Chapter 10

Resilience of green roofs to climate change

Cristina S. C. Calheiros [1,2], Sofia I. A. Pereira [3]

[1]Interdisciplinary Centre of Marine and Environmental Research (CIIMAR/CIMAR), University of Porto, Novo Edifício do Terminal de Cruzeiros do Porto de Leixões, Avenida General Norton de Matos, S/N, 4450-208 Matosinhos, Portugal; cristina@calheiros.org
[2]Institute of Science and Environment, University of St. Joseph, Rua de Londres 106, Macao SAR 999078, China;
[3] CBQF—Centro de Biotecnologia e Química Fina—Laboratório Associado, Escola Superior de Biotecnologia, Universidade Católica Portuguesa, Rua Diogo Botelho 1327, 4169-005 Porto, Portugal; sapereira@ucp.pt

Abstract

The successful management of cities growth rely in part on the maximization of the benefits delivered by the built environment while minimizing the environmental degradation. Circular and resourceful cites are the mainstream for climate change resilience. Green roofs, as a nature-based solution, contribute to climate change adaptation and mitigation through the provision of several ecosystem services. Value of green roofs can be achieved at the level of environmental (e.g., air quality enhancement, carbon sequestration, biodiversity promotion stormwater management, acoustic insulation, and noise reduction), social (e.g., aesthetic integration, wellbeing and life quality, rooftop gardens) and economic (e.g., life span extension, energetic efficiency, energy production, real state valorization, business development) spheres. Build up green roof resilience maybe underpinned by the selection of efficient and sustainable components for its installation. The present chapter aims at giving an overview on the role of green roofs resilience to climate change, highlighting the provision of services and the mitigation and adaption capacity.

Key words: nature-based solutions, circular cities, circular economy, ecosystem services, climate mitigation, climate adaptation, CO_2 emission, biodiversity, water management, societal challenges; water scarcity; drought

10.1. Introduction

10.1.1. Built Environment and urban transition

Built environment is the baseline infrastructure of cities that comprises land-use, specifically buildings, transportation, and roadways. The global share of energy-related CO_2 emissions from buildings and construction in 2020, compared to other sectors, stands at 37% and the global final energy consumption stands at 36% (UNEP, 2021). It is thus important to have in consideration the design, planning and development of the built environment, especially the building envelop, since it can contribute to the mitigation of climate change, support adaption and promote environment and public health, towards sustainable cities. This approach determines the patterns of exposure, social and physical vulnerability and capacity for resilience. For example, the interventions in the morphology of a city-built environment can contribute to the reduction of the urban heat highland effect and minimize the impact of heat waves (IPCC, 2022). At the level of the buildings, there is a great need to implement effective low-carbon policies and decarbonization through cost-effective investments having in consideration the life span and considering the issue of resilience. This latter issue, concerning resilience, is of outmost importance since a building of today will still be in use in 2070, although facing significant differences in climate (UNEP, 2021). Cities should pave the way to consider programmes providing retrofitting, disaster reconstruction and urban regeneration, following a strategic direction towards low-carbon and high resilience urban form and function, in order to counteract the costs for maintenance and reconstruction of urban infrastructure that are predicted to increase with global warming (IPCC, 2022).

In the context of global development urban settlements are of great importance since they will further urbanize over the next decade, from 56 % today to 60 % by 2030 (UN, 2020). They contribute with about 85% of global GDP (gross domestic product), but on the other hand they: i) consume about 70% of global resources and 70% of all energy generated, ii) generate about 50% of all waste, and iii) emit 70% of all greenhouse gases (EIB, 2021). Unplanned and unmanaged urbanization pose a threat to sustainable development being does fulcra well-planned territories that can curb excessive land consumption and all that is implied, towards sustainable urbanization that is a generator of inclusive prosperity. This highlights the relevance to consider the environment footprint to accommodate growing populations (UN, 2020). Thus, the successful management of cities growth will rely in part on how to maximize the benefits for the settlement while minimizing the environmental degradation and other potential adverse impacts (UN, 2019). Having that in consideration it is stated that an environmental transition is needed underpinning by a circular economy approach where not only resources conservation is attained, but also the reduction of environmental and climate impacts (EIB, 2021). Cities have unique features that allow them to be cradles and catalysts for circular change, since they (EIB, 2021):

i) have density and scale of citizens, business, materials and resource flows
ii) can connect stakeholders and promote a culture of collaboration
iii) can lead by example offer/procure circular solutions/services
iv) have autonomy to regulate/incentivize
v) can define and communicate circular vision and strategy
vi) can embed circular principles in city infrastructure and services

Considering the Proposal for the European Partnership Driving Urban Transitions four priority themes have been identified as crucial to support urban transition (JPI, 2020): (i) digital transitions and urban governance, (ii) from resilience to urban robustness, (iii) sustainable land-use and urban infrastructure, and (iv) inclusive public spaces. Following this alignment, it is crucial to consider the Green-Blue Infrastructures and Nature-Based Solutions (NBS) towards urban transitioning (JP, 2020).

