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Analysis of the Microclimatic and Biodiversity-Enhancing Functions of a Living Wall Prototype for More-than-Human Conviviality in Cities

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Abstract: This study analyzes the growing trend of urban green infrastructures, particularly green façade systems, in terms of their infrastructural relationships between nature and culture and their potential to act as bioclimatic layers mediating between the needs of flora, fauna and human habitation. An interdisciplinary approach is taken by combining the perspectives of social and engineering sciences to discuss the contribution of green façade systems for more-than-human conviviality in cities. Green infrastructures can support this endeavor by enabling functions that help to integrate the heterogeneity typical for semi-natural structures into urban ones, especially regarding microclimatic and biodiversity-enhancing functions. The theoretical distinction between "gray", "green", and "revolutionary" infrastructure is used to differentiate between conventional and posthumanist conceptualizations of urban naturecultures. The performance of the UNA TERRA living wall prototype as a green and revolutionary infrastructure is evaluated. The results show that the living wall has beneficial microclimatic effects and adds a heterogeneous habitat structure that supports biodiversity in the urban context. By adhering to "egalitarian humility" in design, the uncertainty and openness of more-than-human conviviality are acknowledged. The study finds that green infrastructures such as green façade systems can fulfill the criteria of revolutionary infrastructure if the contribution to local biodiversity and structural complexity is prioritized and the heterogeneous interrelations between human and non-human actors are taken into account.

Keywords: green infrastructure; green wall; living wall; prototype; bioclimatic layers; microclimate; conviviality; urban naturecultures; urban biodiversity

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1. Introduction

Green infrastructures such as urban green façade systems and living walls form a current design trend in the context of building physics, architecture, and the imagination of the green city [1,2], which attempts to integrate flora and fauna into the otherwise sealed surface area of the built environment. The emergence of green design solutions responds to human-made ecological crises and the need for sustainable urban transformations [3–5]. Cities play a central role in the climate change debate, as they are both major drivers of environmental degradation and climate change, as well as highly vulnerable to its negative impacts and extreme weather events [6–8]. Urbanization continues to expand both inward and outward at a tremendous rate [9,10], sealing more and more land and endangering natural environments that act as climate regulators and as habitats for diverse flora and fauna. As urban populations grow [11], this development will likely exacerbate the negative impacts of climate change on urban ecologies [8,12,13], such as the urban heat island effect [2,14–16], and further reduce urban biodiversity [17–19], especially if the already sparse open spaces within cities are not preserved. However, the socio-ecological crises accelerated by planetary urbanization [20–22] also make cities crucial sites of transformation if their potential for change is acknowledged and realized: “The urban transformation towards sustainability will succeed or fail in the cities” [23] (p. 13). Thus, there is an urgent need for urban design solutions that benefit urban ecologies and help to mitigate the negative impacts of urbanization.

In light of the pressing challenges, we discuss the potential of urban green infrastructure [24–29] to mitigate urban heat islands and biodiversity loss, and to prepare for a paradigm change towards more-than-human conviviality in cities. We use the example of vertical walls as a complementary habitat-forming element to act as bioclimatic layers [30] that benefit flora, fauna and humans alike [31,32]. Green infrastructures do not contribute to climate protection and biodiversity in cities per se, but need to prove their functions in this regard and move away from a utilitarian view of nature as a resource that can be manipulated indefinitely. We offer a unique perspective on these issues by discussing the nature–culture relations and infrastructural requirements of green and living wall systems, vertical habitats, and similar approaches from the perspective of social sciences and engineering studies. Specifically, we want to reflect on how green infrastructure, such as commercially available green façade systems, can act as a revolutionary infrastructure for sustainable transformation [33,34] by enabling functions that help to integrate the heterogeneity typical of semi-natural structures into the urban context, especially microclimatic and biodiversity-enhancing functions. Such infrastructure can contribute to the European Green Deal [35], which makes combating climate change a top priority. As part of this effort, nature-based solutions are prioritized. These measures are based on natural ecosystems and properties of nature [36].

In order to conceptualize the infrastructural characteristics of green infrastructure, the following section first presents the differentiation of “gray”, “green”, and “revolutionary” infrastructure suggested by Boyer [26] as the shared analytical framework for our interdisciplinary perspective. Next, research on urban naturecultures and assemblages is reviewed as a theoretical basis for understanding the nature–culture relations of cities from a social science perspective. We then present the methodological approach for analyzing and benchmarking the performance of a living wall as an example of green infrastructure in terms of its microclimatic and biodiversity functions. To illustrate the differentiation of infrastructure types, we introduce the UNA TERRA living wall prototype [31] located at the university campus in Stuttgart, Germany, as a case study. The characterization and structure of semi-natural environments is compared to urban environments regarding their environmental-physical functions and effects from an engineering perspective, which serves as the starting point for interpreting the performance of the prototype. Next, the results from the case study are presented to show that green infrastructures such as the UNA TERRA living wall can mitigate the lack of complexity and diversity in urban environments. The discussion begins with a general reflection on how human actors and the built environment relate to non-human species and nature in cities. Based on the results of the case study, we then discuss whether green solutions such as the living wall prototype can be considered as gray, green, or revolutionary infrastructure. Our analysis shows that in order to function as revolutionary infrastructure, green infrastructure must prioritize the creation of heterogeneity for non-human species, balance nature–culture relations, incorporate ecological perspectives into human infrastructure design, and embrace the uncertainty and openness of urban naturecultures.

Finally, we summarize the main findings of the case study and propose recommendations for stakeholders regarding the design and implementation of green infrastructures so that the requirements of revolutionary infrastructure can be met. As an outlook, we reflect on whether and how the development of revolutionary infrastructure might lead to a paradigm shift towards urban transformation and more-than-human conviviality. The issues of dissemination of appropriate designs, their adaptability, and the necessary care and maintenance are identified as key challenges to be addressed.

2. Materials and Methods

In this section, we introduce the differentiation of infrastructure types as analytical framework, describe the methods and concepts used to analyze the infrastructural relations and functions of green infrastructures from the disciplinary perspectives of social science and engineering studies, and present our approach for bridging the disciplinary perspectives towards an interdisciplinary analysis.

2.1. Analytical Framework: Differentiation of "Gray", "Green", and "Revolutionary" Infrastructure

The aim of our study is to reflect on the potential of green façade systems to act as bioclimatic layers [30] and as a revolutionary infrastructure for fostering urban transformations and more-than-human conviviality in the context of the Anthropocene and man-made ecological crises [3]. In order to conceptualize the infrastructural relations and functions that would be required for this paradigm shift to take place, a general understanding of infrastructures and a differentiation of infrastructure types is introduced: Infrastructures are commonly understood as "a system of substrates" [37] (p. 380) that exists in the background and forms the basis for other actions and functions to take place. In the context of planetary urbanization [20,22], much of the urban fabric can be seen as having infrastructural characteristics, so that modern civilization becomes inseparable from the "networked infrastructures" [27] we are surrounded by and inhabit [32,38]. However, modern infrastructures are largely based on the exploitation of fossil fuels and the idea of infinite resources. They would encompass certain "energopolitical" [24,25] features that have been pushing the planet to the brink of ecological collapse.

The Intergovernmental Panel on Climate Change (IPCC) explicitly warns of the lock-in effects of carbon infrastructures and the potential maladaptation of urban infrastructures, pointing to the issues of adaptability and affordability [7]. It distinguishes between social, ecological, and gray, physical infrastructure. While gray infrastructure often damages natural ecosystems and habitats, nature-based solutions in the urban context, such as green and blue infrastructure, have the potential to become effective climate change adaptation measures while benefiting biodiversity and human wellbeing [39] (see Chapter 6.3.4 and Figure TS.9 URBAN). Combining green and natural infrastructure with gray infrastructure could contribute greatly to climate change mitigation while reducing adaptation costs [7] (see also Figure 4.4). These findings underscore the importance of rethinking the infrastructural relations of urban environments and working towards the integration of nature-based solutions, such as green façade systems and similar designs discussed in this paper.

Indeed, the devastation caused by modern carbon infrastructures has been sparking increased efforts towards infrastructural transformation and innovation. Boyer [26] distinguishes three types of infrastructure and associated sociotechnical imaginaries of desired futures [40] which we employ as the central analytical framework of our study: "gray", "green", and "revolutionary" infrastructure. Gray infrastructure includes most large-scale technological infrastructures, such as power grids and pipelines, which are based on the principle of "command and control" [26] (p. 56) and assume human dominance over nature [41]. In contrast, green infrastructure recognizes the potential of natural processes to be harnessed for human purposes, including the goal of sustainable transformation. Large wind farms are a prominent example of this approach. However, Boyer argues that "much green infrastructure is really gray infrastructure at heart" [26] (p. 59). This is due to the still prevalent tendency to conceptually and practically exclude and exploit marginalized human and non-human actors in favor of resource extraction, human needs, and economic interests. The European Green Deal is an example of such approaches, as it seeks climate-friendly development within the human priorities of growth and competitiveness. Such practices lead to the same gray infrastructural impacts that have contributed greatly to the Anthropocene. Finally, revolutionary infrastructure is conceptualized by Boyer as an experimental and local practice that seeks to create new kinds of infrastructural relations: It would recognize the heterogeneity of non-human worlds and their innumerable interrelations with human ways of life, rather than homogenizing this diversity into a singular conceptualization of nature under human control. Such infrastructure would try to "create more balanced, respectful, and sustainable alliances between human and nonhuman forces" [26] (p. 63).

