Green infrastructure for human health, climate adaptation, and biodiversity in urban areas.

BSc Thesis

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BSc Civil Engineering

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Preface

Throughout the BSc Civil Engineering degree, I have developed a great passion towards sustainable urban development. Topics such as climate change and spatial development were of particular interest of mine, which peaked during the Module 7, where me and my project group had to propose a new housing development in Zwolle. After that module, I had no doubts that I want to write my thesis in a similar domain and I could not have imagined that I would be given the opportunity to carry out an assignment on such an interesting but at the same, important topic, which is green infrastructure in urban areas.

I would like to thank my University supervisor, Karina Vink, for an overwhelming support and great guidance, which helped me immensely during this thesis project. I am very happy that besides meeting my own academic ambitions, I was able to utilize my creative skills, which resulted in a guideline that hopefully, can be useful for practitioners in the field of urban green infrastructure. This would not have been possible without the freedom I had and support of Karina, which greatly increased my confidence in myself.

In addition, I wish to thank my external supervisors, Joeri Meliefste and Femke Pos from Sweco[1], who were very welcoming and supportive throughout this project. Their expertise, resources and knowledge of the industry helped me considerably with progressing forward with my thesis and getting where I wanted to be with my work. I would not have imagined that my first experience of working in a professional environment would be this fun and inspiring.

Despite the fact that I had to write my BSc thesis mostly at home, I had a very inspiring and fulfilling learning experience, for which I wish to thank my supervisors. Moreover, I would like to thank my family and all my friends in Enschede who were very supportive and caring, especially in the moments of doubt.

This thesis marks the end of my BSc Civil Engineering degree at the University of Twente and now, I hope to contribute further to the topic of sustainable urban development by carrying out an internship in a consultancy firm as a part of my orientation year in the Netherlands.

I hope you will enjoy reading this thesis!

Andrei Moskvin, 23/08/2021

[1] Sweco is a leading European engineering consultancy firm with offices in 14 countries and more than 17000 employees.

Executive summary

Urban green infrastructure is the effective tool for increasing resiliency of cities to effects of climate change and making cities more attractive, both for people and animals. However, while the evidence of the benefits of green infrastructure is mounting, there is a shortage of practical knowledge for green infrastructure design. More knowledge is required on how to design with green infrastructure and unlock its ability to deliver multiple benefits.

This study was conducted under the supervision of Sweco and focused on the developing of green infrastructure design guideline for climate adaptation, biodiversity and human health. Overall, new approach was developed that considers multiple design characteristics, such as the location, structural traits of vegetation and its spatial arrangement. The guideline was applied in Presikhaaf, Arnhem, which showed that implementing green infrastructure in the existing urban landscape is a challenging process due to many spatial constraints. Nevertheless, the objective of the study has been met, and the developed guideline has a potential to be useful for practitioners in the field, especially where the new development is planned.

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1. Introduction

The increasing effect of climate change put at risk the livability of cities. The effect of climate change can be observed in extreme weather events that range from droughts and high air temperatures to heavy precipitations and floods. If the effects of climate change are left ignored, they will intensify existing problems and make it more difficult for cities and countries to achieve sustainable growth (World Bank, 2011).

Cities are particularly vulnerable to climate change because of the high concentration of people and infrastructure. Various factors such as an increasing rate of urbanization, population growth and an evergrowing demand for resources even increase the chance of unpredictable events from climate change (Guillebaud & Hayes, 2008). According to the UN, two-thirds of the global population will live in cities by 2050 (United Nations, 2014), therefore, it is of significant importance for cities to adapt to changing environment and become resilient to various effects of climate change.

Moreover, increasing urbanization poses a threat to not only human well-being but also to natural ecosystems. Expansion of urban land leads to fragmentation of natural habitats, which makes it challenging for many species to move across the landscape and increase their population. Loss of habitats or decrease in food and water availability are some of the effects caused by urbanization, which are even exacerbated by climate change.

One of the remedies against presented issues is green infrastructure, which is often characterized as a network of natural areas, such as urban parks or smaller individual elements, such as trees or green roofs. Besides making cities more resilient to climate change, green infrastructure is an effective tool to restore habitats and even enhance biodiversity in the urban landscape. Moreover, green infrastructure delivers many other benefits to humans besides improving microclimate in cities. It can even improve mental well-being, promote physical activity and contribute to social cohesion.

Overall, green infrastructure does not only make cities resilient to climate change but also makes them more livable and attractive, for both people and animals. This aspect of multifunctionality significantly increases the economic value of green infrastructure, thereby making it a great addition in all urban areas.

This thesis aims to bridge the gap between science and practice by introducing a way how to achieve multifunctionality of green infrastructure in urban areas. The thesis is written within Sweco, which is a commissioning party for this project.

1.1. Problem description

Many countries, including the Netherlands, have started developing strategies for climate adaptation. As it is mentioned in the introduction, green infrastructure is an effective solution for tackling issues resulting from climate change, while making cities more attractive and biodiverse.

One of the Dutch cities that is on the forefront of using green infrastructure is Arnhem, which recently presented a climate adaptation plan for the next decade. Despite the ambitious goals presented by the Municipality, such as increasing the fraction of trees to improve a thermal comfort or replacing a considerable amount of pavement by green, the plan lacks clarity on how to achieve such goals on practice. In addition, multifunctionality of green infrastructure is briefly discussed in the plan, where additional benefits such as improved appearance of the city and attractiveness to animals are mentioned, however, such multifunctional aspect also lacks clarity and practical supporting examples.

Such limitations might create a challenge for the Municipality of Arnhem to achieve the stated goals and successfully increase the fraction of green infrastructure in the city.

1.2. Research gaps

Overall, lack of clarity and specificity in green infrastructure design is not just an issue encountered in the Netherlands. Practical documented knowledge is very scarce in general, despite the growing awareness about the benefits of green infrastructure. Several planning strategies were found in literature, however, most of these strategies seem too theoretical and it unclear how to use them on practice.

For example, common planning principles include connectivity, which refers to the linkage of all components of green spaces and multifunctionality, which refers to the ability of green infrastructure to deliver several benefits (Monteiro et al., 2020). However, questions arise on how to apply such principles and what factors are important to consider during the application process. Moreover, it was observed across scientific literature that green infrastructure elements are frequently not distinguished between each other but taken as an indistinguishable whole. As another limitation, many publications focus explicitly on trees, while other types of vegetation are left ignored. As of now, research is required to make planning strategies more specific and generally increase the knowledge on vegetation other than trees.

Moreover, it is common among planners to consider only one benefit of green infrastructure during the design process (Di Marino et al., 2019). As it was mentioned earlier, green infrastructure is capable at delivering multiple benefits on one site, however, very scarce literature was found that focused explicitly on multifunctionality of green infrastructure and only one publication was found that presented a practical approach for achieving multifunctionality on practice.

1.3. Research objective

From the problem description and research gaps it becomes apparent that there is a shortage of green infrastructure design guidelines and particularly, guidelines that address multiple benefits of urban green infrastructure. This study will attempt to address the research gaps by presenting a design guideline for multifunctional use of green infrastructure. Multifunctionality will specifically concern climate adaptation, biodiversity and human health. Thus, the research objective is as follows:

Develop a design guideline for urban areas that addresses combined benefits of green infrastructure, which are climate adaptation, biodiversity, and human health.

After completion of the guideline, it will be applied in Arnhem, Netherlands, as it will be shown in the validation chapter.

1.4. Research questions

In order to fulfill the objective, the main research question was formulated, which reads:

How can green infrastructure have a combined positive impact on climate change adaptation, biodiversity, and human health in the urban environment?

Besides the main research question, nine sub-questions were formulated that will guide the research process. First sub-question concerns the benefits of urban green infrastructure, which are related to climate change adaptation, human health and biodiversity.

1. *What benefits does urban green infrastructure have in relation to climate change adaptation, human health and biodiversity?*

As a first step towards investigating the practical side of implementing greenery, in the next sub-question, various types of urban green infrastructure are researched, which can be associated with benefits identified in the previous question:

2. *What types of green infrastructure can deliver identified benefits?*

In the following question, disservices of urban green infrastructure are researched, as this information is important to consider when developing a guideline:

3. *What are the possible disservices and trade-offs of implementing this type of green infrastructure?*

Furthermore, existing green infrastructure planning strategies are explored:

4. *What strategies and design principles regarding the implementation of urban green infrastructure exist in literature?*

To conclude exploring the practical side of designing with green infrastructure, planning practices adopted in the Netherlands are reviewed:

5. *What is the state-of-art of implementing green infrastructure in the Netherlands?*

After gathering information on the urban green infrastructure a list of design requirements is drafted:

6. *What requirements can be drawn based on the research phase?*

As a next step, it is examined how these requirements can be translated into specific design instructions for implementing urban green infrastructure:

7. *How can a green infrastructure design guideline be developed that complies with these requirements?*

After completing the design guideline, applicability of it will be checked with experts in the field of green infrastructure:

8. *How does the guideline need to be adapted to be more useful for experts in the field of urban green infrastructure?*

Finally, the guideline will be applied in Arnhem. This is done in order to see how applicable the guideline is in the specific case and whether further revision of the requirements is needed:

9. *How does the initially developed guideline need to be adapted after testing it in a case study?*

1.6. Research limitations

Limited available time for the research assignment and lack of sufficient literature created several constraints that are discussed in this section. Firstly, it is important to mention that green infrastructure is an umbrella term for not only vegetation but also for blue elements, such as lakes and canals. This research will focus explicitly on vegetation in urban areas.

Secondly, the guideline is intended to be applicable in Arnhem, Netherlands, however, it might be possible that it can be used in other locations as well, but it will not be verified in this study.

Finally, it should be noted that effectiveness of the guideline will not be checked via real life application but rather, through theorical application and through interviews, as it will be elaborated in the research methodology chapter. In addition, no additional software (such as heat assessing tools) will be used to check the effectiveness of the guideline.

1.7. Report structure

The thesis begins with the research methodology chapter, where it will be elaborated on methods used to answer research questions. Methodology chapter is followed by the research results on urban green infrastructure in chapter 3, design phase in chapter 4, where the guideline is made, and validation phase in chapter 5, where the guideline is applied in Arnhem. The report ends with conclusions and recommendations for the further research in chapters 6 and 7 respectively. Appendices include any additional information that will be referred to throughout the report.

2. Research methodology

The research follows a design cycle proposed by Wieringa (Wieringa, 2014). The original cycle consists of four phases, namely problem investigation, treatment design, treatment validation and design implementation. The latter will be not included in the cycle as it concerns real life implementation of the proposed design solution, which is outside of the scope of this project. The first three phases will be referred to as research phase, design phase and validation phase respectively, as described in Figure 1:

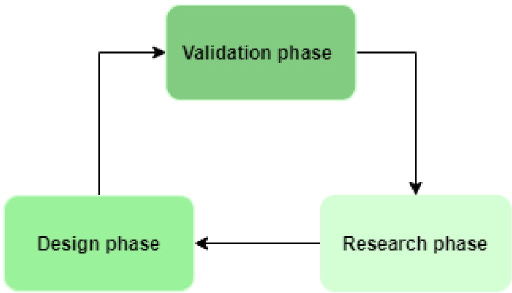

Figure 1: Design cycle (Adapted from Wieringa, 2014)

2.1. Research phase

Literature research is chosen as a method to answer the first four sub-questions in the research phase, as it can be seen in Figure 2. The aim of first three questions is to explore various types of urban green infrastructure that can potentially be multifunctional and determine disservices associated with these types of urban vegetation. The aim of the fourth question is to review existing design strategies that can lead to combined benefits to human well-being, biodiversity, and adaptability to climate change. In addition, maintenance strategies of green infrastructure are reviewed in the fourth question as well.

