ECOLOGY OF GREEN ROOFS

SUMMARY OF THE GROOVES STUDY
GREEN ROOFS VERIFIED ECOSYSTEM SERVICES
2017 - 2019

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FOREWORD

This study follows on from previous research demonstrating how valuable green roofs can be in terms of hosting biodiversity (Madre, 2014) and providing ecosystem services (Dusza, 2016).

YANN DUSZA, IEES-PARIS

Green roofs are urban and built ecosystems that are increasingly widespread in France and around the world. They are associated with several ecosystem services, for instance reducing rainwater runoff flowing into drains, reducing the effects of urban heat islands and increasing biodiversity in cities. Making improvements to the quantity and quality of ecosystem services requires an understanding of the influence of interactions between the components of green roofs (soil composition and depth; plant communities) on related ecosystem functions—and yet these interactions have never been studied in the context of green roofs. With the help of experiments, first in controlled environments and then in actual conditions on roofs in Paris, we tried to understand how the interactions between the components of green roofs influence major functions relating to the biogeochemical cycles of carbon, nitrogen and water and also to pollination. We have highlighted the significant influence of interactions between soil type, soil depth, plant species and plant diversity on (1) how well ecosystem functions are performed and (2) the interactions between these functions. We have showed that the choice of components for a roof can lead to compromises between ecosystem services, and we propose some design and management ideas that would help to develop multifunctional green roofs.

Yann Dusza. *Green roofs et services écosystémiques : favoriser la multifonctionnalité via les interactions sols-plantes et la diversité végétale,* Université Pierre et Marie Curie Paris VI, 2017 / editor Luc Abbadie, iEES Paris

FRÉDÉRIC MADRE, MNHN

Urbanisation destroys and fragments ecosystems and contributes to global change and the erosion of biodiversity. This hostile urban matrix is mainly made up of roads and buildings. Recently, buildings have been covered with a variety of planting systems that are beneficial to humans and make it possible to reduce the hostility of the matrix by making cities more permeable to wild species. There are different types of planting methods that differ in terms of biodiversity. In this thesis we have analysed communities using these different potential habitats: (1) wild plants on roofs, (2) arthropods and birds on roofs, (3) arthropods on façades and (4) arthropods on planted buildings in the urban landscape. We have highlighted the importance of the structural complexity of vegetation with respect to the communities studied.

Frédéric Madre. *Biodiversity et bâtiments végétalisés : une approche multi-taxons en paysage urbain,* MNHN, 2014 / editors Philippe Clergeau and Nathalie Machon, MNHN

Rosalind Franklin elementary school, recently built in Ivry-sur-Seine (94). © Marc Barra | ARB îdF

#1

GREEN ROOFS: GREENWASHING OR A GENUINE CONTRIBUTION TO NATURE IN CITIES?

HALTING LAND TAKE IS A PRIORITY

Over three quarters of Europeans now live in cities. In France, land take has increased steadily over recent decades and has affected between 16,000 and 60,000 hectares annually over the last few years [1]. Land take is one of the factors that contribute to the decline of biodiversity, and it also contributes to climate change. To face this challenge, the French government and local authorities are looking into ways of reducing the pressure exerted by cities on natural land, farmland and woodland, in particular via the "Zero Net Land Take" (Zéro Artificialisation Nette - ZAN) initiative [2].

Inventory of pollinating insects with the help of the SPIPOLL protocol. © Ophélie Ricci | ARB îdF

In addition to urban sprawl, the inorganic nature of cities is problematic for living organisms and helps to worsen the impacts of phenomena relating to climate change (runoff, flooding, urban heat islands, etc.) as well as adversely affecting the health and wellbeing of inhabitants due to a lack of green spaces. Though there are a number solutions to these challenges, increasing the quantity and quality of natural spaces in cities is a multi-facetted response that addresses the complex equation between urban density and the need for nature. In the Paris region, and especially in Greater Paris, the decline of biodiversity in urban settings has accelerated since the 2000s and affects all species [3]. Green spaces are few and far between in many areas, for example in the inner suburbs, which have fewer green spaces than in most other European cities [4]. Increasing the presence of nature must be made a priority in local policy-making at all levels.

Instead of giving nature a merely decorative role, the idea is to integrate it fully into urban projects [5]. All natural spaces are precious, be they areas of urban waste ground, woodland, wetlands, urban meadows, parkways or allotments. Managed ecologically and interconnected, they help to restore biodiversity, reduce climate change (via carbon sequestration and storage in soil and trees) and adapt to the latter (by managing runoff, regulating flooding, limiting heat islands and improving air quality).

Planted areas on buildings or on ground-level slabs also play their part in supporting nature in the urban landscape, although their ecological functions do not replace those of natural open ground [6]. In this context, the development of green roofs has accelerated since the 2000s, going hand in hand with an increased appetite for nature in cities. They are of interest to planners and architects as a way of making the urban fabric more permeable to wildlife and introducing natural spaces into areas where there are none. Moreover, in a context where urban heat islands are on the rise and runoff management is increasingly necessary, putting plants on buildings emerges as a way of adapting dense urban areas to the consequences of climate change. In Berlin, the introduction of the "Biotope Area Factor" has made it possible to put pressure on planners to make more use of plants in their projects in areas where greenery is scarce or absent. Other cities, including Paris, have reproduced this system in their local planning schemes. A study carried out by APUR (Agence Parisienne de l'Urbanisme) in 2013 shows that the total surface area of green roofs in Paris is 44 hectares. According to its authors, there is a potential total of 460 hectares of plantable flat roofs in the city, 80 hectares of which could be rapidly used in this way (the remaining 380 hectares would require more extensive adaptation) [7]. Nevertheless, putting plants on buildings is not an end in itself and must not be used to justify grow-

Planted roof created by Topager at GTM Bâtiment headquarters in Nanterre. © Audrey Muratet | ARB îdF

ing urbanization. The practice has been widely used to greenwash planning operations or as a mere label to ensure projects get the go-ahead. The fashion for planted buildings must not make us lose sight of the main objective, which is to maintain areas of open ground in cities and to engage in a coherent policy of urban ecology on all scales (implementing green, blue and brown grids; protecting existing natural spaces; ecological management; reversing land take; and so on).

For ecologists, green roofs are nonetheless subjects well worth studying. Relatively small, available in large numbers and presenting several variants, they are ideal candidates for large-scale scientific study.

GREEN ROOFS IN FRANCE AND AROUND THE WORLD

Green roofs have a long history and their existence goes back thousands of years, especially in Scandinavia. According to professionals in the sector, “in the 1920s, the widespread use of reinforced concrete and the appearance of flat roofs gave rise to the idea of garden terraces. In the 1970s-80s, growing concerns raised by the degradation of the environment and the rapid disappearance of green spaces in cities sparked renewed interest in green roofs as an ecological solution in Northern Europe”[8]. According to the CSTB (Centre Scientifique et Technique du Bâtiment), the market for green roofs grew significantly in the 1980s in Germany, where almost 40 % of towns and cities offer financial incentives for their development. Switzerland is another country leading the way in this domain: Basel subsidises planting, while in Zurich and the canton of Geneva all newly built terraces must be planted. Currently, over 75 European municipalities offer incentives or lay down regulations for the installation of green roofs.

In France, according to the CSTB, 300,000 square metres of green roofs were installed in 2006. 90 % of these were on new buildings, and 75 % were public-sector initiatives. Incentives are still few and far between in France, with the exception of water authorities, which consider green roofs to be rainwater management systems as long as they fulfil certain depth criteria. Some local authorities encourage the installation of green roofs in their planning schemes (Paris, Strasbourg, Montreuil).

CHANGING PRACTICES: THE CONTRIBUTION OF URBAN ECOLOGY

The market for green roofs is mainly occupied by roof sealing specialists, whose practices have gradually evolved. The growing popularity of planted buildings has accelerated the industrialisation of an entire sector, be it for waterproofing and drainage solutions, protective membranes and geotextiles, substrates, or plants and plant care (watering, fertilisation, etc.). The profession distinguishes three categories of green roofs: extensive, semi-extensive and intensive, determined by the depth of the substrate and the type of management, irrigation and plant strata associated with it. Other typologies have since been proposed, based in particular on the predominant plant stratum [9]. In France and Europe, most green roofs are "extensive", in other words the depth of their substrate is no greater than 15 cm (it is generally between 5 and 8 cm) and their production is most often standardised (using pre-grown trays or rolls).

The latter have become popular because they are lightweight, easy to install, inexpensive and low-maintenance.

The prevalence of "ready-to-use" extensive green roofs has been criticised by landscape designers and ecologists alike, who saw this standardisation as leading to a lack of coherence with respect to the local context, an erosion of expertise (which was nonetheless highly diversified in this area) and an insufficient use of ecological skills (in botany, urban ecology and soil ecology) required in the framework of any urban nature policy. This observation is not restricted to roofs; it applies to all urban green spaces: despite growing interest in questions relating to biodiversity and the emergence of ecological landscape design, the horticultural approach and the idea of controlling nature are still prevalent today where nature in cities is concerned [10]. Approaches are still dominated by landscaping and horticulture, although ecologists and naturalists are gradually playing a more important role.

In his 2014 thesis, Frédéric Madre at the French National Museum of Natural History showed that there are different types of planting that are not equivalent in terms of biodiversity [11]. By analysing communities of species of plants, arthropods and birds that use these different potential habitats, he highlighted the importance of the structural complexity of vegetation for these communities.

In 2017, Yann Dusza at IEES-Paris became interested in ecosystem services associated with green roofs [12]. With the help of experiments, first in controlled environments and then in real-life conditions on a Paris rooftop, he set out to understand the design parameters that influence major functions (the carbon, nitrogen and water cycle and pollination). His work shows that soil type and depth, plant species and

Inventories in progress on the rooftop of a Paris Habitat residential building. © Gilles Lecuir | ARB îdF plant diversity affect these ecosystem functions. He proposes design and management ideas that make it possible to obtain multi-functional green roofs, while stressing that the latter can never be expected to provide the full range of ecosystem services simultaneously.

This work in the field of urban ecology has made it possible to qualify arguments regularly put forward by commercial brochures on ecosystem services provided by green roofs in terms of biodiversity, carbon capture and rainwater retention. It has also made it possible to suggest design parameters corresponding to these services. The GROOVES study carries on from this initiative. ARB îdF and its partners organised a campaign of taxonomic inventories and measurements of certain ecosystem services (water retention, cooling, pollination) on a sample of 36 green roofs in dense urban areas in the Paris Region. Several questions motivated the study: how much biodiversity can be found on green roofs? What are the associated ecological functions? What differentiates roofs from other planting systems? Are roofs comparable to other urban natural spaces? What is the best way to advise project sponsors and project managers on the most effective design and management solutions that promote biodiversity?

Botanical survey on the rooftop of a parisian school. © Marc Barra | ARB îdF

The solar "Sail" blends in with the plantings at La Seine Musicale in Boulogne-Billancourt.
© Marc Barra | ARB îdF

Lucien Claivaz gets ready to apply
the “vacuum cleaner” protocol to collect invertebrates.
© Ophélie Ricci | ARB îdF

#2

THE ROOFS INCLUDED IN THE **GROOVES STUDY**

The 36 green roofs included in the GROOVES study are scattered around the central area of Greater Paris. The selection is based on the desire to represent an even distribution of the different types of planting generally identified by sealing specialists.

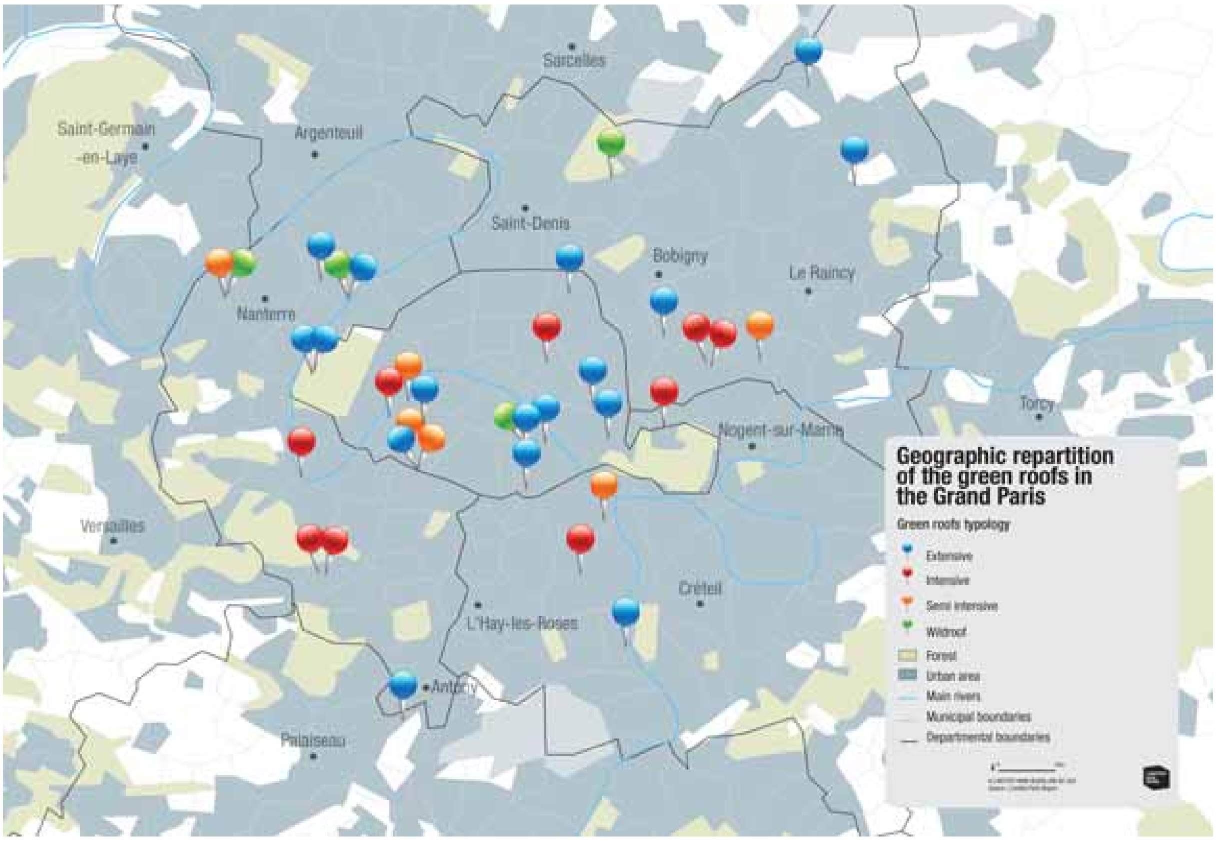


FIGURE 1 Geographical distribution of roofs studied in Greater Paris. © ARB îdF | Institut Paris Region

Although comparative studies require the sample to be relatively uniform, one of the particularities of this study lies in the diversity of the roofs and the buildings on which they are located. Over three quarters of the roofs studied are fairly recent (3 - 15 years old). Roofs more than 30 years old are less common (5 roofs). The "Mozinor" warehouse in Montreuil has the oldest planted roof, designed in 1975. Conversely, the brand new Seine Musicale, which opened in 2017 in Boulogne-Billancourt, has the most recent green roof we have studied.

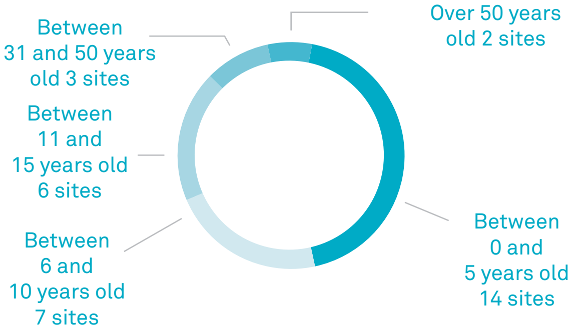


FIGURE 2 Age distribution of roofs selected for the study.
© ARB îdF | Institut Paris Region

The buildings in our selection have a number of divergent characteristics, especially as regards their height. The green roof on the Beaugrenelle shopping centre in Paris is 30 metres from the ground, while the one on top of the technical building at the *Conseil Départemental* of Seine-Saint-Denis is only 2.71 metres from the ground. The green roofs studied also have a variety of different surface areas. Most are between 200 and 600 square metres, but the rooftop of the Olivier de Serres school in the 15th *arrondissement* of Paris measures only 91 sq.m. and the huge Hall 7 of the Villepinte exhibition centre has one of the largest rooftops in the Paris Region: the section studied covers almost 3,000 sq.m., but the entire roof measures 11,000 sq.m.!

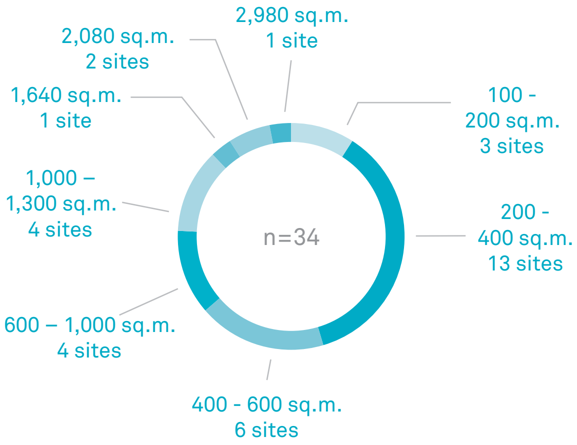


FIGURE 3 Distribution of surface areas of selected roofs
© ARB îdF – Institut Paris Region

Substrate depth is an important parameter in our analysis. Although the average depth of the sample is about 20 cm, the deepest roof covers part of the School of Science and Biodiversity in Boulogne-Billancourt: it is 1 metre deep. The “wildroof” of the technical building at the Conseil Départemental of Seine-Saint-Denis is only 5cm deep.

The typology used in the GROOVES study is based on the definition used by the designers of green roofs:

A. 18 “extensive” roofs, substrate depth less than 15 cm, planted
B. 6 “semi-intensive” roofs, substrate depth 15 - 30 cm, planted
C. 8 “intensive” roofs, substrate depth more than 30 cm, planted
D. 4 “wildroofs”, substrate of variable depth, unplanted


A. “Extensive” green roof
Exhibition centre, Paris Villepinte

B. “Semi-intensive” green roof
Olivier de Serres school, Paris

C. “Intensive” green roof
“Mozinor” building, Montreuil

D. “Wildroof”,
French National Museum of Natural History

FIGURE 4 Typology of green roofs used in the GROOVES study, based on the definition used by the designers of green roofs.
© ARB îdF | Institut Paris Region

THE 36 GREEN ROOFS
AT A GLANCE

ALBAR

PARIS HABITAT APARTMENT BUILDING

TYPE Semi-Intensive
SURFACE AREA 100 sq.m.
AGE 2 years
HEIGHT 20 m
SUBSTRATE Agricultural soil (27 cm)

AMROU

AMIRAL ROUSSIN

TYPE Extensive
SURFACE AREA 468 sq.m.
AGE 58 years
HEIGHT 5 m
SUBSTRATE Mixed (5.6 cm)

ANTHEU

ANDRÉ THEURIET CHILDCARE FACILITY

TYPE Extensive
SURFACE AREA 336 sq.m.
AGE 2 years
HEIGHT 4 m
SUBSTRATE Mineral (6.3 cm)

BOUCHA

BOULEVARD DE CHARONNE

TYPE Extensive
SURFACE AREA 200 sq.m.
AGE 2 years
HEIGHT 20 m
SUBSTRATE Mineral (8.7 cm)

BOUTOU

SCHOOL DES BOUTOURS

TYPE Semi-Intensive
SURFACE AREA 396 sq.m.
AGE 4 years
HEIGHT 7 m
SUBSTRATE Agricultural soil (25.2 cm)

CARON

VAL CARON LEISURE CENTRE

TYPE Extensive
SURFACE AREA 235 sq.m.
AGE 5 years
HEIGHT 10 m
SUBSTRATE Mineral (10.1 cm)

CD93

TECHNICAL BUILDING

TYPE Wildroof
SURFACE AREA 355 sq.m
AGE 48 years
HEIGHT 2.71 m
SUBSTRATE Mixte (3.5 cm)

CHAVIN

CHÂTEAU DE VINCENNES

TYPE Intensive
SURFACE AREA 1,050 sq.m
AGE 10 years
HEIGHT 11 m
SUBSTRATE Mixte (41.8 cm)

CIMOD

CITÉ DE LA MODE

TYPE Extensive
SURFACE AREA 1,640 sq.m
AGE 10 years
HEIGHT 12 m
SUBSTRATE Mixte (11 cm)

CIROB

ROBESPIERRE CINEMA

TYPE Intensive
SURFACE AREA 991 sq.m
AGE 36 years
HEIGHT 4.9 m
SUBSTRATE Mixte (33.3 cm)

ECOBIO FORET

SCHOOL OF BIODIVERSITY

TYPE Intensive
SURFACE AREA 2,080 sq.m
AGE 4 years
HEIGHT 12 m
SUBSTRATE Agricultural soil (100 cm)

ECOBIO PRAIRIE

SCHOOL OF BIODIVERSITY

TYPE Intensive
SURFACE AREA 1,300 sq.m
AGE 4 years
HEIGHT 12 m
SUBSTRATE Agricultural soil (40 cm)

EIDER

EIDERS SCHOOL

TYPE Extensive
SURFACE AREA 404 m²
AGE 12 years
HEIGHT 6 m
SUBSTRATE Mineral (6.75 cm)

FAUTEM

FAUBOURG DU TEMPLE

TYPE Intensive
SURFACE AREA 407 m²
AGE 2 years
HEIGHT 3 m
SUBSTRATE Agricultural soil (33 cm)

FONTA

FONTANES SCHOOL

TYPE Extensive
SURFACE AREA 210 m²
AGE 2 years
HEIGHT 3 m
SUBSTRATE Mineral (5.35 cm)

FONTA WILD

FONTANES SCHOOL

TYPE Wildroof
SURFACE AREA NA
AGE NA
HEIGHT 3 m
SUBSTRATE Mineral (5.35 cm)

FRANK

ROSALIND FRANKLIN SCHOOL

TYPE Semi-Intensive
SURFACE AREA 702 sq.m
AGE 3 years
HEIGHT 12 m
SUBSTRATE Agricultural soil (28.8 cm)

GOOPL

FOUNDATION GOOD PLANET

TYPE Extensive
SURFACE AREA 396 sq.m
AGE 9 years
HEIGHT 5 m
SUBSTRATE Mixte (6 cm)

GRENEL

CENTRE BEAUGRENELLE

TYPE Intensive
SURFACE AREA 1,180 sq.m
AGE 5 years
HEIGHT 30 m
SUBSTRATE Agricultural soil (40 cm)

GTMBA

GTM BÂTIMENT

TYPE Semi-Intensive
SURFACE AREA 590 sq.m
AGE 3 years
HEIGHT 8 m
SUBSTRATE Mineral (12.6 cm)

GTMBA WILD

GTM BÂTIMENT

TYPE Wildroof
SURFACE AREA NA
AGE 3 years
HEIGHT 10 m
SUBSTRATE Mineral (12.6 cm)

LUAUB

LUCIE AUBRAC SCHOOL

TYPE Extensive
SURFACE AREA 360 sq.m
AGE 10 years
HEIGHT 7 m
SUBSTRATE Mineral (5.75 cm)

MECHO

CHOISY LE ROI MEDIA LIBRARY

TYPE Extensive
SURFACE AREA 1,080 sq.m
AGE 5 years
HEIGHT 15 m
SUBSTRATE Mixte (8.6 cm)

MOZIN (MANAGED AND NON-MANAGED)

MOZINOR BUILDING

TYPE Intensive
SURFACE AREA 560 sq.m
AGE 43 years
HEIGHT 21 m
SUBSTRATE Agricultural soil (56 cm)

MUENT

MNHN ENTOMOLOGY BUILDING

TYPE Wildroof
SURFACE AREA 374 sq.m
AGE 2 years
HEIGHT 16
SUBSTRATE Mineral (10 cm)

OLSER

OLIVIER DE SERRE SCHOOL

TYPE Semi-Intensive
SURFACE AREA 91 sq.m
AGE 4 years
HEIGHT 5 m
SUBSTRATE Agricultural soil (28.6 cm)

PAREX

VILLEPINTE EXHIBITION CENTRE

TYPE Extensive
SURFACE AREA 2,980 sq.m
AGE 8 years
HEIGHT 12 m
SUBSTRATE Mineral (5 cm)

PERIS

PÉRISCOPE BUILDING

TYPE Extensive
SURFACE AREA 1,270 sq.m
AGE 2 years
HEIGHT 8 m
SUBSTRATE Mixte (5.9 cm)

PROMA

MOTHER AND CHILD WELFARE SERVICES

TYPE Extensive
SURFACE AREA 237 sq.m
AGE 5 years
HEIGHT 6 m
SUBSTRATE Mineral (5.5 cm)

PULMA

HÔTEL PULLMAN

TYPE Semi-Intensive
SURFACE AREA 315 sq.m
AGE 4 years
HEIGHT 4 m
SUBSTRATE Agricultural soil (24.4 cm)

ROROL

MÉDIATHÈQUE ROMAIN ROLLAND

TYPE Extensive
SURFACE AREA 986 sq.m
AGE 7 years
HEIGHT 10 m
SUBSTRATE Mixte (9.2 cm)

RUWAT

RUE WATTEAU

TYPE Extensive
SURFACE AREA 780 sq.m
AGE 58 years
HEIGHT 17.75 m
SUBSTRATE Mineral (6.5 cm)

SEINE

SEINE MUSICALE

TYPE Intensive
SURFACE AREA 2,000 sq.m
AGE New
HEIGHT 20 m
SUBSTRATE Agricultural soil (40 cm)

SIBUE

RUE SIBUET

TYPE Extensive
SURFACE AREA 320 sq.m
AGE 11 years
HEIGHT 16 m
SUBSTRATE Mineral (7.7 cm)

WWF

FOUNDATION WWF

TYPE Extensive
SURFACE AREA 532 sq.m
AGE 10 years
HEIGHT 4 m
SUBSTRATE Mixte (9.3 cm)

Below: The bishop's Mitre *(Aelia acuminata)*, a regular visitor to rooftops where grasses grow.
© Ophélie Ricci | ARB îdF

The smooth hawksbeard *(Crepis capillaris)* contrasts with the sedums on the rooftop of the Paris Villepinte exhibition centre.
© Audrey Muratet | ARB îdF

#3

FLORA
ON GREEN ROOFS

On green roofs, high temperatures, strong winds, lack of soil and drought are extreme environmental conditions that make it harder for plants to establish themselves. By the same token, less frequent intervention by those who manage such environments can allow species that are usually sensitive to the presence of humans and other external factors to thrive.

