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Research green roof in Leipzig, Germany

Lucie Moeller [a,*], Niels Wollschläger [b], Christian Hecht [c], Dietmar Schlosser [d], Peter Dietrich [e], Jan Friesen [a], Ralf Trabitzsch [f], Katy Bernhard [a], Peter Otto [g]

[a] Department Systemic Environmental Biotechnology, UFZ–Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany
[b] Department of Urban and Environmental Sociology, UFZ–Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany
[c] Department of Community Ecology, Helmholtz Centre for Environmental Research GmbH – UFZ, Permoserstraße 15, 04318 Leipzig, Germany
[d] Department of Applied Microbial Ecology, UFZ–Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany
[e] Geobotany and Botanical Garden, Institute of Biology, Martin Luther University Halle-Wittenberg, Am Kirchtor 1, 06108 Halle (Saale), Germany
[f] Department of Environmental Informatics, UFZ–Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany
[g] Molecular Evolution and Plant Systematics, Institute of Biology, University Leipzig, Johannisallee 21, 04103 Leipzig, Germany

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ABSTRACT

Due to the progressing climate change, cities face the challenge of adapting to new weather conditions, including heavy rains and draught periods. Green roofs are considered a promising solution for sustainable urban development, as they require no additional space and are expected to offer multiple functions. These include rainwater retention and storage, cooling effects, provision of additional space for humans and animals, and functioning as sink for urban pollutants. To validate these functions, a Research Green Roof was constructed on a building at the Helmholtz Centre for Environmental Research campus in Leipzig. The Research Green Roof consists of four roof 80 m^2 segments: extensive and semi-intensive green roofs, a wetland green roof, and a gravel roof serving as a reference. Each segment is equipped with numerous sensors to monitor water and heat balances. Additionally, botanical and entomological monitoring equipment has been installed. The roof segments are the subjects of interdisciplinary research by several working groups. This publication presents the research infrastructure and provides an overview of the ongoing studies.

1. Introduction

Progressive climate change poses significant risks, particularly for urban areas, which are especially affected due to their high degree of sealing. During heatwaves, cities heat up considerably, creating so-called heat islands, where temperatures are higher than in surrounding rural areas. For Leipzig, Schwarz et al. (2012) identified a stable temperature difference between urban and rural zones of 2.9–3.1 K, depending on the distance to the city centre. Moreover, heated air has a higher capacity to hold moisture, which subsequently leads to more intense precipitation events. Over land, the rate of surface-specific humidity increase corresponds to approximately 4.3 % per 1 K (Trenberth, 2005). According to climate models, both the intensity and frequency of extreme rainfall events have already increased. It is expected that for 2 K global mean surface warming, the frequency of such events could double or triple (Myhre et al., 2019). Urban sewage systems were designed under historical climatic conditions and are often not equipped to handle the increased volume of stormwater associated with extreme weather events. The combination of sealed surfaces and more intense rainfall leads to frequent localized flooding and overloading of municipal wastewater treatment facilities. As a result, untreated wastewater can enter rivers, significantly deteriorating water quality.

To protect citizens and the environment, cities must adapt to these challenges by managing stormwater differently than before. Rather than discharging rainwater via traditional sewer networks, it should be retained and utilised on site. In this context, so-called blue-green infrastructures are being integrated into urban landscapes. These nature-based solutions facilitate rainwater retention while also promoting water release into the environment through evapotranspiration or infiltration. One promising type of blue-green infrastructure is green roofs. These have the advantage of not competing for space with other urban infrastructure or transportation corridors – an important consideration in densely built environments. Numerous studies have demonstrated the multifunctionality of green roofs: rainwater retention and runoff reduction (e.g. Raimondi and Becciu, 2021; Wang et al., 2021; Richter and Dickhaut, 2023), microclimate regulation and cooling via

* Corresponding author.
E-mail address: lucie.moeller@ufz.de (L. Moeller).

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evapotranspiration (Peng and Jim, 2013; Gößner et al., 2025), building thermal insulation and associated material protection (Abdalazeem et al., 2024; Khotbehsara et al., 2019), noise reduction (Van Renterghem, 2018), and functioning as sinks for carbon dioxide (Tan et al., 2023), particulate matter (Kostadinović et al., 2023; Viecco et al., 2021), and urban pollutants (Schwager et al., 2015; Seidl et al., 2013; Yang et al., 2008). Green roofs can also purify greywater (Rahman et al., 2023; Thomaidi et al., 2022), enhance urban biodiversity (Colla et al., 2009; Knapp et al., 2019; Wang et al., 2022), and – when combined with photovoltaics – slightly improve their electricity yield (Abdalazeem et al., 2024; Hui and Chan, 2011). Additionally, they can be used for recreation and urban farming (Walters and Midden, 2018).

To ensure that these benefits are fully realized, it is essential to assess and measure the functions of green roofs under specific regional conditions. This allows cities to regulate and design green roof infrastructure in a way that reliably delivers the desired functions. However, the performance of green roofs depends heavily on their construction type and the local environmental conditions.

To address this, a Research Green Roof comprising three different types of green roof structures was constructed on the top of a building at the Helmholtz Centre for Environmental Research (UFZ). The goal of this infrastructure is to test and compare the performance of various green roof systems under local conditions, with the aim to identify optimal configurations. This facility is part of a broader network of blue-green research infrastructures operated by the UFZ and also serves as a demonstration site for researchers, policymakers, and general public.

The aim of this publication is to present the UFZ Research Green Roof as a unique research infrastructure, describe its installed monitoring systems, and provide an overview of the research being conducted there.

2. UFZ Research Green Roof

The UFZ Research Green Roof (Fig. 1) was put into operation in 2020 and is located atop a building in the *Wissenschaftspark* campus in Leipzig (51°21′13"N 12°25′55″E), at a height of approximately 15 m. The research facility consists of four roof segments: an extensive green roof, a semi-intensive green roof, a wetland roof and a gravel roof, each covering a surface area of 80 m^2.

All roof segments have the same structural base, which includes membrane for roof waterproofing and root protection in accordance with FLL guidelines (FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.), 2018), an elastomer bitumen cold self-adhesive membrane, and wooden basins constructed from unpolished OSB installation boards (Fig. 2). The green roof segments additionally consist of the following layers (from top to bottom): substrate layer composed of clay brick fragments and compost with fibrous materials (7 cm height for extensive (Fig. 2a) and 15 cm for semi-intensive green roofs (Fig. 2b)) or, in case of the wetland roof, a water storage mat made of recycled polypropylene fleece (17 mm thickness) (Fig. 2c). All green roof segments are also equipped with irrigation drip hoses, a water dispersion fleece, a drainage layer, and a water- and nutrient-storing synthetic fibre mat.

The gravel roof consists of 60 mm of gravel (grain size: 16/32) placed on water dispersion fleece, with a system filter used as a separation layer (Fig. 2d). The wetland roof is equipped with 9 cm vertical pipes placed on the outlets to enable water retention and keep the marsh plants appropriately moist. The extensive green roof is divided into two sections with separate irrigation systems to allow the development of irrigation strategies. All roof segments have a slope of 2°.

In terms of vegetation, the extensive and semi-intensive green roofs are each subdivided into two segments: one with conventional plantings typically offered by commercial suppliers, and another with conservation-oriented, non-conventional plantings, where predominantly native insect-friendly species were added. The conventionally planted segment of the extensive green roof is dominated by succulent species of the stonecrops group (Table 1). Approximately 20–25 plants were planted per square meter.

The plant species on the semi-intensive green roof segment show greater diversity and include grasses and semi-shrubs (Table 2). Planting density in this segment was approximately 15–20 plants per square meter.

The wetland green roof contains marsh plant species with medium to high nutrient requirements (Table 3). Planting density here was around 6–8 plants per square meter.