For the fifth question, two methods are used, namely literature research and interviews. First, relevant national documents are reviewed to learn about the relevance of green infrastructure for the Netherlands. Secondly, interviews are carried out with experts in the field of green infrastructure to learn about the current planning practices in the Netherlands.

2.2. Design phase

Design phase begins with drafting a list of requirements for the design guideline based on the research phase and in consultation with the commissioning party. The goal of requirements is to determine the content of the guideline and establish a level of detail the guideline must meet.

Secondly, requirements are translated into specific design instructions on implementing green infrastructure for multifunctionality.

2.3. Validation phase

Finally, validation is performed via theoretical application of the guideline in the case area in Arnhem and by interviewing experts in the field of green infrastructure. As an output of the validation phase, recommendations for the further research are given, as it is shown in Figure 1.

The summary of the research methodology can be seen in Figure 2:

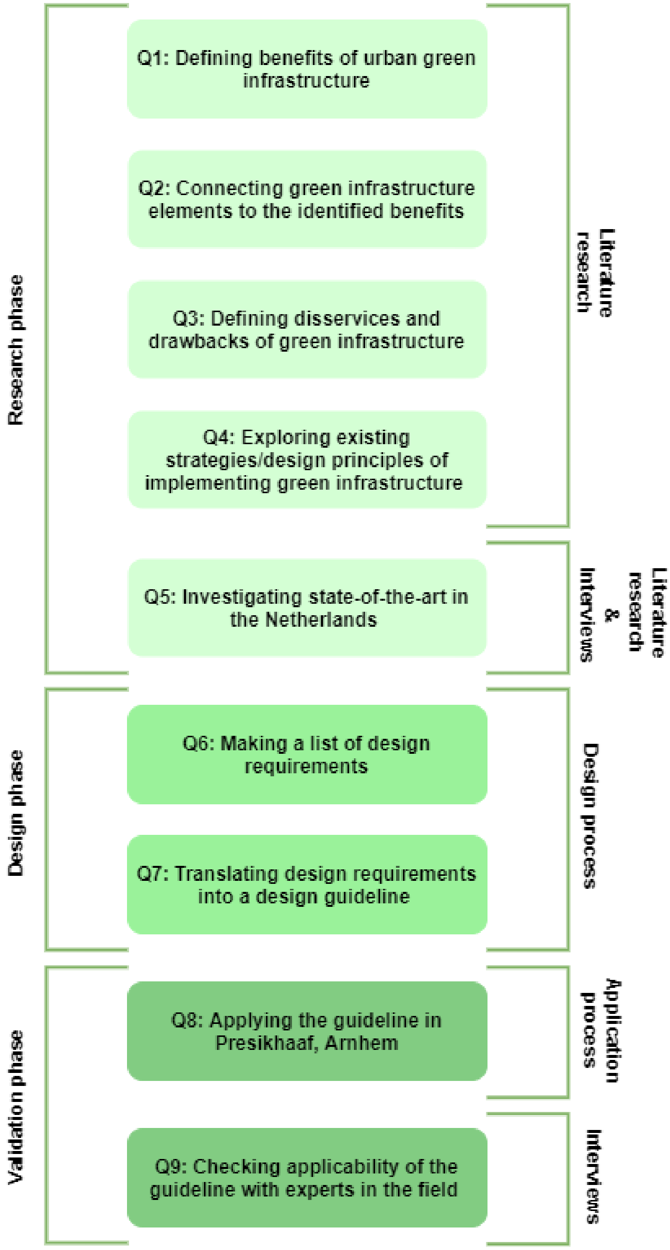

Figure 2: Research methodology

3. Research results

In the following chapter, the research results on urban green infrastructure are presented. As it was mentioned earlier, the research chapter consists out of five sections. In section 3.1, benefits of green infrastructure in regard to climate adaptation, human health and biodiversity are identified and categorized. In section 3.2, different types of urban green infrastructure are distinguished and analyzed in terms of their ability to deliver benefits identified in the previous section. Section 3.3 presents research results on disservices of urban green infrastructure. In section 3.4, existing design strategies and principles are reviewed and discussed. Finally, in section 3.5, approach in the Netherlands is analyzed.

3.1. Green infrastructure and its benefits

Definitions of urban green infrastructure vary greatly throughout the scientific literature, depending on the context and a researcher who contributed to a paper (Mell, 2008; Monteiro et al., 2020). Over the course of the last two decades, the concept of green infrastructure evolved considerably and many new definitions were adopted, such as the one by TEP (TEP, 2005): a “network of open spaces, waterways, gardens, woodlands, green corridors, street trees and open countryside that brings many social, economic and environmental benefits to local people and communities” (TEP, 2005). Another frequently used definition was presented by the European Commission (European Commision, 2013) that described green infrastructure as: “a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services” (European Commision, 2013). This definition has an emphasis on ecosystem services, which is another important concept related to urban green infrastructure. Ecosystem services refer to benefits that people receive from ecosystems (Overpeck et al., 2013) and they can be divided into four categories, mainly regulation, provision, cultural and supportive (Monteiro et al., 2020).

The main regulation services provided by green infrastructure include climate regulation and water management (European Environment Agency, 2011). Regulation services were widely researched and there is a considerable evidence illustrating the ability of green infrastructure to improve climate in urban areas by regulating temperature or reducing stormwater runoff, for instance (Bolund & Hunhammar, 1999a; Demuzere et al., 2014; Institure, 2009; Jones & Davies, 2017; Li et al., 2021; Zölch et al., 2016). The most discussed provision services of green infrastructure include delivery of food and water, while cultural services consist of outputs that affect a human’s physical and mental well-being (Coutts & Hahn, 2015). Finally, supportive services refer to protection and enhancement of biodiversity through the creation of habitats and connections between them (European Environment Agency, 2011; Filazzola et al., 2019; Salomaa et al., 2017).

According to Langemeyer (Langemeyer et al., 2016), delivery of benefits of green infrastructure can be described in a cascade model, which can be seen in Figure 3: first, green infrastructure performs its function, such as slowing down the water runoff. Function leads to the ecosystem service, which, in this case, is a flood protection (regulating service). After that, service leads to a certain benefit and economic value. Here, benefit could be described as a contribution to well-being and economic value resulting from this benefit could be calculated.

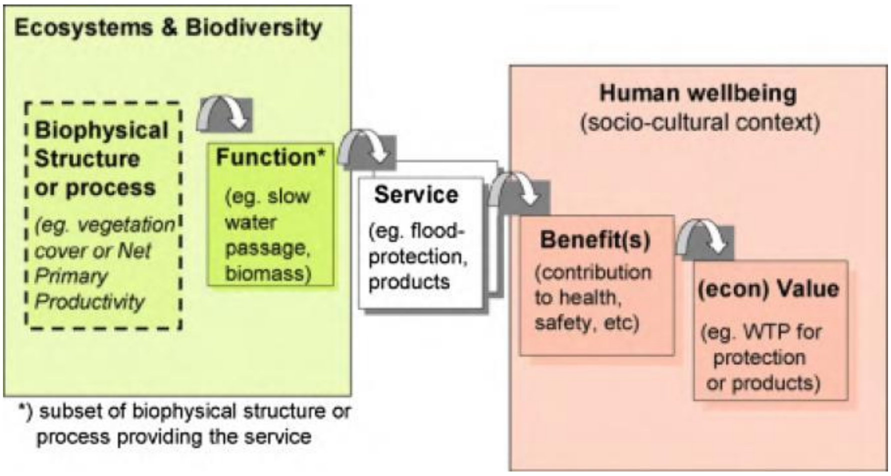

Figure 3: Cascade model green infrastructure (Langemeyer et al., 2016)

3.1.1. Benefits to human health

Urban green infrastructure delivers a wide range of health benefits, which could be categorized into physiological and psychological benefits. It should be noted here that physiological and psychological states are linked between each other, so improvement is physiological well-being can lead to a better psychological health, and vice versa.

First, it is widely acknowledged that urban green infrastructure contributes to the increased levels of physical activity, which, in turn, positively affects both physiological and physiological heath of citizens (Ayala-Azcárraga et al., 2019; Carrus et al., 2015; Reid et al., 2017). Physical activity provides a protective factor for heart diseases, high blood pressure, obesity, and other conditions caused by sedentary lifestyles (Shanahan et al., 2015). Studies showed that exercising lead to the decrease of mortality rate up to 25% in patients predisposed to heart diseases (Myers, 2003) and up to 35% in healthy adults (Viña et al., 2012). Besides promoting physical activity, green infrastructure can increase thermal comfort in the city via shading and evapotranspiration[2] and thereby contribute to a reduction of heat-related injuries amongst population. For example, one experimental study demonstrated the temperature difference of 6 °C between the urban park and surrounding built environment (Feyisa et al., 2014), which shows the importance of nearby green spaces for escaping urban heat. People can also be exposed to high noise pollution levels in urban areas, which can stimulate mental fatigue and high blood pressure (Ayala-Azcárraga et al., 2019). Vegetation is capable to absorb frequencies of the sound, thereby contributing to a calmer and less noisy environment (Amano et al., 2018; Ayala-Azcárraga et al., 2019; Bertram & Rehdanz, 2015). Absorbing gaseous pollutants and particulate matter is another important function of green infrastructure, which is very relevant especially in urban polluted areas (Amano et al., 2018).

Concerning mental well-being, presence of green areas was associated with lower stress levels (Amano et al., 2018; Ayala-Azcárraga et al., 2019; Bertram & Rehdanz, 2015; Cheesbrough et al., 2019; Coutts & Hahn, 2015), increased self-reported positive emotions (Ayala-Azcárraga et al., 2019; Cheesbrough et al., 2019; Kondo et al., 2018), and enhanced cognitive abilities, such as improved memory and attention (Ayala-Azcárraga et al., 2019; Coutts & Hahn, 2015; Kondo et al., 2018). Moreover, natural sounds associated with the fauna (such as birds singing) contribute significantly to the mental restoration and allow people to feel more connected with the nature (Ayala-Azcárraga et al., 2019). Finally, presence of green spaces can increase social cohesion in the community, which is

[2] Evapotranspiration refers to a process when plants release vapor in the atmosphere and thereby increase humidity, decreasing the temperature of the surrounding area.

another important factor positively affecting mental and social well-being (Ayala-Azcárraga et al., 2019).

3.1.2. Climate adaptation benefits

As it was mentioned earlier, urban green infrastructure is considered as promising for reducing the negative effects of climate change in cities. Green infrastructure is an effective tool for temperature regulation and water management in urban areas.