An in-depth study of rooftop flora was carried out based on these observations. What kinds of plants are to be found on green roofs? Are they similar to those found at ground level? Does the typology proposed by green roof designers have an ecological resonance? What are the effects of the characteristics of roofs and their environment on plants? The ecological approach attempts to answer these questions in order to gain a better understanding of rooftop flora.

INVENTORY OF FLORA

PROTOCOL

Assessing the role of green roofs necessarily requires in-depth knowledge of their flora, which plays an essential role in establishing other groups of species such as invertebrates. In addition to biodiversity, flora is connected to several ecosystem services such as water retention and reducing urban heat islands.

The composition and diversity of spontaneous and planted vascular plants were studied, for each roof, by examining 10 squares of 1 sq.m. once a year for 3 years following the Vigie-Flore protocol. Using a protocol originating in the citizen sciences also allows us to compare the floristic diversity of roofs with other environments such as areas of urban waste ground and meadows. Last but not least, making a distinction between planted and spontaneous species and studying related ecological features provides information on the abiotic conditions of roofs and allows us to steer rooftop designs towards more appropriate plant selections.

In addition to the Vigie-Flore protocol, an exhaustive floristic inventory was carried out on each roof in order to identify all the species present and to gain a better understanding of which suites of species are likely to colonise planted roofs.

Audrey Muratet, lecturer at the University of Strasbourg, supervised the floristic inventories.

Bryophytes (mosses) and lichens

Bryophytes and lichens are taxons that are especially sensitive to changes in their environment (sunshine, moisture, pollution). In addition to vascular flora, a comprehensive inventory of bryophytes and lichens was carried out on 20 roofs from the sample, aimed at observing as many micro-environments as possible (soil, gravel, walls, etc.). Sébastien Filoche, Deputy Scientific Director of the Conservatoire Botanique National du Bassin Parisien, supervised the inventories of bryophytes and lichens.

Carrying out the Vigie-Flore protocol: marking out 1 sq.m. squares with stakes. © Lucile Dewulf | ARB îdF

In total, according to the exhaustive surveys, over 400 plant species were observed on the 36 roofs that were studied: this gives an initial idea of the of the diversity of plants found on the rooftops. As for the Vigie-Flore surveys, 292 species were observed across all the squares between 2017 and 2019, 70 % of which were spontaneous (carried by the wind and animals). The most frequently observed species (both spontaneous and planted) in over 200 squares include *Sedum album, Sedum hispanicum, Sedum kamtschaticum* and *Vulpia myuros.*

Some threatened spontaneous species were identified, including *Galium parisiense, Crepis foetida, Laphangium luteoalbum* and *Misopates orontium.* Rare species were also observed, such as *Ornithopus compressus* and *Ornithopus pinnatus.* These observations confirm the role played by green roofs in hosting biodiversity, sometimes including rare species, in cities. In addition to planted or pre-grown species on roofs, the distinction between spontaneous and planted flora provides further insights into the ecology of roofs and their ability to host urban biodiversity.

Plants most extensively represented in the Vigie-Flore inventories. © Audrey Muratet | ARB îdF

TOWARDS A NEW TYPOLOGY OF GREEN ROOFS?

The current professionally approved typology is mainly based on substrate depth. This distribution is not necessarily meaningful in ecology, but it turned out to be a useful classification method. Other typologies have been suggested, based in particular on dominant plant strata [9].
Although we used this classification in our analysis, we also demonstrate its limitations. Analysis of the physical and chemical parameters of substrate such as percentage of organic matter, available nitrogen or clay content, is a more objective way of organising different conceptual methods. The figure below suggests a new typology based on these characteristics.

This new classification distinguishes 4 types of roof:
- Intensive roofs with deep substrates, significant management and irrigation, good water retention capacities, low grain size, low sand content and high clay content.
- Extensive roofs with fine, sandy, large-grain substrates and low water retention capacity requiring little or no management and irrigation. There are three extensive roof typologies following a gradient

of soil activity illustrated by capacity for cationic exchange, nitrogen content, microbial biomass and C/N ratio:

- Low-fertility extensive roofs
- Medium-fertility extensive roofs
- High-fertility extensive roofs

Clearly the existing "extensive" typology fell short of adequately describing all the roof types it included. Moreover, the "semi-intensive" typology does not appear in the categories obtained; instead it is distributed across the new categories: intensive, medium-fertility extensive and low-fertility extensive. Wildroofs find themselves in the new "medium-fertility" and "low-fertility" extensive categories.

To validate these new typologies, we have to test them against the ecological realities found on rooftops. To do this, roof flora was compared for each typology using three indicators: species diversity, phylogenetic diversity and functional diversity (see Figure 6). These indicators point to differences within the former extensive category, which groups together, within the same typology, roofs that are actually very different from an ecological standpoint. And yet, although it is justified in ecological terms, this new new typology is not necessarily more convenient for green roof designers. This classification requires in-depth knowledge of the characteristics of the roof, in based in particular on physical and chemical analysis of the substrate.

Chives *(Allium schorodoprasum),* Paris Villepinte Exhibition Centre.
© Audrey Muratet | ARB îdF

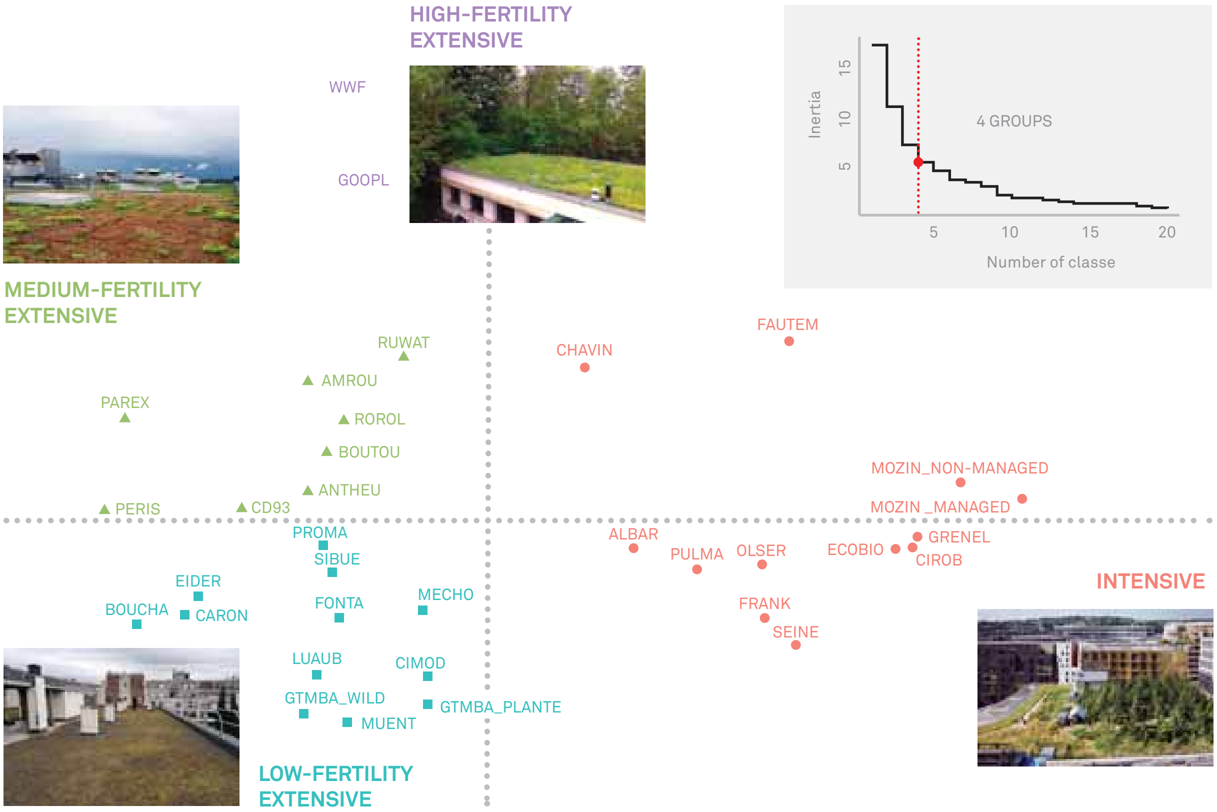


FIGURE 5 Classification of green roof typologies in ascending order. © Audrey Muratet | ARB îdF

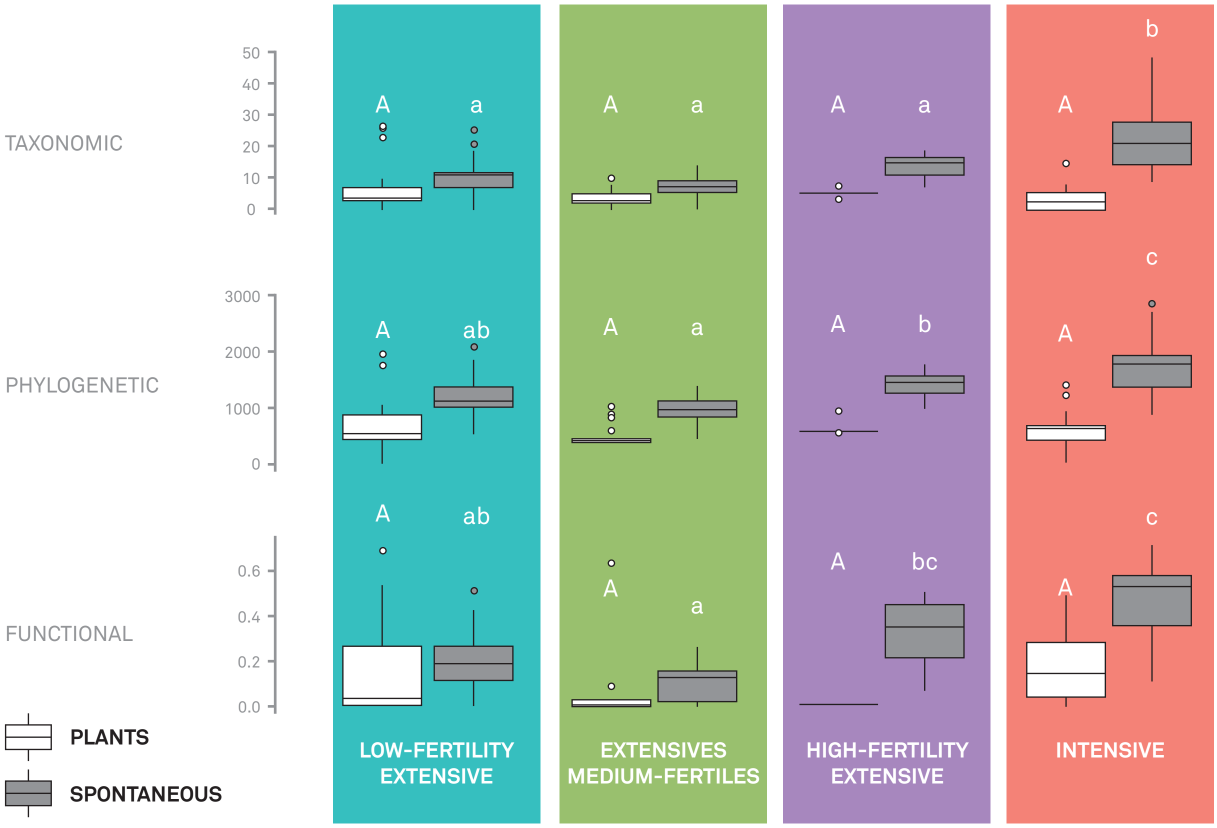
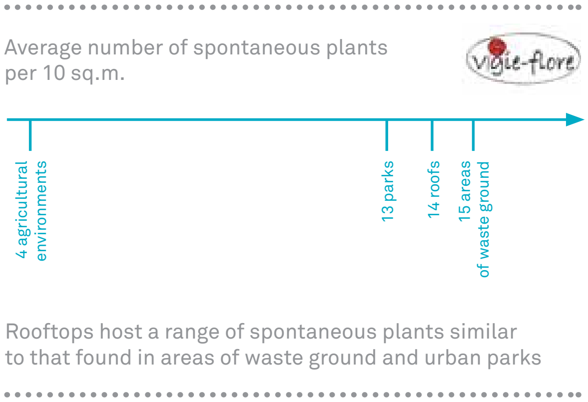


FIGURE 6 Comparison of the taxonomic, phylogenetic and functional diversity of the 4 new suggested typologies.
© Audrey Muratet | ARB îdF

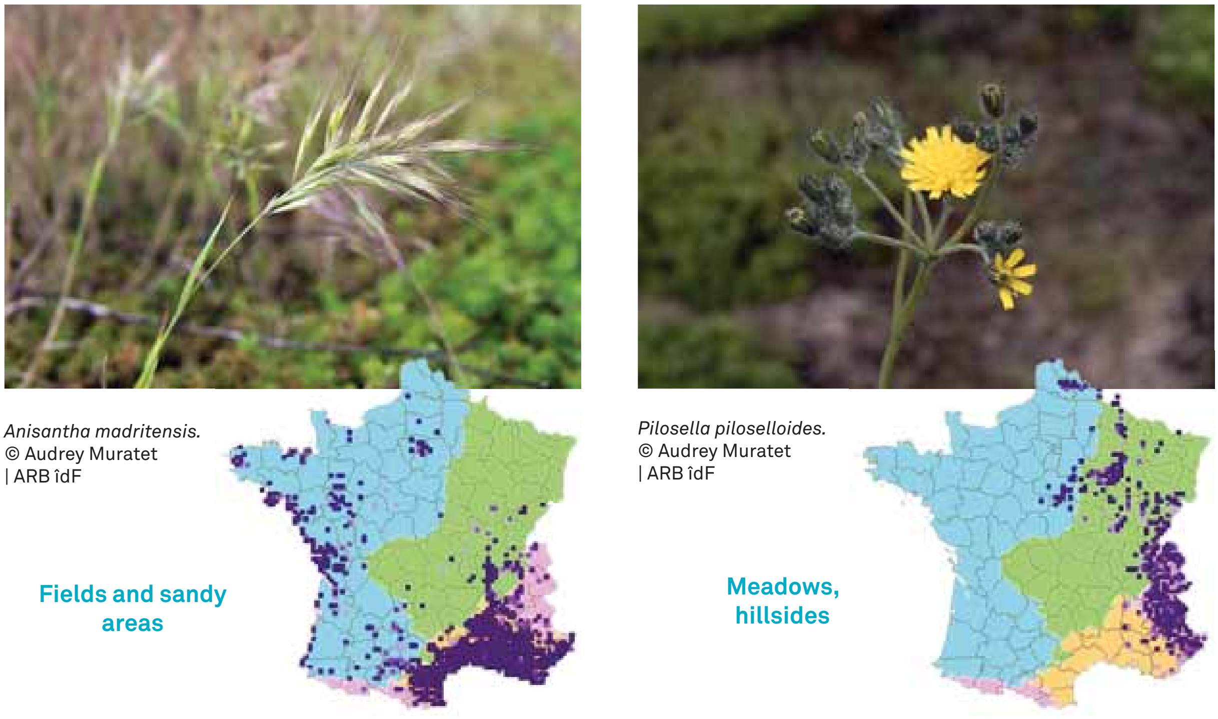
By comparing data from rooftops with data gathered in other green spaces at ground level, we see that, on average, roofs host a range of plants similar to that found in waste ground and urban parks [13].



Rooftops host a range of spontaneous plants similar to that found in areas of waste ground and urban parks

FIGURE 7 Spontaneous plant diversity per environment observed in the framework of the Vigie-Flore protocol.
© Audrey Muratet | ARB îdF

But this diversity is highly variable. The extensive roofs, which have an essentially mineral substrate and/or which are shallow, host a lower diversity of flora than intensive or semi-intensive roofs. Although less diverse, extensive roofs and control roofs known as wildroofs (which are neither planted nor sown) are still valuable as regards biodiversity. Their composition is unique in the city, and they feature original combinations such as planted and spontaneous species that grow in dry, sandy grassland which may either be local or come from further afield: they may be Mediterranean, continental, North American, etc.



Anisantha madritensis. © Audrey Muratet | ARB îdF

Pilosella piloselloides. © Audrey Muratet | ARB îdF

Source : FCBN 2016

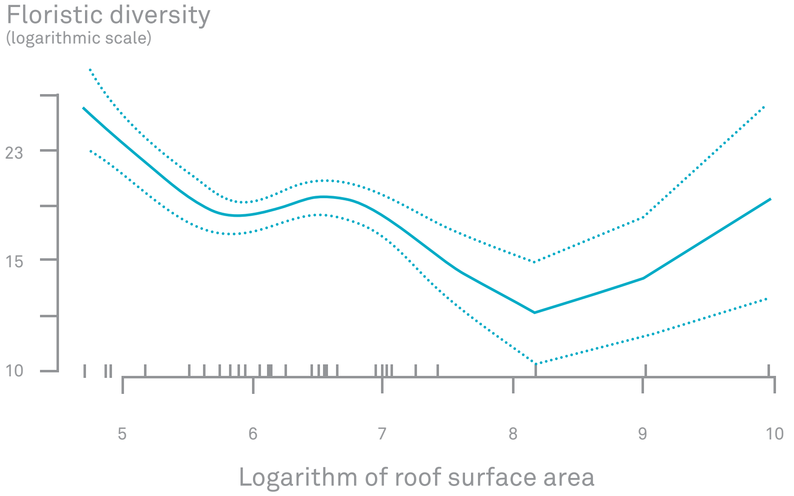
Source : FCBN 2016

FIGURE 8 *Anisantha madritensis* and *Pilosella piloselloides,* two travelling species found on rooftops. © Audrey Muratet | ARB îdF

The first thing the study tells us is that biodiversity is not measured according to species diversity alone: the composition of species is equally important. This means that the floristic value of rooftops has to be adjusted according to the criterion under consideration (diversity, rarity index, composition). It highlights how important it is to diversify design methods and types of green roofs in cities. The results obtained also show that certain design parameters can affect floristic diversity (substrate quality and depth, building height, etc.).

One of the unexpected outcomes of the study was that it highlighted a negative relationship between the surface area of the roof and the diversity of spontaneous plants. This may be due to the fact that the conditions on large roofs can be more extreme in terms of heat and drought as they are less well protected by buildings or natural features and more exposed to the wind. This hypothesis could be assessed by comparing the composition of flora and fauna on large and small roofs to determine the existence of communities that thrive in extreme conditions on larger expanses of roof.

FIGURE 9 Relationship between roof surface area and spontaneous floristic diversity. © Audrey Muratet | ARB îdF



The height of the building is correlated with the number of spontaneous plants, hoverflies and wild bees. The effect is positive up to 10 metres (about 3 floors). Above this height, the amount of flora no longer increases and the number of pollinators decreases. These observations appear to indicate that height is a determining factor, but need to be confirmed by more detailed analysis.

Substrate depth is the factor that best explains not only the richness of flora but also the total number of pollinators, including beetles and wild bees. We observe that flora does not increase beyond a depth of 25cm, whereas the number of pollinators continues to increase beyond this threshold. The composition of the substrate also plays an important role in the establishment of diverse flora: analysis shows that maximum floristic diversity occurs in soil that contains around 10 % clay and 60 % sand.

The effects of the landscape have also been assessed. These mainly include how the ground surrounding the building is occupied (by other built structures, green spaces, etc.). However, the results we obtained do not show that the environment has any influence on rooftop flora. Design factors thus seem to play a decisive role in how successfully different plants establish themselves on roofs.

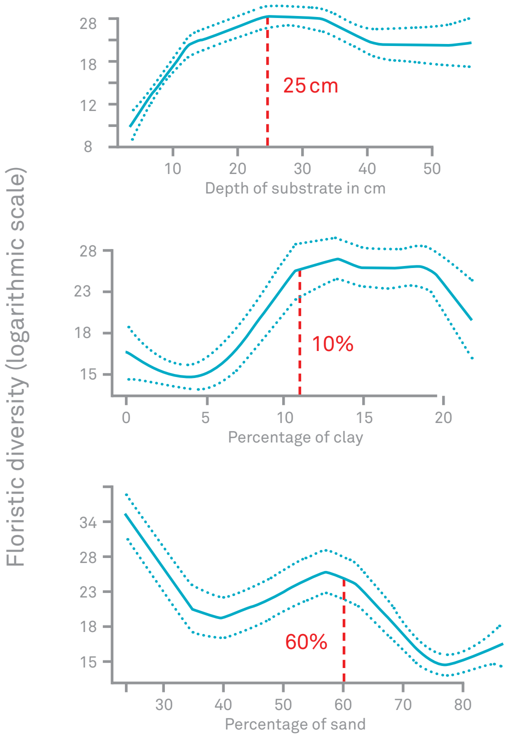


FIGURE 10 Substrate depth and clay/sand content influence floristic diversity. © Audrey Muratet | ARB îdF

ROOFTOP MOSSES

By Sébastien Filoche, Conservatoire Botanique National du Bassin Parisien

Bryophytes (mosses, hornworts and liverworts) are “ancient plants” that are fairly discreet and relatively little understood. They form the evolutionary transition between algae and vascular or higher plants such as flowering species. There are about 25,000 species of bryophytes in the world, including 1,800 in Europe and 1,300 – 1,400 in France. They are quite hard to identify, often requiring a magnifying glass, a microscope and complex specialist books. Observing them reveals forms and characteristics that are surprising and, above all, more varied than is widely believed.

As part of the GROOVES study, the Conservatoire Botanique National du Bassin Parisien (CBNBP) inventoried 20 roofs. In total, 40 taxons were observed on the roofs. 8 species are present on most of them: *Bryum argenteum, Ceratodon purpureus, Funaria hygrometica, Ptychostomum capillare, Barbula convoluta* and *Synthrichia ruralis.* In slightly wetter areas or areas that are not subject to trampling, *Amblystegium serpens* and *Brachythecium rutabulum* are also well represented. Most of the species observed are pioneers of dry environments and doubtless more pollution-tolerant. Bryophytes are excellent indicators of the quality of the natural environment. With no developed vascular system and no roots, they are directly exposed to environmental variations and thus very sensitive to any modification to their habitat. Bryophytes respond quickly to environmental disturbances in a number of ways, in particular via changes within communities of species. Their predisposition to bio-accumulation also allows us to monitor the concentration of pollutants in the environment. They are also good indicaters of the state of conservation of many natural habitats, in particular habitats of special value to the community.

In the concrete areas around the edges of the rooftops, rather than in the heart of the vegetation, the inventories noted the presence of *Grimmia pulvinata* and *Tortula muralis,* which are very common in these conditions.