Regular maintenance activities are performed, including the removal of dead plants, sectoral removal of spontaneous plant species (see

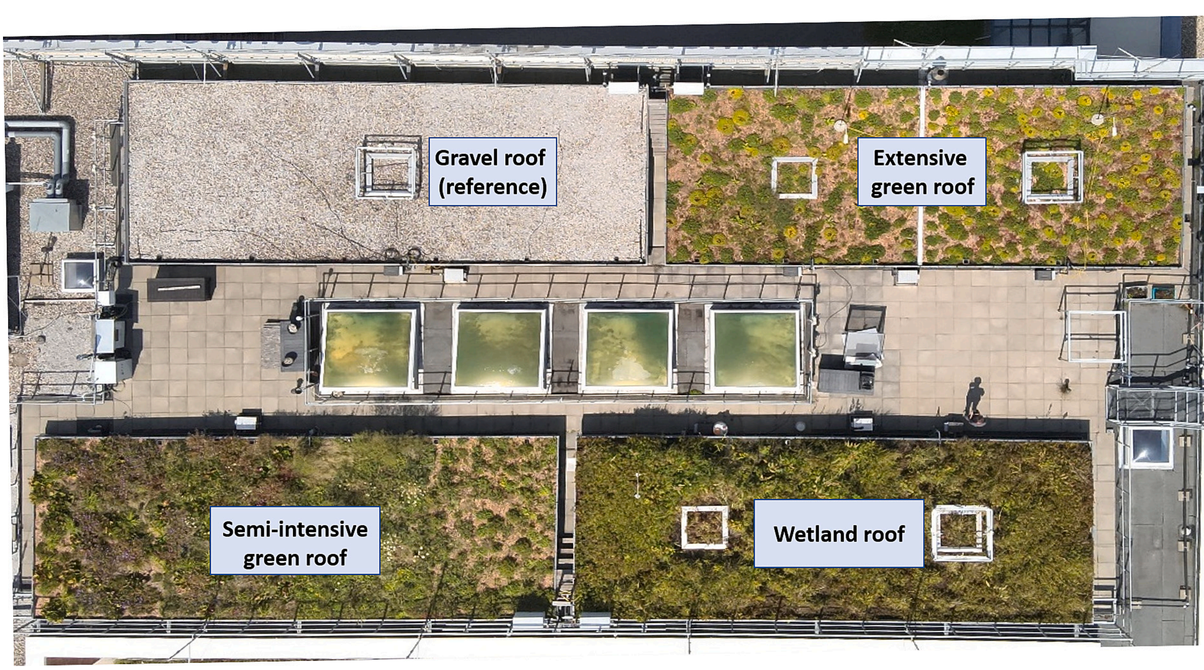

Fig. 1. Drone image of the UFZ Research Green Roof at the Helmholtz Centre for Environmental Research, taken on 31 July 2024 (Photo: Katy Bernhard). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

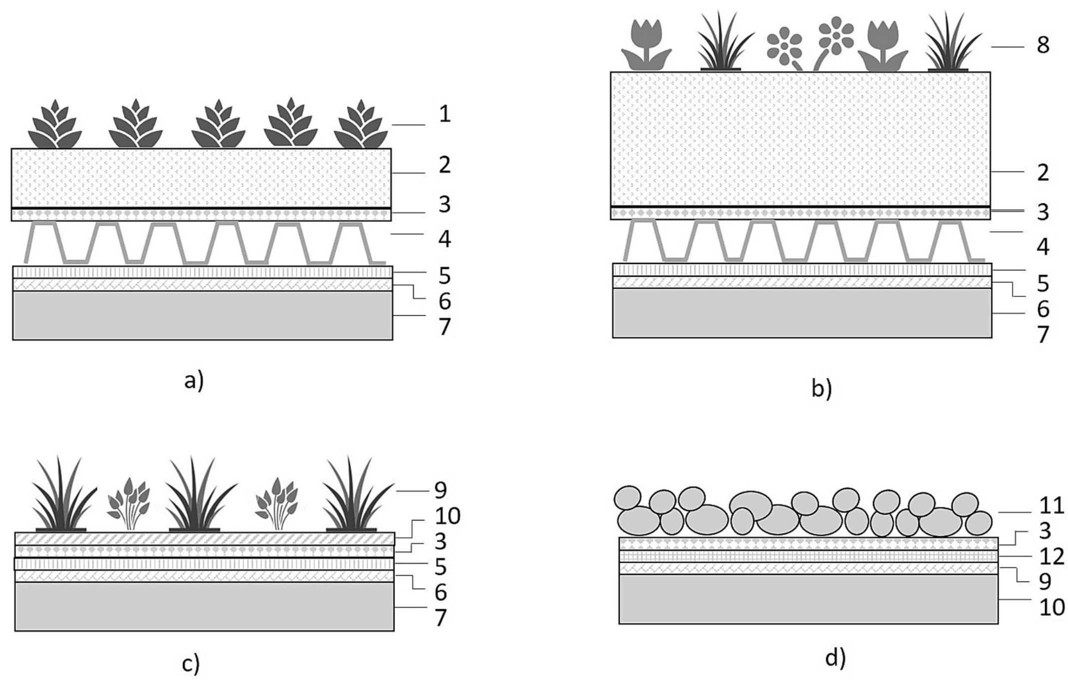

Fig. 2. Cross section of the roof systems (a) extensive green roof, (b) semi-intensive green roof, (c) wetland roof, (d) gravel roof (1 extensive greening, 2 substrate „Steinrosenflur“, 3 aqua fleece, 4 drainage layer, 5 storage protection mat, 6 root protection, 7 wooden construction, 8 intensive greening, 9 marsh plants, 10 water storage mat, 11 gravel, 12 system filter). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Extensive green roof vegetation - Characteristic planted species with high vitality and formative dominance under the existing ecological conditions.

Scientific name of plant species	Morphotype of plant species	Pollination type
Subtype: Conventionally greened		
Phedimus hybridus	herb (succulent), partly evergreen	unspecific insect pollination
Phedimus kamtschaticus	herb (succulent), deciduous green	unspecific insect pollination
Phedimus spurius	herb (succulent), partly evergreen	unspecific insect pollination
Sedum album	herb (succulent), evergreen	unspecific insect pollination
Subtype: Vegetation improved for nature conservation issues (selected species in addition to the conventionally greened subtype)		
Dianthus carthusianorum	herb, partly evergreen	insects, preferably butterflies
Filipendula vulgaris	herb, evergreen	unspecific insect pollination
Potentilla verna	herb, deciduous green	insects, mainly bees and butterflies
Salvia nemorosa	herb, deciduous green	insects, mainly Hymenoptera
Salvia verticillata	herb, deciduous green	insects, mainly Hymenoptera
Thymus pulegioides	semi-shrub, evergreen	insects, mainly Hymenoptera

Table 2
Semi-intensive green roof vegetation - Characteristic planted species with high vitality and formative dominance under the existing ecological conditions.

Scientific name of plant species	Morphotype of plant species	Pollination type
Subtype: Conventionally greened		
Bergenia cordifolia	herb (weakly succulent), evergreen	insects, mainly Hymenoptera
Briza media	grass,	wind pollination
Geranium himalayense x wallichianum	herb, deciduous green	insects, mainly Hymenoptera
Hemerocallis minor	herb, deciduous green	insects, preferably butterflies
Inula ensifolia	herb, deciduous green	insects, mainly bees and butterflies
Subtype: Vegetation improved for nature conservation issues (selected species)		
Hyssopus officinalis	semi-shrub, evergreen	insects, mainly Hymenoptera
Origanum vulgare	herb, deciduous green	insects, mainly Hymenoptera
Prunella vulgaris	herb, evergreen	insects, mainly Hymenoptera
Satureja montana	semi-shrub, evergreen	insects, mainly Hymenoptera
Veronica prostrata	herb, evergreen	insects, mainly Hymenoptera

Chapter 4.1 for more information), soil fertilization, and irrigation during summer months.

The **major research questions** being addressed at the UFZ Research Green Roof include:

1. Urban water management: How can green roofs be integrated into urban stormwater management concepts as storage and retention systems? What effects do different green roof configurations have on the urban microclimate?
2. Biodiversity: Which regional plant species are best suited for the extreme conditions on green roofs? What effect do different green roof types have on biodiversity? How can green roofs contribute to urban biodiversity conservation? Do rooftop-dwelling organisms have the potential to mitigate environmental pollution?

To support answering these questions, various measuring devices have been installed and corresponding estimation methods have been developed. These are described in detail in the following chapters.