Local rise of temperature in cities is called urban heat island effect, which is caused by a large area of heat absorbing surfaces (Bolund & Hunhammar, 1999b). The effect is the most prominent during the night, when such surfaces release the absorbed heat (Moreno-garcia, 1994). Green infrastructure is capable at mitigating the urban heat islands effect through shading (Cameron & Blanuša, 2016; Demuzere et al., 2014; Institure, 2009; Jones & Davies, 2017), which is considered as the dominant factor for pedestrian temperature comfort (Jones & Davies, 2017), and evapotranspiration (Bolund & Hunhammar, 1999b; Institure, 2009; Jones & Davies, 2017), which is another important process that can contribute considerably to cooling the city. Strategic planting of greenery in the city can effectively alleviate urban heat island effect, with even the modest increase in tree canopy producing a noticeable effect (Institure, 2009). Another important benefit of urban green infrastructure relates to the energy consumption. According to one study, electric demand rose by 2–4% for each 1°C increase in daily maximum temperature above a threshold of 15 to 20°C. (Akbari et al., 2001). Through shading the surface of the building, vegetation can significantly reduce the energy consumption for cooling or during colder periods of the year, for heating. For example, in summer, wall vegetation, such as green façades, were able to reduce energy consumption for cooling by 20% through shading the building wall (S. M. Sheweka & Mohamed, 2012).

Moreover, cities are facing many water-related challenges. Modern urban areas are dominated by grey infrastructure, which includes built up, hard, impermeable structures (Kabisch et al., 2017). The water is unable to infiltrate the soil through impermeable surfaces, which increases substantially the probability of urban floods (Bolund & Hunhammar, 1999b; Demuzere et al., 2014; Li et al., 2021; Villarreal & Bengtsson, 2005). In addition, presence of impervious areas in combination with high extraction of water can lead to low groundwater levels, which can damage infrastructure and lead to a loss of vegetation (Van De Ven et al., 2011). Green infrastructure can solve both problems by first, capturing rainfall and thereby reducing the runoff and peak flows and second, by infiltrating water in the soil, recharging the groundwater stores (Bolund & Hunhammar, 1999b; Demuzere et al., 2014; Li et al., 2021). Comparing to impervious areas that contribute to a 60% of runoff, vegetated areas contribute to only between 5 and 15% (Demuzere et al., 2014).

3.1.3. Benefits to biodiversity

Urban biodiversity refers to the variety of living organisms that are present in a particular city or part of the city (Freedman, 2014; Var & Sarıarmağan, 2020). In urban areas, biodiversity can be negatively affected by many factors, including invasion of alien species, climate change and more importantly, increased fragmentation of the landscape caused by urbanization (Salomaa et al., 2017; Var & Sarıarmağan, 2020). Impacts on biodiversity can be divided into direct and indirect ones, where direct include habitat loss and degradation, while indirect ones consist of changes in water and nutrient availability (Elmqvist et al., 2013).

According to the European Environmental Agency (European Environment Agency, 2011), green infrastructure is considered as one of the most important tools to address biodiversity problems. Green infrastructure can tackle these problems by creating or maintaining species-rich areas withing the city and by allowing species movement between isolated habitats through ecological connections (Garmendia et al., 2016; Var & Sarıarmağan, 2020). Urban green infrastructure can offer habitat for species in many ways, such as by providing a substrate for plants, delivering food resources, such as flowers for pollinators, and providing shelter and nesting locations (Filazzola et al., 2019; Garmendia et al., 2016; Var & Sarıarmağan, 2020). In addition, green corridors can help to increase the biodiversity in urban areas. Such corridors facilitate movement of animals, contribute to the animal population growth, and allows processes such as pollination and distribution of seeds (Var & Sarıarmağan, 2020).

Conservation of habitats and the formation of green corridors are the important tasks that should be focused on more often in urban planning practices (Var & Sarıarmağan, 2020).

3.1.4. Relationship between benefits

It should be pointed out that three discussed themes are interconnected between each other. For instance, green measures to make a city more climate-proof would also positively affect human health by, for example, providing thermal comfort and also improving air quality, which deteriorates because of high temperatures (Institure, 2009). Biodiversity would also benefit from climate adaptation measures and measures aimed to improve biodiversity can increase resilience of cities to various effects of climate change (Var & Sarıarmağan, 2020). For example, diversity of species as well as coverage of green in the city is positively correlated with lower urban temperatures (Wang et al., 2021), higher resistance to floods (Berland et al., 2017) and better quality of air (VHG). Besides that, people can also benefit from biodiversity: richness of birds and other species is perceived as more attractive (Filazzola et al., 2019) and availability of urban forests, for instance, can promote physical activity (Eichinger et al., 2015) and improve mental health (Joung et al., 2015). Overall, primary analysis of benefits has shown that green infrastructure has a great potential to be multifunctional and further analysis is required to identify ways to achieve it.

Table 1 presents a summary of the discussed benefits.

		Benefits of GI	References
Health benefits	Physiological benefits	Reduced noise pollution	(Amano et al., 2018; Ayala-Azcárraga et al., 2019; Bertram & Rehdanz, 2015)
		Reduced air pollution	(Amano et al., 2018; Ayala-Azcárraga et al., 2019; Bertram & Rehdanz, 2015; Bolund & Hunhammar, 1999a)
		Temperature comfort for people	(Cameron & Blanuša, 2016; Demuzere et al., 2014; Feyisa et al., 2014; Institure, 2009; Jones & Davies, 2017; S. M. Sheweka & Mohamed, 2012)
		Promotion of physical activity	(Ayala-Azcárraga et al., 2019; Carrus et al., 2015; Reid et al., 2017)
	Psychological benefits	Reduction of stress	(Amano et al., 2018; Ayala-Azcárraga et al., 2019; Bertram & Rehdanz, 2015; Cheesbrough et al., 2019; Coutts & Hahn, 2015)
		Cognition and attention	(Ayala-Azcárraga et al., 2019; Coutts & Hahn, 2015; Kondo et al., 2018)
		Positive emotions	(Ayala-Azcárraga et al., 2019; Cheesbrough et al., 2019; Kondo et al., 2018)
Climate adaptation benefits	Temperature regulation	Mitigation of urban heat islands	(Bolund & Hunhammar, 1999a; Cameron & Blanuša, 2016; Demuzere et al., 2014; Institure, 2009; Jones & Davies, 2017)
	Water management	Flood regulation	(Bolund & Hunhammar, 1999a; Demuzere et al., 2014; Li et al., 2021)
		Drought regulation	(Bolund & Hunhammar, 1999a; Demuzere et al., 2014; Li et al., 2021)
Biodiversity benefits	Conservation and enhancement of biodiversity	Habitats for species	(Filazzola et al., 2019; Garmendia et al., 2016; Var & Sarıarmağan, 2020)
		Permeability for migrating species	(Garmendia et al., 2016; Var & Sarıarmağan, 2020)

Table 1: Benefits of urban green infrastructure

3.2. Green infrastructure typology

Despite the wide range of benefits delivered by green infrastructure, much of the research does not specify the type of green infrastructure being studied, which poses limitations for identifying added value of greenery and restricts its successful implementation on practice. Greater specificity is required to address these issues (Cheesbrough et al., 2019).

According to Koc (Koc et al., 2016), all green infrastructure can be categorized based on its functional, structural, and spatial characteristics. Functional characteristics refer to the ecosystem services delivered by green infrastructure, structural characteristics describe geometry and size, while spatial characteristics describe arrangement of green infrastructure in space. In addition, Oke (Oke, 2006) added scale characteristic, which describes meso-scape (city/regional), local scale (neighbourhoods) and micro-scale, which concerns individual elements of green infrastructure on buildings and in street canyons.

Regarding the typology, urban green infrastructure can be divided into ground vegetation and vegetation on building surfaces. Ground vegetation comprised of three classes, namely low, medium and high vegetation, while vegetation on building surfaces consists out of climbing vegetation and roof vegetation, as it can be seen in Figure 4.

In practice, low vegetation refers to grass or green open spaces, medium vegetation includes bushes, shrubs and hedges and tall vegetation comprises of trees. Climbing vegetation includes vertical green systems, which are primarily subdivided into green walls and green façades. Finally, roof vegetation refers to green roofs and, similar to ground vegetation, it may be classified into three classes. Koc (Koc et al., 2016) also included blue elements in the analysis, however, this information will be left out as it is outside of the scope of this project.

Simplified model of urban green infrastructure typology can be seen below:

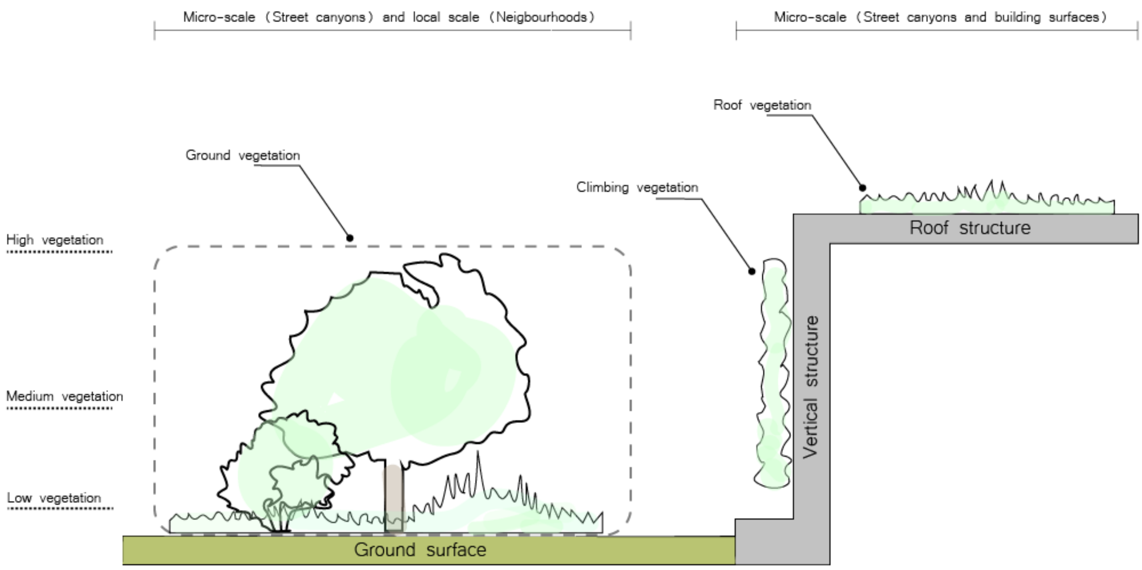

Figure 4: Urban green model (Adapted from Koc et al., 2016)

In the following sub sections, types of urban green infrastructure are discussed in more detail, analyzed in terms of their ability to deliver benefits identified in the previous section and ranked based on their performance.

3.2.1. Types of urban green infrastructure

Trees is the most widely researched type of urban green infrastructure, which can be found in many places across the urban landscape. As it will be shown in the analysis, urban trees can deliver a wide range of benefits, which makes them a very valuable green asset.

Urban hedges are the second common type of vegetation that is often used in green belts. Because of its small size and diverse ecological functions, they often complement other types of green infrastructure such as trees (R. Zhang, 2020). Hedges generally comprise out of low dense vegetation including short woody plants and shrubs (Zou et al., 2019).

Grasslands and urban green spaces are another common type of vegetation that can be found in urban landscape. Generally, grass can be a part of green strips laid along the roads or form larger patches of green in public open areas, such as parks.

Green roof is the first type of green infrastructure on building surfaces, which is gaining more popularity in modern cities. As it was described earlier, green roofs can be divided in three classes, namely low, medium, and tall vegetation (Koc et al., 2016). Based on the type of vegetation and its diversity, two main types of green roofs are often distinguished: intensive and extensive green roofs, as shown in Figure 5. Intensive green roofs refer to roofs with a thick substrate layer, which allows planting a more diverse selection of vegetation, such as shrubs or even small trees. In contrast, extensive green roofs can only accommodate low vegetation such as grasses and moss due to the thin substrate layer (Oberndorfer et al., 2007; Vijayaraghavan, 2016).