Based on this differentiation of infrastructure types, we want to reflect on the potential of green infrastructures to overcome the limitations of conventional designs, using the example of green façade systems. We analyze how these façade types can become a revolutionary infrastructure for more-than-human conviviality by adopting perspectives that also represent the needs of non-humans. To this end, we will integrate functions that help to implement the heterogeneity typical for semi-natural structures in the urban context, especially microclimatic and biodiversity-enhancing ones. Such infrastructures would create more caring cross-species relationships that benefit humans, flora, and fauna alike. This synergy can also be described through the concept of "bioclimatic layers". Davidová [30] uses this term to describe architectural elements such as walls, envelopes, and screens in the urban context that act as penetrable boundaries with a multitude of effects: connecting and separating both species and functions, enabling symbiotic co-living practices, catering to the specific needs of species through stratification, providing nutrition and shelter, as well as cooling and shading indoor and outdoor spaces, thus creating beneficial microclimates. For the context of green façade systems, this would mean that designs would need to overcome conventional limitations of green walls mainly serving the human desire for ever-green ornamental vegetation.

2.2. Social Science Perspective

As a first step towards analyzing the functions and infrastructural relations of green infrastructures with respect to the presented differentiation of infrastructure types, we develop disciplinary approaches that serve as a basis for a holistic interdisciplinary examination. From a social science perspective, we conducted a literature review to identify theoretical concepts that allow us to understand the interdependence between human society and nature for the urban context. These are used to reflect on the socionatural constitution of green infrastructures.

The work of Donna Haraway [42] and Bruno Latour [43,44] sensitized research to the overlooked interrelations and design possibilities between human and non-human habitats and opened up ways to overcome such dualisms methodologically and conceptually. The concept of urban naturecultures takes up this perspective by assuming a multiplicity of possible natures in cities. It does not ascribe a subordinate form of agency to non-human actors per se. Urban naturecultures are viewed as diverse, locally anchored compositions that produce human and non-human actors and artifacts in heterogeneous networks, spaces, and practices [32,45–50]. Similarly, urban spaces are considered as multi-faceted assemblages made up of social, technical, ecological, and geological elements: "The city is thus not an out-there reality, but is literally made of urban assemblages, through which it can come into being in multiple ways" [38] (p. 15). Building on these approaches, green infrastructures [24–26] form hybrid arrangements that link objects, animals, plants, human subjects, spaces, materials, and symbols. In the context of architecture and urban design, Davidová [30] discusses solutions such as Indian jaalis and Portuguese breathing walls as bioclimatic layers that enable microclimates and multispecies interactions.

Complementing these sensitizing concepts, urban political ecology is a theoretical approach that emphasizes the mediation of urban material flows and exchange processes through networked systems, especially infrastructure systems, in capitalist societies [27,51–54]. This school of thought analyzes the social, economic, and political power relations that influence urbanization and produce highly unequal urban environments, both at the local and global level [55,56]. Its scholars argue that the continued separation of nature and culture in modern society reinforces a harmful paradigm of control over nature that focuses on managing rather than preventing ecological crises. Speaking to these concerns, advocates of posthuman approaches call for a radical shift in perspective towards a caring and precautionary approach that takes the complexity of more-than-human relations into account [33,57–60]. From the acknowledgement of the heterogeneity and interconnectedness of urban assemblages [45,61], there comes a responsibility for professionals and users alike to abandon categories and design tools centered solely on humans and instead integrate more-than-human forms of urban co-production and conviviality [28,30,34,62–64].

2.3. Engineering Studies Perspective and Case Study

From an engineering studies perspective, the first step is to examine the characteristics and (physical) functions of semi-natural and urban environments. The differences between these two environments are elaborated based on a literature review, including current results from ecology, environmental and building physics studies. A case study is used to illustrate how the characteristics and functions of semi-natural systems, in terms of climate regulation and enhancing biodiversity, can be integrated into vertical urban areas. The case study exemplifies the construction and testing of the UNA TERRA living wall prototype and serves as the conceptual basis for the discussion of infrastructure types and accompanying nature–culture relations. In February 2022, the prototype was installed and tested as a demonstrator on an 8 m^2 south-facing façade 8 m^2 in size on the campus of the University of Stuttgart in Germany.

Figure 1 provides an overview of the survey concept for determining the data and quantifying the functions of the living wall system. The survey aims to measure the effects of the living wall on the microclimate, as well as biodiversity. To track the microclimatic effects, Narrowband-IoT sensors are used to record the air temperature 40 cm in front of the living wall (ifLWS), in the plant layer (inLWS_P1), and the surface temperature of the substrate (inLWS_P2) at 5-min intervals. To compare the data, the air temperature of the nearby research weather station Lauchäcker (WsL), which collects air temperature according to the requirements of the German Weather Service DWD [65], is used as a reference value. The presentation and interpretation of the results are based on data collected during the third and fourth week of July 2022. A vegetation survey was conducted in the summer of 2022 to exemplify the biodiversity potential of the prototype. Standardized observations of selected species groups, especially insects, were performed. The structural richness and flora were identified by listing all species with information on the cover and abundance of flowers. On 13 July 2022, an exemplary survey of the fauna was conducted. Three sample squares of 1 m^2 each were selected, and all insects sighted in these squares were listed over a period of 5 min per square, and superordinate species groups were distinguished.

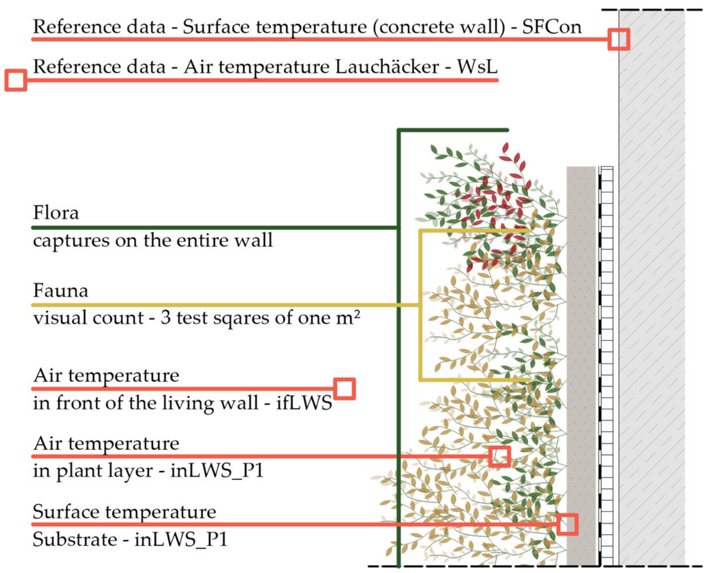


Figure 1. Conceptual survey design to quantify the impact of the UNA TERRA living wall prototype on microclimate and biodiversity. The survey measures parameters such as air and surface temperature, flora, and fauna.

2.4. Interdisciplinary Discussion

After establishing the disciplinary perspectives and prototype performance results, the goal is to combine them into an interdisciplinary holistic evaluation. We use Boyer's distinction of gray, green, and revolutionary infrastructure [24–26] as an analytical framework to jointly discuss the infrastructural characteristics of green infrastructures such as the UNA TERRA living wall and similar green façade systems. This approach allows us to re-evaluate our findings and develop a shared perspective on whether innovative approaches to green infrastructure could represent a paradigm shift towards the creation of revolutionary infrastructures for more-than-human conviviality and sustainable urban transformation in the future.

3. Results

Based on the literature review, the characteristics of semi-natural and urban structures are compared, particularly in terms of microclimatic properties and biodiversity. The design of the case study and the results of testing its performance are then presented.

3.1. Characterization of Semi-Natural and Urban Environments and Functions

Natural environments differ significantly from urban structures in terms of their characterization, diversity, and their microclimatic and biodiversity interactions and functions. Semi-Natural environments, such as forests, exhibit high structural complexity at a finely resolved spatiotemporal scale [66]. This structural complexity promotes biodiversity by increasing environmental heterogeneity, microclimate, and microhabitat variations [66–70]. The positive relationship between species richness and environmental heterogeneity is widely accepted in ecology [69,71,72]. In ecological research, the importance of microclimate in semi-natural structures for influencing flora and fauna, such as plant regeneration and growth, nutrient cycling, and the formation of (specialized) wildlife habitats, has become an important component [73]. In this context, the three-dimensional stratification of animal and plant communities in forests is a prime example of how microclimate and habitat not only interact [68] but also result in differentiated habitat niches for multiple organisms such as epiphytes, wasps, beetles, moths, amphibians, birds, and mammals in a small space. As Figure 2 illustrates, the stratifications are distributed both horizontally (from a treefall gap to a closed canopy) and vertically (from the soil to the canopy). For example, the canopy forms a vertical thermal insulator and buffers the microclimatic conditions below the canopy, affecting biological and ecological processes differently above, within, and below the canopy [74,75]. Flora and fauna follow their environmental preferences, inhabiting different niches in this process. For example, forest lichens and mosses show clear patterns along their distribution and local temperature and moisture gradients [66]. In forest structures, it has been demonstrated that the influence of the microclimate on local biodiversity is significant, and entire amphibian communities can change abruptly across a microclimate gradient of only a few meters [66]. According to Frenne [66], heterogeneous microclimatic conditions should be maintained to provide suitable conditions for the greatest number of species within a stand.

