo P 2010 Green roofs as a habitat for birds: a review *J. Anim. Vet. Adv.* **9** 2041–52

Filazzola A, Shrestha N, MacIvor J S and Stanley M 2019 The contribution of constructed green infrastructure to urban biodiversity: a synthesis and meta-analysis *J. Appl. Ecol.* **56** 2131–43

Fischer J and Lindenmayer D B 2007 Landscape modification and habitat fragmentation: a synthesis *Glob. Ecol. Biogeogr.* **16** 265–80

Francis R A and Lorimer J 2011 Urban reconciliation ecology: the potential of living roofs and walls *J. Environ. Manage.* **92** 1429–37

Fuller R A and Gaston K J 2009 The scaling of green space coverage in European cities *Biol. Lett.* **5** 352–5

Getter K L and Rowe D B 2006 The role of extensive green roofs in sustainable development *HortScience* **41** 1276–85

Grard B J P, Manouchehri N, Aubry C, Frascaria-Lacoste N and Chenu C 2020 Potential of technosols created with urban by-products for rooftop edible production *Int. J. Environ. Res. Public Health* **17** 3210

Grimm N B, Faeth S H, Golubiewski N E, Redman C L, Wu J, Bai X and Briggs J M 2008 Global change and the ecology of cities *Science* **319** 756–60

Group I.W 2006 *World Reference Base for Soil Resources: 2006* (available at: www.cambridge.org/core/journals/experimental-agriculture/article/abs/world-reference-base-for-soil-resources-world-soil-resources-report-103-rome-food-and-agriculture-organization-of-the-united-nations-2006-pp-132-us2200-paperback-isbn-925105114/2350B6849FFF73CD43CE414F1EB926BA)

Guilland C, Maron P-A, Damas O and Ranjard L 2018 Biodiversity of urban soils for sustainable cities *Environ. Chem. Lett.* **16** 1267–82

Harada Y, Whitlow T H, Todd Walter M, Bassuk N L, Russell-Anelli J and Schindelbeck R R 2018 Hydrology of the Brooklyn Grange, an urban rooftop farm *Urban Ecosyst.* **21** 673–89

Heim A and Lundholm J 2014 Species interactions in green roof vegetation suggest complementary planting mixtures *Landsc. Urban Plan.* **130** 125–33

Henneron L, Aubert M, Archaux F, Bureau F, Dumas Y, Ningre F, Richter C, Balandier P and Chauvat M 2016 Forest plant community as a driver of soil biodiversity: experimental evidence from collembolan assemblages through large-scale and long-term removal of oak canopy trees Quercus petraea *Oikos* **126** 420–34

Hiller D A 2000 Properties of Urbic Anthrosols from an abandoned shunting yard in the Ruhr area, Germany *Catena* **39** 245–66

Hoch J M K, Rhodes M E, Shek K L, Dinwiddie D, Hiebert T C, Gill A S, Salazar Estrada A E, Griffin K L, Palmer M I and McGuire K L 2019 Soil microbial assemblages are linked to plant community composition and contribute to ecosystem services on urban green roofs *Front. Ecol. Evol.* **7** 198

Hofmann M M and Renner S S 2018 Bee species recorded between 1992 and 2017 from green roofs in Asia, Europe, and North America, with key characteristics and open research questions *Apidologie* **49** 307–13

Hossain M A, Shams S, Amin M, Reza M S and Chowdhury T U 2019 Perception and barriers to implementation of intensive and extensive green roofs in Dhaka, Bangladesh *Buildings* **9** 79

Isbell F *et al* 2011 High plant diversity is needed to maintain ecosystem services *Nature* **477** 199–202

Jim C Y 2004 Green-space preservation and allocation for sustainable greening of compact cities *Cities* **21** 311–20

Jim C Y 2017 Green roof evolution through exemplars: germinal prototypes to modern variants *Sustain. Cities Soc.* **35** 69–82

Joimel S, Grard B, Auclerc A, Hedde M, Le Doaré N, Salmon S and Chenu C 2018 Are Collembola "flying" onto green roofs? *Ecol. Eng.* **111** 117–24

Joimel S, Jules A and Vieublé Gonod L 2022 Collembola dispersion, selection, and biological interactions in urban ecosystems: a review *Environ. Chem. Lett.* **20** 2123–33