Figure 5: Intensive and extensive green roofs

Finally, green vertical systems are the last discussed type of urban green infrastructure, and they are generally divided into two categories. Green façade is the first category of green vertical systems, and they usually consist out of wall shrubs or climbing plants, such as vines. Climbing species can fix themselves on the wall through their structural characteristics, as it shown on the first image of Figure 6, or by climbing with the support of a framework placed against the wall, with the lower end starting from the ground or a from a planter box, as it is shown on the second and third images respectively.

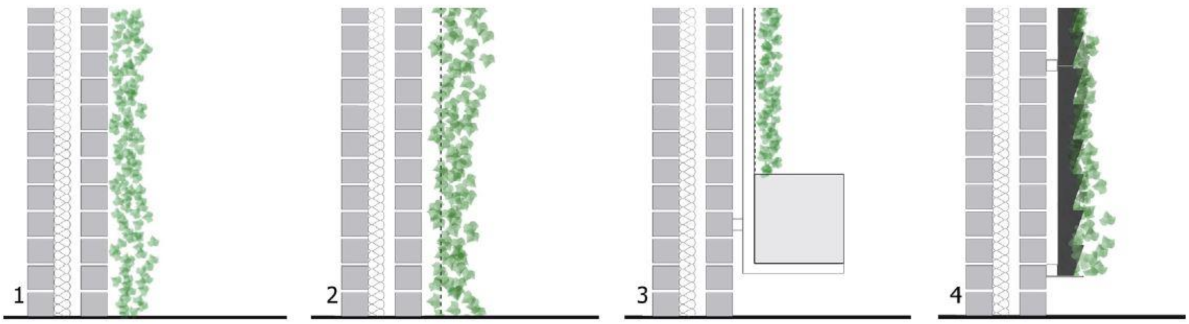

Figure 6: Types of vertical green systems (Perini & Rosasco, 2013)

In comparison, living walls are embedded on the wall through the use of cells of substrate that contain water and nutrients, as it is shown on the fourth image (Koc et al., 2017). According to

Norton (Norton et al., 2015), while living walls can be more beneficial overall, they are considerably more expensive to install and maintain, so green façades have a higher potential to be widely implemented in the urban landscape (Norton et al., 2015).

3.2.2. Analysis of urban green infrastructure elements

The following sub-section presents a critical review of the individual urban green infrastructure elements.

Overall, the primary literature research has shown that urban trees performed the best in terms of their ability to deliver benefits as shown in Table 1. It is well established that trees are highly effective at regulating the temperature by cooling the city via shading and evapotranspiration (Bolund & Hunhammar, 1999b; Konarska et al., 2014; Livesley et al., 2016). One study has shown that through shading, trees were able to reduce the surface temperature by 18.7 °C (Tan et al., 2016). In addition, a large tree can transpire 450 liters of water per day (Bolund & Hunhammar, 1999b), which produces a significant cooling effect in combination with shading. One study has indicated that one tree can save 12-24% of the cooling energy of a one-story building (Zou et al., 2019). In addition, trees capture rainfall and route it to various components of the hydrological cycle, which includes canopy interception, evapotranspiration and infiltration in the soil (Berland et al., 2017; Marapara et al., 2021). In terms of species, coniferous trees are able to reduce water reaching the surface by 20-40%, compared to 10-20% of the broadleaf trees (Marapara et al., 2021). Moreover, substantial evidence indicated that trees are beneficial for human health: increased tree canopy in the area led to improved air quality (Livesley et al., 2016; Wolf et al., 2020), decreased noise pollution (Dobson & Ryan, 2000) and thermal comfort for people (Bolund & Hunhammar, 1999b; Konarska et al., 2014; Livesley et al., 2016). Availability of trees nearby was also positively correlated with the overall physical activity in both adults and children (Eichinger et al., 2015; Larsen et al., 2009). Besides physiological health benefits, positive emotions and cognitive performance were improved amongst residents who had trees nearby (Joung et al., 2015; Martínez-Soto et al., 2013). Biodiversity also benefits from trees: urban trees are used by many species for shelter, nesting materials and breeding locations (Hails & Kavanagh, 2013).

Medium vegetation such as shrubs and hedges could also deliver a number of benefits. Concerning climate adaptation, shrubs did not perform as well as trees due to their limited ability to provide shade (D. Nowak & Heisler, 2010), however, shrubs can still cool the area to a certain extent via evapotranspiration (Blanusa et al., 2019; R. Zhang, 2020). According to one study, evapotranspiration rate of shrubs was 1.29°C min^{-1} m^{-2}, which appeared to be much higher than of short-mown grass, for instance (Zou et al., 2019). Regarding flood and drought mitigation, shrubs can intercept rainfall and infiltrate it in the soil, however, the effect is lower compared to trees as shrubs have a lower biomass[3] (R. Zhang, 2020). However, shrubs were considered quite effective against noise pollution, and the effect was sometimes even higher than of trees, as shrubs have a consistent dense structure throughout its height (Biocca et al., 2019; Cameron & Blanuša, 2016; Dobson & Ryan, 2000). It was also demonstrated that shrubs can effectively capture pollutants (Blanusa et al., 2019) and particulate matter, but trees appeared to be more effective (Berardi et al., 2014). Moreover, there is a scarcity of literature that examined psychological benefits of shrubs, however, some evidence demonstrated that hedges with green and blue hues contributed to a better mental well-being (Blanusa et al., 2019). Hedges also support urban biodiversity through the

[3] Biomass refers to the weight of the biological matter. For example, biomass of a tree could include foliage, branches, stem and bark (Waddell, 1989).

provision of food, shelter and breeding locations for birds, insects and mammals (Blanusa et al., 2019; Hails & Kavanagh, 2013).

Regarding low vegetation, available literature was scarce, which posed some uncertainties. Amongst climate adaptation measures, the most frequently mentioned benefit was that grass can contribute to mitigating urban heat islands. Grassed areas can serve as cool islands in urban landscape and reduce the temperature via evapotranspiration, if irrigated properly (Norton et al., 2015). However, the capacity of grass to provide temperature comfort for people is quite limited, largely due to the fact that grass does not reach the necessary height to block solar radiation that reaches humans (D. Nowak & Heisler, 2010). Yet, grassed areas can contribute considerably with flood and drought mitigation by absorbing rainfall, especially if the grassed area is large. Regarding human health benefits, grassed areas are appealing locations for physical activity (Norton et al., 2019; Reid et al., 2017; Shanahan et al., 2015), so people can benefit from grasslands physiologically and psychologically, as it was discussed in section 3.1.1. No evidence was found on the ability of grasses to absorb sound, except one study indicating that the highest noise absorption occurs at the ground level (Dobson & Ryan, 2000), so it could be assumed that low vegetation can be beneficial for reducing noise pollution. Concerning air pollution, only one study was found that illustrated the limited ability of grasses to absorb pollutants compared to shrubs due to lower leaf area index[4] (Gopalakrishnan et al., 2018). Some studies also examined benefits of grasslands on biodiversity but only meadow-like grassed areas were analysed since short and frequently mowed grasses are usually species-poor (Klaus, 2013; Mollashahi et al., 2020; Norton et al., 2019). Meadows that comprise of diverse species are more attractive for animals, such as bees and birds, and connection between grassed areas can promote species dispersal (Klaus, 2013; Norton et al., 2019).

Similar to low vegetation, many assumptions had to be made in the analysis of green vertical systems, due to a lack of sufficient research. Façade greenery could contribute to mitigating urban heat islands by directly shading buildings, which would reduce the number of surfaces that absorb heat (S. Sheweka & Magdy, 2011), and via evapotranspiration (S. M. Sheweka & Mohamed, 2012; S. Sheweka & Magdy, 2011). It was reported that green façades reduced the temperature of surface area by 14°C, compared to a non-vegetated wall (Tilley & Alexander, 2014). It was also indicated that green façades are able to effectively insulate the building by reducing the energy consumption for cooling by 20%. During winter, façades can also protect the building from cold wind, which can reduce the energy demand for heating by 25% (S. M. Sheweka & Mohamed, 2012). Regarding flood mitigation, one study indicated that wall greenery can retain some of the runoff from roofs and capture a portion of rainfall directly (S. Sheweka & Magdy, 2011). Regarding drought control, it could be assumed that green façades do not have a direct impact on the moisture content of the soil, unless the remaining water runs from wall greenery in the ground. Concerning human health, green façades can offer several benefits, starting from improved air quality. Just like other types of vegetation, green facades can filter airborne particles and absorb gaseous pollutants that move along the street (S. M. Sheweka & Mohamed, 2012). Moreover, façade greenery can absorb some frequencies of the sound (S. Sheweka & Magdy, 2011), up to 3dB, and reduce the internal reverberation between buildings in street canyons (Wong et al., 2010). People can also benefit psychologically: feelings of relaxation and cheerfulness were observed in people after being exposed to façade greenery (Elsadek et al., 2019). Green vertical systems can also be beneficial to biodiversity. According to several studies, green vertical systems can act as corridors or steeping stones to allow movement and dispersal of many species within the urban landscape (Collins et al., 2017; Mayrand & Clergeau, 2018). In addition, many insects were found that use wall greenery,

[4] Leaf area index (LAI) is defined as the area of a leaf per unit ground surface area (Matthews, 2014).

including bees and spiders (Mayrand & Clergeau, 2018). Living walls are considered as more beneficial to biodiversity compared to green façades due to a more complex and diverse vegetation (Collins et al., 2017). However, it appears that there is a scarcity of literature that examined the contribution of façade greenery to biodiversity in fragmented areas, therefore, no conclusion can be made in this regard (Mayrand & Clergeau, 2018).

Finally, in contrast to green vertical systems, there was more available literature on green roofs. Green roofs can provide many benefits with stormwater runoff mitigation claimed as the most important climate adaptation benefit with the intensive green roofs mitigating up to 100% runoff and extensive roofs up to 60% (Berardi et al., 2014). Similar to ground vegetation, green roofs can mitigate stormwater via infiltration in the substrate or by capturing it directly on plant surfaces (Vijayaraghavan, 2016). Moreover, installing green roofs is considered as an alternative measure to decrease ambient temperature when on-ground space for vegetation is limited (Norton et al., 2015). The cooling effect of green roofs, however, is achieved primarily through the evapotranspiration and rarely exceeds a few degrees, according to a few studies (Smith & Roebber, 2011; Vijayaraghavan, 2016). In addition, there was little or almost no improvement in thermal comfort on pedestrian level, so ground vegetation can be considered as more effective in this regard (G. Zhang et al., 2019). One study in Greece demonstrated an annual energy saving up to 44% in poorly insulted buildings with a green roof. Intensive green roofs were shown to be more effective for insulation compared to extensive green roofs (Castleton et al., 2010). Concerning health benefits, green roofs can reduce noise if directly exposed to the urban sound field (noise from rail and air traffic, for instance) and by absorbing particulate matter and gaseous pollutants, similar to other types of vegetation (Berardi et al., 2014; Vijayaraghavan, 2016). Moreover, green roofs provide a greater aesthetical value to people compared to concrete roofs and support psychological restoration (Oberndorfer et al., 2007; K. J. H. Williams et al., 2019). Finally, green roofs can improve biodiversity. For instance, 176 plant species were observed on more than a hundred roofs in a European climate (Mayrand & Clergeau, 2018). Moreover, green roofs are quite popular among birds and various insects (Mayrand & Clergeau, 2018; Oberndorfer et al., 2007; N. S. G. Williams et al., 2014) , however, diversity of flora and fauna of green roofs was highly variable, so the overall contribution of green roofs to biodiversity remains uncertain (Mayrand & Clergeau, 2018). Nevertheless, similar to green facades, it was also mentioned that green roofs can also serve as stepping stones for species and reduce the fragmentation of green areas in the city (Hop & Hiemstra, 2013).

