A PRACTICAL APPLICATION OF NATURE-BASED SOLUTIONS: PARAMETRIC FRAMEWORK FOR LOCAL ADAPTATION AND REPLICABILITY IN EUROPEAN CITIES

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ABSTRACT

As climate change is further threatening our planet and society, nature-based solutions (NbS) are increasingly recognized as impactful measures to address such problems and enhance urban resilience, biodiversity, and human well-being. Yet, their adoption often remains overlooked and misjudged, due to their complexity and sometimes not quite complete understanding of their potential, when dealing with important challenges.

Therefore, this research seeks to facilitate the implementation of NbS, helping decision-makers and communities take informed decisions and navigate the vast information that has been produced on the topic, eventually improving the environmental and social conditions of specific urban spaces at a time, and avoiding major risks of maladaptation or dissatisfaction with the project.

This research aims to investigate the strong relationship that exists among three specific groups of elements: urban NbS, urban morphologies commonly found in Europe, and common urban challenges that can be addressed by the adoption of NbS. This correlation is visualized by the development of an interactive decision-support tool, which is declined into two equivalent options. The first one is an "easy-to-read version", composed of a set of 2D heatmaps plus a Sankey diagram that enables to better understand the threefold connections. It was created to support non-professionals as well, since they may find it difficult to use the second one. The latter consists in a 3D parametric matrix generated using Grasshopper, a plug-in for Rhinoceros; this alternative gives the opportunity to visualize the elements simultaneously, interact with, and test the different combinations of solutions to better understand the degree of suitability of each choice. In both tools, users can select, hide, and change the values as they please, to analyze diverse possible synergies.

Finally, the proposed framework is tested on an urban morphology of choice within the district of Mirafiori, Italy. But the initial intention of generating a tool which adoption could be spread across different European cities, has made it possible for this tool to be tailored to other similar realities across the continent.

KEY-WORDS

Nature-based solutions, Urban morphologies, Urban challenges, Decision-support tool, NbS suitability

RIASSUNTO

Poichè il cambiamento climatico rappresenta una minaccia crescente per il nostro pianeta e la nostra società, le soluzioni basate sulla natura, ovvero nature-based solutions (NbS), sono sempre più riconosciute come misure efficaci per incrementare la resilienza urbana, sostenere la biodiversità e migliorare il benessere delle comunità. Tuttavia, la loro implementazione risulta ancora limitata e talvolta mal interpretata, sia a causa della complessità intrinseca di tali interventi, sia per una comprensione parziale del loro potenziale sistemico nel rispondere a problematiche urbane significative.

Pertanto, la presente ricerca si propone di facilitare l'integrazione delle NbS nei contesti urbani europei, fornendo uno strumento operativo a supporto dei decisori pubblici e delle comunità locali. L'obiettivo è orientare il processo decisionale all'interno dell'ampia produzione scientifica esistente, favorendo scelte informate e consapevoli, capaci di migliorare le condizioni ambientali e sociali di specifici ambiti urbani, riducendo al contempo il rischio di disadattamento o di effetti indesiderati.

L'analisi viene portata avanti attraverso la relazione sistemica tra tre categorie di elementi: NbS urbane, morfologie urbane, morfologie urbane tipicamente diffuse nel contesto europeo, e principali criticità urbane affrontabili mediante l'applicazione di NbS.

Questa correlazione viene formalizzata attraverso la progettazione di uno strumento interattivo, declinato in due versioni complementari. La prima consiste in un sistema di mappe di calore bidimensionali integrate con un diagramma di Sankey, che consente una lettura intuitiva della triplice relazione tra gli elementi ed è pensata per utenti non specialisti. La seconda versione è una matrice parametrica tridimensionale sviluppata in Grasshopper (plug-in di Rhinoceros), che permette di visualizzare simultaneamente tutte le variabili coinvolte, testare diverse combinazioni e analizzare il grado di compatibilità e sinergia tra le NbS selezionate e i contesti morfologici considerati. In entrambe le configurazioni, l'utente può modificare parametri, selezionare o escludere elementi, analizzando così la complementarietà di diverse interrelazioni.

Lo strumento viene infine testato su una delle morfologie urbane individuate nel quartiere di Mirafiori (Torino, Italia), assumendo tale contesto come caso studio applicativo. Nonostante sia applicato e calibrato su questo sito specifico, il metodo è concepito per essere replicabile e adattabile ad altre città europee con caratteristiche morfologiche analoghe.

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01 INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

We are currently facing unprecedented challenges around the world that are slowly forcing us to acknowledge that our current life-style is causing increasing stress to us and to the surrounding environment.

Most of these changes don't always suddenly appear, but they gradually chain to one another, until they become so persistent that we will not be able to find our way out. As climate change accelerates, the systems we are used to rely on will not be able to assist us anymore. This is why our cities, largely built for efficiency and durability, need to change and promote adaptation and sustainable evolution. This transformation requires a shift in perspective: One where nature is not treated as a passive rebound, but as an active actor and collaborator in shaping livable, resilient spaces, where humans and nature can co-exist.

1.1.1 Climate change impacts on urban systems

We have already acknowledged that the impacts of climate change (CC) have become scaringly serious around the entire planet. The global temperatures have already surpassed by **over 1°C pre-industrial levels**, with future estimates that intimate that this measure will be doubled within the next few decades, unless appropriate measures are taken. As the IPCC (2022) reports, by exceeding this limit we could face even more serious consequences than we are today,

with concerning drought levels spreading widely across more susceptible areas, stronger heatwaves hitting our cities, and more torrential rainfall events, causing floodings, deaths, and infrastructural damages (Bednar-Fridl et al., 2022). Researchers have identified some direct consequences of CC, such as the greenhouse gas (GHG) emission increase, the noticeable rise in temperatures, even in colder seasons, the increase in wildfires risk, and damages to biodiversity health. In turn, these main effects can cause **indirect consequences** on a lot of different realms, such as the economy, the availability of water and energy, they can affect infrastructure well-functioning, and most of, all they have an enormous effect on public health and well-being, threatening also agriculture and food sources. Moreover, rising temperatures and biodiversity disturbances can bring to the permanent damage and destruction of several ecosystems, which are not able to adapt as fast and can also be influenced by non-native flora, fauna, and infectious diseases (Bednar-Fridl et al., 2022; Kabisch et al., 2016; Nicolini, 2024).

Taking as reference a city such as Turin (Italy) for example, it is predicted that by 2050 it will have similar climate characteristics as the city of Dallas (Texas, USA) today, showing an annual temperature increase of 2.1°C, while for the warmest month the prediction foresees an even higher increase, of 7.7°C (Fig. 1).

It is interesting to note that, although the urbanized areas occupy only a very scarce percentage of the entire Earth's surface, they are also the biggest attractors and receivers of the total world's population (Bona et al., 2022). This high concentration of people brings eventually to extremely high consumptions of whatever resource a city can offer, from energy supplies, to water and food resources, constantly generating more and more waste and GHG emissions, straining and exploiting the surrounding areas reserves (UN, 2022; Bona et al., 2022).

As reported by the IPCC (2022), a very high percentage of the urban population can be considered vulnerable and exposed to these risks, which can significantly affect their safety and well-being (Bednar-Fridl et al., 2022). For example, they could be struck by a flood or landslide and be displaced within hours, losing their homes, their security, and their routine.

The consequences of climate change are particularly relevant when considering an urban environment. On one hand because of the physical properties that connote such areas, where **highly compact settlements** are also the one with highest impermeabilized surfaces, reinforcing both extreme heat and flooding events. The susceptibility of cities is also given by the high numbers of populations that are concentrated within the area and, therefore, a higher number of people is going to be affected by the same event.

One of the most concerning effects that is particularly recognized inside the urban realm is the lack of drinking water, which is further exacerbated by the increasing demand of a more difficult food production. Another debilitating factor is related to the constant rising in temperatures, that create longer and more intense heatwaves, but also a more concentrated UHI phenomenon, which pose serious health pressure on the most weak and exposed urban dwellers, such as elderly, infants, women, but also outside workers. Furthermore, the lack of green spaces that is generally noted inside highly urbanized spaces, can worsen the physical and mental health state of the citizens. It is also interesting to note that usually, environmental

and well-being repercussions are more detected in already disadvantaged areas within the city (Bernard-Fridl et al., 2022; Kabisch et al., 2016). Within this framework, even though cities are one of the most fragile environments when it comes to CC-related impacts, they can also be very important drivers to guide future change, toward a more resilient and sustainable way of existing. To reach this goal, it is important to have the support and recognition of government institutions, so that real efforts can be defined and put into action immediately (UN-Habitat, 2024).

1.1.2 Possible future climate scenarios for European cities

As climatic statistics highlight, the future climatic frame that is expected for European regions for the next decades is particularly concerning (EEA, 2021). Besides the already stressed condition of being affected from concerning heatwaves, with consequent wildfires and droughts, and the destructive force of more frequent and strong rainfall events, which can cause floodings, other real issues are given by landslides and avalanches that can originate from glaciers' melting and soil instability. Such impacts are going to generate after-effects, causing stress and imbalances within a wide variety of spheres, which are the basis of the artificial system that we created to support our own activities (Fig. 2) (Bednar-Fridl et al., 2022).

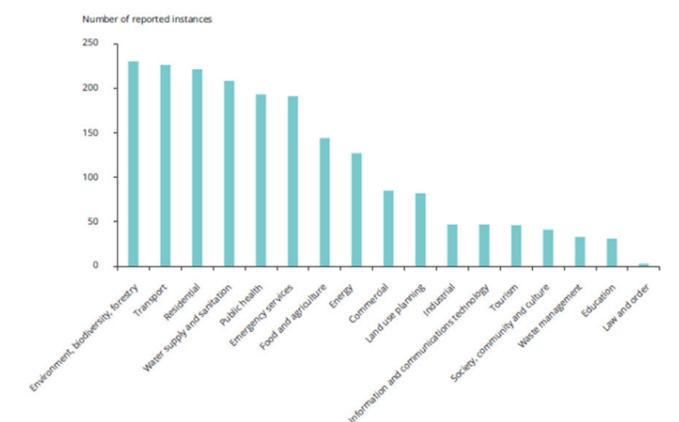**Figure 2 –** Graphic visualization of the most impacted sectors of urban environments across Europe (EEA, 2021, p. 22).

Therefore, EU Nations have commonly agreed to follow certain measures to tackle such problematics. These measures – grouped under

Figure 1 – Increase in temperatures during the warmest month in Europe, based on 2019 predictions (https://github.com/hooge104/future_cities).

mitigation and adaptation strategies – are to be applied and articulated based on national, regional, and local levels and fragilities, since most of the impacts can generate extremely specific consequences, which need to be addressed locally to foster actual positive results. Many cities across Europe have therefore received EU funds to plan and enable these amelioration processes.

Mitigation and adaptation measures are extremely closely related, because the solutions to tackle individual problems can actually have a positive (or negative effect) on other realms. This is why the European Commission further stresses the importance of adopting both types of measures and make sure that the intended actions are somewhat harmonized within the whole vision,

being careful of considering benefits and co-benefits, but also the possible negative side effects that each action can unintentionally bring to the table (EEA, 2020).

As each member state is affected by its own CC-related effects, the European Commission strongly suggests the adoption of singular adaptation plans that can be tailored to each one of them. A potential problem that can be noted following an individual approach – even though Europe-wide policies are still considered when defining these strategies – is the lack of coordination among each State implementation stage of detailed plans, which can potentially hinder progress especially when it comes to mitigation objectives or overall adaptive solutions (Fig. 3) (MATTM, 2015).
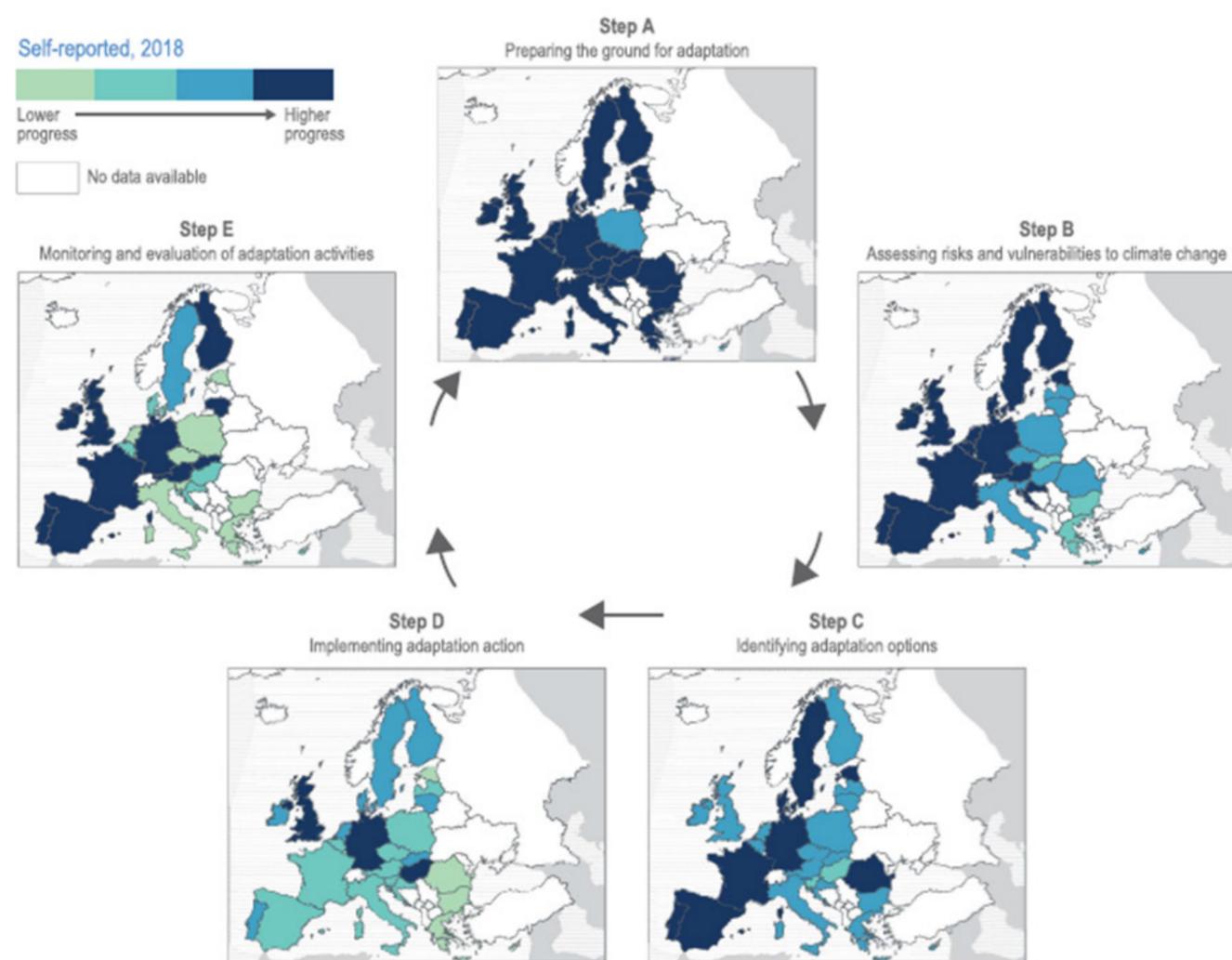

Figure 3 – Graphic view of the progress of single national adaptation strategies, based on a self-report of EU countries in 2018 (Bednar-Fridl, 2022).

Building on the fact that adaptation plans are extremely site-specific, it is not rare that decision-makers will encounter some difficulties when trying to navigate numerous problems, as well as numerous potential solutions, resulting in indecision and possible overlooking on potential critical factors. This is aggravated by the lack of knowledge and confusion that has grown around this topic, requiring solid but cautious and variable strategies supported by updated data and knowledge building (MATTM, 2015).

Climate change mitigation

With the term "mitigation measure" is commonly intended a **long-term action that can act on the causes that brought to the rise of climate change**, hoping to use it to modify, annul or at least mitigate its repercussions. The majority of these measures have the objective of lowering GHG concentrations in the atmosphere or increasing carbon sequestration. Such solutions, for the nature of their function, show the most positive effect if implemented globally and on very high scales, since climate change does not know borders (MATTM, 2015).

A mitigation measure can be implemented in two different ways. The first one is aimed at directly act on the emission source, this means for example switching from fuel sources to renewable ones; this also tackles the way the energy is distributed, favoring less energy-driven processes and goods. For example, a big contributor to carbon emission is the building sector: By adopting sustainable materials and been mindful of the life-cycle assessment of those adopted, these carbon emissions can be significantly diminished. The other possible approach to implementing mitigation measures focuses on emissions that have already been released; this is mainly addressed by increasing tree cover and by maintaining or regenerating forests (Città di Torino, 2020a, p. 9).

In today's world and age, the countries that emit more CO_2 are usually found in the developing areas, since societal and economic pressures are contributing to their faster and energy-driven development. The conditions of their overpopulated cities are deteriorating very

fast, since social imbalances, inequalities, and resource-greedy system is adding to their land's exploitation. This does not mean that the burden of dealing with such harmful emissions should fall on them, since it is a responsibility shared by the entire world (MATTM, 2015, p.22; Tyllianakis et al., 2022).

Climate change adaptation

On the other hand, an "adaptation measure" is an action that aims to **tackle all of the possible CC-related effects**. Researchers note that, even if we entirely stopped generating GHG emissions today, their presence will endure for decades, if not centuries, stressing the importance of adopting adaptation measures as soon as possible and in wider realms (Città di Torino, 2020a, p. 11).

This type of solution is characterized by a wide variety of possibilities. It can be short-, medium- and long-term oriented, mainly defined by the type of problem it is asked to tackle. For example, short-term measures are mainly used to obtain an immediate alleviation of a detected problem, which can be flooding, a wildfire, or any disaster risk that generates instant danger and therefore requires an even quicker solution. This type of action is usually referred to as disaster risk reduction (DRR). But adaptation measures are also implemented for broader reasons, which span from sustaining biodiversity to prevent its disappearance, to helping improve the overall livability conditions within an urban environment, whether by fostering a more equitable distribution of green and recreational spaces, or by improving the physical conditions, comfort, security, and happiness of its citizens (Città di Torino, 2020a, p. 11).

Therefore, it is not possible to define a single adaptation strategy that will reinforce and sustain very different contexts, as every space and culture has its own needs, requirements, and expectations on how a sustainable, equitable, and environmental just dimension should look like.

1.1.3 Risks and adaptation measures in Italy

The future climate scenarios predicted for the Italian territory are obviously negative, but in line with the current trends of environmental conditions that are already affecting the area today.

In the nearest future, the main and more concerning problems are detected on the southern latitudes of the nation. The regions are going to be affected by even more increasing temperatures, generating more serious heatwaves and UHI phenomena, thus worsening the citizens' health and outdoor comfort, especially in warmer seasons (MATTM, 2015).

One of the other important events that are going to be spotted around the Italian territory is the increased likelihood of being affected by torrential rainfalls, storms, and surges, which can cause landslides – further aggravated by the absence of trees and roots that contribute to soil stability – and even more frequently serious flash flooding events, which affect infrastructure stability, local economy, water quality, and human safety. These very time-restricted events of rain surges may take the attention off of the fact that the region is going to be also affected by longer periods of drought, causing potable water scarcity, therefore straining its use for agricultural purposes and food production (MATTM, 2015).

Furthermore, it has been acknowledged how the majority of the habitats that are typically found at a certain altitude are slowly moving upwards, since already established flora and fauna species cannot survive under higher temperatures and search for cooler areas. But unlike the fauna, the ability of the flora to change habitat is extremely slow and cannot therefore survive against the much faster progression of global temperature increase, which will eventually cause biodiversity loss and degradation of lower altitude ecosystems. Moreover, the forest stock present on the Italian territory is at high risk of more frequent and longer wildfires, and soil degradation, which harm its survival (MATTM, 2015).

Furthermore, the economic repercussion that CC-related events can generate on such a territory are also crucial factors to be considered. Aside from the incalculable damages that could be caused to the historical and cultural heritage, there are also important consequences on the hydroelectric production system that generates electricity for a wide range of citizens, given that the water source that generates it could substantially decrease. Moreover, further income could be lost due to reduced tourism, as visitors may choose cooler destinations for their summer holidays (MATTM, 2015).

To overcome this situation, the Italian Government has produced two main policies, in line with the European ones (Città di Torino, 2020a):

- the **National Strategy for Adaptation to Climate Change** (Strategia Nazionale di Adattamento ai Cambiamenti Climatici, SNACC, 2015), that aims to establish the general principles on which the Italian adaptation measures are based on;

- the **National Plan for Climate Change** (Piano Nazionale ai Cambiamenti Climatici, PNACC, 2016), that was created in support of the previous document to foster its application in each Region.

1.1.4 Climate change in Turin

Turin's climatic context

With its 855.000 residents, Turin is one of the biggest cities in northern Italy, only second in size to Milan, and fourth largest in the country (ISTAT, 2024). Geographically, the city is placed right in the middle of the Po Valley, generated by the Alps and by the Po River (Fig. 4). This enclosure actually creates a very severe condition to live in, since it collects all the pollution and particulate matter generated in the area, and with no free access of relevant wind paths to clear the air, this stagnant layer persists, considerably worsening the air quality (ARPAPiemonte; Città di Torino, 2020a).

The city's aspect today is mainly attributable to its strong industrial development era, that mostly contributed to its expansion during the 1960s all the way through the 1990s. Today, the total extent of metropolitan area that has been urbanized amounts to approximately 65%. In the past few decades, the city government tried – and is currently trying – to evolve from a heavy industrial city connotation to a new one, more technology- and culture-oriented. As uplifting as this intention was, the shift in the city's purpose has resulted in a large amount of underutilized industrial heritage fabric and facilities (about 10 million m^2) (Città di Torino, 2020a, pp. 48-49).

Building on the scarce air quality that affects the city constantly and its morphological composition, Turin is also at risk of hydrological instability, since the near hilly zone could easily generate landslides during heavy rainfalls, further increased by human modification of the landscape, through impermeabilization and stream coverings (Città di Torino, 2020a, pp. 41-46).

In fact, the city has already faced numerous floods – in 1994, 2000, and 2016 – partly from its rivers (Po, Dora Riparia, Sangone, Stura di Lanzo), but also due to rain surges (Fig. 5). This aspect is going to be exacerbated as time passes and the climatic consequences worsen (Città di Torino, 2020a, p. 16).

Connected to the increase of flooding events, another concern for the city is related to the sewer system's capacity. Fortunately, when it was conceived for the first time in 1893, the design provided the city with a two-way system, one mainly used to collect black water, while the other one for grey and pluvial water, thus lowering the chance of having to deal with frequent overwhelming. Nonetheless, the system was not measured to deal with current rates and could therefore fail during extreme events. To overcome this problem, the city decided to build a new collector (Collettore Mediano) in the southern part of the city, which can support the sewage system during flash floodings (Città di Torino, 2020a, p. 22).

Simultaneously, the territory is also going to face hotter and drier years, in comparison to the last decades (Fig. 6) (Città di Torino, 2020a, p. 27; CMCC Torino).

As a consequence of hotter seasons, the risk of dealing with more intense heatwaves is also very present in a city like Turin (Fig. 7), which is furtherly aggravated by the strong UHI effect present in more densely built areas. The moist heatwave is especially dangerous for the city, as the presence of clouds impedes the trapped heat to dissipate, therefore creating a "heat cape" that will take several days to dissipate (Città di Torino, 2020a).

This condition is further aggravated by the high rate of impermeabilization around the city (Fig. 8), which is mainly attributed to the big industrial complexes that were built in the city's peripheral areas (e.g., FIAT on the south-western part and IVECO on the north-eastern part) (ARPAPiemonte; Città di Torino, 2020a, p. 22).
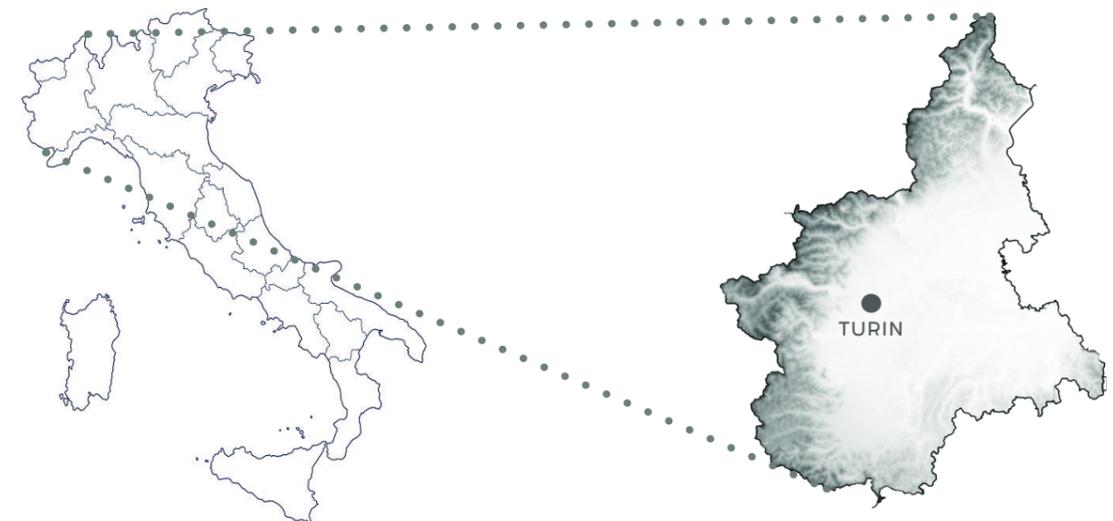
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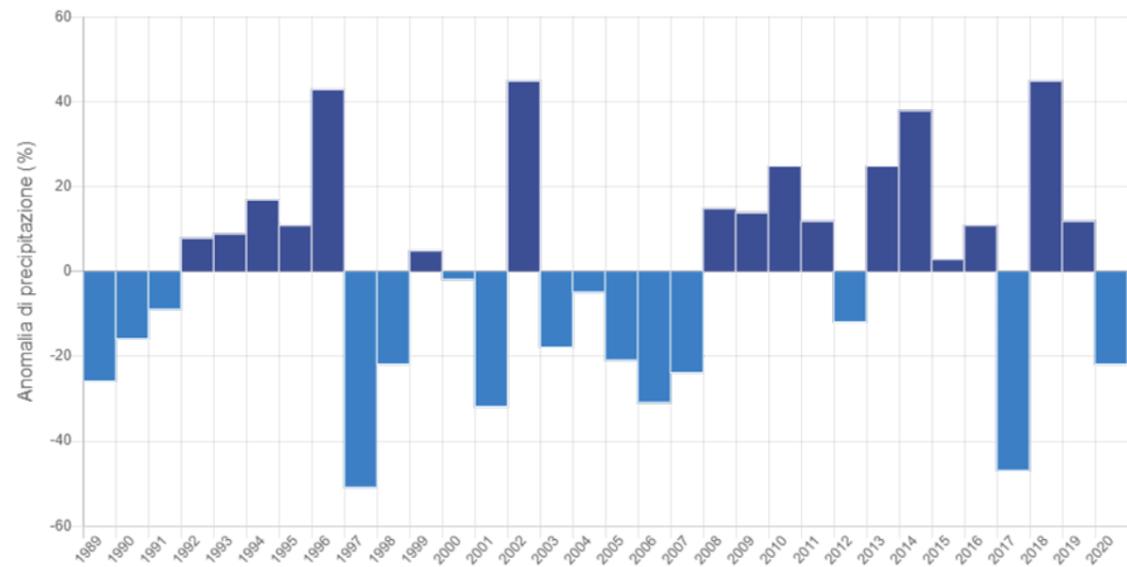
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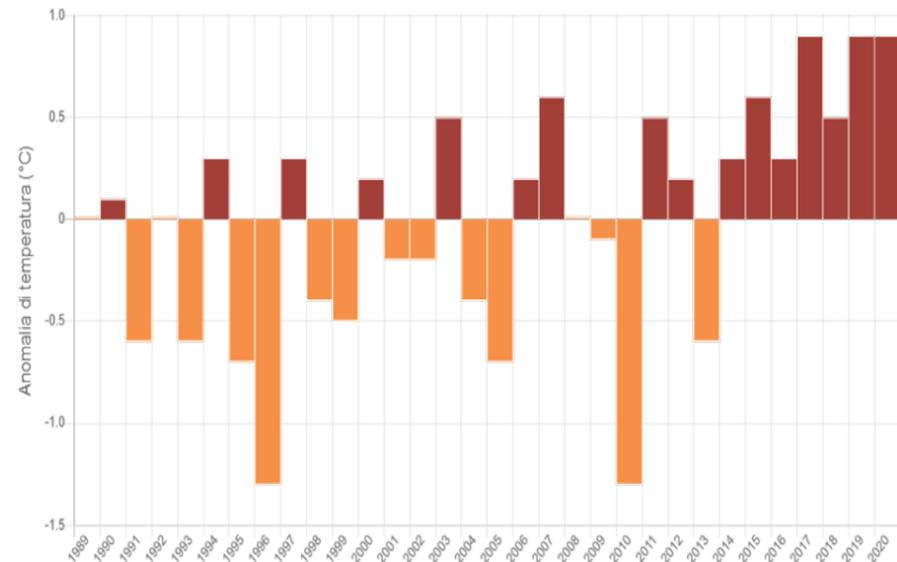
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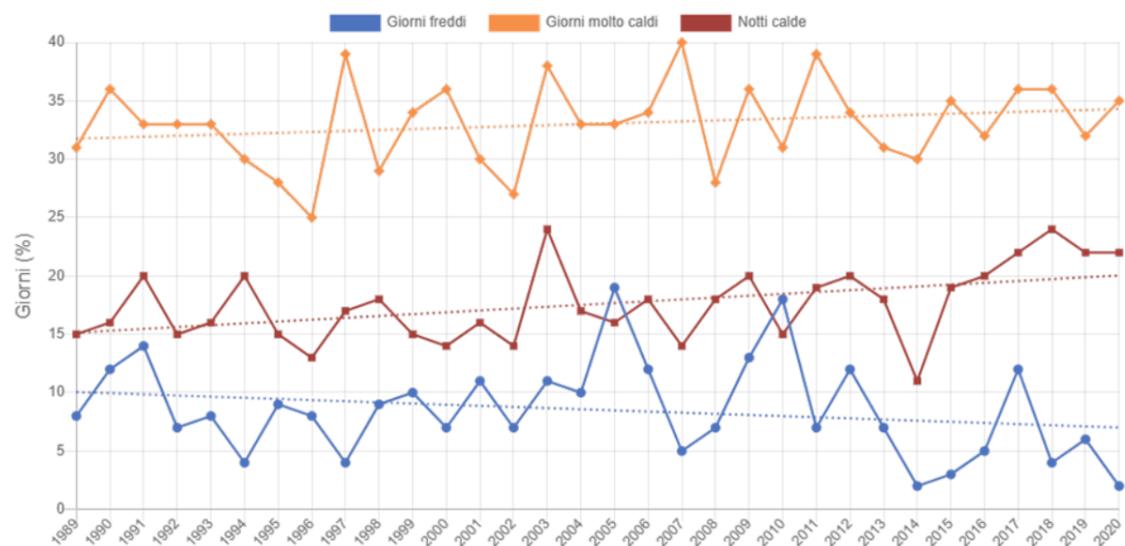
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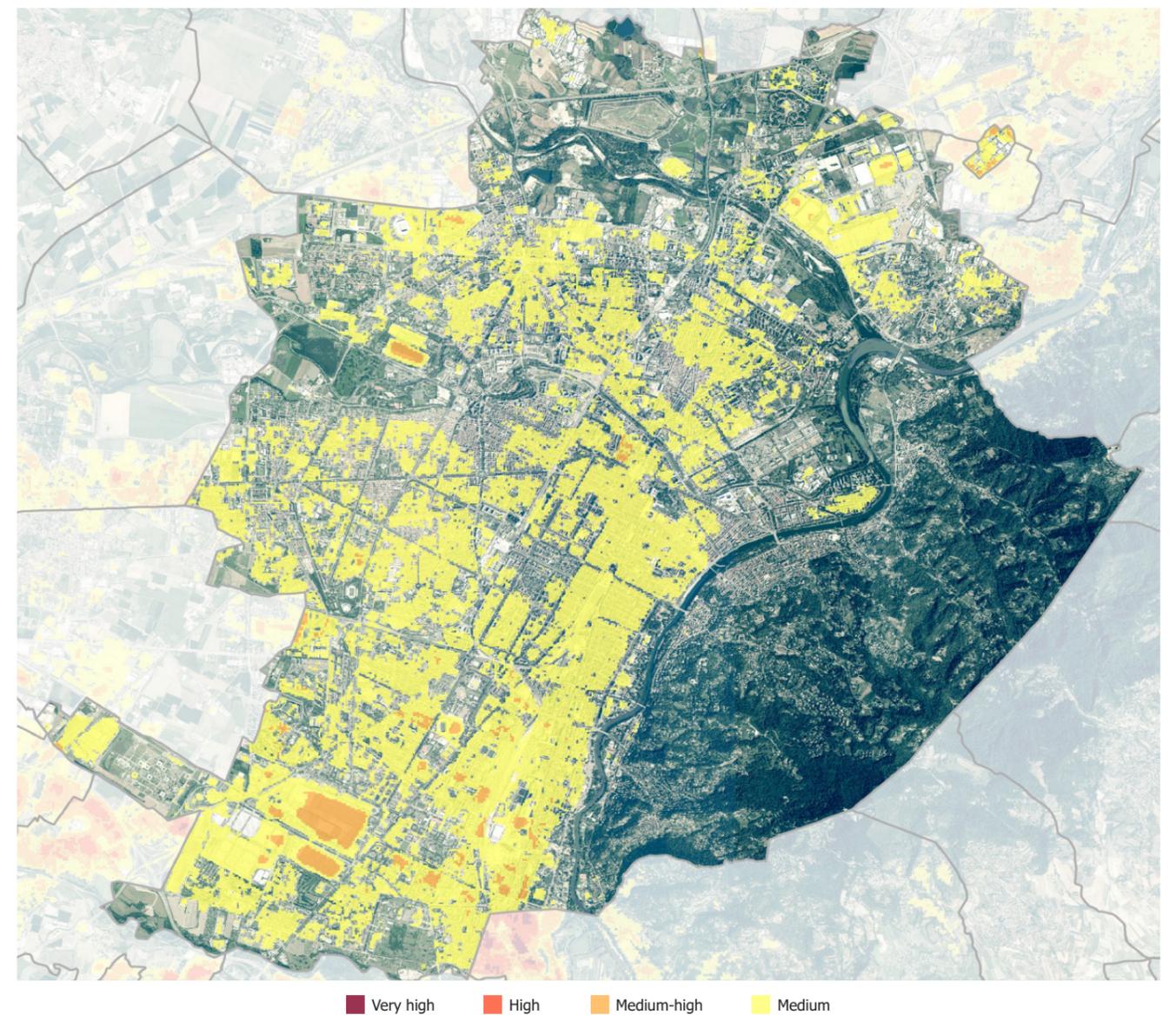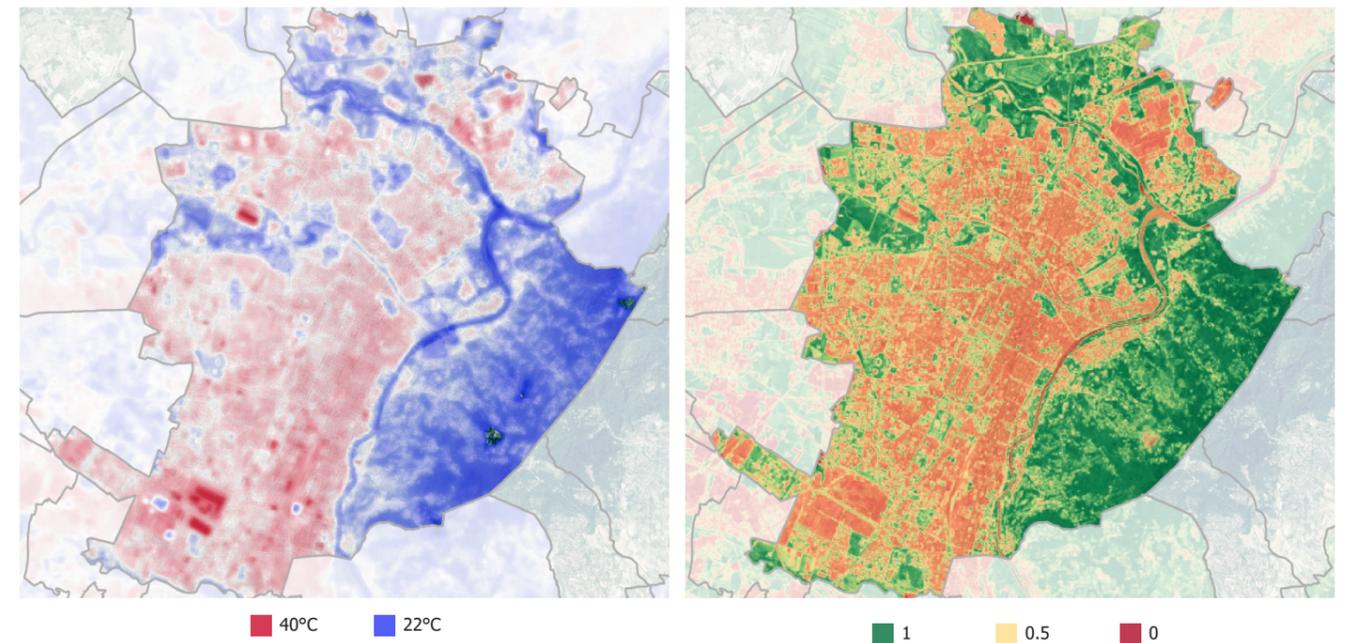
Figure 8 — Maps that measure the UHI effect in Turin, based on 2019 measures: soil temperatures (LST) on the left, normalized vegetation index (NDVI) on the right, and vulnerability of the population to the UHI on the bottom (Geopotale Piemonte).

In response to the European Commission's desire for each member state to generate its own, tailored adaptation plan, the city of Turin participated to the movement "Covenant of Mayors" in 2009 and again in 2019, which was established to support local municipalities around Europe to reduce their carbon emissions and develop adaptation strategies.

Following these prescriptions, Turin has developed its important guiding plans:

- the **Turin Action Plan for Energy**, TAPE (Piano d'Azione per l'Energia Sostenibile), where it established the intention of diminishing by almost one third its carbon emissions within a decade, compared to measurements conducted 20 years before. The main measures involved required the expansion of the district heating network, changing to LED streetlights, and retrofitting the buildings to achieve better performances. Already in 2017 it was acknowledged that the actions were successful to the intended goal and actually surpassed it. Therefore, in 2019 the city renovated its ambition to reduce carbon emissions by 40% by 2030 (Città di Torino, 2020a, pp. 8-11).
- the **Resilience Plan**, 2020, in which they established a set of actions that could be implemented based on the analysis of risk maps for heatwaves and flood events (CMCC Torino). It proposes different kinds of solutions that can be adopted, which span from typical grey solutions, to green solutions (NbS), and soft solutions mainly based on regulatory principles and awareness-raising (Città di Torino, 2020a, Annex 1).

The adaptation measures adopted across the city up to date are mainly related to flood risk reduction, by re-naturalizing riverbanks and levees, restoring floodplains to avoid constricting the river, and adding systems to collect and infiltrate rainwater, such as rain gardens, infiltration basins, and permeable pavements (Città di Torino, 2020a, p. 16).

Substantial importance has been given to the incrementation and amelioration of the green spaces across the city, especially in vulnerable neighborhoods. For example, both intensive and extensive green roofs have been suggested, green facades, community gardens, and the substitution of low-albedo surfaces with more reflective and cool materials (Città di Torino, 2020a, pp. 50-53, Annex 1; Città di Torino, 2020b, Annex 6); PROgiREG).

Thanks to these natural inclusions, but also to the historical boulevards, urban parks, and forests (Fig. 9), Turin is now considered as one of the greenest cities in Italy, able to offer over 55 m² of green space per resident. This means that over 90% of Turin's residents have the possibility to reach a green recreational space within a five-minute walk (300m) from their homes. Nonetheless, the overall city's territory is still extremely built-up, which limits the inclusion of large-scale green solutions within the urban fabric (Città di Torino, 2020a, pp. 21, 40).

1.2 NATURE-BASED SOLUTIONS

1.2.1 The origin and definition of NbS

Over the last couple of decades, an extremely valid and effective solution has been identified in order to support climate change adaptation (CCA) and disaster risk reduction (DRR) simultaneously: Nature-based solutions (NbS). The emergence of this term is to be dated back to the beginning of the millennium.

The initial research supporting this kind of solutions stemmed from international organizations, such as the **International Union for Conservation of Nature** (IUCN), the **World Bank**, and the **European Commission**. During the last fifty years, the scientific community has been very active in searching for alternative solutions to conventional grey structures, that could have similar functions to those engineered infrastructures, but could also adapt and mitigate CC effects, help tackle societal challenges, and restore nature balance. The need for introducing and restoring natural ecosystems in common urban design practice has been stressed ever since (Cohen-Shacham et al., 2016).

The term NbS was introduced alongside its definition in the early 2000s by IUCN, which describes them as:

"Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits."
(Cohen-Shacham et al., 2016, p. 5)

The European Commission followed with another interesting definition, possibly more well-rounded:

"Solutions to societal challenges 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."
(EEA, 2021, p.17)

Since existing restoration and conservation efforts remain often insufficient to offset ongoing environmental degradation, highlighting the need for innovative and holistic solutions is essential. In fact, nature-based solutions, as defined in many scientific studies, can be understood as an inclusive "**umbrella concept**", which can promote "a wide range of ecosystem-based approaches, including the protection, sustainable management, restoration, and creation of natural ecosystems" (IUCN, 2020; World Bank, 2021), while supporting climate change mitigation and adaptation in ways that are able to simultaneously address broader societal challenges, such as food and water security, human health and well-being, disaster risk, and social and economic development, as well as offer a support to biodiversity (Cohen-Shacham et al., 2016; Cohen-Shacham et al., 2019).

These approaches, promoted by an NbS application, can be simplified within a hierarchical

logic (Fig. 9) that prioritizes the conservation of existing ecosystems, followed by improved management, rehabilitation, restoration, and, where necessary, the creation of new NbS. These three approaches can actually be complementary between one another: An effective NbS strategy should therefore evaluate the current condition and integrate all three dimensions, as necessity implies. Moreover, this framework is applicable across multiple spatial scales, from neighborhoods and cities to river basins (World Bank, 2021).
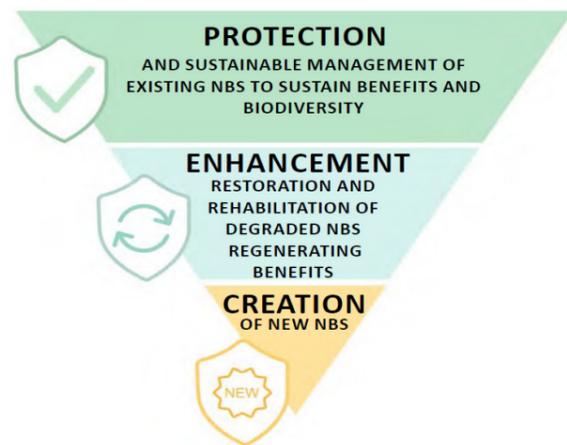

Figure 9 – The hierarchy of ecosystem-based interventions embedded in NbS (World Bank, 2021, p. 20).

Following this intent, NbS can refer to a broad spectrum of interventions, including diverse forms of green and blue infrastructure (BGI) – such as urban parks, wetlands, green roofs, and permeable paving – which emphasize their potential of integrating natural elements into urban environments, generating social, economic, and environmental co-benefits (Fig. 10), rather than relying solely on technical solutions (Kabisch et al., 2022).

NbS have gained increasing importance in scientific research and policy due to their capacity to connect sectors and stakeholders. However, to avoid remaining a vague or purely rhetorical concept, NbS require clear definitions, methodological consistency, and operational frameworks that reinforce their scientific foundation while enabling effective implementation (Cohen-Shacham et al., 2019).

An important characteristic of these solutions is that they can be both applied on their own or in combination with other types of solutions, for example they are also very suitable to integrate grey infrastructure and more technical

Figure 10 – NbS act as an overarching term for strategies that rely on ecosystems to address societal challenges (Cohen-Shacham et al., 2016, p. 11).

applications, such as the case of highly engineered green roof systems or green facades. Another important consideration is that they are highly context-specific, since they are based on traditional, local, and scientific knowledge (Cohen-Shacham et al., 2016; Cohen-Shacham et al., 2019).

Therefore, the planning and implementation of NbS raise a range of interconnected questions, including where such interventions should be located, which areas should be prioritized for revitalization, which types of solutions are most appropriate for specific challenges and local contexts, and what technical and maintenance requirements they entail. Additional considerations need to be addressed to broaden benefits, understand potential trade-offs, and implementation conditions of NbS, deciding the stakeholders who should be involved, the justice implications that may arise, and the planning instruments and approaches best suited to support their deployment (EEA, 2021).

Addressing this complexity requires integrated and holistic methodologies capable of linking ecosystems, human activities, and well-being across multiple spatial scales and within multi-level governance frameworks. Consequently, NbS must be conceived as multi-disciplinary interventions, requiring the coordination of diverse forms of expertise – including ecology, urban design, policy, engineering, and governance, but also local and citizens know-how – in order to ensure effective and equitable outcomes (EEA, 2021).

1.2.2 NbS in International and European policies

In recent decades, research and policies at both global and EU levels acknowledge that biodiversity loss and climate change are strongly connected factors of our times. Therefore, also from a legislative point of view, they have begun to explore how NbS can tackle both issues (EEA, 2021).

Their increasing recognition has brought important documents to add nature-based solutions as valuable instruments for the establishment of both mitigation and adaptation strategies (Fig. 11). In fact, more than half of the countries that participated to the Paris Agreement inserted either ecosystem-based approaches (EbA) or NbS as part of their plans. The rising credit that these solutions are facing is mainly due to their ability to protect human life, support sustainable urban development, ecosystem restoration, and mitigation and adaptation potentials; but also, because they offer a generally cost-effective alternative to conventional grey infrastructure (Tyllianakis et al., 2022).

Scientific evidence has reported that NbS applications could offer great help in achieving the mitigation plans for 2030 to stabilize warming to below 2°C, while also contributing substantially to the defense against long-term climate change-related hazards, such as biodiversity loss (IUCN, 2020).

Policy area	Global policy	EU policy
Cross-cutting	• 2030 Agenda for sustainable development, Sustainable Development Goals (2015) • United Nations (UN) Convention to Combat Desertification (1996) (*)	• European Green Deal (2019) • Bioeconomy strategy (2012) and its update (2018)
Biodiversity (including forestry)	• UN Convention on Biological Diversity (1993) (*) • Ramsar Convention (1975) (*)	• Biodiversity strategy for 2030 (2020) • Green infrastructure strategy (2013) • Habitats Directive (1992) • Birds Directive (1979/2009) • EU forest strategy (2013) • LULUCF Regulation (2018)
Climate	• Sendai Framework for Disaster Risk Reduction 2015-2030 (2015) • UN Framework Convention on Climate Change (1994) (*), Paris Agreement (2015)	• Action plan on the Sendai Framework for Disaster Risk Reduction (2016) • Strategy on adaptation to climate change (2013, 2021)
Water and agriculture		• Farm-to-fork strategy (2020) • Floods Directive (2007) • Water Framework Directive (2000) • Common agricultural policy (2013) • Nitrates Directive (1991)
Urban	• New urban agenda – Habitat III (2016)	• Urban agenda for the EU (i.e. Pact of Amsterdam, 2016)

Figure 11 – Global and EU policies that make specific reference to NbS, EbA or reference to the use of nature, ecosystems, and biodiversity (EEA, 2021, p. 26).

As reported by the previous table, important global and EU agreements mention NbS as valid measures to support CCA and DRR (EEA, 2021). Among these, one of the most important is certainly the **Sendai Framework for Disaster Risk Reduction** adopted in 2015, which is one of the first documents that recognizes the importance of introducing EbA and DRR alongside, when planning to build stronger resilience, reduce impacts, and share resources (EEA, 2021).

Another important plan is the **2030 Agenda for sustainable development**, which was embraced by all the countries in the United Nations in 2015, and was aimed at introducing a global framework for transformative change through **17 different Sustainable Development Goals** (SDGs) and their interconnected targets (EEA, 2019). This document therefore promotes a green and balanced development, as well as human well-being by integrating environmental, social, and economic dimensions, supporting biodiversity, resilience, and societal adaptability. Unlike previous development frameworks, it applies universally to all countries and is grounded in principles of equity and human rights, it relies on scientific research and innovation, sustainable financing, and monitoring, while encouraging cross-sectoral and multi-stakeholder collaborations, and aiming to strengthen health systems toward universal health coverage (Tyllianakis et al., 2022; UN, 2015; UN, 2022).

The 17 SDGs (Fig. 12) encompass a broad spectrum of dimensions related to human development, including health improvement, poverty reduction, education, social equity, economic growth, environmental protection, and the urgent pressure of climate change. Environmental and social health factors are frequently nominated across the SDGs, creating important opportunities for synergistic planning actions that can cover multiple goals and targets simultaneously. However, tensions and trade-offs also exist among the SDGs. For example, the prevailing model of economic growth based on expanding production and consumption has contributed to poverty reduction, while simultaneously accelerating environmental degradation (EEA, 2019).

3 GOOD HEALTH AND WELL-BEING

Ensure healthy lives and promote well-being for all at all ages

1 NO POVERTY Prioritise the health needs of the poor	**2 ZERO HUNGER** Address the causes and consequences of malnutrition	**4 QUALITY EDUCATION** Improve health equity through high-quality education for all	**5 GENDER EQUALITY** Tackle gender specific exposures to environmental risks
6 CLEAN WATER AND SANITATION Prevent disease through safe water and sanitation for all	**7 AFFORDABLE AND CLEAN ENERGY** Sustainable energy use for a healthy environment	**8 DECENT WORK AND ECONOMIC GROWTH** Safe and healthy workplaces and inclusive economies	**9 INDUSTRY, INNOVATION AND INFRASTRUCTURE** Clean and sustainable industry and resilient infrastructure
10 REDUCED INEQUALITIES Reduce environmental health inequalities	**11 SUSTAINABLE CITIES AND COMMUNITIES** Promote clean environments and active living through sustainable urban planning	**12 RESPONSIBLE CONSUMPTION AND PRODUCTION** Reduce pollution and environmental degradation and combat antimicrobial resistance	**13 CLIMATE ACTION** Reduce climate risks to health and support adaptation
14 LIFE BELOW WATER Restore marine fish stocks to support healthy diets	**15 LIFE ON LAND** Access to quality natural environments and ecosystem services	**16 PEACE, JUSTICE AND STRONG INSTITUTIONS** Effective implementation and equal access to services	**17 PARTNERSHIPS FOR THE GOALS** Engage partners to deliver the SDGs

Figure 12 – The 17 environmental and health Sustainable Development Goals, as defined by UN (EEA, p. 18).