Cities have significantly lower structural diversity. At the same time, cities must perform a variety of functions that occur on different urban land uses. Physical components such as residential, commercial, and industrial buildings, roads, and utility infrastructures support a variety of human activities, including living, working, commuting, and recreation. In addition to these physical components, city services such as energy, water, and waste management also play a critical role in maintaining the functionality of the city. For both the physical and service components, numerous damage-free and safety requirements must be met. At the same time, cities and their inhabitants are exposed to risks that result from the design of the city itself. The transformation of semi-natural vegetative structures into sealed "gray" infrastructure surfaces significantly changes the energy balance (storage and exchange of heat) and the water balance as well as biodiversity. In recent years, studies characterizing the urban microclimate, especially the urban heat island effect (UHI) and its adaptation strategies, have increased greatly [76]. The UHI describes the effect of an urban temperature increase compared to rural areas and results directly from the exposure, shape, size, and geometry of buildings and streets, as well as their surface design. Figure 3 summarizes factors responsible for the UHI. Although many complex phenomena and interactions are responsible for the UHI, researchers have already identified circumferential causes of the UHI [2,14–16]:

- Increased surfaces and heat storage mass due to roads and building envelopes
- The change in surface characteristics due to a lower surface albedo
- Outgoing long-wave radiation from the surfaces
- Lower transpiration and evaporation of the surfaces
- Additional anthropogenic heat sources.

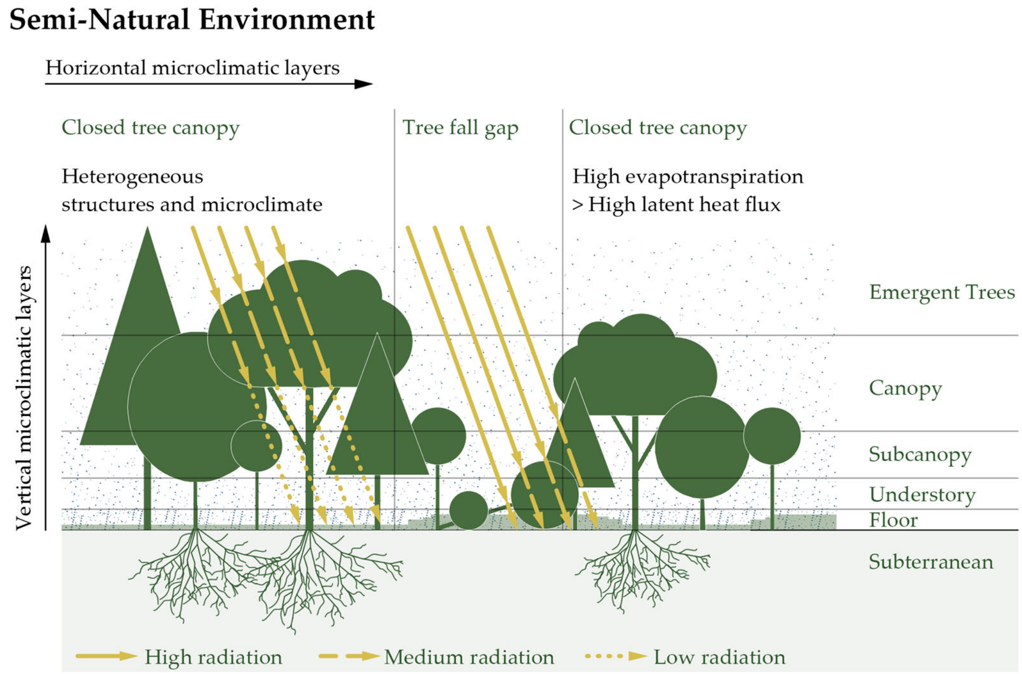


Figure 2. Characterization of semi-natural environments (using the example of temperate forests) and the formation of horizontal and vertical layers that contribute to the formation of heterogeneous microclimates and microhabitats.

As a response to urbanization, climate change, and the urban heat island (UHI) effect, green infrastructure is being recognized as a crucial element of sustainable, socially responsible, and health-promoting urban development [2]. In this regard, green façades are gaining increased importance as a key component of urban green infrastructure [2]. Nevertheless, it is crucial to prioritize compliance with building physical requirements and functions. This includes not only ensuring a damage-free building envelope but also fulfilling hygrothermal, acoustic, and fire protection functions and requirements.

Current studies on green façades primarily address on the thermal effects on the micro- and indoor climate, as demonstrated in recent decades [77–80]. In relation to the UHI, it has been shown that green façades have positive effects on both urban and building physical effects on the exterior, building envelope, and interior. A visual summary of the effects and functions of a green façade compared to a blank wall is illustrated in Figure 4. The green layer changes the energy balance of the surface and the ratio of the reflecting, absorbing, and transmitting radiation [79]. This has an impact on the urban heat island (UHI) effect, building envelope, and indoor climate. On one hand, the green layer provides shading for the building envelope, reducing the incoming radiation and minimizing heat absorption by the heat-storing building components. [79]. As a result, the outgoing long-wave radiation to the environment is reduced [31]. At the same time, plant surfaces are typically cooler than a blank reference surface on sunny summer days. By transpiring water over the leaf surface, plants specifically regulate the leaf surface temperature to counteract overheating [79]. In comparison to a blank wall, a green façade increases the latent heat flux while reducing the sensible heat flux emitted from the surface to the surroundings. This results in a cooler surface temperature of the built environment, which has a positive impact on the human-bioclimatic situation. Additionally, the decreased net radiation input reduces the heat flux density conduction through the building envelope, which can lead to a decrease in heat input to the building's interior [81].

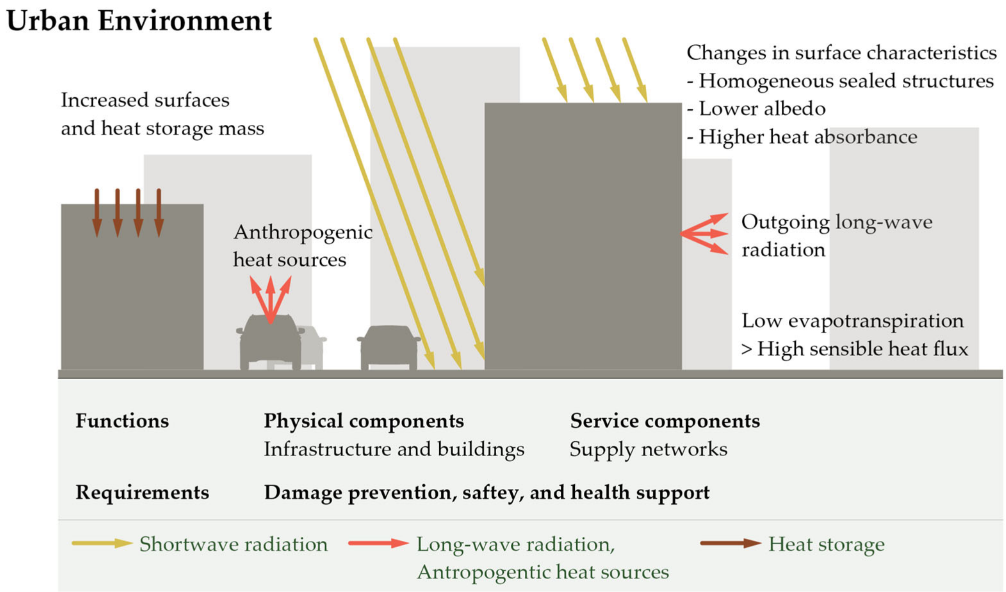


Figure 3. Characterization of urban environments, including their functions and requirements, as well as the effects on surface design and microclimate.

The potential of green façades to increase structural diversity and enhance heterogeneous microclimates and microhabitats has not been fully explored in research so far. While the synergistic effects of an urban flora on the associated fauna are often mentioned, they are not investigated in more detail [80]. The few existing studies that specifically address biodiversity in green façades emphasize that the biodiversity-enhancing potentials of green façades are strongly dependent on plant composition [82,83], structural richness [84] and microclimate [85]. According to Mayrand and Clergeau [83], ecological potentials are often overlooked in the planning and maintenance of green façades, leading to a failure to realize their full potential. The design of the UNA TERRA living wall prototype is designed to address these research gaps and limitations.