→

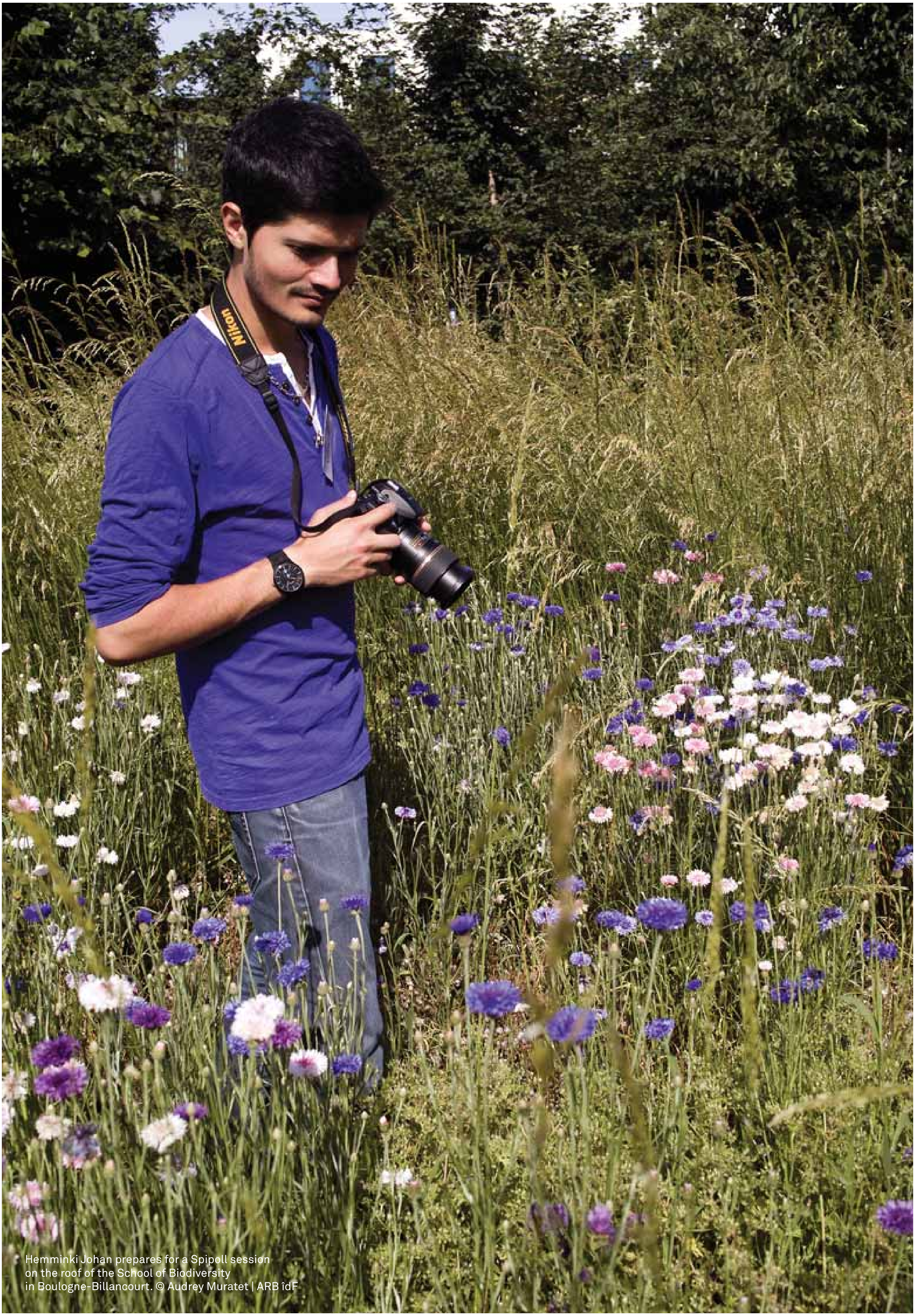
→ Several species typical of dry, sunny environments were observed mainly on sedum rooftops: the commonest are *Brachythecium albicans, Homalothecium lutescens, Polytrichum juniperinum, Tortula squarosa* and *Racomitrium canescens.* On green roofs that have shady, damp spots we see thalloid liverworts, which are rather rare on rooftops: *Lunularia cruciata* and *Marchantia polymorpha* (no examples of foliate liverworts were found).

17 species were only observed in one or two stations: these were either species that grow in a particular situation (shade and damp)—*Fissidens taxifolius, Lunularia cruciata, Marchantia polymorpha, Callergionella cuspidata*—, species that thrive in very dry conditions or "old" settings, or species whose presence is linked to the provenance of the substrate *(Bryum radiculosum, Didymodon luridus, Encalypta vulgaris, Pseudoscleropodium purum, Racomitrium canescens, Tortella squarosa, Tortula cuspidatum, Homalothecium sericeum, Orthotrichum anomalum, Orthotrichum diaphanum, Pseudocrossidium hornschuscianum)*, one woodland species *(Fissidens bryoides)* and one invasive species that is not widespread in urban settings *(Campylopus introflexus)*. The presence of *Oxyrhynchium hians,* observed in several instances, may be a marker of the age of the roof planting and its water retention capacity.

Some particular trends can be noted: RUWAT is the richest roof with 20 taxons (and 6 lichens) followed by AMROU with 17 taxons (relating to the diversity of environments in several small unplanted and sedum roof areas). Only one roof (FAUTEM) has no bryophytes, owing to the thick layer of ramial chipped wood mulch that covers it. The spontaneous roof of the CD93 has the most bryophytes, probably because of its age and the fact that it faces in different directions. Other more general trends can also be observed. On most of the roofs, diversity varies from 7 to 10 taxons. The oldest roofs seem to have more bryophytes (20 bryophytes on RUWAT, 17 on AMROU, 11 on WWF, 12 on CD93). Roofs planted with sedums generally have more bryophytes. As far as surface area is concerned, large roofs tend to be richer in bryophytes (CIMOB, PAREX) except if they have a high density of grasses (SEINE). Prairie roofs that have bare or less dense areas that are sometimes slightly damp can have as many bryophytes as sedum roofs (PULMA, GTMBA, CHAVIN, CIROB, MOZINOR). By contrast, very dense prairie roofs or roofs covered in mulch have very few bryophytes. Last but not least, the provenance of the sedum containers or the substrate (pozzolana) can influence diversity (e.g. PAREX, ROROL: a diverse though recent roof).

Sedum roofs have more bryophytes. © Audrey Muratet | ARB îdF

The roof of the Paris Villepinte Exhibition Centre is also home to Chives (*Allium schoenoprasum*)
© Audrey Muratet | ARB îdF



Hemminki Johan prepares for a Spipoll session
on the roof of the School of Biodiversity
in Boulogne-Billancourt. © Audrey Muratet | ARB îdF

#4

INVERTEBRATES
ON GREEN ROOFS

Invertebrates are characterised by a high level of diversity in terms of species and ecologies. Well represented in urban settings, they are good indicators of characteristics of the environment (humidity, temperature, availability of resources, etc.)

Studying invertebrates by breaking them down into predators, decomposers, prey and pollinators tells us about the ability of roofs to host them and their role in these new ecosystems.

Describing communities of arthropods allows us to consider roofs as potential substitution habitats. However the diverse design and management of roofs can impact communities of arthropods. It is thus necessary to understand the parameters that create optimum conditions for hosting such urban wildlife.

INVENTORY OF INVERTEBRATES

PROTOCOL

For land-dwelling invertebrates, the protocol corresponds to a sampling system by transect. Two techniques were used: invertebrates were first collected using a vacuum catcher (9 min) and then a sweep net (1 min). Two sessions one month apart (between May and the end of July) took place every year for three years. Identification of the invertebrates was carried out in the lab.

Pollinators were inventoried using the SPIPOLL participatory science programme developed by the MNHN. The protocol involves spending 20 minutes photographing interactions between insect pollinators and a flowerbed of a selected species. The pictures are then entered into a national database with information on their environment, which makes it possible to compare roofs with other natural areas.

Carrying out the SPIPOLL protocol on the roof of the Cité de la Mode et du Design in Paris. © Gilles Lecuir | ARB îdF

Studying invertebrates on roofs allows us to demonstrate that life on the rooftops is both diversified and functional. A high diversity of species in a range of different taxonomic groups has been observed: isopoda (woodlice), myriapoda (centipedes) and collembola (springtails), which recycle organic material. Higher up the trophic chain, phytophagous species are well represented by beetles, orthopterous insects (crickets and grasshoppers) and hemipterous insects (bugs and leafhoppers). This diversity leads to the presence of predatory arthropods (including spiders), hymenoptera and certain beetles. A total of 611 invertebrate species were identified between 2017 and 2019.

In parallel with the study of species diversity, we estimated the abundance of each order of insect. The most numerous are clearly hemiptera (bugs), hymenoptera, spiders and beetles. Bugs, which are adapted to a wide range of environments, are able to initiate population explosions in the right conditions. This is the case, for example, for members of the genus Nysius, which were observed in remarkable numbers on some roofs. This genus is generally associated with hot, dry environments and is consequently very widespread in the Mediterranean. 3 different species were found on the roofs selected for study, some with remarkable population density especially on extensive roofs.

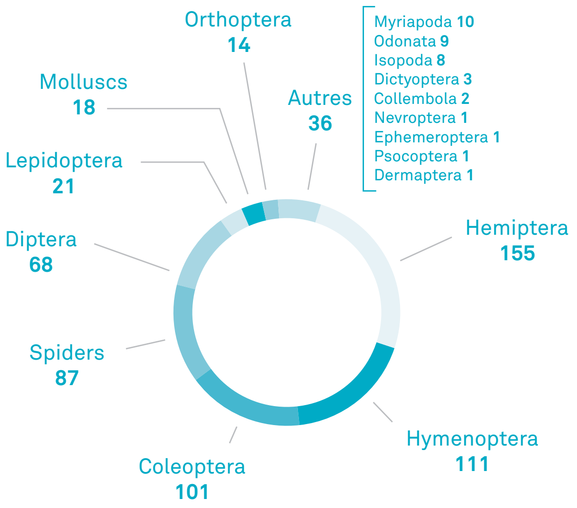


FIGURE 11 Number of invertebrate species per taxonomic group © ARB îdF

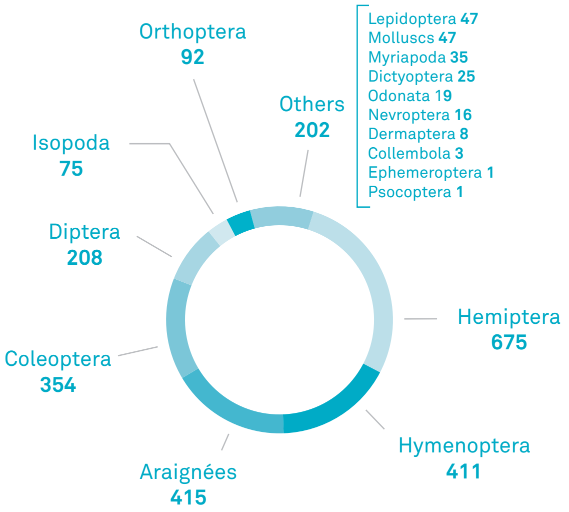


FIGURE 12 Hemiptera (bugs), Hymenoptera, spiders and Coleoptera are the most abundant taxonomic groups on green roofs. © ARB îdF

ROOFTOP PARASITOIDS

A parasitoid is an organism that develops on or inside another organism (the "host") and inevitably kills it at the end of its development, whereas many parasites do not kill their host. Parasitoid insects rely on a more or les diverse range of hosts to feed their larva. On roofs, the presence of these species, which often have limited ability to spread, suggests the existence of populations of invertebrates that are sufficiently diverse and abundant to satisfy their needs. Parasitoids are considered to be population regulators, in the same way as diseases, and play a natural role in the stabilisation of ecosystems. Their presence is thus seen as an indicator of a functional environment.

The Dryinidae (solitary wasps) are a family of asocial hymenoptera that is little known to the general public. Observed on the SIBUET rooftop, these ant-like insects less than half a centimetre long have their own unique characteristics. The wingless females have pincer-like appendages on their forelegs (like those of praying mantises), which they use to hunt leafhoppers. As well as being prey, leafhoppers also serve as hosts for the development of the wasps' larva, which remain attached to their victim and siphon off its hemolymph (the equivalent of blood in insects) in order to develop. This process, which ultimately kills the host, makes this anecdotal family into a valuable ally in the biological control of leafhoppers, which can pass diseases on to plants. Other families of Hymenoptera also play an important regulatory role: we observed an interesting range of Chrysididae (cuckoo wasps) on our roofs. These use bee and solitary wasp larva as parasitic hosts. Having identified the entrance to their nest, the female cuckoo wasp creeps inside and lays a single egg next to the host's brood.

Once it emerges, the larva first consumes the food collected by the adult bee or wasp for its own larva, and then devours the larva itself. Sometimes the victim (which is usually larger than the cuckoo wasp) catches it red-handed. To defend itself, the cuckoo wasp, which has a remarkably thick cuticle, curls up into a ball to avoid damage to its fragile body parts. It is then thrown out of the nest, although this does not necessarily mean it will give up itd quest: cuckoo wasps are known for their perseverance.

Dryinidae larva using a leafhopper as its parasitic host.
© Hemminki Johan | ARB îdF

Dryinidae adult female.
© Hemminki Johan | ARB îdF

The cuckoo wasp,
a parasitoid that specialises in bees
and solitary wasps.
© Ophélie Ricci | ARB îdF

Diversity fluctuates widely from roof to roof, with significant differences between less diverse sites (20 species) and those with the most species (up to 107 species). As we mentioned in the previous section on flora, this disparity highlights the importance of the rooftop design method where biodiversity is concerned: semi-intensive and intensive roofs are similarly diverse, while extensive roofs host a less varied range of species.
Compared to urban green spaces, roofs taken as a whole host significantly fewer species of pollinators. But if we distinguish the different roof typologies, the diversity of semi-intensive and intensive roofs becomes statistically comparable to that of green spaces. These results are similar if we study the abundance and originality of invertebrate populations: here too, extensive roofs rank lower than the other typologies.

Beewolf *(Philantus triangulum)*, BOUTOU roof.
© Hemminki Johan – ARB îdF

A beetle *(Anthrenus sp.)*, GOOPL roof.
© Lucile Dewulf | ARB îdF

FIGURE 13A Diversity of land-dwelling arthropods across different roof typologies. © ARB îdF

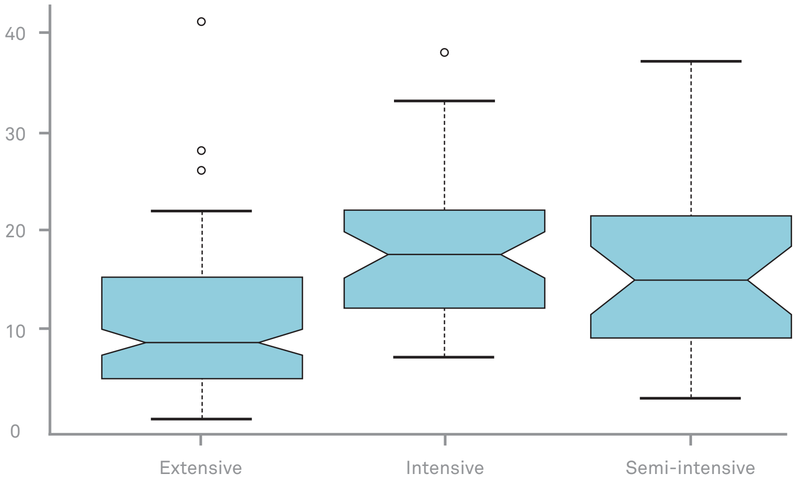
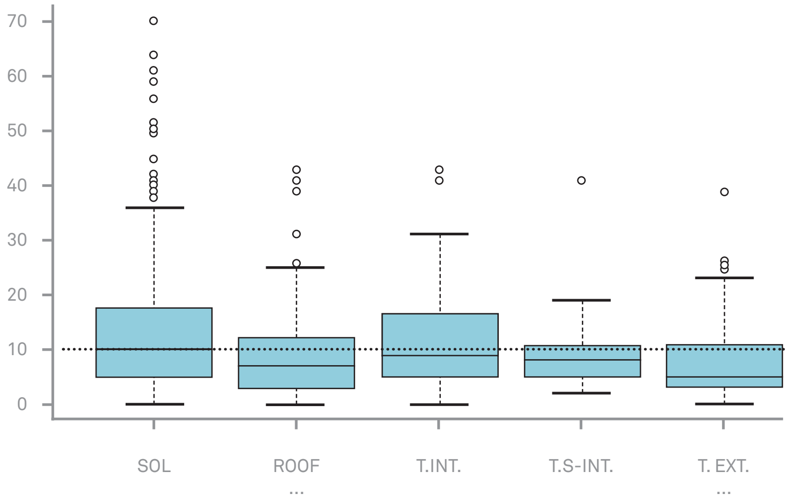


FIGURE 13B Diversity of pollinators across different roof typologies. © ARB îdF



On extensive roofs, environmental conditions are restrictive and similar to those found in very dry environments. By contrast, roofs with more numerous and more dense plant strata that provide more moisture and shade offer milder conditions that attract a wider variety of arthropods.

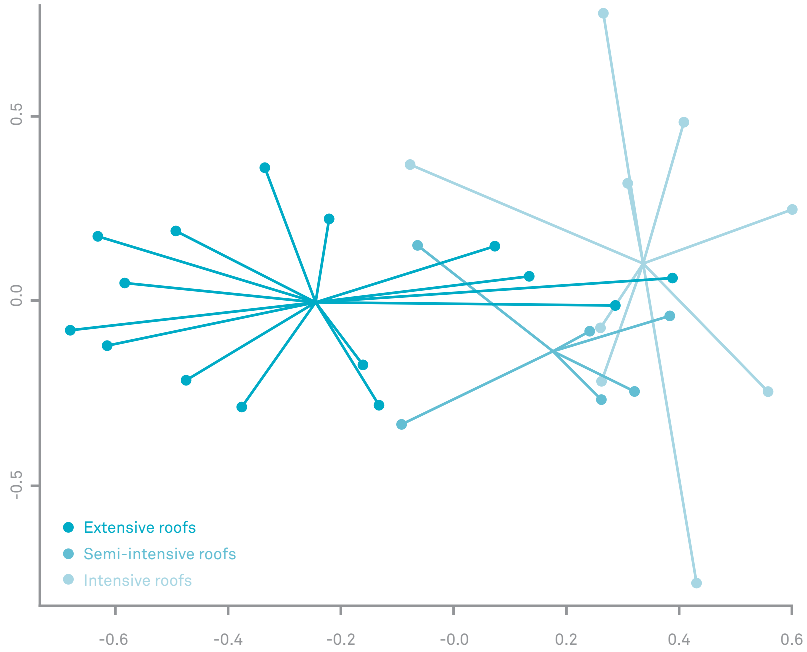


FIGURE 14 Distribution of invertebrate communities across different roof typologies. In this non-metric multi-dimensional analysis, the different roofs in the GROOVES study are represented by dots. The closer the dots are to one another, the more similar the communities of invertebrates are. © ARB îdF

Exploring the data we collected allows us to observe a significant difference between groups of species found on extensive roofs and those associated with intensive roofs. Semi-intensive roofs seem to stand at the interface between the two, offering a more nuanced habitat for invertebrates. The chosen design method for a roof is thus a decisive factor that directly influences the diversity that the roof is likely to accommodate, and will determine which species can colonise a given environment. A similar population difference is observed between the roof and the ground. By comparing the species most widely present on roofs with those that live in urban environments in the Paris Region, we can pinpoint three groups of species that react to this infrastructure in different ways: "roof-lovers" that are usually under-represented in urban settings but are very common on roofs (e.g. *Runcinia grammica, Nysius graminicola, Lygus pratensis*); "generalists" that are common on both rooftops and at ground level (e.g. the firebug *(Pyrrhocoris apterus)*, the garden spider (*Aranea diadematus)* and the southern green shield bug *(Nezara viridula)*); and "roof-haters" that are seldom found on roofs but are common at ground level (e.g. the nursery web spider *(Pisaura mirabilis)*, the mottled bug *(Raphigaster nebulosa)* and the dock bug *(Coreus marginatus)*).

Like plants found outside of their habitual distribution areas, several species of invertebrates that are drawn to Mediterranean or Atlantic habitats have been identified as long-term inhabitants of rooftops. Because of their low dispersion capacity, the question of whether they are imported in substrate or on plants merits further study. In any event, their recurrence in the three years of inventories shows how well they seem to have acclimatised to their new environment.

Example: 3 groups of species that react differently to green roofs
A. The garden spider *(Aranea diadematus),* considered to be a "generalist" © Audrey Muratet | ARB îdF
B. The mottled bug *(Coreus marginatus)*, considered to be a "roof-hater" © Maxime Zucca | ARB îdF
C. *Nysius graminicola*, considered to be a "roof-lover" © Hemminki Johan | ARB îdF

SPRINGTAILS: LITTLE KNOWN—BUT ESSENTIAL FOR SOIL FERTILITY!

By Céline Houssin and Louis Deharveng, Institut de Systématique, Évolution, Biodiversité (ISYEB UMR7205 CNRS, MNHN, UPMC, EPHE), Sorbonne University

Springtails, along with acarids, are the main representatives of micro-arthropods in the soil, where there are 10,000 – 100,000 individuals per square metre. They play an essential role in soil fertility, helping to create micro-porosities (for ventilation and rooting), breaking down organic matter, and thus helping nutrients to circulate. This means that they are important bio-indicators of soil quality as their abundance depends on a range of factors such as pollution, availability of water and quantity of organic matter. Long considered to be insects, springtails actually form a separate class of arthropods. They are classified within some thirty families divided into four orders: Poduromorpha, Entomobryomorpha, Neelipleona and Symphypleona.

As part of the GROOVES study, Céline Houssin and Louis Deharveng analysed springtails on 6 green roofs (1 intensive, 3 extensive, 1 semi-intensive and 1 wildroof). The aim was to ascertain the diversity of springtails present; to compare the roofs to one another; and, in the longer term, to establish a link with the diversity to be found in nearby gardens and to connect the abundance and diversity of springtails with the presence of mycorrhizae, which they eat (see box on Mycorrhizae).

The extraction method involves placing each soil sample on a “Berlèse Apparatus”, which consists of a screen set over a flask containing 96° alcohol in which soil-dwelling fauna are collected. As the substrate dries out, the animals fall into the flask.

The roofs host an interestingly diverse population of springtails that varies according to roof type. The FAUTEM intensive roof hosts 14 species belonging to 3 different families. The CIMOD semi-intensive roof contains 12 species from 3 families. The extensive roofs RUWAT, BOUCHA and PERIS are home to 12, 4 and 5 species respectively. These early results seem to point to greater diversity on semi-intensive and intensive roofs. But it’s the wildroof atop the MNHN entomology building that has the greatest diversity with 19 species. Wildroofs may turn out to be valuable for soil fauna. On the entomology building, which has been monitored for several years, analyses indicate that as time goes by some species stay put on the roof while others appear and disappear. It thus seems that springtails are especially sensitive to substrate type and that the composition of their communities is likely to evolve over time. Further monitoring is required to confirm these evolutions or to observe a state of “maturity” with more stable compositions.

Springtails are soil-dwelling micro-arthropods that play an essential role in soil fertility. © iStock | Henrik_L

Substrate core sample on the Mozinor building.
© Marc Barra | ARB îdF

#5

SOIL AND SUBSTRATES ON GREEN ROOFS

The soil performs essential functions (playing a vital role in the water and carbon cycles, acting as a plant medium, etc.), which largely depend on the complex diversity present within it. On green roofs, we often refer to "substrate" because the soil has been extensively altered and reconstituted. Substrates are mostly not comparable to true soil, although efforts are being made in the field of ecological engineering to reproduce more natural conditions in substrates.

The substrates used for green roofs can have a varied range of sources and compositions, from excavated soils in natural and agricultural environments to substrates created by mixing materials from different sources (mineral fraction – crushed brick, pozzolana, perlite mixed with organic material, agricultural soil, compost, infill, etc.). This lack of consistency, coupled with insufficient knowledge of these "off-ground" soils, prompted us to carry out an in-depth analysis of their physical, chemical and biological features.

INVENTORY OF SOIL QUALITY

The protocol for the study of soil or substrates on green roofs was designed specifically for this study with the help of IEES-Paris and INRAE Dijon. For each roof, 10 core samples were taken to a maximum depth of 12 cm using a bulb planter. The sampling points were randomly spread out. The 10 samples were sent to the Aurea soil analysis lab. Depending on the roof, the volume of substrate collected was around 6 litres. Analysis carried out by the lab focuses on physical and chemical parameters (pH, grain size, CEC, nutrients, Metallic Trace Elements (MTE), etc.); biological parameters (microbial biomass, organic matter, nitrogen, etc.) and physicochemical parameters (maximum water retention, porosity, water reserve, etc.). In parallel with these measurements, INRAE Dijon collected samples in order to assess the microbiological quality of the substrates by studying environmental DNA. To do this, we collected 15 ml substrate samples from each roof at the ten sampling points. Three of them were analysed independently to take account of spatial disparities. When the lab received the soil samples, they were freeze-dried, screened, ground and kept at -40°C for molecular biology analysis. The microbiological quality of roof soil was assessed using three indicators measured by molecular biology instruments based on the microbial DNA extracted from the soil (microbial molecular biomass, fungi-bacteria density ratio, and diversity of communities of bacteria and fungi).