10.1.2 Nature-based solutions towards circular cities

The inclusion of NBS in the urban landscape can contribute to a circular economy, to different extents, and through the provision of ecosystem services can counteract the impact of climate change and urbanization (Calheiros et al, 2021; Pearlmutter et al, 2020). According to the European Commission (EU, 2020, pp4), "Nature-based Solutions to societal challenges are solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. Nature-based Solutions must benefit biodiversity and support the delivery of a range of ecosystem services." Embedding the concept of circular cities, the COST Action CA17133 Circular City has proposed that "NBS are defined as concepts that bring nature into cities and those that are derived from nature. NBS address societal challenges and enable resource recovery, climate mitigation and adaptation challenges, human well-being, ecosystem restoration and/or improved biodiversity status, within the urban ecosystems. As such, within this definition we achieve resource recovery using organisms (e.g. microbes, algae, plants, insects, and worms) as the principal agents. However, physical and chemical processes can be included for recovery of resources (as discussed in WG3 Resource Recovery), as they may be needed for supporting and enhancing the performance of NBS" (Langergraber et al, 2020). Stefanakis et al (2021) further discussed the potential of NBS to stimulate economic growth through a circular model, their contribution to new circular strategies for climate change adaptation and mitigation, and key actions necessary to increase the awareness and attract more investments for their implementation.

In order to shift to circular management of resources the following urban circularity challenges can be addressed with NBS (Atasanova et al, 2021): i) restoring and maintaining the water cycle (by rainwater management), ii) water and waste treatment, recovery and reuse, iii) nutrient recovery and reuse, iv) material recovery and reuse, v) food and biomass production, vi) energy efficiency and recovery and vii) building system recovery. According to Katsou et al (2020) the success for adoption and implementation of NBS in circular cities require four main steps: i) planning, ii) design, iii) assessment, and iv) communication. Besides that, implementation of NBS may be considered at the scale of green building: i) materials, that are nature-based materials (raw or processed) used in the construction of the bulti environment, ii) systems, that are systems for the greening of buildings, and iii) sites, that are considered the open spaces directly adjacent to buildings for nature establishment, playing a role in the blue-green network of the city, intending to promote outdoor comfort, healthy living environments and wellbeing. Green roofs are an example of NBS that can be implemented at a building scale, in new or existing buildings, coping with the societal challenge of "Climate action, environment, resource efficiency and raw materials", identified by European Union. They thus play a pivotal role in the Water-Energy-Materials-Food-Ecosystem nexus (Calheiros et al, 2021).

The present chapter aims at giving an overview on the role of green roofs as NBS towards climate change resilience, highlighting the provision of ecosystem services and the mitigation and adaption capacity.

10.2. Green roof as engineered system

The space in the top of the buildings in urban context is generally unused, although is a considerable area extension since accounts for approximately 40–50% of the impermeable urban surface (Stovin et al, 2010). The inclusion of green roofs in new buildings or retrofitting the existent ones, is a solution that contributes to cities resilience and adaptation to climate change to different extents.

Green roofs are systems that use vegetation as top layer and are installed on a constructed structure regardless the type of construction, meaning that they can be implemented on a top of a building or at the ground level, for example covering an underground parking, being excluded green walls built with climbing plants or vertical gardens systems. Typically, they are arranged in several layers that play different functions to assure effective performance. Modern green roofs are thus engineered systems that follow standard guidelines to assure the compliance with the best practices and avoid malfunctioning (Calheiros et al, 2022).

10.2.1. Green roof classification

Green roofs are classified as extensive, semi-intensive and intensive (ANCV, 2019). The differentiation relies mainly on the substrate depth and type of vegetation, and the maintenance associated (Table 1).

Table 1. Green roofs typical classification and characteristics (adapted from ANCV (2019))

Characteristics	Green roofs classification		
	Extensive	Semi-Intensive	Intensive
Maintenance	After installation of the vegetation the maintenance is low	Periodic/moderate	High maintenance
Substrate layer	. Typically, mineral substrate and porous . 8-15 cm thickness	. Mineral substrate . 15-25 cm thickness	. Different substrates may be used according to the type of plants. Thickness >25 cm
Vegetation	Succulent (sedum), mosses, grass	Grass-herbs, shrubs	Trees, shrubs, lawn
Weight of the system	80-180 kg/m² (0.59-1.77 kN/m²)	150-350 kg/m² (1.47-3.43 KN/m²)	>350 kg/m² (3.43 KN/m²)
Accessibility	Unless for maintenance	Limited stepping	In general, without limitation