Kadas G 2006 Rare invertebrates colonizing green roofs in London *Urban Habitats* **4** 66–86

Klein T, Vasl A, Kadas G and Blaustein L 2017 Measuring the effect of plant-community composition on carbon fixation on green roofs *Urban For. Urban Green* **24** 1–4

Ko A-L and Lee E-H 2010 The change of flora and fauna on extensive rooftop green areas *Korean J. Environ. Ecol.* **24** 334–42

Kokkinou I, Ntoulas N, Nektarios P A and Varela D 2016 Response of native aromatic and medicinal plant species to water stress on adaptive green roof systems *HortScience* **51** 608–14

Ksiazek K, Fant J and Skogen K 2012 An assessment of pollen limitation on Chicago green roofs *Landsc. Urban Plan.* **107** 401–8

Ksiazek-Mikenas K, Herrmann J, Menke S B and Köhler M 2018 If you build it, will they come? Plant and arthropod diversity on urban green roofs over time *Urban Nat.* **1** 52–72 (available at: www.eaglehill.us/urna-pdfs-special/pdfs-URNA-sp1/14%20U127b%20Ksiazek-Mikenas%2021.pdf)

Kyrö K, Brenneisen S, Kotze D J, Szallies A, Gerner M and Lehvävirta S 2018 Local habitat characteristics have a stronger effect than the surrounding urban landscape on beetle communities on green roofs *Urban For. Urban Green* **29** 122–30

Kyrö K, Kotze D J, Müllner M A, Hakala S, Kondorosy E, Pajunen T and Lehvävirta S 2020 Vegetated roofs in boreal climate support mobile open habitat arthropods, with differentiation between meadow and succulent roofs *Urban Ecosyst.* **23** 1239–52

Lamb G C and DiLorenzo N 2014 United Nations, department of economic and social affairs, population division *World Urbanization Prospects: The 2014 Revision* (New York: Springer)

Lehmann A 2006 Technosols and other proposals on urban soils for the WRB [World Reference Base for Soil Resources] *Int. Agrophys.* **20** 129–34 (available at: https://agro.icm.edu.pl/agro/element/bwmeta1.element.agro-article-47837be6-a8c6-4766-9f1a-c7a5b1ff090f/c/Technosols_and_other.pdf)

Li W, Ouyang Z, Meng X and Wang X 2006 Plant species composition in relation to green cover configuration and function of urban parks in Beijing, China *Ecol. Res.* **21** 221–37

Li X, Cao J, Xu P, Fei L, Dong Q and Wang Z 2018 Green roofs: effects of plant species used on runoff *L. Degrad. Dev.* **29** 3628–38

Lockwood J L, Brooks T M and Mckinney M L 2000 Taxonomic homogenization of the global avifauna *Animal Conservation Forum* (Cambridge: Cambridge University Press) pp 27–35

Lönnqvist J, Hanslin H M, Johannessen B G, Muthanna T M, Viklander M and Blecken G 2021 Temperatures and precipitation affect vegetation dynamics on Scandinavian extensive green roofs *Int. J. Biometeorol* **65** 837–49

Lundholm J T and Williams N S G 2015 Effects of vegetation on green roof ecosystem services *Green Roof Ecosyst.* **223** 211–32

MacIvor J S and Ksiazek K 2015 Invertebrates on green roofs *Green Roof Ecosyst.* **223** 333–55

MacIvor J S, Margolis L, Puncher C L and Matthews B J C 2013 Decoupling factors affecting plant diversity and cover on extensive green roofs *J. Environ. Manage.* **130** 297–305

MacIvor J S, Ruttan A and Salehi B 2015 Exotics on exotics: pollen analysis of urban bees visiting Sedum on a green roof *Urban Ecosyst.* **18** 419–30

MacIvor J S 2016 Building height matters: nesting activity of bees and wasps on vegetated roofs *Isr. J. Ecol. Evol.* **62** 88–96

Madre F, Vergnes A, Machon N and Clergeau P 2013 A comparison of 3 types of green roof as habitats for arthropods *Ecol. Eng.* **57** 109–17

Madre F, Vergnes A, Machon N and Clergeau P 2014 Green roofs as habitats for wild plant species in urban landscapes: first insights from a large-scale sampling *Landsc. Urban Plan.* **122** 100–7

