Nature-based Solutions Contribution for Urban Resilience and Sustainability

1. Introduction

The high urbanization in cities, necessary to accommodate the growing urban population in the last decades, led to the replacement of vegetation, natural infiltration and cooling areas by impervious materials and buildings, bringing several negative impacts to the urban environment. The increase in urban air temperature and pollution, the decrease of natural ecosystems and biodiversity, and the difficulty in urban water management, are the main issues that urban areas are facing nowadays. These problems are now exacerbated due to climate change, considering that floods and droughts will be more frequent in many areas of the planet. Until 2050, 68% of the world population is projected to live in urban areas [1] and the harmful impacts, resulting from the rapid urbanization replacing vegetation areas, will be intensified, unless new green technologies are included in urban planning strategies to reverse such scenario. Nature-based Solutions (NbS) are systems inspired and supported by Nature, mainly implemented in the urban environment as a mean to restore vegetation in densely populated areas. The US Federal Emergency Management Agency (FEMA) [2] describes them as sustainable planning, design, environmental management, and engineering practices that weave natural features or processes into the built environment to build more resilient communities. These practices can often be built into a site, a corridor, or a block without requiring additional space.

NbS include green infrastructure (GI) technologies, such as Green Roofs (GR) and Green Walls (GW), that are being implemented as part of a combined sewer overflow abatement strategy and to develop co-benefits of diminished stormwater runoff (including decreased loading of contaminants to the wastewater system and surface waters) [3], besides their benefits to the building envelope regarding thermal insulation improvement and indoor temperaure regulation [4]. The European Commission [5] states that implementing NbS on a larger scale would increase urban areas climate resilience while contributing to multiple Green Deal objectives. Buildings can contribute to large-scale adaptation, for example, through local water retention and urban heat island effect reduction when incorporating GI systems. Rooftops and building's envelope usually are unused spaces that can be used to counteract the negative impacts of impervious structures. In this scope, GR and GW gained increased attention in the last years appearing as a cost-effective sustainable low impact development (LID) technological solution at the building level. Their long spread implementation contributes to achieve best sustainable and resilient cities, and a feasible way to bring nature back to urban areas. Additionally, and in the follow-up of European Green Deal Project goals, where EU aims to be climate neutral in 2050, greening rooftops and walls might be an excellent contribution to reach that target, taking advantage of plant species biological processes such as photosynthesis and evapotranspiration.

However, the wide use and dissemination of GR and GW implementation in urbanized areas, depends not only on being economically advantageous but also on their efficiency and technical improvement regarding their multilayer structure, e.g. vegetation, growing substrate and drainage layer, which are crucial for their correct operation. The main goal of this paper is to present the contributions of GR and GW to the improvement of the urban environment and how their configuration affects its effectiveness.

2. Nature-based solutions: Concept and Contribution

GR and GW, considered ecotechnological nature-based solutions (NbS), consist of growing vegetation on building's roof and/or envelopes through multi-layered systems, thus performing several benefits in the urban area not only in buildings envelope but also to the nearby surroundings, attenuating the environmental negative consequences of urban development, Figure 1.

Figure 1 – Green roofs and green walls solutions: a) public car parking; b) local government building; c) multifamily residential building; d) hotel building. Source: [Ana Briga-Sá]

GR are typically divided into two categories: an intensive GR is supplied with water and nutrients and its substrate is usually thicker than 0.25 m, while an extensive GR is not irrigated and has a much shallower substrate (usually 0.06–0.15 m), limited plant species, relatively low costs, and minimal weight requirements compared to intensive types [6, 7]. GW are usually divided into two main systems: green facades (where climbing plants grow directly along the wall covering it) and living walls (which include a frame to hold elements and vegetation, and support a wider variety of plants, creating a uniform growth along the surface) [8]. Figure 2 presents GR (a) and living walls (b) typical multilayer composition.