All the goals and targets are supported by indicators that enable the measurement of progress and impacts (WHO, 2018). Within this framework, NbS have been proposed as effective adaptive approaches for achieving several SDGs, both directly and indirectly (Bona et al., 2022; Ingaramo et al., 2023). The definition and adoption of the indicators are therefore essential to help establish the convenience of NbS. Indicators allow for the systematic evaluation of NbS projects, enhancing the comparability and measurability of outcomes across different contexts, and thereby strengthening the overall evidence base supporting the implementation of these solutions (EEA, 2019; EEA, 2021; Kabisch et al., 2016).

In this framework, particularly relevant for urban scenarios are (UN, 2015; WHO, 2018):

Goal 2
This goal has the intention of closing the gap that still sees a high number of world's population suffering from food scarcity and malnourishment, by helping local food producers, safeguarding biodiversity and genetic resources, strengthening rural investment and innovation, and improving the stability and fairness of global food markets to reduce vulnerability and food price shifts.

Some important **indicators**:
- **2.1.2** – Prevalence of moderate or severe food insecurity in the population;
- **2.4.1.** – Proportion of agricultural area under productive and sustainable agriculture;
- **2.5.2** – Proportion of local breeds at risk, not at risk or at an unknown level of risk of extinction (WHO, 2018).

Goal 3
SDG 3 seeks to improve global health conditions, trying to sustain the most vulnerable population: mothers, infants, and children. The highest number of deaths is caused by infectious and chronic illnesses, to which the intention is to provide a form of health care system. Moreover, it wants to improve road safety, substance abuse prevention, and reduce health risks from environmental pollution, while enhancing preparedness for public health emergencies.

Some important **indicators**:
- **3.4.1** – Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease;
- **3.4.2** – Suicide mortality rate;
- **3.9.1** – Mortality rate attributed to household and ambient air pollution; 3.9.2 – Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (WHO, 2018).

Goal 6
SDG6 strives to provide drinking water, proper sanitation and hygienic conditions, while addressing also water quality, water-use efficiency, and water scarcity, through sustainably managed water resources. Also, the water-related ecosystems are to be protected, strengthening international cooperation, technological innovation, and the active involvement of resident groups.

Some important **indicators**:
- **6.3.1** – Proportion of wastewater safely treated;
- **6.4.2** – Level of water stress: freshwater withdrawal as a proportion of available freshwater resources;
- **6.6.1** – Change in the extent of water-related ecosystems over time (WHO, 2018).

Goal 10
SDG10 aims to reduce inequalities within and among countries by promoting inclusive economic growth, social and political participation for all, and equal opportunities regardless of personal or socio-economic characteristic. It emphasizes fair policies, stronger regulation of global financial systems, improved representation of developing countries in decision-making, safe and well-managed migration, increased international financial support for vulnerable countries, and lower transaction costs for migrant remittances.

An important **indicator**:
- **10.2.1** – Proportion of people living below 50% of median income, by gender, age and persons with disabilities (WHO, 2018).

Goal 11
SDG11 aims to provide urban dwellers an inclusive and secure space to live in, that can be enjoyed by any citizen. It provides good housing conditions, facilities, sustainable transport, and quality public spaces, while promoting participatory urban planning, protecting cultural and natural heritage, reducing disaster risks and environmental impacts, and strengthening urban-rural linkages through integrated, climate-resilient development policies.

Some important **indicators**:
- **11.3.2** – Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically;
- **11.4.1** – Total expenditure (public and private) per capita spent on the preservation, protection and conservation of all cultural and natural heritage;
- **11.5.2** – Direct economic loss in relation to global GDP, damage to critical infrastructure and number of disruptions to basic services, attributed to disasters;

- **11.6.2** – Annual mean levels of fine particulate matter in cities (population weighted); 11.7.1 – Average share of the built-up area of cities that is open space for public use for all, by gender, age and persons with disabilities (WHO, 2018).

Goal 12

This goal intends to promote sustainable consumption and production by encouraging efficient use of natural resources, reducing waste and pollution across value chains, fostering recycling and reuse, improving chemical and waste management, supporting sustainable business practices and public procurement, raising awareness for sustainable lifestyles, and phasing out environmentally harmful subsidies to enable a circular and resource-efficient economy.

Some important **indicators**:
- **12.3.1** – Global food loss index;
- **12.5.1** – National recycling rate, tons of material recycled;
- **12.8.1** – Extent to which global citizenship education and education for sustainable development (including climate change education) are mainstreamed in national educational policies, curricula, teacher education, and student assessment (WHO, 2018).

Goal 13

Through SDG13 the intention is to build climate and disasters adaptability, supporting it with governance strategies, tutoring, and support. It should help generate income – particularly for vulnerable countries – and supporting inclusive, locally grounded climate governance to address the impacts of climate change effectively.

Some important **indicators**:
- **13.1.3** – Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national DRR strategies;
- **13.3.2** – Number of countries that have communicated the strengthening of institutional, systemic and individual capacity-building to implement adaptation, mitigation and technology transfer, and development actions (WHO, 2018).

Goal 15

SDG15 aims to protect, restore, and sustainably manage terrestrial and freshwater ecosystems by halting deforestation and biodiversity loss, restoring degraded land and soils, combating desertification, preventing invasive species and wildlife trafficking, integrating ecosystem values into planning and accounting, and mobilizing financial and institutional support to educate on conservational approaches.

Some important **indicators**:
- **15.1.1** – Forest area as a proportion of total land area;
- **15.1.2** – Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type;
- **15.2.1** – Progress towards sustainable forest management (WHO, 2018).

Other connected SDGs that can have secondary importance are:
Goal 7
Goal 8

Shortly after the promulgation of the 2030 Agenda, the United Nations Framework Convention on Climate Change (UNFCCC) reunited in 2015 furtherly specified and reinforced the objectives for a climate change response, already present in SDG13. As one of the outcomes of the convention, during the **UN Climate Change Conference** (**COP21**), the adoption of the **Paris Agreement** was imposed to 196 Parties, as an official document regarding climate change considerations. The final aim is not to surpass the 2°C temperature rising limit that was calculated in comparison to the mid-19th century. To accomplish this, the desire is to sustainably maintain ecosystems, and explicitly support the introduction of NbS for CCA and DRR. Each nation's application is then specifically tailored to its habitat and level of development. During COP26 in 2021, the Parties committed to further increasing their ambition, as the initial nationally determined contributions were not sufficient to achieve the goals set in Paris the first time (EEA, 2021).
In line with previous documents, the **New**

Urban Agenda adopted in 2017 by the United Nations, establishes a set of regulations to build resilient, resource-efficient, and inclusive infrastructure and planning frameworks that integrate ecosystem-based and data-driven approaches to reduce disaster risk and enable rapid recovery, particularly in vulnerable and informal areas (UN, 2015). This document further emphasizes that DRR and CCA must be fully embedded within urban planning, design, and governance processes through coordinated, age- and gender-responsive policies, alongside strengthened local institutional capacity (EEA, 2021; UN, 2015).

The **European policy framework** takes reference from the international one and adapts it to its own needs, by defining its specific objectives, intended actions, and employed instruments.
For example, already through the **EU Floods Directive** (2007), NbS were suggested for the prevention and reduction of CCA and DRR, such as flood-related impacts on people, ecosystems, heritage, and infrastructure. It explicitly recognized the role of NbS across natural, rural, and urban contexts in enhancing water retention, managing catchment-scale flood risk, and enabling controlled flooding where appropriate (EEA, 2021).
Adopted in 2016, the **Action Plan for the**

Sendai Framework for Disaster Risk Reduction 2015-2030 supports the 2030 Agenda for Sustainable Development (Fig. 13) by highlighting the importance of preserving, improving, and restoring biodiversity, ecosystems, and the services they provide across urban, rural, coastal, and natural areas. It promotes the integration of DRR, CCA, and biodiversity policies, explicitly encouraging the strategic adoption of natural solutions (EEA, 2021).
Among the wide range of different mitigation policies promoted by the European Union, the **European Green Deal** – introduced by the European Commission in 2019 – is particularly relevant to this framework (EEA, 2021). It frames NbS as essential instruments for preserving and restoring Europe's natural heritage, enhancing ecosystem resilience, safeguarding citizens' well-being, and strengthening preparedness and prevention in the face of climate-related risks (EEA, 2019; EEA, 2021; Tyllianakis et al., 2022). A core objective of this document is the official desire to achieve climate neutrality by 2050, alongside an increased GHG emission reduction target for 2030. In parallel, the agenda acknowledges the importance of adaptation strategies grounded in nature-based approaches and promotes solutions to improve air, water, and soil quality. Additional priorities include accelerating the evolution to sustainable and smart mobility systems and ensuring a just and inclusive transition that leaves no one behind (EEA, 2019).
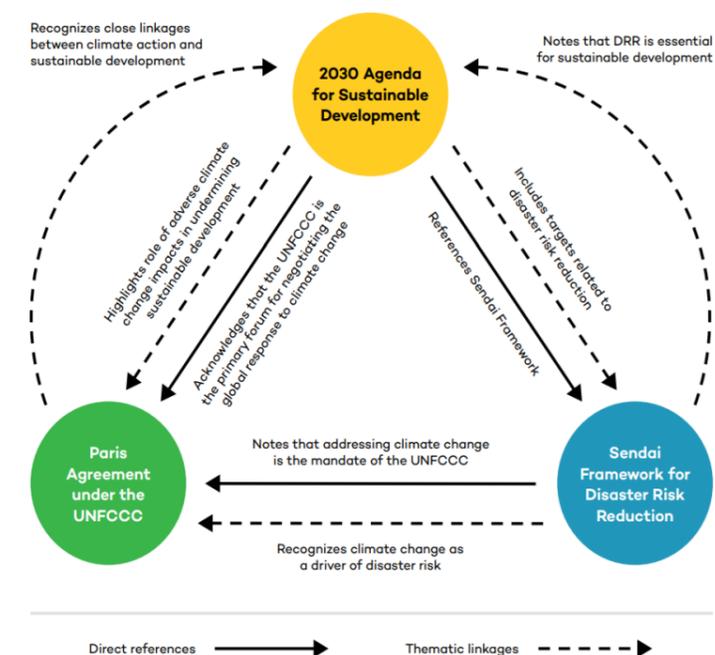

Figure 13 – Interrelation between the 2030 Agenda, the Sendai Framework, and the Paris Agreement (https://napglobalnetwork.org/themes/ndc-nap-linkages/).

Another important instrument is the **Biodiversity Strategy for 2030**, adopted in 2020, which focuses on maintaining healthy ecosystems, enhancing resilience to CC, and preserving biodiversity to promote citizens' prosperity and well-being. Also in this context, NbS are considered vital to reduce emissions and adapt to climate impacts. One key priority in urban areas is increasing tree coverage and expanding green infrastructure to help tackle the UHI phenomenon and the risk of natural hazards. Additionally, the EU has launched in 2021 an Urban Greening Platform as part of a "Green City Accord", which encourages mayors of European mid- to big-cities to implement urban greening strategies. Turin is one of the municipalities that have joined this initiative (EEA, 2021).

Through the **Urban Agenda for the EU** (i.e., Pact of Amsterdam, 2016) cities are seen as potentially significant influencers of ecosystem preservation, CCA, and DRR through the use of various nature-based solutions aimed at reintegrating nature into urban environments. It highlights the role of NbS and blue-green infrastructure for tackling CC impacts, ensuring that urban development supports the environment and overall livability, rather than harming them. The COVID-19 pandemic has further stressed the significance that BGI can have in supporting mental and physical health, while also offering new job opportunities linked to urban NbS (EC, 2021; EEA, 2021).

By analyzing the countermeasures adopted until 2020 by 155 European cities – hence also by the Covenant of Mayors – when dealing with climate adaptation (Fig. 14), it can be noted that the most frequent actions are classified as "soft measures", meaning those that entail knowledge creation, such as information provision, technical measures, and government policies (e.g., through mapping or modelling studies). Only less than 20% represents green and sustainable infrastructure options, while around one fifth of the measures are grey infrastructures. Research shows that soft measures are the cheapest, with the best benefit-to-cost ratio, while grey infrastructure approaches are the most expensive, leaving green infrastructure in

between (EEA, 2020).

Although most European policies still lack mandatory requirements for the inclusion of BGI and NbS and their integration into climate policy has progressed slowly and only recently begun to accelerate, recent years have seen a growing tendency among European cities to incorporate ecosystem-based solutions into planning frameworks. Overall, policies increasingly recognize that ecosystems, despite their vulnerability to climate change, provide essential protective functions for society, including climate regulation, flood mitigation, and temperature control. As climate change and biodiversity loss share common drivers, they are now being addresses jointly within major institutional and policy agendas (EEA, 2020; EEA, 2021).
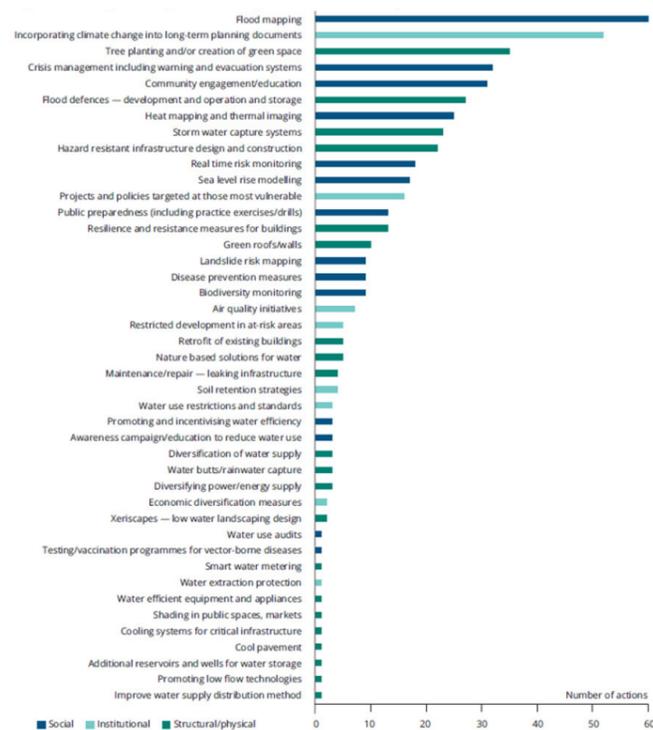

Figure 14 – Graphic representation of the most common types of adaptation actions planned by EU cities. (EEA, 2020, p. 111).

1.2.3 Objectives and co-benefits of NbS

Dealing with today's climate challenges requires building resilience by reducing exposure and vulnerability to climate hazards, while also fostering adaptive capacity (Cohen-Shacham et al., 2016). The **resilience capacity within urban systems** relies on the ability of interconnected social, ecological, and technical systems to operate coherently across multiple spatial and temporal scales, not only by resisting shocks but also by adapting to changing conditions and, when necessary, transforming existing structures that constrain future adaptability. Similarly to the need of reinforcing the natural ability of ecosystems to shield themselves from extreme events, building urban resilience requires strengthening these interdependences, enhancing adaptive capacities, and enabling systemic change that supports long-term flexibility and sustainability (McPhearson et al., 2016).

As supported by numerous policies, nature-based solutions are an excellent option to regain these capabilities, particularly when they are thoughtfully designed and, where appropriate, combined with conventional grey infrastructure or with each other (EEA, 2021). Leveraging on their core essence, NbS can be particularly effective in offering sustainable approaches to lower both exposure and sensitivity to climate change risks and disaster risks, while also building resilience, relying on the preservation and restoration of ecosystems, especially in areas where they can play a buffer role (Cohen-Shacham et al., 2016). The effectiveness of NbS in urban contexts often depends on their integration with conventional grey infrastructure. Hybrid green-grey solutions – such as parks that integrate draining pathways and systems, or blue-green stormwater infrastructure – have been shown to perform more reliably in addressing complex challenges like **flooding** and **heat stress**, while simultaneously enhancing **usability** and **ecosystem service delivery** (EEA, 2021). The way green solutions are combined with grey systems varies according to local socio-ecological conditions, including availability of land, existing green assets, urban morphology, and prevailing

environmental risks (Raymond et al., 2017a). As CC accelerates and uncertainty increases, approaches focused on single hazards or isolated sectors are no longer sufficient. Instead, holistic and systemic strategies are needed – ones that recognize cities as interconnected social, ecological, and economic systems embedded within broader landscapes (EEA, 2021; Raymond et al., 2017b). NbS are particularly well suited for this challenge because they operate across multiple spatial scales and levels of ecological intervention. However, their effectiveness ultimately depends on ecosystems being sufficiently intact and well managed to support their long-term functions (EEA, 2021).

Moreover, the effectiveness of NbS is also strongly influenced by the scale at which they are implemented and by the governance framework that supports them. World-wide cities are increasingly adopting NbS across multiple scales – from micro-scale interventions at the building and street level, to meso-scale for neighborhood and district strategies, up to macro-scale with city-wide and peri-urban systems creation – demonstrating how coordinated, multi-scalar NbS planning can support more resilient, equitable, and sustainable urban futures. In fact, the larger the scale, the greater the number of stakeholders and landowners involved, making participatory processes and inclusive planning strategies essential for both successful outcomes and public acceptance (EEA, 2021).

Benefits, co-benefits, and trade-offs

Within this context, NbS have emerged as flexible, cost-effective, and inherently multifunctional strategies capable of reducing urban vulnerability to climate-related risks while simultaneously delivering a broad spectrum of social, environmental, and economic benefits and secondary benefits (EEA, 2021). As mentioned before, by maintaining, restoring, or creating healthy ecosystems, NbS contribute directly to CCA and DRR, while also advancing wider sustainability objectives related to public health, biodiversity conservation, environmental quality, and social well-being (Raymond et al., 2017b) (Fig. 15).
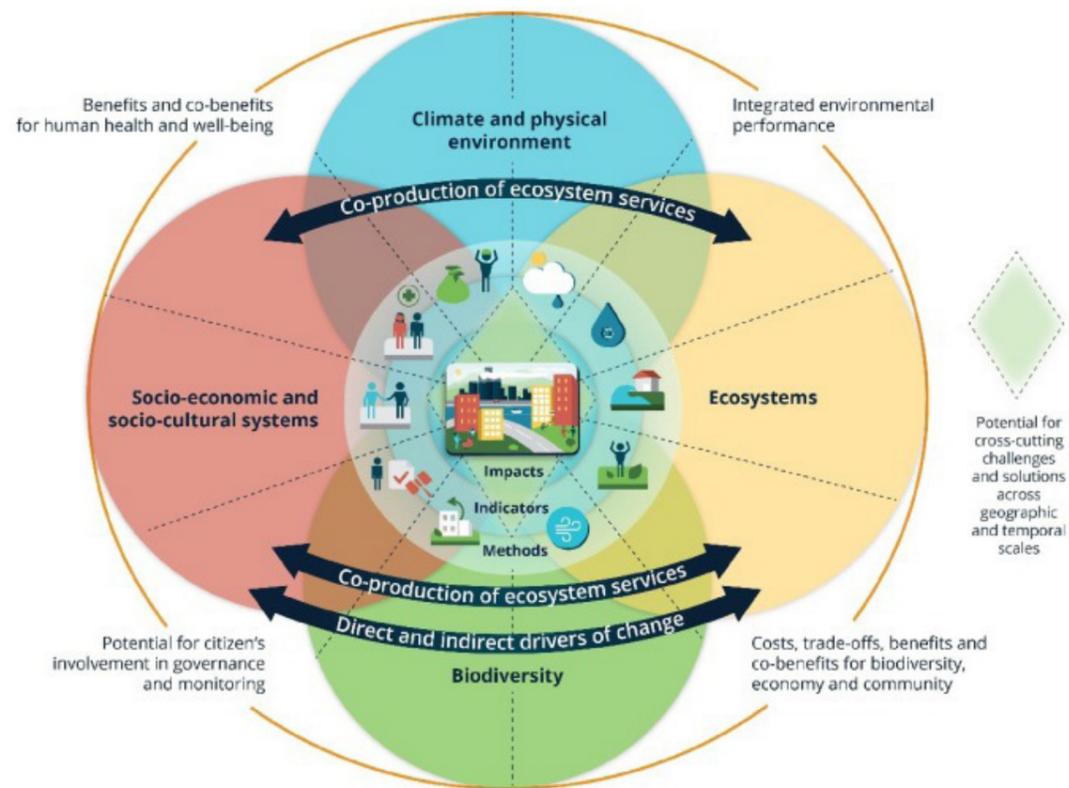
Figure 15 – Graphic visualization outlining the connection among environmental, biophysical, and social realms, and the NbS functioning (Raymond et al., 2017b, p. 17).

From a resilience perspective, NbS are able to help urban scenarios deal with certain challenges by acting across three interrelated dimensions: **reducing exposure, lowering sensitivity, and increasing adaptive capacity**. When ecosystems are sufficiently intact and functional, they can serve as natural buffers against extreme events – for instance, river restoration and wetland conservation increase water retention and reduce flood peaks, while urban green spaces and tree canopies mitigate heat stress by regulating local microclimates. At the same time, NbS stabilize ecological processes and diversify urban landscapes, thereby reducing system sensitivity, and strengthening adaptive capacity through the delivery of important ecological functions such as runoff management, freshening the surrounding air and improving its quality. For example, trees provide shade and cooling through transpiration, reduce soil erosion during heavy rainfall, absorb significant amounts of water to alleviate flooding, and sequester carbon, contributing to climate mitigation efforts (EEA, 2021).

A key advantage of NbS over purely grey infrastructure lies in their multifunctionality (Fig.

16): unlike single-purpose grey infrastructure, they deliver multiple environmental, social, and economic benefits at once. Evidence increasingly demonstrates that NbS are particularly effective in urban contexts, where they support CCA and DRR while also contributing to broader societal benefits. For example, green and blue infrastructure – including parks, urban forests, green roofs, bioswales, rain gardens, and constructed wetlands – can collectively restore ecosystem functions, mitigate floods, droughts, improve drainage performance, regulate microclimates, support biodiversity, and provide attractive, recreational and cultural spaces (Aghaloo et al., 2025; EEA, 2021; Mok et al., 2021; Raymond, 2017b).

Beyond their environmental performance, NbS generate substantial economic secondary benefits. Compared to single purpose grey infrastructure, NbS often deliver multiple services at lower overall cost. For example, floodplain and river corridor restoration can significantly reduce economic losses and human exposure associated with flooding, while green spaces have been shown to increase nearby property values. Blue-green stormwater systems reduce pressure on

Figure 16 – NbS functions categories (Mok et al., 2021, p. 54).

sewer networks and lower water treatment costs, while systematically adopting vegetation in urban areas can be translated into avoided energy demand for both heating and cooling. Many of these benefits yield direct or indirect economic value through reduced healthcare expenditures, energy savings, avoided damage costs, as well as the creation of green jobs (EEA, 2021).

The social and health co-benefits of NbS are equally significant. Ensuring access to green elements has been proven to improve physical and mental health, providing enhanced quality of life, reducing stress, anxiety, depression, and social isolation (WHO, 2025). Well-designed green streets, parks, and green roofs promote active mobility, social interaction, and neighborhood connectivity, while also providing cooling islands during heatwaves. Urban trees and restored riverfronts contribute to place identity, aesthetic value, and cultural continuity, reinforcing the role of NbS in supporting livable and inclusive cities (EEA, 2021; McPhearson et al., 2016).

It is important to acknowledge that biodiversity forms the foundation of effective NbS. As climate change intensifies, extreme events may surpass the adaptive capacity of ecosystems, leading to degradation and reducing the effectiveness of NbS interventions. Hence, diverse and healthy ecosystems are essential for sustaining ecosystem service (ES) provision, and urban NbS can significantly enhance biodiversity

compared to conventional grey infrastructure. Parks, pocket parks, roadside vegetation, gardens, green corridors, green roofs and walls, and constructed wetland basins provide vital habitats and ecological connectivity within highly modified urban environments. For example, NbS for water management are able to improve water quality, reduce combined sewer overflows, enhance groundwater recharge, and restore urban stream ecosystems by filtering pollutants and managing frequent low-intensity rainfall events that typically degrade urban waterways (EEA, 2021).

NbS outcomes are also highly context-dependent, shaped by local climatic, ecological, and fulfilling social circumstances, as well as the degree of susceptibility that can affect local population and infrastructure. The distribution of NbS has also implications on environmental justice. Socially vulnerable populations often experience the greatest exposure to environmental hazards while having the least access to high-quality green spaces (EEA, 2020). When strategically implemented in disadvantaged neighborhoods, NbS can help address these inequities and improve health and well-being; however, poorly managed green regeneration can also contribute to gentrification pressures, furtherly underscoring the need for inclusive planning and governance. Consequently, feasibility assessments must consider potential trade-offs and disservices, as NbS are not universally effective and can also

generate unintended negative consequences, if poorly planned or managed – such as long timeframes required for ecosystem restoration, risks of residents' displacement, unequal access to green and blue spaces, or increased pollen-related allergies (EEA, 2021). Their performance can also be constrained by the vulnerability of ecosystems themselves to climate change, inappropriate species selection, limited space, or inadequate long-term management. Similarly, existing ecosystems do not always benefit automatically from adaptation interventions and NbS may give rise to so-called ecosystem disservices – unintended outcomes that undermine environmental, social, or economic objectives – which are often overlooked, despite their importance for equitable and effective planning (Bednar-Fridl et al., 2022; EEA, 2021). For this reason, the planning and implementation of NbS require careful, holistic assessments to anticipate, balance, and mitigate potential benefits and trade-offs simultaneously (Fig. 17). Trade-offs arise when the enhancement of one ecosystem service leads to the reduction of another, either because multiple services respond differently to similar instances, or because of simultaneous co-existence becomes hard (Raymond et al., 2017b). In urban context, such trade-offs can manifest in multiple ways. Certain tree species may increase allergenic pollen production or emit biogenic volatile compounds (BVOC), potentially exacerbating air quality issues. Maintaining urban green spaces during prolonged droughts may increase pressure on water resources, particularly where irrigation relies on potable supplies. Inadequate spatial planning can also result in uneven distribution of green areas, reinforcing social exclusion and environmental inequities by limiting access to nature for vulnerable groups (EEA, 2021). Green infrastructure is itself vulnerable to CC impacts. Urban vegetation is increasingly exposed

to heatwaves, droughts, storms, and fires, and sustaining healthy ecosystems under these conditions may require additional water, energy, and maintenance inputs unless alternative sources such as rainwater harvesting or recycled water are employed. Moreover, interactions between vegetation, airflow, and air pollution are complex: while plants can filter pollutants and reduce wind speeds where not desired, tree canopies may also trap contaminants in street canyons or pose safety risks if trees fail during extreme weather events. These dynamics highlight the need for fine-grained, site-specific planning that accounts for local microclimates, pollution patterns, and safety considerations (EEA, 2020).

Social and ecological trade-offs can also emerge from competing land uses and stakeholder interests, particularly in highly built-up areas, where space is highly contested. Highly accessible green spaces may suffer from overuse, leading to ecosystem degradation or disturbances to urban wildlife, while poorly designed vegetation layouts can generate perceptions of insecurity (EEA, 2020).

At a broader scale, some adaptation measures may unintentionally contribute to maladaptation – addressing one climate risk while exacerbating others. For example, increased reliance on air conditioning reduces heat exposure but raises energy demand and emissions unless paired with renewable energy or replaced by passive and communal cooling strategies (EEA, 2020).

Although these drawbacks rarely outweigh the overall beneficial aspects of NbS, failing to address and recognize them can compromise long-term effectiveness, public acceptance, and equity. When planned holistically and in a context-sensitive manner, NbS deliver mutually reinforcing health, social, ecological, and economic benefits, making them powerful tools for CCA and DRR (EEA, 2020; EEA, 2021).

Despite growing scientific and policy interest in urban NbS, the evidence base remains fragmented. Most studies still assess a **limited set of benefits or focus on specific NbS types** – such as parks or urban forests – often times **without comprehensively evaluating co-benefits, disservices, and trade-offs**. The wide **variation in assessment methods** and indicators further limits comparability and the ability to evaluate effectiveness, cost-efficiency, or performance (EEA, 2021). Although NbS multifunctionality is particularly valuable in dense urban contexts, it is still insufficiently integrated into planning practice, which remains largely dominated by single-purpose grey or nature-based solutions (Alves et al., 2023).

Key gaps persist in understanding **how NbS benefits interact spatially**, how synergies and trade-offs emerge at the different city scales, and how interventions should be prioritized. Regarding the practical level, on the other hand, NbS planning often lacks the transdisciplinary and participatory approaches needed to address these complexities, resulting in suboptimal siting, uneven benefit distribution, and missed opportunities for environmental justice. Addressing these limitations requires more integrative spatial frameworks, improved performance data, and holistic decision-support tools capable of balancing ecological effectiveness, social equity, and competing urban priorities (EEA, 2021; Sarabi et al., 2021).

Furthermore, research often fails to acknowledge that implementation does not only depend on ecological systems, but also on **administrative boundaries, political priorities, and funding mechanisms**, leading to a persistent disconnection between knowledge and practice. Adopting NbS therefore requires clearer evaluation frameworks, stronger integration into urban planning, and transdisciplinary collaboration among researchers, practitioners, and stakeholders to ensure that NbS are not only conceptually attractive, but also robust, scalable, and effective in real-world urban contexts (EEA, 2021).

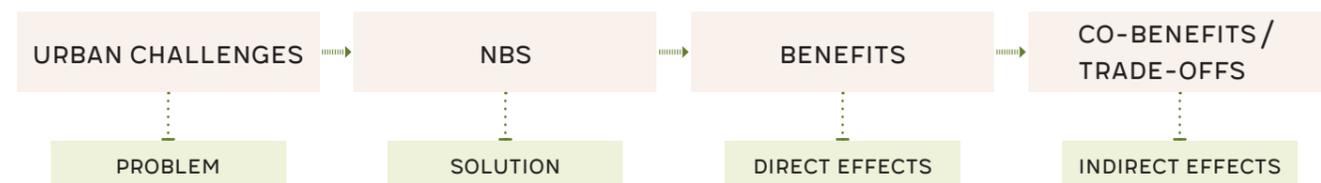| URBAN CHALLENGES	NBS	BENEFITS	CO-BENEFITS / TRADE-OFFS
PROBLEM	SOLUTION	DIRECT EFFECTS	INDIRECT EFFECTS

Figure 17 – Schematization of the connection among urban challenges, NbS, and co-benefits/trade-offs (Author's production).

1.3 CLIMAGEN PROJECT AND LINKS FOUNDATION

This thesis was developed within the research activities of the **Links Foundation** (LINKS), a research center based in Turin. The internship carried out within the foundation allowed the work to be framed within the broader research context of the **European project ClimaGen**, which aims to promote climate-resilient urban regeneration.

Throughout the development of the thesis, I had the opportunity to be part of this ongoing initiative by supporting the early stages for the development of a decision-support system (DSS) for urban decision-makers. The DSS is being developed by LINKS as a pilot application for the City of Turin, with the objective of providing a transferable framework for other national and European cities.

This research collaboration also enabled the thesis to be developed into a scientific paper, which has been submitted to the **ReSBE Conference 2026**.

1.3.1 ClimaGen Project

"Climate-resilient reGeneration and renaturing for, by, and with vulnerable neighborhoods, striving towards net-zero."

(HORIZON, 2023)

ClimaGen was funded by the HORIZON Program, as a European project created to help cities adapt to climate change and reduce their carbon emissions, by adjusting to current and future CC impacts and also fostering building resilience, aiming for a net-zero environment by 2050 (HORIZON, 2023).

The project foresees the interaction among nine European cities: **Five Demonstration Cities** – Belgrade (RS), Gdańsk (PL), Tartu (EE), Torino (IT), and Trondheim (NO) – and **four Replication Cities** – Cluj-Napoca (RO), Eindhoven (NL), Gernika (ES), and Thessaloniki (GR) – that are asked to co-develop strategies to make their urban areas more resilient, inclusive, and low-carbon. It is primarily focused on the regeneration of vulnerable areas within these cities, that are to be regenerated through greening actions, which should improve both their environmental and social conditions (HORIZON, 2023).

The main intention is the one to establish ClimaLabs (Fig. 18), which are intended as local innovation hubs that should foster participatory involvement of different stakeholders and citizens to establish a co-design process and generate ClimaGreens, which are a set of nature-based solutions, to increase urban green spaces of at least 25% (HORIZON, 2023).

To ensure continuous monitoring they also established a support system – through ClimaImpact, ClimaValue, and ClimaGen Games – based on public seminars for decision-makers and citizens (HORIZON, 2023).

Each city is also required to indicate and develop a ClimaLab, where the local population can meet and plan the design project. Thanks to this framework, they strive to establish transparency, knowledge-building, and participatory processes to generate positive solutions in the regeneration of vulnerable neighborhoods. This will also create a support basis for the definition of specific economic studies to create long-term resolutions. Afterwards, through specific indicators, ClimaGen aims to monitor and evaluate environmental, social, financial, and governance consequences of the process. Each research group is then asked to write a report defining the most important steps and results that characterized their experience, in order to foster future replicas of their framework.

Thanks to the organization of such a support network, each partner city will be considered a pioneer for the solutions they choose to adopt, offering an empirical basis for the other participants and help draw conclusions on such practices (HORIZON, 2023).

Turin as a demonstration hub

As one of the partner cities of the program, Turin has its own expertise areas: Fostering food systems circularity, improving public spaces attractivity and accessibility, shared ownership, and business entrepreneurship. The demonstration site has been identified with the post-industrial Mirafiori district, located in the south-western periphery of the city (Fig. 19).

Specifically, the project intends to work on the area of Orti Generali, which is going to be regenerated into a large-scale urban food productive site that supports social, local, and sustainable initiatives. Part of the area has recently been regenerated into an urban park (Parco Piemonte). The remaining part is occupied today by illegal gardens, which, through the funds of this project, should be repurposed to 100 different new publicly accessible areas. Included in this ambitious task, the naturalization of the riversides of the Sangone stream, native tree planting, and innovative NbS are expected. To inspire public use of the new area new cultural and recreational activities are going to be programmed, including a landscape festival, that will also include art and cultural events (HORIZON, 2023).

1.3.2 Links Foundation – Leading Innovation & Knowledge for Society

Within this research group and environment, Links Foundation works in collaboration with the ONLUS Fondazione Mirafiori – the social enterprise of Orti Generali – and the City of Turin, to help generate environmental and social benefits within the Mirafiori district, promoting collaboration among different stakeholders and NbS adoption. The main task for LINKS is the development of a data-driven decision-support tool that is able to assist policy makers in identifying and visualizing co-benefits and trade-offs of the intended naturalization measures across the city.

They intend to base the tool's development by adopting GIS mapping, surveys, participatory and interactive meetings, such as games, to gain precious feedback from cross-sectoral stakeholders, to further tailor the solutions to the actual needs of each partner city.

M1–6	M7–18	M19–30	M31–42	M43–48
ClimaLabs	IC#1: Co-Creation & Local Anchoring	IC#2: Harvesting Local Treasures	IC#3: Exploring New Possibilities	Handover

M1–48	Monitoring, Documentation and Learning

Figure 18 – Methodology followed by ClimaGen to create and deliver their project (HORIZON, 2023, p. 17).
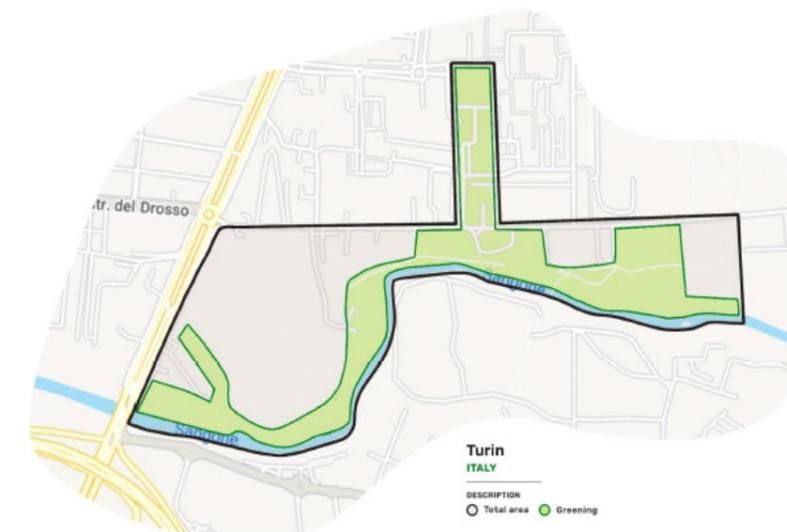

Figure 19 – Representation of the demonstration site of the Mirafiori neighborhood in Turin (HORIZON, 2023).

1.4 RESEARCH OBJECTIVES

The situation of our modern cities poses, today as never before, the need for addressing the excessive urbanization processes, the overpopulation, the consequent lack of limited resources, and all the consequent health, well-being, and environmental concerns that burden modern decision-makers, planners, architects, and designers when they initiate the arduous task of providing the citizens with equitable and sustainable living environments.

While it is true that local governments are supporting the wider application of nature-based approaches, significant gaps can still be noticed that obstacle a more widespread adoption of such measures. The main difficulties that can be encountered when implementing these solutions are generally found in a lack of coordination between policies, that for practical reasons, are based on outdated data, which are not representative of the current needs anymore. This difficulty in updating data can also be attributed to insufficient technical expertise and inefficient monitoring system. Moreover, the co-participation of citizens is not always present in the designing of interventions (EEA, 2021; Ingaramo et al., 2023).

Furthermore, highly specific scientific information is usually required, but this often consists of fragmented and incomplete statistics and numbers, which altogether make such **data not accessible for the average citizen or a non-specialist stakeholder** (MATTM, 2015).

Building on such difficulties, existing decision-support tools still overlook the urban form when analyzing NbS possible suitability locations (Marusik et al., 2023). This entails an wide lack of information, because this makes it really hard to specify and to understand which NbS are effective for addressing which urban challenges within specific urban fabrics.

Similarly, the capacity of NbS to generate multifunctionality, seen in terms of co-benefits and trade-offs, is widely reported by researchers, but it is not always represented in ways that are understandable for different decision-makers that are asked to balance complex social,

ecological, and technical factors. If the context-specific elements are not taken into account, there is the risk to generate a maladapted and undesired project, risking of actually worsening the current conditions. Therefore, practitioners and decision-makers need a tool that can efficiently suggest the most suitable solution to tackle certain problems in certain urban areas, and that can also give an indicative direction on the secondary beneficial or negative outcomes that one or more NbS could generate in such an environment.

Through the literature, a **lack of holistic decision-making tools** was noticed, since the majority of them prioritized specific solutions, or specific objectives, overlooking the more general and comprehensive framework (Almenar et al., 2020). Beside the single element that could be applied or favored in a specific area, also the connected co-benefits, spatial conditions, requirements, and sociological factors are equally important to analyze, in order to strive for a well-established solution.

Based on these conditions, the main aim of this thesis is to **simplify the decision-making process and facilitate access and understandability of key information around nature-based solutions**, urban challenges, and urban morphologies. The tool chosen by the thesis to foster this comprehensive understanding, is based on the creation of a visualization framework, that is supposed to help **share and better understand important criteria for an improved and site-specific, informed decision**. By creating adjustable and interactive evident connections among the three elements just mentioned, this methodology wants to support a wider adoption of NbS in similar European cities and neighborhoods.

To generate such transferable framework, it is crucial to establish which are the recurring urban morphologies that can be commonly found across European cities, which are the most common urban challenges that can be tackled by implementing (urban) nature-based solutions, and finally which are these natural

solutions. The chosen NbS catalogue is treated as an archetypes' selection, created like that to enable broader generalization and objective considerations.

To accomplish this goal, **the thesis is based on the following objectives**:

1. Identify and classify recurring European urban morphologies, by defining a set of morphological typologies, each defined by spatial characteristics and associated urban challenges.

2. Define and classify urban NbS archetypes, by analyzing their main function, related SDG, benefits, co-benefits, trade-offs, and spatial requirements.

3. Assess and evaluate the qualitative relationship between different NbS, urban challenges, and urban morphologies, to identify possible synergies and interactions.

4. Develop a replicable framework to assess appropriate connections at the early design stages, enabling a better implementation of NbS or NbS pockets.

The dynamic and interactive solution developed within this thesis can serve as a foundation for future parametric NbS studies, contributing to building resilience to CC-impacts, and promoting better social inclusion.

1.5 RESEARCH QUESTIONS

As mentioned in the previous chapter, the proposed aim is to help improve the practical implementation of NbS within the urban environment, by providing a qualitative assessment of potential synergies between different elements. To guide this research, **the following research questions will be addressed**:

1. How can a decision-support framework, based on NbS archetypes, urban morphologies, and challenges, be structured to be adaptable to different European urban contexts, and support early-stage design and planning decisions?

2. How can this framework be useful to identify potential synergies or trade-offs among the studied elements, in order to promote the design of NbS pockets rather than isolated interventions?

By answering these questions, the research aims to highlight the fact that NbS have to be considered within a broader network and that, by adopting a comprehensive and integrated approach, the chance of gaining increased and broader positive effect is going to be higher.

1.6 THESIS STRUCTURE

This research is structured in the following way.

Chapter 1: Introduction
This chapter functions as the introduction to the research and aims to introduce the reader to the broader climatic situation of current times and the possible solutions that are embedded within natural measures. After which, it presents the important work that the ClimaGen project and Links Foundation are currently undertaking, to help mitigate CC-related impacts.

1. This sub-chapter depicts a general overview of the impacts arising from climate change, focusing on the differentiation of mitigation and adaptation measures, first on a global level, then Europe-wide, and lastly outlining the Italian context, further framing the City of Turin's action and impacts, since that is the city where the case study is placed, and one of the partner cities defined under the ClimaGen program.

2. This section is dedicated to the introduction of what are the nature-based solutions, how are they defined, and how can they be beneficial when dealing with climate change mitigation and adaptation concerns.

3. This part gives a quick description of the work that the Europe funded program ClimaGen is developing, specifying also Links Foundation's role within the project and its own tasks and activities.

4. This is the sub-chapter dedicated to the definition of the thesis objectives, which aim to define a comprehensive and easy-to-navigate decision-support tool for practitioners and decision-makers.

5. In here the research questions are specifically laid out, which are used to guide the creation of the tool and the understanding of its value.

6. This is right this chapter, where the overall thesis structure is defined.

Chapter 2: Literature review
This chapter is dedicated to the comprehensive analysis of the literature review that was crucial for the definition of the following steps and eventually helped better outline the functions that the developed framework needed to target. This comprises the scientific papers, researches, policies, and case studies that created the backbone of this thesis.

1. The first part is dedicated to urban morphology, starting from the core theoretical definition of the scientific subject, to the analysis of the connection that exists between urban form and local microclimate conditions.

2. The second sub-chapter is related to the study of the recurring challenges that occur within the urban environment, but to restrict the field, this thesis only focuses on those that can be addressed by NbS.

3. The third section intends to study NbS on a deeper level, starting from how they can be implemented within the urban scenarios, what are the important considerations that need to be taken into account when they are to be inserted within a complex urban system, and what is their specific contribution to urban challenges.

4. This sub-section is entirely dedicated to four interesting case studies across Europe that helped better form the theoretical foundation, but also understand the practical implications that are introduced when a good practice is implemented within a highly complex environment.

Chapter 3: Methodology
This chapter aims to establish and define the methodological framework that was applied throughout the second part of the thesis, which entails the setting, creation, and utilization of the proposed visualization tool, by adopting the information gathered throughout the literature analysis.

1. This section shows the graphic flowchart of the steps followed during the application phase.

2. This part describes, step by step, the methodology adopted. It is based on three main sections, with a total of seven steps. The first phase concerns the tool's development, which is centered in identifying the three macro-groups that are to be correlated in the following phases (urban morphologies, urban challenges, and NbS), up until the actual creation of two tool's options (one developed mainly in Power BI, and the other one in Grasshopper). The next phase is dedicated to data analysis, aimed at understanding the specific characteristics and requirements of the site project but also to analyze the results that are generated by the tool, fostering an integration of the two analyses. The final phase is the design application, when, having selected the final NbS (or NbS pockets), it is time to locate them within the site project, defining their disposition on a masterplan level.

Chapter 4: Results and application
This section is dedicated to the application of all the steps laid out in the previous chapter, starting from the definition of the three groups (UM, UC, NbS) to the final design of a masterplan of the site project: a linear slab morphology found in the Mirafiori district, in Turin. Each sub-chapter is dedicated to one of the phases of the methodology framework.

1. The first sub-chapter specifies the single elements that have been chosen within this research: five urban morphologies, twelve urban challenges, eighteen NbS archetypes. Then it is explained how the qualitative evaluation of the single interconnections has been conducted to proceed with the creation of the tool's two options: two heatmaps with a Sankey diagram, and a 3D matrix.

2. The second part depicts the context and site analysis of the case study area in Mirafiori, while showing how the choice of some of the suitable NbS archetypes has been done, leading to the creation of two final NbS pockets: one for alleviating water stress and the other one for cooling the surrounding environment.

3. The final part is related to the design application, where the final spatial distribution of the NbS archetypes is shown on a masterplan level.

Chapter 5: Conclusions
This is the final chapter of the research.

1. This section draws the conclusive remarks of the whole research, providing a final evaluation of the framework.

2. Here the limitations of the presented framework are acknowledged, considering both theoretical and practical restrictions.

3. Finally, this sub-chapter suggests some possible interesting further developments that this framework may inspire.

LITERATURE REVIEW

This chapter has the objective to set the theoretical and methodological backbone of the approach used in the following sessions, mainly concerning morphological typologies, urban challenges, and NbS as conceptual archetypes for the urban regeneration.

For the literature review, peer-reviewed publications were collected using Web of Science, ResearchGate, Scopus, and Google Scholar. The search strings used were: "Nature-based Solutions" OR "NbS" OR "NbS pockets", AND "Urban morphology" OR "Cities", AND "Urban challenges", AND "Parametric Design", in order to select studies describing the characteristics of NbS and how their functions would change in relation to different urban forms and challenges. The review includes peer-reviewed articles, institutional reports and policies (e.g., United Nations, European Commission), and case studies of best practices, thereby integrating scientific and local expertise. The absence of a comprehensive treatment of the interactions between urban problematics, NbS, and urban forms within the existing literature made it necessary to develop a dedicated and integrative analysis based on available frameworks.

Based on this review, recurring types of urban morphologies, urban challenges, and nature-based solutions have emerged and are systematized in Chapter 3 for the creation of the decision-support system.

2.1 URBAN MORPHOLOGY

2.1.1 The discipline of urban morphology

The definition of "urban morphology" is quite varied, but it can be broadly described as the "study of city form". Fundamental pillars within the discipline are the understanding of the processes of urban transformation, spatial functions, and their links to socio-economic dynamics. In fact, urban morphology investigates the form of human settlements and the processes through which they are formed and transformed. Rooted in geography and urban sociology, this study field traditionally seeks to interpret urban structure and character by analyzing patterns in constituent elements, as well as the ownership and use of the built environment.

Even a rapid urban morphology analysis reveals that cities are composed of layered and juxtaposed urban tissues, produced by successive historical phases and planning patterns. Rather than being homogeneous, the urban environment can be read as a mosaic of recurring morphological configurations, each expressing specific spatial logics and, consequently, distinct environmental behaviors. This is particularly evident in European contexts such as Turin, Paris, or Barcelona, where traditional, pre-industrial fabrics coexist with modernist expansions and post-war peripheral districts (Salat et al., 2011, pp. 53-56).

An interesting approach followed by more recent studies analyzes the urban form with an even more objective lens, pursuing a neutral approach that focuses on measurable physical characteristics rather than socio-cultural interpretations. In line with this school of thought, the urban systems are conceptualized as a combination of distinct spatial configurations, including buildings, blocks, streets, but also materials, paved or green spaces, and infrastructure networks (Lehner et al., 2019). These elements are usually shaped differently based on the particular formation process and historical period that produced them. By adopting this concept, hence of considering the urban tissues the basis units of a broader system, it is easier to recognize similarities and patterns across the urban settlement, to allow an easier identification of their constituent elements (Fleischmann et al., 2022).

To support this vision, researchers commonly describe different structure types with specific features that are able to define the spatial relationship between built and open spaces, thus defining the street space, the building typology, and the open spaces enclosed by the constructed forms (Lehner et al., 2019).

On this regard, this research adopts the considerations advanced by Lehner et al. (2019), which propose a **theory-independent conceptualization of the urban form to deliver methodological transferability**. As the thesis opts to generate a replicable framework across diverse European cities and urban types, specifically focusing on the physical and microclimatological relations between the urban form and their surroundings helps transcend the diverse socio-cultural and land-use connotations that influence the urban environment. Such an approach may not be suitable for every research, as the previously mentioned factors are still crucial for a more complete and advanced understanding of the urban dimension, but this research does not intend to consider every influencing factor, but only abstract the physical aspects that allow for the definition of a first step stone towards a better understanding of how urban forms act and react to their surroundings. In fact, the explicit exclusion of land use, cultural use, and socio-symbolic factors allows for a more consistent comparison across cities with different backgrounds, climatic zones, historical ages, and cultural drivers (Lehner et al., 2019), and since the core objective is to enhance transferability and replicability across diverse urban contexts, adopting this approach ensures neutral, objective, and standardized analysis and interpretation. Therefore, these dimensions are currently omitted from the current research, in order to isolate the physical structure and use it as a common denominator to identify generic morphological typologies, that can be systematically related to certain environmental phenomena. The intentionally omitted factors can be eventually introduced with a secondary analysis, to further examine the feasibility of the proposed implementation.

2.1.2 Microclimatic repercussions of the urban form

The urban form plays a crucial role in shaping local microclimatic conditions, sometimes even generating phenomena that are inconsistent with the broader climatic region in which a city is located. As highlighted by Golany (1995), the spatial configuration of the built environment not only influences local thermal performance, but also broader urban events and trends, including energy consumption, public health, pedestrian comfort, economic activity, and long-term social stability. The urban structure, therefore, acts as a spatial interface between climate and human activity, being able to amplify or mitigate environmental stresses at the local scale.

However, from a purely microclimatic perspective, optimal urban forms are rarely achievable in real cities, due to historical stratification, functional constraints, and socio-economic factors. For this reason, rather than seeking idealized solutions, it becomes essential to understand how different urban morphologies interact with environmental variables and how their characteristics affect local climatic conditions. This understanding allows the development of context-specific adaptation strategies, tailored to existing morphological conditions, instead of treating these practices as universal solutions (Fleischmann et al., 2022; Golany, 1995; Salat et al., 2011).

In support of this approach, a set of site-related and morphological characteristics can be identified to understand how these influence urban thermal performance. They include altitude, which affects air temperature through vertical thermal gradients; ventilation patterns, since air movement (Fig. 20) – particularly winds generating from water bodies or higher elevations – plays a crucial role in heat dissipation; and evaporative cooling, especially in areas adjacent to water bodies. Topography is also critical: locations above valleys tend to benefit from better air circulation and reduced thermal inversion, while low-lying areas are more prone to stagnant air, pollution accumulation, and higher energy demand for heating and cooling. Orientation further influences solar exposure, radiation loads, comfort, and energy consumption, while soil characteristics and land stability affect runoff, erosion, wind behavior, and resilience to extreme weather events (Golany, 1995).