Jonathan Flandin takes soil samples in sterile conditions.
© Marc Barra | ARB îdF

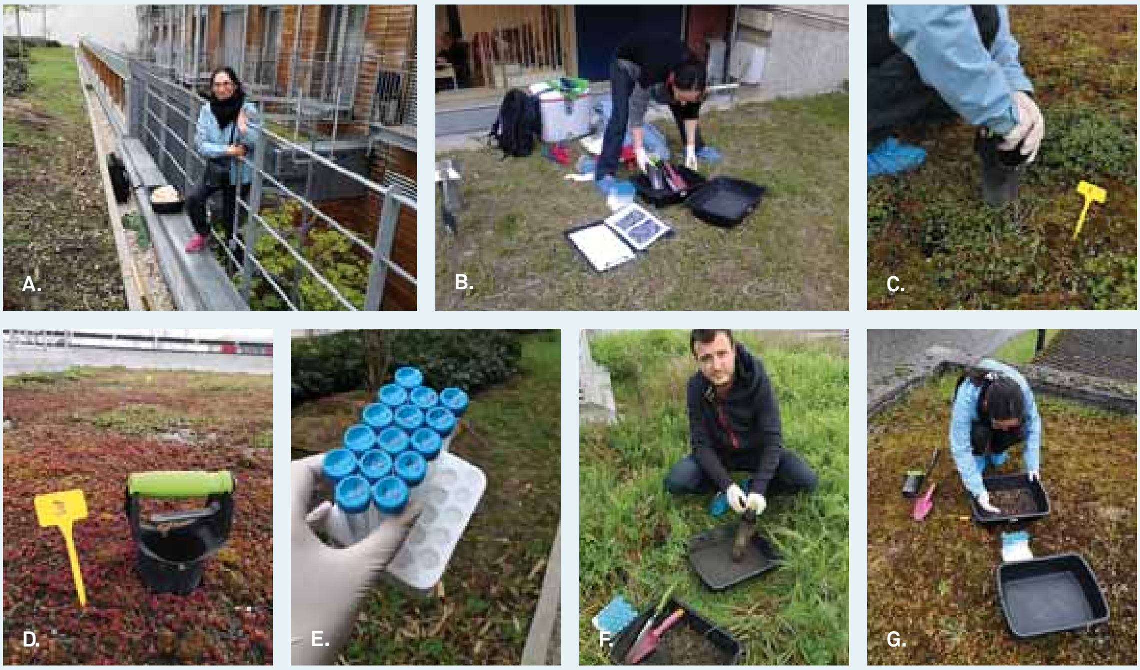
Molecular microbial biomass makes it possible to estimate the overall abundance of micro-organisms in the soil. It is measured by quantifying the microbial DNA extracted from the soil sample. It is an impact indicator as it is sensitive to soil disturbance, to different forms of contamination and to anthropic activities (e.g. agriculture). A loss of molecular microbial biomass indicates a loss of biological function and consequently a loss of ecosystem services. Several steps are required in order to obtain this bio-indicator. Put briefly, the process involves extracting total genomic DNA and then purifying this “raw” DNA and carrying out a fluorescence assay.

The fungal/bacterial density ratio relates the number of bacteria to the number of fungi. It makes it possible to characterise a possible microbial imbalance that may have repercussions on the soil’s biological functions such as the mineralisation of organic matter. The number of bacteria and fungi is obtained via a quantitative PCR technique based on extracted DNA.

Microbial diversity corresponds to the number of different species of bacteria and fungi. This quantification relies on a molecular biology technique called mass sequencing, which makes it possible to rapidly identify the genes of the bacteria and fungi present in the sample. This diversity tells us about the functional potential and biological stability of the soil, which is directly connected to the quality and sustainability of ecosystems. Moreover, this technique allows us to describe the different species and taxonomic groups present in the community.

At each of the 10 substrate sampling points, the plants were collected and placed in envelopes with their roots attached for the identification of endomycorhizae, carried out by researchers Laurent Palka and Yves Bertheau from the French National Museum of Natural History. Last of all, for each roof, substrate depth was measured using a steel rod and a tape measure at all the sampling sites. Average depth was then calculated.

PROTOCOLE



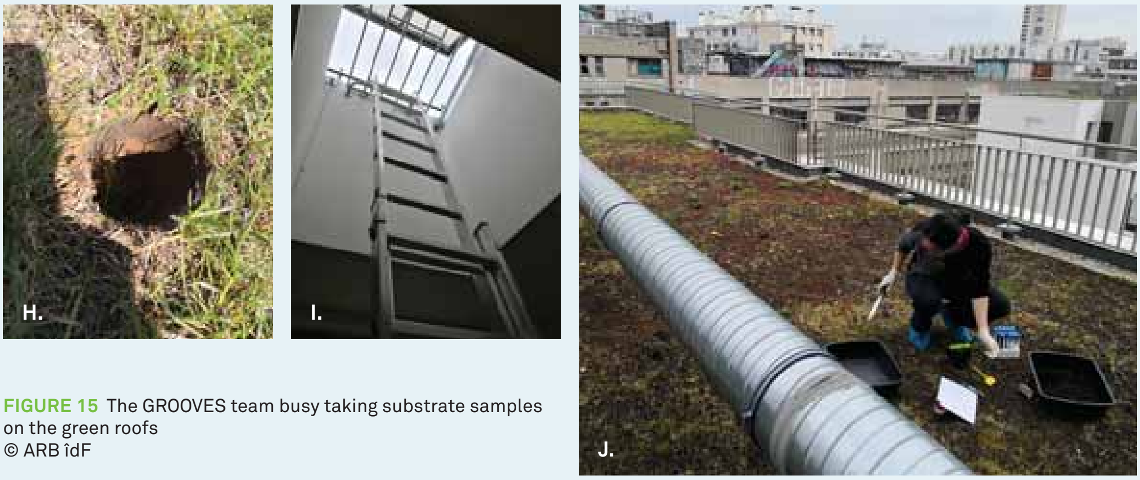


FIGURE 15 The GROOVES team busy taking substrate samples on the green roofs
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- **A.** Access to green roof on Paris Habitat residential building
- **B.** Equipment required for the “substrate” protocol
- **C.** et **H.** Collecting substrate samples using a bulb planter
- **D.** Markers used to determine sampling points
- **E.** 15 ml “Falcon” tubes for microbial biomass analysis
- **F.** et **G.** Mixture of different substrate samples
- **I.** Access to roof via fire hatch
- **J.** Taking samples at a Paris Habitat residential building
- **K.** Processing substrate before sending it to the Auréa lab
- **L.** Envelopes for plants used for mycorrhizal fungi analysis

THE VARIABLE COMPOSITION OF SUBSTRATES ON GREEN ROOFS

Laboratory analysis allowed us to classify the substrates according to the coarse materials they contain (by screening out 8 mm and then 2 mm particles). substrates on extensive roofs contain more coarse materials (38.7 % compared to 6.3 % on intensive roofs), the latter consisting mainly of pozzolana, crushed brick or gravel. The range of values is from 14.54 % to 76.42 % for extensive roofs and from 2.24 % to 18.12 % for intensive roofs, which illustrates the diversity of their design principles. Coarse materials have a direct effect on porosity, water and mineral retention, soil warming rates and resistance to soil compaction.
After screening, the remaining soil fraction, known as “fine earth”, is used for soil texture analysis— in other words, analysis of sand, silt and clay content. Clay content is higher for intensive roofs than for extensive roofs, and the reverse is true for sand. Thanks to analysis carried out by GIS Sol and INRAE Orléans, the green roof substrates studied in GROOVES were compared to the 2,200 soils in the RMQS (French database of soil quality) soil quality monitoring network using a texture triangle, which makes it possible to position roof soils in relation to “natural” soils across France.

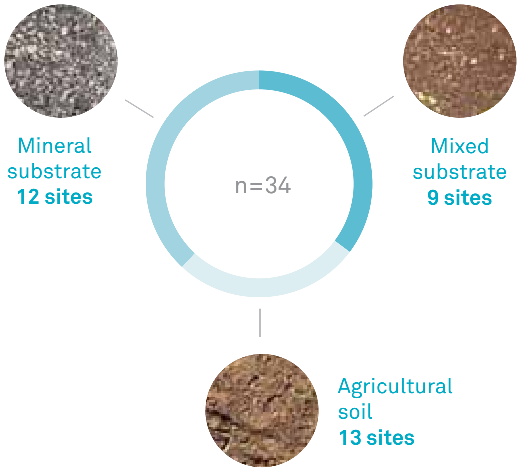

FIGURE 16 Distribution of substrates according to the coarse materials they contain. © ARB îdF

For simplicity’s sake, the substrates were divided into three categories based on their appearance: agricultural soil, mixed substrate (soil and mineral components) and mineral substrate (over 80 % of coarse materials such as pozzolana).
The mineral substrate and mixed substrate samples all belong in the “sand-and-silt” and “sandy” classes, while the “agricultural soil” samples belong in textural classes more usually observed nationally. Roof soils have pH levels and, more importantly, organic car-

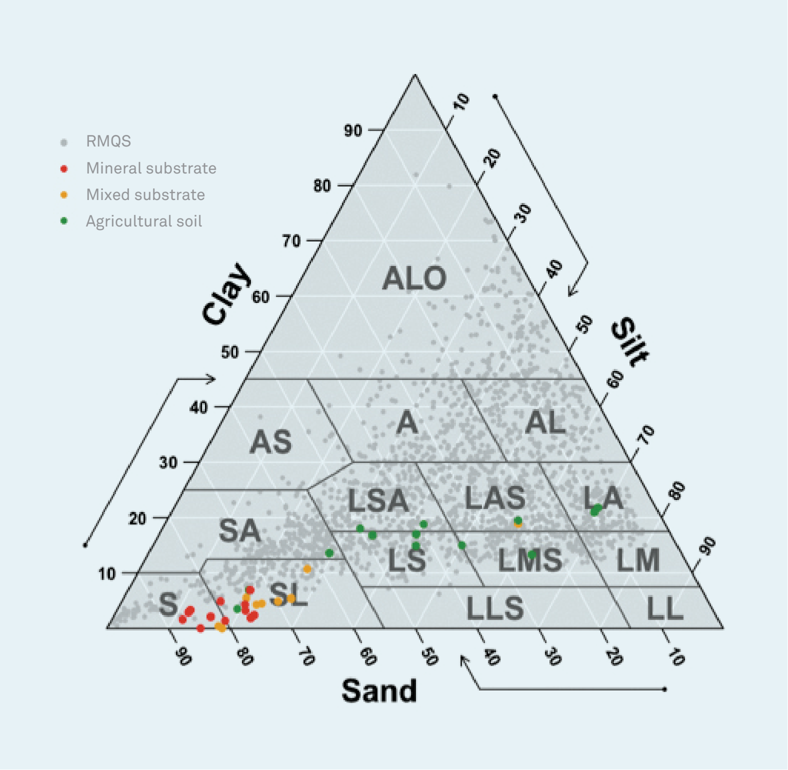

FIGURE 17 The 34 roofs studied were positioned in the texture triangle. The grey dots correspond to RMQS soils. © GIS Sol - INRAE Orléans.

bon levels that are much higher than soils recorded in the national soil benchmark. These results show that green roof soils have very special physiochemical features with combinations of textural and chemical properties that are not represented in the RMQS dataset.

In terms of biological analysis, the carbon/nitrogen (C/N) ratio is an indicator of the ability of organic matter to decompose. Used mainly in agriculture, it highlights the biological activity of soil (the degree of evolution of organic matter and the soil's potential for providing plants with nitrogen). The green roofs studied in GROOVES mostly have a high C/N ratio—higher than normal where 10 of them are concerned—, which means that the breakdown of organic matter is rather slow. This is referred to as soil with low biological activity. Overall, extensive roofs seem to have a higher C/N ratio than semi-intensive and intensive roofs, but this does not appear significantly in the statistical analysis. It should be borne in mind that the C/N ratio is an indicator used in agronomy: it is harder to interpret in the field of urban ecology.

C/N correlates positively with floristic diversity, which may suggest that low C/N substrates (where organic matter decomposes more rapidly) are those that are colonised by a less diverse range of plants. Other substrates, which are probably more complex with a greater variety of resources, may lend themselves to greater plant diversity.

Many other soil quality indicators were studied in the laboratory, such as cation exchange capacity and the characterisation of organic matter, but they were not necessarily any easier to interpret. Analysis of the bacterial biomass was also carried out and converges with that performed by INRAE Dijon and presented later on in this chapter.

METALLIC TRACE ELEMENT POLLUTION

Metallic trace elements (MTEs) such as copper (Cu), lead (Pb) and cadmium (Cd) are present in the soil in tiny amounts (< 0,1%). While some trace elements are necessary for life, they can become toxic if they are too abundant or if they are present in certain chemical forms. MTEs contained in substrates on 34 roofs were analysed as part of the study. While most of them do not present significant levels of pollution, some show particularly high levels of lead and zinc that are above risk thresholds. It is especially difficult, if not impossible, to trace the origin of this pollution. It may come from substrates that were contaminated before being placed on the roof or from atmospheric deposits that have accumulated over the years. Nonetheless, measuring MTE levels can be very useful to green roof managers, either for avoiding risk of contamination where the roofs are open to the public (in schools, for example) or during maintenance. The anthropic origin of zinc may be found in mining and industrial activities, road traffic, or the erosion of roofs and guttering. In France, the contamination threshold set by the French environmental agency Cerema is 88 mg/kg (although slightly higher values are not necessarily classified as pollution). The REFUGE programme (Risques en Fermes Urbaines: Gestion et Evaluation: management and assessment of risk in urban farms) recommends implementing quantitative assessment of health risks when MTE levels exceed 264 mg/kg.

Jonathan Flandin and Marc Barra
collecting substrate from the roof
of the Robespierre cinema
in Vitry-sur-Seine.
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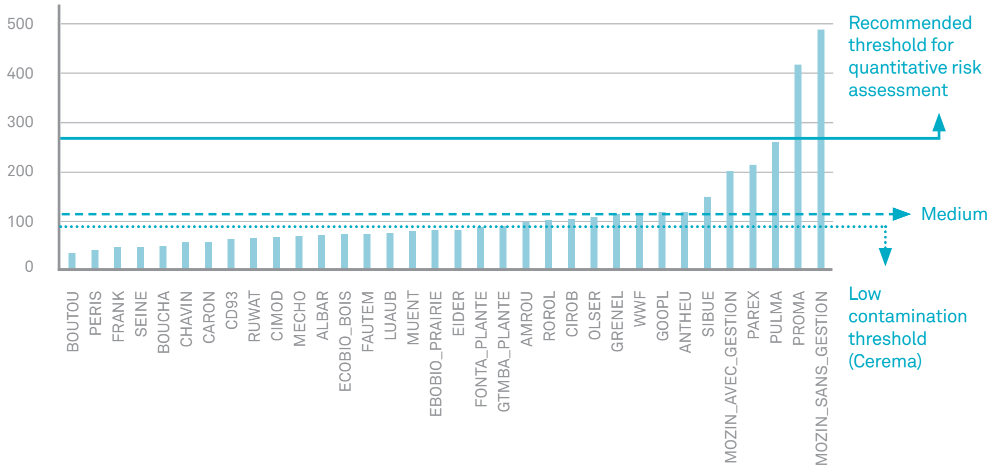
FIGURE 18
Total zinc content in green roof substrates.
© ARB îdF

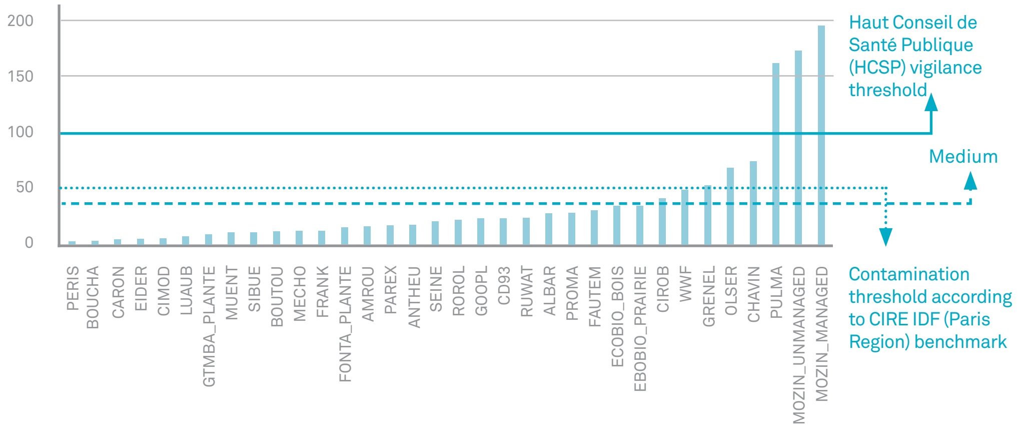


Zinc content on the green roofs studied ranges from 36.73 mg/Kg (BOUTOU) to 487.87 mg/Kg (MOZIN). 14 roofs exceed the Cerema low contamination threshold, while two (PROMA and MOZIN) present values between 400 and 600 mg/kg, exceeding the REFUGE threshold and potentially posing a toxicity risk. It should be noted that PROMA is a child welfare facility and its roof is not accessible to staff.

According to the Paris Region Health Agency, lead content of 53.7 mg/kg in topsoil is usually considered to be the contamination threshold in the Paris Region. This takes into account the regional benchmark for agricultural land, which considers that above this level there is an anomaly that may point to pollution of human origin. The vigilance threshold established by the Haut Conseil de la Santé Publique (HSCP: national health council), above which an assessment of health risks is recommended, is set at 100 mg/kg. Lastly, the threshold above which anyone exposed must be screened for lead poisoning is 300 mg/Kg.

Lead content on the green roofs studied ranges from 3.64 mg/kg (PERIS) to 196.25mg/Kg (MOZIN). Five roofs exceed the HSCP contamination threshold and two (CHAVIN and MOZIN) exceed the vigilance threshold. It should be noted that the MOZIN roof is accessible to staff and regularly maintained. In 2017, IEES-Paris, with support from ARB îdF, supervised Ludovic Foti's thesis on soil quality in the Paris Region, which assessed the concentration of MTEs in grassland and woodland along a rural-urban gradient. Road traffic was identified as the main source of anthropic MTE pollution. The second likely source of cadmium is industrial activity in the Paris area, especially cement factories. The history of land use has been identified as key to understanding levels of soil contamination and pollution caused by MTEs. According to this research, MTE concentration of anthropic origin increases along a rural-urban gradient and the concentration of most MTEs in urban settings is equal to or higher than regulatory reference values, raising the question of long-term monitoring. By way of example, the values obtained by L. Foti in urban grassland and woodland are on average 99 mg/kg in grassland and 188 mg/kg in woodland for lead, whereas for zinc they are on average 106 mg/kg in grassland and 75 mg/kg in woodland.

FIGURE 19
Total lead content (concentration in mg/kg) in green roof substrates.
© ARB îdF



Honey from domesticated bees can act as a bio-indicator in close proximity to sources of pollution. © Marc Barra | ARB îdF

On 15 April 2019, Notre-Dame Cathedral in Paris was ravaged by fire. The resulting smoke, loaded with heavy metals, spread around the city and its constituent elements found their way into the soil. A study [15] published in 2020 focused on the consequences of this pollution and showed that honey from hives located along the trajectory of the smoke contained significantly more lead than the others. Hives can thus act as bio-indicators following pollution events. As green roofs are particularly exposed to this kind of air pollution, it seems logical that they might bear traces of such events. Moreover, although domesticated bees are excellent bio-indicators, it should be kept in mind that they compete with wild pollinators, and that the presence of too many urban hives in densely populated cities can adversely affect wild biodiversity.

MICROBIOLOGICAL QUALITY OF SOIL ON GREEN ROOFS

Molecular microbial biomass is the most complete quantitative indicator used in this study as it reflects the total quantity of micro-organisms in the soil. It is recognised as a soil quality indicator by the Observatoire National de la Biodiversité. Microbial biomass is sensitive not only to soil but also to land use (ploughing, use of pesticides in agriculture) and to roof management methods (compaction, fertilisation, plant management).

Figure 20 shows values of molecular biomass measured on all 34 green roofs compared with values measured in RMQS soil samples.

In general terms, the results show that soils on green roofs have very high levels of microbial biomass (129.4 µg DNA/g soil), which is about twice as much as the average level measured as part of the RMQS benchmark (59.2 µg DNA/g sol). These high values may be explained, in particular, by the high organic carbon content observed on these roofs (via the addition of fresh matter such as compost). Micro-organisms are, for the most part, heterotrophic, which means that they depend on the availability of organic carbon for their development. When we looked at the soil on green roofs, we generally observed large discrepancies in microbial biomass values between the three replicates for each roof analysed. This is probably due to a lack of spatial consistency in terms of the physicochemical parameters of each roof. This lack of consistency may have several different origins (construction method and method of installing the soil; soil partially covered with vegetation, etc.). In any event, the variability of biomass on each individual roof partly masks the significance of differences in microbial biomass observed between different roofs.

Analysis of molecular microbial biomass according to substrate type, roof type, and type of vegetation (by which we distinguish roofs with mainly sedums, mainly herbaceous plants, or “mixed” vegetation) shows that the type of substrate does not significantly influence the level of molecular microbial biomass, even though lower levels tend to be observed in agricultural soil compared to mixed and mineral substrates. Extensive roofs show significantly higher levels of biomass compared to semi-intensive and intensive roofs. Similarly, the nature of plant cover is a highly influential factor, with levels of biomass generally higher

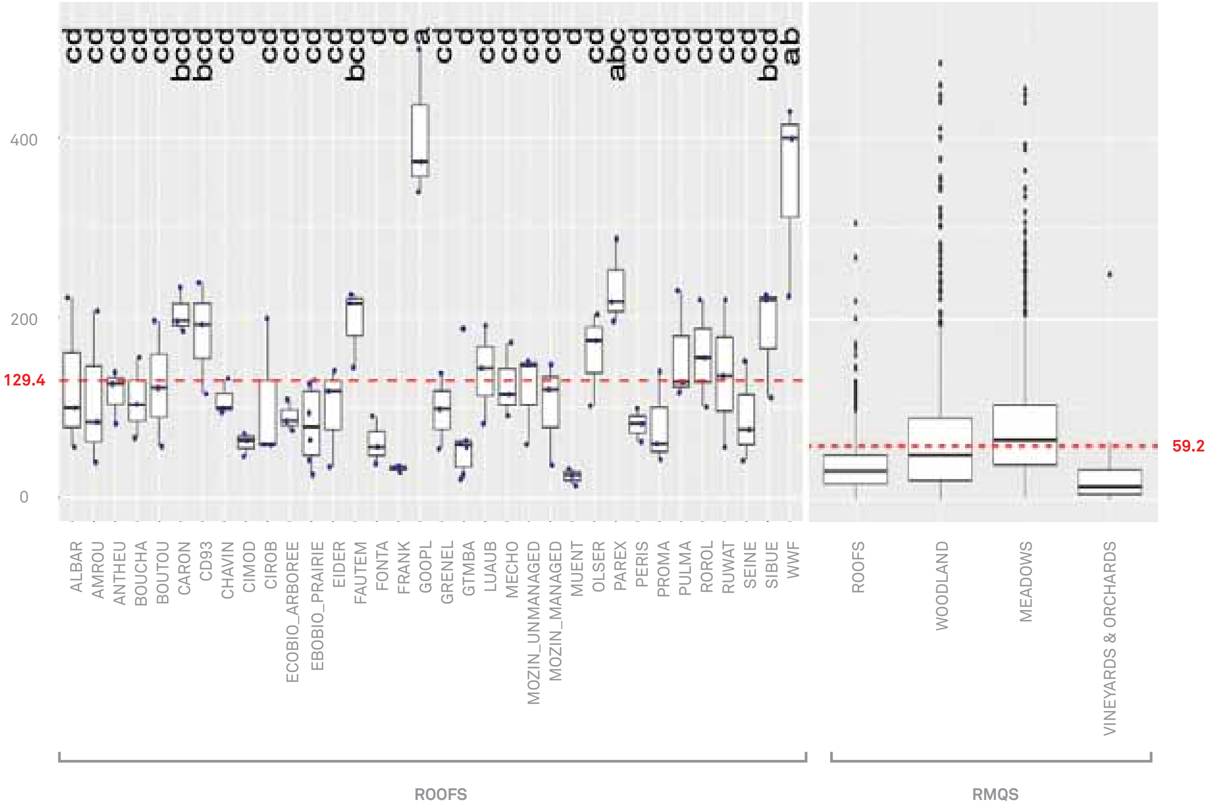


FIGURE 20 Molecular microbial biomass measured in the samples for each of the 34 roofs (n=3 for each roof) as well as in RMQS soils grouped according to how they are used (crops/woodland/meadow/vineyards&orchards). The red dotted line represents the average value of molecular microbial biomass, first for all the roof samples (129.4 µg DNA/g soil), and second for all the RMQS soils (59.2 µg DNA/g soil). © INRAE Dijon

under "mixed" cover compared to roofs covered mainly with sedums or herbaceous plants.