Table 3
Wetland roof vegetation - Characteristic planted species with high vitality and formative dominance under the existing ecological conditions.

Scientific name of plant species	Morphotype of plant species	Pollination type
Subtype: Conventionally greened (selected species)		
Caltha palustris	herb, deciduous green	unspecific insect pollination
Carex acutiformis	herb, partly evergreen	wind pollination
Carex pseudocyperus	herb, evergreen	wind pollination
Juncus effusus	herb, evergreen	wind pollination
Mentha aquatica	herb, evergreen	insects, mainly Hymenoptera
Rumex hydrolapathum	herb, deciduous green	wind pollination
Subtype: Vegetation improved for nature conservation issues (selected species)		
Eupatorium cannabinum	herb, deciduous green	insects, mainly bees and butterflies
Filipendula ulmaria	herb, deciduous green	unspecific insect pollination
Lysimachia vulgaris	herb, deciduous green	insects, exclusively oil bees
Lythrum salicaria	herb, deciduous green	unspecific insect pollination
Myosotis scorpioides	herb, evergreen	unspecific insect pollination
Ranunculus lingua	herb, partly evergreen	unspecific insect pollination

3. Estimation of (micro)climate-related functions of green roofs

Green roofs play a crucial role in urban rainwater management by reducing runoff, improving water retention, and alleviating pressure on drainage networks (Berndtsson, 2010). Rainwater gradually infiltrates the substrate layer, mimicking the hydrological behavior of natural soil. Some of this water evaporates through the roof vegetation, while the rest is stored in the substrate, and drainage layer, with the excess being discharged as runoff. The storage capacity of green roofs depends on substrate thickness - thicker substrates retain more water than thin-layer systems (Mentens et al., 2006).

According to the Research Society for Landscape Development and Landscape Construction (FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.), 2018), extensive green roofs retain an average of 50–60 % of annual rainfall, whereas intensive green roofs with deeper substrates can retain up to 90 %. Similarly, studies by VanWoert et al. (2005) confirm that green roofs significantly reduce peak run-off and delay water discharge. On average, green roof systems offer a storage capacity of around 30 L/m^2, depending on substrate depth, enabling them to absorb significant rainfall during heavy precipitation events (Schmauck, 2019). Currently, there are no published studies describing the retention capacity of wetland roofs. Retention performance of traditional green roofs varies significantly depending on substrate composition and arrangement. Vegetation type also plays a critical role: intensive green roofs with grasses and herbs generally retain more water than extensive green roofs planted with sedum and moss (Gößner et al., 2021).

Green roofs with high retention capacities offer a promising solution to mitigate climate-related urban challenges, such as overwhelmed drainage networks, rising temperatures, and increased surface sealing (Li and Babcock, 2014). However, further research is necessary, particularly regarding the long-term interactions between structural layers, materials, substrates, and vegetation types (Gößner et al., 2021; Richter and Dickhaut, 2023).

3.1. Experimental design and measuring systems

To assess the performance of the various green roof types regarding rainwater management and microclimate effects, several sensors and measuring systems have been installed across the green roof segments.

Each roof segment features six drains that direct water in a small cistern (10.2 L) that is connected with a tipping counter made from polycarbonate (Umwelt-Geräte-Technik GmbH, Germany) with the tilting tray volume of 100 mL, used to estimate the runoff volume. The total area for water balance calculation is the full roof area minus the area of the lysimeters. Five lysimeters (Umwelt-Geräte-Technik GmbH, Müncheberg, Germany) have been installed on the roof segments: one in the gravel roof, two in the extensive green roof, and two in the wetland roof (Fig. 1). For structural reasons, no lysimeter could be installed in the semi-intensive green roof. Each lysimeter device has a surface area of 1 m^2 and is filled with the same material as the respective roof segment. All lysimeters are connected to the irrigation system to replicate the conditions of the entire respective roof segment. The weighing system offers an accuracy of the is 10 g with a resolution of 1 g, corresponding to a water column of 0.001 mm. Lysimeter runoff is recorded using tipping counters of the same type used for the entire roof segments.

Soil temperature and humidity are measured using SMT 100 sensors (Truebner GmbH, Neustadt, Germany), installed at a depth of 5 cm in the substrates of the respective roof plots. Soil heat flux sensors (HFP01SC, Hukseflux, Delft, the Netherlands) are installed at a depth of 4 cm to determine the ground heat flux in the substrate of the extensive green roof and in the gravel roof. Radiation components are measured with net radiometers (CNR4, KIPP& Zonen, Delft, the Netherlands). All sensor data is recorded using a DataTaker DT80 logger at a 2-min resolution and is used to evaluate the thermal and hydrological performance of each roof type.

Precipitation is recorded by a ClimaVIJE 50 weather station (Campbell Scientific, Inc., USA). Irrigation volumes are measured with a Q3 water meter equipped with a Sensus HRI-A4 pulse generator (Sensus GmbH, Germany). Data from the weather station and runoff measuring systems is logged every 10 s using a CR1000X-Logger-1674 (Campbell Scientific, Inc., USA).

The experimental design was used by Wollschläger et al. (2024), who analyzed lysimeter measurements for the gravel, extensive, and wetland roofs over 31 months, assessing evapotranspiration rates (as an indicator of cooling potential) and stormwater retention capacity. The authors evaluated the impact of local climate variability and provided insights into optimal maintenance practices.

An example of runoff data from all roof segments is shown in Fig. 3 for October 2023. After a very dry September with only 15 mm of precipitation, the green roof substrates were notably dry. In contrast, a total of 108 mm of precipitation fell in October. Before the first rainfall in October, the water content in the extensive roof substrate was just 7.0 % (Fig. 3a). The first rain event (10.7 mm) caused no runoff from any green roof, while the gravel roof produced 5.52 mm runoff (51 % runoff reduction) with a delay of 23 min (Fig. 3b). As the month progressed, increasing substrate moisture reduced the roofs' water absorption capacity. During the rainfall event on October 14 with an intensity of 8.40 mm, the extensive roof – now with a substrate moisture of 20.7 % - produced 1.99 mm runoff, corresponding to 76 % retention (Fig. 3c). The gravel roof retained only 42 % of water (4.87 mm runoff). The runoff delay was 57 min for the gravel roof and 81 min for the extensive roof. Neither the semi-intensive nor the wetland roofs showed any runoff during this precipitation event. By October 27, all green roofs had reached saturation, and runoff occurred from all segments (Fig. 3d). At the beginning of this event, the substrate moisture in the extensive roof was 26.4 %, and 9.4 mm of rain fell. Runoff values were as follows: gravel roof retained 31 % (6.45 mm runoff), extensive and semi-intensive green roofs retained 45 and 47 % (5.13 and 4.97 mm runoff), respectively. These results show similar runoff patterns for the extensive and semi-intensive green roofs, likely due to full substrate saturation (Fig. 3c). The wetland roof retained the most water - 75 % (2.34 mm runoff) – with runoff delays ranging from 67 min (gravel roof) to 146 min (wetland roof).