Building on this knowledge, more recent research has systematically linked urban morphology to microclimatic behavior through context-specific climatic simulations. Key **climatic variables influencing urban comfort include air temperature, solar radiation, wind speed, and humidity**, also taking into consideration daily and seasonal variability. While these factors are able to influence the microclimatic conditions of a specific form, it is also true the opposite, since the morphology and dimensions of open spaces, the overall spatial arrangement of surrounding volumes, and building density are perpetrators of positive or negative outcomes (Battisti, 2020; Zou et al., 2021).
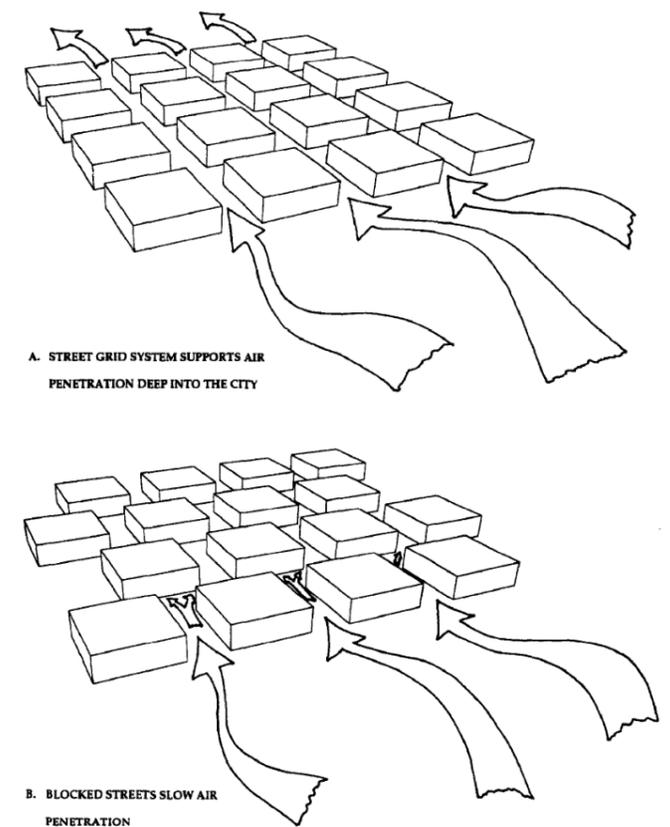

A. STREET GRID SYSTEM SUPPORTS AIR PENETRATION DEEP INTO THE CITY

B. BLOCKED STREETS SLOW AIR PENETRATION

Figure 20 – How street design and orientation can influence wind passage in urban scenarios (Golany, 1995, p. 462).

To evaluate the impact of these aspects on human comfort, several thermo-hygrometric indicators have been introduced. For example, the **Mean Radiant Temperature** (**MRT**) captures the thermal influence of surrounding surfaces and materials, reflecting the level of influence of urban morphology and materiality in shaping the microclimate. Additionally, the **Physiological Equivalent Temperature** (**PET**), specifically developed for outdoor environments, translates complex environmental conditions into a temperature value perceived by users, integrating meteorological variables with human thermoregulation processes; this value is usually set at 25°C, while discomfort levels can be experienced at temperatures higher than 37°C. Although recent studies note that PET may underestimate users' adaptive capacity in outdoor settings, it remains a widely used indicator for identifying comfort trends and comparing different urban configurations (Battisti, 2020; Zou et al., 2021).

In recent years, the adoption of digital tools and modelling techniques has majorly improved climate-related analyses and the possibility of generating positive assertions based on such simulations within the complex urban environment. For example, it is possible, through digital platforms that simultaneously analyze complex physical, thermal, and environmental interactions within the built environment, to determine the most vulnerable areas, thus supporting better mitigation and adaptation strategies (Bassolino et al, 2023).

By understanding this consequential relationship, it becomes possible to systematically relate spatial configurations to specific climatic behaviors and, consequently, to identify combinations of NbS that are both effective and context-sensitive. This approach helps shifting the focus from isolated interventions to morphology-driven adaptation strategies, supporting the development of replicable and scalable frameworks for climate-responsive urban design.

From morphological diversity to environmental performance

Traditional European urban fabrics – often rooted in Roman and pre-industrial models – are typically characterized by fine-grained meshes, strong connectivity, and a close relationship between built volumes and public space. Their spatial organization is frequently described as multi-scalar and coherent: patterns repeat across scales (building-block-street-district), generating continuous urban structure and legible public spaces (Fleischmann et al., 2022; Salat et al., pp. 56-77). In contrast, many modern and industrial-era extensions tend to show discontinuity between scales: isolated buildings, large open spaces, functional segregation, and repetitive forms. Even when density remains substantial, the weakening of intermediate scales and spatial hierarchy often produces oversized or poorly defined public space (Fig. 21) (Salat et al., 2011, pp. 56-77, 312-316).

Because urban resilience and environmental performance depend on how form operates based on different spatial aggregations, morphological analysis cannot overlook the multi-scalar view. In their book, Salat et al. (2011) emphasize that the relevant indicators and mechanisms change from the city scale (resource flows, infrastructures, wider street network), to the district and neighborhood scales (useful for connectivity, density, ventilation, shading, sky-view factor (SVF) considerations), down to the block and building scales (street layout, compactness, envelope geometry, materiality). No single scale is sufficient: understanding microclimatic repercussions requires linking indicators across different city's dimensions (Abdollahzadeh et al., 2022; Salat et al., 2011, pp. 487-488).

A recurring finding in urban climatology is that microclimates are not determined only by regional climate, but also by human-made modifications of geometry and land cover. As a result, climate risks such as heat stress, reduced air quality, and extreme precipitation patterns are increasingly experienced at the local urban scale, especially in dense environments (Albdour et al., 2019; Chatzidimitriou et al., 2016; Xu et al., 2019).
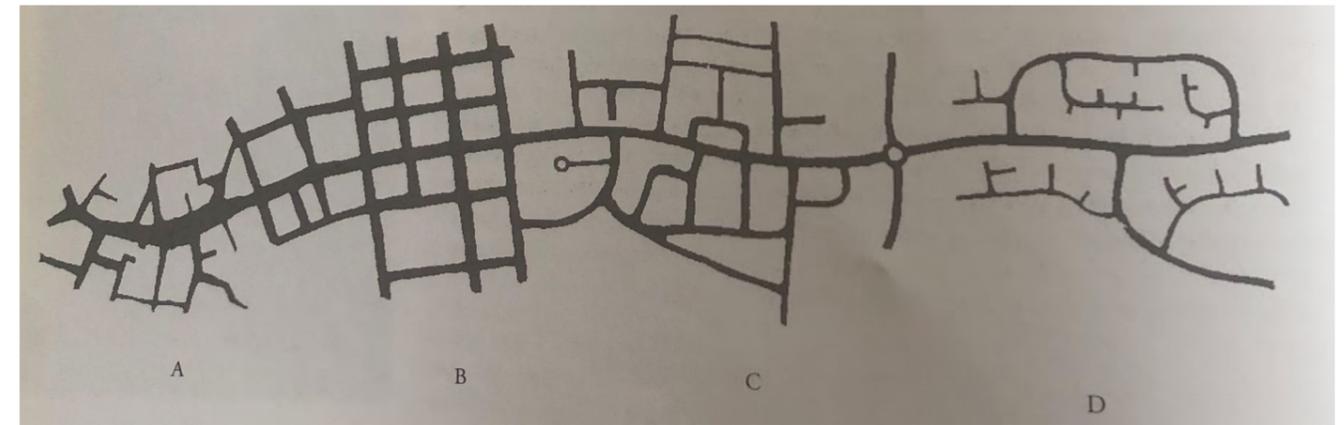

Figure 21 – How street network patterns typically evolve from the city center to the periphery of the settlment: the first type (A) corresponds to the historic center, (B) to orthogonal extensions, (C) to the nearest periphery, while (D) to the residential periphery typical of the suburbs (Salat et al., 2011, p. 254).

An effective method to describe this intra-urban variability in a comparable way, is proposed by Stewart and Oke (2012) with the **Localized Climate Zone** (**LCZ**) framework, which links near-surface temperature differences to measurable physical properties such as building height, density, spacing, surface cover, and material characteristics. This approach can be helpful to provide a standardized evaluation between form and thermal behavior, enabling comparison across neighborhood and cities, but without providing detailed morphological typologies (Stewart et al., 2012).

By analyzing the urban structure through the LCZ logic, it is evident how compact built forms (high-, mid-, or low-rise) are characterized by higher air temperatures and reduced nocturnal cooling compared to more open or vegetated zones (Fig. 22), deducing that **land cover plays a decisive role in urban microclimate affecting evapotranspiration, albedo, and thermal storage** (Stewart et al., 2012). This can help explain why different neighborhoods experience unequal exposure to hazards and why interventions such as NbS must be located and designed with microclimatic mechanisms in mind.

In this thesis, the LCZ framework is not adopted as a final classification of the morphologies, rather as a conceptual support to further justify why distinct urban forms generate recurring microclimatic behaviors.
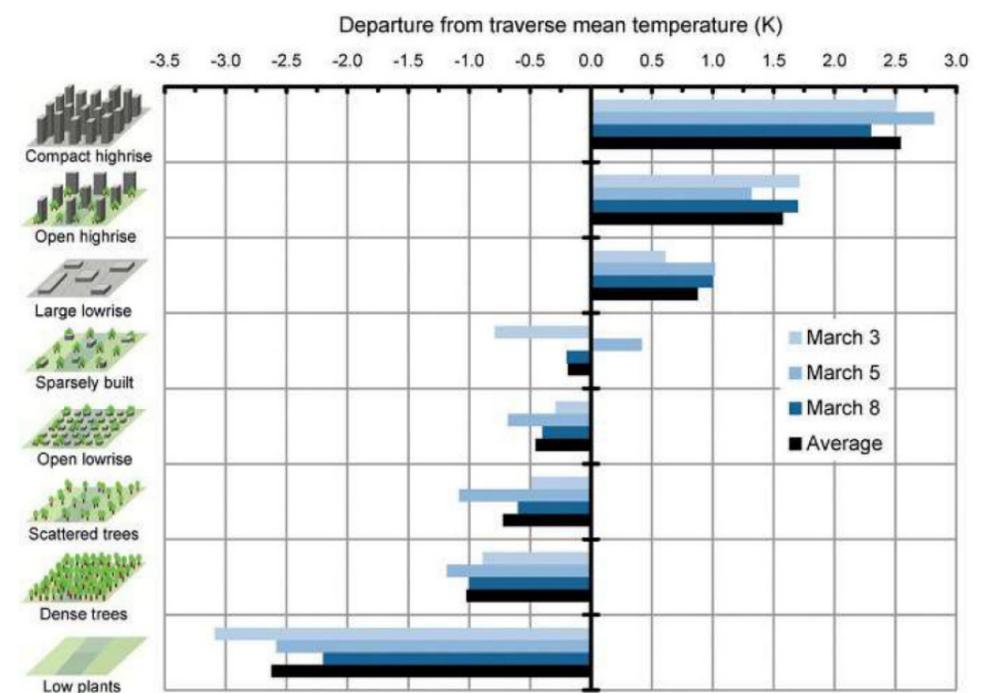

Figure 22 – Thermal differentiation of different LCZs measured by automobile travelers in Vancouver, 2010 (Stewart et al., 2012, p. 1888).

Across the literature, the **microclimatic repercussions of the urban form largely emerge from the interaction between geometry, materials, and vegetation**. Key drivers include: building density, block configuration, building height and orientation, open space layout, surface materials, imperviousness, and vegetation presence – affecting airflow, solar access, heat storage, radiative exchange, cooling loads, and water dynamics (Abdollahzadeh et al., 2022; Albdour et al., 2019; Chatzidimitriou et al., 2016; Dimoudi et al., 2003; Wang et al., 2015; Xu et al., 2019; Zou et al., 2021).

A crucial morphological point is that density alone is insufficient to evaluate this kind of events. While density of the built environment is a useful descriptor across scales (Salat et al., 2011, pp. 118-119), microclimate depends strongly on how solids and voids are arranged and interact with the outside environment: continuity vs. fragmentation of the fabric, enclosure of open spaces, and the resulting effects on wind permeability and radiative exchange (Bassolino et al., 2023; McPhearson et al., 2016).

To understand the climatic performance of street canyons and the microclimatic conditions of neighborhoods, different factors can be used. One of them is the **Sky View Factor** (**SVF**), which quantifies the part of open sky from a specific point placed on a surface – horizontal or vertical – to understand how much of the accumulated radiative heat is able to be released by said urban surface back into the atmosphere. Lower SVF restricts long-wave radiative cooling after sunset, increasing nocturnal temperatures and strengthening nighttime UHI intensity (Battisti, 2020; Dirksen et al., 2019; Golany, 1995; Stewart et al., 2012).

It can be calculated through simulation softwares or by using this equation (Fig. 23) (Dirksen et al., 2019):

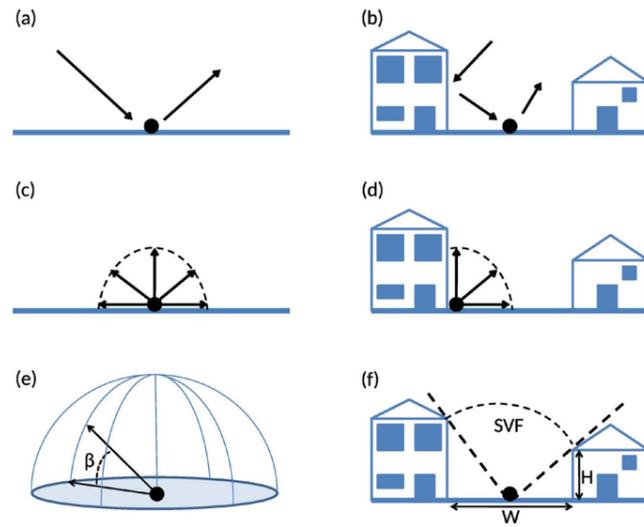$$SVF_{2D} = \cos\left(\arctan\left[\frac{H}{0.5W}\right]\right)$$

Figure 23 – Graphic visualization of how solar radiation impacts surfaces in an open field (a) vs. within a constructed environment (b), also showing how the SVF changes in such conformations (Dirksen et al., 2019, p. 3).

Another factor is the **street aspect ratio** (**H/W**), hence the relationship that stands between a building height and the width of the adjacent street, and it can also measure the level of enclosure of an internal courtyard or a square surrounded by buildings. It can influence shading and airflow regimes, shifting ventilation from street-level penetration to roof-level flow as the value increases, with implications for pollutant dispersion and thermal comfort (Fig. 24) (Golany, 1995; Oke, 1988). It has been acknowledged that for already enclosed spaces, higher H/W ratios (intended from H/W = 1 to 2) contribute to reducing SVF, thus lowering heat dissipation during nighttime and worsening PET values. While for more open configurations, higher values of H/W ratios can increase wind velocity, therefore decreasing air temperatures, whereas for lower ratios the air temperature would be higher, without the positive effects of wind channeling (Chatzidimitriou et al., 2016).

For mid-latitude cities a "compatibility range" can be established, in which multiple objectives (ventilation, radiation control, comfort) can be reasonably balanced – which is often around intermediate H/W ratios, 0.4-0.8 (Martinelli et al., 2016; Oke, 1988). Nevertheless, it is important to know that no geometry optimizes every objective at once. This aligns with the idea that "best" forms are context-dependent and should be understood through trade-offs rather than absolutes assessments (Oke, 1988).
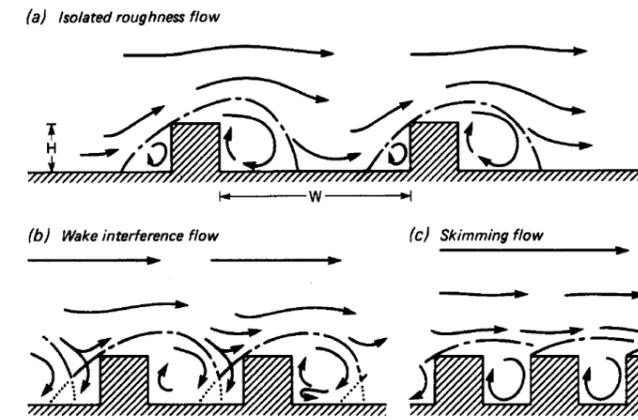

Figure 24 – Wind flow patterns over different buildings' configurations (Oke et al., p. 105).

Beside the aspect ratio, also the **urban grid rotation** has been recognized to have a strong impact on outside thermal comfort: For European cities the best street orientation is the one following the N-S axis, since the W-E one would receive too much solar radiation (Fig. 25). Moreover, the different kind of building morphology design has a great impact on the energy consumption of the structure itself, for both internal and external perceived environment (Abdollahzadeh et al., 2022).
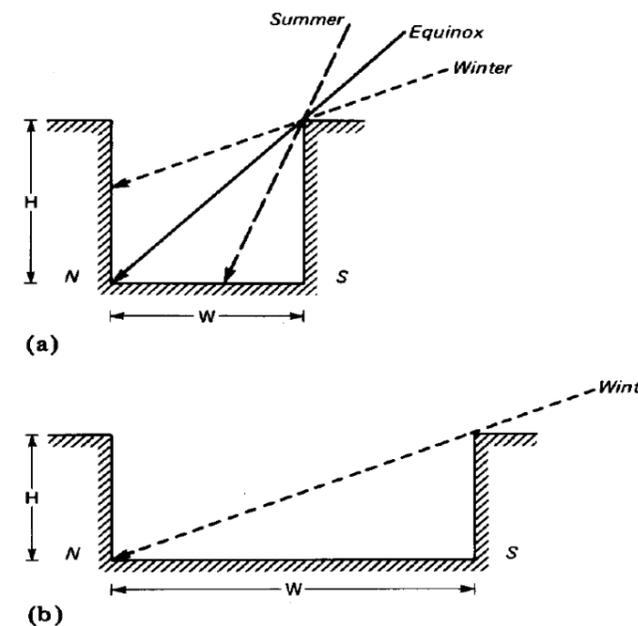

Figure 25 – Schematic view of angles of solar incidence at noon in an E-W canyon, in a city at mid-latitude, also showing how the enclosure of the urban form further influences solar radiation (Oke et al., 1998, p. 111).

In temperate climates, compact forms can provide strong **mutual shading, reduced wind exposure**, and in some cases **lower overall energy demand** – yet they also tend to reduce ventilation and amplify nighttime heat retention by lowering SVF, especially in higher-rise conformations. During daytime the shading can reduce MRT and perceived heat stress; while during nighttime the restricted radiative cooling can maintain higher temperatures and intensify UHI (Golany, 1995; Stewart et al., 2012).

Similarly, enclosed open spaces and **internal courtyards** often show lower MRT and PET compared to exposed squares, due to shading, helping reduce perceived heat stress; but they can be less ventilated and may perform poorly at night if the geometry limits airflow and radiative exchange, retaining higher temperatures and intensifying UHI (Chatzidimitriou et al., 2016; Golany, 1995; Stewart et al., 2012). Moreover, the aspect ratio affects PET differently in day vs. night conditions and in squares vs. courtyards, reinforcing the need to consider diurnal dynamics rather than average conditions (Chatzidimitriou et al., 2016).

Solar radiation represents the primary energy input shaping urban thermal processes. Incoming radiation heats both the urban canopy layer and the built fabric, where it is partly absorbed and partly reflected or redistributed. Dense urban configurations and impervious surfaces promote multiple reflections and higher heat storage during daytime hours, which translates into intensified heat release during the night and elevated cooling energy demand during warm periods (Taleb at al., 2014; Zou et al., 2021).

Urban ventilation constitutes another key regulating factor. Air movement enhances heat dissipation and affects cooling rates at both local and city scale. However, ventilation potential is strongly conditioned by urban morphology, including street aspect ratio (H/W), SVF, street orientation, surface coverage, and overall spatial configuration. As cities densify and expand, wind penetration at building and street level generally declines, reducing natural cooling potential and intensifying UHI effects in the more central areas.

Wind speed also influences relative humidity and evaporative cooling processes, which in turn affect thermal comfort and the body's capacity to dissipate heat (Abdollahzadeh et al., 2022; Taleb et al., 2014; Watkins et al., 2007; Zou et al., 2021).

Open and low-density dispersed configurations

Dispersed, low-density morphologies generally show **weaker climatic control** and may intensify thermal discomfort when open spaces are dominated by impervious surfaces. From a climatic perspective, vegetation belts, trees, and planted surfaces moderate conditions through shading and evapotranspiration, while also supporting ventilation when integrated as corridors rather that isolated patches. The literature also notes that isolated buildings behave very differently from the same buildings embedded in continuous fabrics due to altered exposure, heat exchange, and wind patterns (Golany, 1995; Taleb et al., 2014).

This type of settlement is characterized by the **highest level of solar gain** compared to other more compact ones, as the buildings' distance and lower heights allow more sun radiation to reach the singular building. Conversely, it is affected by higher energy consumptions during colder seasons, as there are no surrounding buildings that can offer a buffering layer between the single building and the outside environment; but also a cooler ambient during hotter periods, as the urban heat island effect is much lower in this kind of morphology type (Taleb et al, 2014).

High-rise morphology and deep street canyons

High-rise districts and deep canyons often exhibit low SVF: **Extensive shading** from the higher buildings can reduce daytime radiant loads at pedestrian level, but heat can be trapped at night due to reduced long-wave radiative losses. The microclimatic outcome depends on geometry and ventilation pathways: **Canyon depth** can improve daytime comfort via shading, yet degrade air quality and nighttime cooling if ventilation is suppressed (Golany, 1995; Oke, 1988; Stewart et al., 2012).
Street orientation and regularity further

modulate these effects. Some studies suggest north-south-oriented streets may reduce solar exposure duration and mean radiant temperature in our latitudes, while east-west orientations often require additional shading strategies to maintain comfort during hotter periods. Increasing height can reinforce shading and change radiative exchange regimes. However, as H/W increases beyond certain thresholds, pollutant dispersion worsens and pedestrian-level air quality can deteriorate due to trapped vortices and reduced exchange with the above-canopy atmosphere (Abdollahzadeh et al., 2022; Nakata-Osaki et al., 2017; Oke, 1988; Taleb et al., 2014).

Similarly to N-S oriented street grids, also slab buildings along said direction can offer higher level of outdoor comfort, providing even a 2°C reduction in the air temperature compared to W-E oriented configurations. However, the latter orientation can generate higher energy savings for the building due to increased solar gains, especially in colder climates (Abdollahzadeh et al., 2022).

Materials and ground permeability

Beyond geometry, also other elements can have a strong impact on urban microclimate. **Surface material properties** used on pavements, facades, and roofs play a decisive role in urban thermal behavior. Low-albedo, impervious materials absorb large amounts of the incoming rays which are then liberated during the dark hours, delaying atmospheric cooling and increasing heat stress. The widespread use of such materials in urban environments therefore represents a critical contributor to UHI intensity and outdoor thermal discomfort.

At the ground level, replacing hard pavements with permeable or vegetated soil can reduce PET, especially when moisture enhances evaporative cooling. Roof/terrace reflectivity can reduce thermal loads without necessarily altering pedestrian-level radiant conditions as strongly as ground materials do, making it a widely adopted mitigation solution (Chatzidimitriou et al., 2016; Wang et al., 2015).

Other influencing factors

Other than geometry, materiality, and permeability, also **shading patterns** and the **presence, distribution, age, and quality of vegetation** are strong influencers of microclimate conditions. Increasing or properly managing green coverage can improve pedestrian comfort and reduce heat island intensity. The main advantage of implementing tree canopies lies in the increase of shading and evapotranspiration, which are able to enhance relative humidity and lower heat accumulation. Together, these factors define the capacity of urban spaces to store, release, or dissipate heat, therefore greatly influencing local thermal conditions. Therefore, elevated temperatures, reduced wind speeds due to roughness, reduced nocturnal heat loss, and shading and reflection patterns affect building cooling loads and outdoor comfort (Chatzidimitriou et al., 2016; Gherri, 2023; Taleb et al., 2014; Wang et al., 2015; Zou et al., 2021).

Overall, other than thermal conditions, the **urban form influences also other environmental performances**, such as hydrological performance, air quality, biodiversity, and human well-being. As cities are furtherly urbanized, through soil sealing, densification, and loss of green space, the ecosystems and human well-being is additionally compromised (Battisti, 2020; McPhearson et al., 2016; Zou et al., 2021). Therefore, microclimatic benefits within the urban realm depend on the match between a proper intervention and local morphology. Shading devices (including tree canopies) can reduce PET substantially, but their side-effects differ: In open squares they may channel wind locally, while in enclosed courtyards they can further restrict ventilation and radiative exchange, unless designed with permeability and openings (Chatzidimitriou et al., 2016; Martinelli et al., 2016). Similarly, vegetation can reduce SVF and improve daytime comfort, but the magnitude and direction of effects depend on street width, tree placement, and urban context (Mazzoli, 2023; Milosevic et al., 2017; Trane et al., 2023; Wang et al., 2015).

In conclusion, the evidence supports moving

away from "one-size-fits-all" climate strategies. Instead, urban forms that combine moderate compactness to guarantee shading but without enclosing the space, vertical heterogeneity, ventilation corridors, and blue and green spaces placed in correspondence of deep urban canyons and wind paths often provide a more balanced compromise among shading, heat retention, ventilation, and air quality (Stewart et al., 2012; Wang et al., 2015).

2.2 URBAN CHALLENGES

In recent decades, urban development policies in Europe have increasingly promoted more intensive and compact urban models, often framed as sustainable responses to land consumption, infrastructure efficiency, and mobility demands. As a result, **cities** have evolved into complex social-ecological-technical systems, in which **multiple challenges, infrastructures, and actors interact in complex ways**, significantly complicating planning and decision-making processes (Kabisch et al., 2022). However, this shift toward high-density urban forms has also raised growing concerns about the reduction in the extent, quality, and condition of urban green spaces. These problems are frequently intensified by densification processes, spatial constraints, and layered infrastructures, fragmented and altered biodiversity patterns, competing stakeholder values, environmental injustices, rooted cultural and planning practices, and persistent misconceptions of cities as artificial environments detached from nature (Kabisch et al., 2022; MATTM, 2015). As a result of these increasing processes, cities account for a disproportionate share of resource consumption, waste generation, and environmental pressures. This concentration amplifies stress on ecosystems through land take, habitat degradation, and soil sealing, with cascading effects on biodiversity and on the environmental conditions that sustain human well-being (Kabisch et al., 2016).

A concerning aspect is that a substantial share of urban development is still ahead of us. Earlier influential estimates suggested that a majority of the urban land expected by 2030 had not yet been built – a point often used to stress how strongly the next development wave can accentuate either unsustainable or regenerative behaviors (Kabisch et al., 2016).

Within this perspective, urban challenges are not merely a list of urban problems, but they can be considered as a way to **describe the pressures and needs that constrain cities' capacity to protect ecosystems, reduce environmental impacts, improve resource efficiency, safeguard health, and promote**
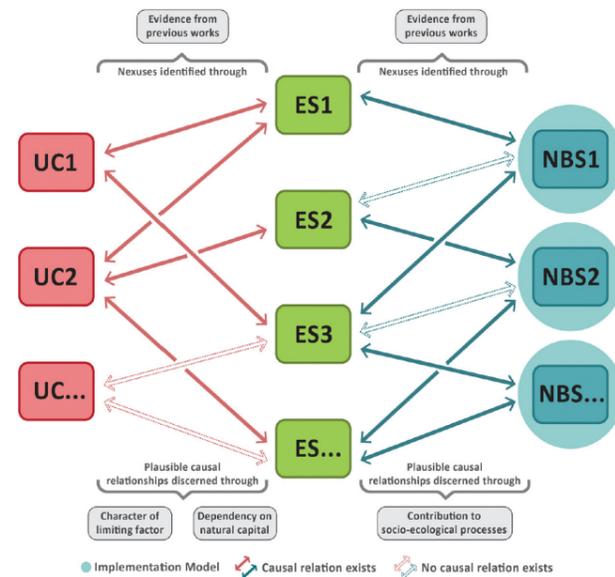

Figure 26 – Graphic connection between urban challenges, ecosystem services, and NbS (Almenar et al., 2020, p. 3).

social inclusion and economic vitality (Almenar et al., 2020). Specifically, the challenges that NbS are able to address can be described as environmental pressures that can arise from climate change dysregulation, as well as social, environmental, and economic repercussions (EEA, 2019).

Recent literature clarifies that urban challenges, ecosystem services (ES), and NbS can be seen as interconnected components of the same system (Fig. 26) (Almenar et al., 2020; Cohen-Shacham et al., 2019; IUCN, 2020). By understanding the ES-NbS connection, it becomes easier to **translate ecological potential into planning and design strategies**: Acknowledging which services are missing or degraded in a given context, NbS can be selected and shaped to address locally relevant needs (Almenar et al., 2020).

Ecosystems contain natural capital (soil, vegetation, water, biodiversity) that generates ecosystem services, i.e., the social and health benefits that are offered by nature – such as local cooling, runoff regulation, air purification, and opportunities for recreation and social interaction. Thus, NbS can be framed as the set of actions that protect, manage, restore, or create ecosystems in order to maintain or increase these benefits (Almenar et al., 2020;

Raymond et al., 2017a; Sarabi et al., 2021). At the same time, the literature is explicit that these relationships are not universal. Not all urban challenges originate from biophysical limitations, and not all of them can be mitigated through enhanced ecosystem service provision; in some cases, there is no meaningful causal pathway between a challenge and the services ecosystems can deliver. This implies that NbS should not be presented as a "solution to everything", but rather as a targeted strategy whose relevance depends on clearly identified links between local problems, ecosystem mechanisms, and expected outcomes (Almenar et al., 2020; Marusik et al., 2023).

Why urban challenges are expected to intensify

In the coming years and decades, the generation and mutual reinforcement of urban challenges – such as heat stress, flooding, air pollution, biodiversity loss, or social inequalities – are estimated to grow, due to the combined effects of climate change, ongoing urbanization, and demographic dynamics, often interacting with local governance conditions, socio-economic vulnerabilities, and competition for scarce urban land, which can generate competing interests and reinforce unsustainable development patterns (Almenar et al., 2020; Raymond et al., 2017a). Processes such as vegetation loss, the expansion of impervious surfaces, high energy demand, mobility patterns excessively dependent on private vehicles, and rising pollutant loads can simultaneously intensify environmental stress. These pressures often trigger cascading effects across economic, social, ecological, and infrastructural systems, leading to service disruptions and negative impacts on health and well-being – especially for vulnerable groups (EEA, 2020; UN-Habitat, 2024; Zou et al., 2021). In this context, it is useful to understand how urban challenges emerge from interacting constraints given by the overall city environment, which may arise from diverse reasons (Almenar et al., 2020):

- biophysical, e.g., limited vegetation and high surface sealing, that intensify heat and runoff;

- technological, e.g., insufficient systems to deliver services equitably;

- financial and institutional, e.g., limited resources or fragmented governance, limiting implementation capacity.

This is the reason why research stresses the need to select and prioritize the challenges based on local relevance and data availability, and that decision-support processes should allow different stakeholders to participate and assign different weights to each identified problem, reflecting varying perceptions of urgency and acceptable trade-offs (Sarabi et al., 2021).

From challenges to measurable indicators

To efficiently describe local pressures and needs, and therefore the potential for NbS to respond to such requisites, urban challenges must be addressed by indicators and levels of importance, even just on a qualitative level. Because many urban stresses vary sharply within the same district or neighborhood, high spatial resolution is often necessary: some indicators are meaningful at site or block scale but become invisible at city scale. Examples commonly discussed in NbS planning identify measuring exposure levels as important indicators for properly addressing thermal comfort; or measuring water depth during heavy rainfall, to understand where the highest flood risk is concentrated; or evaluating the proximity to major roads or to polluting land uses for air quality; or even analyzing and comparing distributional indicators of services or green spaces to address spatial equity (Sarabi et al., 2021).

2.2.1 Main urban challenges

In the context of this research, urban challenges are treated as the basis problem that guides the selection of a certain NbS measure within different morphological typologies. Additionally, by understanding how the different SDGs and their indicators are strictly connected to certain challenges and can be addressed by specific NbS, enables the establishment of comparisons on how diverse urban form and NbS combinations may address these exposures in a site-specific and scalable way.

The following section briefly outlines the most relevant urban challenges that can be successfully addressed by NbS-oriented planning, keeping the UC-ES-NbS relationship as a theoretical background. The goal is not to provide an exhaustive classification, but rather to clarify the types of pressures that most strongly constrain urban livability and resilience, and to illustrate why these pressures require locally grounded evaluations. In particular, as stated in the previous chapters, many urban struggles are intensified by urban geometry and land-cover patterns – such as heat storage and reduced nocturnal cooling, the disruption of hydrological cycles, the concentration of emission, and the fragmentation of habitats – thereby producing uneven exposure within the same city.

Greenhouse gas emissions and air pollution

Environmental pollution represents **one of the most critical global challenges** from a planetary health perspective, with particularly severe implications for urban environments, where people are continuously exposed in homes, workplaces, and public spaces. Europe makes no exception, especially the eastern countries and the Po Valley in northern Italy, as shown in the map illustrating the air pollution concentrations measured across Europe in 2018 (Fig. 27) (EEA, 2019).
Within contemporary climate policy frameworks, air quality management and climate mitigation are closely interlinked, as many measures aimed at reducing air pollution – most notably the reduction of fossil fuel combustion and

the improvement of buildings' performances – simultaneously contribute to lowering GHG emissions (Raymond et al., 2017a; Wang et al., 2015).
Air pollution is widely recognized as the most significant environmental health risk, both globally and within the European region. According to the World Health Organization (2025), exposure to high pollutants concentrations is likely to generate a **worse and reduced quality of life**, causing also different **chronic illnesses**. Based on 2019 statistics, GHG emissions contribute to almost 7 million premature deaths annually around the world, and 180 million lived years affected by disabling illnesses (DALYs) (WHO, 2025). The associated health outcomes are strongly linked to cardiovascular and respiratory diseases, lung cancer, and an expanding set of conditions that includes metabolic and neurological disorders. The pollutants most directly responsible for these impacts include fine and coarse particulate matter ($PM_{2.5}$, PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide, and carbon monoxide. Long-term exposure to $PM_{2.5}$ is causally associated with natural mortality, PM_{10} with lung cancer, and NO_2 and O_3 with respiratory diseases, underlining the severity of chronic exposure in densely populated urban areas (WHO, 2025).
Beyond health outcomes, air pollution also generates substantial **economic and social costs**, including increased healthcare expenditure, productivity losses, and reduced quality of life. However, the literature consistently emphasizes that these economic considerations are secondary to the public health imperative: A large share of the disease burden attributable to air pollution is preventable through improvements in environmental quality and reductions in exposure (EEA, 2019; WHO, 2025).
Furthermore, persistent urbanization processes have contributed to the intensification of temperatures within the cities, increasing the thermal discomfort for urban residents and encouraging energy-intensive adaptive behaviors, such as the widespread use of mechanical cooling systems, which in turn reinforces energy demand and emissions (Battisti, 2020).
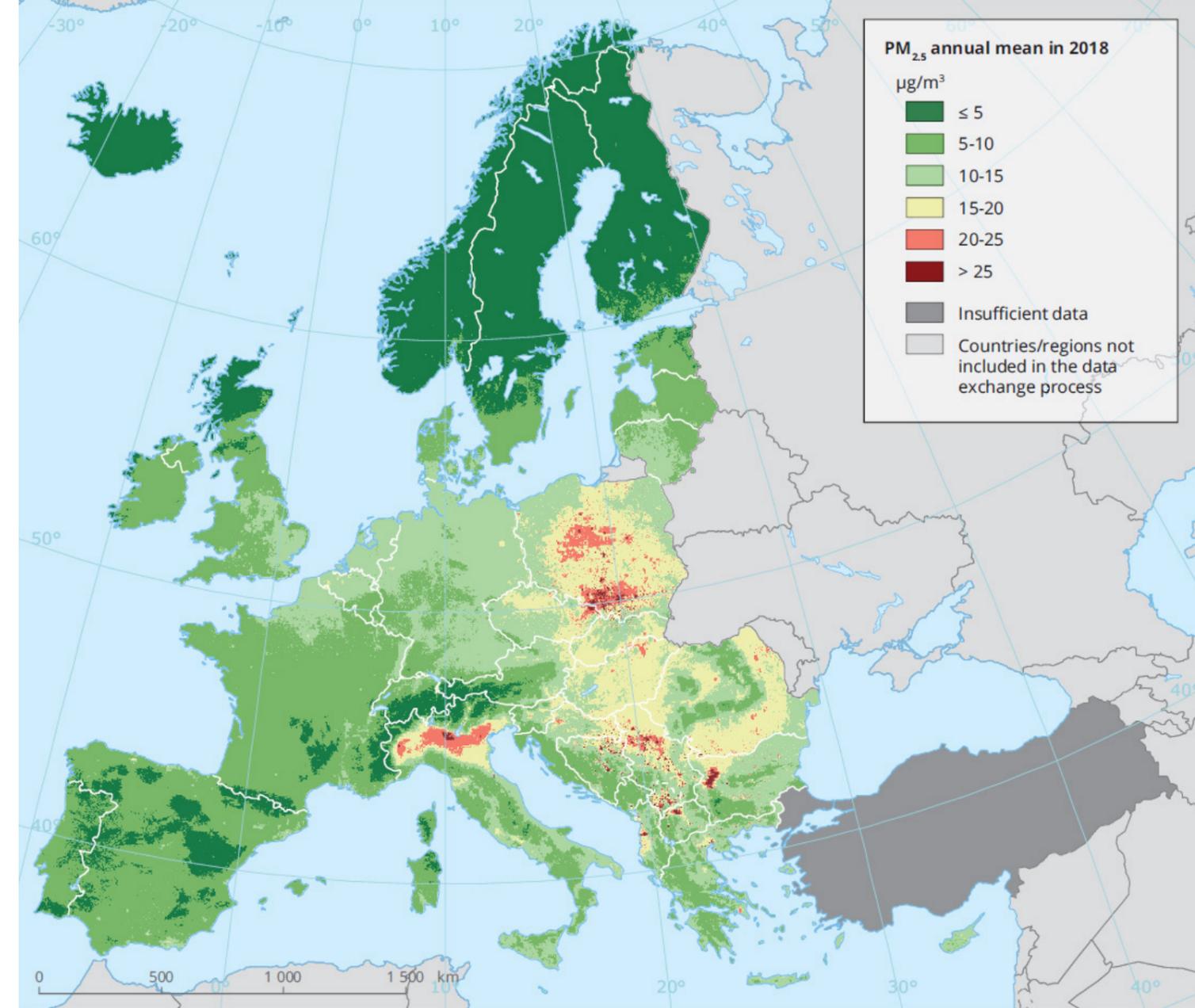
Figure 27 – Concentration of $PM_{2.5}$ for 2018 (EEA, 2019, p. 69).

Therefore, from an urban planning perspective, air pollution and GHG emissions constitute a core urban challenge, shaped by the spatial concentration of emission sources, surrounding geomorphological characteristics, land-use patterns, mobility systems, and urban morphology. These factors influence both emission intensity and exposure levels, making air quality a strongly spatialized issue within cities and reinforcing the need for place-specific strategies capable of delivering co-benefits for climate mitigation, public health, and urban livability.
In this sense, interventions targeting air quality in cities are most effective when they address both emission reduction and exposure mitigation, particularly through spatial strategies that modify land cover, street geometry, and the presence or absence of BGI.

Thermal stress, heatwaves, and the urban heat island

Climate projections consistently indicate a progressive warming trend over the coming decades, accompanied by a growing frequency and intensity of extreme heat events. In urban environments, this tendency is expected to significantly exacerbate thermal stress, making heatwaves and the urban heat island (UHI) effect among the most critical climate change-related challenges for cities (Bednar-Fridl et al., 2022; MATTM, 2015, pp. 16-17; Raymond et al., 2017b; Sarabi et al., 2021; Zou et al., 2021).

Heatwaves are generally defined as extreme meteorological events occurring primarily during the summer season, characterized by abnormally high temperatures persisting for several consecutive days. Although no universally agreed international definition exists, the scientific literature commonly describes heatwaves as periods of at least two to three days during which temperatures significantly exceed average conditions, under both dry and humid regimes. The severity of their impacts on human health depends on a combination of intensity, duration, and atmospheric moisture (WHO, 2025).

In temperate urban contexts, the most harmful events are typically humid heatwaves, during which extreme temperatures are accompanied by high humidity, limited nocturnal cooling due to cloud cover, and reduced ventilation. These conditions promote sustained heat accumulation across both daytime and nighttime hours, substantially increasing thermal stress. Heatwaves often affect large regions simultaneously and lack immediately visible physical effects. For this reason, they are frequently described as "silent killers" and are considered the deadliest category of weather- and climate-related disasters worldwide. Their impact in cities is further aggravated by elevated concentrations of air pollutants – such as O_3 and NO_2 – that tend to co-occur during heat events, aggravating health risks (Città di Torino, 2020a, p. 49; WHO, 2025).

Closely linked to heatwaves is the **urban heat island** (**UHI**) **phenomenon** (Fig. 28), defined as the systematic strong ambient heat disparity generated by the accumulated effects of the built-up surfaces of the city, that are much stronger than in the surrounding countryside, with the highest indexes typically occurring during nighttime. UHI arises primarily from the capacity of urban materials and surfaces to absorb, store, and slowly release solar radiation. Such materials – as asphalt and concrete – exhibit low albedo and high thermal inertia, favoring heat absorption and retention until dawn. This process intensifies nocturnal higher temperatures and increases population exposure during heatwaves events (Città di Torino, 2020a, p. 49).

Building on this definition, literature commonly distinguishes between different types of heat islands, which include (Battisti, 2020):

- **surface heat islands**, associated with the thermal behavior of urban surfaces and detectable through infrared radiation;
- **canopy-layer heat islands**, occurring between the terrain and the rooftops or tree tops, where the majority of outside life happens;
- **urban boundary-layer heat islands**, extending above roof level to the height at which urban influence on the atmosphere dissipates.

Within architectural and urban design practice, particular attention is given to the first two, as these are the scales at which built form, materiality, and site-specific characteristics most directly influence airflow and energy exchange processes (Battisti, 2020).

A substantial body of literature highlights that urban morphology and land cover are central drivers of UHI intensity. Morphological characteristics – including topography, city scale, street canyon geometry and orientation, spatial configuration, and building form – interact with design elements such as vegetation, water bodies, surface materials, and shading systems to promote or mitigate heat accumulation. Additional microclimatic variables, including air temperature, relative humidity, solar radiation, SVF, MRT, anthropogenic heat emissions, and airflow direction and speed, further influence the absorption and storage of solar energy within the urban fabric (Albdour et al., 2019; Wang et al., 2015; Zou et al., 2021).

From a planning and design perspective, thermal stress emerges as a strongly spatial-driven challenge, shaped by urban morphology, land cover, and microclimatic processes. This makes it particularly suitable for morphology-based analysis and for targeted deployment of NbS aimed at reducing heat exposure and enhancing outdoor thermal comfort.

Urban flooding, runoff, and water scarcity

Rapid urban population growth, the concentration of economic activities, and rising pollution levels place increasing pressure on urban water systems, intensifying stress on both **water quality and water availability**. As a result, there is a crucial need of developing a conscientious use and management of water reserves (MATTM, 2015, pp. 16-17).

Climate change is expected to further aggravate these vulnerabilities by altering precipitation regimes and temperature patterns. Across many European regions, projections indicate growing irregularity of rainfall, characterized by **more intense precipitation events alternating with longer dry periods**, while in some areas total annual precipitation is projected to decrease (Bednar-Fridl et al., 2022). These shifts have significant urban repercussions. On one hand, intense rainfall increases the likelihood that **stormwater runoff** will exceed the capacity of drainage and sewer systems, heightening **flood risk** in riverine, coastal, and highly impermeabilized urban areas. On the other hand, the possibility to face irreversible drought conditions is intensifying, consequently putting more pressure on water scarcity and reducing the resilience of urban ecosystems and water supplies.

Urbanization amplifies these dynamics by profoundly **altering the natural hydrological cycle**. The expansion of **impervious surfaces** limits infiltration, accelerates surface runoff, and reduces groundwater recharge. At the same time, urban runoff often carries high pollutant loads – including sediments, nutrients, heavy metals, and hydrocarbons – posing serious threats to surface and groundwater quality. Changes in precipitation patterns further contribute to hydrological instability, soil erosion, and degradation processes, generating cumulative stress on both natural ecosystems and built infrastructures (MATTM, 2015, pp. 22-23; Raymond et al., 2017a; Sarabi et al., 2021). Although overall water availability in Europe is not uniformly critical when considered at the annual scale, urban vulnerability mainly arises from the uneven spatial and temporally distribution
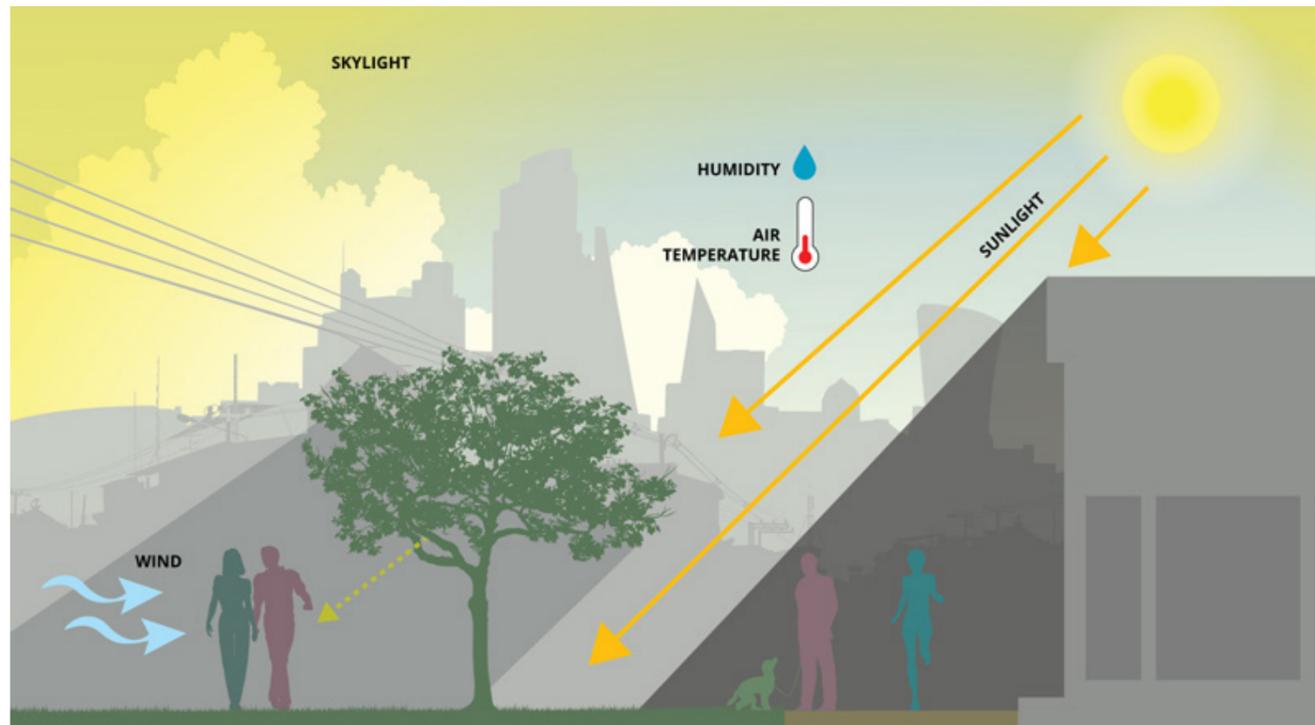
Figure 28 – Graphic visualization of the relationship between microclimatic conditions and urban fabric (https://rwdi.com/insight/how-urban-planners-can-leverage-microclimate-and-thermal-comfort-to-create-high-quality-outdoor-public-spaces/).

of water resources, combined with structural inefficiencies in water management systems. These conditions increase exposure to seasonal shortages, intensify pressure on water bodies, and often lead to altered natural flow regimes. Under climate change, such vulnerabilities heighten risks for ecosystems, agriculture, and urban settlements, particularly where high water demand intersects with limited adaptive capacity, ageing infrastructure, and fragmented governance frameworks (MATTM, 2015, p. 25).

From an urban planning perspective, water-related challenges are therefore not limited to extreme flood events or absolute scarcity, but are closely linked to urban form, land cover, and spatial organization, that highly influence how this natural resource can be managed. The degree of soil sealing, the configuration of open spaces, topography, and the integration – or absence – of blue and green infrastructure strongly influence runoff generation, storage capacity, and water quality. This makes water management a spatially differentiated urban challenge, requiring locally grounded strategies capable of restoring hydrological functions while addressing multiple risks simultaneously.

As the intensity and type of water-related risks vary significantly across different urban forms, it is necessary to treat this challenge as a morphology-dependent factor. This perspective supports the use of NbS not only as technical devices for drainage or storage, but as spatial strategies that strategically reconfigure runoff pathways, enhance infiltration, and increase the adaptive capacity of distinct urban typologies.

Biodiversity loss, habitat fragmentation, and deregulation of ecosystems

Climate change and urbanization pose significant pressures also on biodiversity through **habitat degradation, altered species distributions, physiology, and behavior**, and heighten their extinction, with cascading effects on ecosystem composition and interactions. Shifts in species ranges are increasingly evident, leading to ecological imbalances and the shrinkage of suitable habitats, particularly for species adapted to specific climatic conditions. Mountain and high-altitude ecosystems are especially vulnerable, as upward shifts in species distributions reduce available habitat and increase the risk of local extinctions, while Mediterranean ecosystems also face growing pressure under warmer and drier conditions. Agricultural systems are also becoming more vulnerable as a result of water stress, extreme heat, and changing climatic conditions that affect crop productivity and survival. But this risk can also be evident in urban settlements, where the already restricted biodiversity variety is further threatened by global and local stressors, including ecological disturbance and destruction, aggressive flora and fauna introduction, carbon intensive emissions, and the expansion of urbanization, resulting in heightened vulnerability of ecosystems and a progressive loss of biodiversity (MATTM, 2015, pp. 16-17, 30; Raymond et al., 2017a; Sarabi et al., 2021).

Furthermore, a large part of the territories is vulnerable to declining biological and economic productivity as a result of land degradation and desertification processes, which are expected to intensify under climate change. Rising temperatures and prolonged drought conditions exacerbate soil erosion, salinization, and the loss of organic matter, undermining soil fertility and ecosystem functioning. These dynamics increase the risk of wildfires and intensify water stress across both drylands and wetlands, often in combination with recurring water scarcity events (MATTM, 2015, p. 26).