Briefly, extensive roofs are characterized by having low growing vegetation that can go from grass varieties to meadows and sedum (Figure 1a). The substrate is thus adequate for the growing need of such plants with low thickness. This category is not adequate for frequent stepping. Only periodic maintenance is needed, mostly to verify the drain pipes, inspection pit and overall aspect. It can be considered 4 annual visits after the installation period (Source: https://www.greenroofs.pt/en/faq assessed 21/05/2022). Compared to the other green roofs a minimal capital and maintenance cost is associated (ANCV, 2019). Intensive roofs are characterized by having different levels of vegetation, meaning that can include for instance trees, shrubs, and other ornamental plants (Figure 1b). The substrate topographically is variable, with a greater weight than the extensive, having in consideration the substrate thickness and plants. This category is conceived for frequent stepping and use. Maintenance is adapted to plant requirement, but similar to a garden. Higher implementation capital and maintenance costs need to be attained. Semi-intensive green roofs may have plants that can go from small plants and shrubs to grass, with a moderate substrate thickness, being partially accessible. As seen, maintenance is applied to all categories but at least once a year the green roofs should be checked concerning: i) drainage: verify if there is any obstruction in the drain pipes and inspection pit, ii) invasive plants: removal of invasive plants is recommended that may jeopardize drainage or supporting structure, tending to became dominant, iii) fertilization: depending on the species there may be requirement of fertilization or organic matter addition, and iv) irrigation system: must be adequately programed of the climacteric conditions and plants species watering needs, being kept to minimum (Source: https://www.greenroofs.pt/en/faq assessed 21/05/2022).

Figure 1. a) left side: extensive green roof and b) right side: intensive green roof (Porto, Portugal)

Beside the above-mentioned categories, there are other typologies available in the market, with different designs, with specific purposes, such, biosolar roofs, agrisolar roofs, productive/farm roofs, biodiverse roofs and blue-green roofs. Briefly, biosolar green roofs combine green roofs with photovoltaic (PV) panels delivering renewable energy. Plants increase the efficiency of the photovoltaic panels at the same time that provide other ecosystem services (Nash et al., 2015; Chemisana and Lamnatou, 2014). Agrisolar roofs or agrivoltaics are a general term for combination between agriculture and photovoltaics, delivering both benefits at the level energy and food production (Fraunhofer, 2020). Food production on roof tops as a way to do urban agriculture and access local products is gaining interest (Harada and Whitlow, 2020) (Figure 2).

Figure 2. Food production in a city green roof (Rotterdam, Netherland)

Biodiverse roofs are designed to promote diversity at the level of the building envelop but also in the surroundings (Köhler and Ksiazek-Mikenas, 2018). Blue-green roofs combine vegetation and elements of stormwater management in the roof structure (Busker et al, 2022).

Independently of the design and purpose of the green roof implementation it is important that follows standard guidelines. In general, they may not be mandatory but the recommendations, knowledge, and expertise embed allow for a successful implementation (Calheiros et al, 2022).

10.2.2 Green roof layers

Depending on the systems design a green roof can comprise different layers. The selection of these layers is fulcra to achieve the best performance, cost effective solution and in use of ecofriendly materials (Calheiros et al, 2021). In relation to materials, they should be locally available, recycled or compatible with biological cycles having in consideration their durability, structural integrity and energy dependence (Pearlmutter et al, 2020).

Briefly, these are the main layers that constitute a green roof, although it may vary according to the design and purpose of implementation and use, from top to bottom:

i) Vegetation: this layer is the interface of the green roof being thus a visible indicator of the health status of the system. Selection of plants should be careful undertaken and considering the climacteric conditions, substrate thickness and irrigation requirements. They can be also chosen based on their function, such biodiversity promotion, engaging pollinators, productive or fully covered green carpet benefiting other ecosystem services.
ii) Irrigation system: should be always considered even if kept to a minimum use. Usually, a drop-by-drop system is adequate for most of the green roofs. It will be more valuable at the installation phase to assure plant establishment. Tap water is usually considered for this purpose.
iii) Technical substrate: except some specific situations that may use soil applied to green roofs, the technical substrate is by far the most used approach to support successful plant development and allow for a favorable system hydrodynamics.
iv) Filter layer: main function is to prevent fine substrate to pass on to drainage layer in order to avoid blockage and system saturation. Usually is geotextile based.
v) Drainage layer: main purpose is to assure an effective water flow preventing substrate saturation or overflow of the system. They are in general polyolefin based, although recently other materials have been put is commercialization such the GUL (Green Urban Living) (Tadeu et al, 2018),
vi) Protection layer: addresses the question of protecting the green roof from mechanical pressures being usually made of extruded polystyrene (XPS).

Resilience of green roofs to climate change can be achieved through the selection of the adequate layers and materials to the situation under consideration. When having in mind to optimize and boost green roof resilience, as foster the ecosystem services, it is important that the supporting system for the vegetation is assure and aligned with the understanding of natural cycles.