To further refine our analysis of the microbiological quality of roofs, we applied the biomass prediction model. Huge discrepancies were observed between the measured values and the reference values calculated using the model.

Such discrepancies are never observed in natural soil. They can be explained by the extreme specificity of roof soil, in terms of its physicochemical properties, compared with "natural" soil. Notwithstanding this fact, they raise questions about how robust an analysis based on a benchmark constructed using samples of "natural" soil can be. In other words, these results show how important it is to develop a specific benchmark for green roofs in order to perform a robust analysis of the microbiological quality of their soil.

On the basis of these results, we decided, for the rest of our report, to stop applying the "biodiversity" model to determine the microbiological quality of the samples.

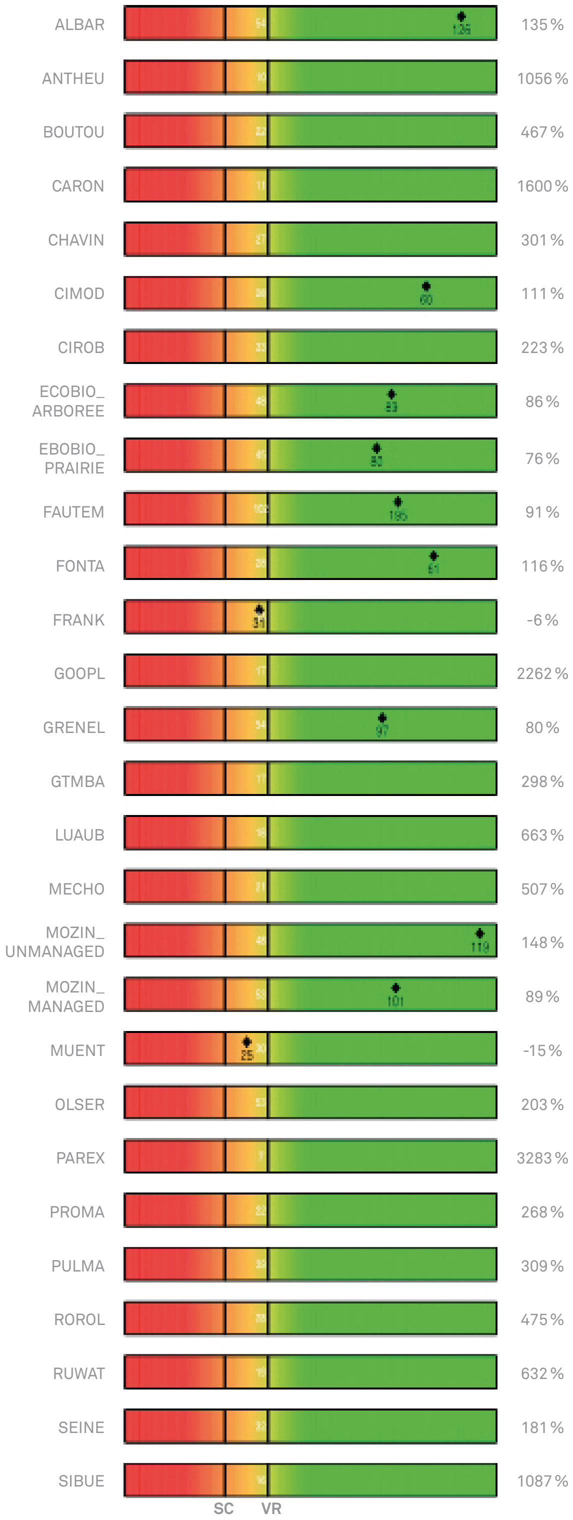


FIGURE 21 Microbiological analysis of green roofs to determine levels of molecular microbial biomass. The reference value (RV) is the value determined by the model. The critical threshold (CT) is the threshold below which soil function may be affected. The percentages quantify the disparity between the reference value and the measured value for each roof.
© INRAE Dijon

Collecting soil samples for lab analysis.
© Marc Barra | ARB îdF

Fungus/bacteria ratio: relative microbial equilibrium

Analysis of the ratio of the density of fungi to the density of bacteria (F/B ratio) makes it possible to detect possible microbial imbalance that may have repercussions on biological soil function. The number of fungi and bacteria is established using molecular biology techniques that involve quantifying microbial taxonomic genes (18S for fungi and 16S for bacteria [16] based on DNA extracted from the soil). In "natural" soils, this ratio presents an optimum of between 1 and 5. A higher value indicates an overabundance of fungi; a lower value points to an overabundance of bacteria. In "natural" soils, this ratio may be influenced by different factors such as ploughing, use of anti-microbial pesticides, quantity and nature of organic fertilisers or soil contamination by certain metals (e.g. copper).

The figure below presents the ratio values obtained for each of the 34 green roofs.

The results show that the roofs mostly fall within the optimum range (1 to 5), but with rather low values (1.5 on average). This indicates that the roofs are home to a microbial community with a more bacterial "signature". Several factors may contribute to this, for example the high availability of easily degradable organic substrates; intense exposure to climatic variations, in particular frequent cycles of drought to which fungi are more sensitive [17]; or a particular soil texture that is more favourable to bacterial development.

As with molecular biomass, we tested whether the variability of the fungi/bacteria ratio might be explained by the type of substrate, the type of roof or the type of plant cover.

The influence of the type of substrate and the type of plant cover on the fungus/bacteria ratio on green roofs is quite low but not insignificant. The relative abundance of fungi in the microbial community generally increases in mineral substrates and on sedum-covered roofs.

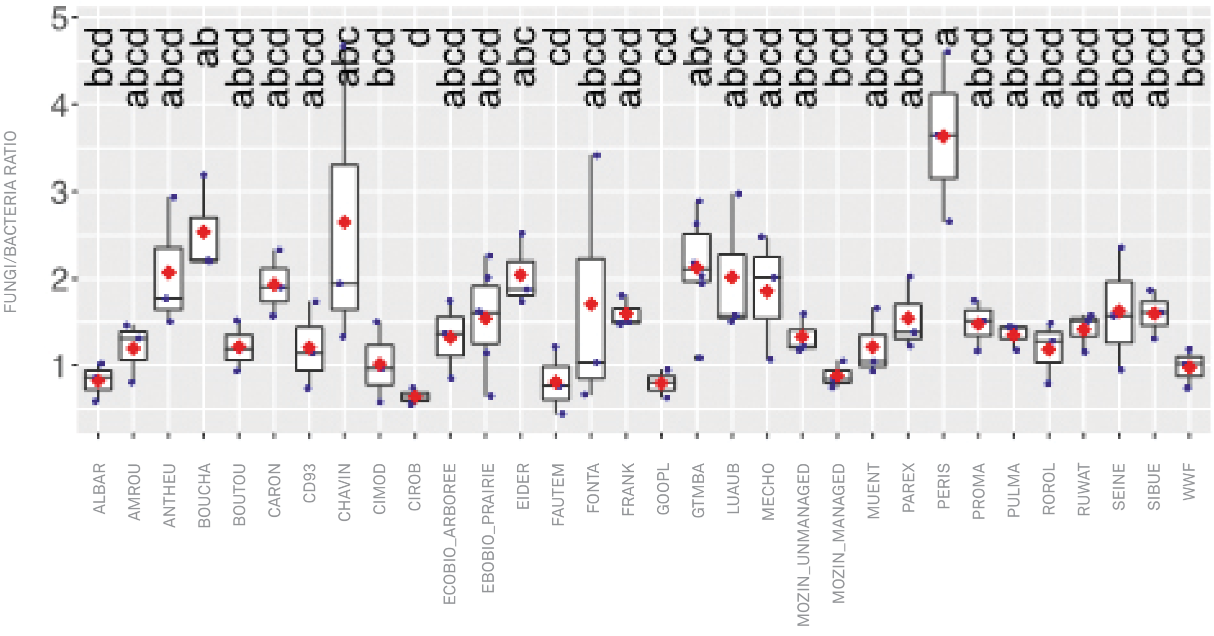


FIGURE 22 Microbial equilibrium assessed by calculating the fungi/bacteria ratio for each roof. For each roof, n=3 repetitions.
© INRAE Dijon

Diversity and structure of bacterial communities: roofs host very rich bacterial diversity

The taxonomic diversity of bacteria and fungi is obtained by the mass sequencing of the taxonomic genes 16S rRNA and 18S respectively extracted from soil DNA.

Bacterial diversity is sensitive not only to soil type but also to soil use and particularly agricultural practices. Ploughing, appropriate ground cover and organic soil amendments generally have a positive effect on bacterial diversity in “natural” soils [18]. The figure below represents values of bacterial diversity measured on the 34 green roofs studied.

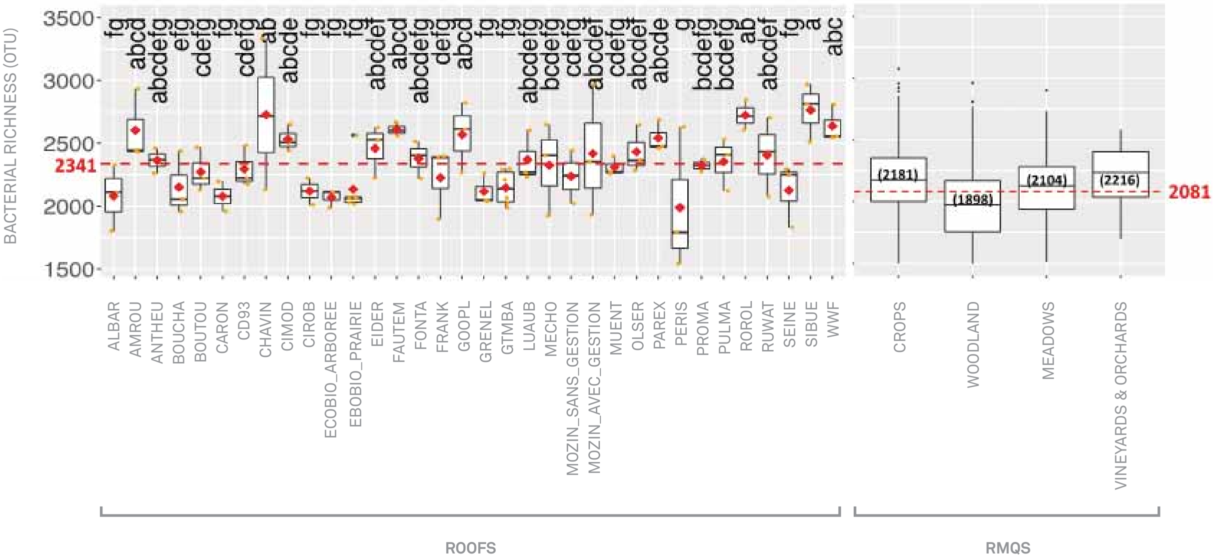


FIGURE 23 Bacterial diversity measured in samples from the 34 green roofs, compared with values obtained in RMQS soils grouped together according to their mode of use: crops/woodland/meadows/vineyards & orchards. The dotted red line represents the average value of molecular microbial biomass for all the roof samples (2,341 OTUs) and the values for all the RMQS soils (2,081 OTUs). Values in brackets represent average bacterial diversity for each mode of use for RMQS soils. © INRAE Dijon

As with the other microbial indicators mentioned previously, the bacterial diversity values for most of the roofs are highly dispersed between the three replicates; this confirms that a high degree of spatial variability exists on these roofs. The different roofs nevertheless present highly variable average bacterial biodiversity values, ranging from 2,071 OTUs for “Ecobio arboré” to 2,765 OTUs for “Sibuet”, thus highlighting a significant disparity between the different roofs. One remarkable result is that with 2,341 OTUs on average, the bacterial diversity of green roofs is higher than that of the RMQS soils (2,081 OTUs). Irrespective of the special properties of roof soils (cf. previous section), this high level of diversity may be explained by the fact that these environments are subject to frequent stress (especially connected to climate fluctuations), which limits competitive selection and exclusion and thus fosters the coexistence of a large number of species (in ecology this is called the “intermediate disturbance hypothesis”). We also see that levels of diversity on roofs are closer to those where modes of use are associated with the highest soil disturbance levels in the RMQS data (i.e. crops/vineyards & orchards).
This hypothesis seems coherent when we assess the influence of the type of substrate, roof and plant cover on bacterial diversity.

Mediterranean hairgrass *(Rostraria cristata)*, which is well adapted to extensive roofs. © Audrey Muratet | ARB îdF

Analysis of bacterial diversity on green roofs according to type of substrate, roof and plant cover shows that diversity is greatest in the shallowest extensive roofs—and thus those most highly exposed to variations in climate. These roofs are often made using "mineral" or "mixed" substrates, which are man-made soils whose structure and, more significantly, porosity probably fail to offer a buffered environment for micro-organisms (unlike "natural" soil), further accentuating exposure to stress. Conversely, diversity is on average lower on "intensive" roofs and in agricultural soil.

Diversity and structure of fungal communities: roofs are home to a high level of fungal diversity

Diversity values for fungal communities measured on the 34 roofs are shown in Figure 24. One remarkable result is that the diversity of fungal communities is on average higher (at 999 OTUs) in roof soils compared with natural soils from the RMQS benchmark (811 OTUs). This shows once again that roofs are environments that lend themselves to microbial development.

As with the other indicators, fungal diversity varies widely between the three replicates for each roof. Despite this variability, which points to a high degree of spatial variability on individual roofs, the average level of fungal diversity is very variable between the different roofs, showing that they are not all equal in terms of providing the right conditions for these communities to develop.

Unlike molecular biomass and bacterial diversity, our results provide no evidence that roof type, substrate type or plant cover type have any influence on the fungal diversity of green roofs.

Analysis of genetic structure shows, however, that these fungal communities differ between extensive /semi-intensive roofs on the one hand and intensive roofs on the other, due in particular to the stimulation of Ascomycetes in extensive/semi-intensive roofs. Similarly, the communities are different in agricultural soil and mixed substrates on the one hand and mineral substrates on the other, due to the stimulation of Ascomycetes in mineral substrates. The stimulation of this particular group can by explained by the ecological traits usually assigned to it in the literature, where they are referred to as "copiotrophic r-strategists". These traits can indeed provide this group with an advantage on shallow roofs that are frequently exposed to climatic events but are also rich in organic matter.

Despite the shallow substrates on green roofs, microbial life is able to thrive there. © Marc Barra | ARB îdF

Micorrhizal fungi: an interesting group that is very abundant on green roofs

Micorrhizal fungi are symbiotic organisms that play a very important role in the growth and health of plants. This symbiosis is acknowledged to increase not only the resistance of plants to hydric and thermal stress, but also their tolerance of certain pollutants [19]. These effects may thus be especially beneficial in urban green roof systems, which are exposed to high levels of atmospheric pollution and hydric and thermal stress.

Analysis of these communities in samples taken from green roofs delivered a remarkable result, namely a large increase in the occurrence of this group in roof soil (400 seq/10,000 on average) compared to natural soils from the RMQS benchmark (50 seq/10,000 on average).

The stimulation of this fungal group may be explained by the special environment that exists on roofs, particularly in terms of exposure to fluctuating climatic conditions and also atmospheric pollution. These conditions may encourage symbiosis that improves the plant cover's chances of survival—a hypothesis that seems to be borne out by the high level of this mycorrhizal occurrence and the fact that it reaches the same level irrespective of the type of roof and substrate, but is impacted by the type of plant cover, with significant stimulation under mixed cover compared to sedum or herbaceous plants.

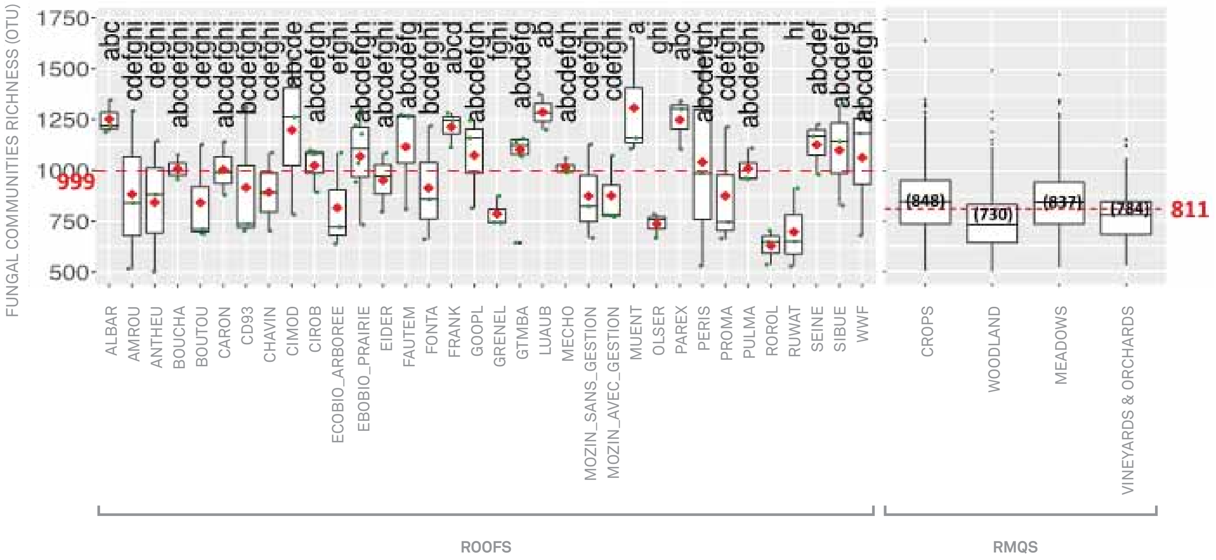


FIGURE 24 Diversity of fungal communities measured on green roofs compared to values obtained in RMQS soils grouped according to mode of use: crops/woodland/meadows/vineyards and orchards. The dotted red line represents the average value of molecular microbial biomass for all the roof samples (999 OTUs) and the values for all the RMQS soils (811 OTUs). Values in brackets represent average bacterial diversity for each mode of use for RMQS. © INRAE Dijon

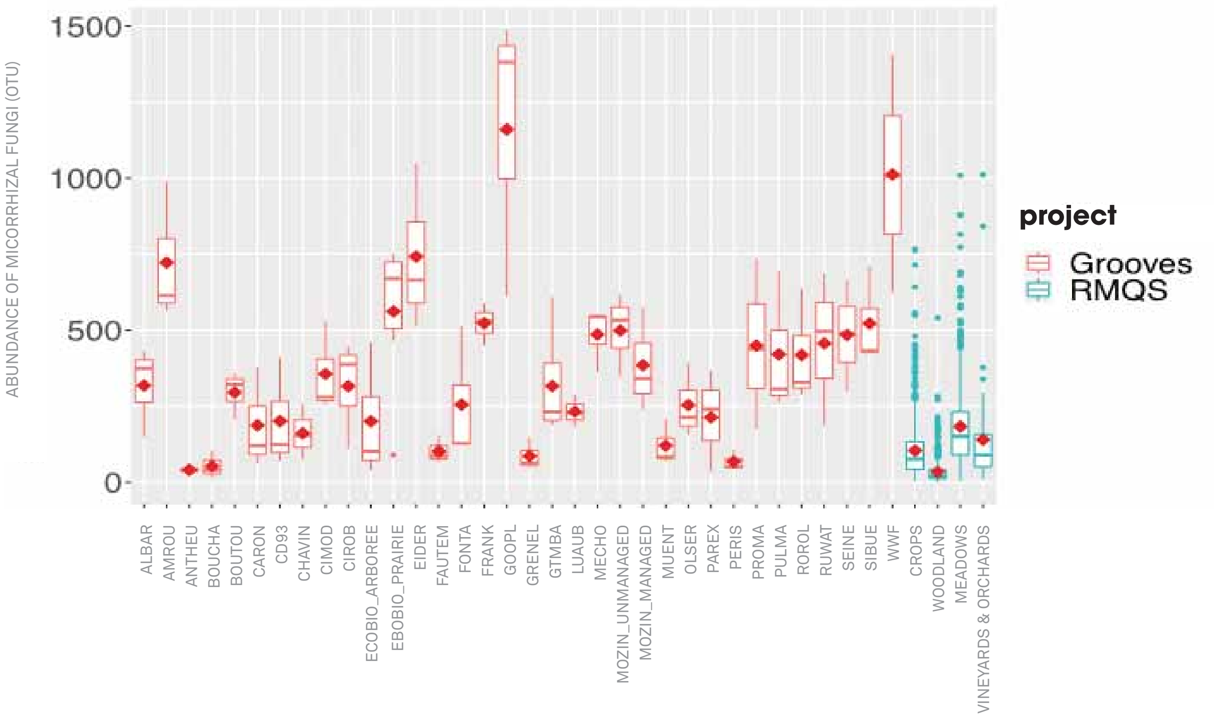


FIGURE 25 Relative abundance of sequences of mycorrhizal fungi in the total fungal community on green roofs, compared with the values obtained in RMQS soils grouped together according their mode of use: crops/woodland/meadows/vineyards and orchards. © INRAE Dijon

While the level of occurrence is not impacted by the type of roof or substrate, the structure of the mycorrhizal community is different in intensive/semi-intensive soils on the one hand and extensive soils on the other. Similarly, the structure of the community differs in mixed substrates, agricultural soil and mineral substrates. This shows that while the relative abundance of this community is high on all the roofs, the conditions afforded by the different types of roof or substrate contribute, to a degree, to the development of the different populations that make up the community.

Pooling the 10 soil samples on the roof of the technical building of the Conseil Départemental of the Val-de-Marne. © Marc Barra | ARB îdF

Microbial co-occurrence networks

Micro-organisms in the soil matrix do not live in isolation but instead cohabit, establishing complex relationships that determine not only how they operate as individuals but also more broadly how the community functions. These interactions can be either beneficial (commensalism, mutualism, symbiosis) or negative (predation, parasitism, competition) according to the impact they have on the species involved [20].