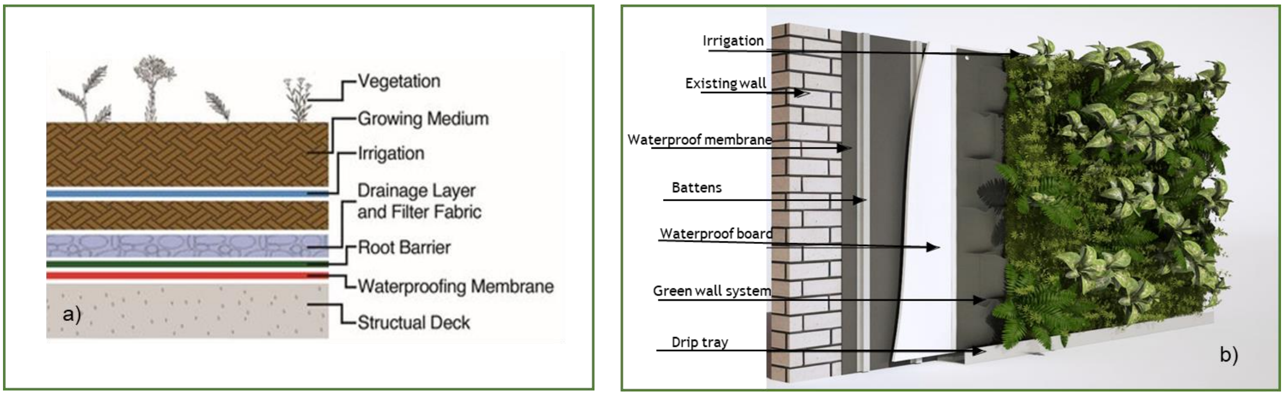

Figure 2 – GR (a) and living walls (b) multilayer typical composition (the irrigation system is optional). Source: [9, 10]

2.1. Stormwater Management

Urbanization in highly densely populated cities brings soil sealing and flood situations when extreme precipitation events occur, once the amount of naturally infiltrated stormwater is significantly reduced. The variability and pressure caused by climate change and seasonal variation in water supply tend to aggravate these problems. According to the European Environmental Agency [11], the use of traditional grey infrastructure to minimize soil sealing problems in urban areas has proven to be insufficient and even damaging, especially as climate change brings more extreme weather events that may lead to high flood levels followed by extended drought periods. As such, site scale GI such as GR and GW, contributes to rainwater management where it falls.

The study reported by Matos et al. (2019) [12] described that impervious cover has important hydrologic impacts, namely the increased runoff volume and peak discharges in the rainwater network, which can lead to significant consequences like rapid urban floods with social, environmental and economic implications. According to the authors, urban LID techniques consist of distributed runoff management measures, like GR, pervious pavements, waterways covered with vegetation and filter trails, among others, that seek to control stormwater in the origin, reducing imperviousness, and therefore avoiding increased runoff rate and volume, by increasing infiltration and groundwater recharge. The LID solutions implemented in the university campus showed peak discharges reduction between 68% and 95%. Also, the study made by Koc et al. (2021) [13] revealed the important contribution of GR to stormwater management in urban areas: amongst different solutions (bioretention cells, permeable pavement and infiltration trench, isolated or in combination), GR provided the highest improvement with approximately 40% in both peak discharge and volume reduction and has been found as the optimal practice among the stand-alone solutions.

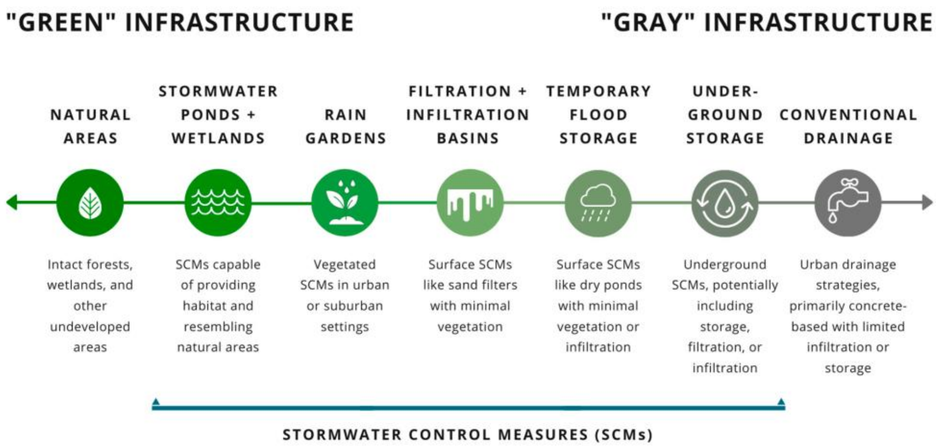

Figure 3: Stormwater infrastructure from “green to “gray”. Source: [14].