10.3 Build up green roof resilience through value

Evidence-based outcomes have shown already the wide range of ecosystem services that NBS can delivered at the level of contributing to a transition to circular economy as to climate change mitigation and adaptation (Stefanakis et al, 2021). It is considered that "Ecosystem services are the benefits people obtain from ecosystems. These include provisioning, regulating, and cultural services that directly affect people and the supporting services needed to maintain other services" (MEA, 2005, pp 40). These benefits are translated in the value that green roofs bring at the level of environment, social and economic aspects. So, the resilience of green roofs to climate change is influenced by the selection of the adequate layers and materials which translates into the extension of ecosystem services delivered. The green roof values below mentioned, in the next sections, will have to consider that the green roof performance will always vary according to different locations (latitudes), local climates, green roof structure, including pant species and the physical environment. It is also important to mention that the values of green roofs have different extensions of impact, meaning that one green roof has a neglectable influence on a site scale or even city scale, but if they are replicated, their benefits will be amplified and can be thus measured and accountable. Nevertheless, one green roof will always have impact at the scale of the building envelope itself.

In order to promote green roofs, and other NBS, inclusion in cities it is important to proceed with: i) identification of barriers and overcome it, ii) setting guidelines and standardization, iii) establishing policies, incentives, and strategies, iv) leveraging organizations delivering related services, and v) promoting awareness, dissemination, and investment in education (Calheiros et al, 2021).

10.3.1 Environmental value

. Air quality enhancement

Air pollution is typically associated to heavily urbanized areas and city centers being a major concern due to the threat that poses to health and life of the citizens, and environmental degradation. Originated from several sources, the air pollutants often present are: CO_2, O_3, NO_x, SO_2, heavy metals, and suspended particulate matter (PM). Green roofs can reduce air pollution does promoting a better air quality (e.g., Nguyen et al, 2022; Suszanowicz and Wiecek 2019; Yang et al, 2008; Currie and Bass, 2008). Increasing green roof areas in cities is a way to reduce the impact of air pollution. For instance, even 10-20% of increase would already make a substantial contribution (Currie and Bass, 2008).

. Carbon sequestration

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities and the increase of its emission has been related to global warming. There is thus an urgent need to capture and store it. Green roofs are considered a technology that can contribute to carbon sequestration (Nguyen et al, 2022; Shafique et al, 2020; Getter et al, 2009). It can be highlighted direct and indirect impacts of green roofs in relation to carbon sequestration. Direct impact refers to the carbon capture by plants through photosynthesis and consequently storing it in plants and roots and carbon storage in the substrate. The plant species and substrate properties (depth and composition) have a great influence on the amount of carbon stored. Indirect impact refers to the long-term effect, being green roofs good insulators, which reduces heating and cooling needs, translated in building energy consumption, and consequently leading to a reduction in fossil fuel consumption (Shafique et al, 2020).

. Biodiversity promotion

In cities, the intensification of urbanization tends to cause an increase of soil sealing and impermeabilization, loss of green spaces and habitat fragmentation, thus leading to biodiversity decrease, habitat loss and general environmental degradation. With green roofs conditions are created for biodiversity establishment, habitat creation and enhancement of urban ecology, allowing natural colonisation of plants, birds, insects and small animals and spots for feeding and nesting. They are also very important as enablers to promote connectivity between green spaces, as green corridor, acting as stepping stones for several species (Calheiros et al, 2022; Köhler and Ksiazek-Mikenas, 2018). Besides that, they attract pollinators, supporting thus diverse pollinator communities at the urban scale (Dusza et al, 2020).

. **Stormwater management**

The impermeabilization of surfaces in urban context brings consequences to different extents on urban water cycle. As the soil sealing increases, the stormwater infiltration area decreases and the surface runoff and the stress on existing grey infrastructure increases, often resulting in cities flooding. With the climate change, in certain areas, there is a frequency increase of precipitation events which exacerbates the pressure on infrastructures and more severe floodings occur (Calheiros et al, 2022; Berndtsson, 2010).

The roofs of the buildings are the first surface to interact with rainwater, being typically directed to drainage (c.a. 85%) (Pearlmutter et al., 2020). A green roof has a direct effect on stormwater runoff quantity and quality. In terms of quality, it is expected that varies according to some leaching of nutrients but also, there is an enhancement of the quality through filtration and adsorption associated with the substrate and plants. Although, rainwater is generally considered as non-polluted there may be other pollutants e.g., heavy metals and pesticides depending on the local pollution sources and prevailing winds (Zhang, 2015; Berndtsson, 2010). It has been suggested that the water coming from green roofs has sufficient quality for non-potable uses in buildings, such as irrigation, flushing toilets or pavement cleaning, regarding its physico-chemical parameters, coupled with an adequate rainwater harvesting system, with first flush discharge (Monteiro et al, 2016). In terms of quantity, the green roof attenuates and delays peak runoff (time lag between the peak from a hard roof and a green roof for the same rain event) preventing. Nevertheless, different studies report a high range of quantitative performance. Green roofs retention capacity maybe affected by: i) green roof characteristics (e.g., substrate thickness, substrate composition, type of layers and materials, vegetation cover and slope of the roof) and weather conditions (e.g., rainfall intensity and duration rainfall, antecedent dry weather period, air temperature and wind conditions) (Berndtsson, 2010).