Marttinen E M, Niemi-Kapee J, Laaka-Lindberg S and Valkonen J P T 2020 Fungal pathogens infecting moss green roofs in Finland *Urban For. Urban Green* **55** 126812

Marzluff J and Rodewald A 2008 Conserving biodiversity in urbanizing areas: nontraditional views from a bird's perspective *Cities Environ.* **1** 6

Mayrand F and Clergeau P 2018 Green roofs and green walls for biodiversity conservation: a contribution to urban connectivity? *Sustainability* **10** 985

McDonald R I, Kareiva P and Forman R T T 2008 The implications of current and future urbanization for global protected areas and biodiversity conservation *Biol. Conserv.* **141** 1695–703

McKinney M L 2002 Urbanization, biodiversity, and conservation: the impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems *Bioscience* **52** 883–90

McKinney M L 2008 Effects of urbanization on species richness: a review of plants and animals *Urban Ecosyst.* **11** 161–76

McKinney M L, Gladstone N S, Lentz J G and Jackson F A 2019 Land snail dispersal, abundance and diversity on green roofs *PLoS One* **14** e0221135

McKinney M L and Lockwood J L 1999 Biotic homogenization: a few winners replacing many losers in the next mass extinction *Trends Ecol. Evol.* **14** 450–3

Mertz O, Ravnborg H M, Lövei G L, Nielsen I and Konijnendijk C C 2007 Ecosystem services and biodiversity in developing countries *Biodivers. Conserv.* **16** 2729–37

Molineux C J, Gange A C, Connop S P and Newport D J 2015 Are microbial communities in green roof substrates comparable to those in post-industrial sites?—A preliminary study *Urban Ecosyst.* **18** 1245–60

Nagase A and Dunnett N 2010 Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity *Landsc. Urban Plan.* **97** 318–27

Nagase A and Dunnett N 2011 The relationship between percentage of organic matter in substrate and plant growth in extensive green roofs *Landsc. Urban Plan.* **103** 230–6

Nicolaisen M, West J S, Sapkota R, Canning G G M, Schoen C and Justesen A F 2017 Fungal communities including plant pathogens in near surface air are similar across Northwestern Europe *Front. Microbiol.* **8** 1729

Nielsen A B, van den Bosch M, Maruthaveeran S and van den Bosch C K 2014 Species richness in urban parks and its drivers: a review of empirical evidence *Urban Ecosyst.* **17** 305–27

Oberndorfer E, Lundholm J, Bass B, Coffman R R, Doshi H, Dunnett N, Gaffin S, Köhler M, Liu K K Y and Rowe B 2007 Green roofs as urban ecosystems: ecological structures, functions, and services *Bioscience* **57** 823–33

Paraskevopoulou A T, Tsarouchas P, Londra P A and Kamoutsis A P 2020 The effect of irrigation treatment on the growth of lavender species in an extensive green roof system *Water* **12** 863

Parkins K L and Clark J A 2015 Green roofs provide habitat for urban bats *Glob. Ecol. Conserv.* **4** 349–57

Partridge D R and Clark J A 2018 Urban green roofs provide habitat for migrating and breeding birds and their arthropod prey *PLoS One* **13** e0202298

Partridge D R, Parkins K L, Elbin S B and Clark J A 2020 Bat activity correlates with moth abundance on an urban green roof *Northeast. Nat.* **27** 77–89

Passaseo A, Pétremand G, Rochefort S and Castella E 2020 Pollinator emerging from extensive green roofs: wild bees (Hymenoptera, Antophila) and hoverflies (Diptera, Syrphidae) in Geneva (Switzerland) *Urban Ecosyst.* **23** 1079–86

Pearce H and Walters C L 2012 Do green roofs provide habitat for bats in urban areas? *Acta Chiropt.* **14** 469–78

Perez G, Decaëns T, Dujardin G, Akpa-Vinceslas M, Langlois E and Chauvat M 2013 Response of collembolan assemblages to plant species successional gradient *Pedobiologia* **56** 169–77

Pickett S T A, Boone C G, McGrath B P, Cadenasso M L, Childers D L, Ogden L A, McHale M and Grove J M 2013 Ecological science and transformation to the sustainable city *Cities* **32** S10–20