3.2.3. Ranking of green infrastructure

In the following section, green infrastructure elements are ranked based on their ability to deliver benefits presented in Table 1. Distinction was made between small and large trees, between meadows and short-mown grasses, intensive and extensive green roofs and green façades and living walls, as it can be seen in Table 2. For rationale behind ranking, see Appendix B: Ranking of green infrastructure.

			Trees		Shrubs	Grassed areas		Green roofs		Vertical green systems	
			Small trees	Large trees	Shrubs/bushes	Meadows	Short-mown grass	Intensive green roofs	Extensive green roofs	Green façades	Living walls
Health	Physiological benefits	Reduced noise pollution	●●●●	●●●	●●●●	●●	●	●●	●	●	●●●
		Reduced air pollution	●●●●	●●●●●	●●●	●●	●	●●	●	●	●●
		Thermal comfort for people	●●●●	●●●●●	●●●	●●	●	●●	●	●●	●●●●
		Promotion of physical activity	●●●	●●●●	N/A	●	●●●●●	N/A	N/A	N/A	N/A
	Psychological benefits	Reduction of stress	●●●●	●●●●●	●●●	●●	●●	●●	●	●●	●●●
		Cognition and attention	●●●●	●●●●●	●●●	●●	●	●●	●	●●	●●●
		Positive emotions	●●●●	●●●●●	●●●	●●	●●	●●	●	●●	●●●
Climate adaptation	Temperature regulation	Mitigation of heat island effect	●●●●	●●●●●	●●●	●●	●	●	N/A	●	●●●
	Water management	Flood regulation	●●●●	●●●●●	●●●	●●	●	●●●●	●●●	●	●●
		Drought regulation	●●●	●●●●	●●●	●●	●	N/A	N/A	N/A	N/A
Biodiversity	Biodiversity conservation and enhancement	Habitats for species	●●●●	●●●●●	●●●	●●	●	●●	●	●	●●
		Permeability for migrating species	●●●●	●●●●●	●●●	●●	●	●●	●	●	●●

Table 2: Ranking of urban green infrastructure elements (● - low positive effect, ●●●●● - high positive effect, N/A – no available information)

3.3. Disservices of urban green infrastructure

Besides analyzing benefits, it is important to identify possible drawbacks of urban green infrastructure, as this information needs to be considered in planning. Shackleton (Shackleton et al., 2016) proposed a definition of ecosystem disservice as "the functions, processes and attributes generated by the ecosystem that result in perceived or actual negative impacts on human wellbeing" (Shackleton et al., 2016). Overall, there was a wide range of disserves that could be classified into aesthetic, health, economic and environmental issues. A summary of common disservices is presented in Table 3:

Aesthetic	Health	Economic	Environmental	References
- Blockage of views	- Allergic reactions due to pollen	- Costs of the repairing infrastructure damaged by roots	- VOCs	(Bertram & Rehdanz, 2015; Cameron & Blanuša, 2016; Demuzere et al., 2014; Filazzola et al., 2019; Gómez-Baggethun & Barton, 2013; Jones & Davies, 2017)
- Plant litter	- Perception of green dark areas as unsafe	- Costs of the maintenance and removing plant coverage	- Increased pollution due to restricted air flow	
- Unpleasant species use urban greenery as their habitat	- Species that can carry diseases use urban greenery as their habitat	- Costs of treating diseases and pests	- Displacement of native species	

Table 3: Disservices of urban green infrastructure

It should be noted, however, that most of the studies only examined disservices of trees, therefore there could be more disservices associated with other types of vegetation. Regarding aesthetic aspects of green, blockage of views is mostly attributed to trees, while plant litter and unpleasant species can also be an issue with other types of vegetation. It is generally recommended to avoid plants that drop fruits onto pavement and produce a large amounts of leaf litter, especially if planting is planned close to pedestrian paths (Cameron & Blanuša, 2016). Regarding species, some animals can be perceived as discussing (such as rats) or unpleasant or not desirable (Bertram & Rehdanz, 2015). One study showed that people do not want to encounter any insects that cause nuisance, such as mosquitos, and some people expressed fear of bees (Barnes et al., 2020).

Regarding health issues, wind-pollinated plants can cause allergic reactions, which should be considered in the planning. It is generally recommended to choose plants with low pollen loads near vulnerable sites, such as schools, hospitals, and care homes (Worsley, 2018). Moreover, people can perceive green areas as unsafe at night, especially if such areas are not illuminated (Bertram & Rehdanz, 2015; Gómez-Baggethun & Barton, 2013; Jones & Davies, 2017). Urban vegetation can also provide habitat for species that can harm human's health – animals that carry diseases for instance, or caterpillars (Bertram & Rehdanz, 2015; Demuzere et al., 2014; Filazzola et al., 2019; Gómez-Baggethun & Barton, 2013; Jones & Davies, 2017).

Economic issues were mostly associated with high costs of having green infrastructure. Repairing the damaged infrastructure such as pavements or cables lead to considerable costs, as well as recurring maintenance activities, such as removal of fallen leaves and debris. In addition, treating diseases can also result in large costs, especially if green elements belong to the same specimen, which is frequently the case in cities (Demuzere et al., 2014; Jones & Davies, 2017).

Finally, environmental issues included production of volatile organic compounds (VOCs), which contribute to ozone levels in cities (Bertram & Rehdanz, 2015; Gómez-Baggethun & Barton, 2013; Jones & Davies, 2017), increased air pollution on the street level caused by restricted air flow (Demuzere et al., 2014) and introduction of invasive species that harm biodiversity (Filazzola et al., 2019; Jones & Davies, 2017).

3.4. Existing design strategies and principles

3.4.1. Main design principles in green infrastructure planning

In the following section, existing design strategies and principles are discussed. According to Monteiro (Monteiro et al., 2020), there is still no consensus regarding urban green infrastructure implementation strategies and existing design principles seem too theoretical, which makes it difficult to successfully use them in urban planning (Monteiro et al., 2020). The number of design principles vary greatly across the literature, however, the most common design principles that are claimed to be an integral part of green infrastructure planning, are connectivity and multifunctionality.

Connectivity is defined as a property of landscapes that reveals the link between the landscape structure and its function (Ahern, 2007). In literature, two types of connectivity are often distinguished: structural and functional (Hansen & Pauleit, 2014; Johanna, 2010; Kambites & Owen, 2006; Lundberg, 2018; Mollashahi et al., 2020). Structural connectivity refers to the physical connection between various components in the ecological network, and it is acknowledged that green infrastructure delivers more benefits when it is part of a larger ecological system. For instance, a local park has more value to people when it is connected to other city parks via bicycle paths. Similarly, a physical connection between natural reserves via a corridor is more beneficial as it allows wildlife movement between different habitats (Rouse & Bunsier-Ossa, 2013). Functional connectivity, on the other hand, refers to the *ability* of species to move within a landscape (Hansen & Pauleit, 2014; Mollashahi et al., 2020). High structural connectivity does not necessarily lead to a high functional connectivity and vice versa. If, for instance, despite the obvious physical connection between green infrastructure elements, species do not use that connection, this connection does not perform well in functional terms (Lundberg, 2018). Thus, functional connectivity is often perceived as more important as it allows creation of more valuable connections between various green elements of the landscape (Johanna, 2010; Salomaa et al., 2017). According to the EU Environment Agency, connectivity is the key for biodiversity conservation and resilience (European Environment Agency, 2011). In addition, it is also possible to achieve multiple benefits of green infrastructure by using connectivity principle when, for instance, benefits to recreational usage and wildlife habitats are achieved. It should be noted here, however, that sometimes it is necessary to keep certain functions separate to avoid conflict – for example, by preventing human movement in the protected areas that house wildlife species (Kambites & Owen, 2006).

The second design principle that forms a core of green infrastructure planning is called multifunctionality. The goal of multifunctionality is to allow effective use of limited space by combining several functions. Multifunctionality is usually achieved when there is a spatial overlap in various factors that lead to different benefits (Tran et al., 2020). According to Liquete (Liquete et al., 2015), in Europe there is a high potential for spatial multifunctionality of green infrastructure with the quarter of the continent being selected as a high priority area for green infrastructure placement (Liquete et al., 2015). Multifunctionality is considered highly important as it does not only lead to the effective use of the scarce space, but also resiliency of green ecosystem increases considerably when it delivers multiple benefits (Meerow & Newell, 2017; Tran et al., 2020). Some of the examples of multifunctional green infrastructure include green roofs, as they do not only effectively slow down stormwater runoff but also create aesthetical value for people. It should be mentioned that total multifunctionality is often regarded as impossible, especially in cases when one function demands a high land use intensity (Hansen et al., 2019).

Multifunctionality and connectivity principles go together as connectivity concerns the spatial configuration of green infrastructure elements and consequently the number of benefits they provide (Hansen & Pauleit, 2014).

3.4.2. GIST model

Since green infrastructure can deliver multiple benefits on a single site, it can be considered as an attractive option to complement grey infrastructure in urban areas. However, it is not guaranteed that multifunctionality can always be achieved if underlying factors that lead to certain benefits contradict each other (Tran et al., 2020). Main factors that affect the performance of green infrastructure as well its capacity to deliver multiple benefits include structural and spatial characteristics. As it was discussed in section 3.2, structural characteristics refer to the size and geometry of green infrastructure and spatial characteristics describe configuration of green infrastructure in space. In addition, green infrastructure located in one part of the city has a higher chance of delivering multiple benefits than in the other part of the city (Tran et al., 2020).

Tran (Tran et al., 2020) proposed a GIST (Green Infrastructure Space and Traits) model that addresses both characteristics, however, the green infrastructure was taken as indistinguishable whole, which might restrict the successful use of the model in urban planning. In addition, spatial characteristics only referred to priority areas, such as polluted areas or areas with impermeable surfaces (Tran et al., 2020). Spatial arrangement of green infrastructure has not been discussed, which also poses limitations for the application of the model in real life. It is important to differentiate types of green infrastructure and examine individual structural traits as well as recommended spatial arrangement that can potentially lead to multifunctionality. Combined information on location, arrangement and structural traits of urban green infrastructure will also give insight into possible conflicts in planning, which will help to make intelligent choices in urban planning practices.

3.4.3. Structural and spatial characteristics of green infrastructure

A comprehensive analysis of both structural and spatial characteristics of discussed types of urban green infrastructure can be found in Appendix C: Analysis of structural and spatial characteristics . Overall, analysis of structural characteristics has shown that plant size characteristics and leaf characteristics are the most relevant for climate adaptation and for delivering human health benefits such as improved air quality and reduced noise pollution. Visual characteristics such as colorfulness and flower size are the most important for biodiversity and psychological health. In addition, it was observed across the literature that the increase in the diversity of vegetation is beneficial overall, as the enhanced diversity would mean increased variety in structural traits that lead to certain benefits. For instance, for effective air pollution mitigation, it is recommended to include a variety of species, as different species absorb different pollutants. As another example, diversity in species is considered beneficial for human psychological health, as people perceive a variety of greenery as more pleasant compared to just one type of green infrastructure/one specimen.