The stormwater management in cities facing climate change is being looked deeply through the concept of "sponge city" approach that includes NBS with the intention to promote "an urban environment that is devoted to finding ecologically suitable alternatives to transform urban infrastructures into green infrastructures so these could capture, control and reuse precipitation in a useful, ecologically sound way" (Liu et al, 2017).

. Acoustic insulation and noise reduction

Activities producing noise that influence human health and well-being are considered to cause noise pollution. The limits of noise may differ from country legislation although is commonly origins are: heavily traffic roads**,** airports, industrial facilities and some recreational activities (Nguyen et al, 2022). Green roofs have shown to have a positive performance in reducing the sound exposure near or inside a building. The green roof layers influence the sound absorption to different extents having impact on how the diffraction of sound waves over (parts of) roofs occurs and how the transmission of sound develops through the roof system **(**Renterghem, 2018**).**

10.3.2 Social value

. Aesthetic integration

Green roofs have an important aesthetic landscape integration value, since results from greening a grey surface. Although is an intangible benefit, it has implications on the perception of how a green roof integrates on a building and also the acceptance by the public (Calheiros 2021; Kotzen, 2028; Sutton, 2014). They soften the artificial urban landscape and provide visual relief, besides enhancing architectural designs and often create iconic landmarks in the city (Rahman and Ahmad, 2012).

. Wellbeing and life quality

Green roofs can improve the health and well-being of people. They can either be of private use or publicly available with the possibility of access to social amenities such cafe´s, bars, restaurants, and swimming pools (Kotzen, 2018). They allow for recreational activities and pleasant leisure areas (Shafique et al 2018; Mesimäki et al, 2019). Furthermore, the access to green space in an hospital context increases both patients' and staffs' overall satisfaction. It has been shown that they contribute to reduction of emotional distress, improvement of mental health, increase of socialization and community connection, increase physical activity, decrease cardiovascular and respiratory diseases and decrease pain management needs (O'Hara et al, 2022).

. Rooftop gardens

Gardening can promote social cohesion and cultural activity. When considering rooftop gardens they can improve household livelihood through enhanced income, being considered for urban food production (Khan et al, 2020; Nugent, 2000). The receptivity of rooftop gardens can be attributed to the pproximity to the people's living and working spaces, delivering social interaction, passive recreation, education and self-achievement. Social values have been pointed out as the most important benefits of urban rooftop farming, compared with economic and environmental values (Wang and Pryor, 2019).

10.3.3 Economic value

. Life span extension

Roofs are subject to mechanical damage (e.g., direct stepping and dirt), direct solar radiation and wide range of temperatures variation (suffering daily expansion and contraction of the roof materials). Having that in consideration when considering a green roof for a building it will allow for a longer lifetime than conventional roofs, because of the lessen exposure of the roof membrane. While increasing life expectancy of the building the cost of building maintenance is reduced. When compared to conventional roofs, it is expected that the green roof life span may increase up to 40 years. This aspect is of great importance when doing a life cycle assessment (Calheiros et al 2020, 2022; Shafique et al, 2018).

. Energetic efficiency

Green roofs contribute to reduction of energy consumption by reducing the roof temperature of the building, with repercussion indoors, with savings for cooling and heating demand and improvement of thermal comfort, and outdoors, leading to the reduction of the heat island effect and microclimate. With green roofs the thermal insulation on the building is thus improved providing a more balanced temperature within and having impact on reducing the carbon footprint (Nguyen et al, 2022**;** Mutani G, Todeschi, 2020; Suszanowicz and Wiecek 2019

. Energy production

Local energy production can be enhanced through photovoltaic green roofs thus promoting renewable electricity production. The benefits of this type of production could offset the construction cost of the green roof on the building. Nevertheless, more studies are needed to fully cover the outcomes of electricity production against different latitudes and photovoltaics panels performance (Arenandan et al, 2022; Shafique et al, 2020**)**.

. Real state valorization

The roofs are often underestimated in terms of their use and versatility. By turning into green roofs there is an increment in the property value due to benefits that they can bring in terms of ecosystem services delivered, but also in becoming a usable space for instance for leisure or recreational activities (Kotzen, 2018). The values for apartments rentals tend also to be higher when having green roofs (Ichihara and Cohen, 2011). Green roofs may be considered short-term investments in terms of net returns and with low-risk investment (Bianchini and Hewage, 2012).