Risks to human health, well-being, security, and social inequalities

Climate change is already generating significant risks to public health, well-being, and population safety through the combined effects of **heatwaves, extreme weather events, and environmental degradation**, which facilitate the **spread of climate-sensitive diseases**. These impacts extend beyond direct thermal stress to include **degraded air and water quality, compromised food safety and nutrition**, and heightened **risks for the most exposed and socio-economically disadvantaged populations**. Urban areas are particularly subjected to such threats due to high population density and limited adaptation approaches, for example, due to flooding events that force **displacements**, resulting in growing social and economic incumbencies (MATTM, 2015, pp. 36-38; Raymond et al., 2017a; Sarabi et al., 2021). **Socio-economic fragility** is therefore further amplified by these impacts, particularly where pre-existing environmental vulnerabilities are present, leading to long-term degradation processes (MATTM, 2015, pp. 16-17, 26).

Moreover, CC-related risks can exacerbate existing social and environmental **inequalities**. The uneven spatial distribution of these impacts underscores the necessity for context-specific urban adaptation strategies that respond to local climate vulnerabilities and strengthen urban resilience (MATTM, 2015, pp. 16-17; Raymond et al., 2017a; Sarabi et al., 2021).

2.3 NBS AS TOOLS FOR URBAN RESILIENCE

2.3.1 Why are NbS relevant in urban scenarios?

As mentioned in the previous sections, urban areas present unique conditions and **critical challenges that require tailored planning principles capable of integrating green and natural elements into compact urban structures**, while preserving their ecological, social, and environmental functions.

Based on this knowledge, NbS can be regarded as a key urban planning instrument for enhancing urban resilience. Although originally conceived at landscape scales, their application within cities reveals additional and significant synergistic potential, particularly in relation to energy and water management, infrastructure and building design, transport systems, insurance mechanisms, and waste management (MATTM, 2015, p. 74). Therefore, the adoption of such measures has to be understood not as a single intervention, but **as a sequence of interconnected processes that extend beyond the execution of an isolated project**. This process includes identifying problems or opportunities, selecting and assessing appropriate NbS actions, designing and implementing interventions, engaging stakeholders throughout all phases, and ultimately transferring or upscaling successful solutions (Raymond et al., 2017b).

Urban residents are often exposed to multiple environmental stressors simultaneously, and these pressures can interact – sometimes all together – to intensify negative health outcomes.

Air pollution and high temperatures, for example, are known to amplify one another's effects, leading to increased morbidity and mortality. Cities tend to concentrate many of these stressors: compared with rural populations, urban dwellers are typically exposed to higher levels of noise, ambient air toxicity, and chemical contaminants, moreover they are often equipped with less natural spaces, due to scarce land availability. This combination makes urban populations particularly vulnerable to the cumulative impacts of environmental hazards (EEA, 2019).

For this reason, in **urban environments**, the inherent **multifunctionality of NbS makes them key supporters of the transition** from linear **to circular development models** (Bona et al., 2022; Kabisch et al., 2016; Raymond et al., 2017a). Nature-based solutions are particularly efficient in addressing the mitigation of the urban heat island effect, as they can lower ambient air temperatures and contribute to improved air quality. Moreover, this type of solution can provide multiple benefits simultaneously (Fig. 29), for example by regenerating natural water cycles, addressing first waste water management and treatment, therefore influencing how both flood and droughts events affect the urban space, ultimately improving water quality and increasing treated water reuse. Moreover, solutions that see natural elements integrated within the built environment – such as green facades, green roofs – are able to offer a simple grey infrastructure an improved performance,

energy efficiency, reduce internal thermal stress, facilitate the regeneration and adaptive reuse of building systems, thus improving overall urban environmental quality (Bona et al., 2022; Woods-Ballard et al., 2007).

Beyond these immediate effects, urban green and blue spaces also support **long-term urban ecosystem resilience** by enhancing carbon storage and sustaining ecological processes essential for human well-being (Fig. 30). Moreover, they are able to address and **mitigate natural disasters, regulate the local microclimatic conditions**, while providing city dwellers with sport and **recreation amenities**, thanks to which their general well-being is highly improved (Bona et al., 2022; EEA, 2019; Zou et al., 2021). An important aspect of these solutions is that they are built to foster local knowledge and empower communities, through active engagement and participation of various stakeholders during decision-making processes. This helps further reinforce a public local sense of space and identity (Giordano, 2024; Kabisch et al., 2022).

Despite this broad potential, current evidence indicates that NbS in urban contexts have been applied primarily to deliver local ecosystem services, such as flood regulation, heat stress alleviation, public health benefits, and cultural or recreational values – with green roofs and urban forests receiving the greatest research attention – rather than including climate mitigation goals as well. This, for example, has resulted in a notable knowledge gap regarding the global potential and constraints of urban forests to sequester GHG emissions (EEA, 2021; Teo et al., 2021).

Similarly to the relationship that UC and ES have, each NbS is capable of providing only a limited quantity of ecosystem services. Direct connections among NbS and ES can exist only when that solution contributes to the ecological processes responsible for generating that service. For NbS that take the form of physical or created ecosystems – such as green roofs, wetlands, or urban parks – this contribution depends on whether their biological and physical characteristics actively support those realms (Almenar et al., 2020).

Even though in this research NbS-ES relationship is not going to be specifically addressed – rather it focuses on NbS-UC nexuses – it is still important to acknowledge the fact that, beside the evidence that certain relationships between these factors exist, understanding how strongly the NbS are able to influence specific ecological processes is still relevant. In fact, some interventions may generate only marginal benefits, while others can significantly enhance service delivery. Beyond the ecological dimension, the factors determining the implementation of an NbS – including governance arrangements, financial mechanisms, and management practices – also play a critical role in determining their effectiveness in delivering ecosystem services and mitigating urban challenges (Almenar et al., 2020).

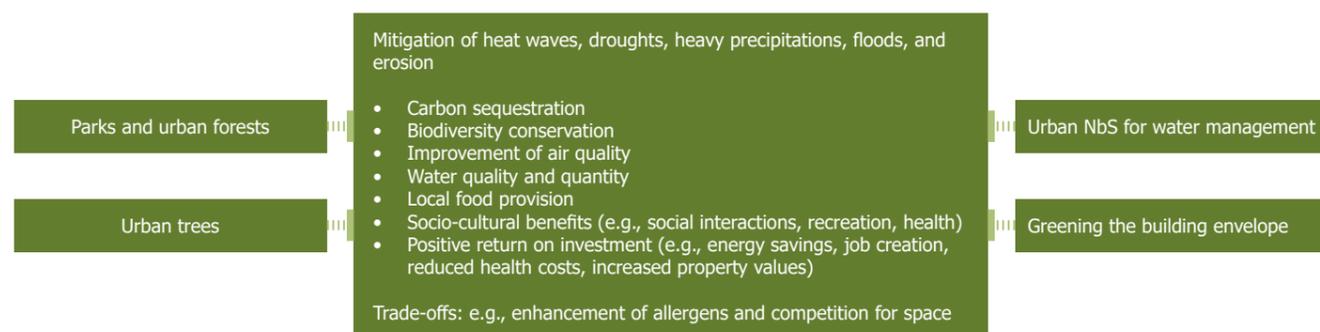**Figure 29 –** Graphic visualization of key NbS for addressing CC-related effects within urban contexts, specifying their benefits, co-benefits, and trade-offs (Author's production, based on EEA, 2021, p. 65).

Figure 30 – Graphic visualization of key NbS for addressing water-related stress within cities, specifying their benefits, co-benefits, and trade-offs (Author's production, based on EEA, 2021, p. 65).

2.3.2 Understanding NbS effectiveness

One of the key steps in the implementation and evaluation of NbS for urban climate resilience lies in the definition of the spatial scale at which interventions are designed and applied. Climate mitigation actions can operate across different spatial dimensions – single buildings, districts, cities, regions, and ultimately the global system – where their cumulative effects influence atmospheric GHG concentrations. **Climate adaptation measures**, in contrast, are primarily conceived and **implemented at local to regional scales**, where their benefits and impacts are directly experienced by communities. Although some actions, indicators, and assessment criteria are shared across scales, many are inherently scale-dependent. This underscores the need for multi-scalar approaches when assessing the effectiveness of NbS in addressing climate resilience challenges (Raymond et al., 2017a).

Empirical research consistently shows that NbS implemented to address specific urban challenges also contribute to enhancing overall climate resilience. Both mitigation and adaptation measures can be deployed at macro-, meso-, and micro-scales. Considering the natural spectrum, the first one corresponds to the broader connotation of typologies within the ecologic realms, the second one refers to landscapes, while the last one indicates all the ecosystems, down to individual organisms. From an institutional perspective, the macro-scale aligns with global and international governance, the meso-scale with regional, metropolitan, and urban levels, while the micro-scale with neighborhoods, streets, and individual buildings (Raymond et al., 2017a).

The spatial suitability of each NbS can vary within the same neighborhoods, as it depends on physical, environmental, and regulatory characteristics, but also on planning, policy, and land-use conditions. Certain NbS are only effective under particular site conditions, as surface slope, groundwater depth, land ownership, existing land use, and site function impose specific constrictions. For instance, rain gardens are unsuitable on steep slopes or in areas with shallow groundwater tables, while trees deliver the greatest cooling benefits in highly sun-exposed spaces. Assessing these constraints helps determine not only whether an NbS is technically feasible, but also whether it can be realistically and effectively integrated within the said urban fabric and governance framework (Sarabi et al., 2021; Woods-Ballard et al., 2007).

In many cases, the **environmental impact of NbS depends on physical processes operating at micro- and meso-scales** – including water flows, heat exchange, and pollutant dispersion – where it is crucial to account for contextual factors, such as street configuration and urban morphology, which strongly influence heat fluxes, shading, and evapotranspiration dynamics. However, assessing impacts at the city scale is often challenging, as the effects of smaller NbS interventions may be too mild to be detected on such broad scales, where their relevance emerges primarily through the cumulative implementation of multiple interventions across the urban fabric, such as systematic implementations of green roofs on a city scale, for example. Whereas measuring other benefits at the minor scales – such as pollutant removal, microclimate regulation, or water quality improvement – can offer an important contribution for site contexts (Raymond et al., 2017a).

Therefore, to properly determine the impacts of specific natural solutions, it is necessary to provide considerations on the typology and scale of the application, as well as the specific problems that are to be addressed. Certain functions, such as rainwater storage provided by a green roof or a bioretention system, can be evaluated at the micro-scale of individual buildings or structures, while their cumulative effects – such as reduced runoff volumes and associated flood risk mitigation – may become more relevant if evaluated at the street or broader urban scale. Similarly, micro-scale analyses can offer important considerations when addressing the level of exposure to heat stress of a neighborhood, since it can be directly connected to increased or decreased needs for cooling, whereas the evaluation of related carbon emission reductions typically occurs at larger urban, regional, or national scales (Raymond et al., 2017a).

For this reason, this research mainly focuses on the micro-scale, as it is the most appropriate for analyzing and evaluating NbS implementation on the neighborhood and district dimension. For example, social impacts of NbS are more effectively assessed at these scales, with particular attention to accessibility and use. In this context, ecological connectivity does not necessarily coincide with physical proximity, as movement may be constrained by physical, social, or infrastructural barriers. At the same time, social effects may interact across spatial scales, suggesting the need for future research to better capture cross-scale dynamics in the social outcomes of NbS (Raymond et al., 2017a). On this regard, enhancing ecological connectivity among NbS sites is essential, both within individual neighborhoods and across wider urban regeneration areas, in order to support biodiversity and reinforce ecosystem networks. This can be achieved through interventions such as rain gardens, façade greening systems, pocket parks, and community gardens, which simultaneously sustain ecological functions and promote community engagement (Raymond et al., 2017a).

To design and implement NbS within complex urban systems, the spatial and systemic dimensions are therefore fundamental aspects that need to be taken into consideration, in order to better understand the urban dynamics, as well as carefully considering the local context. But also, other dimensions are equally relevant when planning NbS interventions, particularly those related to co-governance, stakeholder engagement, and displaying iterative learning and communication processes (Kabisch et al., 2022) – these, however, remain outside the scope of this research.

While such guidelines provide an important conceptual framework for structuring NbS planning, they remain largely under-operationalized in spatial and morphological terms. In particular, the principle of context consideration, although widely acknowledged, lacks concrete tools capable of translating contextual variability into actionable, morphology-specific design guidance (Kabisch et al., 2022).

Examples of NbS adoption across scales

To better understand the spatial considerations that need to be taken into account when implementing NbS within the built environment, three interconnected levels can be identified (Bona et al., 2022; EEA, 2021). At the **city and peri-urban scale**, NbS are implemented as part of broader, systemic strategies with more pronounced cumulative impacts. At this level, measures often involve the creation or restoration of ecosystems across large areas, including urban forests, extensive green-blue networks, or city-wide water sensitive infrastructure, which embody resilient and regenerative approaches to challenges such as climate change mitigation, microclimate regulation, and noise reduction (Bona et al., 2022; EEA, 2021). City-scale NbS initiatives may take different forms: some may favor the adoption of a singular solution, as it happened in Basel and Hamburg, where the systematic implementation of green roofs happens on such wide scales that it became a standard practice for the whole cities (ClimateAdapt, Basel; ClimateAdapt, Hamburg); others target a specific challenge, such as climate-proofing or flood risk reduction, as the urban wetland in London shows (PANORAMA, London).

At the **neighborhood scale**, NbS are adopted to form larger, contiguous systems that significantly influence the surrounding urban fabric. Interventions at this level often include the creation of tree-based connections, as the Green Ring in Vitoria-Gasteiz (ClimateAdapt, Vitoria-Gasteiz), the restoration or daylighting of urban streams, the development of interconnected canal systems linked to rivers, the greening of riverbanks, and the transformation of brownfield or former industrial areas into climate-resilient neighborhoods (Bona et al., 2022; EEA, 2021). These projects typically aim to combine hydrological regulation, microclimate improvement, biodiversity enhancement, and public space provision. For example,

the conversion of brownfield sites into green areas contributes to urban regeneration, by restoring ecological functions while increasing the availability and accessibility of green space (Raymond et al., 2017a).

At the **smallest scale**, NbS are applied to individual elements of the built environment, such as buildings, streets, parking areas, or schoolyards, all of which contribute to environmental regulation and improved building performance. Typical interventions at this scale include green roofs and facades, green building materials, rain gardens, vegetated swales, eco-streets, green playgrounds, pocket parks, and permeable or vegetated car parks. For example, increasing greenery on urban facades and integrating NbS into building design can further support energy efficiency through improved insulation, natural ventilation, infiltration, and optimized building aesthetics and performance (Bona et al., 2022; EEA, 2021; Raymond et al., 2017a). Many documented urban NbS case studies operate at this level, either as single interventions – such as a standalone rain garden alongside a residential road in Nottingham (NWRM, Day Brook) – or as concentrated and coordinated combinations of multiple small-scale solutions, such as the Greenest of the Green Block in Helsinki (OPPLA, Helsinki). This synergistic adoption of multiple types of NbS, which can address a wider range of challenges simultaneously, is generally referred to as NbS pockets or clusters. For example, eco-street designs for decentralized rainwater management, such as those implemented in Ober-Grafendorf (ClimateAdapt, Ober-Grafendorf), integrate vegetation, water storage substrates, and infiltration systems to filter pollutants, recharge groundwater, and generate local cooling through evapotranspiration, offering wider ameliorations to the local environment.

Across all these levels, many NbS projects allow the introduction of renewed ecosystems inside urban voids or degraded parts of the city, reflecting the potential of built environments as active socio-ecological systems, rather than purely artificial spaces. Together, macro-, meso-, and micro-scale interventions illustrate how NbS

can be strategically deployed to address urban challenges through both localized actions and systemic transformations, depending on the scale, context, and objectives of singular urban planning initiatives (EEA, 2021).

The spatial scale of NbS

Upscaling NbS is a crucial strategy for extending their implementation and amplifying the range of benefits they can deliver. Some NbS generate **additional or synergistic effects when applied across larger areas**. For instance, green roofs primarily provide localized thermal regulation and improvement of building's performance, but their widespread adoption at the scale of an entire urban catchment area can also enhance habitat connectivity and improve water regulation. However, NbS do not always produce proportional benefits when scaled up. Empirical studies have highlighted the positive contribution of a certain type of retention systems when they are given little surface to spread, and could actually lose their efficiency when applied over larger areas, highlighting the need for further research into scale-dependent performance and thresholds (EEA, 2021).

The **effectiveness** of urban NbS is therefore strongly **influenced by both the scale and the contextual conditions** of their implementation. In many cases, successful outcomes require landscape-level approaches and the coordination of multiple stakeholders and landowners. Participatory planning processes are thus essential: Early stakeholder involvement supports ecological performance, strengthens the delivery of multiple co-benefits, enhances public acceptance, and helps ensure inclusive and equitable outcomes. Designing NbS through participatory and justice-oriented approaches is fundamental to fully realizing their potential and aligning interventions with diverse societal objectives (EEA, 2021).

The temporal scale of NbS

The literature provides limited empirical evidence on the time required for individual NbS to reach full effectiveness. As a result, NbS impacts are commonly described using three broad temporal categories: **short-term** (within five years),

medium-term (five to ten years), and **long-term** (beyond ten years). The timeframe over which benefits emerge varies substantially depending on the typology of intervention, local site characteristics, and the indicators considered. Some outcomes, as for example the social benefits introduced by a more accessible urban park, can be observed relatively quickly, whereas others – most notably improvements in air quality – tend to develop more gradually. Likewise, although access to green spaces can trigger immediate behavioral responses, sustained changes in physical activity, health outcomes, or place attachment typically require longer periods to materialize (Raymond et al., 2017a).

Accordingly, while many NbS begin delivering benefits soon after implementation, a temporal gap often exists between initial effects and full effectiveness. Several NbS unfold their complete range of benefits – and associated costs or potential disservices – only over longer time spans, once restored ecological processes and natural functions are fully established. The perseverance and scale of these benefits significantly depend on habitat quality and long-term maintenance, as most assessments assume that nature-based components are both successfully established and kept in favorable conditions over time. Temporal dynamics are further shaped by the ecological components involved; for example, carbon capture and sequestration rates depend on ecosystem type, structure, and maturity, influencing both the timing and scale of climate mitigation outcomes. Given this variability, NbS assessments should explicitly account for the time required for different interventions to become effective, particularly in relation to the urgency and nature of the challenges they are intended to address (Raymond et al., 2017a).

Limitations for the implementation of NbS

The long-term success of NbS implementation ultimately depends on their capacity to provide variety and a mixture of functions and services, but also on the effective integration of existing and newly introduced NbS within urban landscapes, reflecting processes of conservation,

adaptation, and transition (Andersson et al., 2014). However, several factors may limit their effectiveness in practice. These include **gaps in technical expertise, insufficient capacity for participatory and multidisciplinary management** that determines limited community involvement, scarce long-term maintenance, weak institutional support and economic incentives, inadequate identification of priority intervention areas, and ineffective communication strategies that fail to ensure inclusiveness. The inherent complexity of planning NbS in contexts marked by fragmented property ownership and competing land-use priorities and interests further complicates decision processes. Additional constraints arise from the frequent neglect of multifunctionality, inadequate communication strategies, and limited consideration of ecosystem disservices. Uncertainties related to the technological maturity of certain NbS, together with the challenge of aligning interventions with governance frameworks and ensuring meaningful community engagement at both operational and financial levels, further complicate their implementation (Ingaramo et al., 2023; Raymond et al., 2017a). Addressing these limitations requires institutional innovation, the development of a shared language for communicating the value and performance of NbS, stronger networking among actors, and the adoption of place-based and holistic approaches to urban regeneration. Ultimately, developing more effective ways of demonstrating the long-term benefits and effectiveness of nature-based solutions (Raymond et al., 2017a).

Although research and studies on the positiveness of natural-based solutions is strongly increasing, it is still quite hard to assess their real and precise contribution when analyzing social, economic, and environmental sectors. As the assessment methods and indicators widely differ across , it becomes difficult to build a strong unified support basis, and this makes comparison very limited. For this reason, a quantitative evaluation of NbS performance falls outside the scope of this research. Instead, the qualitative impacts of the selected NbS are assessed through their alignment with literature findings, relevant SDGs, and associated indicators.

2.3.3 Main NbS typologies

NbS for climate mitigation

Climate mitigation potential is intended as the capacity to reduce greenhouse gas (GHG) emissions. In this research, NbS are used to diminish carbon emissions, thereby contributing to mitigation efforts. Beyond direct carbon storage, these solutions can also support mitigation indirectly, by reducing temperatures at the meso- and micro-scales, lowering thus energy demands and associated emissions (Raymond et al., 2017b).

Carbon sequestration through NbS occurs primarily **via dry deposition through vegetation and soils**, making green spaces such as trees, urban forests, parks, building-integrated greenery, wetlands, grasslands, and other vegetated systems central to mitigation strategies. To maximize their effectiveness over time, careful species selection is essential to ensure adaptability to future climatic conditions, alongside appropriate and sustained management practices (Giordano, 2024; Raymond et al., 2017a; Teo et al., 2021). More broadly, NbS are increasingly promoted as tools to mitigate rising emissions by converting land from intensive, polluting uses to lower-impact functions through revegetation, rewilding, and ecosystem restoration. As emissions increase – and as larger populations are exposed – the urgency to implement and scale up NbS becomes more urgent (Tyllianakis et al., 2022). Moreover, NbS often result in lower lifecycle emissions than grey infrastructure solutions with similar functions (Raymond et al., 2017a).

Mitigation-oriented NbS have traditionally focused on land management interventions in rural contexts, particularly through the safeguard, sustainable administration, and repair of **parks, trees, meadows, constructed wetlands, and agricultural landscapes at large spatial scales**. However, complementary strategies are also emerging in urban environments, including **green building solutions and local food production systems** such as urban gardens, which reduce food-related transport emissions through short supply chains (Teo et al., 2021). In

both rural and urban contexts, land restoration can generate substantial secondary benefits that support more sustainable and resilient urban environment, including improved surface runoff management, enhanced soil carbon storage, strengthened ecosystem functioning, biodiversity conservation, bioenergy production, and support for local livelihoods and economies (EEA, 2019; MATTM, 2015, pp. 74-76; Raymond et al., 2017a; Teo et al., 2021).

Recent research has specifically assessed the carbon sequestration potential of **urban forests** in areas that are biophysically suitable for reforestation, such as grasslands or shrub-covered areas within forest, boreal and savannah biomes. At the global scale, the study estimates that approximately 17% of suitable urbanized surfaces could be converted into reforestation areas, corresponding to a mitigation potential of just over 1% of total urban carbon emissions. In Western Europe specifically, estimations assess that urban reforestation could be applied to roughly 25% of current impermeabilized areas, potentially offsetting about 1,3% of total urban carbon emissions (Teo et al., 2021).

However, compared to non-urban settings, urban forests face specific biophysical and spatial constraints, including poor soil conditions, light pollution, anthropogenic disturbances, land scarcity, and intense competition among land uses. While site-specific advantages – such as CO_2 fertilization and indirect emission reductions from decreased cooling demand – may enhance their performance, poorly planned interventions can generate unintended side effects and limit long-term effectiveness (MATTM, 2015, pp. 74-76; Raymond et al., 2017a; Teo et al., 2021). In response, some urban reforestation initiatives adopt intensive planting approaches, such as the Miyawaki method (Fig. 31), which combines soil restoration with high-density, multi-layered planting of native species and has been shown to significantly enhance carbon sequestration rates. By contrast, monoculture plantations may achieve rapid biomass growth but entail higher risks to carbon permanence due to vulnerability to pests and disturbances (Schirone et al., 2025; Teo et al., 2021).
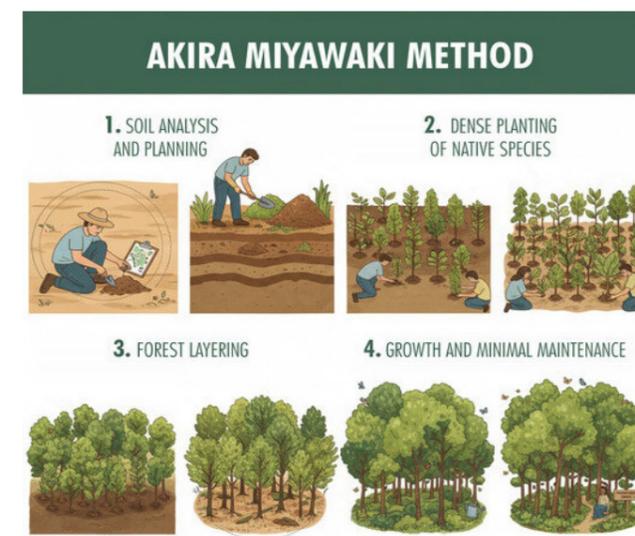

Figure 31 – The four steps defined by the Miyawaki method to create a self-sustaining forest (Schirone et al., 2025, p. 5).

Although smaller-scale urban vegetation contributes only marginally to reducing overall GHG and pollutant loads compared to the total urban emissions, integrating greenery into cities remains a critical component of broader mitigation and environmental quality strategies. **Trees**, in particular, increase their carbon uptake capacity as they age, reinforcing the long-term value of GI investments (EEA, 2019; Raymond et al., 2017a).

Aside their capacity of sequestering carbon, trees and other forms of green infrastructure can also reduce particulate matter (PM) concentrations in their immediate surroundings. Large-scale vegetation has also demonstrated measurable pollutant removal – for example, natural vegetation in the United Kingdom removed an estimated 1.4 billion kilograms of pollutants in 2015. **Green roofs and vegetated walls** can also contribute to improved air quality, particularly in narrow street canyons where vegetation can enhance pollutant deposition and lower concentrations of nitrogen dioxide and PM, but where there is not enough space for full grown street trees. Additional side-benefits extend to both outdoor and indoor environments, such as enhanced water retention and infiltration, reduced energy demand due to improved thermal insulation, improved acoustic comfort and noise reduction, and provision of shelter and support for multiple species, resulting in more pleasant and resilient urban spaces (EEA, 2019; Raymond et al., 2017a).

The contribution of urban forests and other NbS applied for air quality improvement – similarly to GHG emission sequestration – is generally

limited when compared to overall urban pollutant loads. Empirical studies indicate that vegetation accounts for only a small fraction of particulate matter removal and makes a marginal contribution to reducing city-wide GHG and nitrogen dioxide emissions. As a result, the effectiveness of NbS in improving air quality is strongly constrained by the availability of space, and even large-scale greening interventions yield relatively modest reductions in pollutant concentrations. This limitation highlights the necessity of coupling NbS with broader mitigation policies aimed at reducing emissions at their source, both within and beyond urban areas. Moreover, the performance of urban forests varies considerably depending on local context and the type of intervention, leading to mixed outcomes across different urban settings (Raymond et al., 2017a). Additional challenges and **trade-offs** must also be considered to understand the overall effectiveness of vegetation-based solutions. Such interventions in fact are affected by species selection, location, and urban form. Certain tree species also produce biogenic volatile organic compounds (BVOC) and allergens, that may contribute to ozone or particulate formation. These ecosystem disservices can have negative impacts on people who already suffer from hay fever or asthma, therefore partially offsetting the benefits of pollutant removal and improvements of net air quality. Local microclimatic and morphological conditions further influence outcomes, as street trees may either enhance or hinder pollutant dispersion depending on wind patterns, canopy structure, and street canyon geometry: Dense tree planting in narrow streets can impede air circulation and actually worsen local air quality and increasing pollutant levels. For these reasons, vegetation generally offers meaningful but context-dependent air-quality benefits, best achieved through careful species selection and intelligent spatial planning rather than relying on non-strategic greenery adoptions as a city-wide solution. Practical constraints also affect implementation, including high irrigation requirements and limited lifespan of green walls, potential damage to pavements and infrastructure from tree roots, and stresses on vegetation caused by heat, water scarcity, vandalism, and inadequate maintenance (EEA, 2019; Raymond et al., 2017a).

Local microclimatic conditions are shaped by the morphology of buildings, the composition of the urban settlement, and the presence and quality of green spaces. In dense and compact urban environments, these factors interact to intensify or mitigate the UHI effect, which worsens when materials such as asphalt and concrete absorb and store heat. Elevated urban temperatures increase thermal stress and heighten the risk of heat-related mortality, therefore requiring the promotion of passive mitigation strategies, including green infrastructure, to counteract urban overheating. As open spaces play a fundamental role in urban life – supporting social activities and contributing to environmental quality – their spatial proportions and material characteristics have significant social, economic, and climatic implications. A thorough study on how **trees and canopies composition, water elements, spatial configuration, and material choices** influence microclimate can therefore support more informed and climate-responsive design decisions, as they are able to affect air temperature, wind patterns, relative humidity, overall improving outside human activities and perception (Chatzidimitriou et al., 2016; Gherri, 2023; Zou et al., 2021).

Strategies to reduce heat accumulation in urban areas have been extensively discussed within the literature review, often resulting in the acknowledgment that fostering a **"cool city" concept** based on vegetation introduction and the adoption of sustainable interventions, will guide future urban scenarios to a more resilient path, simultaneously improving air temperatures, quality of primary resources, and reduce energy consumption (Golany, 1995; Zou et al., 2021).

From a landscape and urban design perspective, green infrastructure (GI) – such as tree canopies and ground cover – plays a central role in regulating microclimatic conditions. Trees **intercept solar radiation**, lower surface temperatures through **shading**, enhance latent heat exchange via **evapotranspiration,** and **provide permeable surfaces**, which in turn increase local relative humidity and limit heat accumulation (Città di Torino, 2020b, p. 41; Raymond et al., 2017a; Wang et al., 2015; Zou et al., 2021). The beneficial effects of green spaces on these factors have been noticed up to 60 m from their boundaries (Fig. 32). Moreover, vegetation is able to absorb a considerable amount of incoming solar radiation, therefore diminishing heat retention within the urban fabric: Differing from species to species, the type of soil,

and spatial configuration, urban green areas can produce local temperature reductions in the order of 1-4 °C (Gherri, 2023). It has been noticed, how more complex vegetation structures exhibit a greater capacity for microclimate regulation, with multi-layered plants identified as one of the most effective configurations for cooling and humidification. Recent studies on planting design therefore emphasize the importance of selecting appropriate tree species and densities, strategically placed according to their specific characteristics and local environmental conditions (Gherri, 2023; Zou et al., 2021).

The highest cooling potential for trees can be achieved when they are planted in **clusters**, but being careful of keeping a sufficient distance among each element, to be sure that wind is able to pass through. The strongest cooling effect from vegetation is observed in high-rise areas, where larger open spaces allow tree shading to operate more effectively. Studies have shown how tree coverage can reduce temperatures of up to 10 °C in open spaces and 5.5 °C in courtyards. However, nighttime conditions require a different approach: Dense tree canopies can trap warm air beneath the crowns, limiting heat removal during hot nights, particularly under low wind conditions. Ensuring adequate ventilation and integrating **open meadow** or low-vegetation areas therefore becomes essential to also support nocturnal cooling. Moreover, the cooling effectiveness of vegetation can be further enhanced by combining tree planting with grass-covered surfaces. In the absence of water stress, grass evapotranspiration can exert a cooling influence comparable to, or even greater than, tree transpiration in terms of human thermal comfort, especially at pedestrian level (Chatzidimitriou et al., 2016; EEA, 2021; Erlwein et al., 2021; Lee et al., 2016; Wang et al. 2015; Zölch et al., 2019).

Green roofs and green facades can be considered when dealing with heat stress in urban areas, particularly in space-constrained urban contexts where there is not enough space for trees to grow. While both measures significantly reduce surface temperatures – up to 22 °C for green roofs and 14-16 °C for green facades – their

impact on pedestrian-level thermal comfort is very limited. According to empirical evidences, neither green roofs nor green facades are able to produce a meaningful reduction in PET at 1.5 m height. Cooling effects on air temperature were detected only very close to facades (within 2-4 m), indicating that these NbS mainly act at the building envelope scale. When NbS are assessed in combination – as an NbS pocket –, the results highlight important synergies and conflicts. Trees combined with green facades further reduce façade surface temperatures – up to 21 °C – but this synergy does not translate into additional PET reductions at the pedestrian level, beyond what trees already provide alone. This shows that trees cannot be substituted by green roofs or facades when the goal is specifically reducing outdoor heat stress (Erlwein et al., 2021; Ysebaert et al., 2021).

Also, water features are often conceived as engineered elements contributing to cooling and ecosystem processes. The most pronounced improvements in thermal comfort related to water bodies have been observed within approximately 10-20 m from the water edge. When combined with appropriately designed vegetation, water sources can generate synergistic cooling effects, further enhancing their positive impact on the microclimate. Moreover, flowing and dispersed water sources, such as fountains, are able to provide even more benefits compared to stagnant bodies (Zou et al., 2021).

Beyond their thermal role, urban blue-green spaces deliver broader ecosystem services, which can support human health and well-being inside the urban realm. This means providing better air quality in their vicinity, carbon sequestration, noise attenuation, stormwater retention, microclimate regulation, the provision of recreational opportunities, and increased property values. But also, they provide an important social and cultural dimension: They can be a source of aesthetic improvement, recreation, social interaction, education, and support healthy living inside the urban space (Gherri, 2023; Raymond et al., 2017a).

The effectiveness of these solutions in mitigating temperature is subject to important **limitations**.
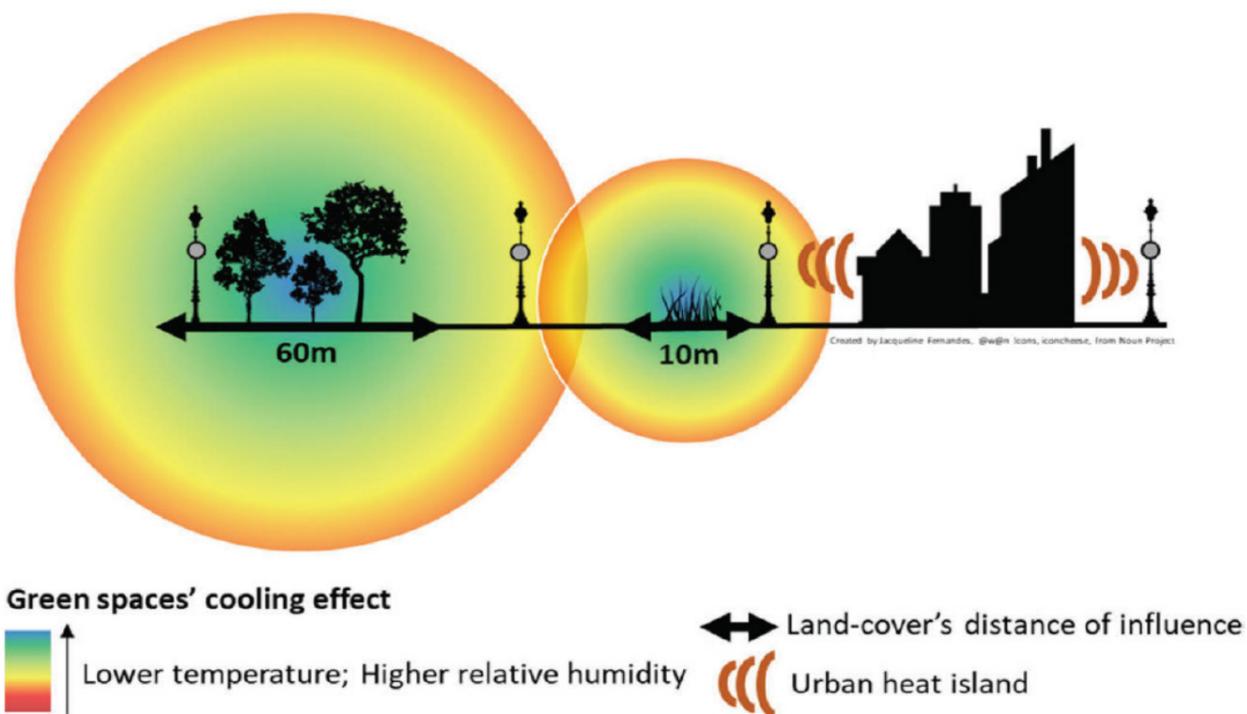

Green spaces' cooling effect

↑ Lower temperature; Higher relative humidity

↔ Land-cover's distance of influence

))) Urban heat island

Figure 32 – The cooling effect of green space (Zou et al., 2021, p. 4).

Aside from the plant species, sizes, spatial distribution, and health, it is also important to evaluate the soil conditions: If the soil is not correctly irrigated, the area is actually not going to respond to the climate variations as it is supposed to, since this strongly limits the capacity of evaporative cooling that it can provide. As a result, shallow-rooted plants and low vegetation are often unable to sustain sufficient latent heat exchange, leading to negligible or even adverse impacts on ambient temperature during the hottest hours. In mid-latitude and temperate regions, drought conditions and elevated air temperatures can cause physiological stress to the plants, consequently reducing evapotranspiration capacity and producing sensible heat release from plant surfaces, which can contribute to local temperature increases rather than cooling. Such effects are particularly relevant in urban areas characterized by extensive green masses or highly vegetated zones where irrigation is limited and elevated air temperatures are frequent. Under such conditions, the capacity in the future of lowering ambient temperatures through vegetation is going to be lowered by the fact that plants will not be able to dissipate all the heat that they have absorbed (Gherri, 2023; Zou et al., 2021).

Sealed soil replacement

Material-related choices, including **surface color, texture, and form**, greatly influence thermal performance, through their radiative properties. **Natural soil**, even within urban environments, provides essential ecosystem services that play a fundamental role in citizens' well-being and mitigation of future climatic scenarios. In particular, enhancing the soil's capacity to infiltrate stormwater and to regulate surface temperatures should be a key objective in the selection of design solutions aimed at reducing climate-related vulnerabilities. In this context, systems composed of plastic elements or concrete blocks installed on natural, permeable sub-bases – without rigid concrete layers – allow for effective load distribution while partially preserving soil naturalness. These solutions maintain some of the soil's ecosystem functions,

particularly natural stormwater drainage and local surface temperature reduction. Substituting hard pavements with soil and grass leads to notable **reductions in thermal stress**, lowering PET by approximately 4 °C in urban open spaces and 2.5 °C in courtyards. Permeable pavements can be applied in a wide range of urban contexts, although not all materials and installation techniques are suitable for vehicular traffic. For example, stone setts or cobblestones, while capable of withstanding vehicle loads, are more appropriate for pedestrian-oriented surfaces. Typical applications of permeable pavements include cycle and pedestrian paths, public squares, street edges, and areas where motorized vehicles do not circulate excessively (Chatzidimitriou et al., 2016; Città di Torino, 2020a, p. 96).

Urban morphology, surface exposure, and seasonal conditions can have repercussions even on material-based mitigation strategies. For example, replacing asphalt with **higher-albedo** concrete **pavements** increases solar reflectance and reduces heat storage, with the greatest cooling impact observed in middle-rise areas where ground surfaces are most exposed to solar radiation. An empirical study conducted in Toronto showed how cool ground surfaces were characterized by lower midday temperatures of almost 8 °C compared to usual urbanized surfaces. In contrast, the effectiveness of cool pavements is reduced in detached housing areas due to usually more extensive tree shading, while in high-rise areas due to limited solar exposure at ground level. **Cool roofs** – like green roofs – demonstrate a stronger overall effect than cool pavements, demonstrating a reduction of even 11 °C, particularly in low-rise areas where roof surfaces are closer to pedestrian levels. In high-rise areas, the influence of roof albedo on outdoor thermal conditions is less pronounced due to greater vertical separation (Wang et al., 2015).

Furthermore, materials with high solar reflectivity – high albedo – are able to absorb less radiant heat during daytime hours and therefore play an important role in mitigating the UHI effect. This factor strongly depends on the color, construction,

and texture of the chosen material. To reduce heat retention in urban enclosed areas, light-colored, smooth materials are to be preferred (Abdollahzadeh et al., 2022; Zou et al., 2021).

Shading improvement

During the summer period, densely built and highly urbanized areas are subject to significant thermal energy accumulation and reduced capacity for heat dissipation. Green infrastructure designed to maximize shading is fundamental for considerations on energy savings and enhancing the thermal comfort and usability of public urban spaces. **Vegetation** contributes significantly to solar absorption – approximately, plants **can absorb 60-90% of the incident solar radiation** – and heat dissipation in urban environments, while also supporting air humidity regulation. The effectiveness of these functions depends on several plant-specific characteristic, including canopy density, growth rate, leaf persistence, and overall size and form, which collectively influence the degree of solar radiation absorption and shading provided (Città di Torino, 2020a, p. 107).

For example, a study conducted in Naples by Bassolino et al. (2023) showed that by implementing different climate proofing solutions inside a courtyard morphology with 12 m high buildings – mainly de-paving actions, using cool materials, additional trees, rain gardens, and flowerbeds to decrease superficial temperatures – a decrease in median temperatures between -2°C and -5°C could be perceived, as well as decrease in CO_2 emissions (between -0.6 and -1.2%), and in PMV (between -50% and -67%). Though these results were true for that morphology, the same solutions were not generating the same beneficial impact in less high courtyard blocks. The different behavior of the two results is mainly attributable to the morphological differences, since the first morphology was more enclosed, so with higher shading, hence a better starting point to combat higher temperatures, while the second one, by being more open, it is more subject to sun radiation (Bassolino et al., 2023).

Highly urbanized spaces are increasingly affected by flooding events and threats during heavy rainfalls. This situation requires solutions that are able to offer an integrated response by addressing flood risk, water scarcity, and water quality simultaneously. This kind of solutions are generally referred to as **Sustainable Drainage Systems** (**SuDS**), which consist of measures designed to manage urban stormwater in a way that restores hydrological balance within water bodies, by leveraging the ecosystem services provided by nature-based and semi-natural solutions. By harnessing or **replicating natural processes** such as infiltration and retention, they can provide a perfect source of accommodation for rain and water runoff, even helping with the following provision of filtered and cleaner water, through phytoremediation, NbS can enhance urban water management while strengthening climate resilience (Città di Torino, 2020a, p. 60; Raymond et al., 2017a).

Preventing urban flooding requires the effective **management of rainwater** in areas where its accumulation may threaten human safety and damage infrastructure. The creation of artificial water bodies or ecosystems within cities, as well as the conservation and enhancement of existing natural systems, can play a key role in retaining and storing stormwater and urban runoff. In fact, the use of NbS over conventional grey infrastructure for water storage, simultaneously enhances infiltration processes, thereby reducing system overload, delaying and attenuating flood peaks, and enabling more controlled water release. For example, simple vegetated surfaces, green spaces, and urban wetlands can provide transitory accumulation of rainwater, therefore preventing direct discharge of precipitation into sewer networks. Moreover, flood mitigating solutions can be combined with other measures aimed at groundwater recharge, to provide additional water supplies, for instance through phytoremediation of stored wastewater and urban runoff. This enables water to either be safely and slowly reintroduced into natural streams or the sewer system, through infiltration, or it can be stored and filtered to

promote a safe non-potable water reuse on-site – such as for flushing toilets and irrigating green spaces –, thereby reducing pressure on freshwater resources and strengthening drought resilience. Such implementations can transform impermeable urban surfaces into multifunctional water systems that support renewed ecosystems and integrate water cycle functions (Eisenberg et al., 2022; Morello et al., 2019; Raymond et al., 2017a).

Some of these options include river restoration, bioswales, retention and detention basins, wetlands, rain gardens, permeable pavements, and green roofs. Research shows that even small-scale solutions can lower such risks, for example one to two thirds of run-off can be intercepted by porous pavements, more than half by infiltration trenches, and even obtaining a total catchment capacity provided by rain gardens. Moreover, it has been calculated that due to the water retention capacity of a park or forest substrate, the lost water to run-off is only 13%, compared to the 50-90% of the run-off experienced in built-up areas. That being so, green surfaces and forests can be extremely useful when regulating storm water flows and alleviating flooding hazards. Similarly, only on a smaller scale, urban trees in public squares and car parks can reduce the frequency and severity of sewage water overflows during heavy rainfall events (EEA, 2021).

Beyond their hydrological role, NbS and hybrid grey-green water management solutions provide multiple **secondary benefits**, including enhanced urban biodiversity, improved environmental quality and living conditions, better air quality and associated public health benefits, and improved urban microclimates through evaporative cooling that helps mitigate UHI effects. They can also contribute to climate mitigation by enabling carbon sequestration in vegetation and soils, although the magnitude of this contribution is generally insufficient to meet local GHG reduction targets on its own – particularly where irrigation is required for vegetation maintenance (Raymond et al., 2017a). However, the effectiveness of NbS for runoff reduction and effective management in urban areas is strictly influenced by a range of spatial, technical, and environmental constraints. Stormwater retention requires the availability of urban space for water storage, which can conflict with other land-use demands and with compact city restrictions, unless multifunctional solutions – such as green roofs or temporary water storage in streets and squares, like detention ponds – are implemented. In warmer climates or seasons, the maintenance of urban green areas often increases water demand due to irrigation needs, although this challenge may be partially addressed through water reuse strategies (Fig. 33). The use of infiltration systems for groundwater recharge must also be carefully evaluated to avoid transferring pollutants from runoff into aquifers, taking into account runoff water quality, soil filtration capacity, and rainfall characteristics (Raymond et al. 2017a, Woods-Ballard et al., 2007).

Moreover, the capacity of NbS to absorb and retain rainfall typically declines under high-intensity precipitation events, as **most solutions are calibrated on low to moderate rainfall scenarios**, often overlooking more critical emergencies. Trade-offs may also arise between flood mitigation and water availability, as certain fast-growing tree species enhance infiltration but increase evapotranspiration, which may be beneficial in flood-prone regions but problematic in arid or semi-arid contexts. Finally, some drought-resistant plant species may cause infrastructure damage due to aggressive root-systems or generate ecosystem disservices, including risks associated with water borne diseases, pests, and existing pollution (Raymond et al., 2017a).

Given the specific environmental requirements and potential risks of negatively affecting existing contexts, the implementation of stormwater infiltration measures must always be supported by detailed soil analyses and careful design, and by a thorough assessment of the general site. This is essential in order to avoid locating infiltration systems in areas with shallow groundwater tables, contaminated soils or subsoils, closely spaced abstraction or artesian wells, or conditions that could increase hydrogeological risk or cause ground instability. Infiltration solutions should also be designed to prevent significant risks of soil or groundwater pollution arising from highly contaminated first-flush run-off or accidental spills, as well as to avoid seepage or structural damage to adjacent buildings (Città di Torino, 2020a, p. 104; Woods-Ballard et al., 2007).

NbS to support human health and well-being

Extreme climate events, particularly heatwaves and the UHI effect, are among the most significant threats, as they are associated with increased morbidity and premature mortality. Urban vegetation mitigates these risks by providing climate regulation services – such as **shading** and **evapotranspiration** – that reduce local temperatures, help prevent heat-related consequences, improve air quality, and reduce noise levels (Raymond et al., 2017a).

Beyond physical health benefits, NbS are able to provide urban dwellers with a lot of different beneficial aspects when it comes to human health. **Access to and interaction with urban green spaces** has been shown to promote stress reduction, psychological restoration, and increased opportunities for physical activity. Proximity to green spaces and even visual exposure to greenery are associated with **improved mental and physical health** outcomes, including reduced depression, enhanced mental well-being, lower cardiovascular risk, and even a reduced risk of getting diabetes. Green spaces also support child development by encouraging exploratory behavior and may enhance immune system functioning. The importance of being able to utilize or even just be able to see a natural green source was particularly acknowledged through the whole COVID-19 pandemic. In this context, the design and implementation of nature-based restorative spaces is recognized as a promising strategy for responding to public health crises and support satisfied living inside the urban space (Bona et al., 2022; Raymond et al., 2017a). Nevertheless, urban green spaces may also entail potential health risks, such as **increased exposure to allergenic pollen, vector-borne diseases, or injury risks** associated with physical activity, particularly among children. These potential adverse effects highlight the importance of careful design, appropriate species selection, and ongoing maintenance and management to maximize health benefits while minimizing ecosystem disservices (Raymond et al., 2017a).
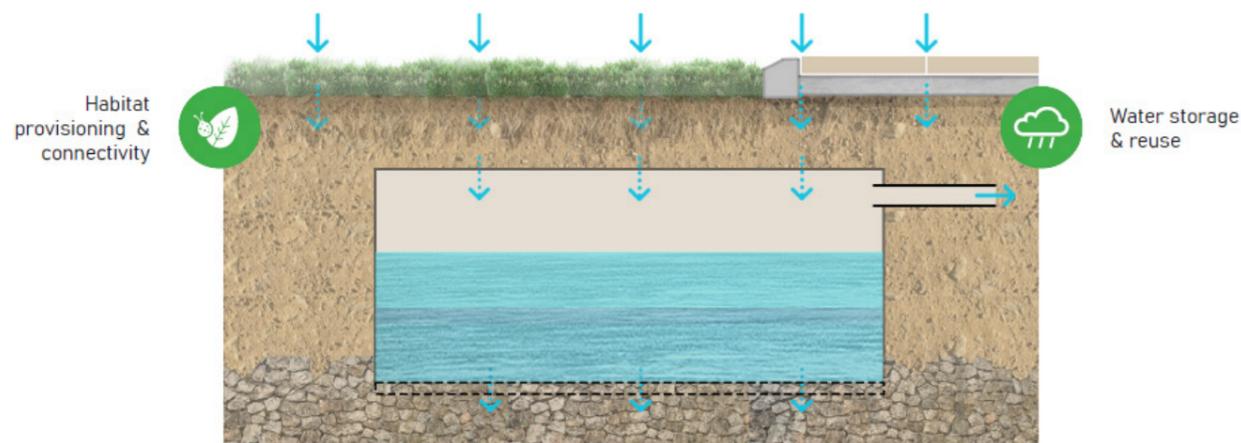

Figure 33 – Example of an underground water storage retention basin (Eisenberg et al., 2022).

Habitat provisioning & connectivity

Water storage & reuse

NbS for social cohesion, equity, and justice

Beyond environmental benefits, these approaches enhance the social and cultural quality of urban environments by promoting richness and diversity in public space design. Ensuring **diversity of uses, appropriate densities, and ease of movement** supports more inclusive and livable cities. Actively involving residents in the design and management of buildings and public spaces further strengthens social equity outcomes, while increased green open space and improved urban connectivity contribute to greater cultural richness, social cohesion, and overall urban quality of life (Raymond et al., 2017a).

Social justice acknowledges that societies are composed of diverse social groups with different needs, rights, and responsibilities, requiring mutual support, cooperation, and recognition to function equitably. Within the context of green infrastructure planning, environmental justice has been strongly addressed, by considering three different dimensions: distributional, procedural, and recognition-based justice. The first one concerns the uneven social and spatial allocation of environmental benefits and burdens, while the procedural justice addresses fairness and inclusiveness in decision-making processes and the enforcement of rules. Recognition-based justice emphasizes the acknowledgment and inclusion of groups that are often marginalized, such as older adults, migrants, women, and people with disabilities. Advancing environmental justice within green infrastructure strategies can also strengthen social cohesion in urban areas by fostering inclusive environments and supporting intercultural understanding, for instance by enabling immigrant communities to feel a sense of belonging in their neighborhoods (Raymond at al., 2017a).