Pickett S T A, Cadenasso M L, Grove J M, Nilon C H, Pouyat R V, Zipperer W C and Costanza R 2001 Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas *Annu. Rev. Ecol. Syst.* **32** 127–57

Rumble H and Gange A C 2013 Soil microarthropod community dynamics in extensive green roofs *Ecol. Eng.* **57** 197–204

Salman I N A and Blaustein L 2018 Vegetation cover drives arthropod communities in Mediterranean/subtropical green roof habitats *Sustainability* **10** 4209

Salmon S 2018 Changes in humus forms, soil invertebrate communities and soil functioning with forest dynamics *Appl. Soil Ecol.* **123** 345–54

Sarah P, Zhevelev H M and Atar O Z 2015 Urban park soil and vegetation: effects of natural and anthropogenic factors *Pedosphere* **25** 392–404

Scalenghe R and Ferraris S 2009 The first forty years of a Technosol *Pedosphere* **19** 40–52

Schindler B Y, Blaustein L, Lotan R, Shalom H, Kadas G J and Seifan M 2018 Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production *J. Environ. Manage.* **225** 288–99

Schindler B Y, Vasl A, Blaustein L, Gurevich D, Kadas G J and Seifan M 2019 Fine-scale substrate heterogeneity does not affect arthropod communities on green roofs *PeerJ* **7** e6445

Scholtus N, Leclerc E, de Donato P, Morel J L and Simonnot M O 2009 Eluto-frontal chromatography to simulate chemical weathering of COx by low-molecular-weight organic compounds and early pedogenesis processes *Eur. J. Soil Sci.* **60** 71–83

Schrader S and Böning M 2006 Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans *Pedobiologia* **50** 347–56

Séré G, Schwartz C, Ouvrard S, Renat J-C, Watteau F, Villemin G and Morel J L 2010 Early pedogenic evolution of constructed Technosols *J. Soils Sediments* **10** 1246–54

Seto K C, Fragkias M, Güneralp B and Reilly M K 2011 A meta-analysis of global urban land expansion *PLoS One* **6** e23777

Shwartz A, Shirley S and Kark S 2008 How do habitat variability and management regime shape the spatial heterogeneity of birds within a large Mediterranean urban park? *Landsc. Urban Plan.* **84** 219–29

Solodar A, Bawab O, Levy S, Kadas G J, Blaustein L and Greenbaum N 2018 Comparing grey water versus tap water and coal ash versus perlite on growth of two plant species on green roofs *Sci. Total Environ.* **633** 1272–9

Toland D C, Boyer M E, McDonald G V, West C P and Haggard B E 2014 Plants influenced by growing media and compost addition on mock green roofs within the Ozark highlands *J. Green Build.* **9** 130–44

Tonietto R, Fant J, Ascher J, Ellis K and Larkin D 2011 A comparison of bee communities of Chicago green roofs, parks and prairies *Landsc. Urban Plan.* **103** 102–8

US 2011 The benefits and challenges of green roofs on public and commercial buildings a report of the united states general services administration (G.S.A.)

van der Kolk H-J, van den Berg P, Korthals G and Bezemer T M 2020 Shading enhances plant species richness and diversity on an extensive green roof *Urban Ecosyst.* **23** 935–43

van Mechelen C, van Meerbeek K, Dutoit T and Hermy M 2015 Functional diversity as a framework for novel ecosystem design: the example of extensive green roofs *Landsc. Urban Plan.* **136** 165–73

Washburn B E, Swearingin R M, Pullins C K and Rice M E 2016 Composition and diversity of avian communities using a new urban habitat: green roofs *Environ. Manage.* **57** 1230–9

Williams N S G, Lundholm J and Scott Macivor J 2014 Do green roofs help urban biodiversity conservation? *J. Appl. Ecol.* **51** 1643–9

Wong G K L and Jim C Y 2016 Do vegetated rooftops attract more mosquitoes? Monitoring disease vector abundance on urban green roofs *Sci. Total Environ.* **573** 222–32

Wooster E I F, Fleck R, Torpy F, Ramp D and Irga P J 2022 Urban green roofs promote metropolitan biodiversity: a comparative case study *Build. Environ.* **207** 108458