3.2. Case Study of the UNA TERRA Living Wall

This section presents the development of the UNA TERRA vertical living wall prototype, which suggests how gray, vertical infrastructures can be transformed to include additional functions of more-than-human conviviality. To achieve this, functions are activated that contribute to the formation of heterogeneous structures and layers, which in turn enhance microclimatic richness and biodiversity in urban areas. Organic and mineral materials are used to increase the structural richness in the vertical dimension. The system thus combines greening, habitat structures, and food supply for selected insects in a synergistic manner.

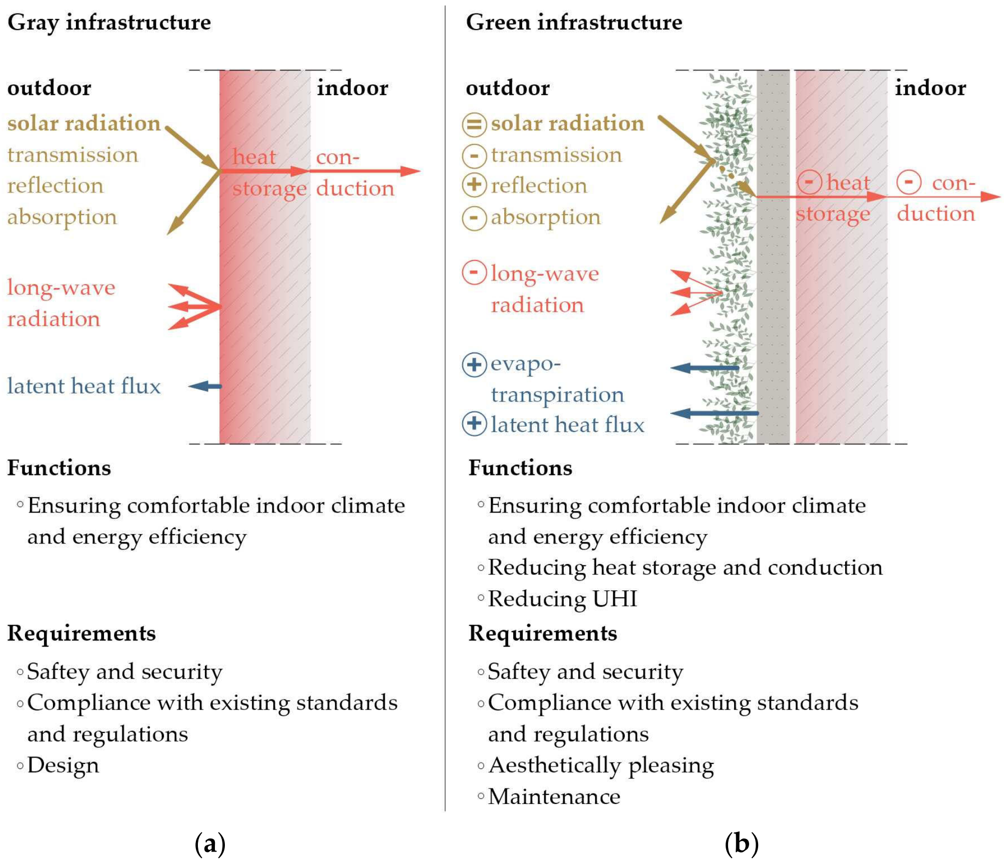
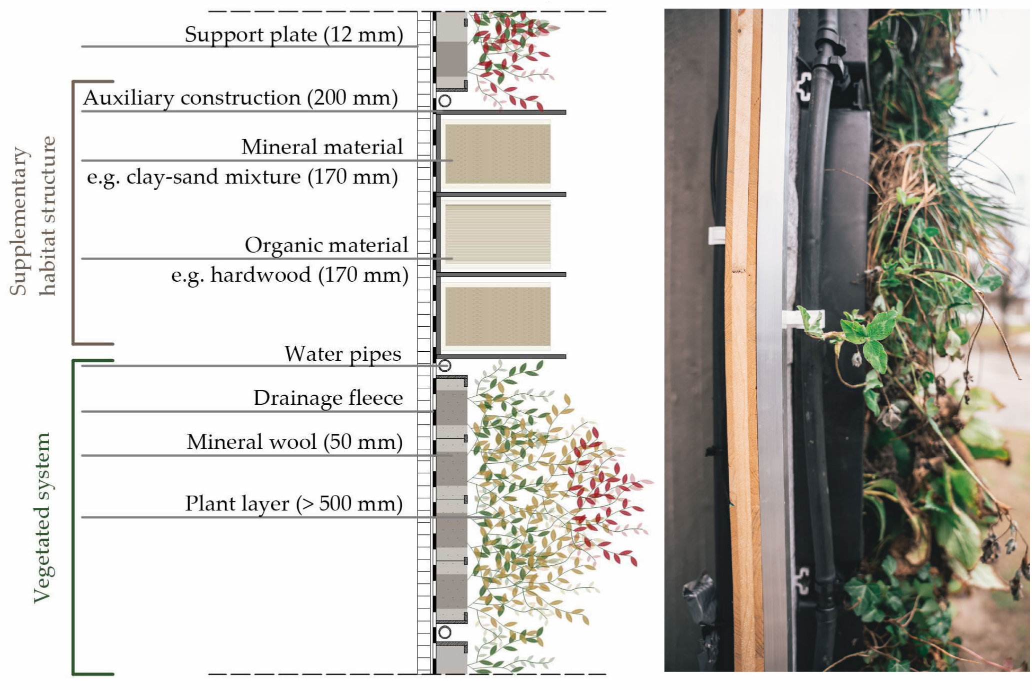


Figure 4. Comparison of gray infrastructures (**a**) and green infrastructures (**b**) using the example of a vertical wall: (**a**) Illustration of a bare concrete wall with physical effects on the microclimate and indoor climate, as well as functions and requirements. (**b**) Illustration of a living wall system with physical effects on the microclimate and indoor climate, as well as functions and requirements. The "+" illustrates the increase in an effect and the "−" a reduction compared to the concrete wall (gray infrastructure).

3.2.1. Concept

Basis of the development of the UNA TERRA prototype is the Biomura-Module of HELIX Pflanzensysteme GmbH. The prototype explores the integration of organic and mineral materials to increase the structural richness on a vertical wall. Figure 5 illustrates the construction of the UNA TERRA prototype. It consists of a weatherproof vertical support plate covered with a drainage fleece. A 50 mm layer of mineral wool forms the substrate layer for plants. The plants that are used in the module are pre-cultivated in the greenhouse and placed, along with their root balls, directly into the mineral wool. The choice of plant species in the UNA TERRA prototype was made by the researchers with the aim of ensuring a heterogeneous structure with changing and high flowering occurrence, as well as nectar and pollen content, from April to October. Horizontally oriented drip hoses automatically water the plants. In addition, habitat elements for insects were added to the design, such as untreated hardwood with holes of different nesting diameters, or clay and sand mixtures. The habitat structures are installed vertically with the help of an auxiliary construction made of non-toxic and waterproof fiberboard. The choice of the materials and the structures of the components is intended to appeal to a large range of insects and birds, especially cavity-nesting wild bee species of various sizes.



(**a**) (**b**)

Figure 5. Illustration of the structural design of the UNA TERRA living wall prototype. (**a**) Technical drawing of the vertical profile of the prototype. In addition to heterogeneous plants, further mineral and organic structures are considered for the formation of habitats for insects and birds. (**b**) Photograph of the construction in February immediately after the installation.

3.2.2. Microclimatic Functions

The plant layer significantly modifies the microclimate of the UNA TERRA prototype. Figure 6 illustrates the air temperature of WsL (sensors at the Lauchäcker research weather station), ifLWS (sensors 40 cm in front of the green wall) and inLWS_P1 (sensors directly in the planting layer). The comparison of data from WsL and ifLWS shows that the air temperatures at ifLWS, influenced by the campus buildings, have already increased by several Kelvin. On the one hand, peak daytime temperatures are significantly higher, while on the other hand, nighttime cooling is reduced. The comparison of WsL and ifLWS shows the typical characteristics of the UHI compared to rural areas. The mean value of WsL over the observation period of 2 weeks is 21.7 °C and for ifLWS 24.6 °C. The air temperature of inLWS_P1 shows significantly lower temperature amplitudes compared to WsL as well as ifLWS. For example, the maximum measured air temperature of inLWS_P1 is 30.6 °C on 20 July, which is 10.6 K lower than ifLWS. Thus, the air temperature is also lower than the air temperatures of WsL. At the same time, nighttime cooling is reduced at inLWS_P1. The temperatures at night are not only significantly above the temperatures of WsL, but are also slightly higher than the temperatures of ifLWS. The mean value over the observed two weeks is 21.2 °C at inLWS_P1 and is thus below the mean value of WsL due to the lower temperature peaks. In summary, a significant buffering of the air temperature by the plant layer can be identified. The plant layer contributes to the reduction in both the maximum and minimum temperature peaks.