Therefore, ensuring social equity in the implementation of NbS requires their proper spatial distribution across urban areas, so that a wide range of urban contexts can equally benefit from the positive effects that they provide. Investing in NbS across multiple neighborhoods increases opportunities for a wider and more diverse population to experience and benefit from contact with nature, while supporting

experiential learning and capacity-building initiatives. Actively engaging a wide variety of citizens, with different backgrounds, is the key to reaching a strong and shared project. Supporting **inclusive governance processes** is therefore the only just methodology to address social disparities (Raymond et al. 2017a).

The implementation of NbS in urban contexts may involve trade-offs within environmental justice objectives, particularly where greening initiatives contribute to processes of gentrification and social displacement. Identifying and addressing these risks is therefore a critical component of equitable urban climate adaptation. Equally important is the recognition of diverse social perceptions and priorities regarding climate adaptation and urban change (Raymond et al., 2017a).

NbS to support local economy and green jobs creation

A growing body of research demonstrates that expanding green areas within urban environments delivers substantial co-benefits, including **increased property values, positive health outcomes, improved water management, and enhances recreational opportunities**. These findings suggest that NbS represent a **cost-effective approach** to addressing a wide range of urban environmental challenges, as well as contribute to the generation of **avoided costs**. Beyond their direct contributions to climate adaptation and mitigation, NbS generate additional economic and social benefits that can reduce costs for households and public administrations while fostering new economic opportunities in the growing green economy. Moreover, the implementation of NbS supports the **creation** of a wide range of **jobs** that can be reconducted to the green sector, whether it involves the maintenance works, or the specialized planning of such measures (Raymond et al., 2017a).

2.4 BEST PRACTICES AND LESSONS LEARNED

Transferability is a key criterion for identifying and evaluating best practices in the implementation of NbS. Evidence shows that transferability is generally high when measures and implementation strategies are carefully adapted to local environmental conditions, governance frameworks, and socio-cultural contexts. Rather than offering rigid models to be literally replicated in other realities, analyzing best practices provides the ability to understand **how adaptable approaches and design principles work in different cities**, and can therefore inspire and inform new and better actions, building from already existent examples. In this sense, even highly context-specific interventions can generate valuable lessons (EEA, 2021).

The best practices presented in this chapter are drawn from a selection of **four European initiatives** that demonstrate how NbS can be successfully implemented to support sustainable and resilient urban development, by acting on micro- and meso-scales. The focus on European cases ensures a degree of **comparability in terms of climatic conditions, urban**

structures, and planning cultures, thereby strengthening the relevance of the lessons for similar contexts.

The presented review intentionally covers diverse project scales, different NbS typologies, a broad range of environmental and social challenges, and differentiated geographical and microclimates conditions. The geographic location of the four best practices implies two different climatic classes, as defined by the updated **Köppen-Geiger climate classification** (Kottek et al., 2006): Paris, Bristol, and Copenhagen all share the warm temperate oceanic climate (**Cfb**); while Barcelona is characterized by the warm temperate mediterranean climate (**Csa**).

The main climate hazards tackled by the selected cases include flooding and drought, soil impermeabilization, heatwaves and UHI effect, water stress and management, social inclusion, health, and well-being. Together, these projects offer a robust foundation for understanding how NbS can be designed, implemented, and adapted to support future urban scenarios across the European context.

Figure 34 – Geographical disposition of the selected case studies (iStock site; author's production).

Detected urban challenges:
- Heat stress
- Air and noise pollution
- Water management issues and scarcity
- Lack of access to quality green spaces
- Social inequalities

Year of implementation: 2017 onward
Site area: urban districts with no GI
Main objective: reshape urban landscape, improve livability, enhance citizens' access to green space

The Superblocks (Superilles) program was developed as a comprehensive urban transformation strategy aimed at improving environmental quality, public health, and social equity, and to try and respond to the pressing CC-related events that are affecting the citizens. It stands out as a well-designed, inclusive, and carefully monitored strategy that demonstrates how urban morphology can be leveraged as a framework for NbS clustering.

The **main objectives** of the Superblock program include the expansion of green infrastructure, the reduction of private motorized traffic, and the explicit integration of equity considerations into planning and design processes, reclaiming public spaces for pedestrians, cyclists, and community uses (Fig. 35). By **limiting car circulation** within superblocks and prioritizing active mobility, large portions of street space are freed for new green elements, permeable surfaces, and social activities. This transformation allows streets and intersections to function as multifunctional public spaces rather than traffic corridors. From an environmental perspective, the program addresses heat stress by **increasing tree canopy cover**, shading, and surface reflectivity. Asphalt surfaces with very low solar reflectance are progressively replaced by lighter, more reflective materials and permeable pavement (Fig. 36). As a result, shaded areas are significantly expanded, particularly in squares and intersections, contributing to lower surface and air temperatures during heatwaves (Fig.

37). The increase in permeable surfaces also improves stormwater infiltration and reduces runoff pressure on the sewer system, helping to mitigate flooding during heavy rainfall events.

By being careful of **multiplying the natural areas** within the built-up areas, the program has also launched a city-wide network of "**climate shelters**". These spaces – equipped with shade, seating, and water fountains – provide refuge during extreme heat events and can offer a resting area, especially for elderly people and children.

Social equity and inclusion are also central to the program's design. Participation has been embedded throughout planning, implementation, and monitoring phases, with particular attention paid to the needs of underrepresented groups. Issues related to gender, age, disability, and safety are explicitly addressed, resulting in more walkable, accessible, and secure public spaces. At the same time, the city has sought to mitigate potential negative effects such as gentrification by considering impacts on local commerce and residential stability.

In neighborhoods such as Sant Antoni, car use decreased significantly following implementation, accompanied by notable reductions in nitrogen dioxide and particulate matter concentrations. Noise levels have also declined, while street safety has improved due to lower traffic speeds and volumes (Fig. 38). These changes have encouraged more active lifestyles and increased the diversity of activities taking place in public space, ranging from play and social interaction to walking, shopping, and informal recreation.

The city's long-term vision foresees the expansion of the Superblocks model across Barcelona through the creation of a **network of green corridors connecting neighborhoods** and reorganizing street hierarchies (ClimateAdapt1; Report on Superilles).

Restructuring the street grid and embedding multiple green and mobility-related interventions, makes this project a relevant reference for approaches that seek to move beyond stand-alone measures toward integrated, morphology-sensitive NbS implementations.

Figure 35 – Graphic schematizations showing how a public space inside the Sant Antoni district in Barcelona has been repurposed from a simple road intersection to a viable public green space. The architects utilized a specific graphic pattern, as an expedient to draw and characterize the outside space. The first one on the top represents the top view, connecting diverse blocks, while the second one on the bottom is a detailed axonometric view of the crossroad (https://www.archdaily.com/938244/superblock-of-sant-antoni-leku-studio/5ea20830b35765254e000025-superblock-of-sant-antoni-leku-studio-photo?next_project=no).

Figure 36 – Photo of one of the streets that have been permeabilized troughout the project in the St. Antoni's district, by de-paving the asphalted surfaces and adding infiltration green areas and trees (https://www.barcelona.cat/surveyfotografic/en/project/superilla_poblenou.html).
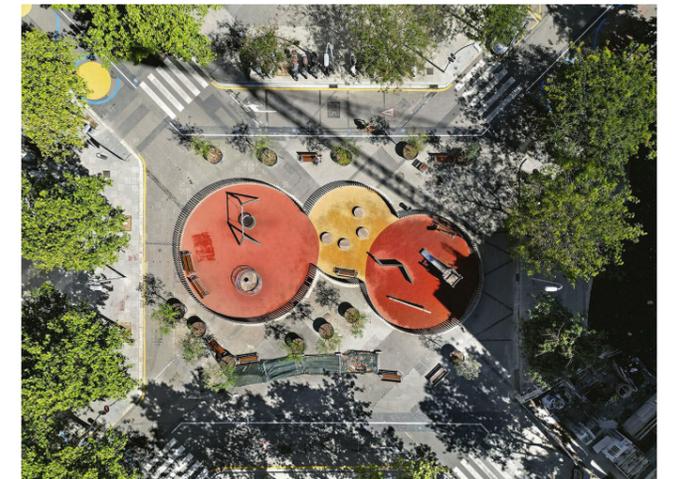

Figure 37 – Aerial photo of an internal squares that has been created in the St. Antoni's district, improving permeabilization, street safety and access to recreational spaces (https://www.barcelona.cat/surveyfotografic/en/project/superilla_poblenou.html).

Figure 38 – Photo on one of the collective spaces that has replaced a classic crossroad in the St. Antoni's district (ClimateAdapt1).

Detected urban challenges:

- Heat stress
- Flood risk
- Limited availability of green spaces
- Air and noise pollution
- Social inequalities

Year of implementation: 2018 onward
Site area: schoolyards in dense areas
Main objective: address heat stress in dense urban areas, improve public health, well-being, and knowledge building

The OASIS Schoolyards program was developed within the broader Paris Resilience Strategy as a climate adaptation and social inclusion initiative, aimed at **supporting the most vulnerable groups**, such as childrens, elderly people, and other socially fragile groups. The project is based on a simple but strategic observation: schoolyards are evenly distributed across the city and collectively represent a large amount of sealed surface. By transforming these spaces into green, permeable, and shaded environments, the program introduces a **network of small-scale "cool islands"** embedded within the dense urban fabric.

The program was initially tested through a **pilot phase**, involving ten schoolyards of different educational levels (Fig. 39). The selection of pilot sites was based on a combination of social, environmental, and technical criteria, including exposure to heat stress, neighborhood vulnerability, and feasibility of public access. An important spatial discriminator was that the regenerated space could be publicly accessible from the street, so that the intervention would benefit also other citizens.

The primary objective of the program is to **mitigate heat stress** by reducing surface and air temperatures at the local scale, while simultaneously improving stormwater management through increased infiltration and temporary water storage (Fig. 40). Beyond environmental goals, the project aims to **enhance public health and well-being**, provide healthier learning environments for students, raise awareness of climate risks, and strengthen social cohesion by opening schoolyards to local communities outside school hours.

To achieve these goals, schoolyards are redesigned through a **combination of NbS**. Interventions include the removal of asphalt and impermeable materials, the introduction of trees, lawns, gardens, and orchards, and the use of light-colored, low-carbon, and porous ground substrates that reduce surface temperatures (Fig. 41). Rainwater is reused to enhance evaporative cooling and support vegetation, while green walls and roofs, shaded structures, and selected technical installations contribute to the overall cooling strategy (Fig. 42). Together, these measures function as integrated NbS clusters rather than isolated interventions.

A defining feature of the OASIS program is its strong participatory approach. Students, teachers, school staff, and local stakeholders were actively involved in the co-design process through workshops and consultations (Fig. 43), fostering local ownership and environmental awareness. This inclusive governance model contributed to the success of the pilot phase and to the program's subsequent expansion. By 2022, more than 75 schoolyards had already been transformed, with the city aiming to further upscale the initiative through a **standardized yet adaptable methodology**.

This program demonstrates how small-scale, distributed NbS interventions can collectively address multiple urban challenges and support a wide variety of societal needs inside the urban realm. While each schoolyard operates at a local level, together they form a city-wide network of cooling, permeable, and socially inclusive spaces (Fig. 44). This makes this program highly transferable to other European cities facing similar climatic and morphological constraints, particularly where dense urban fabrics limit the availability of large green areas. Nevertheless, it is important to be aware that trade-offs may arise, such as additional maintenance costs, security requirements, or residents' disturbance due to childrens' noise (ClimateAdapt2; Oppla1; Report on OASIS).
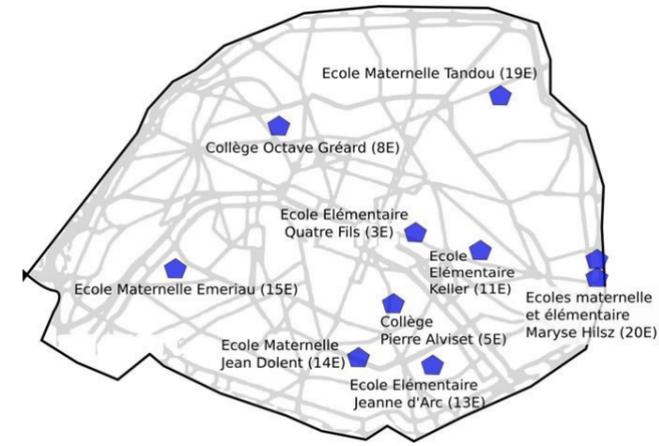

Figure 39 – Spatial positioning of the ten first implemented OASIS pilots (ClimateAdapt2).

Figure 42 – Shading structures adopted in the OASIS n. 16 in the Ecole Thionville, 19arr (Oasis Site).
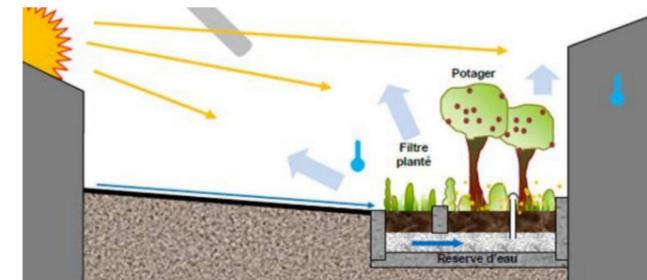

Figure 40 – Graphic schematization of the functioning of the water collection and retention system applied in the schoolyards (Oppla1).

Figure 41 – OASIS n. 12 in the Ecole Jenner, 13arr. (OASIS Site).

Figure 43 – OASIS n. 12 in the Ecole Keller, 11arr (Oasis Site).

Figure 44 – Illustration of one of the schoolyards, by Gaetan Amossé (https://www.arep.fr/en/our-projects/oasis-schoolyards/).

Detected urban challenges:
- Flood risk
- Water management and quality problems
- Limited availability of quality green spaces
- Biodiversity loss

Year of implementation: 2015
Site area: ex post-industrial wasteland with former gas works, next to the harbour edge
Main objective: regenerating an underused brownfield, by addressing water-related concerns

The regeneration of Bristol Harbourside, formerly known as Canon's Marsh, represents a large-scale transformation of a post-industrial waterfront into a mixed-use urban district combining houses, cultural functions, public space, and green-blue infrastructure. Historically at the core of Bristol's maritime economy, the area fell into decline following the closure of commercial docks in the 1970s, leaving behind underused warehouses and fragmented public spaces. The regeneration project is part of a bigger intervention and sought to reconnect the city center with its floating harbour while redefining the waterfront as a socially active and environmentally responsive urban environment. Guided by a masterplan (Fig. 45) that met the linear morphology of the harbour edge, the project integrates new buildings, public spaces, and landscape systems within the spatial constraints of the historic docklands. Although not explicitly framed as an NbS approach, the regeneration incorporates a wide range of **green and blue interventions** that collectively address water management, biodiversity enhancement, and public well-being. These measures operate in close relationship with the waterfront form, demonstrating an implicit morphology-driven aspect, given by the harbour itself (Fig. 46).

A central component of the project is the **redesign of the public realm along the harbour**. A network of promenades, public squares, and tree-lined routes improves access to the water and strengthens visual and physical connections between the city and the waterfront. Previously inaccessible areas, including parts of the historic Harbour Walk (Fig. 47), have been reopened, contributing to a continuous and legible public space system, that supports everyday social activities while reinforcing the cultural identity of the area.

NbS interventions are distributed across the district and function as interconnected elements rather than isolated features. Green roofs and an extensive living wall contribute to microclimatic regulation within a dense built environment. SuDS collect and convey rainwater from rooftops and paved areas trough visible green strips and vegetation trenches alongside the promenade. Buoyant cane strips are also adopted to infiltrate the rainwater before it reaches the harbour (Fig. 48), simultaneously improving water quality and creating new aquatic habitats. Together, these measures increase infiltration, reduce runoff, and enhance biodiversity within the urban waterfront context.

The regeneration also emphasizes **accessibility and active mobility**. Walkways and pontoons integrated alongside the reed beds allow residents and visitors to experience the waterfront ecology closely, while investments in cycling and pedestrian infrastructure have encouraged shifts away from car use. By integrating newly built housing, offices, and cultural institutions, a more active environment perfuses the district and attracts a diverse range of users throughout the day. Social and cultural functions play an important factor for ensuring a positive outcome of the entire project: Involving local communities as well as artists and ecologists, was an integral part to ensure the integration of the different sectors (Grant Associates Site; Oppla2).

Overall, the Bristol Harbourside regeneration illustrates how multiple NbS typologies can be integrated within a waterfront morphology to support urban regeneration objectives. While urban morphology is not explicitly defined in the project description, spatial constraints imposed by the harbour system clearly shape the selection and combination of interventions.

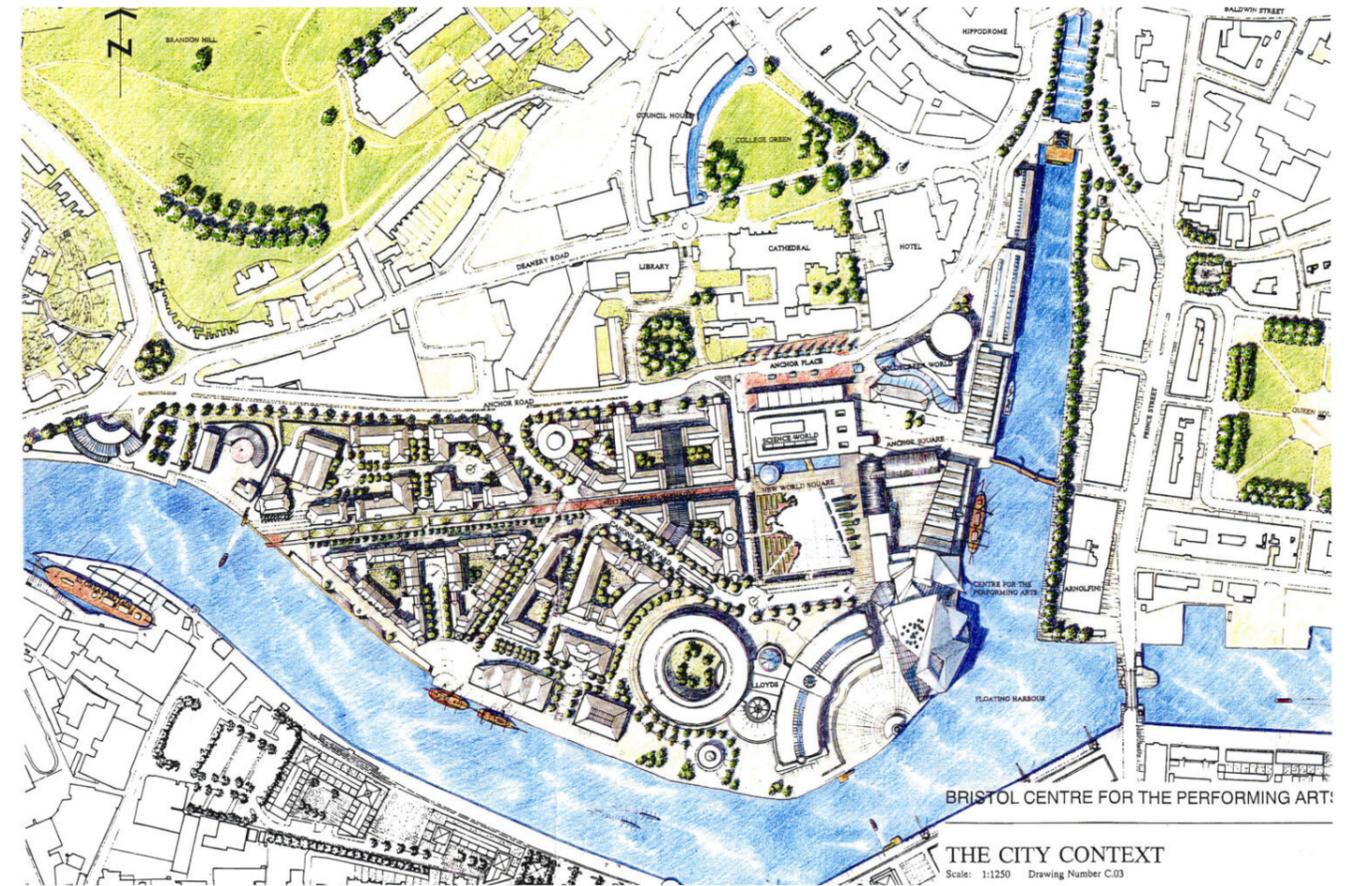**Figure 45 –** Masterplan illustration of the Bristol Harbourside new project, by the AlecFrenchArchitects (AlecFrenchArchitects Site).
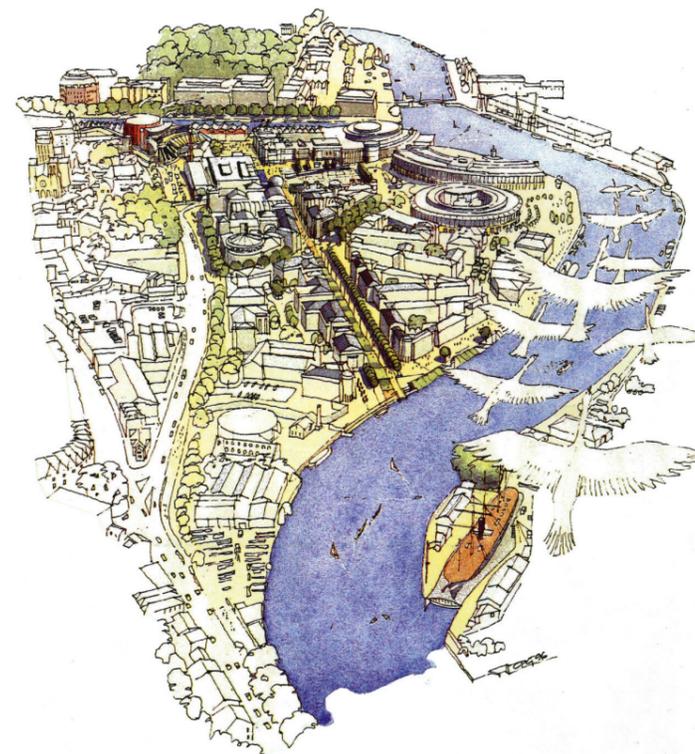

Figure 46 – Graphical aerial view of the regeneration project, by the AlecFrenchArchitects (AlecFrenchArchitects Site).

Figure 47 – New promenade created as the core riqualification part of the project (OASIS Site).

Figure 48 – Buoyant cane strips along the promenade (Oppla2).

Detected urban challenges:
- Flood risk
- Water management
- Limited availability of quality green spaces
- Biodiversity loss

Year of implementation: 2013-2015
Site area: public square within dense urban fabrics
Main objective: reshaping urban landscape, improve well-being and social gathering, addressing flooding and water management

Tåsinge Plads is an example of site-specific NbS implementation inside an established urban fabric. The square is located at the center of Copenhagen's first climate-resilient neighborhood, in the dense residential district of Østerbro (Fig. 49). Conceived as a multifunctional public space, the square addresses the increasing frequency of heavy rainfall events while simultaneously providing a green, socially active environment within a compact urban fabric. Rather than concealing water infrastructure underground, the project makes **rainwater management visible, experiential, and educational**, turning a former asphalted area into a recognizable green landmark for the neighborhood.

The project responds primarily to cloudbursts and sewer overload by retaining, delaying, and infiltrating rainwater locally. Through a carefully shaped topography, the square is organized into a sequence of elevated and lower areas that guide water flow to the infiltrating part while supporting diverse uses. Raised, sun-oriented slopes provide dry and comfortable spaces for sitting, socializing, and playgrounds, while lower areas function as rain gardens and temporary retention basins during storm events, significantly reducing pressure on the sewer system (Fig. 50). From a spatial perspective, Tåsinge Plads exemplifies how urban morphology and NbS can be tightly interwoven. The design combines hard urban elements – such as paved areas and defined circulation pads – with "wild" vegetation

zones, creating a gradient from structured public space to more natural, biodiverse environments. Sealed surfaces were removed and replaced with permeable soils and diverse planting, allowing vegetation to thrive according to variations in sunlight, soil conditions, and moisture levels. Rainwater collected from surrounding roofs is stored in underground tanks and reused for irrigation and play, while surface water allows visible channels toward vegetated basins. Sculptural elements such as "water drops" and rain parasols (Fig. 51) collect, store, and release water in playful ways, encouraging interaction and helping users understand the logic of the **urban water cycle**. At the same time, polluted runoff from road surfaces is treated separately through planted swales and filtration layers before being safely discharged, ensuring environmental protection.

Beyond its technical performance, Tåsinge Plads functions as a social and ecological promoter. The square supports a wide range of everyday activities – resting, walking, cycling, playing, and informal gatherings – while offering both sunny and shaded areas (Fig. 52). The vegetation strategy emphasizes biodiversity and seasonal variation, with plant species selected to tolerate fluctuating moisture conditions, road salt, and urban stressors.

A defining feature of the project is its strong participatory process. Long before construction, residents were actively involved through temporary installations, events, and testing phases that allowed different design options to be explored and discussed. This incremental and inclusive approach fostered local ownership and ensured that the final design responded to both technical requirements and community expectations (Fig. 53).

By aligning topography, vegetation, water systems, and social uses within a dense urban morphology, the project illustrates the potential of small-scale, integrated NbS pockets to address climate adaptation challenges while enhancing everyday urban life (Klimavarter; Landezine).

Figure 49 – Masterplan map of the area, showing how the project intends to deploy the square (Klimavarter).

Figure 52 – Picture of citizens enjoying the features installed in the square (Klimavarter).
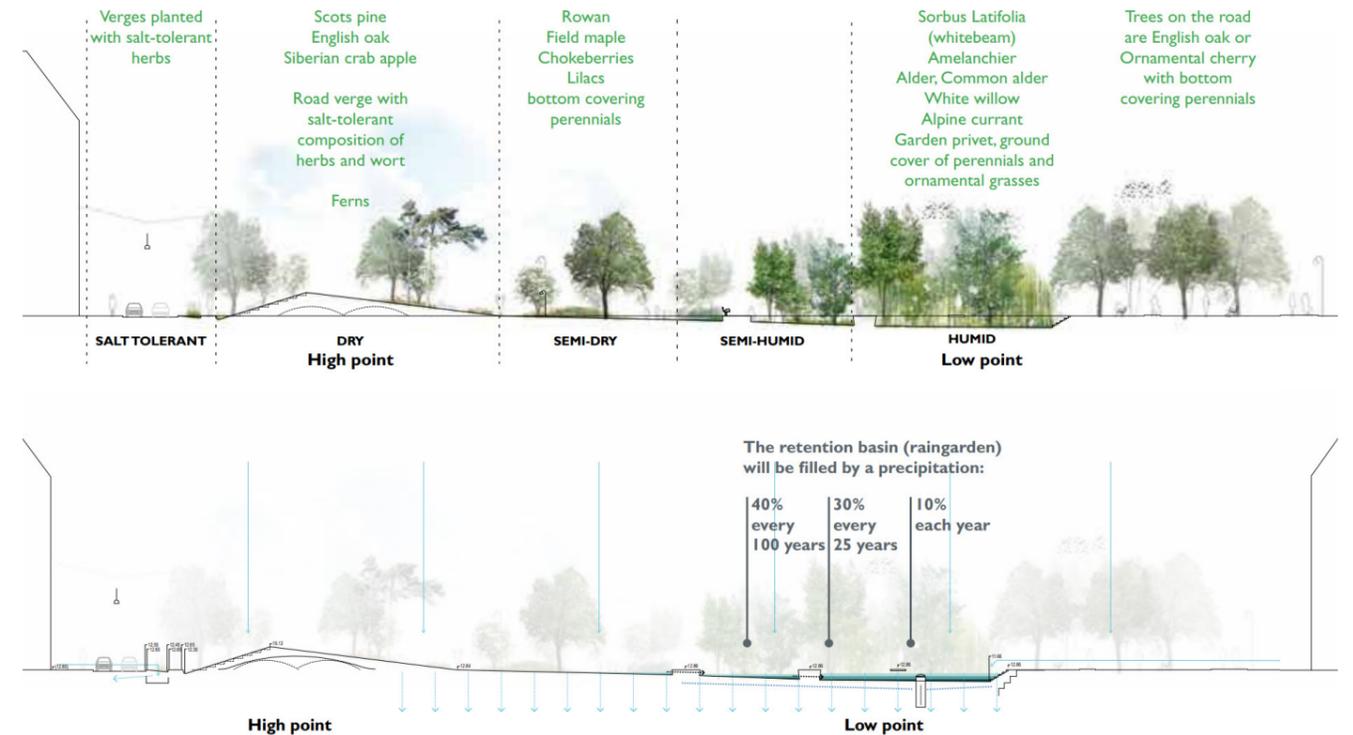
Figure 50 – Territorial sections of the square showing how the different soil gradients contribute to an improved water management. A wide variety of tree species has been selected to adapt to diverse humitidy conditions, since parts of the squares are designed to be submerged for longer periods of time (Klimavarter).

Figure 51 – Schematization of the functions of the design solutions implemented to help gather rainwater and infiltrate it (Landezine).

Figure 53 – Aerial view of the new square, showing how the project contributes to the characterization of the area (Urban water).

Taken together, the four case studies – Barcelona Superblocks, Paris OASIS Schoolyards, the Bristol Harbourside regeneration, and Tåsinge Plads in Copenhagen – demonstrate how NbS can be adopted for a myriad of different reasons in very diverse contexts, they can be implemented to reach climate adaptation, environmental quality, and social well-being. Despite their differences in scale, context, and implementation approach, all four cases share a common characteristic: **they combine multiple interventions into spatially complex and coherent systems rather than relying on isolated measures**. This confirms the growing recognition of NbS as multifunctional and systemic tools capable of delivering extremely assorted co-benefits.

Simultaneously, the comparison reveals significant differences in how explicitly the relationship between urban form and NbS is considered. In **Barcelona**, the Superblocks program is grounded in a clear morphology-driven strategy, **using the existing street grid and block structure as a framework for clustering greening, mobility, and social interventions**, which are easily replicated through the city. In **Paris**, the OASIS Schoolyards program adopts a **distributed, micro-scale approach, embedding small NbS pockets within dense urban fabrics** through the reuse of schoolyards. Tåsinge Plads in **Copenhagen** illustrates how a single **public space, shaped by topography and water flows, can integrate stormwater management, urban nature, and everyday social life** within a compact neighborhood. On the other hand, the **Bristol** Harbourside regeneration demonstrates how **NbS clusters can emerge through site-specific design responses to natural or infrastructural constraints**, even in the absence of an explicit morphology-based framework.

This comparative analysis highlights a key limitation of current practice: while NbS are often implemented in ways that are implicitly responsive to urban morphology, these relationships are rarely formalized, compared, or translated into transferable decision-making tools. As a result, the selection and combination of NbS frequently depend on local expertise, design intuition, or project specific conditions, making it difficult to replicate successful strategies across different urban contexts.

The case studies therefore provide both inspiration and evidence for the need of a structured, morphology-sensitive framework capable of supporting early-stage decision-making. They show that NbS effectiveness depends not only on the choice of individual solutions, but on how multiple interventions interact with each other and with the spatial, climatic, and social characteristics of urban form. By making these interactions explicit, a framework such as the one proposed in this thesis, can help bridge the gap between exemplary projects and systematic urban planning practice, supporting the design of NbS clusters that are adaptable, equitable, and context-appropriate across European cities.
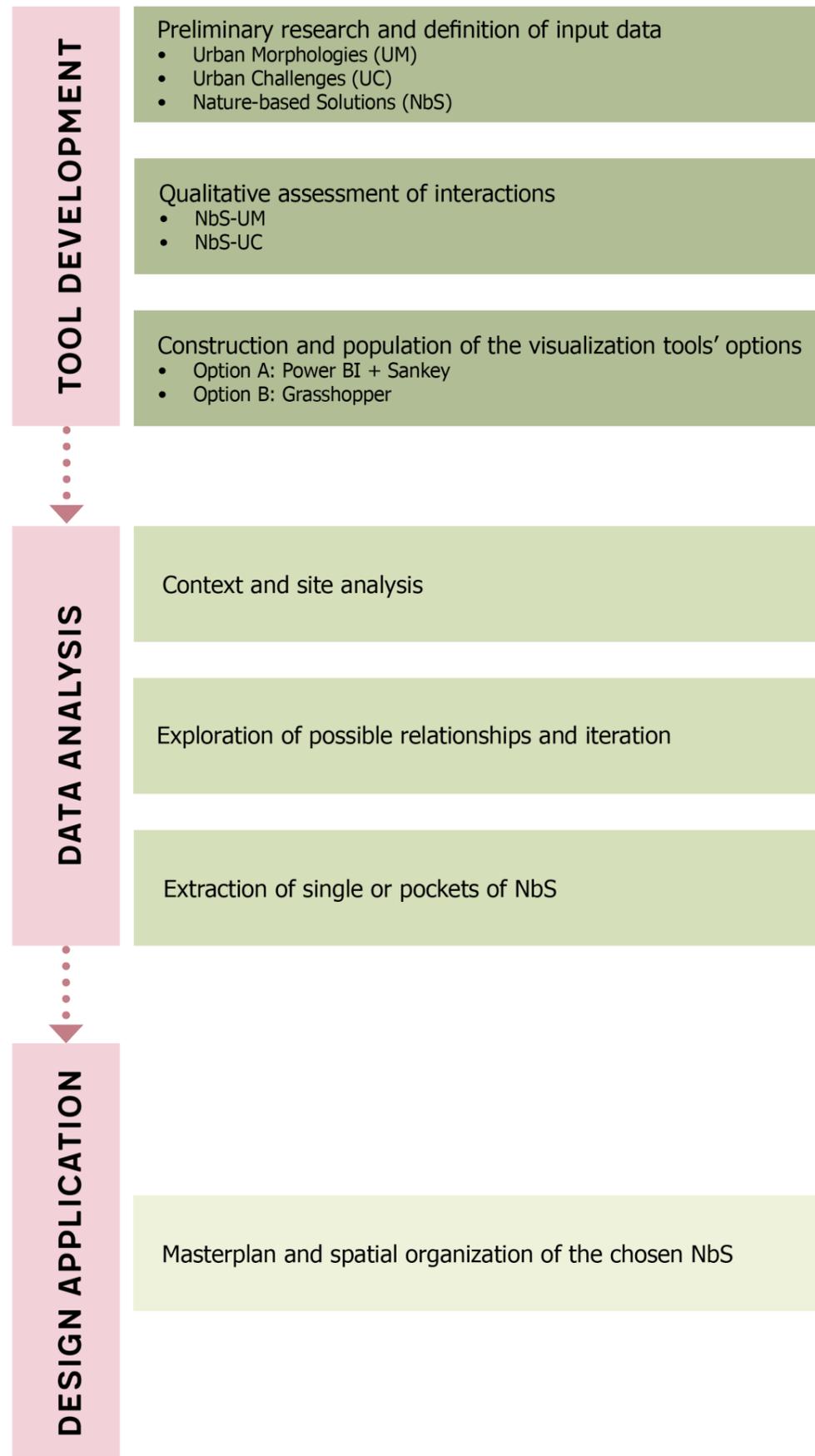
03

METHODOLOGY

TOOL DEVELOPMENT

Preliminary research and definition of input data
- Urban Morphologies (UM)
- Urban Challenges (UC)
- Nature-based Solutions (NbS)

Qualitative assessment of interactions
- NbS-UM
- NbS-UC

Construction and population of the visualization tools' options
- Option A: Power BI + Sankey
- Option B: Grasshopper

DATA ANALYSIS

Context and site analysis

Exploration of possible relationships and iteration

Extraction of single or pockets of NbS

DESIGN APPLICATION

Masterplan and spatial organization of the chosen NbS

Figure 54 – Flowchart depicting the methodology implemented within this research (Author's production).

As discussed by Sarabi et al. (2021), **decision-support tools are crucial supporters of effective NbS design** and organization, as they enable the visualization, analysis, and combination of complex spatial information in ways that are accessible to multiple stakeholders. By supporting the **exploration of alternative scenarios and the integration of diverse perspectives**, such tools can enhance collaborative planning processes and improve the quality of decision-making.

However, many existing tools remain highly specialized and difficult to use outside expert circles, limiting their effectiveness in participatory and interdisciplinary contexts. This highlights the **need for planning approaches** and methods that are both **analytically robust and accessible**, capable of considering diverse dimensions simultaneously while supporting **multi-criteria and multi-scale decision-making** (Marusik et al., 2023; Sarabi et al., 2021).

Against this background, this research aims to **propose a structured and transparent decision-support and planning tool** for visualizing the **synergistic relationships between nature-based solutions archetypes, urban morphologies, and targeted urban challenges**. This can help identify suitable intervention areas, compare alternative solutions, and assess trade-offs and synergies across urban forms, allowing parametric and iterative explorations, informed prioritization of NbS strategies in urban environments, and ultimately improved stakeholder engagement.

This approach strives to reflect a **holistic perspective** on NbS planning, to enable the combination of NbS functions with the awareness that such solutions can generate diverse effects in relation to the spatial context in which they are integrated, considering synergistically their benefits, co-benefits, trade-offs, and requirements.

The methodology adopted in this research, further explained below, was developed progressively throughout the thesis, drawing on existing studies and methodological approaches, addressing nature-based solutions, urban morphology, and climate-related urban challenges. It follows a structured, step-by-step workflow (Fig. 54), designed to be replicable and adaptable to different neighborhoods, districts, and cities across Europe.

In the following sections, this methodology is then applied to a specific case study to demonstrate **its application**: a neighborhood characterized by linear slab morphology, found in the **Mirafiori district of Turin**.

The methodology can be divided into three primary phases, which together consist of seven main steps. The first and second phases can be conducted simultaneously, to make sure that the data from the decision-support tool are coherent with the specificities of the project location.

STEP 1 – Tool development

The first step establishes the theoretical and analytical foundation of the research. It is based on an extensive literature review and a comparative analysis of existing case studies. The objective is to clarify how NbS, urban morphologies, and urban challenges are interrelated. Particular attention is given to understanding which NbS can contribute to addressing climate adaptation, mitigation, and disaster risk reduction challenges within specific urban forms, respecting their spatial constraints, to avoid maladaptation.

The outcomes of this step define the thematic framework of the thesis and are presented in the first two chapters, forming the knowledge base upon which all consequent analytical and design decisions are grounded. The elements identified through this analysis are organized into three different main operational macro-groups:

- a set of recurrent **European urban morphologies** (**UM** - five elements);
- a set of **urban challenges** that can be addressed through NbS implementation (**UC** - twelve elements);
- a set of commonly applied urban **nature-based solutions** archetypes (**NbS** - eighteen elements).

Every **interaction NbS-UM** and **NbS-UC** is evaluated using a dimensional and/or color-coded scoring system to evaluate spatial suitability and capacity of addressing the challenge. The performance indicators related to each group are derived from existing Europe-wide NbS assessment frameworks and translated into **qualitative suitability scores**, enabling comparative evaluation across different NbS-morphology-challenge scenarios.

All the elements and their weighted values are translated into **two complementary visualization-based tools**, developed as comparative and interactive frameworks, but for two different targets. The first one is based on a set of 2D visualizations, including heatmaps (developed with Power BI) and a Sankey diagram, to simultaneously illustrate the threefold relationship. The second consists of a single 3D parametric matrix developed in Grasshopper, enabling interactive testing of NbS suitability through parametric logic. This framework allows for the visualization of relationships, compatibilities, and potential synergies between NbS archetypes, urban forms, and targeted challenges. In both methods, users are able to select one or more elements to visualize synergies. This step represents a methodological innovation of the thesis, as it structures complex interactions into an analytical tool that supports informed decision-making rather than prescribing fixed solutions.

STEP 2 – Data analysis

The second step focuses on analyzing and understanding the context of the case study area, recognizing that NbS must be tailored to local climatic, spatial, and socio-institutional contexts. This step is structured around three main analytical processes:

- **climatic and environmental analysis**, including local climate conditions, climate change-related risks, and relevant municipal policies (e.g., Turin's climate and adaptation strategies, and cartographic analysis);
- **urban and morphological analysis**, examining the physical characteristics of the chosen area, understanding the relationships between built vs. open spaces;
- **in situ inspection**, supported by photographic documentation and direct observation of spatial, environmental, and social conditions.

Together, these analyses provide the contextual basis that enables the identification of site-specific challenges and opportunities for NbS implementation (as shown by the combined SWOT analysis). Therefore, by interacting with the decision-support tool, it is possible to recognize suitable NbS for the desired urban context and problems observed. This step enables the exploration of the tool to highlight plausible implementation solutions through a comparative and iterative analysis of its outcomes.

By filtering and combining the different elements, it becomes possible to:

- identify individual NbS archetypes that are particularly suitable for the case study;
- explore combinations of NbS that may work synergistically, therefore defininig NbS pockets, understood as clusters of complementary solutions that produce cumulative and non-linear benefits.

This iterative process allows the assessment of different strategic pathways and supports an easier definition of combinations of solutions that are able to address diverse challenges simultaneously.

STEP 3 – Design application

The final step translates the analytical outcomes into a design-oriented output.

Based on the selected NbS (pockets), this research proposes a preliminary design for a linear slab morphology located in the Mirafiori district. Two main **NbS pockets** are created and implemented, based on the 3D matrix analysis: one primarily addressing heat stress, and the other focusing on urban water management. The spatial distribution of such interventions is organized on a **masterplan level**, illustrating how the selected NbS can be integrated into the existing urban fabric.

04
RESULTS AND APPLICATION

4.1.1 Preliminary research and definition of input data

Building on the literature review, this thesis translates existing knowledge into an operational analytical framework. As stated in the previous chapters, to enable the creation of the tool, these three main macro-groups are defined as the three comparison elements of the tool:

1. urban morphology types (UM);
2. urban challenges (UC);
3. nature-based solutions archetypes (NbS).

It is now necessary to define a finite set of elements for each group in order to create the base reference to allow establishing interconnections and comparison between them.

Set of urban morphologies

As a first step to create the tool it is necessary to **define a specific group of recurrent urban morphology types commonly found in European cities**. Rather than aiming for an exhaustive typological representation, the focus is set on a limited number of representative urban forms, that can be clearly identified through measurable spatial characteristics. These typologies are used as analytical categories to investigate how different urban patterns influence microclimatic conditions, environmental vulnerability, and the suitability of NbS at the building, block, neighborhood, and district scale.

The classification is mainly based on Salat's work (2011) on European urban form, complemented by additional literature (e.g., Bassolino et al., 2023; Lehner et al., 2019), and defines urban morphologies according to a set of form indicators, such as building footprint, height, density, and spatial arrangement. This morphometric approach allows complex urban fabrics to be abstracted into recognizable and comparable typologies, facilitating both analysis and transferability. The objective of this classification is not only to describe urban form,

but to establish a consistent framework through which different morphologies can be compared in terms of their climatic performance and their capacity to host and support NbS interventions. By reducing morphological complexity to a manageable set of types, the research creates a common ground for linking urban form, environmental challenges, and design strategies.

The set of the **five identified urban morphologies** is represented on the following page (Fig. 55). These typologies were **identified within the Mirafiori district** (Fig. 56) in order to support the selection of the final catalogue, ensuring that the proposed morphologies are representative of urban forms that can be found in a real European city such as Turin.
In addition, they informed the subsequent selection of the case study plot, which was chosen from among the various morphological elements present within the district. For each of the five morphologies included in the final UM selection, a **corresponding real urban fabric was identified within Mirafiori** (Fig. 57). Among these, the linear slab morphology was selected as the final case study area for the application of the proposed framework.
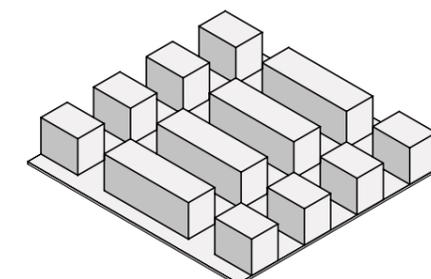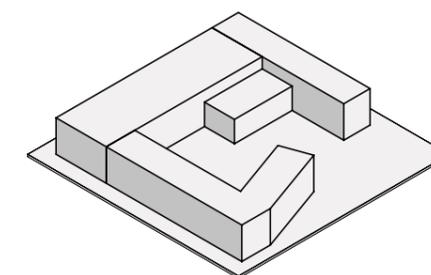
High-rise housing: Isolated towers
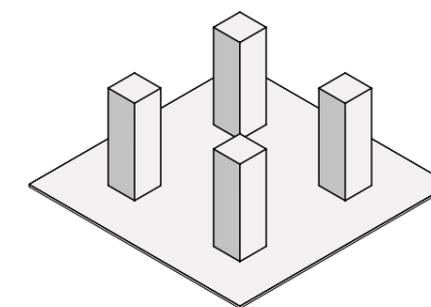
Mid-rise housing: Courtyard blocks
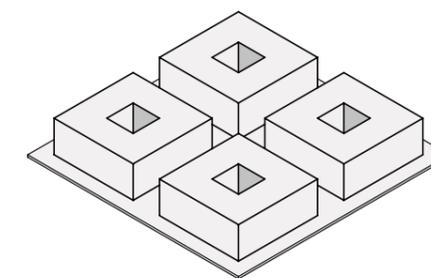
Mid-rise housing: Linear slabs

Low-rise housing: Dense village houses

Low-rise housing: Isolated individual houses
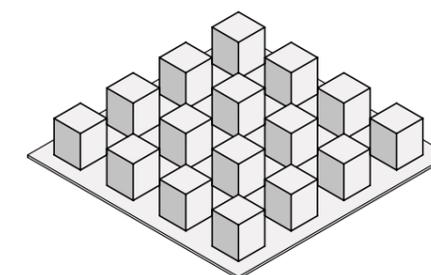
Figure 55 – Schematization of the 5 UM chosen as generic topologies to conduct the following analyses and comparisons (Author's production).

High-rise buildings: Isolated towers
Mid-rise buildings: Courtyard buildings
Mid-rise buildings: Linear slabs
Low-rise buildings: Dense village houses
Low-rise buildings: Isolated individual houses

1:30.000

UM1: High-rise isolated towers in Centro Europa
UM2: Compact courtyard blocks in Borgo Cina
UM3: Linear slabs in the INA-Casa neighborhood
UM4: Dense village housing of Borgata Mirafiori
UM5: Isolated individual housing in the Garden City

1:30.000

Figure 56 – Map illustrating the spatial disposition of the fabrics inside the Mirafiori district, corresponding to the previous morphological selection (Author's production).

90

Figure 57 – Map of the selection of five representative real urban morphologies for each of the selected urban typologies inside the Mirafiori district (Author's production).

91

UM1 – High-rise housing: Isolated towers

Figure 58 – Zenital view of the Centro Europa towers placed in the western part of Mirafiori, taken from Google Earth.
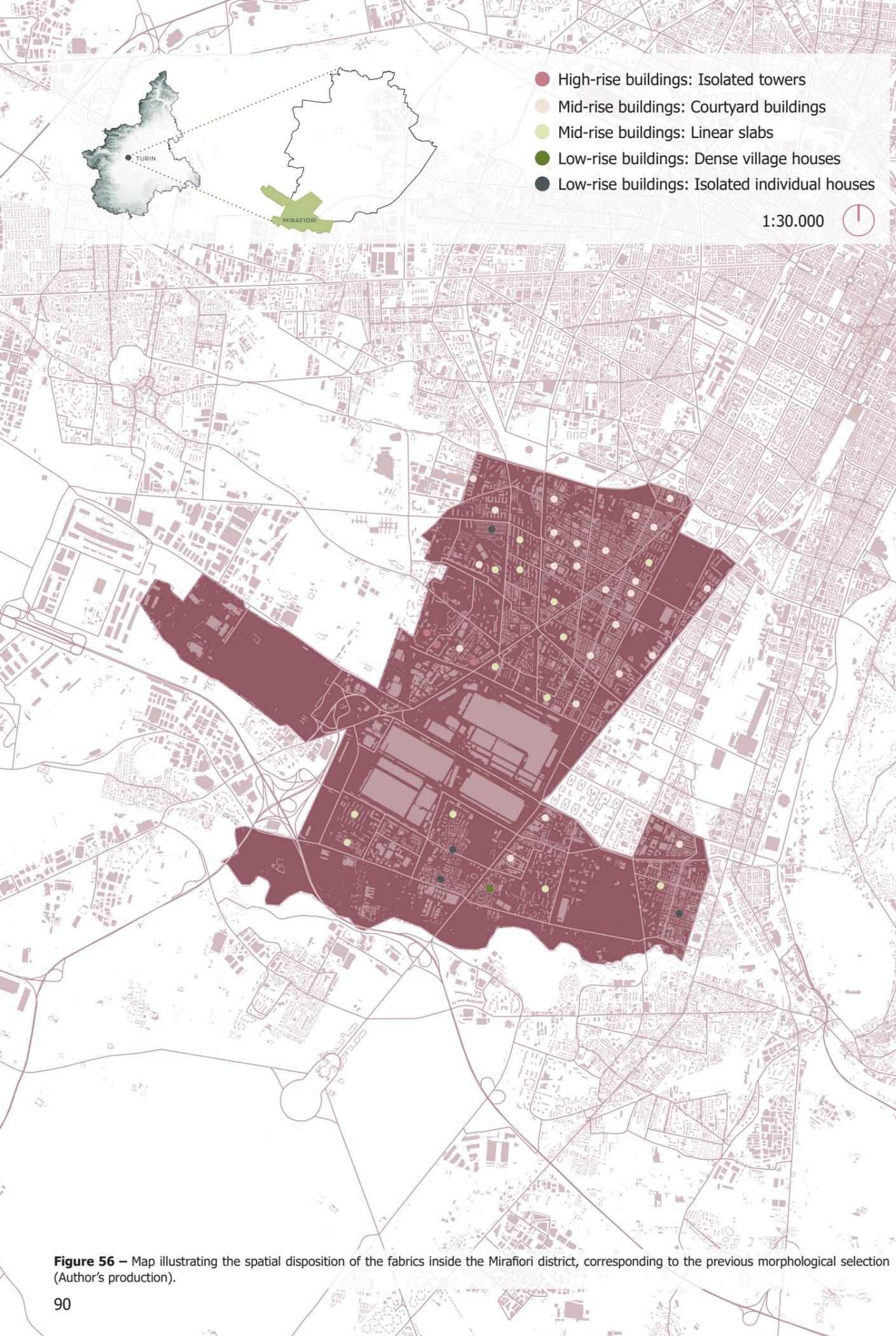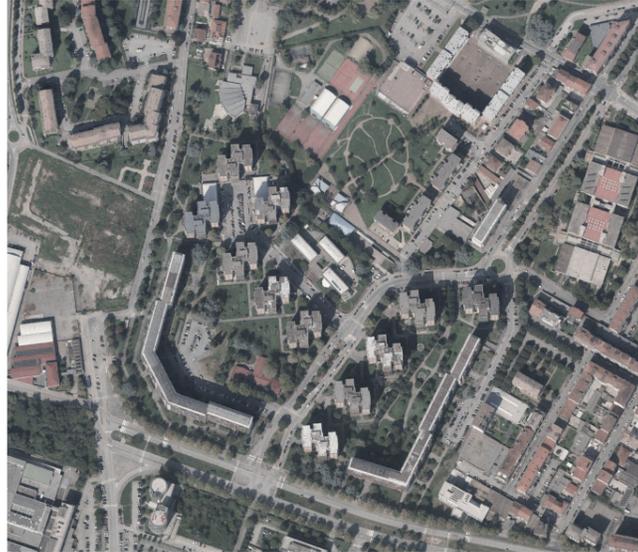
This morphology is characterized by standalone residential towers, which were constructed with prefabricated modules in the late 1960s, under a subsidized housing plan. Based on the arrangement of the buildings within the plot area, a low building density can be acknowledged, as the vertical development is favored to optimize open ground floor space. The open arrangement of the towers lets enough sun and air pass through them, allowing each cantilevered balcony to have enough exposure. The high buildings are surrounded by diverse semi-public green spaces, planted with lawn, flowers, shrubs, and trees. The accessibility occurs via internal pedestrian pathways or by car, up to the underground parking, specific to each tower (TO - Mirafiori sud).