GR provide the closest operation characteristic to a natural basin by capturing the rainfall with its pervious surface and increase the transportation time of a water drop before it reaches the drainage system. Many factors were studied to understand the retention performance of GR, but it seems that the most relevant ones are the substrate depth (intensive GR have higher retention rates than extensive ones) and the rainfall characteristics. GR retaining capacity is limited and once the substrate becomes saturated, stormwater retention volume decreases significantly, and the water starts to runoff to the drainage system. However, even in those worst cases, the GR plants absorb part of the infiltrated water and extend the path taken by the water (through the pores created by their roots), leading to the decrease of the amount of runoff and consequently, to the delay of the flood peak.

Previous investigations on the field also revealed the capacity of extensive GR systems to retain and therefore delay rainwater runoff, when exposed to Mediterranean climate conditions [15] when using native selected aromatic plant species. GR effect in rainwater harvesting volume has also been studied and the results pointed to a reduction in the rainwater runoff volume that can be collected [16]. The amount does not seem to be high enough to withdraw the potential of rainwater harvesting systems to improve water use efficiency in buildings, but further investigations are needed to assess this reduction and the impacts on such systems once, in some cases, the harvested rainwater quality has shown disappointing results such as in the study of Zhang et al. (2014) [17]. An opposite trend has been reported by Monteiro et al (2017) [18], when testing different substrate compositions (which included expanded clay and crushed eggshell in their formulation), showing that rainwater runoff met standard quality values required for non-potable purposes.

GR substrate composition affects not only the adequate development and growth of the vegetation, but also the retention amount and quality of the collected rainwater. Plants, substrates, soil insects and microorganisms are expected to remove pollutants from rainwater. However, GR substrate can also be a sink for heavy metals, nitrogen and generally, a source of phosphate and dissolved inorganic and organic carbon in the growing seasons, as presented by Carpenter et al. (2016) [3], once the concentration of these parameters is

higher in the runoff than in the precipitation water. This reveals significant concern about the effects of GR in urban water resources. Higher concentrations of pollutants were found in GR with deeper substrate and the performance of the extensive GR is, in most cases, better than the intensive systems. Intensive GR usually need fertilizers that remain in the substrates and are continuously leaching in the runoff. Since nutrients are essential for the plants especially in the first establishment years and in the growing seasons, it is not a surprise that the age of the GR has a beneficial effect on the chemical leaching of GR, as presented by the long-term studies [19, 20]. However, once that the runoff volume from GR is smaller than runoff from traditional roofs, the total discharged loads of these pollutants are smaller.
It is important to highlight that each GR is a unique system, thus differing from each other in their performance. Their nature-based characteristics make them to develop and interact with the surrounding environment in their own terms. The leaching problem is already defined, and solutions must be developed to minimize its consequences. First, the use of fertilizers must be very controlled and mostly avoided. Then, the implementation of layers that retain nutrients are also being considered in the present developed research studies. Also, the control of the discharged GR water may avoid the contamination of water courses: first-flush systems might be considered, or drainage pipes can lead to gardens and/or to infiltration trenches in order to dispose the nutrients in the soil. In that scope, combined solutions of GR with other LID structures must be considered when implementing GR in a neighbourhood or site scale. Table 1 resumes the factors that can be a source or a sink of pollutants in GR.