Figure 7 compares the temperature distribution of the surface temperature at the substrate (inLWS_P2), the air temperature in the plant layer (inLWS_P1), the air temperature 40 cm in front of the green layer (ifLWS), and the surface temperature of a bare concrete wall (SFCon). Each case shows the minimum and maximum temperatures (excluding outliers) as well as the lower and upper quartile with the median. It can be observed that the plant layer helps in buffering the temperatures. The effect of temperature buffering increases as the sensor gets deeper into the plant layer. Thus, comparable effects to the microclimatic effects of natural stratification can be identified. Comparable to the canopy in semi-natural forests, the plant layer acts as a thermal insulator. The temperature buffering effect observed in the UNA TERRA green layer can also be observed in conventional green façades available on the market. However, as shown below, the microclimatic heterogeneity within the green structure is increased by the integration of habitat modules made of mineral and organic materials. As demonstrated in Section 3.1, there is a consensus in ecology that these microclimatic variations increase structural diversity and enhance biodiversity.

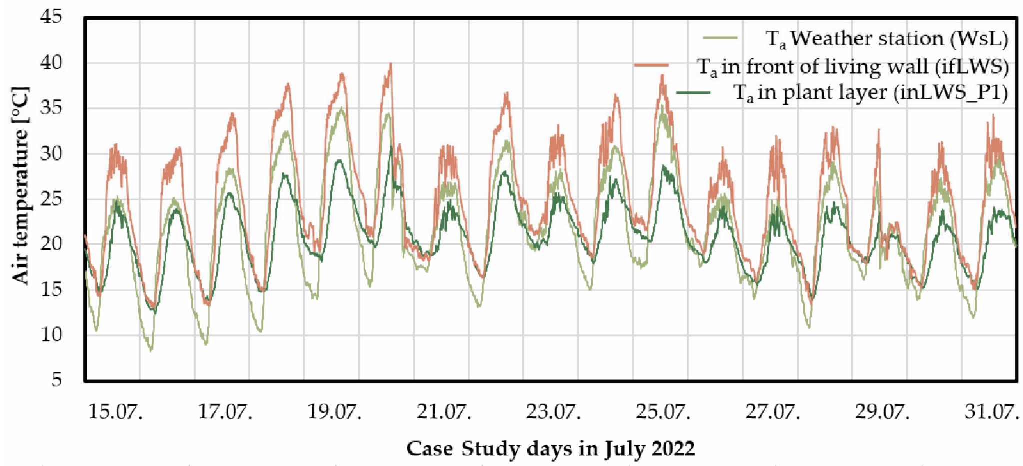


Figure 6. Comparison of the measured air temperatures from 15 to 31 July 2022 of the weather station Lauchäcker—WsL (light green), 40 cm in front of the living wall—ifLWS (red) as well as in the plant layer—inLWS_P1 (dark green).

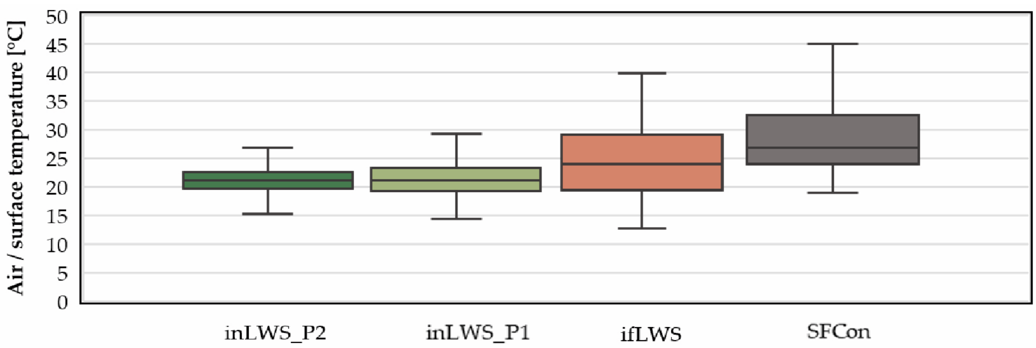
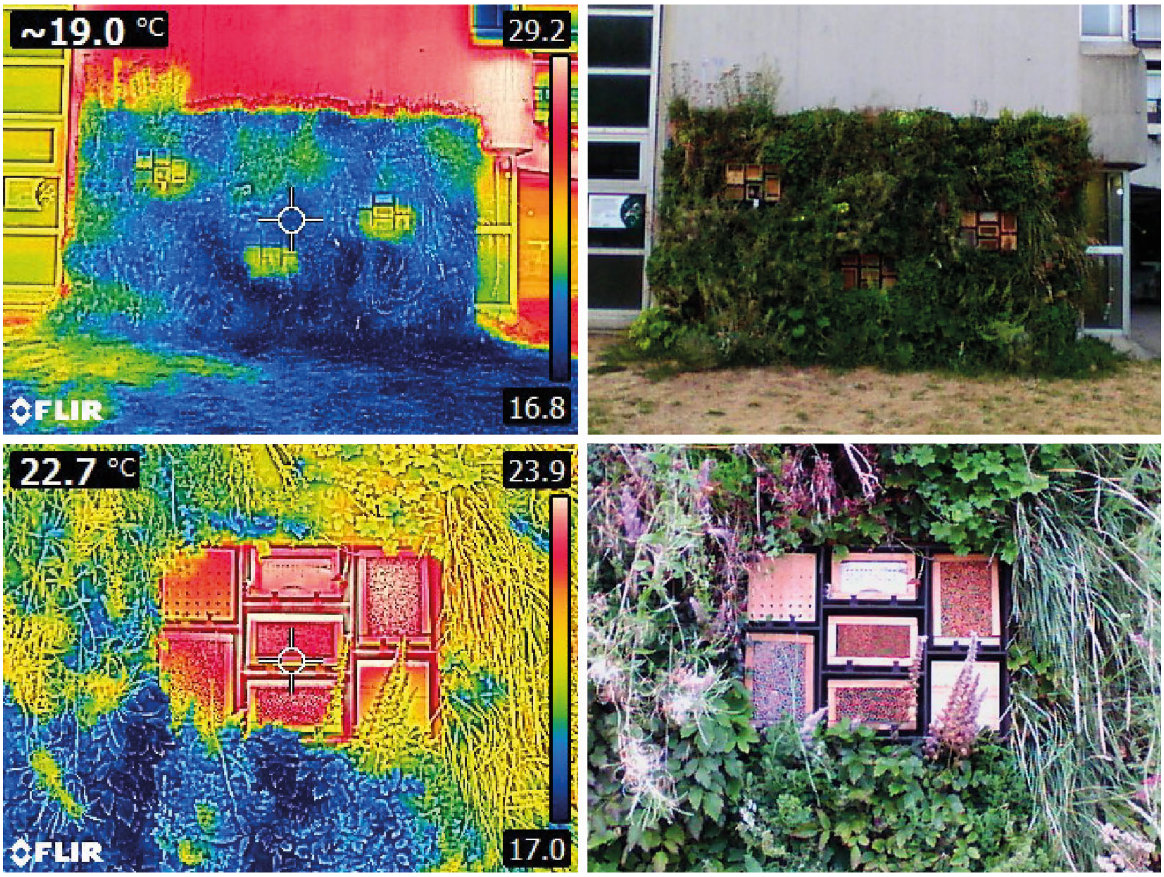


Figure 7. Comparison of the temperature distribution with a box plot diagram. Illustrated is the surface temperature at the substrate—inLWS_P2 (dark green), the air temperature in the plant layer—inLWS_P1 (light green), the air temperature 40 cm in front of the living wall—ifLWS (red) and the surface temperature—SFCon (gray).

This effect is demonstrated by a thermographic image taken in the evening hours after sunset, without the influence of direct solar radiation (Figure 8). The surface temperature of the prototype is significantly cooler than the reference concrete wall, and the deliberate combination of plants and habitat structures creates more heterogeneous surface temperatures. The concrete surface has a nearly uniform temperature of over 26 °C, whereas temperatures in the prototype range from over 16 °C to under 25 °C.



(**a**) (**b**)

Figure 8. Thermographic images of the prototype in the late evening hours on 26 July 2022, after a radiant summer day. Above is the entire wall and below is a section with a habitat module. (**a**) Illustration of temperature profile. (**b**) Image of the thermographic object as a photograph.