. **Business development**

Given the limitation of space in the cities for in-ground agriculture, the roof top farms are not just becoming a trend but also a business. Besides that, there are already policy support and public funding from green building and green infrastructure initiatives, which underpins this business. Thriving urban agriculture contributes to food security and equity, efficient food supply chains, waste management using compostable waste and job creation (Nguyen et al, 2022; Harada and Whitlow, 2020; Walter and Midden, 2018).

10.4 How to increase green roofs' resilience to water scarcity?

Green roofs have been installed in temperate and cold climates without need of irrigation. However, their implementation in arid and semi-arid regions, as well as in the Mediterranean zone is more challenging. To increase the resilience of green roofs to dry climates the selection of efficient and sustainable components for its installation is extremely important.

In the following sections it is summarized how the main green roofs' components, including the vegetation and substrates may improve the resilience of green roofs undergoing dry conditions.

10.4.1 Vegetation

Green roofs often face more extreme weather conditions than natural habitats on the ground. Therefore, the survival and development of plants in green roofs depends on their tolerance to several abiotic factors, including solar exposure and radiation, temperature, rainfall intensity, drought, salinity, among others. It is also important to consider the constraints associated to the substrate depth that influence the development of plant root system and water retention, as well as substrate pH, salinity, and nutrient-deficiency that may affect plant survival and growth. Thus, the selection of plants well-adapted to the local edaphoclimatic conditions is crucial for the success of any green roof (Vijayaraghavan 2016; Xie et al. 2018). Several authors advise the use of native species, especially because they are well-adapted to the local environment and may attract native wildlife contributing to boost the biodiversity in urban areas, while they are blended into the natural landscape which is aesthetically pleasant (Butler et al. 2012; Li and Yeung 2014; Paço et al. 2019). Despite the benefits, green roofs with native plant community are susceptible to colonization by invasive or exotic species, which will greatly increase the cost of maintenance if the strategy was to maintain only the original plant species (Li and Yeung 2014; Aloisio et al. 2019).

Semi-arid and Mediterranean climate zones are characterized by hot and dry summers with growing occurrence of extreme events such as heat waves and long drought periods (IPCC 2019). Plants colonizing green roofs in that regions often experience harsh growth conditions, as such the need for irrigation is unavoidable, as plants may fail to survive (Dvorak and Volder 2013; Razzaghmanesh et al. 2014; Savi et al. 2016). However, since water is one of most limiting natural resources in the world, its utilization in urban green areas is limited since this is often considered a low-priority use (Van Mechelen et al. 2015). Therefore, it is crucial to make an adequate selection of plant species to cope with water scarcity in green roofs, by using:

- native plant species adapted to local climatic conditions and with physiological traits related to drought and/or heat resistance (Dvorak and Volder 2013; Van Mechelen et al. 2014; Caneva et al. 2015; Gioannini et al. 2018; Paço et al. 2019)
- non-native plants colonizing natural habitats with growth conditions similar to those found in green roofs, including scree slopes, limestone pavements, grasslands on nutrient poor soils or annual and perennial wildflowers from agricultural systems (Lundholm 2006; Van Mechelen et al. 2014; Rayner et al. 2016)

- polycultures or mixtures of vascular plants and mosses (Gioannini et al. 2018; Paço et al. 2019)

Succulent plants (e.g. *Sedum*) are generally considered the most appropriate ones to use in green roofs (Dvorak and Volder 2013; Rayner et al. 2016; Vasl et al. 2017), as they present high tolerance to extreme drought conditions resulting from the succulence of their leaves, shallow root systems, and high water use efficiency due to physiological adaptations as the crassulacean acid metabolism (CAM) (Farrell et al. 2013a; Starry et al. 2014; Cascone 2019). Indeed, a green roof exposed to semi-arid climatic conditions and colonized by *Sedum sediforme* showed minimal irrigation demands since plants were able to survive without irrigation for 14 months (Nektarios et al. 2014). Azeñas et al. (2018) compared the performance of 5 Mediterranean species, *Asteriscus maritimus* L. Less., *Brachypodium phenicoides* (L.) Roem. Et schultes, *Crithmum maritmun* L., *Limonium virgatum* (Willd.) Fourr, *Sedum sediforme* (jacq.) Pau and *Sporobolus pungens* (schreber), planted in experimental modules under well-watered and water-limited conditions and concluded that *S. sediforme* was the plant that better performed under water-limited conditions followed by *B. phenicoides*.