Table 1- Potential of different factors, to be source or sink of pollutants [Source: adapted from [21]]

	Pollutant Source	Pollutant Sinks
Inherent factors	- Substrate, including component materials and depth, may contain heavy metals and nutrients that could contribute to leachate. - Structural layers may contribute to heavy metal accumulation due of metal, plastic, and polymer materials used in construction. - Plants are ambiguous: they can also act as an uptake of contaminants, or as a pollutant source.	- Plants behave as an uptake of contaminants by physiological metabolism of plant tissue and rhizospheric microorganisms. - Natural or artificial substrate added components that have the capacity of nutrient retention.
External factors	- Irrigation: if water supply is contaminated (especially reclaimed water), with diverse nutrients such as N and P. - Fertilizer and pesticides (including organic phosphor, chlorine, and nitrogen). - Atmospheric deposition, including dry and wet deposition resulting from gravity and rainfall, respectively. - Age, as over time the plant biomass and ecological functions of the GR as well as levels of metal pollutants will increase, and substrate nutrients will decrease.	- GR age, can influence water conductivity, substrate pollutant retention and the nutrient content of runoff. Newly-built GR have temporarily high nutrient levels that are steadily assimilated and degraded over time.

2.2. Temperature Regulation

Cities are complex systems under constant evolution. Today, buildings are responsible for 40% of European energy consumption and 36% of CO_2 emissions [22] and the energy demand for heating and cooling is still raising, due to the constant urban development and the occurrence of more and frequent extreme events. Comparing with vegetated surfaces, buildings increase the absorptive surface and the heat storage capacity by accumulation of high density and high heat capacity materials, which leads to longwave radiation emission during the night and the formation of Urban Heat Islands (UHI) – contributing to heat stress both indoors and outdoors [6]. Controlling the internal temperature through cooling units can be energy inefficient, and lead to the release of more greenhouse gases into the atmosphere which, in turn, intensifies climate change [23].
Extensive and intensive GR have been showing good performance in reducing outdoor air temperature and lowering buildings' cooling energy demand in different urban densities of arid and semi-arid regions [16, 24]. Preliminary studies developed in Portugal, allowed to analyse the thermal transmission coefficient and indoor hygrothermal characteristics of a GR

system under real climate conditions. It was concluded that the integration of a GR solution, comparing to a traditional one, allowed a reduction on the relative humidity values and lower temperature fluctuation inside the test cell. Lower oscillation patterns in heat flow variation were also verified [25, 26]. GR installation have proven to increase the thermal performance of buildings, by promoting a better thermal insulation, and thus ensuring energy savings – interior spaces of the buildings with GR present lower and moderate air temperature than buildings with bitumen roof [7]. Morakinyo et al. (2017) [27] presented an indoor cooling effect with GR, ranging between 0.4–1.4 ◦C, depending on the GR type, the urban density and the time of the day. Besides, GR are also able to mitigate the UHI effect in summer without penalizing the thermal performances of the roof in winter, by maintaining limited exterior temperature variation throughout the year and thus containing heat losses in winter and overheating in summer [28]. Moghbel et al. (2017) [7] revealed air temperatures 3.7 ˚C cooler than that of a reference roof and relative humidity 8.46% higher, with an average air CO_2 concentration 20.71 ppm lower. Similar values were found by Huang et al. (2016) [29] with a hydroponic GR system (with a water depth of 10 cm) that reduced the rooftop temperatures and heat amplitude by 5 ºC and 55%, respectively, with even better results when adding vegetation. They also revealed that an extensive GR contributed to a greater rooftop temperature and heat amplitude reductions, when comparing to the hydroponic one, due to the convection and conducting effects, as well as the transparent property of water substrates. Smaller values were presented by Morakinyo et al. (2017) [27] with an outdoor cooling effect ranging only between 0.05–0.6 ºC and an outdoor night-time warming effect of not more than 0.2 ºC, more obvious in semi-extensive GR. Authors reveal that hot-dry climates can benefit cooling demand reduction of 5.2% in the hottest days of the year with full-intensive GR while lowest savings of about 0.1% can be felt in semi-extensive GR in temperate climate. The study made by Bevilacqua et al. (2017) [28] revealed peak temperatures of 74.3 ºC in June, with GR allowing a surface temperature reduction from 0.57 to 0.63 times lower.

Three main phenomena have been described to characterize the thermal dynamics of a GR [30]: (1) soil and vegetation reduce the surrounding temperature through the evapotranspiration processes, (2) vegetation absorbs thermal energy for photosynthesis and acts as a shadow device, protecting the soil from the solar radiation and (3) the soil layer presents high heat thermal capacity and low dynamic thermal transmittance, thus creating a good thermal insulation for the building.