3.2. Remote sensing approaches

Surface temperature estimation is conducted using a Mavic 2 Enterprise drone equipped with a thermal sensor (160 × 120 px). An example of a thermal image of the UFZ Research Green Roof is shown in

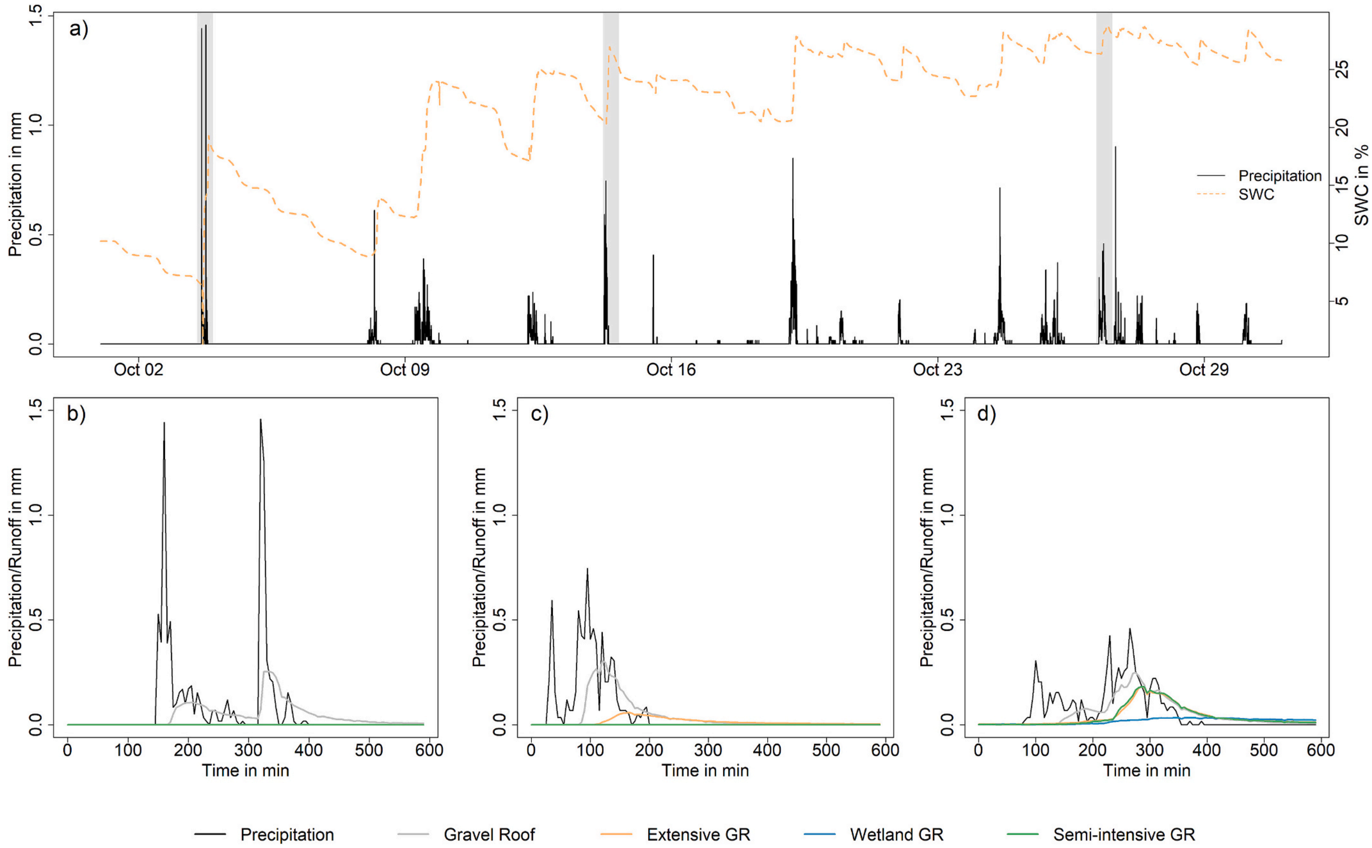

Fig. 3. Runoff of green roof segments for October 2023: Graph (a) shows daily precipitation and the substrate water content (SWC) in the extensive green roof. Three rain events of comparable intensity - highlighted gray in (a) on October 3 (b), October 14 (c), and October 27 (d) - are shown in detail with the corresponding runoff measurements from all four roof segments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

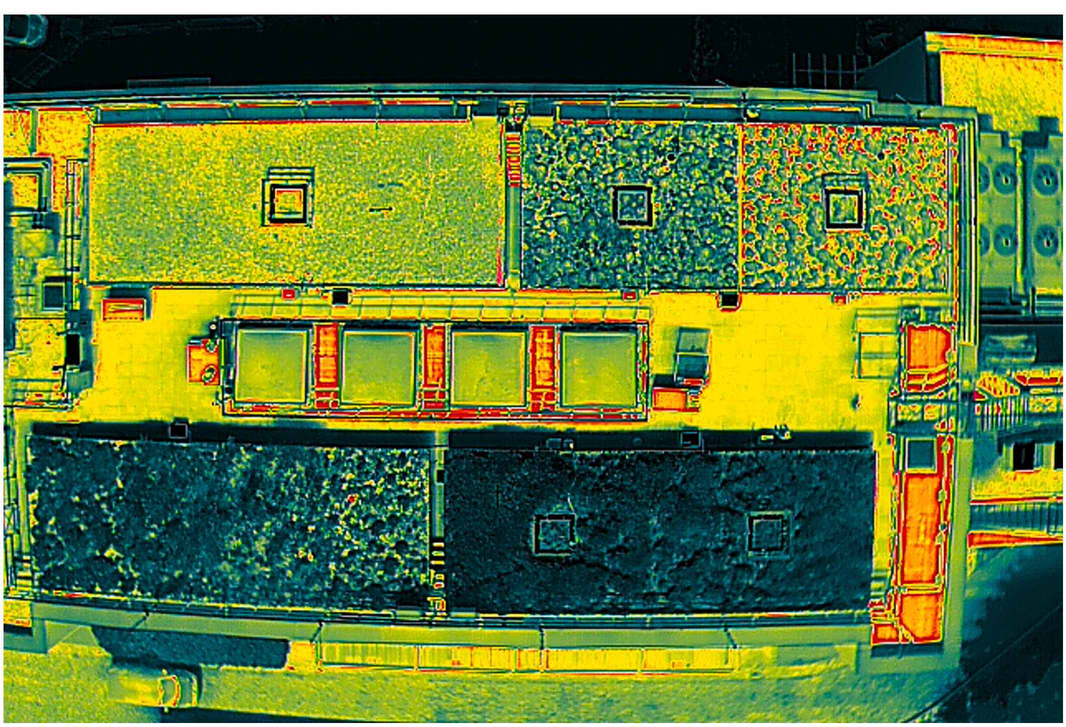

Fig. 4. Thermal image of the UFZ Research Green Roof taken on 31 July 2024 (Photo: Katy Bernhard). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Thermal images of the roof segments are taken at regular intervals throughout the year. These aerial images are processed into georeferenced orthomosaics using photogrammetric techniques (PyExpress), corrected by surface characteristics and atmospheric influences, enabling the derivation of spatially resolved surface temperature maps. These thermal datasets allow for species-specific analysis by correlating temperature data with plant species, thus enabling quantification of heat mitigation potential across distinct plant species. To ensure methodological accuracy, the drone-derived surface temperatures are cross-validated against in situ net radiometer measurements through spatio-temporal alignment of datasets. Furthermore, the influence of different irrigation regimes is analyzed to assess their effects on surface temperature and cooling potential.

4. Investigation of green roofs as areas for biodiversity

Green roofs can enhance urban biodiversity and contribute to improved habitat connectivity. By supporting diverse plant communities, they create habitats for a wide variety of organisms, thereby promoting local biodiversity and increasing ecosystem resilience. For some organism groups, such as vascular plants and arthropods, these positive effects are already rather well documented (Wang et al., 2022); however, for others, e.g. mosses, chordates, mollusks, nematodes, as well as fungi in general, evidence remains strongly limited. Moreover, the extent of these effects strongly depends on green roof maintenance activities (no, extensive or intensive management).

4.1. Studies on vegetation development, suitability of biodiversity-supporting plants, and management effects

4.1.1. Plants as key indicators of ecological functionality and biodiversity

In order to understand the biological functionality of green roofs, the vegetation of seed plants in particular must be recorded and evaluated. Trophically and structurally, seed plants are the determining factor for the formation of biocenoses on green roofs. Knowledge of vegetation conditions allows reliable basic conclusions about other organism groups, such as mosses, insects, and fungi. In this context, studies on the diversity, abundance, dominance, vitality, growth performance, and reproduction of seed plants are of high information value. Repeated data collection allows for analysis of seasonal dynamics and long-term developments (succession), as well as for the formulation of predictions. Horticultural approaches are typically limited to studies of planted vegetation. However, to investigate the impacts on the ecological significance of green roofs, spontaneously occurring species must also be considered (e.g. Dunnett et al., 2008; Madre et al., 2014; Catalano et al., 2016; Thuring and Dunnett, 2019; Vanstockem et al., 2019; Schrieke et al., 2021, 2023).