In the previous sections we saw how soils on green roofs have high levels of bacterial and fungal biodiversity, often above the average values of soils included in the RMQS benchmark. In addition, we analysed microbial interaction networks in order to determine, beyond levels of diversity, the level of complexity of the interactions within the microbial community. To do this, we determined microbial co-occurrence networks. These networks have the advantage of providing an overview including all the relationships between soil-dwelling micro-organisms. Two species can interact in several different ways at once. The result of all these interactions is the joint evolution of the organisms in the environment (a positive relationship called co-occurrence), or their separate evolution (a negative relationship called co-exclusion), or the absence of a relationship. On the scale of the communities, all these positive or negative relationships make up a co-occurrence network. Figure 26 shows the number of links in the microbial network (bacteria and fungi) calculated according to the type of substrate. The results obtained on all the roofs studied show that the networks are less complex in soil-rich substrates compared to mineral and mixed substrates. This tendency is confirmed by the results of the individual analysis of two roofs (Figure 27):

- ECOBIO-PRAIRIE (45 links): intensive roof, “agricultural soil” substrate
- GTMBA (61 links): semi-intensive roof, mineral substrate

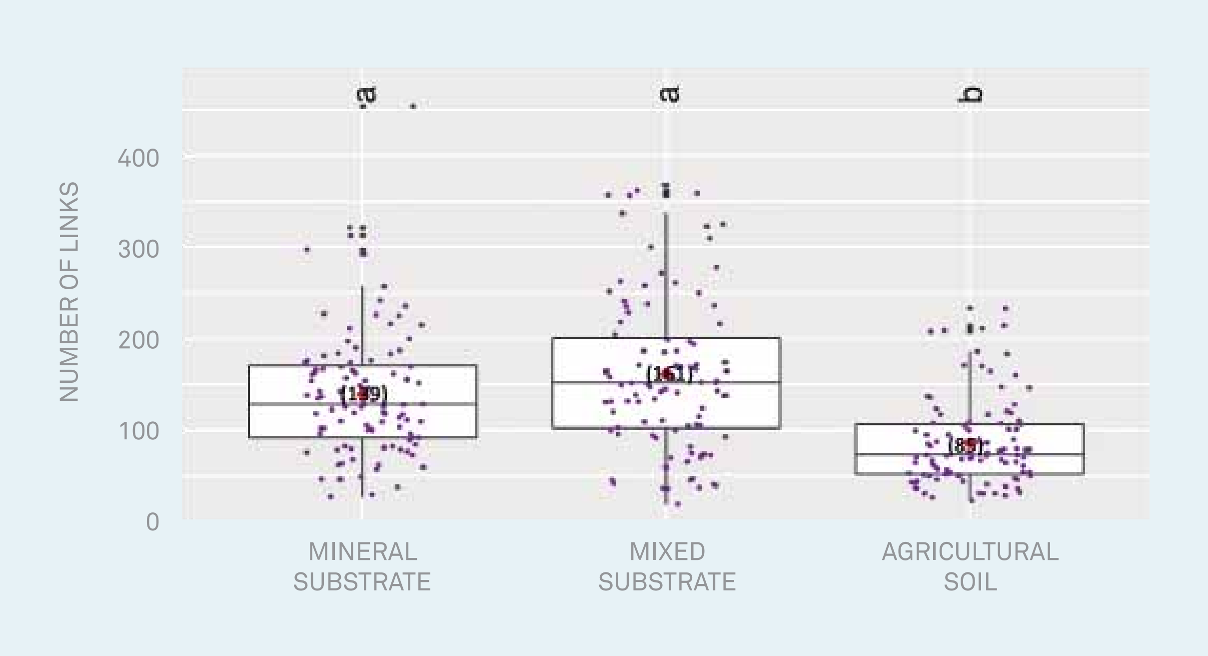


FIGURE 26 Complexity of microbial co-occurrence networks (bacteria/fungi): estimation based on the number of links in the network calculated on all the green roofs according to substrate type. Each point corresponds to one roof. Values in brackets correspond to average values for each category. © INRAE Dijon

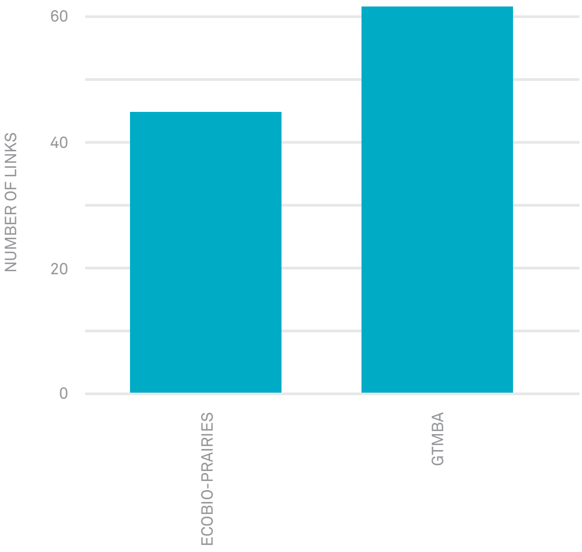


FIGURE 27 Complexity of microbial co-occurrence networks (bacteria/fungi): estimation based on the number of links in the network calculated on two green roofs: Ecobio-prairie and GTMBA. © INRAE Dijon

Further research would be required to determine the parameters that explain this simplification of networks in soil-based substrates compared to more constructed substrates.

The results of the microbiological analysis show that green roofs are environments conducive to the development of microbial communities (bacteria et fungi), both in quantitative terms (biomass) and qualitative terms (diversity). Average levels of microbial abundance and diversity on roofs are thus higher than those reported nationally in “natural” soils by the RMQS benchmark. This work also suggests a particular microbial ecology for these environments relating nopt only to the specificity of these matrices in terms of their physico-chemical properties but also to the exposure of these environments to large fluctuations in climatic conditions and atmospheric pollution. In addition to the results obtained on the scale of total bacterial and fungal communities, the stimulation of mycorrhizal communities appears to be a noteworthy result meriting further investigation. By the same token, analysis of networks of microbial interactions on these roofs opens up promising research avenues. This work also illustrates that roofs are such specific environments that analytical tools developed using benchmarks based on “natural” soils cannot be used. In other words, it shows the need for benchmarks that are specific to these environments in order to assess their ecological quality.

ENDOMYCORRHIZAE ON GREEN ROOFS

By Laurent Palka and Yves Bertheau,
French National Museum of Natural History

Mycorrhizae are the result of co-evolution between a microscopic fungus and a root. There are five different types, the most important of which are ectomycorrhizae and endomycorrhizae. Ectomycorrhizae are external structures that surround the root, while endomycorrhizae are found inside the roots. In the framework of GROOVES, Laurent Palka and Yves Bertheau, researchers at the French National Museum of Natural History, focused on endomycorrhizae, which are the most frequent structures among plants as they affect 72 % of angiosperms, mostly herbaceous plants. Endomycorrhizae (phylum Glomeromycota) form the basis for intense interactions thanks to a symbiotic relationship where the fungus provides the plant with water and nutrients. Water and minerals are taken up into the above-ground parts of the plant and foster the production of plant biomass, helping the plant resist different kinds of abiotic stress such as drought. In return, the fungus recieves up to 20 % of the nutrients produced by the plant during photosynthesis.

Green roofs are characterised by various kinds of abiotic stress affecting plants such as limited space, shallow substrate, leaching of minerals, lack of mineralisable organic matter, large temperature swings and too much or too little water. With the exception of certain xerophytic species that are able to colonise such areas, plant species must thus resist these multiple stress factors. Associating with mycorrhizogenic fungi can help them do this, and thus helps to diversify species in these ecosystems. One study has shown, for instance, that when *Medicago truncatula* (barrelclover) experiences a constant 1,5 °C increase in nighttime temperature, it produces significantly more flowers, more seeds, and a greater biomass of stalks and roots when in the presence of the arbuscular fungus *Rhizophagus irregularis,* and limits the effect of the increase in air and soil temperature. The literature tells us that that the presence of highly diverse Glomeromycota increases plants' chances of resisting several kinds of stress.

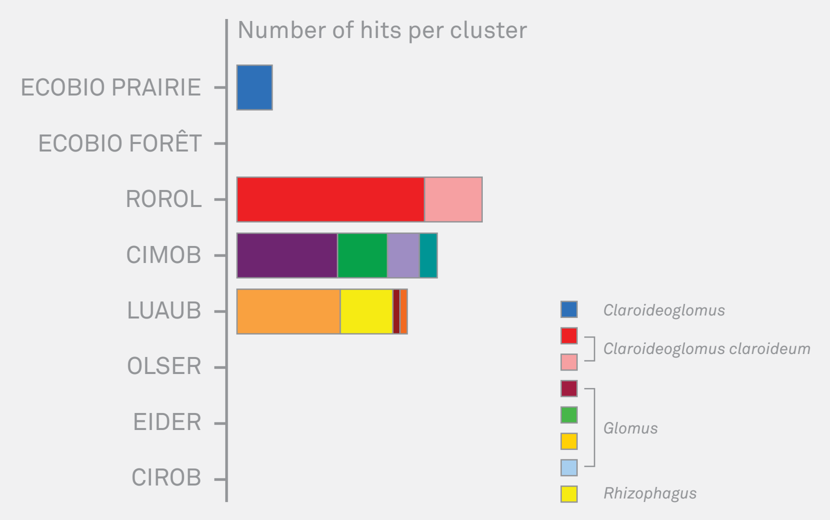
A high specific diversity of Glomeromycota will thus help to maintain herbaceous plants on a roof. The main aim is thus to determine the specific diversity of Glomeromycota on the sample roofs and to extrapolate a corresponding map for the Paris Region.

As part of GROOVES, Glomeromycota taxons are identified thanks to DNA extracted from roots, amplified by PCR. Amplified sequences common to eukaryotes are tested using specific Glomeromycota primers. The sequences of the amplified fragments are then compared with those of the Glomeromycota. A genus is identified for a sequence similarity of between 90 % and 95 %, while a species is identified when the sequence similarity is at least 97 %.

In 2017, root samples were taken from 9 green roofs (ECOBIO PRAIRIE, ECOBIO FORÊT, ROROL, FONTA, CIMOB, LUAUB, OLSER, EIDER and CIROB). Glomeromycota were identified for 8 roofs, the FONTA roof returning negative results. Just 4 sequencing passes produced enough sequences assignable to the genuses Claroideoglomus (on ECOBIO PRAIRIE and ROROL), Glomus (on CIMOD) and Rhizophagus (on LUAUB). Species assignment was only possible for ROROL, where the dominant species is C. claroideum.

The roots from two roofs (ECOBIO and ROROL) seem to present a less rich and diverse array of fungal taxons than the other two roofs (CIMOB and LUAUB). Differences seem to exist from roof to roof: Rhizophagus is only present on LUAUB, Claroideoglomus on ECOBIO PRAIRIE and ROROL. We now need to attempt to correlate these differences with biotic factors (plant species present, fungal taxons in nearby grassy areas, comparison of taxons in roots and substrates, etc.) and abiotic factors (origin, depth and nature of substrates, etc.). In the light of these preliminary results, we need to carry out the sequencing again in order to: 1) refine the results until species assignment is possible; 2) add in missing amplified DNA. It will also be of interest to compare Glomeromycota taxons associated with roots (Palka and Bertheau's results) with those present in the substrate (Ranjard and Maron's results) to find out if their presence in substrate necessarily implies their association with roots.

FIGURE 28 Diversity of endomycorrhizae found in plants varies greatly between sites. © Laurent Palka and Yves Bertheau - MNHN



Marc Barra and Laurent Palka collecting roots for analysis of endomycorrhizae from the roof of the school on Rue Eider in Paris. © Maxime Zucca | ARB îdF

Paris Habitat social housing
in the 15th arrondissement in Paris.
© Marc Barra | ARB îdF

#6

WATER RETENTION CAPACITY OF GREEN ROOFS

Alternative rainwater management techniques are becoming increasingly popular among local authorities coping with surges in runoff. They rely mainly on the use of open ground and direct infiltration into the soil and involve creating multiple planted areas and rehabilitating wetlands and watercourses.

In densely populated urban areas, available land is increasingly scarce and storing rainwater on the roofs of buildings, as a complement to other systems, can be a useful solution.

To gain a better understanding of the parameters that influence water retention on green roofs and to assess the storage potential of roofs during rainfall events, several analyses have been carried out based on the study of substrates.

ASSESSMENT OF WATER RETENTION

PROTOCOL

Maximum Water Retention or MWR (at Maximum Water Capacity or MWC) is obtained in the laboratory by mass differential [FLL protocol]. The substrate sample is compacted into a cylinder, saturated with water and allowed to dry out for 2 hours. MWR is the difference between the mass after drying and the mass before saturation. There is a protocol defined by ADIVET to determine MWR and other MWC measurements [21]. These measurements require almost 20 litres of substrate. We felt that such a sample, as well as causing significant damage in the eyes of those responsible for managing the roofs, would be very harmful to small, shallow roofs. We thus agreed with Aurea that a minimum volume of 4 to 5 litres would be sufficient to carry out all the physico-chemical, biological and physical measurements. In return, the MWC measurements were carried out twice. The other analyses were carried out once and repeated if the values were aberrant. Water retention on each roof is obtained by measuring water retention per unit of surface area (L/sq.m.) and total water retention (L/roof).

Substrate depth, composition, grain size and texture all influence the water retention capacity of green roofs.
© Audrey Muratet | ARB îdF

Several variables can affect the water retention capacity of green roofs. Some depend directly on the substrate (its depth, composition, grain size or texture), while other factors such as plant biomass can also affect water storage potential. The results obtained in the laboratory show that "agricultural soil" and "mixed" substrates can store more water than "mineral" substrates owing to their composition (percentage of clay, organic matter content, etc.) and structure (grain size, porosity, etc.). For the same volume of substrate, intensive roofs hold more water than extensive roofs: MWC is 49.5 % compared to the average of 37 %. These differences can be explained by the fact that extensive roofs possess a higher level of macroporosity and thus hold more air than water. This is more variable for "mixed" substrates whose composition is more heterogeneous.

The relationship between substrate depth and maximum water retention capacity allows us to estimate the theoretical volume of water that different green roofs are able to retain. We observe significant variations between the least absorbent roof (CD 93 with 6 L/sq.m., Mineral substrate, 3.5 cm deep) and the most absorbent (Ecobio_Bois with 532 L/sq.m., agricultural soil substrate, 100 cm deep). For effective water retention, it is essential to take substrate depth into account at the design stage. The values calculated indicate, in theory, that there is a threshold at 25 cm beyond which the retention capacity of green roofs increases significantly. However, these values are theoretical and presuppose that the roofs are totally dry before rainfall. Moreover, rainfall frequency is not taken into account and the role of vegetation in absorption is not assessed. These purely mathematical calculations thus have quite a large margin of error.

To enrich these initial results and include parameters that were previously ignored (type of vegetation, amount of rainfall), the FAVEUR model, developed by Cerema to estimate the impact of green roofs on urban runoff, was applied [22]. The model makes it possible to estimate water retention capacity of roofs while taking into account biogeographical climate, substrate depth, maximum water retention capacity and vegetation. The model simulates the average hydric efficiency of each roof based on several years' meteorological data collected by Cerema. The model thus makes it possible to predict the maximum rainwater retention capacity of each roof. The results confirm the trend previously observed, with values ranging from 200 to 500 mm of runoff retained per year and per roof (1 mm of rain corresponding to 1L/sq.m.). These values may be useful to anticipate the need to manage rainwater on the scale of a development project. In the Paris Region, the Seine Normandie water authority considers that all planted developments must at least be able to cope with "ordinary" rainfall, i.e. 8 mm runoff in 24 hours. According to these calculations, this corresponds to a substrate depth of 8 cm, which is the minimum depth required to qualify for subsidies for planting in the framework of rainwater management initiatives.

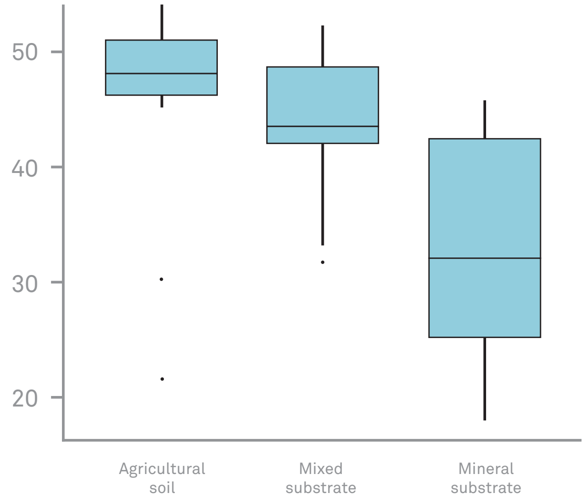


FIGURE 29 Maximum water retention capacity according to substrate type. © ARB îdF

Putting these values into perspective with regard to an average rainfall of 48 mm in 4 hours observed over a ten-year period shows that only 5 roofs out of 26 are able to regulate this kind of extreme event (CIROB, FRANK, ALBAR, OLSER and PULMA). All are covered in agricultural substrates to a depth of nearly 30 cm. The FAVEUR tool suggests that the high water retention capacity threshold is around 30 cm, and that the threshold for medium retention capacity is between 10 and 30 cm.

These results may be useful for local authorities in the framework of climate change adaptation strategies. These municipalities can partially rely on planted roofs in priority areas (in terms of runoff) by adapting the substrate to their water retention needs—in other words by defining the nature and depth of the substrate according to the available plantable surface area.

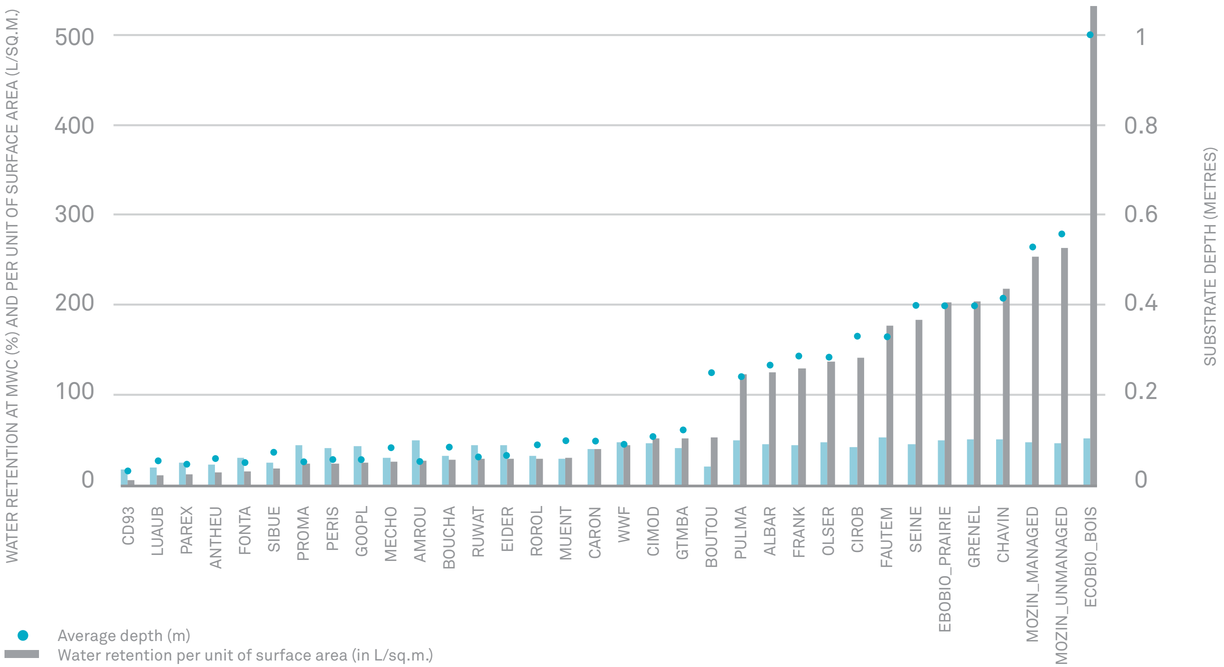


FIGURE 30 Evolution of theoretical water retention capacity depending on substrate depth. © ARB îdF

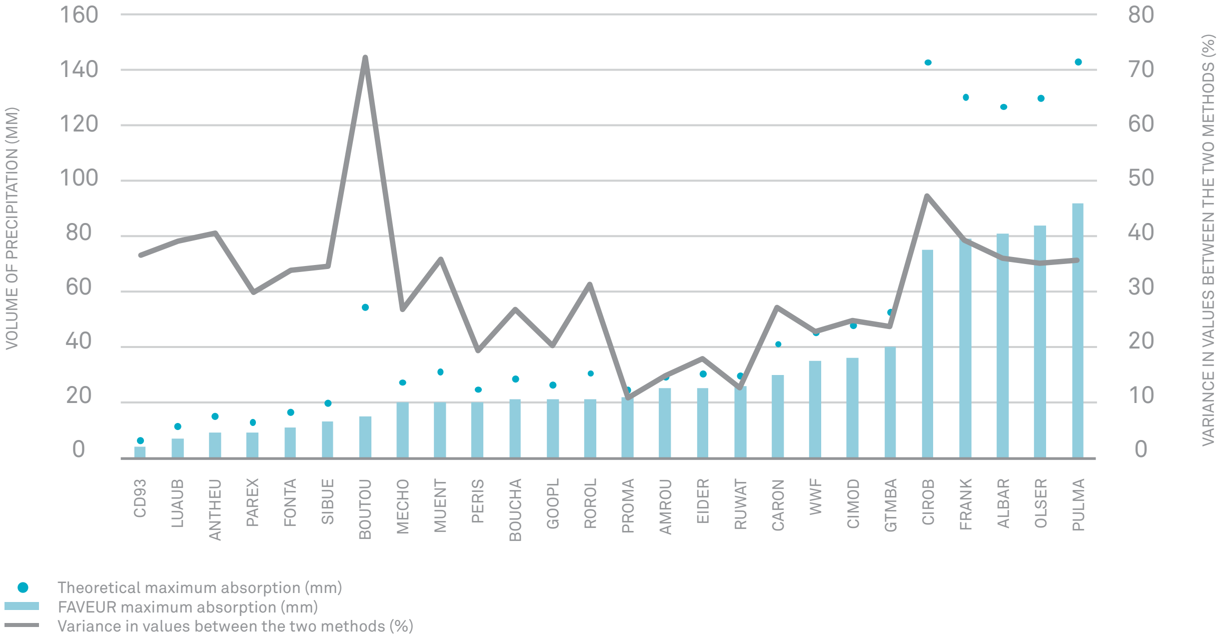


FIGURE 31 Comparison of theoretical water retention potential (calculated using the physico-chemical parameters of the substrate) and retention according to the FAVEUR model developed by Cerema. © ARB îdF - Cerema

Roof of the school of Boutours in Rosny-sous-Bois. © Audrey Muratet | ARB îdF

The roof of La Seine Musicale in Boulogne-Billancourt has a water retention capacity of about 184 L/sq.m. © Audrey Muratet | ARB îdF

Sometimes you come face to face with an earthworm!
Roof of the Cinéma Robespierre in Ivry-sur-Seine
©Marc Barra | ARB îdF

#7

THE COOLING EFFECT OF GREEN ROOFS

Temperatures in cities are generally higher than in the semi-urban or non-urban areas around them: the term “urban heat island” is used. In the Paris Region, sharp contrasts have been observed between the inner suburbs and the countryside, especially in summer and at night (e.g. a difference in minimum temperatures of up to 8 - 10 °C during one heatwave in Paris). Several studies confirm the role of plants in cooling urban areas. As part of his thesis on green roofs, Yann Dusza presents the results of several research projects that show the real cooling potential of such roofs [12].

However, the effect that the partial greening of cities would have on heat islands is trickier to estimate. Bass et al. (2002) modelled the effects of planting 50 % of the roofs in Toronto using sedum-type extensive systems and predicted an overall reduction in temperature of 1 °C. Irrigating the roofs would lead to a 2 °C drop. Smith and Roebber (2011) modelled the impact of planting all the roofs in Chicago and estimated that a reduction of 2 - 3 °C in the city’s ambient temperature would be feasible in hot weather. As part of the GROOVES study, David Ramier, a researcher at Cerema, took on-site measurements of the cooling potential of several green roofs selected according to their typology.

ASSESSMENT OF EVAPOTRANSPIRATION POTENTIAL

In order to test the hypothesis of cooling generated by green roofs, evapotranspiration was measured by members of the Cerema team (David Ramier, Walha Riahi, Rémi Val, Jean-François Durmont and Emmanuel Berthier) on 13 green roofs from the sample in June and October 2018. An evapotranspiration chamber was used to take the measurements. The principle is to assess the variation in humidity winside an enclosed space in order to deduce its evapotranspiration level. The chamber is a Plexiglas box 30 cm deep covering a surface area of 1 sq.m. A metal rim ensures that the box is relatively airtight when placed on the ground. Humidity inside the chamber is measured using a gas analyser. Temperature and net solar radiation are also measured inside the chamber in order to check possible modifications to these parameters while it is being installed.

The chamber is set up for 2 minutes, and only the measurements taken during the first minute are used to calculate evapotranspiration.

For the GROOVES project, measurements were taken every hour for one day on 13 roofs in 2018 and 13 roofs in 2019. The roofs were selected for their accessibility, their substrate depth (3 - 56 cm) and the type of vegetation (grasses, sedums, or a mixture of both). In 2018, evapotranspiration measurements were carried out in two seasons, in summer (June and July) and autumn (October). Three of the roofs monitored in 2018 were also measured in 2019 (FAUTEM, BOUTOU and ECOBIO). In 2019, measurements were only taken between June and July.

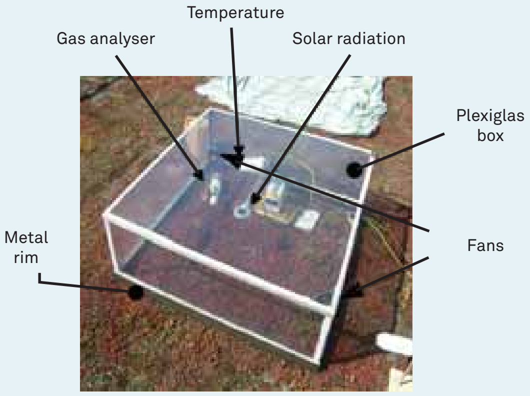


FIGURE 32 Cerema evapotranspiration chamber. © Cerema

Two or three areas were chosen on each roof in order to observe how evapotranspiration levels vary according to differences in vegetation. During the evapotranspiration process, the consumption of energy to transform the water into vapour makes it possible to limit increases in surface temperature, to increase the humidity of the air, and also to lower the temperature of the surrounding air, which then locally cools the atmosphere. The presence of vegetation on roofs fosters evapotranspiration and can thus contribute to urban cooling. Experimental monitoring has shown, for example, that green roofs make it possible to evapotranspire between 50% and 70% of annual rainfall. As evapotranspiration is very variable according to the type of planting and varies in the course of a single day, further measurements are still required. The GROOVES project made it possible to carry out measurements on a varied selection of green roofs.