Concerning spatial characteristics, performance of urban green infrastructure depends on the location and configuration in space. Regarding the location, street canyons were discussed the most frequently (Kumar et al., 2019; Norton et al., 2015), although performance of green infrastructure in other types of public spaces, such as city squares, was also previously researched (Zölch et al., 2019). As Norton (Norton et al., 2015) motivated it, street canyons, which are characterized by a presence of buildings of both sides of the road, are interesting for the research, as they occupy a significant space in cities and it is possible to translate the knowledge to other locations, such as parking lots and intersections (Norton et al., 2015). Commonly, three types of street canyons are distinguished:

narrow, medium and wide canyons (Kumar et al., 2019; Norton et al., 2015). Based on the type of a canyon, one or another type of green infrastructure is usually recommended. For example, for medium street canyons, as illustrated in Figure 7, locating large trees is generally not advisable, as such trees can trap heat and pollutants under their crown due to a limited exchange of air inside and outside the canyon, so medium vegetation is more appropriate in this case. In addition, green façades are encouraged in every street canyon regardless of the geometry. Complete explanation of street canyons can be found in Appendix A: Microclimate in street canyons.

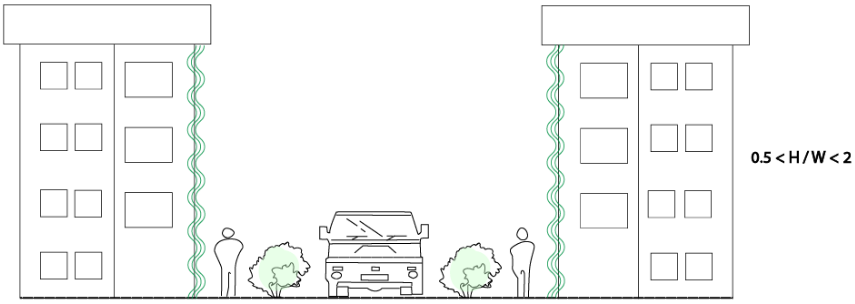

Figure 7: Medium street canyon

Regarding configuration in space, it is generally recommended to space trees generously from each other to prevent heat trapping, allow dispersion of pollutants and give space for tree growth. Regarding medium and low ground vegetation, dense planting is the most appropriate solution in the most cases.

Vegetation on building surfaces had fewer specific requirements in terms on placement. While green vertical systems are recommended in almost all scenarios, green roofs are mostly encouraged on low and large buildings to be the most effective for climate adaptation, human health, and biodiversity.

Interaction between various types of urban green infrastructure is another important factor to consider in planning practices. While green elements alone can deliver certain benefits, it is through the combination of various types of greenery it is possible to achieve the maximum positive effect on climate change adaptation, biodiversity, and human health. The degree of interaction depends not only on the mutual proximity of green infrastructure elements but also on their ability to complement each other.

For complete literature research of both structural and spatial characteristics of green infrastructure see Appendix C: Analysis of structural and spatial characteristics

3.4.4. Trade-offs in green infrastructure traits

Analysis of the structural and spatial traits has shown that there is a limited number of trade-offs between traits of green infrastructure elements. In structural characteristics, the only traits that could cause nuisance is the plant height and structural density. While these traits are generally beneficial for achieving multiple benefits such as provision of shade, noise attenuation and more effective interception of rainfall, increase in these traits might not be desirable in certain cases. For instance, tall trees might block views or cast undesirable shade (such as on roofs covered with solar panels, for example) as it was discussed in section 3.3. Trees with dense crowns can also trap heat and pollutants under their crowns and thereby negatively affect the microclimate of the street. Moreover, dense greenery might not be perceived safe especially during the night time, so careful considerations should be made to avoid such nuisances.

Regarding spatial configuration, only one conflict was observed and it concerns the density of planting. It has been shown that dense planting is beneficial for alleviating noise pollution the most effectively, however, it can also increase air pollution and slow down the dissipation of heat on the street level. In addition, dense planting was shown to be more beneficial for biodiversity compared to more scattered planting, which also created a conflict with other benefits. These concerns, however, generally apply only to trees, while hedges and grass can be planted densely regardless of the situation. Since locating trees away from each other could lead to more benefits, such configuration should be prioritized, at least in street canyons. Shrubs and grass can be planted as an alternative measure to reduce noise pollution and ensure continuity of green belts.

Analysis of the remaining characteristics has shown that green infrastructure has a high potential for multifunctional use. While some structural traits were frequently overlapping (such as species richness), other ones (such as availability of fruits) were observed only for a specific benefit. Spatial characteristics could be combined in all cases to achieve multiple benefits, only excluding the density of planting, as it was discussed earlier. It should be noted that often it might not be even necessary to achieve all benefits (for example, residential streets might not experience a lot of noise pollution) so such information can be easily left out in the design process. Nevertheless, the goal of this study is to provide a sufficient information on how to achieve multifunctionality of urban green infrastructure, so it is up to a user of a guideline to decide what information is relevant in a specific scenario.

3.4.5. Maintenance of urban green infrastructure

Finally, it is important to address maintenance of green infrastructure, as it is an important aspect, which is often considered as a disservice (see section 3.3). Urban areas make a challenging environment for green infrastructure due to many factors, ranging from poor quality of soil and lack of space for growth to inappropriate maintenance and various development activities, such as trenching (Roloff, 2016). While the evidence of benefits of green infrastructure is mounting, the green budgets are often reduced and the life-expectancy of green infrastructure, especially trees, is low (D. J. Nowak et al., 2004). Careful planning is required to distribute scarce resources and preserve green infrastructure, both existing and newly planted (Roloff, 2016).

3.4.5.1. Maintenance of ground vegetation

As it was discussed earlier, ground vegetation comprises out of trees, shrubs and hedges, and grassed areas. Each type of ground vegetation has its requirements in terms of maintenance, which will be discussed below.

Regarding urban trees, preservation can be challenging as many human activities, mostly construction, can pose significant threats to healthy trees. Trenching, installation of utilities, demolition, use of heavy machinery – all of these activities can disturb trees and do damage to their roots. In order to avoid damage, careful survey of trees is required, where information such as height, position of roots, and branch spread is gathered. It is of paramount importance to map roots as damaging them could lead to a complete deterioration of a tree (Roloff, 2016).

In case of newly planted trees, it is often recommended to support them with stems, especially when the wind predominantly blows in one direction. Tree crowns that have weak branches can also be supported by cables to prevent the failure of the crown. Collision with trees is also a major cause of failure of the tree structure. In order to prevent such cases, bollards could be installed that would protect a tree from vehicles. In case of pedestrians, it is recommended to put mulch, gravel or other hard to walk on material to prevent people from damaging tree roots due to soil compaction[5]. For similar reasons, other types of green infrastructure, such as shrubs or flowers could be planted next to a tree. Lack of appropriate water supply is another major issue that can deteriorate the health of a tree. Impermeable surfaces contribute largely to this issue, however, other factors such as low soil volume can also play a role. It must be ensured that trees have at least 0.75m^3 of soil for each square meter of crown area to provide a sufficient amount of water. Regarding provision of water, trees could be irrigated manually or by directing rainfall via micro-catchments, for instance. Manual irrigation should be carried out consistently by contractors, however, local residents can also contribute to irrigation (Roloff, 2016).

Regarding other human activities, applying de-icing salt can also affect a health of a tree. De-icing salt can reduce a capacity of soil to absorb water, which can lead to a water deficit to trees. Reduction of quantities of de-icing salt could be an option to minimize risks. Pruning is another common maintenance activity, which is done for various reasons. Raising a crown of a tree to clear the way for vehicles and pedestrians, removing some of the leaf mass to decrease undesirable light attenuation and removing dead leaves and branches are some of the common reasons for pruning trees in urban areas (Roloff, 2016).

Overall, newly planted trees provide less benefits and maintenance is associated with higher costs compared to mature trees. However, as tree matures, it starts to provide greater net benefit, which could be described as the difference between the benefits the tree provides (for example, purifying the air) and costs for maintenance (for example, pruning) (Hauer et al., 2015). Thus, when planting a tree, future potential benefits resulting from trees should be taken into consideration, which can help with the decision making.

Maintenance activities also depend on tree species. For example, deciduous trees require more fertilization and they are more sensitive to the quality of the soil, while coniferous trees can thrive in a less nutrient soil. In addition, deciduous trees generally require more pruning compared to coniferous trees.

Regarding the frequency of maintenance, it can vary greatly, depending on species and location. While trees can deliver some benefits without maintenance, it is inevitable that maintenance will be required at some point of the life cycle of a tree. It is more efficient to carry out proactive (consistent) maintenance, compared to reactive (when as issue occurs). For instance, formative pruning at the early stage of a tree appeared to be less expensive than pruning a tree in the later stages of life. Similarly, watering young trees is less expensive compared to replacing dead trees that have not been watered properly. Finally, regarding pest management, sanitation three times a year is cheaper than sanitation once a year in the long term, as less frequent sanitation significantly increases the mortality of a tree (Hauer et al., 2015). Similar recommendations can also be given to medium vegetation due to the similar structure.

In some cases, less frequent maintenance could be considered as an option. So far, high maintenance was considered as a norm in case of some types of urban green infrastructure, such as urban grasslands. Short-mown grasses are quite popular in urban areas due to many reasons, ranging from provision of recreational space to clear maintenance protocols. However, intensive management is usually required, where cutting grass every 2-3 weeks has become a norm in countries such as UK. In addition, fertilizer and irrigation is often provided, which can result in high

[5] Soil compaction can make the soil denser and thereby reduce the permeability for water and oxygen, which are vital for the survival of a tree (Roloff, 2016).

costs, both in monetary values and environmental. An alternative option could be to let plants to increase its height and diversity, which could provide several benefits, such as reduction of costs for mowing, creating more value to biodiversity and improving the visual appearance. Removal of fallen tree leaves is also a frequent maintenance activity, as lack of leaf litter is perceived as more attractive due to the neat appearance. However, leaves provide organic matter and nutrients to the tree, so not removing leaves would not be only beneficial to a tree health but also save costs for maintenance.

3.4.5.2. Maintenance of vegetation on building surfaces

Overall, vegetation on building surfaces requires more complex maintenance compared to ground vegetation, as it is shown in the following section.

Regarding green vertical systems, green façades generally comprise out of climbing species, such as ivy, which can cover the wall relatively quickly with little maintenance. Maintenance costs would depend not only on the selected species, but also whether supporting elements are present, such as cables or frameworks, as it was shown in section 3.2.1.

Installation and maintenance of direct green façades are associated with lower costs, resulting from primary installation and pruning, and cladding renovation and disposal. Other types, such as living walls, would need significantly more maintenance, such as panels adjustment, irrigation and replacement of broken irrigation pipes (Perini & Rosasco, 2013).

Concerning green roofs, maintenance costs would depend on many factors. As it was discussed earlier, there are two main types of green roofs: intensive and extensive. While extensive green roofs can only accommodate low vegetation such as mosses and grasses, intensive green roofs can have shrubs and even small trees. Costs for installing green roofs varied greatly with the installation costs (per square meter) of intensive roofs being 27 times more expensive than of extensive roofs Maintenance also was considerably more expensive for intensive green roofs: Environmental Agency has estimated it to be 20 times more expensive compared to extensive roofs. Drastic increase in price could be explained by the fact that intensive green roofs have a thicker substrate level and more diverse greenery, which requires constant and intensive management, whereas extensive green roofs generally do not require frequent management, especially if only one type of growth medium, such as sedum, is present. In addition, in case of intensive green roofs, probability of roof failure is considerably larger due to the increased weight, which results from a higher water holding capacity and diverse vegetation of different weight. Therefore, additional maintenance activities, such as fixing the roof leakage, are more likely to occur with the intensive green roofs.