Although biological research on green roofs has been carried out worldwide for decades, comparative, multi-year studies across various green roof types remain rare and underexplored. Furthermore, previous research has not sufficiently addressed the use of native species for planting and seeding from a nature conservation perspective. The question of how maintenance management influence the state of vegetation and how they can be reduced to a cost-effective level also requires further investigation (Williams et al., 2014; Lundholm, 2015; Aloisio et al., 2019, 2020).

To address these gaps, a comprehensive study design has been established, enabling long-term monitoring and providing valuable insights into the complexity of green roof biocenoses. Moreover, the inclusion of organism groups of different trophic levels (producers, consumers, destructors) in relation to several abiotic factors will contribute to a deeper understanding of the ecological processes occurring on green roofs. In respect of seed plants as the biotic key players the main objectives are as follows:

(1) Evaluation of already used conventional planting types;
(2) Optimization of vegetation by introducing native species with relevance for nature conservation;
(3) Identification of the most suitable species under Central German climatic conditions for forming stable and diverse plant communities;
(4) Investigation of long-term vegetation dynamics, including trends in degradation;
(5) Analysis of the impact of maintenance practices on diversity changes and succession.

4.1.2. Study design and ongoing monitoring

The three green roof types are each divided into conventional and conservation-oriented (non-conventional) sections (see Chapter 2). These sections are further subdivided into managed and unmanaged zones (Fig. 5). A total of 48 permanent plots were established: for each green roof type, four large vegetation plots (V-plots) of 2.25 m^2 area and twelve small experimental plots (*E*-plots) of 1 m^2 area were installed. These plots allow for comparisons of the roof types among themselves but also for the examination of the impact of conventional planting types versus conservation-oriented planting types, and between managed and unmanaged conditions. The conservation-oriented sections aim to achieve a high proportion of species relevant to conservation through redesigns and planting of native species, thereby enhancing biodiversity and supporting pollinators. This design further enables the systematic analysis of vegetation dynamics across different roof types and temporal scales, including colonization processes and changes in plant trait composition.

Management primarily involves cultural practices, with fertilization applied only when necessary. In the managed areas, unwanted plant colonizers are removed. At the same time, care is taken to ensure that dominant planted species do not excessively inhibit the establishment and persistence of less competitive species, thereby promoting biodiversity and ecological balance.

Vegetation surveys are ideally conducted on each roof for 2.25 m^2 V-plots and for 1 m^2 E-plots (Fig. 5) at regular year intervals. Species identification and nomenclature follows standard literature, primarily Müller et al. (2021). To estimate plant cover and abundance, a modified scale based on Braun-Blanquet (1964) and Londo (1975) is applied. In addition, the total cover/abundance of all vascular plant species, including mosses and litter, is estimated in percentage per plot, and the average vegetation height is measured in centimeters (Fig. 6a).

In the permanent plots of both managed and unmanaged non-conventional (nature conservation-oriented) sections (Fig. 5), selected native species from extensive and semi-intensive (e.g., *Filipendula vulgaris, Veronica prostrata, Salvia verticillata, Inula hirta*), and wetland roof types (e.g., *Epilobium hirsutum, Eupatorium cannabinum, Lysimachia vulgaris*) are evaluated for their vitality and growth performance to draw conclusions about their suitability to be used as green roof vegetation. Vitality is assessed using a multi-stage scale ranging from "very vital/ robust" to "dead". Additionally, data are recorded on maximum growth height, number of shoots or branches, number of flower clusters, quantity of fruiting bodies, as well as discolorations or presence of dead biomass of the respective plants. Furthermore, the position of each species within the plant community is documented, including whether it is being suppressed or restricted in its growth (Fig. 6b).

Overall, Fig. 7a illustrates the differences in plant species composition – including the spontaneously occurring species – between the roof types. The wetland roof shows the most distinct differences, not only in terms of species composition but also in structural parameters such as vegetation height (Fig. 7b).

In addition to the standard monitoring for V-plots in the extensive and semi-intensive roof segments, detailed vegetation analyses are conducted based on evaluation of photos and field surveys. These surveys result in vegetation maps. Coverage can be calculated for each species as well as for larger individuals, allowing precise statements to be made about changes over seasons and years (Fig. 8). The photos allow

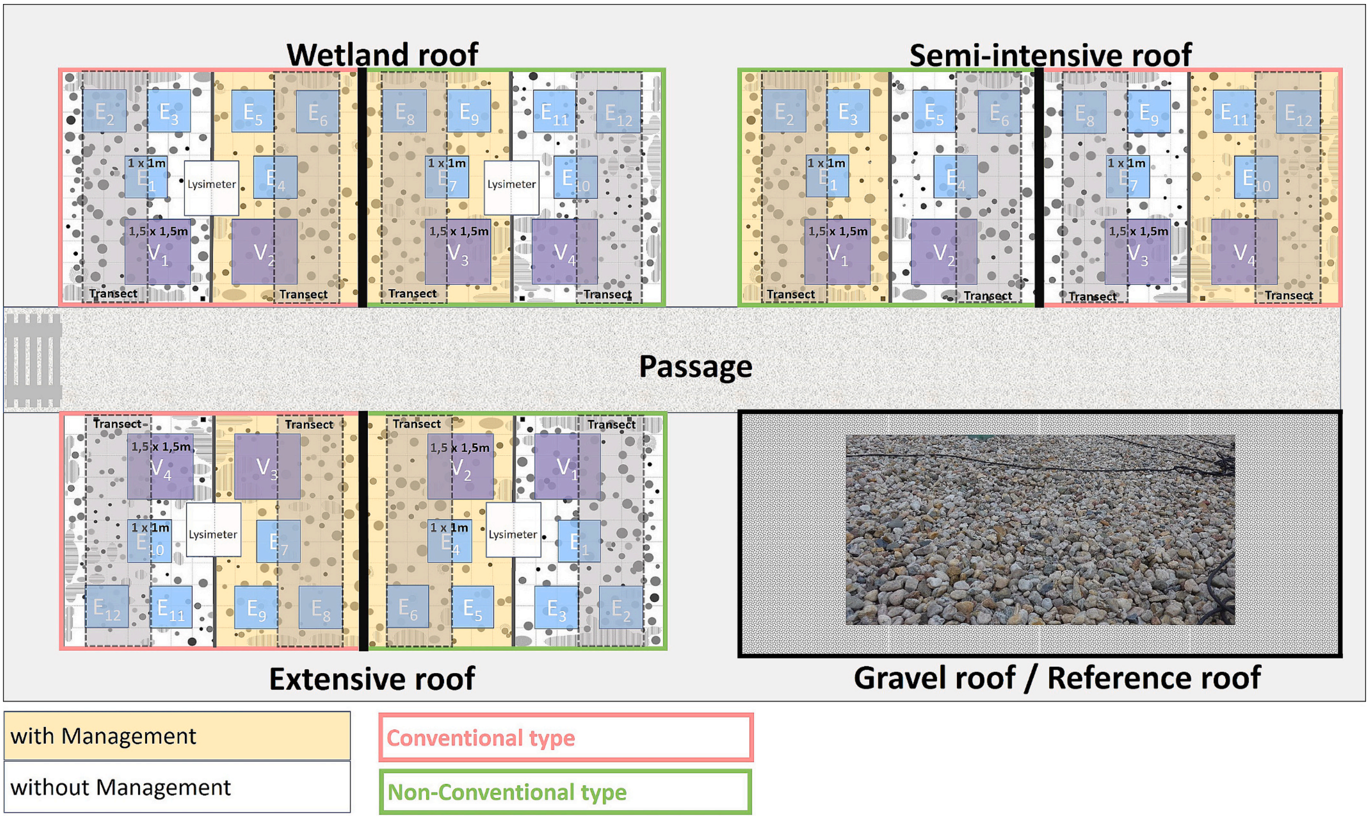

Fig. 5. Design of the three green roof types (wetland, extensive and semi-intensive), showing the division into conventional and non-conventional (conservation-oriented) sections. Each green roof includes permanent V-plots (large vegetation plots, 2.25 m^2), permanent *E*-plots (small experimental plots, 1 m^2), and transect areas (1.5 m × 4.5 m) (Illustration and photo: Christian Hecht). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