Similar conclusions were drawn from the studies developed on GW, essentially related to the envelope protection against external environment, energy saving (resulting from the temperature regulation), and also wind protection barrier [4, 31]. Depending on the type of climate, orientation and constructive details, GW can lead to energy savings varying between 35% and 90% and can reduce a building's energy costs by as much as 23% [32]. The replacement of a traditional solution by a GW system can lead to a minimum decrease of 12ºC and a maximum of 20ºC for the inner surface temperature values. A reduction of 70% in the heat flow can also be achieved [31].

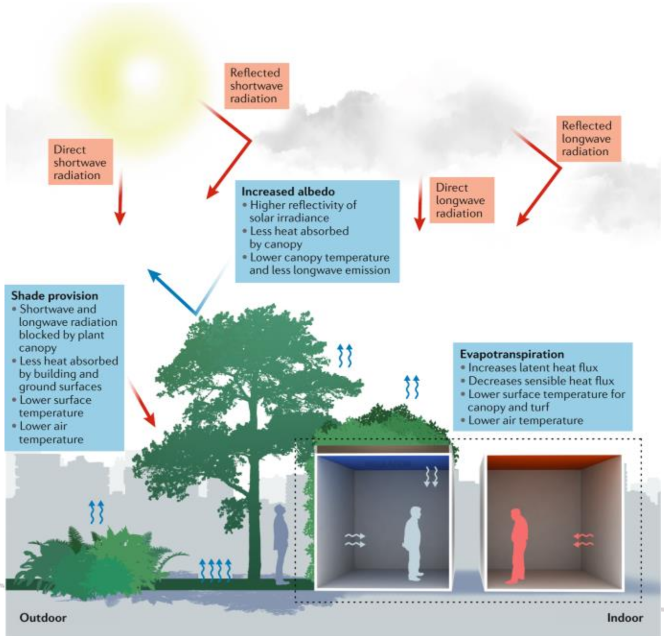

Figure 4: Greenery as a mitigation and adaptation strategy to urban heat. Source: [33].

2.3. Other Benefits

Moreover, vegetation implementation on rooftops and walls delivers multiple benefits from and to urban areas contributing to vegetation restoration and biodiversity into the urban environment, taking advantage of an area that is usually an unused space, besides providing a system of services that create value for both people and local ecosystems. For example, GR installation encourages people and neighbours to live and work together, in community gardening projects, reinforcing human relationships with all the benefits that come out [34] or even creating jobs for local inhabitants. Regarding the building itself, GR and GW implementation improves the aesthetics and consequently buildings rating, besides increasing building's materials lifespan and sound insulation, which could be particularly relevant in densely populated urban areas with high road traffic.

At the same time, GR and GW provide additional advantages thanks to the interaction among the different involved sectors: water, food and energy. For instance, the harvested water drained out from the GR can be used not only for GR irrigation to enable the vegetation/food development, but also for green areas irrigation or street cleaning, thus highlighting the strong water-food-energy nexus [34]. Furthermore, large scale implementation of GI contributes to the achievement of the Sustainable Development Goals (SDG) from the United Nations Agenda 2030, specifically contributing to the SDG 11 (sustainable and resilient cities and communities) and SDG 13 (climate action) [35].

2.4. Limitations

GR and GW implementation in city centres is still limited due to some constraints that can arise from their implementation, not only for the urban environment but also to the building itself. Substrate incorporation in their structure could bring several problems to the building structure such as excessive load, with the negative consequence to the building security.

Furthermore, the installed water retention layer, besides bringing an additional weight, also brings a constant humidity to the building envelope, that can cause water infiltration and consequently structure damage. For that reason, GR/GW implementation must be designed and installed by qualified professionals and calculated/designed to the building where it will be installed, to prevent any future damage to the structure. Also, it is of utmost importance that the impermeabilization layer is properly installed (to prevent infiltrations) and also that it could also resist to roots penetration from more vigorous vegetation.

On the other hand, the choice of vegetation to be installed into these GI must be carefully chosen among the native species available of the region, in order to prevent any attraction of undesired insects that may cause plagues. Also, by choosing native species adapted to the region climate, they will be more resistant to the climate conditions, and thus growth and develop more resilient and unaffected by climate variations. A mix of vegetation species is preferred (instead of a single species) as they can be an ecosystem to different wildlife. In addition, choose certain species over others will decisively affect the thermal performance of the green infrastructure and, consequently, the hygrothermal conditions of the outdoor environment and inside buildings.