3.5. Approach in the Netherlands

In the following section, state-of-the-art of green infrastructure design in the Netherlands is presented. First, green infrastructure relevance to the Netherlands is described, after which existing planning documents on green infrastructure planning are described and analyzed. Finally, interview results with experts in the field of green infrastructure are presented.

3.5.1. Green infrastructure in the Netherlands

Overall, there is a number of national documents that acknowledge the importance of green infrastructure, including the Delta Program and the National Climate Adaptation Strategy. The Delta program specifically aims at the resiliency of the water system and adaptation to periods of drought. Chapter on spatial adaptation presents green infrastructure as a tool for reducing flood probabilities, tackling drought but also, reducing heat in urban areas. Various implementation examples from Dutch cities were included, ranging from small scale green measures such as renovated car park with green façades to larger scale actions such as promoting the removal of paved surfaces and disconnecting rainwater from the sewers (Delta Commissioner, 2018).

The National Climate Adaptation strategy also acknowledged the same benefits of green infrastructure as described in the Delta Program, however, it also included the idea on solving several issues simultaneously via one spatial adjustment (this notion of multifunctionality was referred to as cross-over). Several examples were presented on how green infrastructure can be multifunctional, such as that more green in the city leads to less heat but also creates new recreational opportunities (NAS, 2016).

Overall, benefits of green infrastructure are acknowledged in national Dutch documents and the principle of multifunctionality appears to be indeed relevant for the Netherlands.

3.5.2. Green infrastructure design strategies in the Netherlands

Despite the wide acknowledgment of the benefits of urban green infrastructure, a shortage of documents that include recommendations on green infrastructure design was observed. Royal Association of Gardeners and Landscapers (VHG) introduced a journal on green infrastructure, which included information on structural characteristics and spatial arrangement of green infrastructure, both on street level and building surfaces. Provided recommendations were consistent with findings presented in the section 3.4 and no conflicts in knowledge were observed.

Klemm (Klemm et al., 2017) developed another green infrastructure design guideline for climate adaptation. The guideline included recommendations on implementing green infrastructure on a city, street and park levels. Various operational principles, such as species selection, position in space and orientation to the sun were also included in the guideline, which can provide more clarity in planning practices. However, as a possible limitation of this study, no other benefits regarding climate adaptation, such as flood mitigation, were addressed in the guideline.

Finally, a comprehensive design guideline was included in the book on climate adaptive design written by Lenzholzer (Lenzholzer, 2015). The book included recommendations on designing for resiliency of cities to climate change using green infrastructure. As one of the highlights of the book, a lot of attention was paid to the role of wind in regulating the climate in a city. Recommendations were given to avoid blocking the wind via dense planting of vegetation and rather allow the cool air to flow downwind via green corridors that connect parks and neighborhoods.

Overall, in the Netherlands, the majority of literature on green infrastructure specifically concerns climate adaptation. No literature was found explicitly on multifunctional green infrastructure design, although Lenzholzer (Lenzholzer, 2015) included a chapter on different design solutions that can lead to multiple benefits, such as urban waterfall, however, it is not explicitly related to green infrastructure.

3.5.3. Interview results on green infrastructure planning in the Netherlands

Overall, three interviews have been conducted with various experts in the field to learn about the state-of-art of implementing green infrastructure in Dutch cities. First interview was conducted with a lecturer-researcher from the Amsterdam University of Applied Sciences, who specializes in the climate-proof city and worked on guidelines such as the Coolkit (HVA, 2020). Second interview was with the landscape architect from Bosch en Slabbers who worked on StraaDKrant (Bosch en Slabbers, 2016), which is a large-scale initiative to make cities resilient to climate change. Third interview took place with the senior board advisor on green living environment at the Municipality of Arnhem. It has been acknowledged by all interviewees that green infrastructure plays an important role for making cities more livable, attractive and resilient to various effects of climate change. Additional information gathered from the interviews is presented below.

3.5.3.1. Multifunctionality of urban green infrastructure

Ability of green infrastructure to deliver several benefits indeed appeared to be an important factor, which is considered in planning. In Arnhem, multifunctionality is checked during the design process, where green infrastructure is selected which can not only improve appearance of the neighborhood, but also deliver other benefits, such as cool the surrounding area. However, trade-offs between functions are not yet considered in planning practices, as the board advisor indicated.

Landscape architect shared that multifunctionality is not “built in the design process” and it often considered on an intuitive level. However, multifunctionality should be considered as usefulness of green infrastructure is not defined only by a single benefit it provides.

3.5.3.2. Design approach in the Netherlands

It appeared that there is no universal way for designing with green, and there are many factors that influence the decision making. While quality of soil, availability of underground space and street geometry are important design factors to consider, selection of vegetation is conducted only after it is clear who are the users of the public space and what are their needs. Landscape architect from Bosch en Slabbers indicated that only 40% of the space is considered to be public, while the rest is private, therefore, promoting the use of green for private stakeholders is a necessary step to make a city greener.

Regarding public spaces, green measures should be implemented after the site has been analyzed on the possible climate risks, such as heat, for instance. Lack of space could indeed be an issue, so implementing other types of greenery is important, such as green façades and green roofs, which are gaining more popularity in recent years. Many factors are considered during the selection of species as well. For example, trees that produce a lot of plant litter should be avoided next to parking spots or people can express discontent that a tree casts a shadow in their garden. This reinforces the statement that stakeholder inclusion is vital. Board advisor on green living environment from Arnhem mentioned that at the outskirts of the city, more diverse green infrastructure can be implemented, while in the city core green infrastructure should be planted where possible, depending on available space and the ability of green to be multifunctional.

Maintenance also is vital and should be assessed during the design process, as was indicated by the landscape architect. While aesthetics and visual appearance are important, thinking about the functionality of green infrastructure and its maintenance is necessary. If green infrastructure is not maintained properly, it is less likely to deliver benefits. While maintenance can be expensive, implementing green infrastructure would pay off in the long term, 3-5 times more the initial investment. In addition, board advisor on green living mentioned that maintenance does not have to be expensive if people would do it less frequently. Instead of planting green that requires high maintenance, such as expensive roses, it could be better to plant diverse green, which requires less maintenance, in case as of meadow-grass, which is more attractive for biodiversity but also improves visual appearance. Finally, maintaining existing green infrastructure and utilizing it as much as possible can be cheaper than planting new greenery.

Board advisor of green living indicated that diversity of species is also crucial not only for improved aesthetics but also for a higher resiliency of the green infrastructure. There is a need for a paradigm shift, where people would move from a neat green design with mono-culture species to a more diverse and less maintained urban greenery. For instance, board advisor mentioned that despite a wide range benefits delivered by coniferous trees, they are rarely seen in Dutch urban landscape, as it was often just a “matter of taste” when choosing green. Change in the way people think about green infrastructure can take some time but overall, such change is needed to make cities more resilient and livable in the future.

4. Design phase

The following phase is dedicated to making the design guideline. This phase is comprised of two sections: design requirements and design guideline. The requirements are needed to determine the content of the guideline and establish a level of detail that the guideline will have. The design guideline is compiled in the next step.

4.1. Design requirements

Overall, seven requirements have been selected that form a foundation for the guideline. Following requirements were drafted based on the research phase and in consultation with the commissioning party. All design requirements carry equal weight, so it is important that each requirement is met in the guideline.

1. *The guideline must include green infrastructure elements that have the capacity to be beneficial for climate change adaptation, human health, and biodiversity in urban settings.*

As it was shown in the research phase, there are several types of urban green infrastructure that allow multifunctional use: trees, shrubs and bushes, grassed areas, green roofs and green vertical systems. These green elements will be used in the guideline.

2. *The guideline must include information on the scale of application and relevant scenarios.*

Since there are many cases in which urban green infrastructure could be implemented, it is important to define the scale within which the guideline is relevant and include scenarios to illustrate possible applicability of green infrastructure. The commissioning party expressed interest in applicability of the guideline on a street and neighborhoods scales with scenarios including varied geometry of street canyons.

3. *The guideline must include recommendations on structural characteristics and spatial arrangements of green infrastructure that increase the probability of achieving multifunctionality.*

Preliminary analysis of design strategies showed that performance of green infrastructure is highly dependent on two main factors: structure of vegetation and its spatial configuration. The guideline will include recommendations on both to achieve multifunctionality of green infrastructure.

4. *The guideline must provide information on how to combine different types of vegetation to improve the overall performance of green infrastructure in the city.*

As it was mentioned in section 3.4, green infrastructure elements deliver benefits more effectively when combined into one ecosystem. The guideline will provide recommendations on combining different types of vegetation to have a maximum positive impact on climate adaptation, human health and biodiversity.

5. *The guideline must provide information on how to maintain urban green infrastructure.*

The commissioning party expressed interest in the maintenance of urban vegetation. Thus, recommendations on appropriate maintenance of individual green infrastructure elements will be included.

6. The guideline must be applicable in Arnhem.

Since the guideline is primarily designed to be applicable in Arnhem, it is important to ensure that requirements drawn by the Municipality of Arnhem in the climate adaptation plan are considered and integrated in the guideline where possible.

7. The guideline must take into consideration existing green infrastructure.

The developed area rarely lacks any green infrastructure, which can pose restrictions for the planning (such as lack of space for new trees, for example). It is important to consider existing green infrastructure during the design process in order to avoid any nuisances.

4.2. Design guideline

This sub-section presents information on the structure of the guideline, while the guideline itself can be found in Appendix D: Design guideline.

The structure of the guideline consists out of three phases: preparation phase, design phase and general recommendations phase. Preparation phase includes certain steps that are recommended to take during the analysis of the site where green infrastructure is planned. Such steps include mapping existing green infrastructure in the area or investigating underground utilities and measuring height-to-width ratio of a street. In addition, information sheet is provided on street canyons, which can assist in choosing the appropriate type of urban green infrastructure depending on the geometry of a street and orientation towards the sun.

After determining the suitable type of urban green infrastructure, design phase begins, which includes recommendations on both the structural characteristics and spatial arrangement of all types of urban green infrastructure, including ground vegetation and vegetation on building surfaces. The goal of the design phase is to inform about benefits one can acquire when choosing a certain trait of green infrastructure (for example, dense crown of a tree) and a certain configuration in space (such as locating trees away from each other). In addition, comparison is made between species or types of vegetation, such as deciduous and coniferous trees, or extensive and intensive green roofs. In addition, information on maintenance is provided, where common maintenance activities are listed, and intensity of maintenance is compared between types of vegetation.

Finally, in the last phase, general recommendations on green infrastructure design are provided. These recommendations mostly apply to all types of vegetation, therefore, there were grouped for clarity. Recommendations are given for the street level design (such as that diversity of vegetation is recommended) and for the neighborhood level design (such is that urban parks need to be connected with each other via green corridors).

5. Validation phase

In the following phase, the design guideline is validated by applying it in the neighborhood Presikhaaf in Arnhem and through interviewing various experts in the field of green infrastructure. The results are presented below.