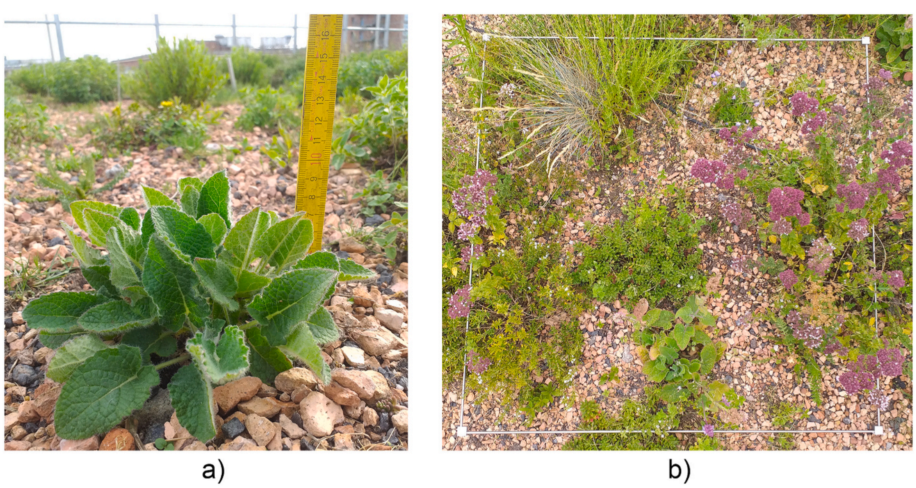

Fig. 6. (a) Assessment of vitality and growth behavior of *Salvia verticillata*; (b) Example of a small vegetation plot (E-plot) in the non-conventional section (conservation-oriented) of the semi-intensive green roof (Photos: Christian Hecht, 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conclusions regarding plant vitality, biomass increase, species dynamics and climatic influences. The plant pattern in 2023 is also presented as a vegetation map (right picture in Fig. 8), where each colour represents a distinct plant species (the base colour green indicates moss cover). A general trend is observable: the expansion of thick-leaved plants (Crassulaceae) and mosses, in combination with a decline in the total number of plant species. This trend is mainly attributed to dry climate conditions in 2022, as well as competitive interactions between plants.

Supplementary transect surveys (Fig. 5) are conducted, primarily in the extensive and semi-intensive green roof sections. Species are recorded for vegetation mapping as well, cover values are quantified using photographic analysis, and size measurements are performed on selected plants. These parameters, combined with plant trait data from Kattge et al. (2020), are used to model growth development, following the approach of the GRASSMIND model (Taubert et al., 2020a, 2020b).

Independent of the permanent plots and transects, all plant species

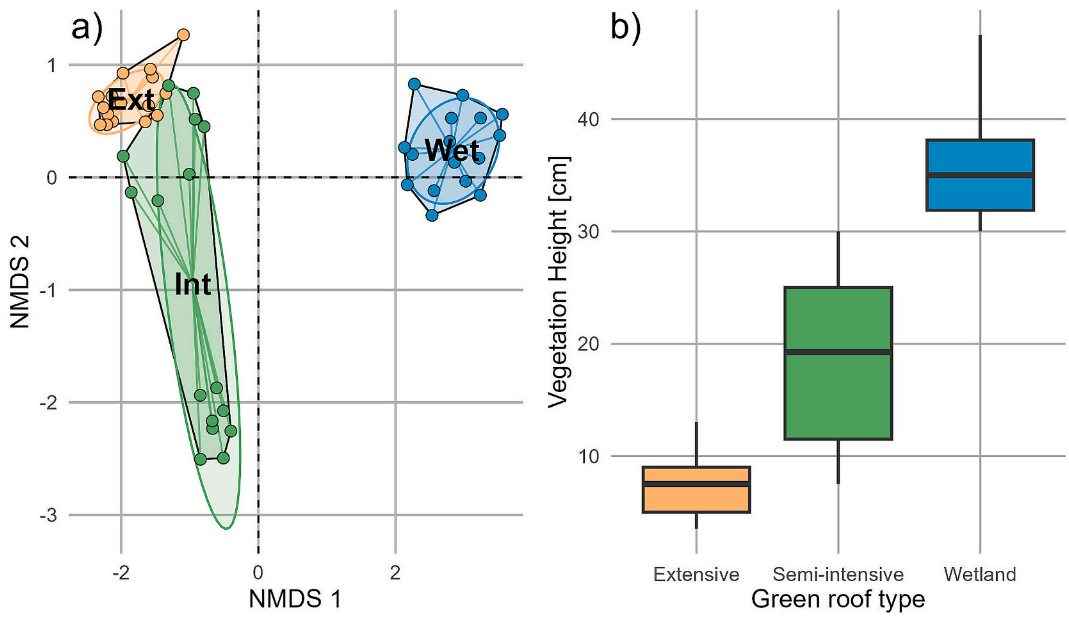

Fig. 7. (a) Ordination (NMDS - Non-metric Multidimensional Scaling with stress = 0.039) based on plant species abundances from the initial 2022 survey of the permanent plots, showing centroids, spider hulls, and ellipses by roof type; (b) Average vegetation height measured in the plots of the three green roof types. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. A permanent plot (1.5 m × 1.5 m) of extensive greening (unmanaged) in the fall aspect - comparison between November 2021 and November 2023 (Illustration: © Linda Machts & Peter Otto).

occurring on each roof are regularly documented, along with rough estimates of their local abundance.

4.2. Inventory studies of arthropods

The settlement areas of Central Europe are particularly characterized by a very strong decline in insects (Grevé et al., 2024). As a result, insects have received special attention in nature conservation activities over the past several years. Their occurrence on green roofs is also important from health, hygiene, and emotional perspectives, particularly in relation to arthropods phobias, which may lead to the rejection of green roofs.

Insects on the UFZ Research Green Roof are recorded and analyzed using various traps, including window traps, yellow traps, and ground traps. The aim of using different trap types is to capture as broad a spectrum of insects and other arthropods as possible. The identification of trapped arthropods focuses on Hymenoptera (especially bees and bumblebees), beetles, highly ground-bound (low mobility) arthropods, as well as groups of pests and nuisances (e.g., spiders, wasps, ants, woodlice, and earwigs). So far, insect collecting was conducted in 2021 and 2023, during August and September, respectively, resulting in the capture of a total of 22,335 individuals (Fig. 9). The results will be discussed in more detail elsewhere, but they demonstrate a clear preference of most of the recorded species for intensively greened roofs with a high diversity of plant species and biomass, whereas their presence on extensive roof areas was significantly lower.

4.3. Inventory studies of fungi and their ecosystem services

One of the most underrepresented yet ecologically crucial groups in the field of green roof research are fungi. Saprotrophic fungi are key drivers of decomposition processes, facilitating nutrient cycling and availability. Symbiotic fungi, such as mycorrhizal species, form associations with plants and are essential for plant growth, health, and diversity. Conversely, pathogenic fungi also play a critical role due to top-down control mechanisms, thereby shaping plant community dynamics. To address the related research gap, we are investigating the fungal communities on the UFZ Research Green Roof using three