3.2.3. Biodiversity-Enhancing Functions

Figure 9 provides an exemplary view of the prototype in February 2022, immediately after the installation, as well as in April, May, June, September 2022, January and March 2023 (two, three, four, seven, eleven, and thirteen months after the installation). The plants have adapted to the vertical habitat, and a dense green layer has formed with the support of the controlled irrigation, which includes nutrient addition. On the wall, 34 species of plants were installed according to a planting plan. Just four months after installation, ecological monitoring identified 36 plant species on the wall. *Taraxacum sect Ruderalia* (common dandelion) and *Cirsium arvense* (field thistle) were not intentionally planted, but established themselves spontaneously. The prototype has developed two vertical plant layers in response to site conditions and microclimatic effects, as shown in Figure 10. The first layer, starting from the substrate, contains plants that can tolerate less sunlight, such as *Hedera* Helix (common ivy). The second outer layer contains plants that grow in half-light to full-light conditions, such as *Linaria vulgaris* (true toadflax). Like semi-natural structures, the plants have formed stratifications in response to the microclimate. On 13 December, selected plants were carefully pruned by a landscaping expert, taking care not to destroy potential habitat structures. For example, the pithy and dead stems of *Cirsium arvense* (field thistle) and the *Achillea millefolium* (yarrow) are used by various insects for overwintering or egg-laying, and these plants were left standing.

Figure 9. Development of the prototype over an entire year (from top left to bottom right): on (**a**) 8 February 2022; (**b**) 3 April 2022, (**c**) 19 May 2022; (**d**) 21 June 2022; (**e**) 20 September 2022; (**f**) 23 January 2023, and (**g**) 22 March 2023. These photographs illustrate the condition of the living wall immediately after the installation and two, three, four, seven, eleven, and thirteen months later.

Figure 10. (**a**) Photograph of the plant depth in July. In response to the site conditions and the microclimate, two vertical plant layers have formed. The first layer (starting from the substrate) is formed by herbs up to a depth of 45 cm. The second layer contains plants that grow in half-light to full-light conditions, such as *Cirsium arvense* (field thistle), *Trifolium pratense* (meadow clover), and *Epilobium* (willowherb). (**b**) Detailed photograph of the planting layer in June. In the background grows *Hedera helix* (common ivy) and in the foreground *Geranium x cantabrigiense* (cranesbill).

An ecological monitoring of the associated fauna was carried out on 13 July 2022. Since only one ecological monitoring has been carried out so far, the results are to be evaluated as initial, not yet completed, and exemplary findings. To consolidate these initial findings, further investigations must be carried out in the following months and years. During the observation period of 15 min, a total of 62 animals were observed on the three test squares with a total of 3 m^2. Figure 11 illustrates the observations made on the three test squares A to C. Wild bees constituted the largest proportion with a total of 29 observations, followed by bumblebees (a specific genus of wild bees) and hoverflies. Other taxa observed included beetles, ants, and butterflies. No animals were observed on the reference concrete wall during the same period.

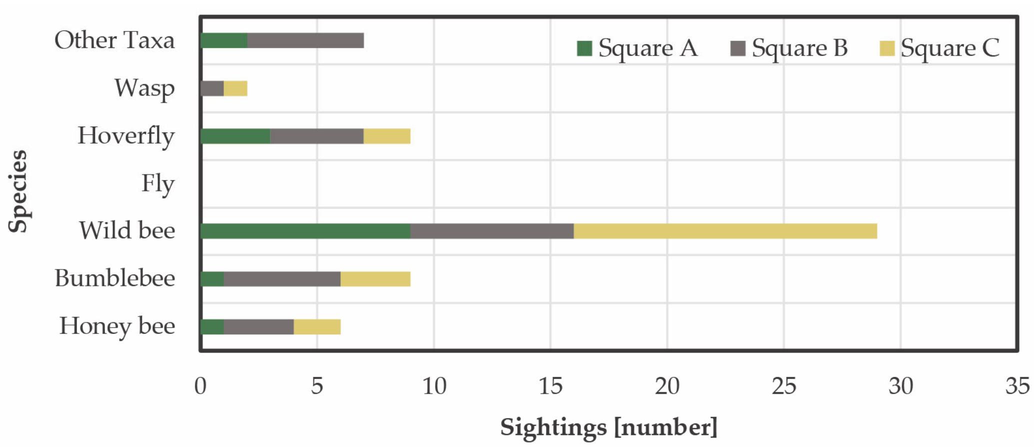


Figure 11. Sightings of different species within test quadrats A through C over a 15-min observation period during an initial exemplary survey of the accompanying fauna that took place on 13 July 2022.

Figure 12 exemplifies some of the species observed on the prototype. However, these sightings are not part of the systematic observations and were instead unsystematic and explorative/supplementary. In addition to using the plants as a food supply, the supporting habitat structures such as the sand and clay mixture or the hardwood block were used by wild bees as nesting sites, with the hardwood block with a hole diameter of <2 mm being particularly well accepted. In October, all nest entrances in this test field were closed as shown in Figure 12e in the bottom left corner. Nest closures can be identified by a sealed nest tube entrance. In this case, the tubes were closed with wood particles, small stones, and clay. Such closures are made, among others, by the Heriades species and the Passaloecus species.

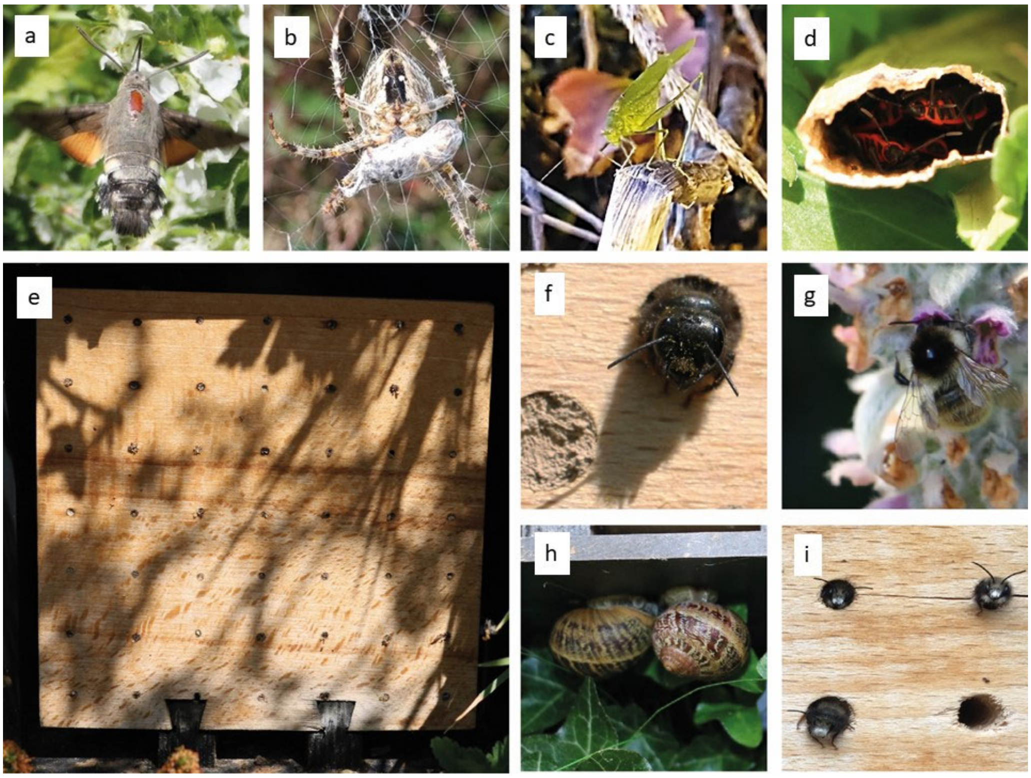


Figure 12. Exemplary photograph of the species on the prototype. (**a**) *Macroglossum stellatarum* (Hummingbird hawk moth). (**b**) *Araneus diadematus* (European garden) spider with a bee in the web. (**c**) *Tettigonia viridissima* (Green bush cricket). (**d**) *Pyrrhocoris apterus* (European firebug) in dead plant stem. (**e**) Hardwood block with nest entrances completely closed. (**f**) Wild bee leaving habitat structures. (**g**) Wild bee on flower. (**h**) *Cornu aspersum* (European brown garden snail). (**i**) Several wild bees leaving the habitat structure.

3.2.4. Summary

The case study demonstrates that the UNA TERRA living wall has a significant impact on microclimate modification. In addition to the cooling effect provided by the plants, the integration of mineral and organic habitat modules increased microclimatic heterogeneity, mimicking semi-natural structures. However, this study only provides a preliminary and exemplary insight into the development and effects of biodiversity-enhancing façades. While numerous benefits have already emerged after the first year, further research is necessary to investigate the long-term impacts of the prototype on microclimatic and biodiversity-related functions.

4. Discussion

In the previous section, we first compared the structure of semi-natural and urban environments and argued that urban structures lack the heterogeneity and complexity of vertically and horizontally stratified microclimates and microhabitats provided by ecosystems such as forests. To illustrate how green infrastructures could address this, we presented the design approach of the UNA TERRA living wall prototype. The results showed that this system provides beneficial ecological and environmental-physical functions similar to those of semi-natural structures. We continue by conceptualizing the interdependence of human structures and ways of life with non-human species and nature in cities using the concept of urban naturecultures and post-humanist approaches to cohabitation. This is followed by a discussion of the different types of infrastructure, as established by our analytical framework, in relation to the infrastructural characteristics and functions of the UNA TERRA prototype and similar systems. The goal is to reflect on the potential of green infrastructures to open up a space for more-than-human conviviality.