N° OF FLOORS
10

BUILDINGS HEIGHT
h = 30 m

STREET ASPECT RATIO
H/W = 1

MAIN PROBLEMS
- Sun and wind exposure in unprotected paths
- Lack of shading
- Stormwater management issues

INVOLVED IMPACTS
- Air and water quality improvement
- Carbon sequestration
- Heat stress mitigation
- Stormwater runoff reduction
- Biodiversity enhancement
- Quality green space provision
- Mental and physical health improvement

COMPATIBLE NbS
Large- to medium-scale NbS, vertical and rooftop solutions (where possible), high potential for community-driven interventions, possibility for bigger ecological interventions

| PLOT SURFACES	m²	%
TOTAL AREA	72.257 m²	100%
● Buildings	15.360 m²	21%
● Impermeable surfaces	8.660 m²	12%
● Green surfaces	48.237 m²	67%
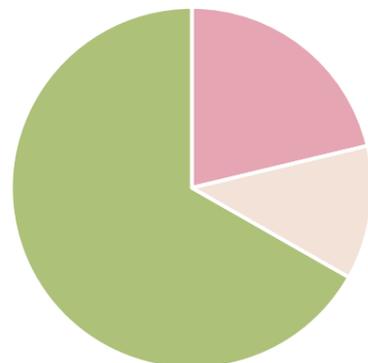
UM2 – Mid-rise housing: Courtyard blocks

Figure 59 – Zenital view of the courtyards of Borgo Cina, placed in the eastern part of Mirafiori, taken from Google Earth.

This morphology is characterized by large, compact and enclosed buildings, that creates an independent residential block. It was built in the post-war period of the late 1940s for industrial workers' families, and it is integrated into the city's urban fabric, following for its main direction the NE-SW axis. The buildings' height variability creates a less continuous perimeter and a more breathable environment, which alternates pitched-roof structures and smaller 1-floor high, flat-roofed symmetrical blocks. The outside facades are aesthetically improved by decorations and cantilevered balconies. Due to its large block-size and the relatively low height of the buildings, good sun exposure can be assured for the internal courtyard, though this urban form limits ventilation, leading to heat accumulation. The urban layout offers the possibility of introducing green spaces within the internal private courtyard: this area has been planted with lawn, shrubs, and trees. The latter are not the most suitable greening solution for this configuration, due to their dense canopies which can hinder heat dispersion. Plus, there is still possible improvement concerning the impermeabilized surfaced of the internal courtyard (TO - Mirafiori sud).

N° OF FLOORS
1, 3, 4

BUILDINGS HEIGHT
h = 3, 9, 12 m

STREET ASPECT RATIO
H/W = 0,2 - 0,7 - 0,9

MAIN PROBLEMS
- Overheating risk in the courtyard
- Need for better ventilation
- Stormwater management issues

INVOLVED IMPACTS
- Air and water quality improvement
- Heat stress mitigation
- Stormwater infiltration and management
- Biodiversity enhancement
- Noise mitigation
- Support healthier local ecosystems
- Mental and physical health improvement

COMPATIBLE NbS
Compact medium- to small-scale NbS, vertical and rooftop systems (where possible), permeable paving, storm-water oriented measures, shading for the inner courtyard, avoid cluttered greening solutions which can hinder ventilation, community-based interventions

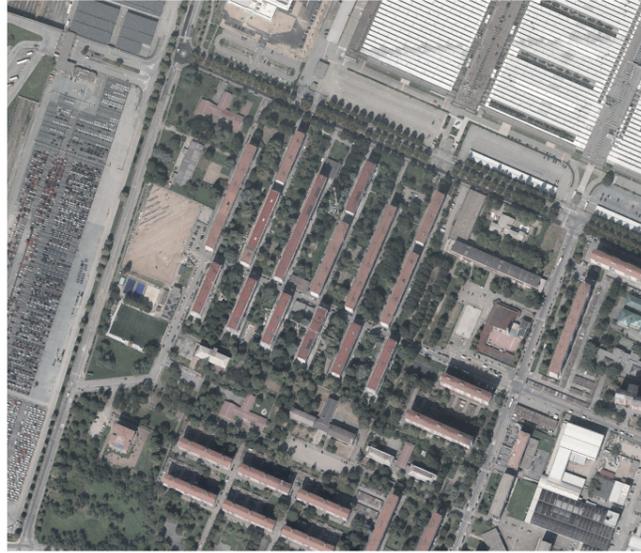| PLOT SURFACES	m²	%
Total area	72.578 m²	100%
● Buildings	18.250 m²	25%
● Impermeable surfaces	21.242 m²	29%
● Green surfaces	33.086 m²	46%
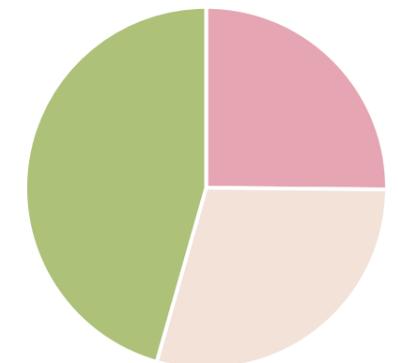
UM3 — Mid-rise housing: Linear slabs

Figure 60 — Zenital view of the slabs of INA-Casa, placed in the south-western part of Mirafiori, taken from Google Earth.

This morphology is mostly characterized by linear residential slabs, organized in regular and repetitive comb-like configuration, creating an open block, with the main dimension oriented along the NE-SW axis, very optimal for wind penetration. It was created with heavy prefabrication techniques during the 1960s under a public housing program for medium- to low-income families. The arrangement of the buildings allows internal secondary roads to connect each building with the main street axis that runs peripheral to the plot. Every slab is surrounded by semi-public interstitial green spaces, mainly planted with lawn, shrubs, and trees, which serve as multi-functional spaces: pedestrian and car circulation, social gathering areas, and car parking. The slabs are characterized by pitched roofs and internal loggias along the entirety of the longest facades, living the front and back ones blank (TO - Mirafiori sud; TO - Mirafiori nord).

N° OF FLOORS
8

BUILDINGS HEIGHT
h = 21 m

STREET ASPECT RATIO
H/W = 0,6

MAIN PROBLEMS
- Presence of localized UHI effect near the facades
- High impermeabilization of internal paths
- Underused green areas

INVOLVED IMPACTS
- Mitigation of UHI effect
- Air and quality improvement
- Carbon sequestration
- Stormwater management
- Biodiversity enhancement
- Reuse of water resource
- Reduction of building energy

COMPATIBLE NbS
Medium-scale NbS, linear and soil-based, street- and courtyard-oriented, shading amelioration for both vertical and horizontal surfaces
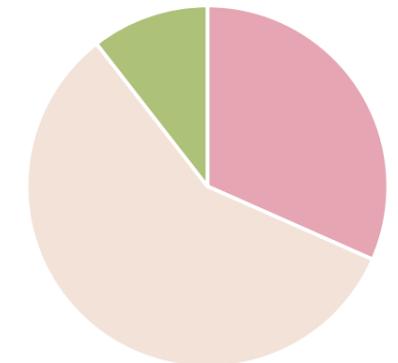
PLOT SURFACES	m²	%
TOTAL AREA	103.550 m²	100%
● Buildings	13.737 m²	13%
● Impermeable surfaces	56.953 m²	55%
● Green surfaces	32.860 m²	32%
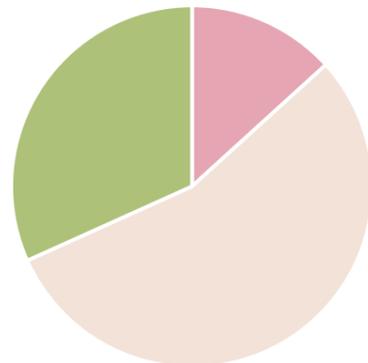
UM4 — Low-rise housing: Dense village houses

Figure 61 — Zenital view of the Borgata Mirafiori, placed in the south-eastern part of Mirafiori, taken from Google Earth.

This morphology is characterized by an agglomeration of semi-rural villas and courtyard, with a fine-grained fragmented morphology of mid-low rise buildings, arranged irregularly along narrow village roads. This fabric dates back to the 1600s as an agricultural support to the royal palace and inhabited by the farming families. The structure is the one of a traditional farmhouse, with pitched roof, and many exhibit quite large inner courtyards, often private and not visible from the street, which translates to a high building density. The street layout is predominantly narrow, short, and irregular, reflecting the building arrangement. Most streets only allow one-way vehicular passage, while several courtyards and widened areas have been repurposed into paved or unpaved parking lots. The green coverage allowed by this urban settlment is mainly provided by various, fragmented, inner courtyards and small backyards, which also constitute the block's primary open spaces, while the front gives directly on the street (TO - Mirafiori sud).

N° OF FLOORS
1, 2, 3

BUILDINGS HEIGHT
h = 3, 6, 9 m

STREET ASPECT RATIO
H/W = 0,5 - 1 - 1,5 (varies widely)

MAIN PROBLEMS
- Low availability of space
- High impermeability
- Stormwater runoff
- Heat accumulation due to compact form

INVOLVED IMPACTS
- Mitigation of heat stress
- Water quality improvement
- Stormwater runoff reduction and infiltration
- Enhancement of propery values

COMPATIBLE NbS
Small-scale NbS, distributed, low-impact ecological interventions, vertical solutions, private-based, water management and reuse-oriented measures

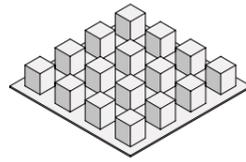| PLOT SURFACES	m²	%
Total area	29.274 m²	100%
● Buildings	9.258 m²	32%
● Impermeable surfaces	16.935 m²	58%
● Green surfaces	3.081 m²	11%

Figure 62 – Zenital view of the Garden City, placed in the northern part of Mirafiori, taken from Google Earth.

This morphology is characterized by compact row houses and small detached villas, arranged in a medium-to-low density and open layout, featured with small pitched roofs. This system was developed between the 1950s and '70s to provide improved living standards and services to industrial workers. This configuration was created to prioritize sunlight, ventilation, and privacy. The disposition of the internal grid rigidly follows the N-S axis, following the most appropriate orientation for this latitude. Each house has its own private garden, usually surrounding it or as a back-yard, but in large part they have been impermeabilized. The street network is typically residential, with larger, tree-lined roads at the outskirts of the block, so each house has easy access to them, while the internal connections are two-ways streets. No connections are foreseen between the internal private open spaces (TO - Mirafiori sud; TO - Mirafiori nord).

N° OF FLOORS
2, 3

BUILDINGS HEIGHT
h = 6, 9 m

STREET ASPECT RATIO
H/W = 0,5 - 0,7

MAIN PROBLEMS
- High fragmentation of green spaces
- Possible water scarcity stress
- Lack of shading

COMPATIBLE NbS
Distributed medium- to small-scale NbS, either through individual or community-based initiatives (e.g., private or shared rain gardens, or small vertical constructed wetlands), possibility for new technologies implementations, low-impact ecological interventions

INVOLVED IMPACTS
- Air and quality improvement
- Stormwater management
- Biodiversity enhancement
- Reuse of water resource
- Reduction of building energy consumption
- Enhancement of property values
- Provision of aesthetic values

PLOT SURFACES	m²	%
TOTAL AREA	64.535 m²	100%
Buildings	19.035 m²	30%
Impermeable surfaces	24.358 m²	38%
Green surfaces	21.124 m²	33%
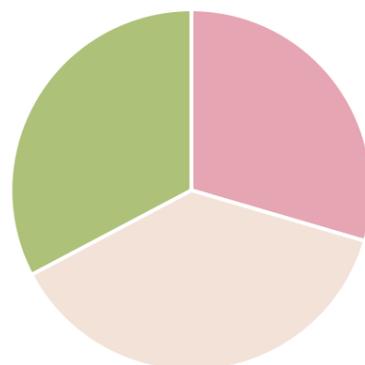
Set of urban challenges

After defining the set of urban morphologies, the second operational step focuses on identifying the urban challenges addressed in this research. The challenges considered are intentionally limited to those that can be effectively mitigated or alleviated through the adoption of NbS; this selection does not aim to provide an exhaustive overview of all the challenges that can affect urban areas.

Therefore, the proposed set reflects the most relevant environmental and socio-spatial issues currently threatening cities. While this research does not explicitly assess ecosystem services, the ES framework contributed to guide the selection processes by clarifying which urban problems can be addressed through NbS.

In total, twelve key urban challenges are identified and described here, together with relevant indicators and potential nature-based approaches that could help tackle them, following definitions outlined in the literature (e.g., GreenUP, 2018; Raymond et al., 2017a).

Absence or limited access to affordable fresh food

Limited access to fresh, affordable food affects physical health, social equity, and local resilience. In many urban areas, especially dense or disadvantaged neighborhoods, residents face long distances to food outlets offering nutritious products, while reliance on processed food increases. This challenge is also related to increasing urban population additioned to broader loss of productive land and disconnection between cities and food systems, which can lead to insufficient quantity and quality of food resources.

Indicators commonly include distance to fresh food outlets, presence of food deserts, share of household income spent on food, and availability of local food production spaces.

NbS actions include urban gardens, community farms, rooftop agriculture, edible landscapes, and agroforestry systems, which can improve access to fresh food, strengthen local economies, and enhance social cohesion (GreenUP, 2018; Raymond et al., 2017a).

Air pollution

Urban air pollution poses serious risks to human health, contributing to respiratory and cardiovascular diseases, premature mortality rates, and reduced quality of life. It is exacerbated by traffic, industrial activities, and high urban temperatures, which favor the formation of secondary pollutants.

Indicators include concentrations of $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and health-related indicators such as hospital admissions or premature deaths.

NbS actions such as urban trees, green roofs and walls, parks, and attention to preserving the existing green infrastructure can improve air quality by capturing pollutants, reducing temperatures, and increasing oxygen levels, while also delivering co-benefits like shading, stormwater management, and biodiversity support (GreenUP, 2018; Raymond et al., 2017a).

Biodiversity loss

Urbanization often leads to habitat fragmentation, species decline, and reduced ecological connectivity. Biodiversity loss weakens ecosystem functioning and reduces the capacity of cities to deliver essential ecosystem services.

Indicators include green space per capita, species richness, habitat connectivity, presence of native species, and ecological corridor continuity.

NbS actions focus on creating, restoring, and connecting green and blue infrastructure, such as urban forests, pocket parks, green corridor, rain gardens, and façade greening, combined with participatory management and biodiversity-sensitive design (GreenUP, 2018; Raymond et al., 2017a).

Extreme heat

Extreme heat is one of the most critical urban climate risks, amplified by dense built environments, impervious surfaces, and lack of vegetation. Heat stress, heatwaves, and the UHI phenomenon affect public health, energy demand, and urban livability.

Indicators include mean and peak air temperatures, number of tropical nights (>20°C) and hot days (>35°C), surface temperatures, and thermal comfort indices, such as PET.

NbS actions include increasing tree canopy cover, green roofs and walls, vegetated open spaces, and water features, which cool cities through shading and evapotranspiration and reduce heat-related health risks (GreenUP, 2018; Raymond et al., 2017a).

Flood risk

Urban flooding results from intense rainfall, sealed surfaces, insufficient drainage capacity, and altered hydrological cycles. Due to CC-related impacts, rain events are turning into more frequent hail storms or storm surges, placing urban infrastructure and population at risk.
Indicators include runoff volumes, flood frequency, inundation extent, sewer overflow events, and exposure of critical infrastructure.
NbS actions include SuDS, as rain gardens, bioswales, permeable pavements, urban wetlands, retention ponds, restored floodplains, vegetated riverbanks, and bioretention cells, which enhance water infiltration, retention, delay runoff, and reduce flood impacts (GreenUP, 2018; Raymond et al., 2017a).

Greenhouse gas emissions

Cities and building constructions are major contributors to GHG emissions, which worsen air quality and environmental conditions both globally and locally. Aside from energy-intensive activities and industries (e.g., building construction), even inefficient building performances that generate high energy demand for cooling or heating necessities are part of the problem. Dense urban form and lack of vegetation further worsen cooling needs.
Indicators include building energy consumption, CO_2 emissions, cooling and heating demand, and the share of emissions offset or sequestered by vegetation.
NbS actions can range from increasing urban vegetation for carbon sequestration, integrating green roofs and facades to improve insulation and reduce energy demand, to including passive building strategies, and supporting circular construction and material reuse (GreenUP, 2018; Raymond et al., 2017a).

Lack of social cohesion

Social fragmentation, unequal access to resources, and weak community ties undermine urban resilience. Environmental burdens often disproportionately affect vulnerable populations, as a result of poorly planned and designed interventions, executed without a cross-sectoral participation of a variety of stakeholders and the local population.
Indicators include social participation rates, trust and neighborhood attachment, perceived safety, inclusiveness, and access to shared public spaces.
NbS actions emphasize participatory design, actively engaging excluded or under-represented social groups, co-management of green spaces, community gardens, inclusive parks, and governance models that foster social interaction, knowledge sharing, and empowerment (GreenUP, 2018; Raymond et al., 2017a).

Limited access to quality green and recreational spaces

Access to well-designed and integrated green and recreational spaces is essential for providing better physical and mental health, social interaction, and quality of life. In many cities, green spaces are unevenly distributed among population groups and parts of the urban space, poorly connected, or not properly designed.
Indicators include green space accessibility (distance or travel time), area per capita, diversity of uses, and recreational activity levels.
NbS actions include converting brownfields into parks, creating pocket parks, green corridors, schoolyards, and multifunctional public spaces, while ensuring universal accessibility, community involvement, and the creation of a "sense of place" (GreenUP, 2018; Raymond et al., 2017a).

Noise pollution

Urban noise from traffic, infrastructure, and human activities negatively affects health, sleep quality, and well-being. Noise exposure often overlaps with other environmental stressors.
Indicators include average and peak noise levels (dB), population exposed above thresholds, and reported disturbance.
NbS actions include tree belts, green walls, and strategic planting to create vegetated buffers, which absorb and deflect sound while also improving visual quality and improved air conditions (GreenUP, 2018; Raymond et al., 2017a).

Soil erosion

Soil erosion reduces land stability, increases sediment loads in water bodies, and undermines food production and ecosystem health. Within highly urbanized environments, this often stems from vegetation loss and surface sealing.
Indicators include erosion rates, soil layers stability, vegetation cover, landslide susceptibility, and slope.
NbS actions involve re-vegetation, slope stabilization with plants or green-grey integrated solutions, green embankments, and urban forests (GreenUP, 2018; Raymond et al., 2017a).

Water pollution

Another problem linked to urban runoff is that it transports pollutants such as heavy metals and hydrocarbons into water bodies, degrading water quality, aquatic ecosystems, and groundwater tables.
Indicators include pollutant loads and concentrations, groundwater quality, and frequency of combined sewer overflows.
NbS actions include SuDS, as constructed wetlands, bioswales, vegetated retention systems, riparian buffers, and infiltration-based solutions and water treatment systems that filter pollutants and improve water quality (GreenUP, 2018; Raymond et al., 2017a).

Water scarcity

Water scarcity is intensified by climate change, over-extraction of groundwater, and inefficient urban water and green management. Cities increasingly face competition between uses and reduced water availability.
Indicators include groundwater levels, water stress indices, soil infiltration capacity, and drought frequency.
NbS actions focus on increasing infiltration through green surfaces, rainwater harvesting, urban trees, and bioretention systems, to enhance filtering, groundwater recharge, and possibly make it suitable for non-drinkable reuse (GreenUP, 2018; Raymond et al., 2017a).

Set of NbS archetypes

After identifying the main urban types and challenges, the third phase consists of determining the set of NbS that best fit the area's characteristics, its requirements, and needs. The nature-based solutions selected for this research are **explicitly focused on the urban environment and on spatial scales relevant to urban planning** and design.
Given the strong dependence of NbS effectiveness on spatial scale, context, and urban morphology, three spatial levels were defined:

1) block or neighborhood scale;
2) street scale;
3) building scale.

Larger-scale NbS, such as urban-, rural-, landscape- or regional-level interventions, are not considered, as they exceed the intended spatial scope of this research.
Another key component of the NbS selection process concerns their spatial suitability within specific urban spaces (i.e., continuous or discontinuous fabrics, open urban space, or building solutions), as this directly affects both their feasibility and their replicability in areas with similar characteristics. The suitability analysis was structured as a constraint-based assessment, grounded in an extensive review of the literature (Alves et al., 2023; EEA, 2020;

Fleischmann et al., 2022; Raymond et al., 2017a; Sarabi et al., 2021; Woods-Ballard et al., 2007). First, NbS capable of addressing the targeted urban challenges were identified. For each solution, specific requirements were acknowledged to define, if present and potentially concerning, physical and planning constraints for its implementation, to arrive at the definition of qualitative values to evaluate their potential allocation area in certain urban spaces.

Some of the constraints were recognized in surface types, as each NbS is suitable only for specific urban surfaces (e.g., green roofs require roof surfaces, rain gardens require permeable, scarcely sloped ground). Additional physical characteristics, requirements, and limitations – such as soil type, groundwater depth, and surface slope – were also considered, as these factors can significantly influence feasibility and efficiency (e.g., green roofs are unsuitable for excessively steep roofs).

Assessing spatial suitability is also essential to determine whether individual NbS can be implemented effectively on their own or can be part of an integrated NbS cluster, known as an "NbS pocket", which is particularly relevant in urban environments where synergistic effects and cumulative benefits are required (Choi et al. 2021; Hansen et al. 2017). Overall, this suitability analysis provides a structured and replicable method to evaluate **where NbS can be implemented, under which conditions,** **and how they can be combined into coherent NbS pockets**, supporting informed decision-making in urban planning and design. Additional guidance is provided by identifying the Sustainable Development Goals (SDGs) – both primary and secondary – to which each NbS can contribute. This allows for a qualitative assessment of the broader benefits, impacts, and functions supported by each solution, which could be further deepened by the identification of SDGs' specific indicators, following the framework of the UN 2030 Agenda (Almenar et al., 2020; UN, 2015, 2022).

This analysis brought to the definition of **eighteen NbS archetypes**, which were firstly selected from a broader internal LINKS' NbS catalogue and then backed up by an extensive review of literature, where the chosen solutions were identified as the most commonly applied and documented interventions for addressing urban challenges (Alves et al., 2023; Bona et al., 2022; Cardinali et al., 2021; Dessì et al., 2016; EC, 2021; EEA, 2020; EEA, 2021; Erlwein et al., 2021; GreenUP, 2018; Interreg, 2024; Morello et al., 2019; Raymond et al., 2017; Sarabi et al., 2021; UNALab, 2022; World Bank, 2021). For analytical clarity, the selected NbS were organized into **five main categories** (Fig. 63), which are relevant in an urban environment, taking as guidance the classification proposed by LINKS and supported by the relevant literature mentioned above.
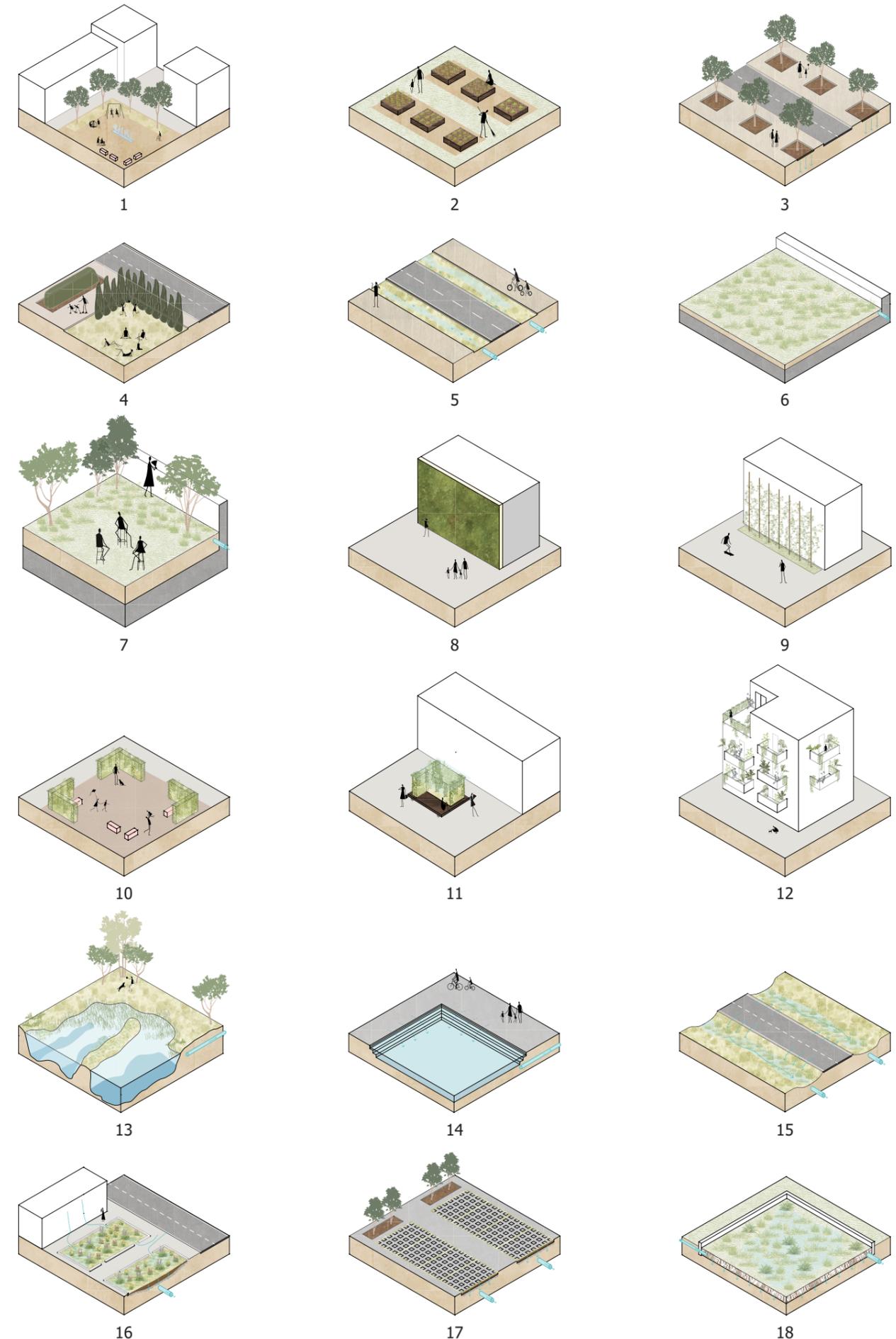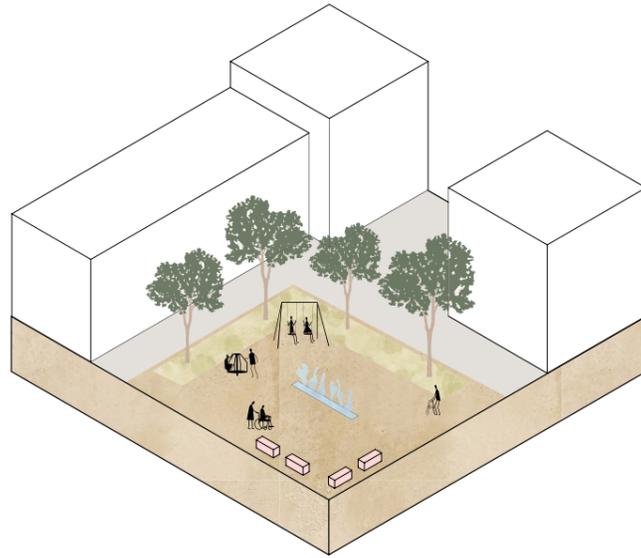
CATEGORIES		NATURE-BASED SOLUTIONS
Green spaces	1	Pocket park
	2	Urban garden
Green elements	3	Street trees
	4	Hedges/shrubs/green fences
	5	Green strips
Built environment	6	Green roof – extensive
	7	Green roof – intensive
	8	Green wall – facace-bound
	9	Green wall – ground-based
	10	Free-standing green wall
	11	Mobile vertical greening
	12	Greening balconies
Natural or semi-natural water storage	13	Constructed wetland
	14	Retention/detention pond
Infiltration, filtration, and biofiltration structures	15	Bioswales
	16	Rain gardens
	17	Permeable paving system
	18	Biofilter

Figure 63 – Table representing the NbS archetypes' adopted list, chategorized by the five main categories (Author's production).

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18

SCALE
Block / neighborhood

SUITABLE LOCATION
Urban voids, raesidual open land

MAIN CHALLENGES ADDRESSED
- Heat stress
- Air pollution
- Flood risk
- Lack of social cohesion
- Limited access to quality green and recreational green spaces
- Biodiversity loss

A pocket park is a compact, publicly accessible green space – typically smaller than 0.5 ha – developed within residual or underused urban areas such as vacant lots, spaces between buildings, or street corners. Designed for dense urban environments, it usually includes elements like seating, shaded areas, small play or recreational elements, and gardens. Pocket parks serve as compact, multifunctional NbS, providing localized environmental, social, and economic benefits to dense urban areas and their inhabitants. Their effectiveness is particularly enhanced when implemented as a distributed, multi-site strategy, allowing cumulative and synergistic impacts at the neighborhood scale rather than relying on a single, larger green space. Due to its high adaptability and small size, it can be highly scalable to various urban settings.
There are different types of pocket parks, it can range from simple installations with minimal landscaping to more elaborate designs with various amenities (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Soil health improvement
- Noise pollution reduction
- Community health and well-being enhancement
- Provides aesthetic value

MAIN TRADE-OFFS
- Potential for soil and water contamination (e.g., pesticide use)
- Potential introduction of non-native species can disrupt local ecosystems
- Accessibility and equitable distribution are key factors

MAIN FUNCTIONS
- Evapotranspiration, shading
- Water conveyance, infiltration, retention, storage
- Water filtering
- Air deposition, biofiltration
- Erosion control
- Habitat provision, connectivity
- Usability, functionality
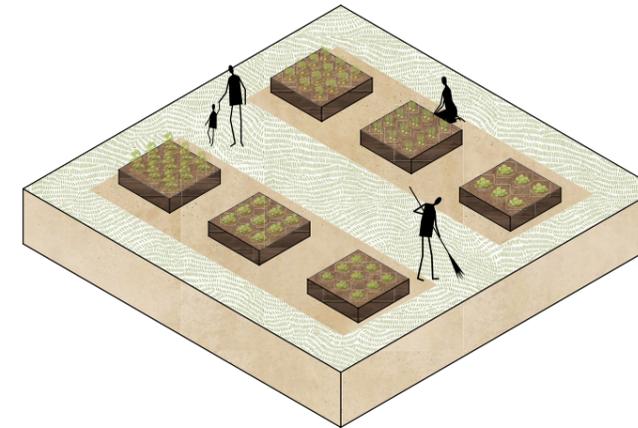
PRIMARY SDGs
3, 10, 11, 13

SECONDARY SDGs
15

POTENTIAL SYNERGIES with other NbS
Rain gardens, permeable pavements

SCALE
Building / block

SUITABLE LOCATION
Courtyards, vacant lots, undeveloped areas

MAIN CHALLENGES ADDRESSED
- Absence or limited access to affordable food
- Lack of social cohesion
- Limited access to quality green and recreational green spaces
- Biodiversity loss
- Soil erosion

The urban garden is a shared urban green space where residents collectively cultivate vegetables, fruits, herbs, and flowers. Typically managed by local communities, schools, or organizations on public or donated land, these types of gardens promote local and sustainable food systems while helping to reduce food insecurity. Beyond food production, they deliver significant social benefits by strengthening community ties, fostering collaboration, and creating opportunities for education and cultural exchange. They also support health and well-being by encouraging physical activity, improving mental health, and increasing access to fresh produce. From an environmental perspective, they enhance urban biodiversity, support pollinators, and contribute to green infrastructure, thereby improving urban resilience. Overall, urban gardens function as inclusive, productive green spaces that provide environmental, social, and economic value while reinforcing residents' connection to nature and to one another.
There is a wide variety of possible urban gardens (e.g., community gardens, botanical, meadow) and their design complexity can vary depending on the size of the garden, the site conditions, or features incorporated (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Contribution to heat stress reduction
- Reduction in local water and air pollution
- Improvement of soil health and fertility
- Flood risk mitigation
- Improved mental and physical well-being

MAIN TRADE-OFFS
- Potential for soil and water contamination (e.g., pesticide use)
- Potential introduction of non-native species
- Gentrification or displacement if measure significantly increases property values in low-income neighborhoods
- Exclusion if access or participation is limited

MAIN FUNCTIONS
- Evapotranspiration
- Water infiltration, retention, storage
- Air biofiltration
- Habitat provision
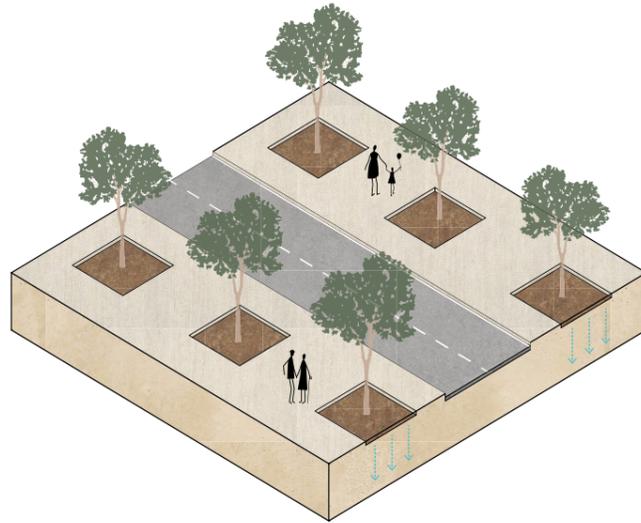- Usability, functionality

PRIMARY SDGs
2, 3, 12

SECONDARY SDGs
1, 4, 8, 10, 11

POTENTIAL SYNERGIES with other NbS
Rain gardens, bioswales, green roofs

STREET TREES

Street trees are trees strategically planted along urban streets, sidewalks, and public rights-of-way, forming a fundamental component of urban green infrastructure. They deliver a wide range of ecosystem services, including microclimate regulation through shading and evapotranspiration, reduction of the UHI effect, carbon sequestration, air pollutant filtration, and improved stormwater management by reducing surface runoff and enhancing water quality. In addition to their environmental functions, street trees contribute to aesthetic values, improve walkability, and foster community satisfaction, thereby enhancing the overall quality of urban life. Careful planning and design are required to ensure adequate soil volume and to avoid conflicts with underground utilities and infrastructure, particularly in dense urban contexts. When designing this measure, special attention needs to be given to species selection and spacing between the single elements, because wrong configurations could impede ventilation flows (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

SCALE
Street / neighborhood

SUITABLE LOCATION
Roads, medians, sidewalks, bikepaths

MAIN CHALLENGES ADDRESSED
- Heat stress
- Air pollution
- Flood risk
- Soil erosion
- Biodiversity loss
- Greenhouse gas emissions

MAIN CO-BENEFITS
- Soil health improvement
- Noise and water pollution reduction
- Provides aesthetic value
- Increased property values
- Promotes physical activity through comfortable walking and cycling routes

MAIN TRADE-OFFS
- Potential allergenic pollen production can trigger respiratory issues
- Competition with existing flora for nutrients and space
- Roots can cause infrastructure damage

MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Water infiltration, retention
- Air deposition, biofiltration
- Erosion control
- Habitat provision, connectivity
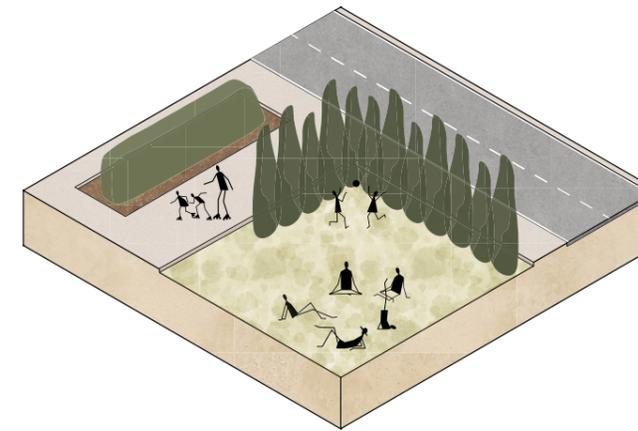
PRIMARY SDGs
11, 13

SECONDARY SDGs
3, 15

POTENTIAL SYNERGIES with other NbS
Green strips, green balconies, biofilter

HEDGES / SHRUBS / GREEN FENCES

Hedges and shrubs plantings are structured, predominantly linear or clustered vegetated elements composed of shrubs or small trees, commonly used to define boundaries, enhance safety, and structure open space. Traditionally employed around gardens, private plots, roadways, and field edges, hedges also provide a wide range of ecosystem services, including habitat provision, pollinator support, landscape connectivity, and wind and noise buffering. Typically composed of native or regionally adapted species, they may include a diverse mic of woody and flowering plants. They can also contribute to soil stabilization and water retention, particularly on sloped, fragmented, or disturbed land. When allowed to develop structural diversity – such as layered heights, mixed species composition, and seasonal variation – they become especially valuable for biodiversity. In addition to continuous hedges along property boundaries, shrubs can also be arranged as standalone groupings or clusters, to enhance visual interest, create microhabitats, and stabilize soils, while mimicking natural vegetation patterns and functioning as buffer zones within larger green infrastructures. Overall, this measures function as living barriers and landscape elements that combine ecological performance with spatial definition and visual quality (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

SCALE
Building / street

SUITABLE LOCATION
Property boundaries, parks, courtyards, gardens

MAIN CHALLENGES ADDRESSED
- Heat stress
- Noise pollution
- Air pollution
- Flood risk
- Soil erosion
- Biodiversity loss

MAIN CO-BENEFITS
- Contribution to heat stress reduction
- Reduction in local water and air pollution
- Contribution to soil stability
- Enhanced aesthetics
- Improved privacy

MAIN TRADE-OFFS
- Potential allergen and pollen release
- Displacement of native species if not managed
- Competition with nearby vegetation for nutrients and water
- Visual obstruction if not well planned
- May require frequent maintenance (trimming)

MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Water infiltration, retention
- Air deposition, biofiltration
- Erosion control
- Habitat provision, connectivity
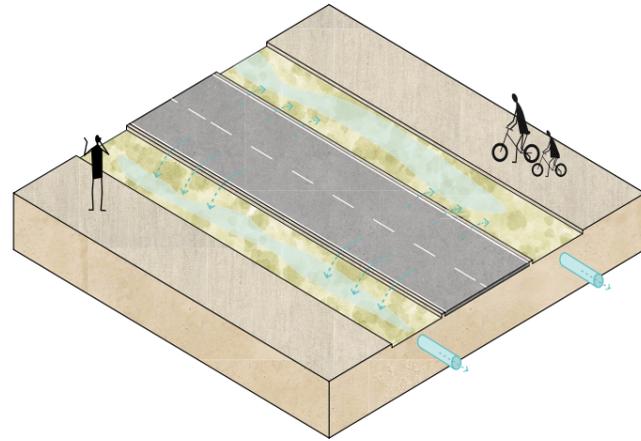
PRIMARY SDGs
3, 11

SECONDARY SDGs
15

POTENTIAL SYNERGIES with other NbS
Street trees, urban gardens, detention ponds

SCALE
Street / block

SUITABLE LOCATION
Roadsides, medians, parking-lots, sidewalks

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Heat stress
- Water pollution
- Flood risk
- Biodiversity loss

Green strips are narrow, linear vegetated areas typically located along roadsides, in medians, and within public pathways like along sidewalks, or other urban infrastructures. Composed of grass, low groundcover, shrubs, and occasionally small trees, they function as multifunctional elements of urban green infrastructure. Green strips contribute to urban microclimate regulation, surface runoff management, and pollutant filtration, while also providing visual relief and ecological continuity within highly urbanized environments. By acting as buffers between hard infrastructure and pedestrian or mobility zones, they enhance pedestrian comfort and safety. They are suitable for both retrofit interventions and new urban developments. They require typically a linear, permeable strip of land – long and narrow – with widths often constrained by adjacent infrastructure. Also referred to as vegetated buffer strips or verges, they play an important role in habitat connectivity and contribute to the aesthetic and ecological performance of urban landscapes. They work best when integrated within a bigger water management system, when they can be used as a pre-treatment area to block bigger debris (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Air and water pollution reduction
- Enhanced biodiversity
- Visual amenity
- Opportunity for community participation in design and maintenance

MAIN TRADE-OFFS
- Potential for soil contamination from runoff if not properly treated

MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Water infiltration, retention
- Air deposition, biofiltration
- Erosion control
- Habitat provision, connectivity
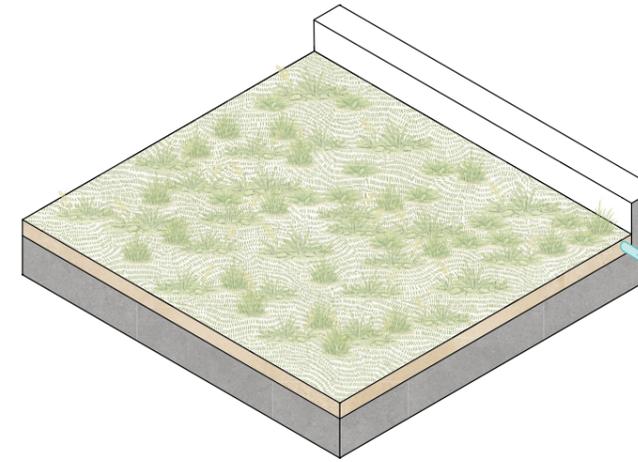
PRIMARY SDGs
9, 13

SECONDARY SDGs
6, 11

POTENTIAL SYNERGIES with other NbS
Shrubs, constructed wetlands, retention ponds

SCALE
Building

SUITABLE LOCATION
Rooftop

MAIN CHALLENGES ADDRESSED
- Heat stress
- Air pollution
- Water pollution
- Flood risk
- Biodiversity loss
- GHG emissions

Extensive green roofs are lightweight vegetated roof systems characterized by a shallow substrate (typically ≤15 cm) and low-growing, drought- and heat-resistant plant species, like the Sedum genus, grass, herbs, and moss. Composed of layered systems including a growing medium, root protection membranes, drainage and water retention layers, and insultation, their structure is determined by plant selection and performance objectives. Typically non-accessible (only for maintenance), extensive green roofs are particularly suitable where ground-level space for greenery is limited, making them an effective solution in high-density urban areas. They support urban biodiversity and pollinators, reduce stormwater runoff trough rainfall interception and retention, and – when implemented over large roof surfaces – contribute to local cooling and mitigation of the UHI effect. Extensive green roofs can be implemented on most roof types, provided that the structural load-bearing capacity is assessed in advance (generally in the range of 70-120 kg/m2). They can be successfully adopted for retrofit purposes, but certain constraints may apply to historical buildings, and careful evaluation is required to avoid roof materials that could release pollutants into the growing substrate. These systems are generally suitable for roof slopes between 1% and 30%, with optimal hydrological performance at low gradients (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Reduction in local water pollution and scarcity
- Aesthetic improvement of the urban landscape
- Sequesters carbon dioxide
- Decreased building's energy consumption
- Improved mental health
- Provides opportunities for community engagement

MAIN TRADE-OFFS
- Potential for introduction of non-native species
- Embodied energy in the construction of the roof structure and materials (though this is typically offset over its lifetime)
- Potential displacement/gentrification in surrounding areas due to increased property values

MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Building insulation
- Water conveyance, retention
- Habitat provision, connectivity
- Usability, functionality
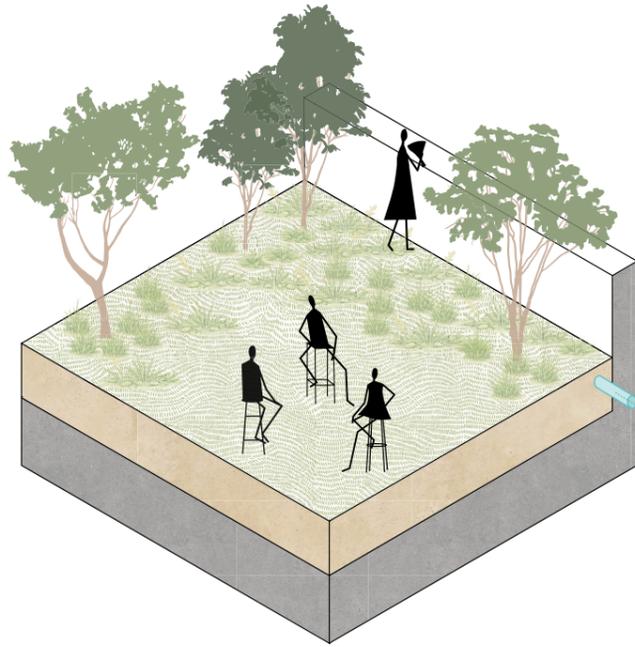
PRIMARY SDGs
11, 13

SECONDARY SDGs
3, 6, 8, 9

POTENTIAL SYNERGIES with other NbS
Green walls, permeable pavings, detention ponds

GREEN ROOF – INTENSIVE

Intensive green roofs are highly engineered vegetated roof systems installed on flat or gently sloped rooftops (preferably ≤15°), characterized by a deep growing substrate (20-100+ cm) that supports a wide range of plant species, including shrubs, perennials, grass, and small trees. Unlike extensive systems, they can function as multifunctional spaces, delivering both environmental benefits and recreational or social uses. Composed of layered assemblies – including vegetation, growing medium, drainage and water retention layers, protective elements, and root-resistant waterproofing membranes – intensive green roofs require robust structural support (at least 300 kg/m2) to accommodate substantial static and dynamic loads, this is why their implementation is more suitable for new buildings. As the extensive ones, this system is particularly valuable in dense urban areas where ground-level space for large NbS is limited. Their benefits are similar to the extensive version but more significant, and include stormwater retention, mitigation of the UHI effect, reduction of roof surface temperatures and cooling energy demand, enhanced urban biodiversity, and the creation of accessible rooftop gardens that provide social and aesthetic value. Versions of this system may also include rooftop gardens and recreative functions (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

SCALE
Building

SUITABLE LOCATION
Rooftop

MAIN CHALLENGES ADDRESSED
- Absence or limited access to affordable fresh food
- Heat stress
- Air pollution
- Water pollution
- Flood risk
- Lack of social cohesion
- Limited access to quality green and recreational spaces
- Biodiversity loss
- GHG emissions

MAIN CO-BENEFITS
- Reduction in local water pollution and scarcity
- Aesthetic improvement of the urban landscape
- Sequesters carbon dioxide
- Decreased building's energy consumption
- Improved mental health and well-being
- Provides opportunities for community engagement
- Enhances property values

MAIN TRADE-OFFS
- Potential for introduction of non-native species
- Embodied energy in the construction
- Potential displacement/gentrification
- Potential for rooftop damage if not properly installed and maintained

MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Building insulation
- Water conveyance, retention, storage
- Water filtering
- Deposition
- Habitat provision, connectivity
- Usability, functionality

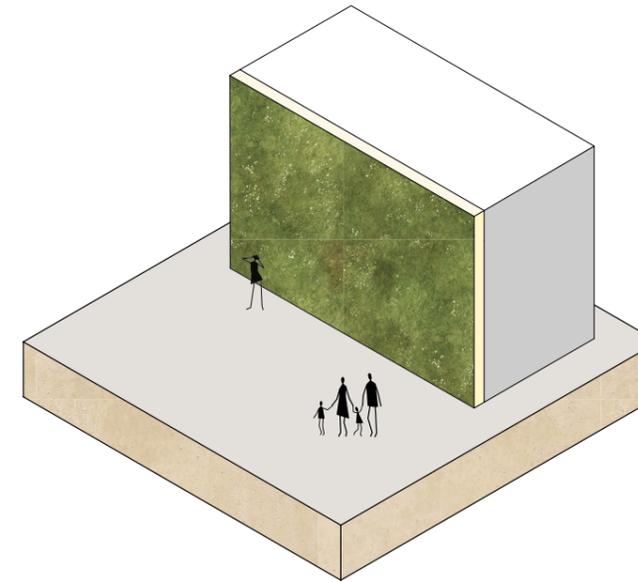**PRIMARY SDGs**
11, 13

SECONDARY SDGs
2, 3, 6, 8, 9

POTENTIAL SYNERGIES with other NbS
Green walls, permeable pavings, wetland

GREEN WALL – FAÇADE-BOUND

Modular green facades are vertical greening systems in which vegetation is directly integrated into building envelopes through pre-cultivated panels or planted containers mounted on support structures. Depending on the building context, these systems may be fully integrated into new facades or installed as independent frameworks in retrofit applications, typically using metal brackets, grids, or frame systems. Due to the limited substrate depth, modular green facades rely on technologically advanced solutions such as lightweight growing media and controlled irrigation systems (e.g., drip or capillary). This makes them sensitive to extreme cold and frost, requiring careful climatic suitability assessments and, in some cases, seasonal removal of panels. Generally planted with small species such ad mosses and perennials adapted to vertical growth, these systems are best suited to facades with adequate solar exposure and mild climatic conditions. It would be best to implement this strategy on large and continuous facades, with no or few windows. Buildings height is inherently irrelevant, though irrigation and maintenance get more complicated as the height increases. Despite their technical complexity, this system delivers multiple environmental benefits, including improved thermal performance of buildings, mitigation of the UHI effect, stormwater runoff reduction, air pollutant filtration, noise attenuation, biodiversity support, and enhanced architectural and aesthetic quality (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

SCALE
Building

SUITABLE LOCATION
Vertical wall

MAIN CHALLENGES ADDRESSED
- Heat stress
- Noise pollution
- Air pollution
- Limited access to quality green and recreational spaces
- Biodiversity loss
- GHG emissions

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Reduced building energy consumption
- Aesthetic improvement of the urban landscape
- Sequesters air pollutants
- Improved thermal comfort inside buildings
- Improved mental health and therapeutic benefits (stress reduction)