Despite their good performance under drought conditions, succulents may not be the best choice for green roof installation in Mediterranean region which is characterized by hot and dry summers but also by rainy and cold winters, as they have a low water use making them not effective to reduce runoff and increase building cooling effect (Farrell et al. 2013b; Vaz Monteiro et al. 2017; Li et al. 2018). Hence, there is a growing interest in exploring alternative plant species, including herbaceous, shrubs, and grasses, as well as other native species adapted to water shortage. Indeed, Du et al. (2019) recommended the use of the scrubs *Correa glabra* and *Calytrix tetragona* in green roofs experiencing hot and dry climates. It has also been reported that *Cotinus coggygria* and *Prunus mahaleb* plants have high drought and heat resistance being suitable for green roof installation in warm and dry climates.

Several authors have reported the importance of using polycultures to enhance plant resilient to severe environmental stresses and consequently improve the green roofs' performance and ecosystem services (Lundholm et al. 2010; Butler and Orians 2011; Paço et al. 2019), while contributing to increase biodiversity in urban areas. According to Lundholm et al. (2010) and Lundholm (2015) the use of mixtures of plant species improves green roofs' ecosystem services, outperforming monocultures. Butler and Orians (2011) also reported the importance of combining *Sedum* sp. with and non-succulent plants to reduce the negative effects of abiotic stress on green roofs. In a study performed by Nagase and Dunnett (2010), 12 species of forbs, sedums and grasses were planted, as monocultures and as mixtures of 4 and 12 species, in extensive green roofs. Under dry conditions, it was observed a higher survival in the green roofs with mixtures of species, while sedum plants showed higher drought tolerance than forbs and grasses. In addition, Paço et al. (2019) recommended a mixture of vascular plants and mosses to increase the resilience of green roofs to drought. The success of this approach stems from the high water-holding capacity and drought tolerance of mosses, which allows plants to be hydrated for longer periods, improving their performance.

Plants in natural ecosystems in the ground are in close connection with a variety of microbial communities that foster their development and resilience to a plethora of climate change-related abiotic stresses, as well as underpin biodiversity (Kumar and Verma 2018; Pereira et al. 2020; Inbaraj 2021). However, plant microbe interactions in newly installed green roofs are limited since substrates are usually sterilized prior to installation to prevent spontaneous weed seedlings (Fulthorpe et al. 2018). In fact, only a narrow number of studies have evaluated the plant-associated microorganisms in green roofs systems. John et al. (2014) monitored the colonization of arbuscular mycorrhizal fungi (AMF) and dark septate endophyte (DSE) in plants grown for 4 years in a green roof. All plant species were colonized by both AMF and DSE with exception of *Sedum acre* which roots were not colonized by

AMF. More recently, Hoch et al. (2019) reported that green roofs planted with *Sedum* sp. or with a mixture of succulents, grasses, and wildflowers showed distinct bacterial and fungal communities, suggesting that microbial communities are closely linked to the type of vegetation.

The application of commercial bioinoculants, comprising AMF and/or the plant growth-promoting bacteria (PGPB) can be a good strategy to foster microbial communities in green roofs. However, despite their importance for biological systems only a few studies have considered the use of microbial inoculants and their potential to foster the resilience of plants to abiotic stresses in green roofs. Molineux et al. (2014) showed that the addition of AMF and compost tea (a live mixture of beneficial bacteria) increased the biomass of bacterial groups in sub-plots with a narrower layer of substrate. Likewise, Molineux et al. (2017) observed significant improvements on plant performance and on AMF root colonization of plants single and/or mixed inoculated with a commercial AMF inocula and compost tea. On the other side, Rumble and Gange (2017) did not observe a significant improvement on plant diversity and coverage by application of microbial inoculants. Schröder et al. (2019) reported the effect of AMF inoculation in 11 native grassland species growing under moderate and severe drought conditions. Despite the benefits observed in AMF-inoculated plants regarding aboveground biomass (2.5 times higher than non-inoculated plants), under severe drought inoculated plants shriveled on average 2 days earlier than non-inoculated ones.

Despite the promising results reported so far, the application of microbial inoculants in green roofs needs to be deeper analyzed. Future research should address the use of PGPB and AMF to enhance plant resilience, as well as the improvement of key ecosystem services of green roofs, particularly in areas prone to drought.

10.4.2 Substrates

Unlike humid regions where precipitation occurs throughout the year, underpinning plant growth, in dry regions it is necessary to irrigate green roofs which increase the cost of maintenance (Dvorak and Volder 2013; Razzaghmanesh et al. 2014; Savi et al. 2016). However, several strategies can be used to maintain/increase moisture and decrease temperature in the root zone, including: (1) deeper layers of substrate (Zhang et al. 2014; Reyes et al. 2016); (2) use of substrates with higher water retention capacity; (3) addition of water retention materials to substrates (Cao et al. 2014; Savi et al. 2014; Young et al. 2017; Chen et al. 2018; Werdin et al. 2021).