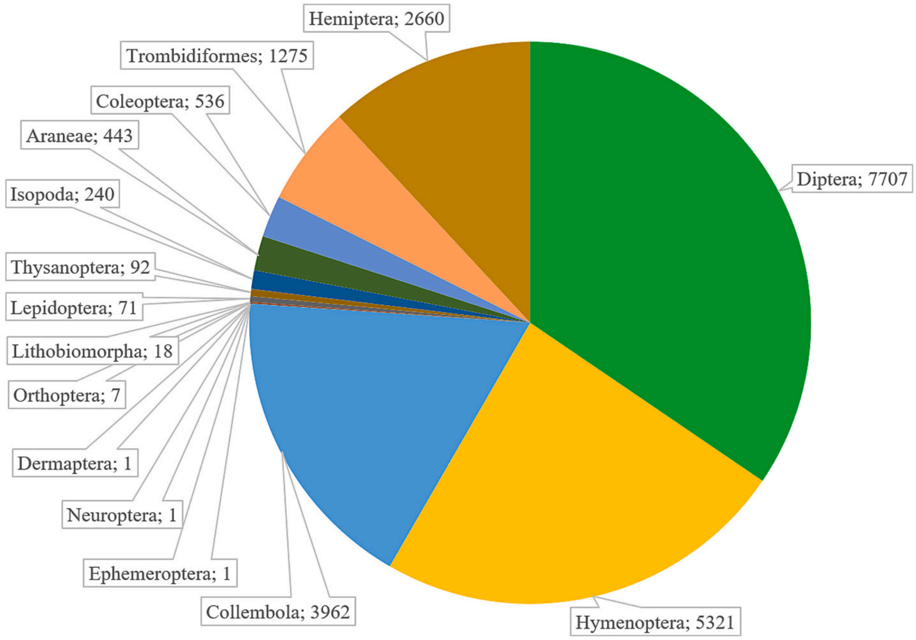

Fig. 9. Overview of arthropods trapped on the UFZ Research Green Roof in 2020 and 2022, summarized by order. The total number of individuals is shown by order rank. Due to their high frequencies, plant lice were excluded from the count. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

complementary approaches:

1) Optical methods: Since the establishment of the Research Green Roof complex, fungi have been recorded across all types of its vegetation. As a proven and cost-effective method - visual detection using a magnifying glass – has been used to identify active fungal stages, i.e. spore-forming mycelia or even complex fruit bodies. Fungal samples are collected, studied under microscope and identified to species level. The investigations focus on saprotrophic and obligate phytoparasitic fungi. The latter sometimes determine whether a plant species is able to survive on a green roof under the particular climatic conditions. So far, around 30 species of fungi have been identified on the UFZ Research Green Roof using the traditional microscopy. The lowest number of fungal species was found on the extensive green roof segments, although a few drought-adapted species with relevance for nature conservation aspects were detected.
2) Molecular biological methods: In addition to classical fruiting body identification, microbial DNA extraction from bulk soil samples is performed using commercial soil DNA extraction kits. PCR amplification and library preparation, specifically targeting the ITS region as a genetic marker for fungi, are then conducted. Soil fungal DNA is subsequently sequenced using Illumina MiSeq. After obtaining the sequencing data, quality filtering is applied and Operational Taxonomic Units (OTUs) are generated. These are further assigned to taxonomic groups by matching them to reference sequence databases such as UNITE (Nilsson et al., 2019) and EUKARYOME (Tedersoo et al., 2024) to get information about the community composition of soil fungi. Furthermore, fungal diversity across green roof types is assessed using OTU richness and diversity indices (e.g., Simpson diversity and evenness). Finally, the identified species are classified into different trophic groups (e.g., saprotrophs, symbionts, plant pathogens) using databases such as FUNGuild (Nguyen et al., 2016). This allows estimation of the proportion of plant growth-promoting and plant-damaging species, as well as those that play a crucial role in the decomposition of organic matter within the community.
3) Staining assay: Special attention is given to fungi that grow within plant roots, particularly arbuscular mycorrhizal fungi (AMF). These fungi are essential for plants, with more than 80 % of all terrestrial plants forming symbiotic relationships with them (Smith and Read, 2008). The AMF penetrate the plant root cells, facilitating the exchange of energy-rich carbon compounds from plant to fungus, and nutrients like phosphorus from fungus to plant. Additional important functions of AMF include protection against pathogens (Sikes et al., 2009) and enhanced drought stress tolerance (Wu, 2017) – functions especially relevant for green roof systems. The degree of root colonization by mycorrhizal fungi can provide valuable insights into both the soil condition and the overall health of the plants. To investigate this, root samples are excavated and their AMF are stained using the trypan blue staining method, following the protocol of Vierheilig et al. (1998). Mycorrhizal colonization is then quantified microscopically according to Trouvelot (1986). Initial investigations conducted in autumn 2024 on the species *Phedimus hybridus*, which occurred on both the extensive and semi-intensive (conservation-oriented) green roofs revealed that mycorrhization levels in this species are generally very low (relative abundance of arbuscules: 0.04 % ± 0.04 % [SD]). The type of green roof, extensive or semi-intensive, had no effect on the arbuscule abundance.

Together, these three approaches provide a comprehensive understanding of the diversity and complexity of the fungal community across different types of green roofs, their contribution to ecosystem functioning, and the identification of rare species that utilize green roofs as a refuge or stepping stone.

Pollutant mitigation by fungi on green roofs

Beyond taxonomic classification, it is important to investigate the functional capacities of fungi on green roofs – particularly their potential to alleviate environmental pollution. Typical classes of organic pollutants potentially entering green roofs via wet and dry atmospheric deposition include traffic-related compounds as polycyclic aromatic hydrocarbons (PAHs; arising from fuel combustion), benzothiazoles (vulcanizing accelerators), anti-corrosive benzotriazoles, and tire and road wear particles (all released through tire, brake and road abrasion), microplastics, endocrine-disrupting phthalic acid esters (plasticizers), as well as numerous biocides/pesticides found in plasters, paints, antifouling, and wood preservation agents (Müller et al., 2020; Rødland et al., 2022; Sun et al., 2022; Teil et al., 2006; Wicke et al., 2021; Wright et al., 2020; Zeng et al., 2010). Like in other types of ecosystems, plant-microbial associations on green roofs can be considered as sunlight-driven hotspots for the turnover and degradation of anthropogenic pollutants (Fester et al., 2014), whereby the essential microbial drivers of the natural degradation of pollutants can be found among bacteria, archaea and fungi. A very large variety of different fungi can attack organic environmental pollutants quite non-specifically in a co-metabolic manner, depending on a suitable and frequently plant-derived source of carbon and energy (Fester et al., 2014). Fungi are major decomposers of plant-derived organic matter and can closely interact with plants as mutualists or pathogens (Větrovský et al., 2019). Fungal diversity and functionality have often been demonstrated to be driven by plant diversity (Gil-Martínez et al., 2021; Shen et al., 2021, 2022), a relationship also observed on green roofs (Droz et al., 2022). Taken together, these characteristics advocate for a particularly close interrelation between the vegetation and fungal communities of green roofs with regards to biological pollutant transformation or degradation. In contrast, bacteria often employ more specific enzymatic pathways for attack on pollutants, often utilize them as carbon and energy sources, and can also involve alternative electron acceptors thus enabling metabolic activity also in anoxic zones (Fester et al., 2014). However, the relationship between bacterial and plant diversity is generally less pronounced than that between fungi and plant communities (Shen et al., 2021).

For the aforementioned reasons, the current research activities at the UFZ also aim at fungal capacities on green roofs for pollutant degradation, in the perspective of potentially employing such activities as part of a conceivable but certainly also complex pollutant barrier functioning of green roofs and other blue-green infrastructures in water cycles of urbanized areas. Moreover, due to the diverse environmental conditions with respect to vegetation and climate found there we also consider the UFZ Research Green Roof as a valuable and so far unexplored potential source of fungal producers of robust and efficient enzymes with applicability in recent circular bioeconomy approaches, examples for this being the current research activities aiming at the enzymatic re- (FINEST Project, 2025) or upcycling of plastic waste (Satellite Project PUreValue, 2025).

4.4. *Inventory studies of other soil organisms (e.g., bacteria, protists, nematodes)*

In addition to fungi, other important groups of soil microorganisms, such as bacteria and protists, are also underrepresented in green roof research (Wang et al., 2022). Bacteria play essential roles similar to fungi: many of them are crucial for decomposition processes, some can trigger plant diseases, and others form symbiotic relationships with plants. Protists, in contrast, are primarily important as consumers of bacteria; they may stimulate bacterial growth and accelerate decomposition processes. Both groups are detected and analyzed using the same DNA sequencing methods described in 4.3, with the 16S rRNA gene serving as a marker for bacteria and the 18S rRNA gene for protists.