4.1. Rethinking the Nature of Cities

While nature is typically externalized in gray infrastructures and objectified primarily as a resource to be exploited and optimized in green infrastructures [26], revolutionary approaches to ecology aim at fundamentally recognizing the uncertain interconnections between human habitation and natural co-worlds [50]. From an ecological point of view, buildings are primarily planned as containers for people, but at the same time they can be seen as spheres of a contextually defined conviviality, transforming urban natural planning and its results into cosmopolitical projects. Based on the relationship of "symbiotic mutualism" [86], humans and non-humans are inextricably linked in urban naturecultures: "'We' humans, both as a species and as particular groups of humans, both generally and specifically, also appear as dependent on 'them', systematically, for our existence" [63] (p. 39). Regarding this interdependence, it is important to recognize that the transformation of urban ecologies is not only the result of human design, but also gets triggered by non-human creatures. They are reshaping urban open spaces and backyards, adapting their foraging and living behaviors to the urban environment while also changing human practices and self-conceptions [57]. Our case study illustrates how animals such as wild bees, bugs, and spiders are adapting the provided human structure for their own needs.

Since the 2000s, urban development concepts such as the green city or green infrastructure have changed the perception and valuation of urban green spaces under the pressure of rapid sealing through indoor and outdoor growth, i.e., (re)densification and suburbanization [1]. As a result, the question of where more-than-human species and artifacts are accepted and integrated, and where they are confined to residual spaces, is decided in shifting processes of classification and association [49,57]. Today, negotiations of urban naturecultures are taking place against the backdrop of desired "ecosystem services" and crisis management [87], whereas earlier ideals were aimed at recreation, leisure, and subsistence, especially for the middle and working class. In the case of the UNA TERRA prototype, the selection of plant species can be seen as an expression of research cultures and controversial public interests, and as a subject of political negotiation of the "common good". Analogous to the migration debates, projects for urban green spaces often integrate native species and assemblages, while once absent species such as the Canadian goldenrod are fought as foreign invaders.

In the following, nature–culture relations enabled by green infrastructures such as the UNA TERRA living wall are discussed in relation to the infrastructure types developed by Boyer [26].

4.2. Green Façade Systems as Gray Infrastructure

The roofs and walls of buildings, as well as roads and pavements, can be understood as a massive gray infrastructure [26] that provides a durable and flat shield against the natural environment and non-human actors. For example, there are numerous information sheets for engineers and architects that present design and material-specific solutions (with and without biocidal agents) to counteract microbiological growth on façades [88,89]. These surfaces are designed to prevent the emergence of unwanted and uncontrollable habitats, such as algae growth or insect invasion. As a result, not only is the interior human domain separated from the exterior natural environment, but non-human species and natural processes are framed as disturbances that must be expelled from cities at all costs [57,63]. From the perspective of building physics, these envelopes also serve a climatic function: They insulate the indoor climate from outside climatic conditions, ensuring a comfortable indoor climate and while conserving (carbon) energy used to cool or heat the interior. Combined, these design characteristics lead to the already discussed homogeneity of urban structures and their negative impacts on microclimates and biodiversity.

In contrast, green façade systems, living walls, and other forms of green infrastructure, such as parks or urban gardens, appear as a green infrastructure that is added to the sealed surfaces of cities to mitigate the harmful effects of gray infrastructure. In the case of the UNA TERRA prototype, one of its main accomplishments is to integrate a heterogenous, three-dimensional structure that mimics natural environments. Therefore, we argue that green infrastructure solutions do not function as gray infrastructure per se, as they generally integrate otherwise excluded non-human species and natural processes into urban life rather than externalizing them. However, green infrastructure might still function similarly to gray infrastructure, which will be discussed in the next section.

4.3. Green Façade Systems as Green Infrastructure

According to Boyer's definition of green infrastructure, it is defined more by its specific relationship to nature than by the implementation of greenery or wildlife. Green façade systems and wind farms both fit into the same general principle: "[N]ature becomes a kind of robo-engineer in this model, an ensemble of materials and forces that can easily be co-opted by humanity to achieve its goals" [26] (p. 58). In the case of green façade systems, conventional approaches have been focusing on the aesthetic appearance alone. The thermal benefits and reduction in air pollution and noise from greening are being studied and discussed as a complement in recent years, due to the need for climate change adaptation. As the results from the case study of the UNA TERRA prototype show, the living wall indeed improves the thermal performance of the concrete wall through the creation of bioclimatic layers. The dense green layer acts as a thermal protective layer and buffers the temperature peaks. This shows comparable microclimatic effects that can be observed in forests as a result of the temperature buffering of the canopy layer. However, these results are case-specific and cannot be directly translated to other contexts. The successful design and implementation of similar green infrastructures requires careful analysis of the local urban ecology and built environment it is deployed in.

When comparing the blank concrete wall with the prototype, nature is the better engineer. However, as Boyer [26] points out, green infrastructure is at risk of having similar effects like gray infrastructure by simplifying the heterogeneity of nature into a passive resource that can be managed and controlled: "By treating nonhuman entities (in Nature) as Objects that lack agency, and therefore "inferior" to Subjects who act, modern cultures develop technological instruments aimed at controlling Objectified Nature and its dynamics, if only to facilitate incessant resource extraction" [33] (p. 250).

As discussed, most conventional green wall solutions pay little attention to biodiversity and structural complexity. The selection of plant species often follows anthropocentric concerns, such as the desire for evergreen vegetation regardless of the season, and the whole infrastructure might be imagined to serve a garden-like aesthetic function rather than acting as a habitat for wildlife. Through such design decisions, the separation between the human and natural worlds [42–44] typical for gray infrastructure is essentially reproduced: The inorganic surface of the building still shields the human structure from its natural environment, with the plant layer acting as an additional resource for cooling. The resulting urban assemblage [45,61] presents an infrastructure for reinforcing the nature–culture separation performed by the wall rather than actively engaging in the more-than-human co-living practices of urban naturecultures.

We therefore argue that urban green infrastructures may reproduce the notion of "City-ness" [63] as the antithesis of nature and countryside by limiting ecological interrelations and non-human lifeforms to separate spaces that can be controlled and managed: zones in which flora and fauna are tolerated, such as parks, lawns, tree beds, or botanical and zoological gardens. This way, cities are being imagined "as places that have somehow risen above the physical constraints of "nature"—as places of enlightened human value and technological mastery" [28] (p. 192). This contradicts the messy, hybrid reality [47] of "living cities", meaning the process of "ecological co-fabrication in which the life patterns and rhythms of people and other city dwellers are entangled with and against the grain of expert designs and blueprints" [34] (p. 134). Whether green infrastructures recognize the "multispecies entanglements" [28] of both natural and urban ecologies or not, we humans are inextricably connected to innumerable non-human species inhabiting the natural habitat of the city. This becomes clear when the monoculture of a green wall collapses due to a lifeform labeled pest, or when rare animals flourish in an urban habitat niche despite all odds [62]. To summarize: If the functions and structure of green infrastructures follow mainly human concerns without accommodating the diversity of life forms, they cannot truly contribute to a paradigm shift towards more-than-human conviviality and sustainable urban transformation.

4.4. Green Façade Systems as Revolutionary Infrastructure

In general, green façade systems and infrastructures try to overcome the limitations of urban gray infrastructure by adding flora and fauna to the predominantly sealed surfaces of the built environment. Finally, we want to reflect on more holistic approaches to the design of green infrastructures, such as the UNA TERRA prototype, and their potential to prepare the ground for the emergence of revolutionary infrastructures that care for more-than-human conviviality and introduce heterogeneity into the otherwise homogeneous structure of urban environments.

According to Boyer [26], revolutionary infrastructure strives to reconfigure the existing ecologies and infrastructural relations of gray and green infrastructure. It gets realized through experimental, diverse, and local practice and represent subscendental rather than transcendental attitudes [90], meaning that it does not assume the dominance of human subjectivity over the whole heterogeneity of nature. By doing so, it contributes to the "politics of conviviality" aiming to recognize the "diversity of ecological attachments and heterogeneous associations through which the politics of urban nature is fabricated" [34] (p. 135). "Organism-plus-environment" [64] in this case also applies to human habitation and built structures and their interdependencies with natural co-worlds.

Green infrastructures have the potential to support place-specific cross-species co-living practices by catering to the needs of flora, fauna, and humans in a holistic way rather than focusing solely on anthropocentric concerns. In the case of the UNA TERRA living wall prototype, the separation between the interior human space and the exterior environment is still provided by the building envelope. However, on the outside, the flat surface of the wall is extended by layers encompassing both organic and mineral material (Figure 5). This three-dimensional habitat provides functions comparable to those of natural environments: the two plant layers and integrated habitat elements create heterogenous microclimates and microhabitats able to support biodiversity through a stratified structure. The system thus also enables bioclimatic function [30]: The outer plant layer acts as a natural protection against thermal effects, such as solar radiation, for species growing on the second plant layer (Figure 10). As shown in Figure 9, the vegetation changes with the season and forms uncontrolled wildlife rather than a neat park or flower garden. Insects adopted the provided structures as food supplies and nesting spots, as can be seen in Figure 12.