Evapotranspiration will depend on the energy received on the surface, the capacity of the air to absorb humidity (the difference between the quantity od water vapour in the air and the quantity of water vapour at saturation in equivalent conditions of temperature and pressure) and windspeed (the wind being a vector for transporting humidity). Climatic conditions will define the quantity of water that is potentially evapotranspirable. Real evapotranspiration will, on the other hand, be limited by the availability of water in the substrate and the capacity of the soil and plants to transfer this water to the atmosphere due to aerodynamic and stomatic resistance. The latter relates to the development of the vegetation: leaf size, stage of growth, etc.

The quantity of evapotranspired water can be expressed as an energy flow (LE, in W/sq.m.) or as a hydric flow (E, in mm/hr, for example, with 1 mm/hr ≈ 680.5 W/sq.m.)

FIGURE 33 Evapotranspiration measurement points. © Cerema

The photos of measurement points in Figure 33 show the spatial and temporal variability of the areas that can be observed, even on a single green roof. Figure 34 presents rainfall before and during the measurements. The rainiest period was the one preceding the measurements taken in June-July 2018. The subsequent measurement period was quite dry, with no rainfall the week before the measurements were carried out (note that during the measurements on FAUTEM, on 05/07/18, 0,4 mm of rain was recorded). During the measurements of October 2018, total rainfall was low (12.7 mm) in the month preceding the measurement on PERIS on 10 October 2019. Rain last fell 3 days before the measurement. 2.2 mm of rain fell during the night following the measurement on FAUTEM, and no rain fell during the week before the measurements on BOUTOU and ECOBIO.

For the measurements carried out in 2019, 45 mm of rainfall was recorded 30 days before the first measurements, on 18 June 2019. 6 mm of rain fell on the two following days, then none was recorded until 18 July. This means that except for SEINE, where it rained on the previous day, all the measurements were taken after several rainless days (3-27 days without rain). Most of the evapotranspiration measurements were thus carried out in hydric conditions that are not particularly conducive to evapotranspiration. Overall weather conditions in the Paris Region are presented in Figure 35.

While microclimatic conditions on the roofs may be locally different from the values presented (possible shade in particular for FAUTEM and PERIS, local cloud, wind circulation modified by urbanisation), the measurements were generally taken on warm, dry, sunny days. Maximum temperatures during the measurements are generally higher than 25 °C and sometimes (as in 2019) higher than 30 or even 35 °C. Minimum humidity is generally lower than 50 % and even 40 % on some days. Overall solar radiation is generally higher than 800 W/sq.m. and the very smooth shape of the daily cycles indicates an absence of cloud, with a few exceptions. On 5 July 2018 during measurements on FAUTEM there was some cloud (rain was recorded that day), which also meant lower solar radiation, lower temperatures and higher relative humidity. In 2019, some cloud was also observed during measurements on FAUTEM, CIMOD and PAREX, which matches observations made locally while the measurements were being carried out.

When the measurements were taken in autumn 2018 there was a similar amount of sunshine but solar radiation was lower—around 500 W/sq.m.—, and recorded humidity and temperature were slightly different in mid- and late October.

Hydric conditions were thus not very conducive to evapotranspiration, while climatic conditions tended to promote evapotranspiration.

Climate and hydric conditions influence the cooling capacity of green roofs. “Mozinor” logistics building, Montreuil.
© Audrey Muratet | ARB îdF

FIGURE 34 A, B ET C Daily rainfall during the month preceding the different measurement periods and during those periods (in blue, source infoclimat.fr, Paris-Montsouris station). The orange bars represent days on which evapotranspiration was measured. © Cerema

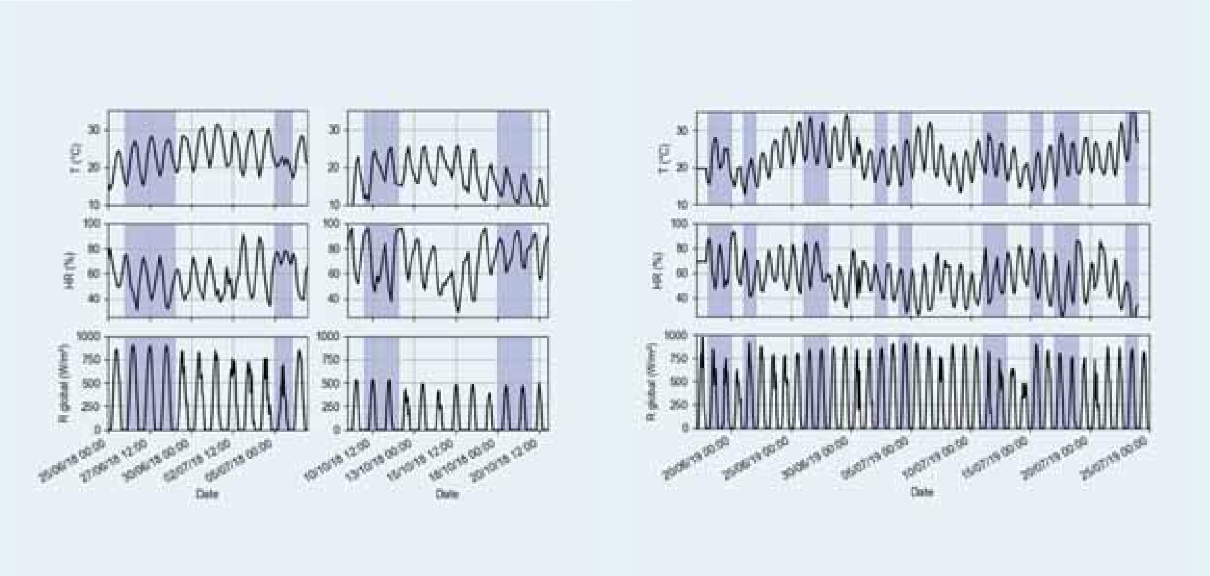


FIGURE 35 A ET B B Temperature (T), relative humidity (RH) and overall solar radiation (SR) during evapotranspiration measurements in 2018 and 2019 (blue shaded areas indicate measurement days).
Sources: Météo-France, Orly station for temperature and humidity and Roissy for overall solar radiation. © Cerema

Evapotranspiration values and variability

Figure 36 shows the maximum value of evapotranspiration obtained for each roof during the daily measurement sessions. The measurements carried out on the roofs are highly variable. The maximum values measured during the daily sessions vary from 0.01 mm/hr on MUENT (about 7 W/sq.m.) in July 2019 and 0.28 mm/hr (190 W/sq.m.) obtained on ECOBIO in June 2018. In autumn 2018, the lowest maximum daily evapotranspiration was 0.02 mm/hr on PERIS (14 W/sq.m.)—slightly higher than on MUENT in July 2019.
For only 6 of the 14 roofs studied (BOUTOU, ECOBIO, FAUTEM, PULMA, SEINE and CIROB), maximum evapotranspiration values higher than 0.15 mm/hr (about 100 W/sq.m.) were measured. All these roofs are classified as semi-intensive or intensive, which seems to confirm the importance of substrate depth and type of vegetation.

Sedums take root in the tiniest cracks along the top of the wall. School of Science and Biodiversity, Boulogne-Billancourt.
© Audrey Muratet | ARB îdF

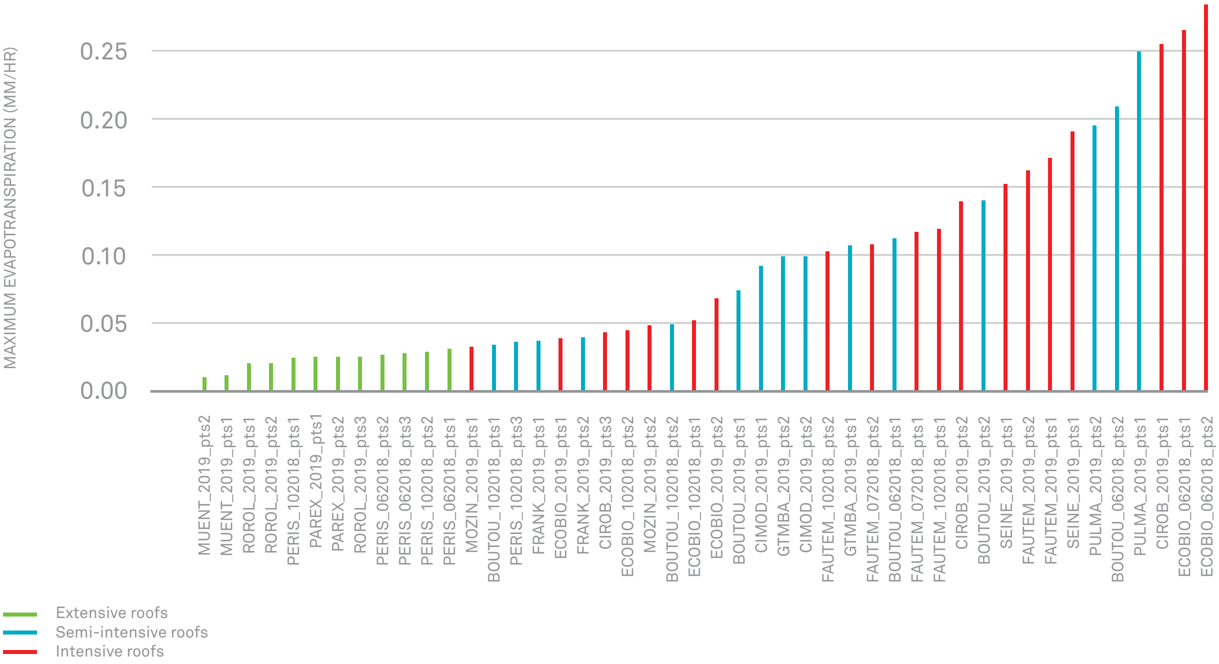


FIGURE 36 Maximum evapotranspiration obtained on each roof. © Cerema

Effects of vegetation

However, even for these semi-intensive and intensive roofs, evapotranspiration will depend on the state and nature of the vegetation. Figure 37 shows that for CIROB, evapotranspiration can be 6 times greater at points where vegetation is more highly developed.

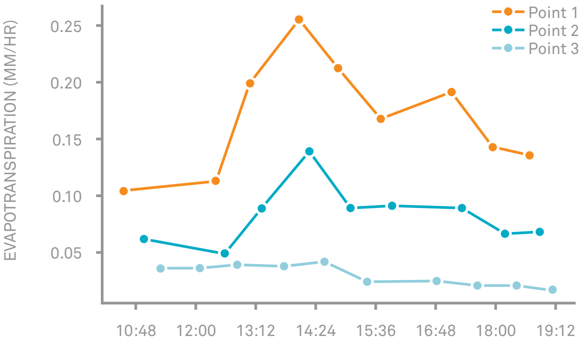


FIGURE 37 Daily evapotranspiration cycle measured in three different places on CIROB roof, 4 July 2019 © Cerema

The state of the vegetation on FRANK and MOZIN at the time of the measurements probably explains why, although they are classified as semi-intensive and intensive roofs, measured evapotranspiration was low (less than 0.06 mm/hr).

Effect of water availability

The state of the vegetation is highly dependent on hydric conditions; FRANK and MOZIN suffered a long dry period before the measurements. Even for deep substrates (up to 50 cm for Mozin) with no water and vegetation undergoing hydric stress, evapotranspiration will be very low, reaching a similar level to that observed on extensive roofs.

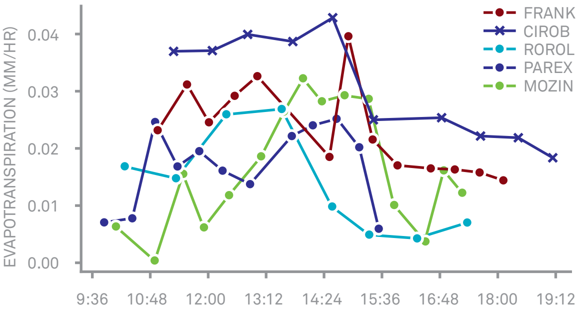


FIGURE 38 Daily evapotranspiration cycle measured on different green roofs after 12 - 27 days without rain
(FRANK – point 2, 2 July 2019; CIROB – point 3, 4 July 2019; ROROL – point 2, 11 July 2019 ; PAREX – point 1, 12 July 2019, MOZIN – point 1, 17 July 2019).
© Cerema

Lack of water can have long-term effects. For ECOBIO in 2018, total rainfall in the month preceding the measurement was 168 mm (including 78 mm by 11 June: 16 days before the measurement); there was no rain at all during the 8 days preceding the measurement. However, maximum evapotranspiration was rather high (around 0.28 mm/hr, the highest value recorded on any of the roofs).

By contrast, for the same roof in 2019, the period preceding the measurements was drier: there was only 6mm of rainfall over the preceding 30 days. Although this rain fell in the 5 days preceding the measurement, recorded evapotranspiration was 4 times lower than in June 2018. Evapotranspiration values measured in July 2019 were quite close to those obtained in October 2018.

The different state of the vegetation (Figure 33) between June 2018 and July 2019 clearly shows the effect of lack of water on vegetation.

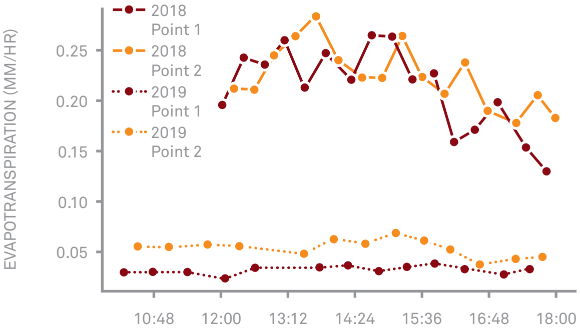


FIGURE 39 Daily evapotranspiration cycle at the two spots on the ECOBIO roof in 2018 (27 June: unbroken line) and 2019 (23 July, dotted line). © Cerema

Maxime Zucca can enjoy the view from the roof of the Romain Roland media library in Romainville. @ Gilles Lecuir | ARB îdF

Potential effect on urban cooling

The presence of vegetation may have an effect on cooling because of the use of energy available on the surface, which limits increases in surface temperature and heat transfer towards the atmosphere. Available surface energy is estimated using net solar radiation (Rnet, which is the total solar and incident infrared radiation reflected back into the atmosphere). It is thus supposed that the more net radiation is used for evapotranspiration, the higher the local cooling effect will be on the roof. Figure 40 presents the average relationship between evapotranspiration and net radiation at each measurement point on each roof.

The six roofs with the highest levels of evapotranspiration (BOUTOU, ECOBIO, FAUTEM, ULMA, SEINE and CIROB) are thus also the ones that "use" the greatest amount of net radiation (20 % - 47 %). Depending on the characteristics of the roofs, this relationship is very variable, even on a single roof. For FAUTEM, for example, where maximum evapotranspiration was observed when measurements were made in July 2018, a little less than 25 % of net radiation was used. But when measurements were taken on 11 October 2018—when evapotranspiration was at its lowest—, an average of 47 % of net radiation was used. This can be explained by the relatively fine weather that day: it was sunny, the air temperature was over 25°C and relative humidity was very low for the season with a minimum of 40 %. These climatic conditions were better than those of 18 June 2019, another day on which measurements were made on FAUTEM.

The weather conditions in October 2018 were similar for PERIS on 10 October 2018, for which the LE/netR ratio was also greater on that day than in June 2018 on the same roof. However, the characteristics of the roof (sedums, 6 cm of substrate) meant that less available energy was used for evapotranspiration and thus the effect on cooling may also have been less significant.

These measurements confirm that green roofs can help cool the atmosphere via evapotranspiration, as other studies have demonstrated. However, as this phenomenon is highly variable, these few ad hoc measurements, although they highlight trends relating to the characteristics of the roofs being studied, do not allow us to quantify their contribution completely.

It has nonetheless been observed that an appropriate choice of substrate and vegetation makes it possible to obtain green roofs that are more conducive to evapotranspiration. However, evapotranspiration on such roofs is quickly limited by the availability of water (even for intensive roofs). Their efficiency could thus be very limited during heatwaves with very low rainfall. On the scale of a city, the contribution to urban cooling by roof-dwelling vegetation must be seen as complementary to other practices, and all available surfaces (roofs, façades, the ground, etc.) must be used. Sufficient available water in soils or substrates is also required.

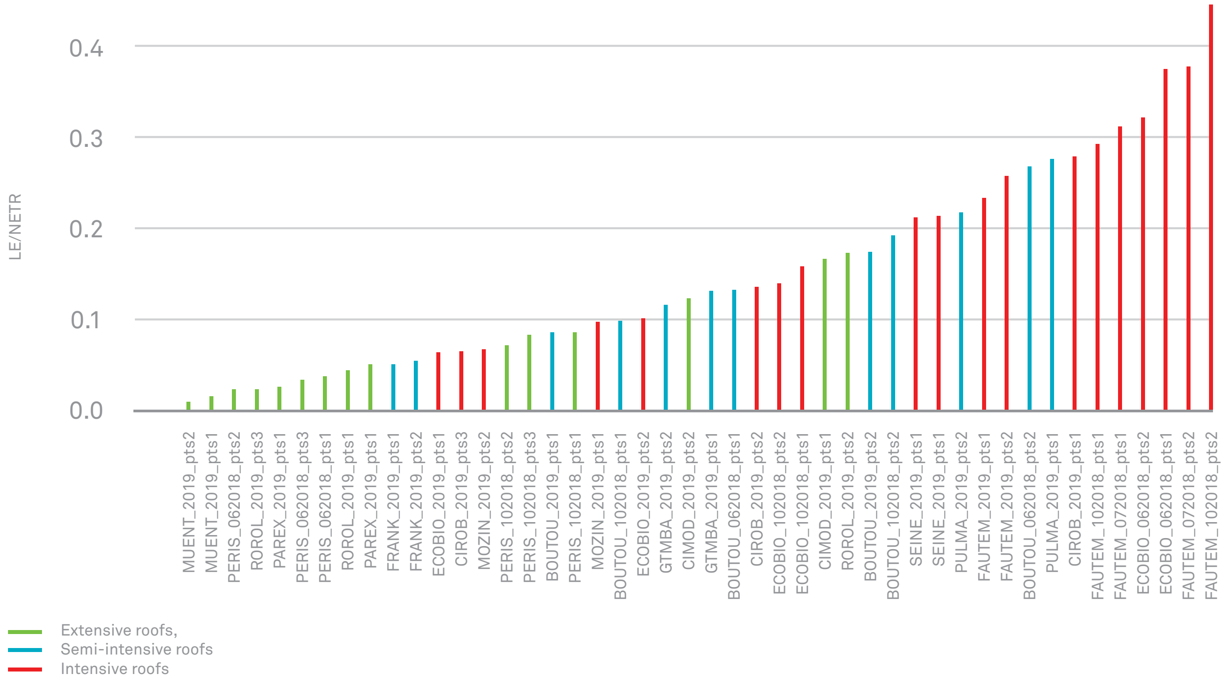
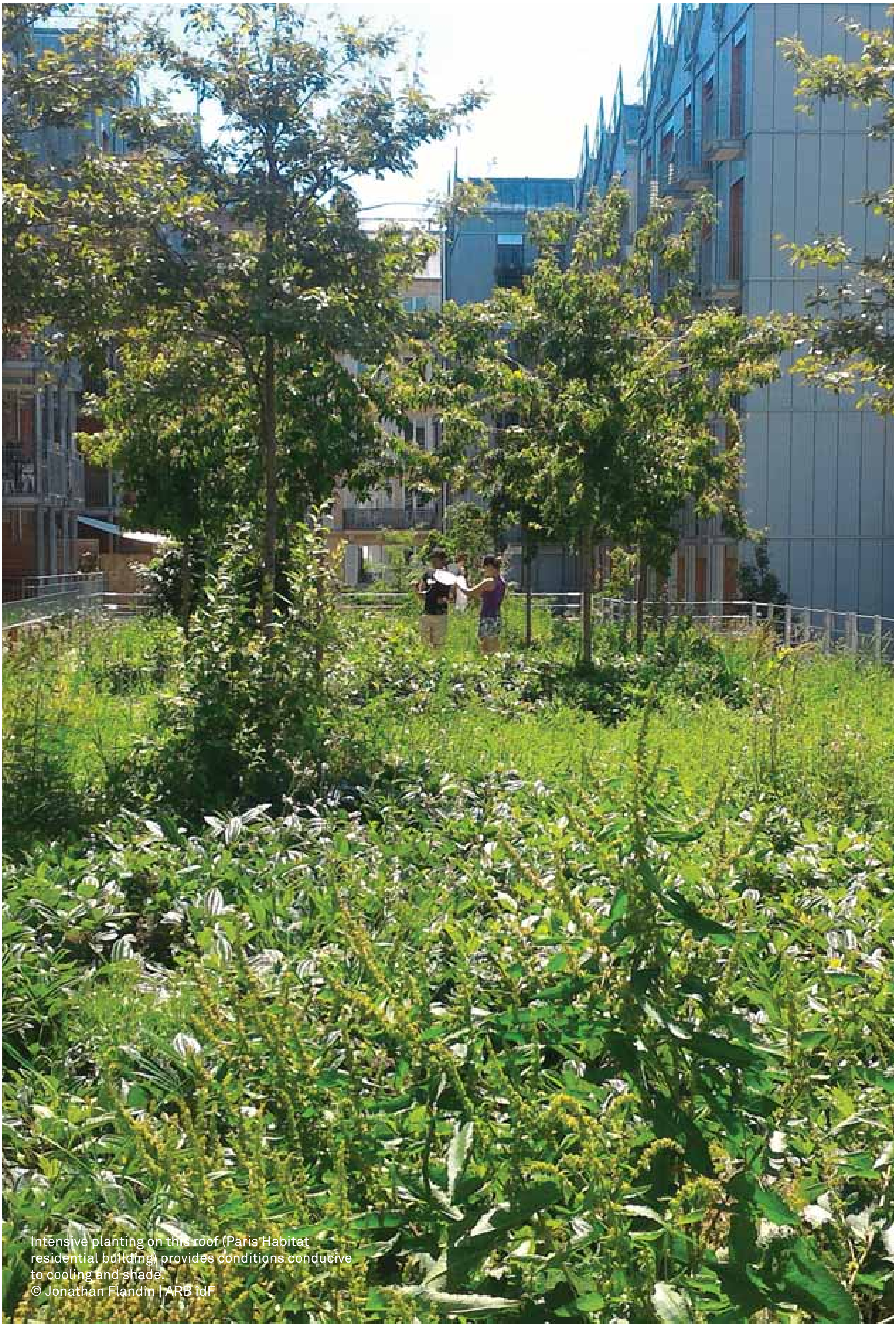
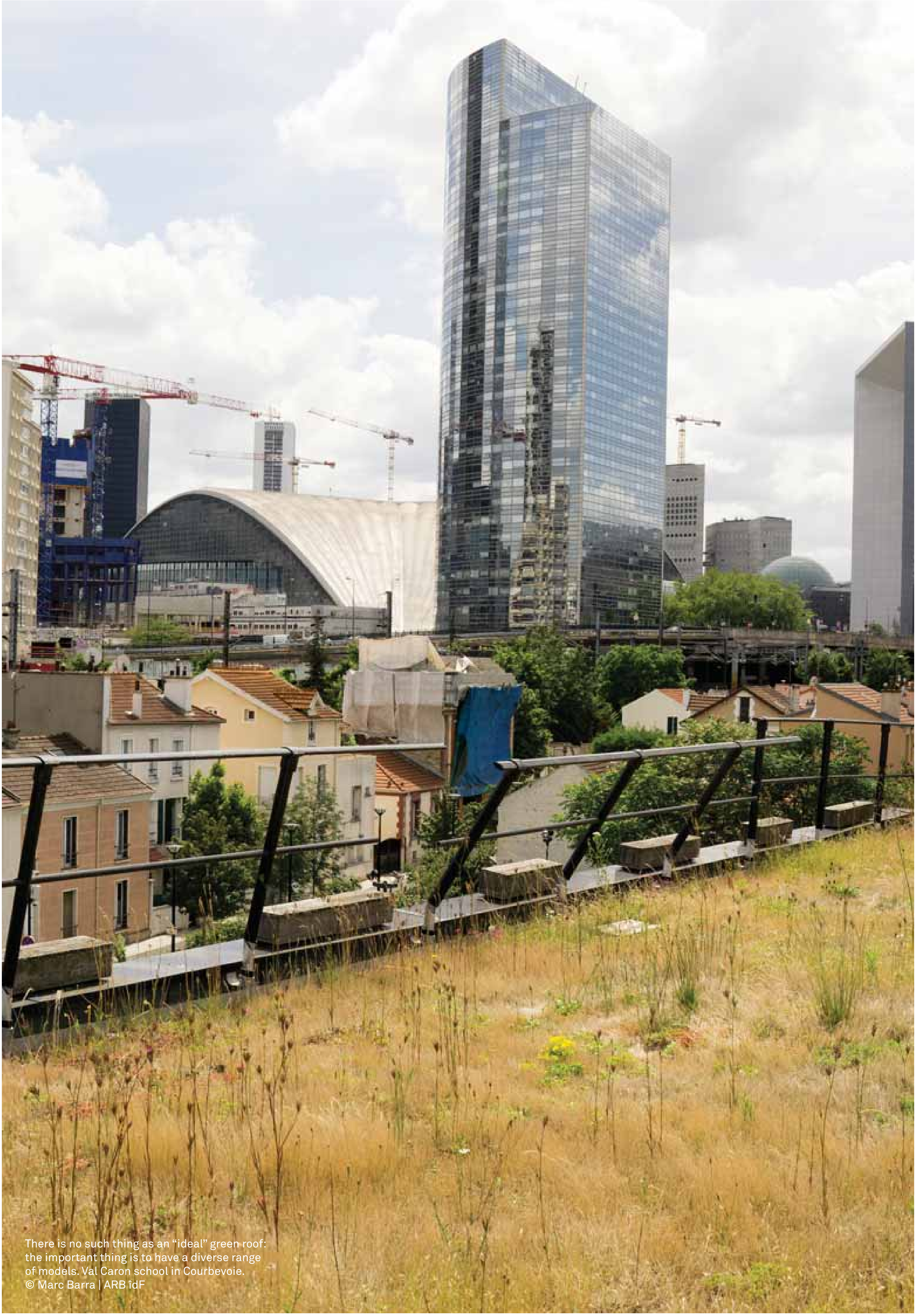


FIGURE 40 Average ratio between evapotranspiration (LE) and net solar radiation (netR) for each measurement point on each roof (the ratio between LE and netR is calculated for each hour of measurement, and then an average of this ratio is calculated for each measurement point on each roof). Extensive roofs are in green, semi-intensive roofs are in blue, and intensive roofs are in red. © Cerema



Intensive planting on this roof (Paris Habitat residential building) provides conditions conducive to cooling and shade.
© Jonathan Flandin | ARB îdF



There is no such thing as an "ideal" green roof: the important thing is to have a diverse range of models. Val Caron school in Courbevoie. © Marc Barra | ARB îdF

#8

DEVELOPING
DESIGN AND MANAGEMENT

While green roof designs vary greatly from country to country, industrial solutions have rapidly spread throughout the world. Sedum roofs manufactured using standardised processes (pre-grown trays or rolls) are now the most widespread.