3. Main Challenges

Green infrastructure dissemination stands ups to several challenges when they are planned to be installed. Both GR and GW need to be carefully designed and constructed, with suitable materials in order to avoid deterioration of runoff water quality and damages to the building structure, while achieving the higher performance. The selection of the substrate type affects not only the water runoff quality but also their thermal performance: extensive GR provide significant benefits for saving energy mainly in dry and hot periods while intensive GR can be satisfactorily performing in different climatological regions, including colder areas [34]. GR might also not be technically feasible in particular situations (namely in existing buildings, where a previous careful structural analysis must be made) and be the source of problems (e.g. water infiltrations through the ceilings) when the execution is not properly done.

Another important fact is the maintenance requirements and investment costs of this engineered solutions that can be substantially higher than traditional roofs/walls, although they can be compensated with the reduction of energy consumption inside. In fact, the study made by Peng and Jim (2015) [36] showed a payback period of 6.8 years for extensive and

19.5 years for intensive GR, considering 40-years of expected lifetime. Besides, no two roofs are the same, and the evaporative cooling functions of GR have been linked to a number of attributes including plant species combinations and cover, substrate type, and the use of supplemental irrigation [37]. In sum, the performance of GR and GW, related both to thermal control (inside buildings and on its surroundings) and to stormwater management, is influenced by the following key elements:

- the choice of the vegetation plays a crucial role in lowering temperature differences on GR/GW and plays a crucial role on water retention [38]. Sedum cools the roof significantly more than meadow vegetation and should be promoted to improve GR cooling due to constant, near 100% vegetative cover [37]; Aromatic plants used in the study reported by Monteiro et al. (2016) [15] have shown to be a good option for GR vegetation, since they have resisted the operating conditions, with the advantage of usage in other economical areas (food and cosmetic industries).
- daytime temperature reductions promoted by GR/GW also vary with the climate conditions due to the interplay between solar intensity/air temperature and relative humidity between different regions [27];
- the level of water content in the substrate is a variable that significantly influences the surface temperature of GR/GW, being an effective mean for temperature regulation [28]. Substrate saturation, when the precipitation event begins, also determines the system capacity for stormwater retention.
- Recently, there is an increasing interest in developing more cost-effective NbS design, to use alternative building materials for liners and substrates, to combine green infrastructure with solar energy production, and to create multi-purpose recreational space. Given the sustainability of GR/GW over their full life cycle, policies are needed that encourage their use through regulation or financial incentives (such as water or property fee reduction). Setting up quality standards for these greenery systems, it is important to scale up these NbS [6] and more integrated studies considering the Water-Energy Nexus and feasibility analysis must be considered.

4. Conclusions

The present climate change scenario and the arising negative environmental consequences, especially in densely populated urban areas, especially stormwater management (with more frequent and intense precipitation events, followed by severe drought periods) and urban heat island effect, is a major concern that world population are facing and need to find cost-efficient solutions to overcome such situations. GR and GW, characterized as urban NbS, have been increasingly implemented within urban areas due to their positive contribution to regulate microclimates into the urban environment and minimization of stormwater management constraints. Also, they promote urban areas sustainability and resilience, thus improving their capacity to deal with growing environmental and socioeconomic issues. The decision of which GR or GW system is more appropriate to a certain project must depend not only on the construction and climatic restrictions but also on the environmental impact of its components and associated costs during its entire lifecycle. Moreover, the implementation of green infrastructure such as GR and GW, is an additional measure that must be adopted by the stakeholders and in charge policy making, to help climate change mitigation in the urban populated cities, integrating different elements (plans, guides, strategies, frameworks).
NbS is being implemented in urban areas as a consequence of changing attitudes towards cities sustainability and resilience, and their development needs the participation of the all community (urban planning, political will and social participation) to make the world a better place. Nevertheless, further efforts should be made to enhance knowledge about GR and GW operation impacts, both quantitatively and qualitatively, to help overcome some social and economic barriers.

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