As a technological artifact and artificial structure, the UNA TERRA living wall requires care and maintenance during the design and operation stages to unfold its potential. It thus acts as an interface for human–nature relationships, rather than conceptualizing non-human life forms as invaders from which human structures must be protected. This raises the question of how more-than-human encounters enabled by such systems can be understood. The concept of "becoming-with" helps to understand how humans and non-humans can approach each other in multispecies entanglements: “With regard to the more-than-human, [. . .] becoming would involve a process of encounter in which humans accept the alterity of the nonhuman and introduce the latter’s manner of existence into the way humans think and act [. . .]. In such a process, binary codings of human/nonhuman dissolve into a coding of more-than-human” [28] (pp. 198–199).

However, posthumanist approaches still caution against conflating human and non-human capacities, submitting to seemingly natural forces, or acting as a spokesperson for nature [28,63]. Even when taking responsibility for more-than-human conviviality, it should be reflected that human agency still assumes the position of a designer and planner who accommodates—or at least tolerates—the shared and conflicting needs of different species.

Accordingly, the design of the UNA TERRA prototype is based on environmental-physical and ecological considerations. This approach is summarized in Figure 13. It integrates non-human concerns into man-made structure by enabling the microclimatic and biodiversity-enhancing function conventional green infrastructures lack. For example, the plants selected for the initial setup were chosen depending on their preferred climatic conditions and optimal nectar and pollen content. Despite careful preparation, the system still leaves room for the spontaneity of natural encounters and refrains from human control once the system is in place, as the diversity of sighted animals and unplanned vegetation show. Embracing such “egalitarian humility” [33] (p. 251) by integrating uncertainty into design and research is crucial when caring for urban naturecultures.

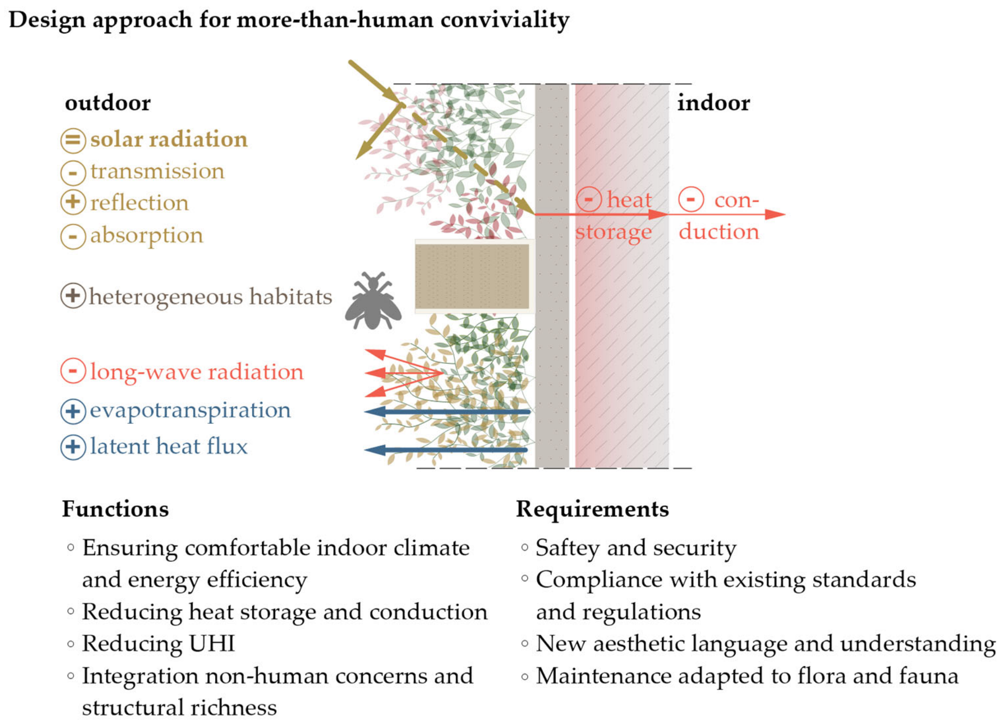


Figure 13. The figure shows a design approach for more-than-human conviviality using the example of a vertical living wall system. In addition to the microclimatic and biodiversity effects, the functions and requirements of the system are listed. The “+” illustrates the increase in an effect and the “−” a reduction compared to gray infrastructure.

The holistically planned and, at the same time, open approach pushes the project beyond the anthropocentric desire for control to a more-than-human perspective: The living wall is not purely utilitarian, not reducing flora and fauna to a kind of technology, resource, or aesthetically motivated design that can be harnessed. It still provides beneficial thermal effects, as shown in Figures 6 and 7, while at the same time recognizing that humans and non-humans inevitably inhabit the same urban ecology.

This means that species usually considered a nuisance in the built environment, such as weeds, bees, or wasps, are accepted by the openness of the living wall. To ensure its biodiversity-enhancing functions, withered plants were only carefully cut back to preserve the pithy and dead stems that serve as shelter for insects in winter (Figure 9). The presence of animals and brown vegetation on the previously lifeless concrete wall requires not only acceptance on the part of humans, but a new perspective on living with non-human urban dwellers in general. The people involved in the maintenance of such systems, as well as critical bystanders, need to get used to the varying appearance of a living wall, which may not correspond to the familiar aesthetic of a flower box. To realize the full potential of green façades as bioclimatic layers, urban populations will have to learn to live with the changes in nature–culture relations they bring. However, it is important to distinguish egalitarianism from indifference. There needs to be constant reflection and negotiation about what kinds of life forms, natural processes, and nature–culture relations are beneficial, or at least acceptable, to more-than-human conviviality. Damage to the built structure by flora and fauna is unacceptable from the point of view of its human dwellers, just as the inhabitation of living walls by mice or hornets once a certain threshold has been crossed.

5. Conclusions

Considering the urgent need for urban transformation towards sustainable and livable cities, we discussed the potential of green infrastructures solutions to act as a revolutionary infrastructure that benefits the local microclimate and biodiversity while enabling forms of more-than-human conviviality. To reflect on the possibility of such a paradigm shift, we approached the question of infrastructure from an interdisciplinary perspective, combining insights from engineering studies with relational social science theories. The differentiation between gray, green, and revolutionary infrastructure served as our shared analytical framework. The UNA TERRA living wall prototype was introduced as a case study to discuss suitable design properties and measure its microclimatic and ecological performance in light of the identified infrastructural requirements.

First, the comparison and characterization of semi-natural and urban environments shows that urban structures lack environmental heterogeneity as well as microclimate and microhabitat variation due to large-scale sealing, which negatively affects floristic and faunal diversity. Second, the case study illustrates that the UNA TERRA prototype contributes to buffering microclimatic conditions through its planting and maintenance concept, which is comparable to semi-natural structures. The formation of a heterogeneous microclimate can be further enhanced by the targeted use of mineral and organic habitat structures. Third, a significant increase in faunistic diversity can be generated by the combined design elements. Overall, the system has the potential to contribute to the promotion of structural richness and biodiversity in urban areas.

Accordingly, our results illustrate that the tested prototype and similar green infrastructures can act as a revolutionary infrastructure for more-than-human conviviality by actively engaging with and caring for the heterogeneity and ecological interdependence of non-human species. The UNA TERRA living wall exemplifies how these aims might be achieved. However, its design characteristics and performance cannot be generalized. Local changemakers need to find place-specific solutions that fit the specific urban environment and ecology. A key characteristic of revolutionary designs that should be implemented across all kinds of urban infrastructures is the adherence to “egalitarian humility”, meaning that the uncertainty and openness of urban naturecultures is recognized. This requires new forms of acceptance of the wildness of nature in cities and a change in aesthetic designs and sensibilities. This is not only a technical challenge, but a sociopolitical one that concerns property management, local administration, and government.

As an outlook, we want to reflect on the trend towards green infrastructures and their potential to lead to a paradigm shift in nature–culture relations and the challenge of urban transformation. While the discussed prototype and similar designs can indeed fulfill the characteristics of revolutionary infrastructure, their success depends on the eco-social adoption of practical solutions. According to Boyer [24–26], such a paradigm shift would be horizontally organized, tailored to the local situation, and would prioritize the use of local materials and technologies. Therefore, there is a gap in research on how expert designs such as the UNA TERRA prototype can be disseminated throughout society, tailored to the specific use case, and made more adaptable, simple, and reproducible. Another key issue is the ongoing care, maintenance, and professional expertise that green infrastructures like living walls require. The synergistic effects and cross-species co-living practices made possible by such designs can only be sustained through the long-term involvement of human actors. Whether this responsibility will be delegated to experts and service providers, creating new forms of dependency, or taken on by engaged citizens, as in the case of urban gardening [91], remains an open question.

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