However plants or artificial components are processed for use on roofs, it is useful to assess the ecological footprint of these systems, whose widespread use can have indirect impacts on the environment.

WHAT THE GROOVES STUDY TELLS US

With GROOVES, ARB îdF and its scientific partners wanted to improve their understanding of how green roofs function in order to provide designers and managers with advice. Given the extent of possible analyses, these initial conclusions merely serve to open a window onto the subject.

Because of their height above ground, their small surface areas or restrictive urban conditions such as pollution and heat, roofs might easily appear to be inhospitable environments for living organisms. GROOVES shows, however, that species demonstrate an astonishing capacity for adaptation and colonisation in these new urban ecosystems, which can serve as substitute habitats or refuges that complement other urban green spaces.

RECOMMENDATIONS FOR IMPROVED DESIGN

As is so often the case in ecology, the results show that there is no “ideal recipe” but that recommendations vary according to the group of species, the analysis criteria, the geographical location, etc. Where substrate depth is concerned, we observe that floristic diversity reaches a threshold at around 30 cm deep, whereas diversity among pollinators continues to increase beyond this threshold. A “mixed” or “agricultural” substrate with at least 10 % clay, 60 % sand and a depth of about 30 cm will be more able to support the development of a specifically diverse range of species and will retain rainwater more effectively.

If we turn our attention to mosses and lichens, it turns out that “sedum roofs” are richer than other types of roof. The reverse is true of floristic diversity, which is greater on semi-intensive and intensive roofs than on extensive sedum roofs. However, as we have said, Biodiversity cannot be reduced to the number of species in a particular environment: particular combinations of species and degrees of rarity matter just as much when defining a suitable environment. Often criticised for their low number of species, sedum roofs host a particular combination of species (plants that thrive in dry environments and/or travelling plants), and this makes them into special habitats. Nonetheless, some remain too artificial in terms of their composition because they make use of pre-grown solutions that tend towards standardisation. These observations help us to understand the value of diversifying roof types and designs on the scale of a district, town or city.

The way plants are packaged has not escaped industrialisation, which tends to standardise products for sale.
© Marc Barra | ARB îdF

The results of GROOVES converge with a study carried out between 2014 and 2016 by the Haute Ecole du Paysage, de l'Ingénierie et de l'Architecture (Hepia) in Switzerland on thirty green roofs in Geneva [23]. Analysis of vegetation has shown that “intensive roofs have a higher coverage rate and specific diversity in terms of vascular species. Extensive roofs are home to more threatened species and fewer invasive neophytes”. Half of the flora recorded is spontaneous. Where fauna is concerned, it seems that intensive systems are more conducive to the establishment of animal species. The benefits of a green roof for biodiversity depend on a deep substrate (> 12 cm) of variable depth with several different plant strata. The rainwater retention properties of green roofs have also been confirmed. In the light of Yann Duzsa’s thesis (IEES-Paris), it is clear that we cannot expect green roofs to provide all the solutions, be it in the realm of hosting biodiversity, water management, cooling or pollination. On the other hand, it is possible to design and manage green roofs in such a way as to optimise some of these functions according to their location or the goals of the local authority. These new ways of taking biodiversity into account are also reflected in rules on planted roofs for landscaping professionals established by the Union Nationale des Entreprises du Paysage, with special attention paid to ecological aspects and biodiversity.

The way plants are packaged does not escape industrialised processes that tend to standardise products for sale. Most green roofs are sold in the form of plants that have been pre-packaged, in nurseries or factories, in boxes, trays or pre-grown rolls. These are assembled directly on the roof, as is the case with 10 of the roofs in the GROOVES study. Other design methods more akin to landscaping techniques involve planting micro-plugs directly in the substrate (7 roofs) or sowing or planting seedlings (14 roofs). The less common practice of hydroseeding was used on 2 of the roofs studied. It involves mixing an emulsion on the ground containing water, seeds, fertilisers and primers in order to rapidly create plant cover. Last but not least, wildroofs require no planting: vegetation grows there spontaneously as seeds are brought by the wind or by animals.

Other roof designs inspired by natural habitats could be imagined (dry grassland, sandy habitats, Mediterranean environments, etc.). It is also possible to opt for local species better adapted to local climate conditions, taking inspiration from nearby environments to create the green roof (e.g. using locally sourced substrate, planting wild seeds collected nearby, etc.) or to use short supply chains, as does the "Végétal Local" programme run by Plante & Cité. Following the GROOVES study, the green roof of the School of Science and Biodiversity in Boulogne-Billancourt is currently being reseeded by scattering hay and seeds (meadow sage, meadow brome, quaking grass) gathered in a nearby meadow. The Chartier Dalix architecture firm and the ecologist Aurélien Huguet, who initiated this operation, want to encourage the development of a larger proportion of local perennial flowering species adapted to the conditions of the site.

The origin of the substrates is not known for all the roofs. Further investigation might allow us to trace their source, but this is not always easy given the age of certain roofs and the difficulty of gaining access to certain commercial compositions. Increased demand for green roofs (and consequently substrate) raises the question of their mode of production. This is the case in particular for roofs that use agricultural soil, which is mostly sourced by stripping fertile topsoil from fields and thus causes negative impacts elsewhere. Opting for recycled substrates (excavated earth from building sites, mixtures of excavated earth and crushed stone, compost) seems to be the way to go in future in order to reduce the ecological footprint of green roofs.

Ophélie Ricci and Amandine Gallois busy looking for invertebrates on the roof of a childcare facility in Paris. © Audrey Muratet | ARB îdF

RECOMMENDATIONS FOR IMPROVED MANAGEMENT

Management of green roofs may entail checking watertight seals, removing undesirable woody plants, or taking action to comply with the manager's aesthetic requirements. It is also possible to avoid maintaining them and to allow biodiversity to flourish—if the roof design allows this and if the manager accepts the presence of spontaneous flora. 21 of the 34 roofs roofs studied in GROOVES are unmanaged. Interventions on managed roofs vary: scything, mowing (observed on one roof), and even mulching. As is the case for green spaces, the management of urban ecosystems is often associated with a particular organised vision of nature that has no ecological justification. Constant intervention is unnecessary; one or several visits per year to weed out woody plants is enough for the long-term maintenance of a roof.

Overintensive management may have a negative impact on floristic diversity and cause excessive soil compaction. Similarly, it is not necessary to water green roofs on a regular basis. Although certain roofs are chosen for aesthetic reasons, accepting the seasons and the changing colours and appearance of plants reflects a different way of looking at nature.

Allowing vegetation to proliferate and fostering the development of multiple plant strata provide essential support to pollinators and other invertebrates. Moreover, a dense, well-developed herbaceous stratum will improve the roof's capacity for evapotranspiration and water retention. To provide pollinators and other invertebrates with a welcoming environment, creating micro-habitats (dead wood, stones, hollow stems, bare sandy substrate for wild bees, etc.) is a solution that can also increase the attractiveness of roofs provided it is combined with suitable vegetation.

The seasons and the changing colours and appearance of plants are an integral part of the cycles of nature.
Green roof on the headquarters of GTM Bâtiment in Nanterre designed and managed by Topager. © Maxime Zucca | ARB îdF

Dead wood or treestumps can provide additional habitats for wildlife. © Marc Barra | ARB îdF

ECOLOGICAL FOOTPRINT

The aim of green roofs is to benefit the environment. Still today, the market for green roofs all too often uses industrial processes, with planting systems combined with an array of synthetic components such as watering systems, fertilisers, plastic trays, non-biodegradeable geotextiles, etc. These choices can affect the carbon footprint—and the overall ecological footprint—of green roofs.

Green roofs are often sold in the form of factory-packed plants.
A Life Cycle Assessment (LCA) may be necessary to evaluate their overall impact © Marc Barra | ARB îdF

In the framework of the GROOVES study, it was not always possible to trace the roof back to its designer and access the composition of the commercial systems used. We thus recorded the components of the planting systems by direct observation. In addition to the roof sealing complex, which is essential to both the substrate and the plants, green roofs can contain up to four man-made elements. These are mainly plastic trays containing the plants or used as a drainage layer; non-biodegradeable geotextiles, membranes or felt; plastic netting or coir matting; or built-in drip watering systems. If we take the sealing and drainage complex into account, this number can rise to 8 (steam shields; insulating layers; aluminium strips; root barriers). Among the 36 roofs studied in GROOVES, 13 had no man-made components, only substrate and plants, which confirms that it is possible to limit the use of potentially energy-guzzling materials that can leave traces on the roof (e.g. plastic debris left behind when the systems decay—sometimes on very recent roofs). This aspect must not be neglected, especially as these artificial components add to the cost of green roofs. It may be necessary to carry out a carbon footprint assessment or a Life Cycle Assessment (LCA) of the planting systems.

Some planting systems decay and can leave traces behind. Avoiding the use of plastics is more essential than ever in the design of green roofs. © Marc Barra | ARB îdF

Audrey Muratet identifies flora on the roof of a Paris Habitat residential building on the Boulevard de Charonne in Paris. © Ophélie Ricci | ARB îdF

CONCLUSION

The GROOVES study has made it possible to improve our knowledge of green roofs, both in terms of their contribution to hosting biodiversity and the benefits they may provide within the urban environment. The results confirm that talking about the "benefits of green roofs" is insufficiently informative because various design and management methods influence their ecology. By using a sampling process that covers this diversity and implementing specific protocols, the study offers a more accurate view of the performance habitually assigned to green roofs. Rainwater retention, air cooling and carbon storage are services that are taken for granted by designers whose efficiency is, in reality, far from universal. This study confirms that green roofs are attractive in terms of urban biodiversity and can become complementary or even substitute habitats with respect to natural areas at ground level. This biodiversity value has been confirmed for all types of roofs, including typologies habitually criticised for their low level of diversity, which, as GROOVES shows, represent original ecosystems offering very specific habitats.

It seems unrealistic to look for an ideal, universal model for green roofs, and GROOVES encourages us to continue to apply a variety of different design principles on an urban scale. However there is room for improvement in current techniques: the design of some roofs is either too uniform or too disconnected from the ecosystem services it aims to provide, making it of limited environmental value. In future, the design and management of green roofs could draw more inspiration from the way certain natural ecosystems function. Such a paradigm shift can only be achieved if ecologists, landscape designers and green roof designers work closely together.

Although policies promoting nature in cities are being rolled out everywhere, many of them reflect little more than passing fads. GROOVES was eager to highlight a genuinely scientific approach that will make it possible to provide guidance to roof managers by formulating recommendations and advice relating to future generations of green roofs. Since the study was carried out, this approach, which involves assessing biodiversity and its benefits, has been applied to other types of development such as urban farms (BiSEAU study) and cemeteries (COOL study) with the aim of providing more useful information to local authorities.

Viper's bugloss in flower on the roof of GTM Bâtiment HQ in Nanterre. © Audrey Muratet | ARB îdF

Lucile Dewulf looks at the largest green roof included in our study, on Hall 7 at the Villepinte Exhibition Centre.
© Audrey Muratet | ARB îdF

GROOVES
A SCIENTIFIC APPROACH
THAT PROVIDES ROOF
MANAGERS
WITH GUIDANCE,
RECOMMENDATIONS
AND ADVICE
FOR FUTURE GENERATIONS
OF GREEN ROOFS.

© Ophélie Ricci | ARB îdF

IN BRIEF

OBSERVATIONS

01

The GROOVES study focuses on the biodiversity and ecosystem services of

36 ROOFS

IN GREATER PARIS

18 extensive roofs, 6 semi-intensive roofs, 8 intensive roofs, 4 wildroofs.

02

The origin of the plants varies : local or more remote, Mediterranean, continental, North American.

03

On average the roofs are home to a **plant diversity** similar to that found in **areas of waste ground** and **urban parks.**

04

The **height of the building correlates with the diversity of spontaneous plants,** hoverflies and wild bees. The effect is positive up to 10 metres in height (3 floors).

© Myr Muratet

05

The total surface area of green roofs has **multiplied tenfold** since the 2000s.

06

Because of the industrialisation of design methods, **uncertainties** remain regarding their **ability to respond to a range of environmental challenges.**

07

400

PLANT SPECIES HAVE BEEN INVENTORIED

70% of which are spontaneous. Floristic composition is unusual and often comparable to that found in dry sandy grassland.

08

Soils containing about **10% clay and 60% sand** allow maximum floristic diversity.

09

Soils on green roofs have **very particular physicochemical characteristics,** with combinations of textural and chemical properties that are not represented in the French soil quality monitoring network (RMQS).

10

We can distinguish (1) "roof-loving" species that are usually not very well represented in the urban environment but which are very common on rooftops (e.g. *Runcinia grammica* (a spider), *Nysius graminicola* (a seedbug), and *Lygus pratensis* (a plant bug)); **(2) "generalist" species** that are common on both roofs and the ground (e.g. the firebug *(Pyrrhocoris apterus)*, the garden spider *(Aranea diadematus)* and the green stink bug *(Nezara viridula)*); **and (3) "roof-hating" species** that are not well represented on roofs while being common at ground level (e.g. the nursery web spider *(Pisaura mirabilis)*, the mottled bug *(Raphigaster nebulosa)* and the dock bug *(Coreus marginatus)*).

11

40 TAXONS
OF BRYOPHYTES (MOSSES) AND LICHENS

have been observed on all the roofs.

12

"Extensive" roofs
have less diversified flora and fauna than the others.

13

The **abundance of pollinators** on intensive and semi-intensive roofs is comparable to that observed in other urban green spaces.

14

Invertebrate diversity fluctuates greatly from roof to roof, with large discrepancies between the least rich sites (20 species) and the richest sites (107 species).

15

WHEN SOIL DEPTH EXCEEDS
25 cm

floristic diversity
no longer increases whereas pollinator diversity continues to rise.

16

611
SPECIES OF INVERTEBRATES

belonging to many taxonomic groups, mainly Hymenoptera (bees), Hemiptera (bugs), Coleoptera (beetles) and spiders.

17

Roofs made up of **“agricultural” and “mixed” substrates can store more water** than roofs with “mineral” substrates.

18

Observations show that, on a single roof, **evapotranspiration can be 6 times greater with more abundant vegetation.**

19

ONLY
5 ROOFS OUT OF 26
ARE ABLE TO REGULATE 10-YEAR RAINFALL EVENTS

These roofs (CIROB, FRANK, ALBAR, OLSER and PULMA) have agricultural substrates almost 30 cm deep.

20

Soils on green roofs have **very high levels of microbial biomass** (129.4 µg DNA/g soil), about twice the average level measured with the RMQS benchmark (59.2 µg DNA/g soil).

21

While roofs can help with cooling, their **efficiency will be very limited during heatwaves** with very low rainfall.

22

While metallic trace element pollution is not significantly high on most of the roofs, some have **particularly high levels of lead and zinc,** above risk thresholds.

23

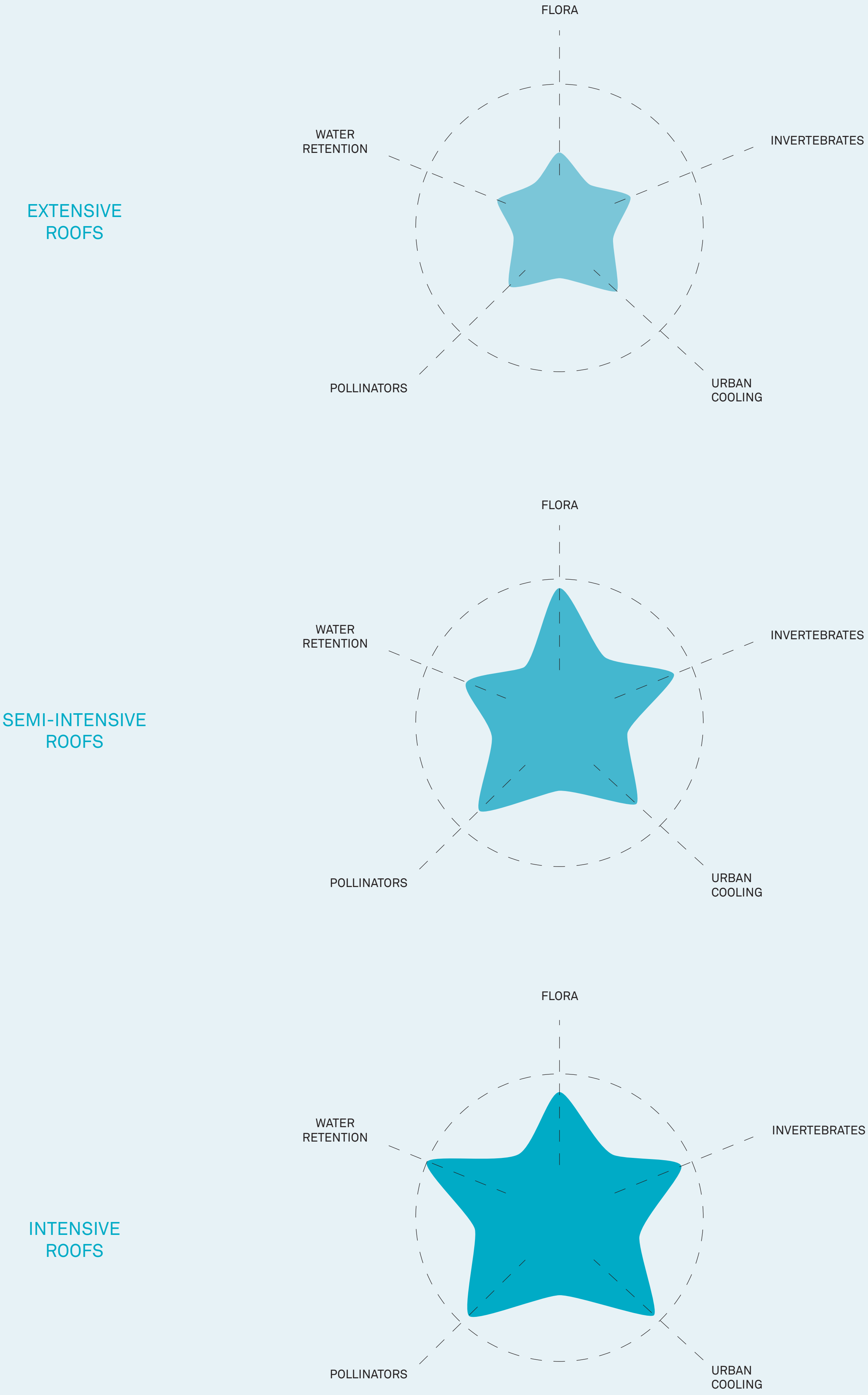
There are **wide variations between** roofs in terms of their **water retention capacity:** 6 L/sq.m. for the least absorbent roof compared with 532 L/sq.m. for the most absorbent.

24

Extensive roofs are less rich in invertebrates than intensive and semi-intensive roofs. They do, however, host original communities.

25

Where cooling is concerned, there is **the evapotranspiration capacity of roofs varies widely,** with a ratio of 28 to 1 between the lowest maximum daily evapotranspiration (PERIS) and the highest (ECOBIO).



Comparison of efficiency of ecosystem services provided by different types of roofs. Extensive roofs turn out to be 50% less efficient than semi-intensive and intensive roofs for the services assessed.

IN BRIEF

RECOMMENDATIONS

01

On buildings scheduled for renovation, first perform a **load-bearing and waterproofing analysis** to determine load capacity and adapt substrate depth accordingly.

02

It is possible to plant nothing and **allow spontaneous vegetation to establish itself** (wildroofs).

03

To reduce the ecological footprint created by materials, it is necessary to **adopt a low-tech approach at the design stage** in order to limit the number of artificial components (geotextile membranes, plastic trays, etc.).

04

Items can be placed on the roof **to create extra habitats for species:** piles of rocks, dead wood, a pond, etc.

05

For planted roofs, opt for local plant varieties from trusted suppliers (e.g. in France those participating in the "Végétal local®" programme). It is also possible to collect wild seeds from neighbouring environments.

06

It is advisable to **vary substrate depth** on a roof to **create different conditions for living organisms.** By the same token, the **diversification of plant strata** (moss layer, herbaceous layer, shrubs or even trees) is a sign of quality.

07

Plan for maintenance in the design: over-frequent maintenance can adversely affect biodiversity (through cutting, mowing, trampling, etc.).
One or two simple annual checks are usually enough (to get rid of undesirable woody plants and rubbish). If the roof is accessible to the public, include footpaths and "keep off" areas.

08

Avoid the use of pre-grown systems (trays, rolls, etc.). Instead plant plugs or sow seeds and define your own floristic composition.

09

Avoid using imported agricultural soil. Opt for a substrate comprising recycled materials (crushed brick, compost, excavated soils).

10

If the roof is **uncultivated,** it is **not necessary to include a watering system** (even if the roof changes with the seasons!)

12

On the scale of a town or city, it is preferable to have a **varied range** of green roof designs.

13

Climbing plants can be used to **connect the green roof with the ground.**

11

Green roofs are **dynamic ecosystems whose vegetation is likely to change over time.** This is an inevitable natural process that forms part of the life of the roof. It is not necessary to seek to maintain the initial palette of plants.

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ECOLOGY OF
GREEN ROOFS

Summary of the GROOVES study
Green Roofs Verified
Ecosystem Services
2017 – 2019

Since the 1990s, the escalation of nature-oriented urban policies has been coupled with renewed interest in green roofs. Many ecological advantages are generally associated with planted roofs—hosting biodiversity, water retention, carbon storage, etc.—, but these benefits are still inadequately assessed. To remedy this, and to continue on from existing research work on the subject, the Agence Régionale de la Biodiversité en Île-de-France launched the GROOVES study (pour Green ROOfs Verified Ecosystem Services) in 2017, with support from the French National Museum of Natural History (MNHN), the Conservatoire Botanique National du Bassin Parisien (CBNPB), the Institut d'Ecologie et des Sciences de l'Environment IEES-Paris and the Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environment (INRAEUMR Agroécologie Dijon). 36 roofs of different types (extensive, semi-intensive and intensive) were analysed via inventories of plants and invertebrates (including pollinators) and substrate sampling, to gain a better understanding of their status and their ecological role.

After 3 years of study, early results have confirmed the role played by green roofs in hosting biodiversity and fulfilling ecological functions.
They also show that these benefits vary greatly between different planting systems,
and this makes it possible to outline some major trends for roof designers and managers.