Nematodes represent another essential group in the soil ecosystem, which has received little attention in green roof research so far (Wang et al., 2022). Nematodes are the most abundant metazoans globally and occupy all trophic levels, i.e., there are herbivores, bacterivores, fungivores, omnivores and predators, making them key components in the soil food web. Additionally, nematodes serve as valuable bioindicators, providing insights into ecosystem health. For instance, a high abundance of small, fast-growing nematodes can indicate major disturbances such as frequent droughts, whereas larger, slow-growing species tend to be absent under such stress conditions. Nematode community indices offer valuable information on environmental conditions, soil ecosystem functioning, pollutant levels, and whether a system is primarily driven by bacteria or fungi. Despite their substantial bioindicative potential, nematodes remain underrepresented in green roof research, with only one study published to date (Joimel et al., 2022). At the UFZ Research Green Roof, the aim is to address this knowledge gap by conducting regular nematode sampling across different green roof types. Soil samples are first collected and sieved. Nematodes are then extracted using a modified Baermann funnel method (Ruess, 1995), then fixed in hot formalin. All nematodes in each sample are counted under the microscope, and approximately 150 individuals per sample identified to the genus level (Bongers, 1988). Nematode diversity and community structure are assessed by calculating genus richness and diversity indices (Neher and Darby, 2009) and by classifying into the trophic groups (Yeates et al., 1993). Moreover, nematodes are categorized based on the colonizer (c)–persister (p) scale to calculate different indices to assess soil food web complexity and disturbance levels (Bongers and Bongers and Bongers, 1998; Ferris et al., 2001). Initial investigations were conducted in autumn 2024. Preliminary results indicate that green roofs can support a high diversity of nematodes. Notably, the semi-intensive roof showed particularly high values for both abundance and diversity, whereas the extensive roof showed significantly lower values. The detailed results are in preparation for a separate publication.

5. Multifunctionality and co-benefits

Multifunctionality and co-benefits are similar, yet distinct concepts for blue-green infrastructure, such as green roofs. Multifunctionality refers to the functionality (Cook and Larsen, 2021; Vijayaraghavan, 2016) associated to aspects of the design as well as to the operation and maintenance of a green roof system. Co-benefits, on the other hand, generally refer to positive impacts (Mayrhofer and Gupta, 2016), associated to blue-green infrastructures, that go beyond its original or primary design intent. Currently, both concepts are often being mixed in literature.

The different roof types on the UFZ Research Green Roof (see Chapter 2) have been designed and dimensioned towards stormwater – in terms of their storage and retention capacities (Fig. 3) – and biodiversity – in terms of their plant composition (Tables 1–3). With regard to operation and maintenance, the main initial functionality was biodiversity, both for irrigation as well as for weeding. Later, the green roofs were also operated in two modes (i) to maximize cooling or (ii) to save water (drought).

Next to the multifunctionality, the different roof types are used to map co-benefits. As co-benefits were not explicitly considered in the original design, dimensioning, or operation and maintenance, they are assessed using individual studies and experiments conducted at the research infrastructure. To visualize and map co-benefits associated to the UFZ Research Green Roof an analysis of different studies carried out at the different roof types from 2021 to 2024 was conducted. The co-benefits were extracted by systematically reviewing the key findings and the mentioned co-benefits from these studies (Arnold, 2021; Clauß, 2021; Sehrt, 2021; Stoeckel, 2021; Fischinger, 2022; Härtel, 2022; Hofmann, 2023; Münch, 2023; Ziehlke, 2023; Wollschläger et al., 2024).

Four overarching themes were identified: ecosystem services, climate adaptation, water resource management, and air quality improvement. Key facts and outcomes of each study were highlighted, and the co-benefits were categorized into subcategories and overarching categories. This systematic approach provided a comprehensive synthesis, contributing to a mapping of the collective green roof benefits (Fig. 10).

The co-benefits illustrated in Fig. 10 are based on a review of studies associated to the UFZ Research Green Roof and its specific design and operation modes. The different categories are based on different numbers of studies, a weighting of categories was intentionally not conducted. Additional studies will be included regularly to map co-benefits for the UFZ Research Green Roof.

6. Conclusions

The unique Research Green Roof infrastructure enables the

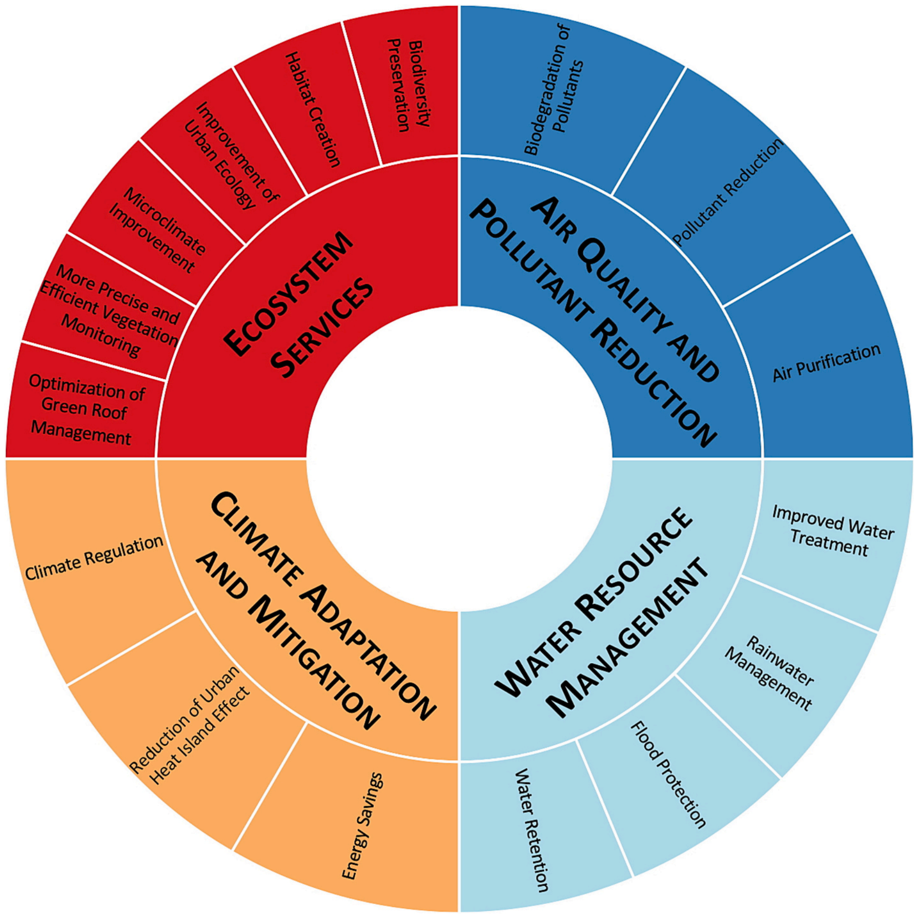

Fig. 10. Overview of co-benefits of the UFZ Research Green Roof. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

simultaneous investigation of multiple green roof functions while allowing for direct comparison between three different green roof structures and a gravel roof. Since 2020, a wide range of research activities has been conducted at this site, summarized in this paper. Further information on the research activities is available on the website https://www.ufz.de/researchgreenroof, along with a quarterly newsletter published there every three months.

Beyond its current use, the infrastructure is open for additional research activities and collaborations. Additional process engineering, meteorological, as well as biological investigations are possible. The green roof segments may also serve as reservoir of underexplored or untapped genetic resources with high potential value in resource- and energy-saving circular (bio)economy applications. Furthermore, the design allows key components to be transferred and applied to other experimental roofs, enabling comparative studies across sites with different regional and climatic conditions.

CRediT authorship contribution statement

Lucie Moeller: Writing – original draft, Supervision, Project administration, Investigation, Conceptualization. **Niels Wollschläger:** Writing – original draft, Visualization, Methodology, Investigation. **Christian Hecht:** Writing – original draft, Visualization, Methodology, Investigation. **Dietmar Schlosser:** Writing – original draft, Methodology, Investigation. **Peter Dietrich:** Writing – original draft, Methodology, Investigation. **Jan Friesen:** Writing – original draft, Visualization. **Ralf Trabitzsch:** Writing – review & editing. **Katy Bernhard:** Writing – original draft, Visualization, Methodology, Investigation. **Peter Otto:** Writing – original draft, Visualization, Methodology, Investigation.

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Declaration of competing interest

All authors have nothing to declare.

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Data availability

Data will be made available on request.

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