MAIN TRADE-OFFS
- Potential for introduction of non-native species
- Uneven distribution of benefits if implemented only on certain buildings
- Potential water misuse if not managed efficiently
- Potential displacement/gentrification in surrounding areas due to increased property values

MAIN FUNCTIONS
- Evapotranspiration
- Building insulation
- Air deposition, biofiltration
- Habitat provision, connectivity
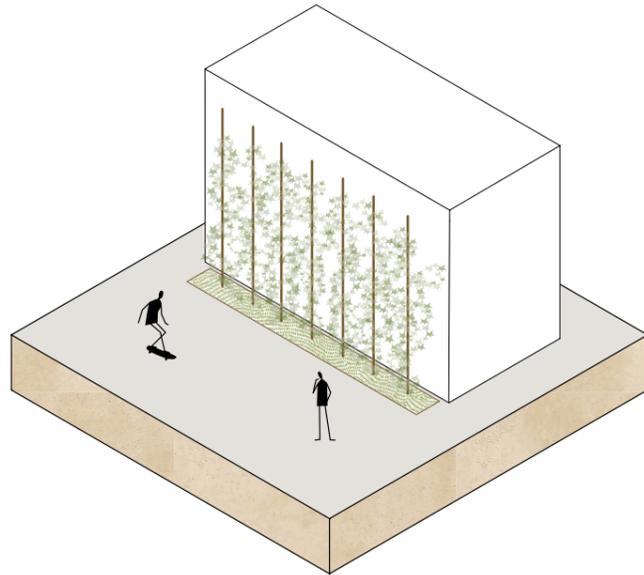- Usability, functionality

PRIMARY SDGs
11, 13

SECONDARY SDGs
3, 8, 9

POTENTIAL SYNERGIES with other NbS
Green roofs, green balconies, permeable pavings

SCALE
Building

SUITABLE LOCATION
Vertical wall

MAIN CHALLENGES ADDRESSED
- Heat stress
- Noise pollution
- Air pollution
- Limited access to quality green and recreational spaces
- Biodiversity loss
- GHG emissions

A ground-based green façade is a vertical greening system in which climbing plants are rooted at ground level and grow upward along a building façade. The planting base typically consists of a small in-ground soil area or containers filled with a balanced, well-draining, and nutrient-rich substrate. A key design consideration is the selection of plant species. Self-climbing species adhere directly to the façade through adhesive roots or pads and therefore require continuous, gap-free wall surfaces to prevent water infiltration or surface damage. Alternatively, climbing plants that require structural support can be used in combination with trellises or frame systems installed at a slight distance from the wall, allowing for ventilation and protecting the building envelope. This approach usually involves one dominant plant species and represents a long-term intervention, as full façade coverage may take between 5 to 20 years. The natural growth of such plants biologically stops at 15-20m, so interventions on higher buildings are still suitable. Compared to façade-bound and modular systems, this intervention has minimal structural and technical requirements, making them suitable for both new constructions and retrofit projects. The vegetation can be installed as free-standing systems and, if necessary, removed with limited or no permanent alteration to the building. This type of façade provides multiple ecosystem services, including local microclimate cooling, habitat provision, air pollutant filtration, and enhanced aesthetic value (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Reduced building energy consumption
- Aesthetic improvement of the urban landscape
- Sequesters air pollutants
- Improved thermal comfort inside buildings
- Improved mental health and therapeutic benefits (stress reduction)

MAIN TRADE-OFFS
- Potential for introduction of non-native species
- Uneven distribution of benefits if implemented only on certain buildings
- Potential water misuse if not managed efficiently
- Potential displacement/gentrification in surrounding areas due to increased property values
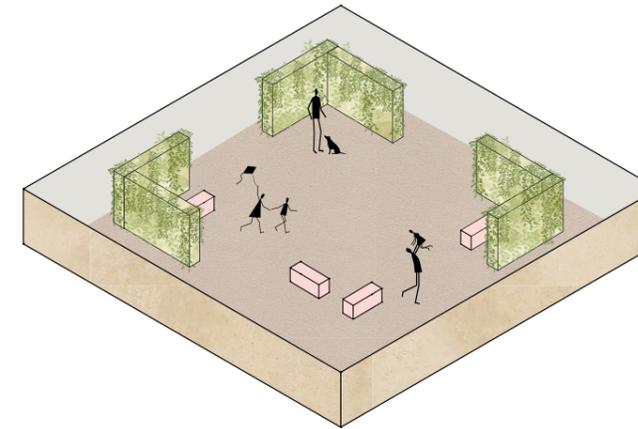
MAIN FUNCTIONS
- Evapotranspiration
- Building insulation
- Air deposition, biofiltration
- Habitat provision, connectivity
- Usability, functionality

PRIMARY SDGs
11, 13

SECONDARY SDGs
3, 8, 9

POTENTIAL SYNERGIES with other NbS
Green roofs, green balconies, permeable pavings

SCALE
Building / block

SUITABLE LOCATION
Squares, open spaces, courtyards

MAIN CHALLENGES ADDRESSED
- Heat stress
- Noise pollution
- Air pollution
- Lack of social cohesion
- Limited access to quality green and recreational spaces
- Biodiversity loss

A free-standing living wall is a self-supporting vertical structure, designed to accommodate dense plant growth where horizontal space is limited. This structure is built by vertically layering soil or substrate inside metal cage modules, often designed with an L-shape and additional supporting elements, to reinforce the whole system. This construction can reach up to 4 m in height and 40 cm in thickness hence a solid underground load-bearing strip foundation is necessary to allow its stability. An organic or synthetic fabric layer is needed inside the metal cages to prevent soil erosion. This type of wall supports vegetation growth both on its sides and at the top and can support a wide range of plant species (e.g., perennials, shrubs, and even small trees), as long as local biodiversity is respected and plants are correctly maintained. It is usually designed to function as noise barrier, privacy screen, or decorative installation in urban environments. This system is also well suited to act as a visually pleasant noise barrier, especially in traffic-heavy areas. Thanks to their thermal mass, it is also resistant to low temperatures. It is mainly introduced to combat the UHI effect, since it can help with shade provision, evaporation, and evapotranspiration that cool the surrounding air down. Additionally, it can help retain surface runoff (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Aesthetic improvement of the urban landscape
- Sequesters air pollutants
- Enhanced psychological well-being

MAIN TRADE-OFFS
- Potential for introduction of non-native species
- Could compete with other land uses
- Could block views or cast shadows
- Potential safety issue due to wall instability if not carefully implemented
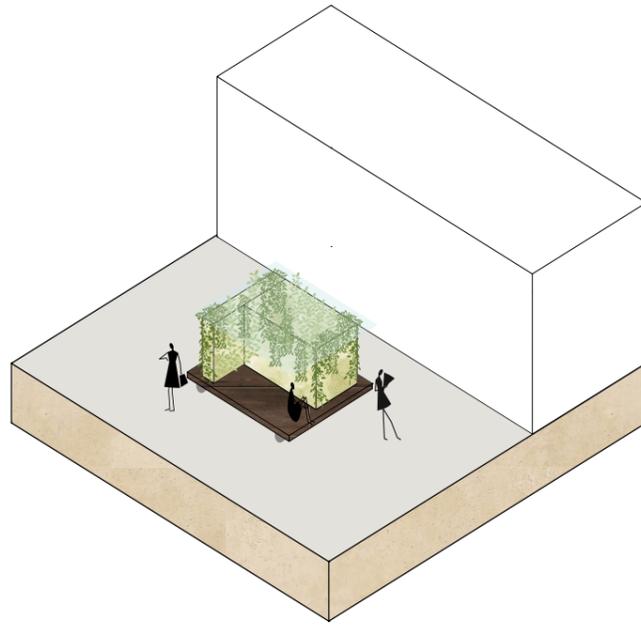
MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Air deposition, biofiltration
- Habitat provision, connectivity
- Usability, functionality

PRIMARY SDGs
3, 11

SECONDARY SDGs
9, 13

POTENTIAL SYNERGIES with other NbS
Green roofs, green balconies, permeable pavings

The mobile vertical greening system stands from the knowledge of free-standing vertical walls, but is specifically designed to be transportable, to deliver immediate environmental, educational, and social benefits in urban areas. Structurally, this strategy consists of wire-frame compact modules stacked onto a hook-lift container platform. This cage is then filled with substrate (soil or hydroponic) and planted with a diverse mix of plants (e.g., perennials, shrubs, small trees), that need to be resistant to local climate and vertical growth. Moreover, a lightweight, partially vegetated structure provides shade and outdoor comfort. This way, a movable semi-autonomous unit is formed, equipped with its own water tank that can last up to a week and an irrigation system (usually drip) which only temporarily requires energy supply. Given its limited size, its environmental performance is reduced compared to a permanent solution, even though it can still improve local outdoor usability. Additionally, it can serve as a test installation for a permanent project, helping to understand the suitability of the location (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

SCALE
Building

SUITABLE LOCATION
Vertical wall

MAIN CHALLENGES ADDRESSED
- Heat stress
- Noise pollution
- Air pollution
- Lack of social cohesion
- Limited access to quality green and recreational spaces
- Biodiversity loss

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Aesthetic improvement of the urban landscape
- Enhanced psychological well-being
- Provides opportunity for community engagement and education

MAIN TRADE-OFFS
- Requirements for transporting mobile elements may eclipse the environmental benefits
- Size is limited, which means benefits are limited

MAIN FUNCTIONS
- Evapotranspiration, shading, reflection (albedo)
- Air deposition
- Habitat provision, connectivity
- Usability, functionality, education
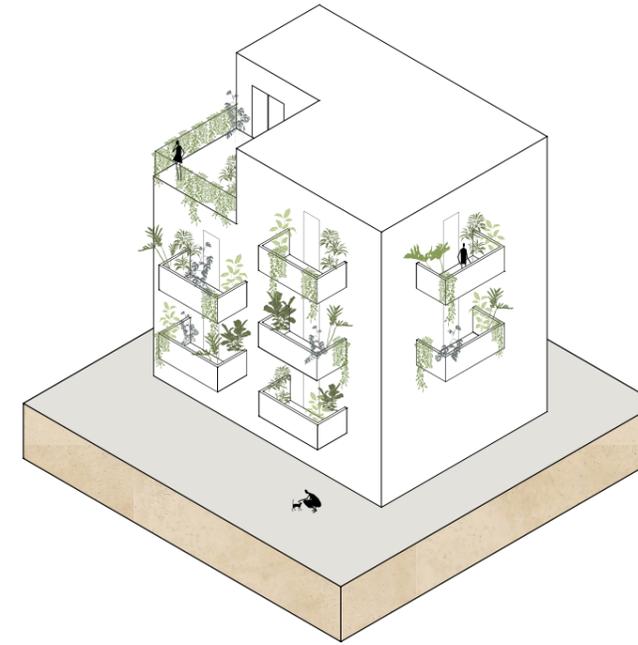
PRIMARY SDGs
3, 11

SECONDARY SDGs
4, 12, 13

POTENTIAL SYNERGIES with other NbS
Green roofs, detention ponds

Green balconies represent a modest yet impactful form of urban greening, which provides residents with private outdoor green areas inside the urban environment. In spite of their size, they can bring a wider urban transformation, when adopted collectively or as part of a building's design strategy. This implementation requires at least a 1m depth of the suspended surfaces, with sufficient load-bearing capacity and sunlight. Vegetation can be directly integrated into the architectural design, leading to a greater mitigation of the UHI effect, enhancement of biodiversity, improvement of real estate value, and regeneration of the surrounding urban fabric. If not, they are equally significant when they are implemented as simple domestic practices of planting diverse vegetation in pots or planters, helping reduce local air pollution, heat stress, and supporting small species, while also providing an aesthetic value. Generally, this solution is flexible, low-tech, and highly accessible to anyone (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

SCALE
Building

SUITABLE LOCATION
Balconies, loggias

MAIN CHALLENGES ADDRESSED
- Heat stress
- Noise pollution
- Air pollution
- Limited access to quality green and recreational spaces
- Biodiversity loss

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Aesthetic improvement of the urban landscape
- Sequesters air pollutants
- Enhanced psychological well-being
- Habitat creation for pollinators, birds, and insects
- Increased property values

MAIN TRADE-OFFS
- Potential for introduction of non-native species
- Potential misuse of water resources, if not sustainably sourced
- Could block views or cast shadows
- Potential for pesticide use
- Potential for gentrification
- Access might be limited to residents with balconies
- Potential accessibility issues for elderly and disabled

MAIN FUNCTIONS
- Evapotranspiration, shading
- Air deposition, biofiltration
- Water interception, retention
- Habitat provision

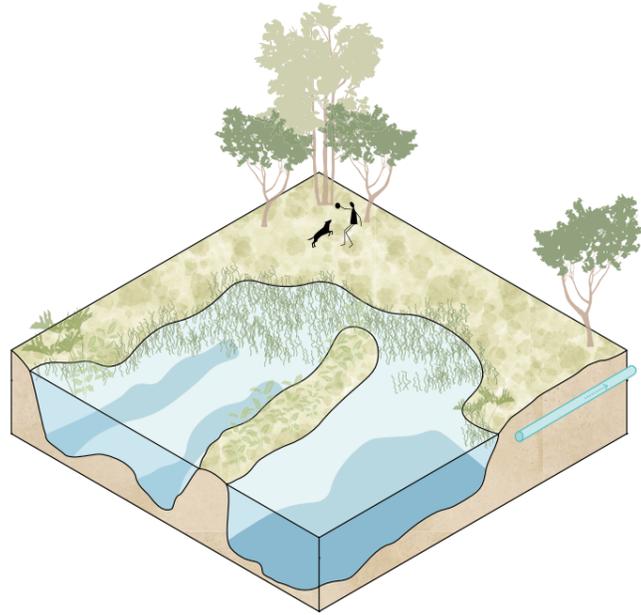**PRIMARY SDGs**
3, 11

SECONDARY SDGs
8, 9, 13

POTENTIAL SYNERGIES with other NbS
Street trees, green roofs, bioswales

SCALE
Block / neighborhood

SUITABLE LOCATION
Open areas, floodplains, parks, large vacant areas

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Heat stress
- Water pollution
- Flood risk
- Lack of social cohesion
- Limited access to quality green and recreational spaces
- Biodiversity loss
- GHG emissions

Constructed wetlands are engineered NbS designed to mimic the processes of natural wetlands in order to treat and temporarily store wastewater or stormwater runoff in urban and peri-urban contexts. By integrating vegetation, soil or substrate layers, controlled hydrology, and microbial activity, these systems rely on natural filtration and biological processes to improve water quality in a cost-effective and sustainable manner. Typically consisting of shallow basins with climate-appropriate vegetation and inlet and outlet structures, these systems can also enhance urban biodiversity and provide ecological and landscape value when designed with diverse planting and accessible shorelines. In addition to water purification, they contribute to stormwater management and reduce reliance on conventional treatment infrastructure. Constructed wetlands generally require large, permeable, low-lying sites and are subject to specific design constraints, including gentle side slopes, shallow water depths (1-2m), adequate distance from buildings, and sufficient separation from groundwater tables, to avoid possible contamination. As a result, they are rarely suitable for dense urban cores; however, smaller-scale adaptations such as vertical-flow systems or pocket wetlands may be implemented in spatially constrained environments (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Contribution to provision of quality green spaces
- Aesthetic value, recreational and educational opportunities
- Enhanced psychological well-being
- Drought alleviation
- Removal of pollutants from wastewater
- Habitat creation

MAIN TRADE-OFFS
- Initial construction can disturb exisitng habitats
- Potential for methane emissions
- Mosquito breeding
- Potential odour issues
- Accessibility concerns for some user groups
- Possible negative acceptance, unless effective communication is done

MAIN FUNCTIONS
- Evapotranspiration
- Water conveyance, infiltration, retention, storage, reuse
- Water filtering, bioremediation
- Habitat provision, connectivity
- Usability, functionality, education
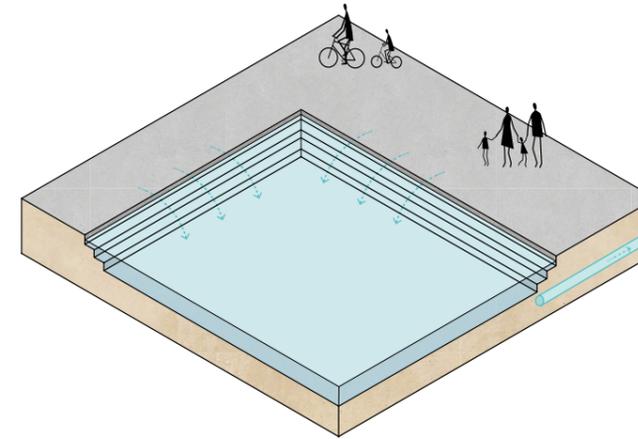
PRIMARY SDGs
3, 6, 11, 13

SECONDARY SDGs
4, 9, 14, 15

POTENTIAL SYNERGIES with other NbS
Green roofs, permeable pavings, bioswales

SCALE
Building / neighborhood

SUITABLE LOCATION
Open areas, parks, large voids, courtyards

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Heat stress
- Water pollution
- Flood risk
- Soil erosion
- Limited access to quality green and recreational spaces
- Biodiversity loss

Retention and detention ponds are engineered basins designed to manage stormwater runoff by temporarily or permanently storing water and controlling its release. Retention ponds maintain a permanent pool of water, providing continuous water quality treatment and habitat for aquatic and semi-aquatic species, while detention ponds remain dry under normal conditions and temporarily store stormwater during rainfall events, slowly releasing or infiltrating it after peak flows. These systems typically include a depression basin (naturally occurring or excavated), stormwater inlets, controlled outlet structures, and vegetated areas that support sedimentation, infiltration, and pollutant removal. When properly designed and maintained, these ponds reduce flood risk, improve water quality, and contribute to urban biodiversity, while also offering recreational and landscape value and potentially lowering long-term stormwater infrastructure costs. From a spatial and technical perspective, they require adequate separation from buildings and groundwater tables. Pre-treatment measures, such as forebays, may be required to manage sediments and pollutants, and implementation should avoid areas where natural wetlands already exist, to avoid negatively affecting established habitats (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Potential for groundwater recharge
- Provision of recreational green spaces
- Aesthetic improvement of the urban landscape
- Enhanced psychological well-being
- Habitat creation
- Educational opportunities

MAIN TRADE-OFFS
- Potential habitat disruption during construction
- Potential for introduction of non-native species
- Potential for mosquito breeding
- Potential safety hazards
- Potential for decreased surrounding property values

MAIN FUNCTIONS
- Evaporation
- Water retention, storage, reuse
- Water filtering
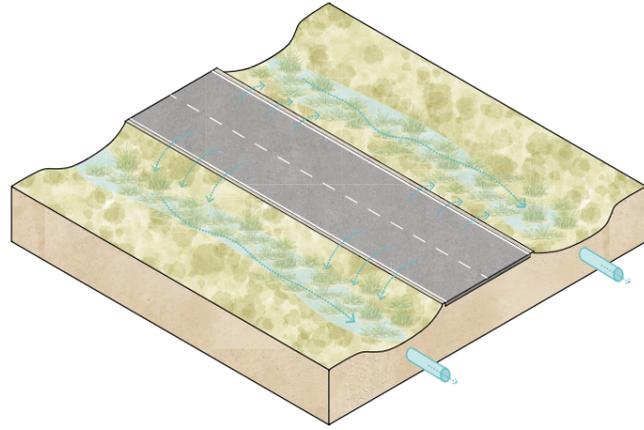- Usability, functionality, education

PRIMARY SDGs
3, 6, 11, 13

SECONDARY SDGs
4, 9, 14, 15

BIOSWALES

SCALE
Street / neighborhood

SUITABLE LOCATION
Road edges, medians, parking-lots, sidewalks

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Water pollution
- Flood risk
- Soil erosion
- Limited access to quality green and recreational spaces
- Biodiversity loss

Bioswales are vegetated, shallow, and gently sloped channels designed to capture, convey, and treat stormwater runoff while promoting infiltration into the ground. As a form of green infrastructure, they mimic natural drainage processes by slowing water flow, filtering pollutants, and reducing surface runoff volumes. They are typically filled with engineered soil mixes and planted with native or adapted vegetation, such as grasses, shrubs, and occasionally small trees. Their geometry is often linear but may also be distributed or scattered depending on spatial conditions and drainage patterns. The primary benefits of bioswales include stormwater retention, pollutant removal, erosion control, and improved water infiltration, while also enhancing urban aesthetic and contributing to ecological connectivity. Due to their flexibility and relatively low spatial requirements, this solution is well suited to integration within streetscapes, parking areas, and public open spaces as part of broader green infrastructure networks (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Contribution to heat stress reduction
- Potential for groundwater recharge
- Enhanced soil health
- Aesthetic improvement of the urban landscape
- Enhanced psychological well-being
- Habitat creation

MAIN TRADE-OFFS
- Potential for soil contamination if polluted runoff is not properly treated
- Potential habitat disruption during construction
- Mosquito breeding

MAIN FUNCTIONS
- Evaporation
- Water conveyance, infiltration, retention, storage
- Water filtering, bioremediation
- Habitat provision, connectivity
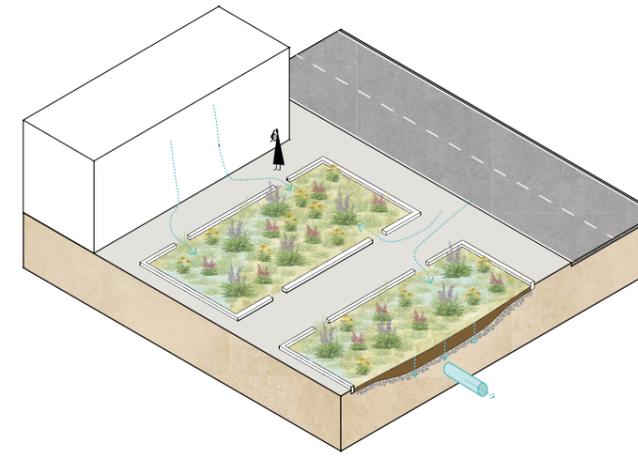
PRIMARY SDGs
6, 11, 13

SECONDARY SDGs
3, 9

POTENTIAL SYNERGIES with other NbS
Green roofs, permeable pavings, retention ponds

RAIN GARDENS

SCALE
Building / street / block

SUITABLE LOCATION
Courtyards, parks, open areas, road verges

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Heat stress
- Water pollution
- Flood risk
- Lack of social cohesion
- Limited access to quality green and recreational spaces
- Biodiversity loss

Rain gardens are shallow, vegetated depressions designed to collect, temporarily store, filter, and infiltrate stormwater runoff from impervious surfaces such as roofs, roads, sidewalks, and parking areas. Functioning as small-scale green infrastructure, they support localized stormwater management by reducing runoff volumes and removing pollutants before water infiltrates into the soil or is conveyed to the drainage system. Typically implemented within the built environment as public or private installations, rain gardens are planted with dense, native or locally adapted vegetation selected according to site-specific hydrological conditions. Engineered soil mixes, gentle slopes, and layered design zones allow rain gardens to accommodate periodic flooding while promoting infiltration and evapotranspiration. Additional elements, such as mulch layers, grass filter strips, sand beds, or shallow ponds, may be incorporated to enhance performance. Rain gardens provide a cost-effective alternative to conventional stormwater infrastructure, delivering benefits such as improved water quality, habitat creation, and enhanced urban aesthetics, while also contributing to long-term reductions in infrastructure and maintenance costs (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Reduces pollutant loads entering waterways
- Potential for groundwater recharge
- Provision of recreational green spaces
- Aesthetic improvement of the urban landscape
- Enhanced psychological well-being
- Habitat creation
- Enhances property values

MAIN TRADE-OFFS
- Potential habitat disruption during construction
- Potential for mosquito breeding and standing water issues
- Potential pollutant mobilization, requires careful site selection to avoid pollutin groundwater
- Possible accessibility issues if not maintained properly

MAIN FUNCTIONS
- Evapotranspiration
- Water infiltration, retention, storage, reuse,
- Water filtering, bioremediation
- Habitat provision, connectivity
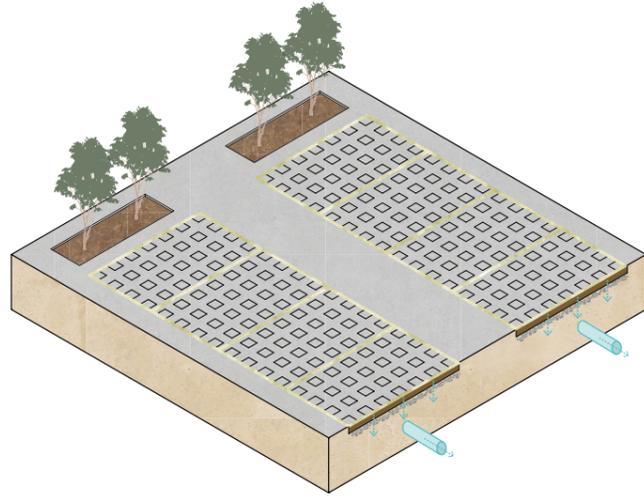- Usability, functionality

PRIMARY SDGs
3, 6, 11, 13

SECONDARY SDGs
9

POTENTIAL SYNERGIES with other NbS
Green roofs, green strips, constructed wetlands

SCALE
Street / neighborhood

SUITABLE LOCATION
Sidewalks, low-speed roads, parking-lots, bike lanes

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Heat stress
- Water pollution
- Flood risk
- Soil erosion

Permeable paving systems are hard surface solutions designed to allow stormwater to infiltrate through the pavement into an underlying storage or drainage layer, thereby reducing surface runoff and promoting groundwater recharge directly at the source. It is important that the surface has no- to low-inclination percentage, otherwise its infiltrating potential is lost due to high velocity of runoff water. While maintaining full functionality for pedestrian and vehicular use, these systems help delay peak flows and reduce pollutant load entering urban drainage networks. Typically composed of a permeable surface layer – such as porous asphalt, permeable concrete, interlocking pavers with open joints, or vegetated grid systems – over a gravel or stone sub-base, permeable pavements temporarily store water before allowing it to infiltrate into the soil or be conveyed to a subsurface drainage system. Different systems vary in construction and performance, with some increasing vegetated or substrate-covered areas to enhance infiltration and evapotranspiration. Commonly applied in parking areas, residential streets, sidewalks, and public spaces (slow and lightweight traffic), this system contributes to stormwater management, water quality improvement, and groundwater recharge. Regular maintenance is essential to prevent clogging and ensure long-term performance (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Reduced runoff volume and peak flow
- Groundwater recharge
- Slight reduction in surface temperatures, especially if low-albedo materials are adopted

MAIN TRADE-OFFS
- Limited load on paved area is required, often not suitable for high speed or highly trafficked roads
- Prone to clogging without regular maintenance

MAIN FUNCTIONS
- Transpiration, reflection (albedo)
- Water infiltration, retention
- Water filtering
- Usability, functionality

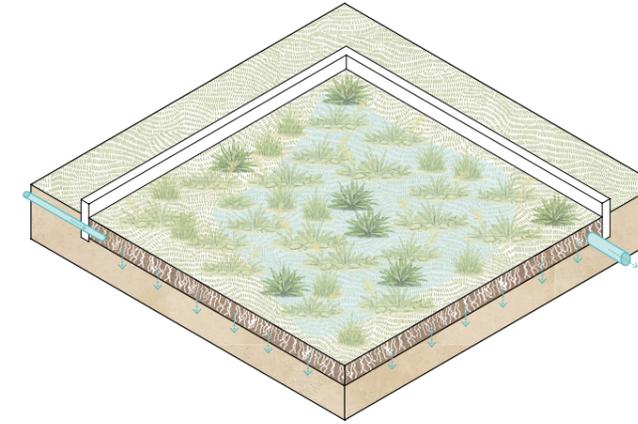**PRIMARY SDGs**
11, 13

SECONDARY SDGs
9

POTENTIAL SYNERGIES with other NbS
Green roofs, bioswales, constructed wetlands

SCALE
Block / neighborhood

SUITABLE LOCATION
Brownfields, industrial, dump or construction sites

MAIN CHALLENGES ADDRESSED
- Water scarcity
- Heat stress
- Air pollution
- Water pollution
- Flood risk
- Soil erosion

Biofilters are engineered bioretention systems designed to treat stormwater or greywater runoff by removing pollutants through a combination of physical, chemical, and biological processes. They typically consist of a vegetated filter bed composed of engineered soil media or granular materials, underlain by a gravel drainage layer, and planted with grasses, shrubs, or small trees adapted to periodic wet conditions. As runoff flows through the system, contaminants such as nutrients, sediments, metals, and organic compounds are removed through adsorption, filtration, and biodegradation driven by microorganisms forming a biofilm within the filter media. In addition to improving water quality, biofilters temporarily store stormwater and help reduce peak flows, making them particularly suitable for space-constrained urban environments and for integration within streetscapes or drainage corridors. Biofilters function as flexible NbS that can be configured as swales, trenches, or filter beds, contributing to sustainable water management while reducing reliance on conventional stormwater and wastewater treatment infrastructure (GreenUP, 2018; Morello et al., 2019; Raymond et al., 2017; UNALab, 2022).

MAIN CO-BENEFITS
- Reduces pollutant loads entering waterways
- Reduces stormwater runoff
- Aesthetic improvement of the urban landscape
- Enhanced psychological well-being
- Habitat creation
- Enhances property values

MAIN TRADE-OFFS
- Requires open land area
- Potential for mosquito breeding
- Potential pollutant mobilization, requires careful site selection to avoid pollutin groundwater
- Possible unpleasant odours through anaerobic processes

MAIN FUNCTIONS
- Water conveyance, infiltration, retention, storage, reuse
- Water filtering, bio-remediation
- Habitat provision

PRIMARY SDGs
3, 6

SECONDARY SDGs
9, 11, 13

POTENTIAL SYNERGIES with other NbS
Street trees, green strips

Once the three components of the framework have been defined – urban morphologies (UM), urban challenges (UC), and NbS archetypes (NbS) – the methodological process shifts from a conceptual definition to the tool construction. By systematically relating these three dimensions, the framework enables the exploration of how NbS can be strategically planned and combined within specific urban contexts.

The resulting tool functions as an **exploratory and qualitative decision-support framework**. Its purpose is not to prescribe a single optimal solution, but rather to support users in identifying which NbS are most compatible with a given urban morphology, which challenges they can address, and how multiple NbS can be combined to help generate synergistic effects. In this sense, the framework moves beyond the evaluation of individual NbS and supports an integrated understanding of NbS interactions and cumulative impacts, through a transparent and replicable structure.

Rather than relying on isolated pairwise relationships – such as direct NbS-UC or NbS-UM – the framework explicitly considers their combined and interdependent relationships. This **threefold perspective** makes it possible to detect synergies, compatibilities, and potential tensions that remain difficult to capture through single-nexus approaches. As such, the tool transforms the conceptual framework into an analytical and exploratory system, supporting comparison, iteration, scenario testing, and strategic decision-making in urban NbS planning.

NbS-UM interaction – Spatial suitability

The **first interaction matrix relates the 18 NbS archetypes to the 5 urban morphologies** (Fig. 64). This matrix evaluates the spatial suitability of each NbS within each morphology using a **qualitative scoring** system ranging from 0 to 2:

- 0 – not suitable
- 1 – partially suitable
- 2 – highly suitable

Scores were assigned based on a comparative review of scientific literature, European case studies, and NbS catalogues assessing compatibility among various NbS archetypes and different urban forms (Alves et al., 2023; Bona et al., 2022; Cardinali et al., 2021; EEA, 2020; EEA, 2021; GreenUP, 2018; Morello et al., 2019; Sarabi et al., 2021; Woods-Ballard et al., 2007; World Bank, 2021).

This first correlation matrix functions as a **filtering mechanism**, highlighting which NbS are realistically implementable within a given morphology considering physical constraints, spatial configuration, and functional requirements.

NbS-UC interaction – Challenge performance

The **second interaction matrix relates the 18 NbS archetypes to the 12 urban challenges** (Fig. 65). Here, the scoring system (0-2) expresses the **qualitative capacity** of each NbS to address a specific challenge:

- 0 – not able to address
- 1 – partially able to address
- 2 – highly able to address

Values were derived from a synthesis of European-scale reports, academic studies, and applied research, in order to reduce, as much as possible, bias factors linked to local or site-specific outcomes (Alves et al., 2023; Eisenberg et al., 2022; GreenUP, 2018; Raymond et al., 2017a; Sarabi et al., 2023).

While these values are informed by empirical evidence, they remain qualitative and context-sensitive. As such, they represent an informed approximation rather than a definitive performance ranking and may vary depending on specific local conditions.

NATURE-BASED SOLUTIONS		URBAN MORPHOLOGIES				
		Isolated tower	Courtyard block	Mid-rise slab	Dense individual houses	Isolated individual houses
1	Pocket park	2	2	2	0	0
2	Urban garden	1	2	1	0	0
3	Street trees	2	1	1	0	1
4	Hedges/shrubs/green fences	2	2	2	2	2
5	Green strips	2	2	2	0	1
6	Green roof – extensive	2	1	0	0	1
7	Green roof – intensive	1	0	0	0	0
8	Green wall – facace-bound	0	1	2	1	2
9	Green wall – ground-based	0	2	2	2	2
10	Free-standing green wall	2	2	2	0	0
11	Mobile vertical greening	2	2	2	0	0
12	Greening balconies	2	2	2	1	0
13	Constructed wetland	1	0	1	0	0
14	Retention/detention pond	1	1	1	0	0
15	Bioswales	2	1	2	0	1
16	Rain gardens	2	2	2	0	1
17	Permeable paving system	2	2	2	2	2
18	Biofilter	2	1	1	0	1

Figure 64 – Initial table showing the interactions between NbS and UM using a matrix created in Excel (Author's production).

NATURE-BASED SOLUTIONS		URBAN CHALLENGES											
		UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12
1	Pocket park	0	2	2	2	2	0	2	2	0	1	0	0
2	Urban garden	2	1	2	1	1	0	2	2	0	1	1	0
3	Street trees	0	2	2	2	2	0	0	0	1	2	1	0
4	Hedges/shrubs/green fences	1	2	2	2	2	0	0	0	1	2	0	0
5	Green strips	0	1	1	2	2	0	0	1	0	0	2	2
6	Green roof – extensive	0	2	2	2	2	2	0	0	1	0	2	1
7	Green roof – intensive	1	2	2	2	2	2	2	1	0	2	2	2
8	Green wall – facace-bound	0	2	2	2	0	2	0	2	2	0	0	0
9	Green wall – ground-based	0	2	2	2	0	2	0	2	2	0	0	0
10	Free-standing green wall	0	2	2	2	1	1	1	2	2	0	0	0
11	Mobile vertical greening	0	1	1	2	0	0	2	2	0	0	0	0
12	Greening balconies	1	2	2	2	0	0	0	2	0	0	0	0
13	Constructed wetland	0	1	2	1	2	0	2	2	0	0	2	2
14	Retention/detention pond	0	0	1	1	2	0	2	2	0	1	2	2
15	Bioswales	0	1	1	1	2	0	0	2	0	1	2	1
16	Rain gardens	0	0	2	1	2	0	2	2	0	0	2	2
17	Permeable paving system	0	0	0	2	2	0	0	0	0	1	2	2
18	Biofilter	0	1	1	1	2	0	0	1	0	1	2	2

Figure 65 – Initial table showing the interactions between NbS and UC using a matrix created in Excel (Author's production).

4.1.3 Construction and population of the visualization tools' options

To make the framework accessible to users with different backgrounds and technical skills, two complementary visualization options were developed:

- **Option A**: two 2D heatmaps combined with a Sankey diagram
- **Option B**: a parametric 3D matrix

Together, these tools enable both intuitive exploration and advanced analytical use.

In order to finalize the creation of both options, an additional step was required first: Since all the software used are not able to process data organized in a matrix layout, it was necessary to convert the first two data matrices into long-format tables, pairing each interconnection on a single line. In order to get to this outcome, the **Excel's Power Query function** was utilized, which translated the matrix conformation into a long three-columned table output (Fig. 66).

To combine the interaction matrices qualitative scores into single-value linear tables, a conservative aggregation rule was applied, for which the lowest compatibility number is selected, once for the NbS-UM matrix and then also for NbS-UC one. This prevents overestimating performance when one condition is not met.

The adopted equation to guide the single final value selection is the following:

if [Val_UM] < [Val_UC] then [Val_UM] else [Val_UC]

	NbS1	NbS2	NbS3
UC1	0	1	0
UC2	2	0	1
UC3	1	0	2
...			

UC1	NbS1	0
UC1	NbS2	1
UC1	NbS3	0
UC2	NbS1	2
UC2	NbS2	0
UC2	NbS3	1

	NbS1	NbS2	NbS3
UM1	2	2	0
UM2	0	1	1
UM3	0	2	1
...			

UM1	NbS1	2
UM1	NbS2	2
UM1	NbS3	0
UM2	NbS1	0
UM2	NbS2	1
UM2	NbS3	1

Figure 66 — Schematization of how the Power Query function in Excel merges a matrix table into a single long, linear disposition (Author's production).

Option A – Heatmaps and Sankey diagram

The first visualization option was developed using the Microsoft Power BI tool and a Sankey diagram software. By adopting this process, the numerical matrices can be translated into interactive graph-based graphics, instead of only relying on numerical values.

Through **Power BI two heatmaps** were developed (Fig. 67):

- NbS-UM heatmap for spatial suitability;
- NbS-UC heatmap for challenge performance.

The **color coding** reflects the qualitative scores previously defined in the initial matrices:

- Red/yellow/green indicate suitability levels (0/1/2) in the heatmaps.

Nonetheless, to overcome the limitation of two-dimensional analysis, a **Sankey diagram** (Fig. 68) was also introduced to better visualize the threefold relationship between morphologies, NbS, and challenges simultaneously. Here, instead of a color coding, a **size variation of the connections** has been adopted to show the level of suitability among the variables:

- No connection/thin link/thick link indicate suitability levels (0/1/2) in the left side of the Sankey diagram (UM-NbS), while the same dimensions represent the challenge-addressing capacity (0/1/2) on the right side of the diagram (NbS-UC).

This option is highly intuitive and interactive, allowing users to explore relationships simply by hovering over colored rectangles or connections. Outputs from both tools can be exported as static images (PNG) or used interactively within the software.

Option B – 3D parametric matrix

The second option was developed using **Grasshopper** (a plug-in for Rhinoceros), exploiting parametric modelling to construct a **three-dimensional interaction matrix**. The axes of the 3D matrix represent (Fig. 69):

- X – urban morphologies
- Y – NbS archetypes
- Z – urban challenges

The same qualitative values adopted in the first option are used also within this version, but the graphical representation slightly differs:

- Red/yellow/green still indicate spatial suitability levels (0/1/2);
- Little/small/large cubes indicate challenge-addressing capacity (0/1/2).

This option is more technically demanding and may seem more complex, but it also allows advanced filtering, more customization potential, and analytical control (Fig. 70). Users can isolate specific morphologies, challenges, or NbS through parameters selection – in the Grasshopper canvas they are listed under separate drop-down lists – and iterate this process until satisfied with the outcome. After that, users can export the resulting configurations as a simple PNG or a .gh file, if they want to save the entire selection process and their parametric connections. The comprehensive functioning and use of the 3D matrix are furtherly explained in this **video** [https://uploadnow.io/files/mYJkPzD].
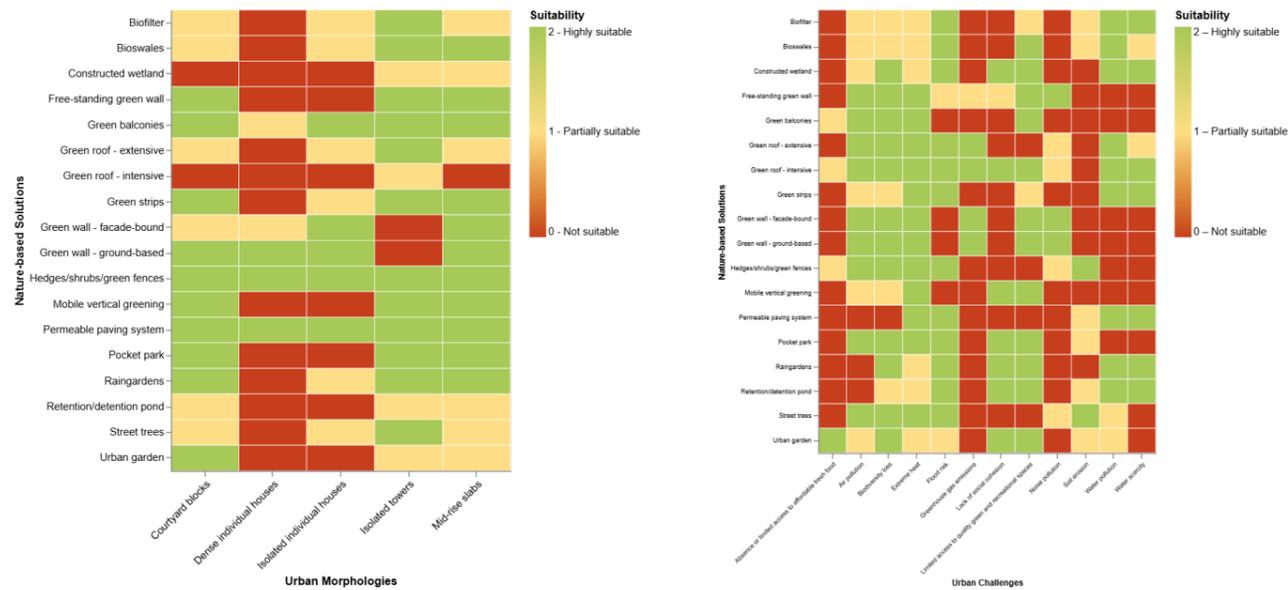
Option A – Heatmaps and Sankey diagram

Figure 67 – The two heatmaps representing NbS–UM interactions on the left and NbS–UC interactions on the right, created in Power BI (Author's production).

Figure 68 – The Sankey diagram representing the threefold connections between the main groups, starting from the left: UM, NbS, and UC (Author's production).

Option B – 3D parametric matrix

Figure 69 – Conceptual disposition of the three groups on the 3D matrix's axes (Author's production).
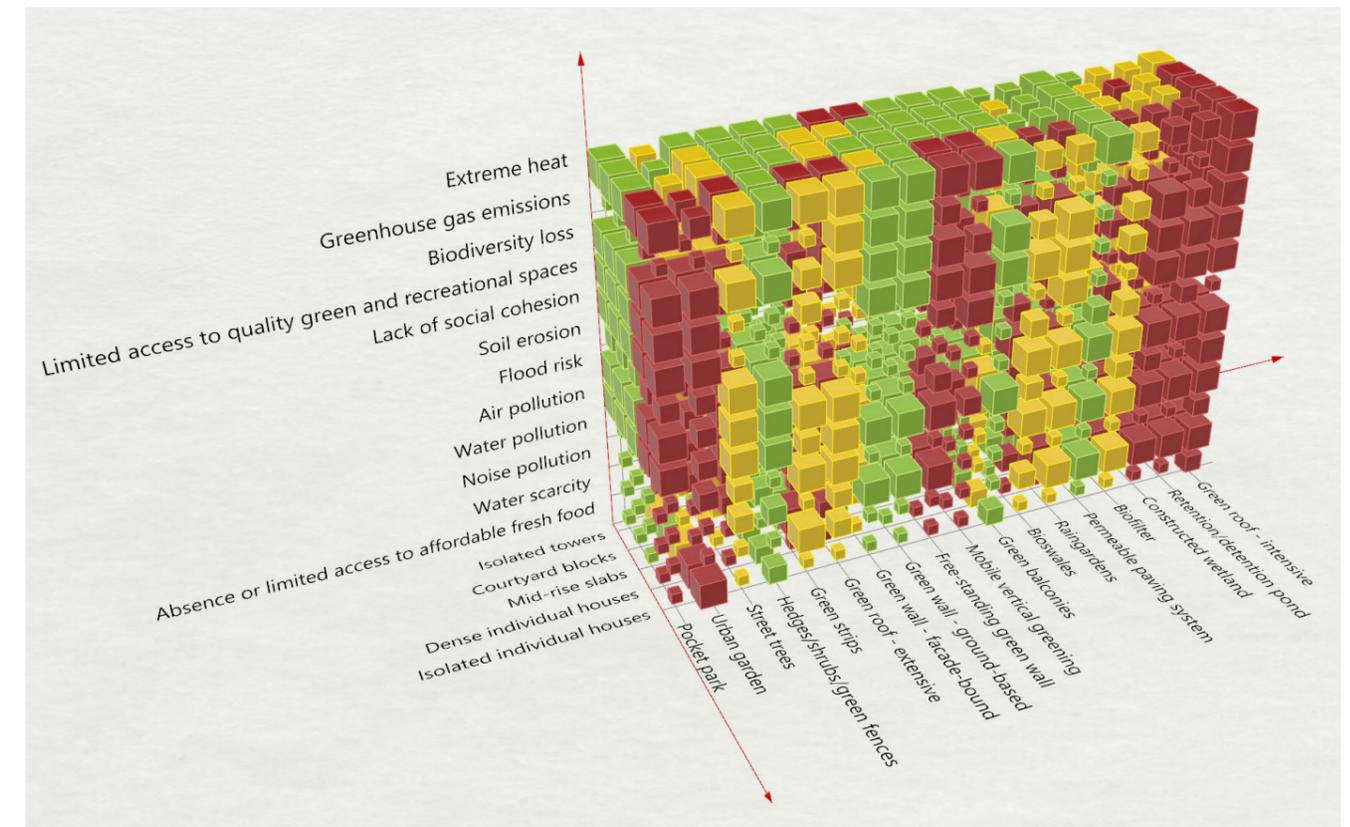
Figure 70 – Final 3D matrix generated in Grasshopper (Author's production).

From NbS archetypes to NbS pockets

Both visualization options support the identification and definition of NbS pockets, understood as coherent clusters of NbS that can be jointly implemented to generate cumulative and non-linear benefits.

It is important to add that NbS pockets are not predefined within the framework. Instead, they emerge through exploration of high-compatibility intersections between the variables. This avoids locking the system into predetermined solutions and preserves its open-ended, exploratory nature.

Once high-performing NbS archetypes are identified for a given context, compatible solutions can be aggregated into NbS pockets addressing one or multiple challenges. These pockets then serve as candidates for design application and spatial testing within the masterplan.

The definition of potential NbS pockets will be showed in the following application study for the linear slabs in Mirafiori.

4.2 DATA ANALYSIS

4.2.1 Context and site analysis

Selection of the project site

This section is strictly correlated to the initial analysis that saw the identification of the different morphologies within the chosen dis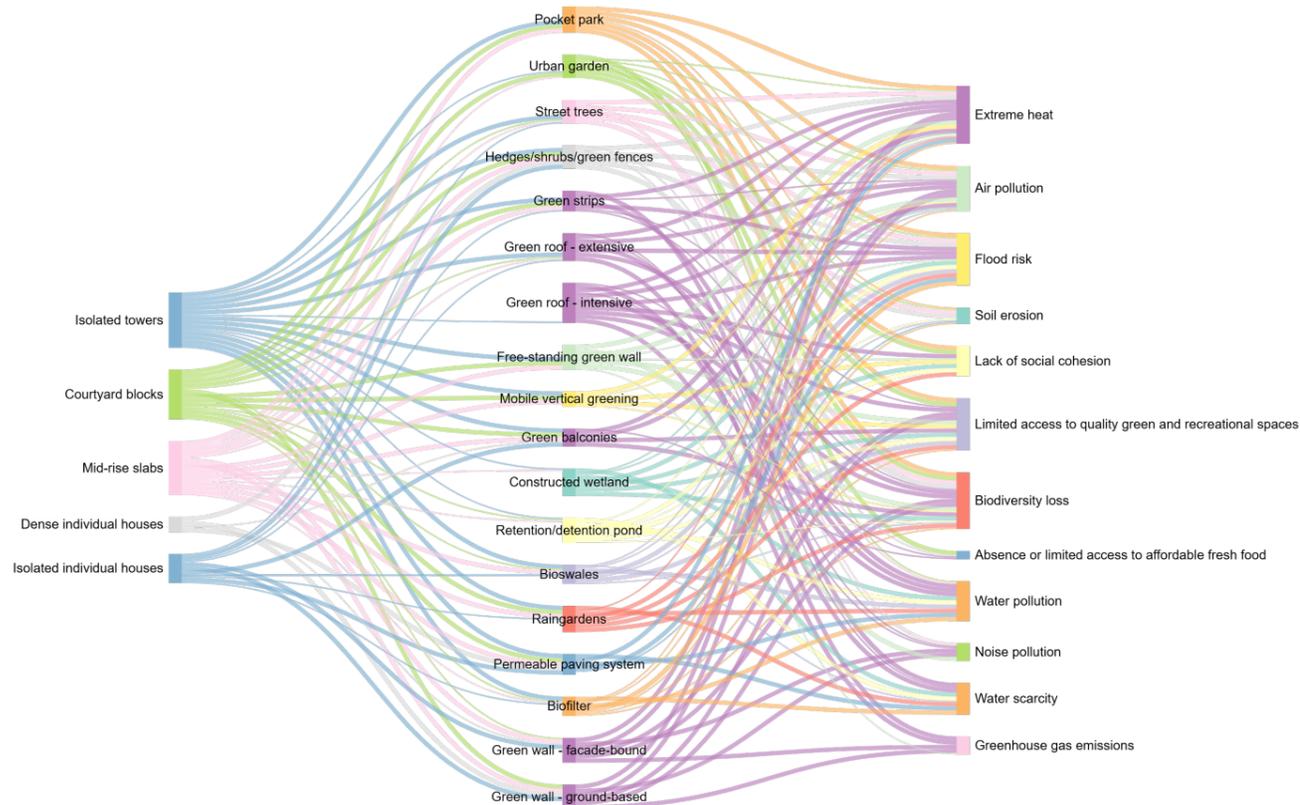trict, where diverse fabrics have been identified (ref. Fig. 56), and the consequent thorough analysis of the five specific real morphologies inside Mirafiori (ref. Fig. 57, pp. 94-98). Together, these five specific typologies capture a broad spectrum of European urban forms and provide the basis for the detailed morphological and climatic analyses that follow.

Among the five identified real urban morphologies based in Mirafiori, the thesis further proceeds with the selection of a single one, which is treated as the **case study**, on which the proposed framework is tested. The chosen typology is the **UM3 morphology**, hence a **mid-rise linear slab neighborhood placed in the southern part of the district**, embedded in the industrial area.

This typology is particularly relevant due to its widespread presence in post-war social housing developments and its strong interaction between built form, open spaces, and environmental performance, which together create significant factors to be evaluated from both social and environmental perspectives.

Cadastral data on buildings, blocks, street networks, as well as for data on population and environment factors were sourced from the analysis of papers, official georeferenced portals, and reports (Fig. 71-74) (i.e., Bednar-Fridl et al., 2022; Ellena et al., 2023; ISTAT Turin; 8milaCensusISTAT; Piedmont Geoportal). These data were then processed using the Geographic Information System (GIS) software, allowing for the structured analysis and sorting of spatial attributes associated with each urban morphology.