The substrate guarantees the proper establishment and stability of plants in green roofs as it can retain water and provides nutrients and physical support to plants (Cascone 2019). Hence, increasing the depth of substrate layer will improve moisture and reduce temperature in the roots (Reyes et al. 2016; Chenot et al. 2017). Zhang et al. (2014) evaluated the effect of different substrate depths (10 cm, 15 cm, and 20 cm) on survival and performance of 18 non-succulent species in non-irrigated extensive green roofs. Plant survival increased with substrate depth during water stress period. A similar trend was observed for growth index and visual rating which were higher in plants growing in deeper substrates (20 cm). Only one species, *Allium senescens*, showed ability to grow in non-irrigated green roofs with the shallower substrate (10 cm). Likewise, Reyes et al. (2016) showed that substrates depths of 10 and 20 cm provide a better water content if compared to a shallower layer (5 cm), while contributing to reduce the temperature in the root zone.

Despite the undeniable benefits for plants, increasing substrate depth impacts installation cost, as well as the weight charge for the building structure. Therefore, the use of substrates with different compositions tailored to thrive plant development under dry conditions could be a successful alternative. Growing media usually comprise several components with different characteristics mixed at different rates (Vijayaraghavan 2016; Cascone 2019). Low-density inorganic materials are the main constituents of green roofs' substrates and may include pumice, zeolite, scoria, vermiculite, expanded clay, perlite, peat, sand, coco-peat, crushed brick, among others (Farrell et al. 2012; Ondoño et al. 2015; Sandoval et al. 2017). Moreover, it is important to incorporate organic constituents such as mulch, recycled organic waste, and compost to supply nutrients to the plants and increase biodiversity (Lata et al. 2018). Recently, Jusselme et al. (2019) showed that amending a commercial substrate with a mixture of earthworms and vermicompost significantly increased plant biomass and plant-pollinator interactions.

The ability of substrates to retain water can be enhanced by changing the composition of growing media and by decreasing the particle size of inorganic materials, since the increase of pore space favor the retention of water (Graceson et al. 2013; Raimondo et al. 2015). Chenot et al. (2017) showed that a 15 cm-depth substrate composed by fine and coarse elements (75% clay-silt and 25% pebble-sand) is the best option to achieve an optimal vegetation colonization under a Mediterranean climate. It has also been reported that substrates containing bottom ash foster plant survival under severe drought conditions, probably due to its higher ability to retain water (Farrell et al., 2012). Ondoño et al. (2015) evaluated the effect of different artificial substrates: green compost and clay-loam soil, green compost and expanded clay and green compost and crushed bricks, on the development of 6 native Mediterranean species - *Silene vulgaris*, *Silene secundiflora*, *Crithmum maritimum*, *Lagurus ovatus*, *Asteriscus maritimus*, and *Lotus criticus*. It has been observed that the substrates containing expanded clay and bricks showed better aeration conditions than the loam soil containing-substrate. Despite the higher retention capacity of the latter, the germination rate and plant growth were better in lightweight and highly porous substrates.

The amendment of substrates with water-retention additives such as hydrogels and biochar, can also enhance the moisture retention properties of green roofs in dry regions and their application is gaining ground in the last decades. There is evidence that adding increasing doses of sludge biochar (0-20%, v/v) significantly increased water holding capacity of substrate and the availability of water to the plants, while reducing roof substrate temperature (Chen et al. 2018). Cao et al. (2014) also demonstrated that biochar significantly improved water holding capacity and plant available water. Similar results were obtained by Savi et al. (2014) by adding a polymer hydrogel to the green roofs' substrate to increase the amount of available water to the plants. The addition of this hydrogel enhanced plant performance and allowed the reduction of substrate depth. Farrell et al. (2013b) evaluated the ability silicate granules and hydrogel to increase the substrate water holding capacity, the plant available water and growth in two substrates based on scoria and crushed terracotta roof-tiles. Silicates best performed regarding water holding capacity and plant growth for both substrates. However, the ability to increase plant available water by both additives is depended on plant species and substrates.

10.5 Conclusions

Green roofs, as nature-based solutions, have been proven to contribute with multiple environmental, social, and economic benefits in the built environment, towards cities resilience. They can enhance biodiversity, support stormwater management, provide benefits in term of energy reduction on consumption, thermal human comfort, with positive impact on outdoors microclimate and heat urban effect. Resilience of green roofs to climate change can be achieved through the selection of the adequate layers and materials to the situation under consideration. There is a need for and holistic view of the territories in order to optimize the flow of resources and materials having a circular economy as baseline. It is important that they integrate the built environment embracing the existing gray infrastructure, towards circular, resilient, and resourceful cities. In order to amplify their impact new buildings should integrate these systems as the retrofitting of existing ones. Innovative approaches have been addressed for green roofs in order to cope with high dry climates.

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