Site analysis of the case study area – UM3

The case study focuses on the regeneration of the UM3, which in Turin is known as the **INA-Casa neighborhood** (Fig. 75). This intervention was developed during the 1960s within the framework of the INA-Casa national public housing program, aimed at providing **affordable housing for medium- to low-income families**, many of whom were employed by FIAT. As a consequence of its original function and planning logic, the neighborhood is located in close proximity to highly impermeabilized and infrastructure-dominated urban fabrics. Still today, the district is less equipped with general public services and amenities, as the majority of restaurants, museums, and entertaining facilities are generally gathered towards the city center (TO – Mirafiori sud).

Being situated at the **city's periphery**, the area strongly prioritizes **vehicular mobility** over pedestrian and lighter means of transportation. Car traffic and on-street parking dominate both the main road network and the internal secondary streets, to the extent that vehicles are frequently parked directly in front of private garages. This condition contributes to increased noise levels, reduced air quality, and a limited availability of high-quality communal and social spaces across the entire block (Torino Atlas).

Climatic and environmental context

The city of Turin is characterized by a **warm temperate, humid climate** (Cfa) (Kottek et al., 2006), typical of low-altitude areas in the Po Valley.

In this climatic context, the **regular spacing** between the slabs allows sufficient daylight penetration and supports natural ventilation across the block. However, the **extensive** presence of **asphalted streets and sidewalks** in close proximity to building facades contributes to localized UHI effects, which are particularly perceptible near ground-level facades.

Orientation, environmental exposure, and microclimatic implications

The dominant orientation of the morphology results in the longitudinal axis of the **slabs aligned north-south**. This orientation favors the penetration of wind flows into the block, enhancing natural ventilation potential. However, it also exposes the **largest façade surfaces to east-west solar radiation**, increasing solar gains during summer months, particularly on west-facing facades.

Given that the building stock is now more than 50 years old, it no longer meets contemporary energy performance and insulation standards. The block is currently undergoing a regeneration process aimed at improving energy efficiency, primarily through the application of an external insulating system, accompanied by facades refurbishment.

Urban morphology and building characteristics

The urban morphology is circumscribed within a rectangular plot and is composed of **17 buildings**, resulting in a moderate overall building density. Fifteen buildings are residential and organized into **six slightly misaligned rows of eight-storey linear slabs**, arranged in a rectangular comb-like pattern. This configuration generates an open block morphology, with buildings positioned perpendicularly to the adjacent primary road axis. The layout creates a sequence of interstitial green spaces intersected by secondary asphalted routes. The residential slabs feature **double-pitched roofs** and are

characterized by integrated loggias, replacing traditional cantilevered balconies. The remaining **three buildings** differ from the prevailing morphology: they are **single-storey structures with flat roofs**, centrally located within the block, and accommodate public service functions such as a local grocery store and a bar. These elements contribute to the functional diversity of the neighborhood, although in a limited manner. From a constructive perspective, the buildings were realized using **heavy prefabrication systems**, with reinforced concrete frame structures typical of the period. Even the two smaller buildings, even though they are characterized by an outer layer of bricks, the load-bearing structure is made out of reinforced concrete, as suggested by the roof.

Circulation system and open spaces

The spatial arrangement of the slabs allows for the presence of **internal secondary roads** running adjacent to building facades, connecting the block's interior to the surrounding street network. While this configuration improves vehicular accessibility, it also fragments the continuity of green spaces and reinforces **car dominance** within the block. Moreover, it currently serves multiple overlapping functions, including pedestrian movement, car circulation, and parking.

The neighborhood is characterized by a relatively large amount of open space. Each slab is surrounded by **semi-public interstitial green areas** on all four sides. These spaces are mainly planted with lawn, shrubs, hedges, and mature trees, as (Fig. 76).

Despite their spatial extent these green areas are significantly **underutilized**. Architecture barriers limit their general accessibility, particularly for elderly residents and people with reduced mobility, including wheelchair users and families with strollers. No dedicated equipment or amenities were observed during the site visit, reducing the attractiveness and multifunctionality of these spaces as social or recreational areas.

Nevertheless, the **environmental potential of the green infrastructure is considerable**. The presence of mature, high-canopy trees,
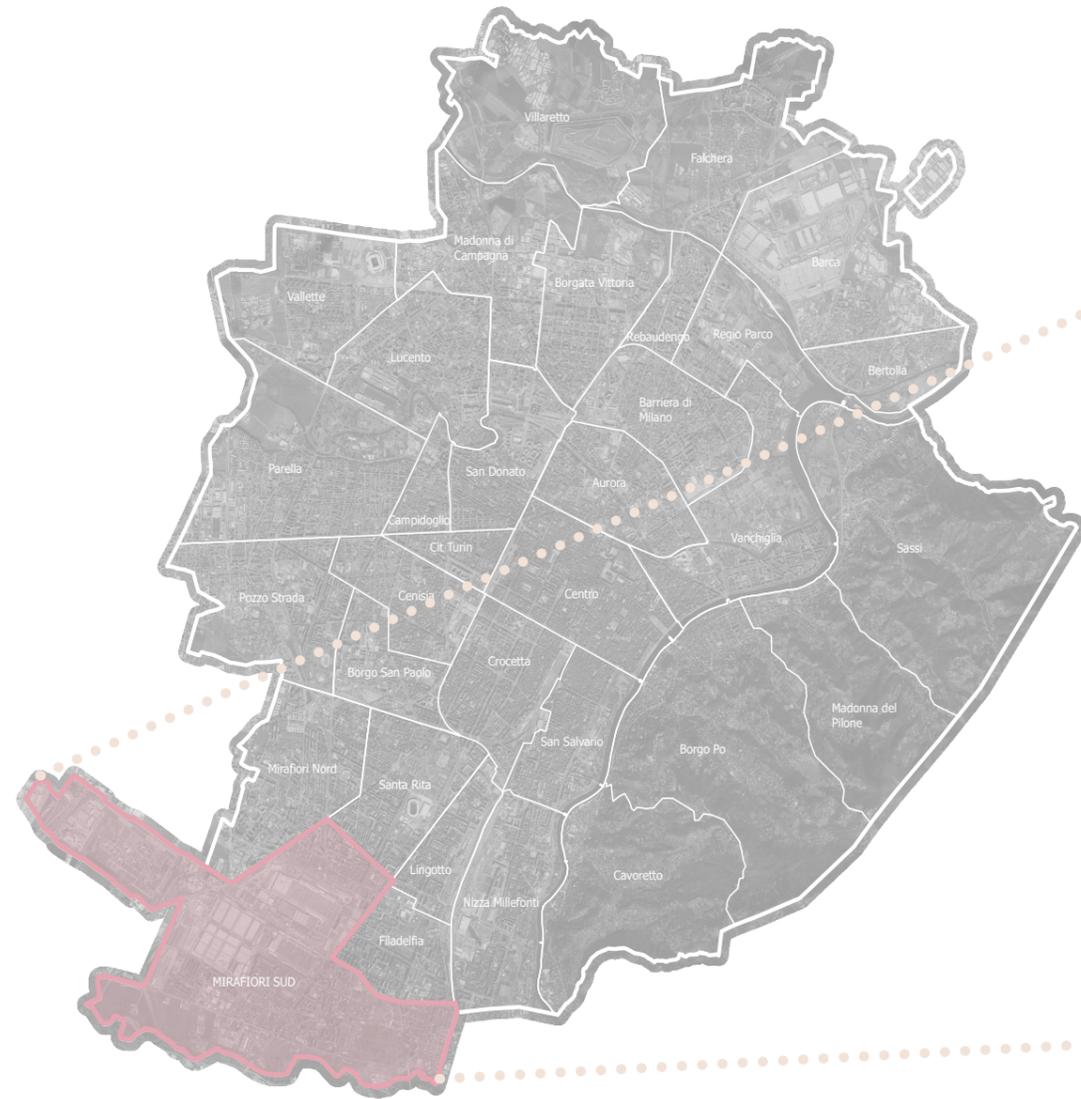
0   1   2km

Figure 71 – Graphic visualization of the geographical boundaries of the City of Turin and its districts, based on data retrieved from Geoportale Piemonte (Author's production).

☐ UM3

Figure 73 – Zenital ortophoto of the Mirafiori South district, highlighting the morphological forms and the important presence of the FIAT industrial site, covering the majority of the area and causing environmental disturbances within the whole area, based on data retrieved from Geoportale Piemonte (Author's production).

Green areas percentage   UHI hazard   Ischemic heart diseases risk
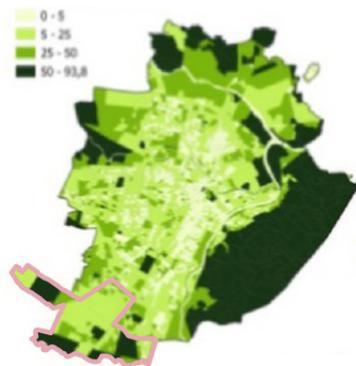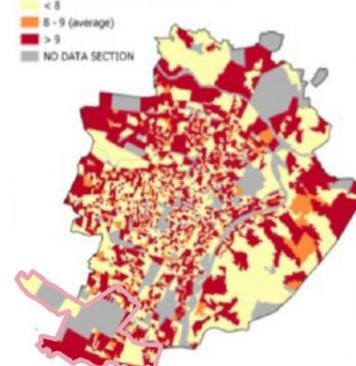
Figure 72 – Geographic spatialization of health risks and outdoor environmental attributes within the boundaries of the city: The first map represents the percentage of green areas; the second and third ones represent the health risks connected to ischemic heart diseases and diabetes among the population (Ellena et al., p. 10).

Older population percentage   Social isolation rate   Ethnic minorities presence
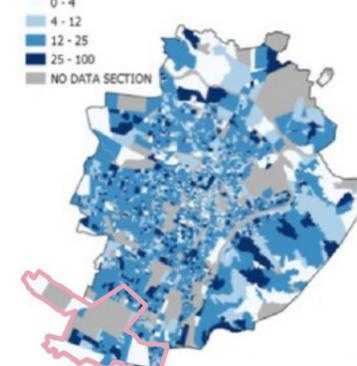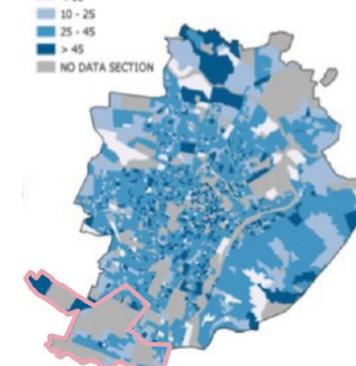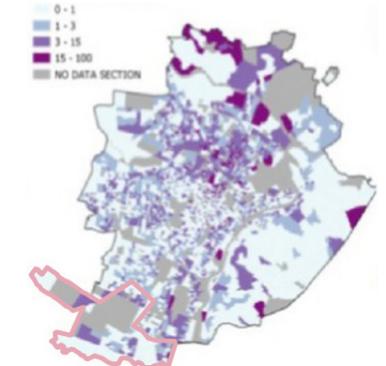
Figure 74 – Geographic spatialization showing demographic and socioeconomic data within the boudaries of the city: the first one on the left represents the percentage of older citizens living within the area (considered from +65 to +85 years old); the second one represents the rate of social isolation that can be encountered across the urban sites; while the third one represents the presence of ethnic minorities coming from poor countries with high migration pressures (Ellena et al., p. 10).

likely planted during the original construction phase, provides substantial shading capacity and contributes to long-term carbon storage. From a naturalistic perspective, the vegetation includes a variety of tree species, including tall conifers (i.e., Ash tree, Lime tree, Hackberry, Plane tree), which offer effective solar protection and relatively low maintenance requirements due to their resilience and established root system, as well as deciduous trees, which are especially beneficial in temperate climates (TorinoAtlas).

Although heat stress is partially mitigated by the presence of adjacent green areas and mature trees, the lack of spatial continuity, equipment, and active use limits their overall microclimatic effectiveness and social value.

- Educational facilities (kindergartens, primary, secondary schools)
- Sports facilities (football, volleyball, tennis courts)
- Coffee shops, bars
- Convenience and grocery stores
- Churches
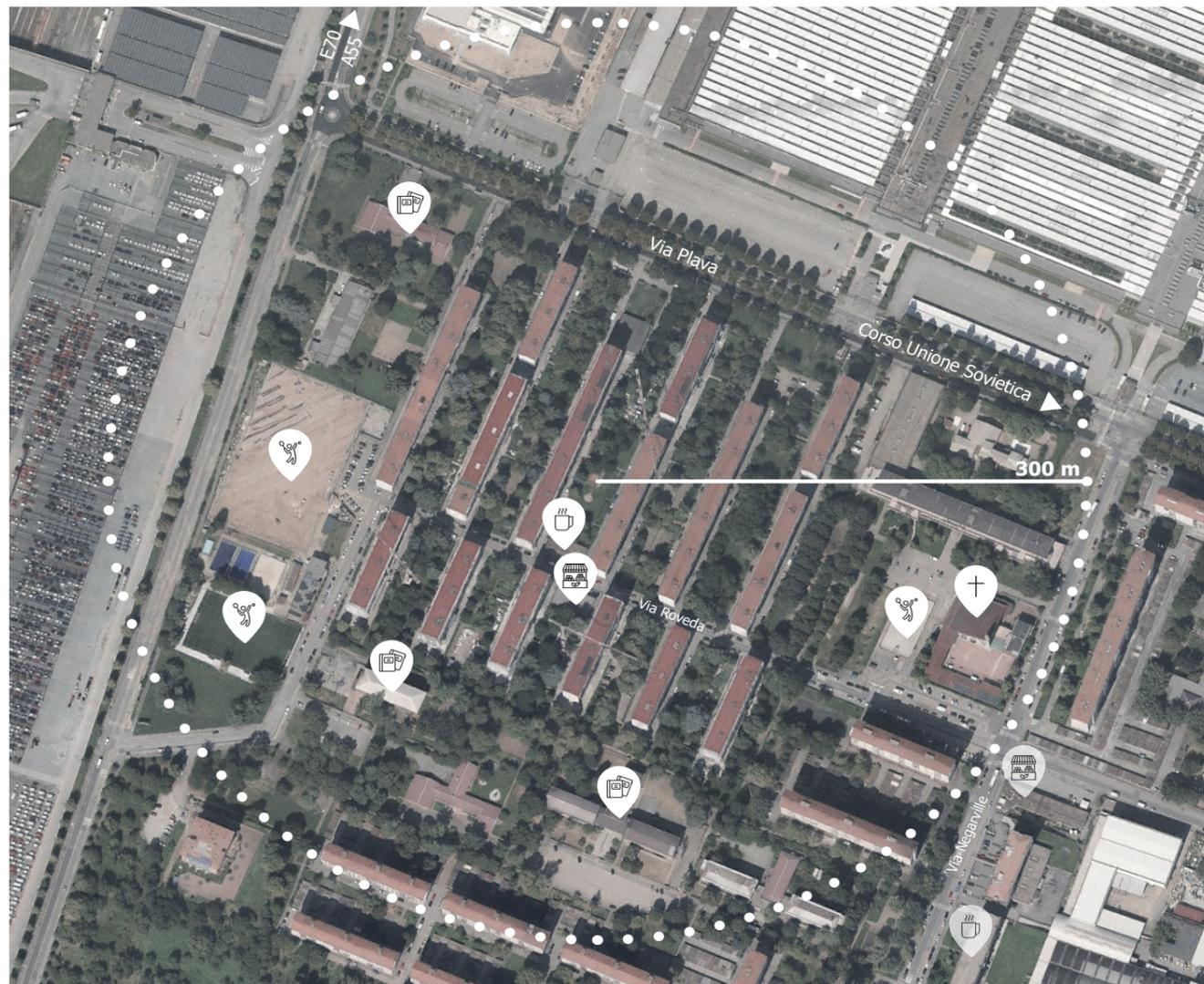
Figure 75 – Orthophoto of the project area and its immediate urban context, illustrated with primary vehicular connections to the city center and highroads, as well as the location of key public amenities and servicies, calibrated within a 5 minutes walk from the center of the analyzed area (Author's production).

Project area
Industrial area
Existing trees   1:500
  Evergreen
  Deciduous
—— Car lanes
—— Mixed paths
---- Pedestrian paths
---- Bike lane
P Parking lots

Figure 76 – Illustration of the context plan in which the urban morphology is inserted (Author's production).

Figure 77
Photo taken at the outskirts of the project area, showing a linear boulevard typology characterized by a central bidirectional bike lane, parallel parking strips, and aligned street trees. These trees are planted in small cut-outs within the paved surface, with limited permeable soil area visible around the trunks. Signs of pavement deformation suggest root damages to the road surface, likely due to constrained rooting space.
This spatial allocation prioritizes vehicular parking along both sides of the street, while tree pits appear undersized relative to canopy growth, potentially affecting long-term tree health and ecosystem performance (Author's photo, November 2025).

Figure 80
Photo showing one of the two one-storey commercial buildings inserted between the parallel slabs. The structure hosts local services, including a café and small retail activities, and represents one of the few active ground-level interfaces within the neighborhood.
The reduced height of the building creates a discontinuity in the otherwise uniform slab morphology, lowering the perceived enclosure and introducing visual permeability between the internal courtyards and the street.
However, the front of the structure directly faces an asphalted roadway with on-street parking and no vegetated buffer or transitional space. The absence of shading elements, permeable surfaces, or spatial separation from vehicular traffic reduces environmental comfort and limits the quality of this potential social attractor (Author's photo, November 2025).

Figure 78
Photo taken along the central street crossing the neighborhood, characterized by a linear sequence of eight-storey residential slabs arranged following a parallel alignment. The street section appears relatively narrow in proportion to building height, generating a vertically enclosed spatial condition.
The short facades facing the main street are largely blank, while window openings are concentrated along the longitudinal sides oriented toward the internal green areas. This configuration limits visual permeability and building-street interactions along this central path.
At ground level, the public realm is dominated by asphalted surfaces and parking spaces, increasing localized microclimatic disturbances related to heat accumulation (Author's photo, November 2025).

Figure 81
Photo summarizing the overall spatial characteristics of the neighborhood. The image captures the relationship between mature vegetated courtyards, impermeable pedestrian pathways, and slab buildings with service-oriented ground floors.
The geometrical path is framed by green edges and mature trees, while a vehicle positioned directly at the end of the axis interrupts pedestrian continuity and limits universal accessibility.
The contrast between sealed circulation surfaces and permeable but minimally equipped green areas highlights a fragmented integration between landscape and the rigid mobility infrastructure. While vegetation coverage is extensive, its maintenance and functional aspects appear limited, suggesting challenges in managing and enhancing the ecological performance of these internal courtyards (Author's photo, November 2025).

Figure 79
This photo illustrates a typical internal vehicular pathway within the slab-block morphology. The street section is narrow in proportion to building height, generating a highly enclosed linear corridor.
Horizontal surfaces along buildings throughout the area are entirely sealed with asphalt, with no visible permeable strips or infiltration areas along the building edge. The ground floor is predominantly occupied by garages and service entrances, creating an inactive and impermeable façade condition.
Parallel on-street parking occupies one full side of the pathway, further reducing pedestrian space and reinforcing the vehicular character of the space.
This configuration suggests limited capacity for stormwater infiltration and possible heat accumulation due to high surface impermeability and restricted sky view factor, further decreased by the grown vegetation (Author's photo, November 2025).

Figure 82
Photo showing the current condition of the internal pedestrian pathways within the neighborhood's green courtyards. The paved surface presents visible cracking and localized deformation, due to root growth. These irregularities generate uneven walking conditions and reduce overall pedestrian comfort.
The pathways are bordered by raised curbs that clearly separate circulation areas from planted surfaces. The lack of continuous level transitions or integrated ramps limits universal accessibility, creating physical barriers for wheelchair users, elderly residents, and people with strollers. As the entirety of these green areas is planted with overall grass coverage, such surfaces remain not structurally stabilized. As a result, accessibility to these spaces is limited, particularly during wet conditions.
This configuration highlights a fragmented relationship between pedestrian infrastructure and vegetated areas, where the presence of greenery is not fully integrated with accessibility and surface design strategies. Moreover, the absence of seating, lighting, or designated gathering elements limits the functional attractiveness of these green areas, reducing their capacity to support prolonged or diverse forms of use (Author's photo, November 2025).

S

- Open and offset building configuration, enabling effective solar access and natural ventilation;
- Peripheral urban location, with a relatively high availability of interstitial open spaces to create ecological connectivity;
- Presence of a multi-generational and multi-ethnic dwellers, offering a strong basis for inclusive and socially diverse public space use;
- Presence of mature trees, providing ES;
- High presence of sealed surfaces that could be converted into permeable areas;
- Spatial potential for on-site stormwater management.

W

- Limited pedestrian accessibility, particularly for vulnerable users;
- Predominance of vehicular traffic within internal secondary paths, despite the high presence of garages, resulting in inefficient land use and reduced spatial quality;
- Underuse of existing green spaces due to poor accessibility, lack of multifunctionality, and diversity;
- Weak sense of place and belonging, probably linked to limited opportunities for social interaction;
- High degree of surface impermeability, particularly along internal pathways and around buildings, contributing to local UHI effect.

O

- Prioritizing slow mobility and pedestrian accessibility of the internal paths;
- Enhancement of green space quality to promote equity, cohesion, and improved quality of life;
- Implementation of SuDS to support flood mitigation, water harvesting, and reuse;
- Expansion and improved management of green infrastructure to reduce heat stress and local UHI, improve air quality, and enhance carbon sequestration;
- Co-benefits including noise reduction, biodiversity support, and ecosystem resilience.

T

- Risk of excluding local residents from the design and decision-making process, potentially leading to low acceptance, misuse, or abandonment of interventions;
- Risk of increasing water scarcity, due to higher irrigation demands associated with expanded green elements;
- Climate uncertainty and the possible occurrence of extreme events that may hinder the efficiency of design solutions.

4.2.2 Exploration of possible relationships and iteration

The following design exploration and assessment of NbS pockets were conducted based on the outcomes of the context analysis, hence the SWOT assessment. In particular, the exploration of the 3D matrix allowed for a systematic comparison of suitable NbS in relation to the detected local challenges within UM3 (Fig. 83), in order to be able to understand the qualitative performance and synergistic functions of different NbS archetypes in terms of benefits, co-benefits, and potential trade-offs.

By analyzing all the spatial, morphological, and environmental elements emerging from the selection of UM3, it was possible to identify a restricted number of suitable NbS archetypes. This process did not aim at maximizing the number of interventions, as that is not a good indicator of a proper NbS design implementation, but rather at selecting those solutions that are form-fitting, spatially feasible, and capable of generating synergistic effects when combined. Based on this evaluation, **two distinct – but interrelated – NbS pockets were defined**.

4.2.3 Extraction of single or pockets of NbS

To guide and constrain the choice of NbS archetypes, only **eight solutions were selected from the 3D matrix**. Most of them show a high level of compatibility with the selected urban morphology and are therefore marked with green:

1. **Pocket parks**, already present in the form of trees clusters and shrubs, but requiring improved design and management;
2. **Street trees**, already present but requiring improved management and soil conditions;
3. **Hedges / shrubs / green fences**, already present but requiring improved continuity, variation, and management;
4. **Green strips**, already present in smaller sections, but requiring a widespread adoption, especially alongside the boulevard in Via Plava, to provide already present trees enough breathable soil and avoid root damages;
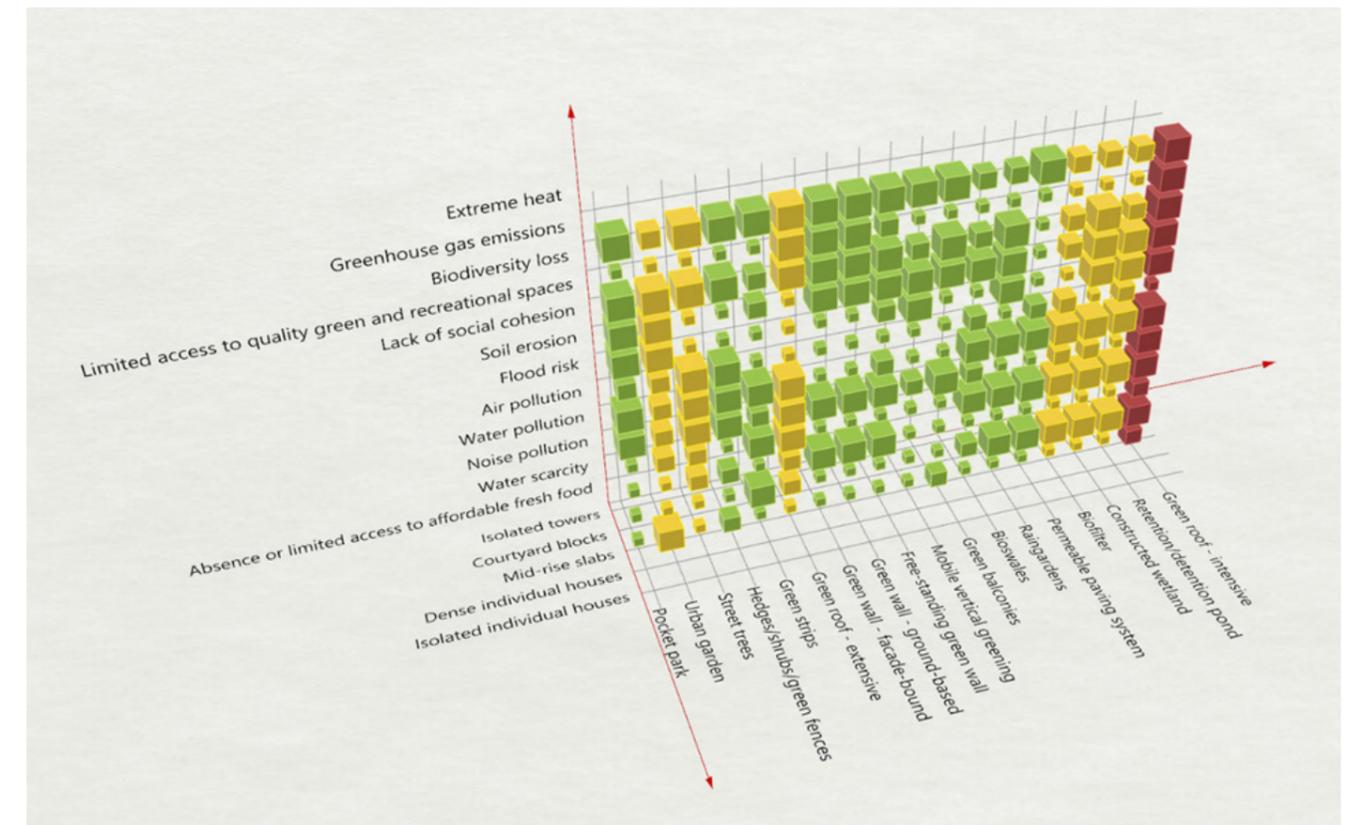

Figure 83 – The selection of UM3 – mid-rise linear slabs – in the 3D matrix created in Grasshopper. This action allows for the visualization of all the connected suitable NbS and possible challenges that can be addressed within that specific space (Author's production).

5. **Extensive green roofs**, newly implemented on the three one-storey high buildings, since they are the only flat-roofed

6. **Ground-based green walls**, newly implemented on the south-west facing facades, that are characterized by blank walls, with no windows;

7. **Rain gardens**, newly implemented near some of the buildings and on the northern part of the block, alongside Via Plava, to collect and infiltrate runoff water from the street and buildings;

8. **Permeable paving system**, newly implemented to replace asphalted internal pathways and sidewalks, using draining concrete, which is considered one of the most durable solutions among these types of systems.

As just mentioned, not all selected NbS are conceived as new additions. In fact, an important design principle of this project is the **recognition and enhancement of existing ecological and spatial values**, rather than their full replacement. Existing green elements therefore represent the structural backbone of the NbS strategy and are **upgraded and inserted within a broader system** to improve their quality and performance in terms of ecosystem services provision and social services.

Other NbS archetypes were excluded because of insufficient space to ensure effective performance, or because local conditions did not meet their technical or ecological requirements. For example, this selection criterion guided the choice of green roof typology. Since only the three smaller buildings are characterized by flat roofs, while the remaining ones present steeply inclined surfaces that exceed the advised inclination, this type of greening was allocated exclusively to these three structures. Moreover, the flat-roofed buildings are only one-storey high. This condition makes the adoption of extensive green roofs particularly advantageous: unlike extensive green roofs placed at higher elevations, which have a limited impact on

pedestrian-level thermal comfort, low-rise green roofs can directly contribute to mitigating localized heat stress along adjacent streets and pathways, as they would substitute a low-albedo concrete structure. Following a more conservative approach, the extensive green roof typology was preferred over the intensive one due to structural uncertainty and load-bearing constraints of the existing reinforced concrete structure, while still ensuring benefits in terms of rainwater retention, evapotranspiration, and surface temperature reduction.

A similar cost-benefit logic guided the preference for ground-based green walls over façade-bound living wall systems. While both solutions are compatible with the building heights, living walls would entail higher installation, maintenance, and irrigation costs. Ground-based systems, instead, provide comparable long-term benefits for microclimate regulation and air quality improvement, while remaining more economically feasible when implemented as part of a broader projects that merges various strategies together.

Definition of the NbS pockets

The identification of the most effective NbS pocket configurations was guided by the **exploration of the 3D matrix** and the parallel **evaluation of primary benefits, co-benefits, trade-offs, and contribution to the SDGs**.

This integrated approach enables a qualitative yet structured assessment of NbS pockets, moving beyond single-solution performance, toward a more complex effects evaluation.

This is particularly relevant to avoid isolated or compartmentalized NbS implementation. By doing so, the aim is to ensure that limitations or "gaps" in one solution are compensated by another, thus promoting **complementarities** and a broader range of ES provided. For instance, rainwater harvesting and runoff control measures can be addressed with diverse SuDS and GI elements on different levels, but by adopting them together, water management, and also enhanced biodiversity, thermal comfort, and social benefits could be ensured.

Based on this methodology, two NbS pockets prototypes were developed for UM3.

NbS POCKET 1 – Water-sensitive system

The first major challenge identified in the area concerns stormwater management. Although the district is characterized by extended green areas and mature trees, these elements require increasing amounts of water to maintain their health and functionality, particularly under future climate scenarios marked by hotter and drier periods. At the same time, the presence of highly impermeable surfaces close to building facades exacerbates runoff concentration, surface deterioration, and localized water stagnation after heavy rainfall events.

This situation highlights the need for a comprehensive water management strategy addressing the entire water cycle: interception, infiltration, filtration, temporary storage, and reuse. Such an approach reduces flooding situations right underneath the buildings' edges, improves groundwater recharge and water quality, and supports non-potable reuse, for example for irrigating green infrastructure or even flushing toilets.

The first NbS pockets is therefore conceived as a water-sensitive system, combining the synergistic interventions showed on the following page.

These newly implemented solutions are supported and enhanced by existing street trees and green strips, which are upgraded to improve soil permeability, vegetation diversity, and hydraulic performance.

Moreover, underground tanks can be added to retain water collected from buildings runoff and make it available for a secondary reuse, reducing irrigation demand and employment of potable water for uses that do not necessarily require it. Rather than attributing all phases of the water cycle to single NbS, the pocket functions as an integrated system in which different components collectively sustain each other to reach more sustainable water urban processes and uses.

NbS POCKET 2 – Urban cooling and environmental quality

The second major challenge identified in UM3 is related to heat stress and localized UHI effects. Despite the presence of green areas, high rates of surface impermeabilization, low-albedo materials (such as asphalt and concrete), and proximity to elevated summer temperatures. These conditions are further associated with reduced air quality, due to pollutant accumulation linked to both near industrial activities and the broader geographical and climatic context of the city.

To address these challenges, the second NbS pocket focuses on urban cooling and environmental quality, combining the elements indicated on the bottom.

These elements contribute to surface and air temperature reduction through shading and evapotranspiration, while also improving air quality by filtering pollutants and trapping particulate matter. Mature trees play a particularly critical role, offering immediate and effective thermal regulation.

Beyond their environmental performance, these interventions also enhance spatial quality and social well-being. The redesign and better equipment of pocket parks increase opportunities for social interaction, reinforce a sense of place, introduce recreational functions, and improve overall livability of the district.

Synergies and integrated vision

It is important to note that many of the selected NbS archetypes simultaneously contribute to a certain extent to both water management and urban cooling objectives. This overlap further supports the need to abandon compartmentalized approaches in favor of integrated NbS strategies, where cumulative and synergistic effects are explicitly considered, therefore offering a more complete beneficial effect (Fig. 84).

The NbS pockets developed for UM3 therefore demonstrate the necessity and positive approach of **combining multiple, modest-scale interventions** that can generate broader environmental, social, and economic benefits, reinforcing the relevance of the 3D matrix as both an analytical and design-support tool.

WATER SENSITIVE POCKET

URBAN COOLING AND ENVIRONMENTAL QUALITY POCKET

Stormwater peak delay, building insulation

Pollinator vertical continuity, aesthetic value

Aerial habitat extension

Water caption and retention

Biodiversity introduction

Carbon storage reinforcement

Subsurface recharge

Shading, surface temperature reduction

Hydrological load redistribution

Microclimate cooling

Public space attractiveness

Wind shielding

Water interception, conveyance

Evapotranspiration

Soil stabilization

Linear ecological connectivity

Acoustic buffering, biodiversity hotspot

Hydro-ecological buffering

Groundwater recharge

Peak mitigation

Biodiversity, carbon sequestration

Traffic fumes deposition

Nutrient filtration

Soil stabilization

Figure 84 – Graphical visualization of how both NbS pockets contribute to the benefits and provisions of the other one, specifying throguh the connections what are the most important services for each specific component (Author's production).

0 20 40 60 80m

Rain gardens near the street

Street trees

Green strips

Permeable paving on internal pathways

Hedges, shrubs, green fences

+254m

+255m

Ground-based green walls on south facing facades

Rain gardens near buildings

Pocket parks with recreational or sport equipments

Extensive green roofs on flat-roofed buildings

+256m

+258m

Figure 85 — Masterplan of the project site, specifying the spatial disposition of the adopted NbS (Author's production).

4.3.1 Masterplan and spatial organization of the chosen NbS

This project seeks to introduce **spatial variability**, ecological abundance within a large plot that has remained significantly underdeveloped relative to its potential. Instead of imposing a radically new structure, the strategy is based on incremental ecological enhancement, using NbS to activate latent environmental and social capacities already present on site (Fig. 85, 86). It is important to add that the final solution does not have to be considered as the only possible variation of NbS interactive implementation in this site, rather just one of the many possibilities that these solutions can offer.

A fundamental principle guiding the intervention is **minimal disturbance of existing and spatial conditions**. The project avoids unnecessary soil sealing, excavation, or removal of established vegetation, thereby preserving ongoing human, animal, and ecosystem cycles. All existing mature trees have been retained, recognizing their irreplaceable ecological value in terms of carbon storage, canopy cooling, habitat provision, and soil stabilization. Instead of clearing space, the new interventions are carefully inserted within the interstitial areas between trees, reinforcing rather than disrupting the existing ecological structure.

The preservation of the existent layout created the optimal conditions for the introduction of a network of **small but frequent pocket parks**. These spaces leverage the already established shade, microclimatic comfort, and spatial enclosure provided by the trees and **green fences**. Equipped with water fountains, recreational amenities, and seating areas, they enhance social gatherings and multifunctionality within the area.

To support the long-term vitality of the **street trees** along Via Plava, the impermeable asphalt directly surrounding their trunks has been removed and replaced with permeable **green strips**. Root guidance barriers are introduced vertically to prevent lateral root expansion beneath pavement layers, which leads to surface cracking, higher management costs, and safety risks, especially for the bike lane alongside. This solution improves root aeration, soil permeability, and stormwater infiltration, while reducing mechanical stress on the pavement. Moreover, by enlarging the permeable soil volume available to each tree, the intervention increases resilience during drought periods and enhances evapotranspiration during heat waves. The position of the **rain gardens** was determined through topographical evaluation. These systems are implemented in two complementary configurations: Along the northern edge adjacent to the roadway, in combination with green strips, where they intercept, slow down, and pre-filter runoff from the street; or in proximity to buildings, where they collect and treat roof runoff before temporary storage and potential reuse. The natural topographic inclination of approximately 4 m throughout the catchment area from south to north supports this strategy, enabling gravity-driven conveyance into the rain gardens, therefore avoiding relevant terrain modifications and reducing excavations. A critical design precaution concerns the separation of hydrological flows: Runoff from the street contains higher concentrations of pollutants (heavy metals, hydrocarbons, particulate matter), and although rain gardens provide filtration and a certain capacity of phytoremediation, their treatment performance cannot guarantee complete purification for reuse – for this a more structured SuDS is required. For this reason, two distinct water management systems are required: Roof runoff collected by rain gardens near buildings is filtered and directed to underground storage tanks for non-potable reuse (e.g., irrigation or ordinary building uses), while the street runoff passes through the rain

Water sensitive pocket

Urban cooling and environmental quality pocket

Solar radiation

Evapotranspiration effect

Surface water runoff

Water infiltration

Asphalted surfaces

Permeable surfaces

Green surfaces

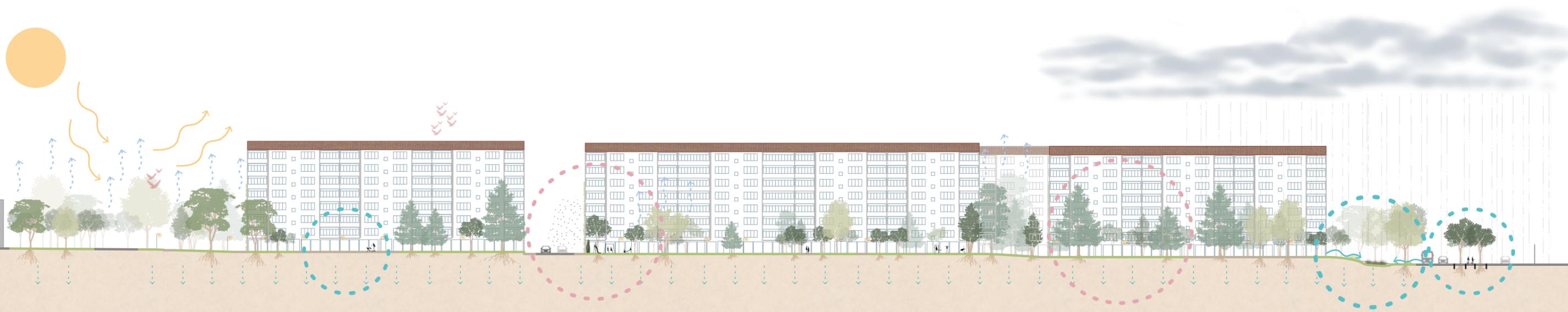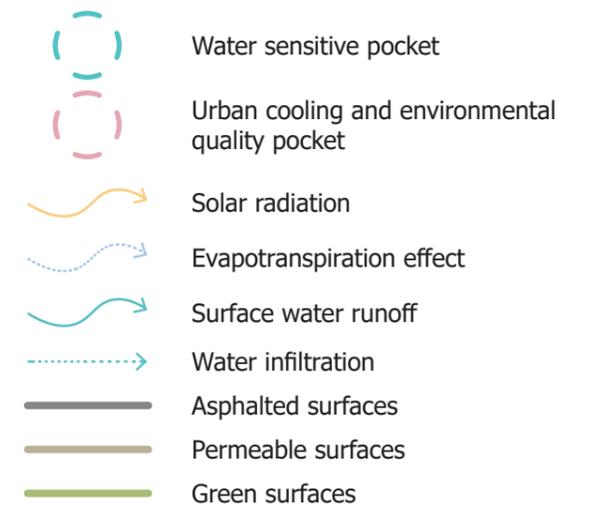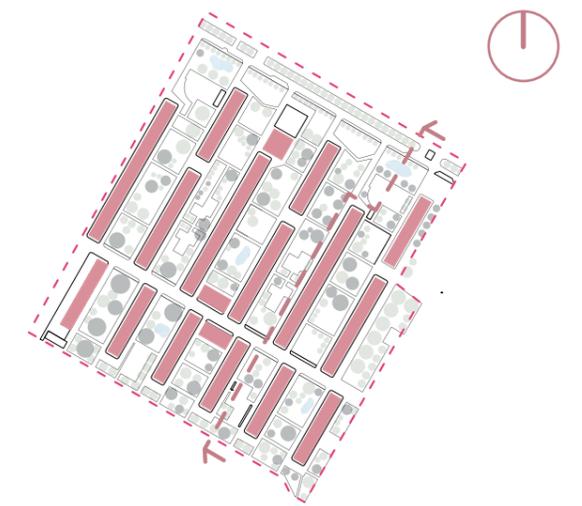0   20   40   60   80m

Figure 86 – Territorial section of the area, highlighting the NbS pockets' main ecological functions (Author's production).

gardens primarily peak attenuation and partial pollutant filtration before being discharged into the nearest grey water collector. This distinction ensures both environmental safety and functional reliability.

Permeable pavements are implemented throughout the internal pathway network to enhance on-site stormwater infiltration and prevent surface runoff accumulation near building facades. By increasing the pervious surface ration within the plot, it reduces localized water stagnation, limits splash-back effects on facades, and mitigates long-term moisture-related deterioration of building envelopes. At the same time, the permeable sub-base layers act as a temporary storage reservoir, attenuating peak flows during intense rainfall events and supporting gradual groundwater recharge.
The redesign of the internal circulation surface supports a broader spatial reorganization of the plot. The existing configuration prioritizes vehicular movement, resulting in a fragmented and pedestrian-unfriendly environment. The introduction of permeable paving accompanies a transition toward a low-traffic internal layout: Vehicular access is restricted exclusively to garage entry points, while other parking areas are maintained along the perimeter of the site. No additional parking spaces are foreseen within the internal pathways, to support walkability, social interaction, and green infrastructure integration. From a car-dominated environment to a pedestrian-oriented and ecologically integrated urban space.

Green walls are introduced along the south-facing facades, where solar exposure is highest and optimal for the plants, and passive cooling potential is therefore maximized. A lightweight support structure is installed to guide and sustain the natural ventilation growth of climbing species without imposing excessive loads on the existing building structures. The system is designed as a low-impact, soil-based solution rather than a fully technological living wall, ensuring lower maintenance requirements and costs, while introducing similar ecological integration. The

climbing vegetation is rooted within vegetated cut-outs integrated into the permeable walkway system. These ground-level planting beds provide sufficient soil volume for root development while maintaining pedestrian continuity. By directly connecting the vertical greenery to open soil rather than sealed containers, the intervention improves plant vitality, increases infiltration capacity, and enhances evapotranspiration cooling. Beyond shading the facades and reducing solar heat gain during summer months, the green walls contribute to thermal buffering of interior spaces, lowering cooling demand. They are also crucial for improving air quality through particulate capture from the direct traffic fumes, reduce reflected heat from the façade surface, and provide vertical habitat connectivity with other horizontal layers.

Extensive green roofs are implemented on the one-storey buildings, where regular, flat roof geometry and reinforced concrete structural systems make their installation both technically feasible and structurally compatible without requiring major reinforcement interventions. They can intercept and temporarily retain rainfall, reducing peak runoff and delaying discharge into the drainage network. The substrate layer enhances water storage capacity and promotes evapotranspiration, thereby contributing to localized cooling effects. From a building performance perspective, the additional substrate layer improves thermal insulation, reducing heat gains during summer – which is crucial for such little structure among the higher slabs – and limiting heat loss in winter, lowering overall energy demand. Although their contribution to mitigating UHI effect on pedestrian comfort is limited, their contribution is accentuated when combined with vertical greening, permeable surfaces, and canopy cover. Moreover, these surfaces introduce additional vertical habitat layers within the built fabric, increasing overall ecological services.

05
CONCLUSIONS

5.1 CONCLUSIVE REMARKS

As defined in the research objectives and questions, this thesis aims at developing a decision-support framework capable of organizing, visualizing, and assessing nature-based solutions in relation to specific urban contexts and related challenges. While the revised existing literature has widely demonstrated that individual NbS can mitigate particular urban challenges, such results often remain fragmented. They typically focus on a limited set of solutions or objectives, and rarely address how multiple NbS interact with one another or with the specific characteristics of different urban morphologies. As a result, the implementation of NbS frequently fails to respond adequately to local conditions, reducing their overall effectiveness and limiting their potential secondary benefits.

This thesis addresses this gap by proposing a framework that explicitly analyzes context through the definition of urban morphology types and systematically links them to NbS archetypes and urban challenges. By doing so, the framework shifts the focus **from isolated interventions in a less specified spatial environment, toward a relational understanding of NbS functioning**.

The core contribution of the proposed framework – articulated through two complementary visualization options (heatmaps combined with a Sankey diagram, and a 3D matrix) – lies in the provision of a **structured and interactive checklist of morphology-challenge-NbS relationships, that enables the qualitative assessment of synergies**, complementarities, and trade-offs among such elements. This tool allows users to explore how different NbS perform across diverse dimensions, making explicit not only their primary benefits, but also secondary positive or negative implications that may arise. In this sense, the framework acts as an **intermediary between NbS research and urban planning practice**, translating complex, multi-dimensional knowledge into a format that is legible and actionable for designers, planners, and decision-makers.

Furthermore, the framework explicitly promotes a shift from viewing NbS as stand-alone measures toward their **interpretation as integrated systems or pockets**. By visualizing how multiple NbS can support one another and collectively address multiple diverse or similar challenges, the tool reinforces the importance of adopting synergistic strategies, capable of delivering a more oriented project.

Therefore, one of the key strengths of the framework is its ability to support **early-stage urban design** and planning processes. Rather than providing prescriptive or performance-optimized solutions, it enables a **preliminary qualitative evaluation of how different NbS may affect a given urban morphology**. This supports more informed prioritization processes, helping municipalities and practitioners avoid poorly targeted interventions driven by incomplete information.

Although the design application presented in this thesis focuses on the Mirafiori district, **the framework itself is not site-specific**. It is grounded in Europe-wide literature, classifications, and recurring urban patterns, and was conceived as a transferable methodological tool rather than a context-bound solution. The chosen morphology in Mirafiori (UM3), therefore, served as a testing ground to demonstrate the framework's applicability, rather than as its ultimate scope. As such, the proposed approach is adaptable to other European cities characterized by similar morphological and environmental conditions.

Overall, this thesis contributes to ongoing efforts to bridge conceptual NbS frameworks with the practical needs of urban planning and design. By making NbS synergies, co-benefits, and spatial suitability explicit in relation to urban forms, the proposed methodology offers a structured yet flexible tool to support more context-sensitive, equitable, and effective NbS implementation strategies.

5.2 LIMITATIONS

As it has emerged in the previous chapters, one of the strengths of this research may be attributed to its positioning between academic research and planning practice. The proposed framework is neither a purely technical simulation tool nor a purely theorical research, but rather a decision-support system aimed at facilitating early-stage reasoning about NbS adoption. However, this same factor also determines the limitations of the thesis.

From a **methodological perspective**, the framework is based primarily on qualitative and comparative assessments of NbS suitability. This entails that the identification of complementarities and trade-offs among NbS, morphologies, and challenges relies on an extensive literature review and on logical assumptions, which take reference from empirical data and numerical simulations calculated in diverse case studies around Europe, but is **not able to provide quantified outputs, at this stage at least**. In fact, the output has to be treated as a methodology to obtain structured indications of relative suitability and complementarities, which might not be universally shared or recognized as such.

In a similar way, the evaluation of NbS impacts on microclimatic and spatial conditions is conducted at a qualitative level. While specific numerical microclimate simulations could offer more precise, site-oriented results, their inclusion would have conflicted with the broader objective of developing a transferable framework applicable across diverse geographical realities. Simulation-based approaches are inherently dependent on localized climatic data and detailed physical measurements, which would limit the broader application of the framework. For this reason, the methodology is intentionally designed to support early-stage design and planning decisions, rather than detailed performance optimization. Its output should therefore be interpreted as indicative rather than absolute, and as a preliminary step preceding more detailed, site-specific, empirical proof.

Another limitation concerns the **range of influencing factors** that are included in the framework. While environmental performance, spatial compatibility, and social implications are considered, the research does not incorporate assessments on economic feasibility, life-cycle costs, maintenance requirements, or governance constraints. Though, these factors are crucial to secure the long-term success of the project and can significantly influence decision-making outcomes. However, their systematic inclusion would require extensive data research, that exceed the practical feasibility of this one.

In conclusion, the framework alone **does not intend to directly indicate where exactly** interventions should be prioritized within a given morphology, but rather **which types of NbS are most appropriate for that morphological condition**. In order to correctly place the intended solutions, a more detailed context analysis is required, basing the choice on cartographic and empirical proof. This choice reflects the primary focus of the thesis on urban form as a structuring dimension, independent of the spatial intensity of individual conditions. While morphology strongly influences microclimatic behavior and NbS suitability, it does not capture the full spatial variability of single urban realities.

5.3 FUTURE DEVELOPMENTS

The adoption of the proposed methodological framework opens up a wide range of opportunities for future research, technical development, and practical adoption. While the framework is intentionally designed as a qualitative, early-stage decision-support tool, several extensions could significantly enhance its analytical depth, predictive capacity, and operational relevance, especially leveraging on the parametric connotation introduced with the 3D matrix developed in Grasshopper.

A first path of future development may concern the integration of quantitative performance assessments. The framework could be coupled with numerical simulation tools, such as microclimatic models (e.g., Envi-MET, Honeybee, etc.) or hydrological models, to further detail the relationships currently assessed through the visualization tools. By linking NbS archetypes and urban forms to performance indicators derived from simulations, the framework could provide a more robust evaluation of cumulative NbS effects, co-benefits, and trade-offs, guiding a better assessment of diverse NbS pocket solutions. This would enable to express the relationship between the three groups in terms of likelihood or degrees of effectiveness, to help introduce a greater variability component. For example, by establishing differentiated temporal scenarios and time-related performance of NbS (short., medium., and long-term), the framework could assist decision-makers in selecting the solutions more capable of delivering measurable performance improvements within defined time horizons. Moreover, it would be possible to distinguish between readily deployable, low-complexity solutions suitable for near-term targets, versus more complex, resource-intensive interventions, whose benefits unfold over longer timeframes.

Closely related to this, future work could focus on the parametric automation and optimization of NbS pocket generation. At the moment, NbS pockets are identified through relational logic and interpretative analysis. Embedding this logic within parametric components would allow automated generation, comparison, and refinement of diverse NbS pockets based on predefined objectives and constraints. In this context, benefits, co-benefits, and trade-offs could be integrated directly into the visualization environment, reducing the need for parallel analytical steps and enhancing the framework's usability for practitioners. This would ensure a faster and potentially more complete evaluation process for the final composition of NbS pockets. Overall, these future developments result as ways to evolve the framework from a qualitative decision-support system toward a more comprehensive quantified planning instrument, capable of bridging design exploration, quantitative assessment, and policy implementation while retaining its morphology-sensitive and context-aware foundation.

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