5.1. Case study

As it was described in the introduction, Municipality of Arnhem has developed a climate adaptation plan for 2020-2030, where several measures were proposed to make Arnhem more climate-proof (Gemeente Arnhem, 2020b). In addition, Municipality of Arnhem presented a Tree Plan, which describes the intentions of the Municipality towards planting and management of trees (Gemeente Arnhem, 2020a). Overall, the ambition of the Municipality is to tackle various issues resulting from climate change, including extreme heat, drought and urban floods through the strategic creation of green infrastructure and implementing other measures, such as disconnecting rainwater from the sewers. Other benefits of green were also addressed in both documents, such as enhanced biodiversity, improved human health and improved aesthetics. Specific measures varied throughout the city since some areas are more prone to certain effects of climate change due to geographical or other reasons. In this section, only measures relevant to the case area will be discussed.

5.1.1. Description of the case area

The case area is the neighborhood called Presikhaaf III, which is a part of the larger neighborhood Presikhaaf located in the south of Arnhem. Larger map can be seen in Figure 9 and the case area is shown below in red:

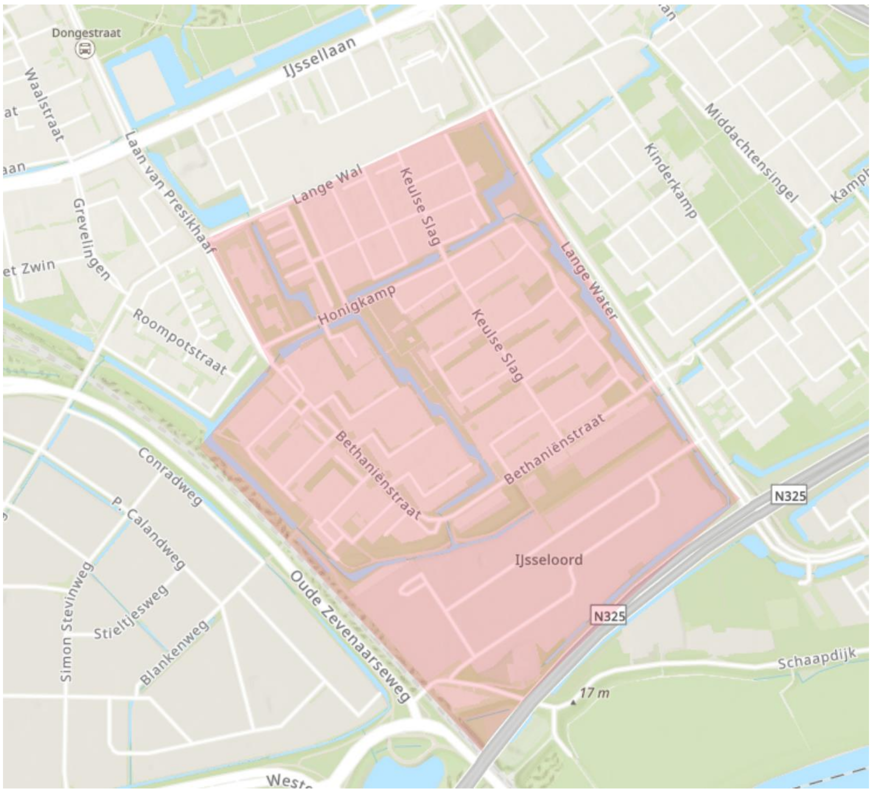

Figure 8: Case study area (in red)

The neighborhood is close to various amenities, such as a large shopping area and park Presikhaaf to the north of the neighborhood. Regarding housing types, the neighborhood includes both low- and high-rise buildings, predominantly rental type. In addition, Presikhaaf III accommodates a business park Ijsseloord to the south of the neighborhood. This area is interesting for the research as it has scarce vegetation but also varied microclimate due to the presence of buildings of different heights.

According to the climate adaptation plan, Presikhaaf consists of mostly low risk climate zones and the main objective is to ensure that the microclimate does not get worse in this areas. However, there are two areas that are prone to heat stress, one is the shopping area to the north of the case area and the second one is IJsseloord to the south of Presikhaaf III. Regarding other areas, Park Presikhaaf, which is shown in light blue above Presikhaaf III in and greenery stretching along A12 to the south are the most unbuilt areas that contribute to the cooling in the neighborhood. National Park Veluwe to the North of the city also exerts a cooling effect with the wind blowing towards Presikhaaf. It was pointed out in the climate adaptation plan that winds from Veluwe contribute significantly to the cooling of the city, so it can be said that allowing the wind to freely enter the Presikhaaf would produce a stronger cooling effect. Moreover, south of Arnhem is susceptible to flooding due to high waters of the Rhine, so it is important that during rainfall, the water is retained in the North as much as possible to reduce probabilities of flood events (the case area is located 300-500m from the river). The climate map of Arnhem made by the Municipality can be seen below:

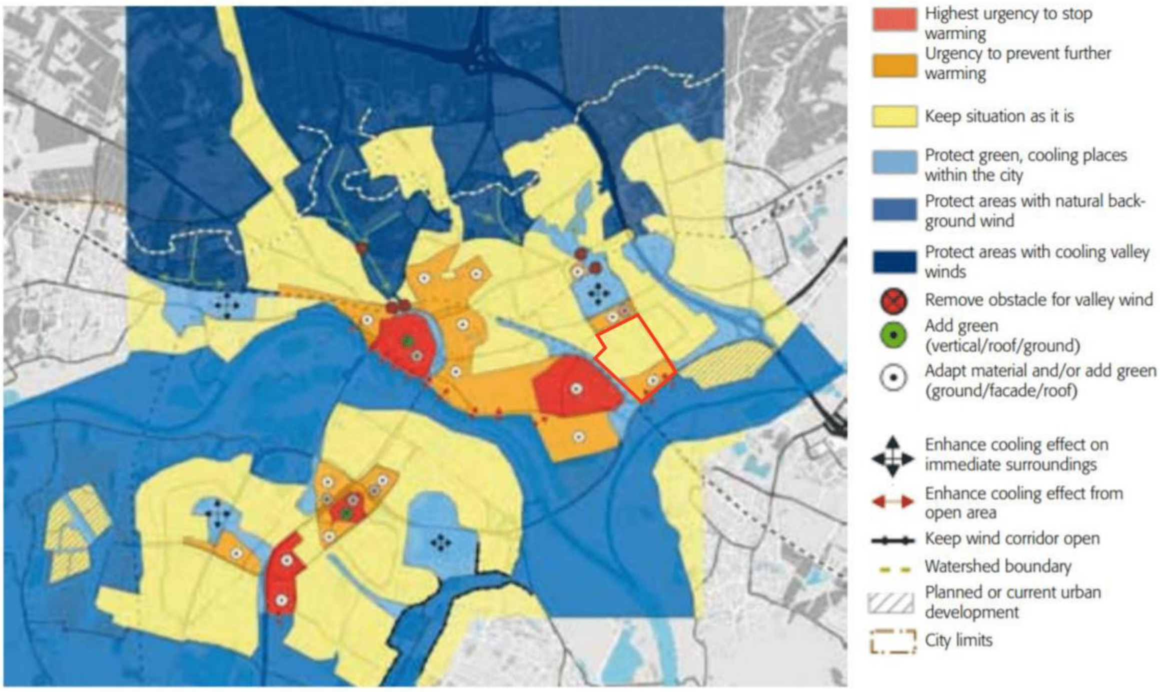

Figure 9: Climate map of Arnhem (Presikhaaf III is shown with red boundaries with no fill)

Regarding city-wide measures, the Municipality aims to disconnect 90% of rainwater from the sewers, realize connected shaded pedestrian paths and ensure that cooling areas are present within 250 meters proximity to residential buildings, especially in medium and high-risk climate zones. All mentioned interventions are planned for the years 2020-2030.

The importance of green and specifically trees was also acknowledged in the Tree Plan. There are currently 40000 trees in Arnhem and the ambition is to increase the tree cover by 5% over the whole Arnhem and by 10% in areas that are vulnerable to heat stress. Moreover, both structural and spatial characteristics of trees were also mentioned in the Tree Plan. As a starting point, locations where trees are needed should be identified and after that, species should be carefully selected so that they have enough space for growth, both underground and on-ground. Importance of species diversity was also acknowledged: single species are more susceptible to various diseases and pests and less effective against storm-water mitigation, for instance. Planting native species is more beneficial to biodiversity and species that can provide food and shelter for birds, mammals and insects should be prioritized. Combining different types of greenery is also considered beneficial, both for biodiversity and for improving the appearance of the neighborhood. In addition, trees might not have enough space for growth, so realizing other types of green such as shrubs and façade greenery could be an alternative. As trees become larger and start to give more shade, growth of nearby shrubs and herbs can get disturbed, so occasional thinning of trees should be done to give more light to other greenery. Finally, trees contribute to the increased aesthetics of the city and improve health of citizens. The Tree Plan is part of the national Green Vision for the years 2017-2035 (Gemeente Arnhem, 2020a).

5.1.2. Validation results from interviews

In order to validate the guideline, interviews were carried out with various experts in the field of urban green infrastructure. Interviews took place via email, where the guideline and a list of questions was sent to interviewees. Questions were asked on the clarity of the guideline, usefulness and applicability. This sub-section presents the summary of the feedback given by interviewees.

Overall, three respondents gave feedback on the guideline, two urban planners from the Municipality of Nijmegen and one self-employed landscape architect from Hertogenbosch. Regarding the clarity of the guideline, all respondents agreed that the guideline is easy to understand, however, more introductory text could, perhaps, be added to improve clarity. Concerning usability, the landscape architect shared that the guideline is quite an accurate representation of his own process and that presented steps (such as that in preparation) are considered automatically in his work. Regarding other feedback, urban planners found the guideline useful and expressed interest in the application results.

5.1.3. Application of the guideline

Extensive application of the guideline can be found in Appendix E: Application of the guideline. Overall, two locations were chosen in Presikhaaf III where the guideline was applied. It appeared that the guideline was useful in assisting during the site analysis and in making decisions particularly on structural characteristics of vegetation. It was not feasible, however, to apply all recommendations on the spatial arrangement as vegetation could be located only where space allowed it.

Overall, the guideline was not adjusted after the application, as the guideline is intended to present an “ideal” case scenario, which could be modified based on the specific situation, as it was done in the validation study.

6. Discussion

In this section, discussion is presented on every phase of the research, namely research, design and validation phases. Firstly, it is important to mention that no other research was found that this study could be compared to, as all examined design studies focused either on the practical knowledge of individual benefits (such as heat stress reduction) or on theoretical design principles (such as connectivity).

6.1. Discussion of the research phase

As it was stated in chapter 2 on the research methodology, the research phase included five research questions. Overall, there was considerable evidence of the benefits of urban green infrastructure, however, specificity was often lacking across scientific publications, especially concerning individual types of urban green infrastructure. In this sub-section, encountered issues are elaborated.

Before the research has begun, it was prognosed that there would be only one type of urban green infrastructure (which is trees) that could certainly be multifunctional. However, throughout the research phase it became apparent that other types of green infrastructure, both on the ground and on building surfaces, could be multifunctional as well, although to a lesser extent. Thus, additional research was conducted to investigate benefits that can be provided by other types of green infrastructure. During this process, one major limitation was encountered, which turned out to be a general lack of sufficient research on vegetation apart from trees. The majority of examined scientific literature focused explicitly on trees, while literature particularly on vegetation on building surfaces was very scarce, which made it challenging to critically assess the contribution of such vegetation to the benefits identified earlier.

A similar issue was encountered during the third research question, where the majority of literature described disservices of urban trees, while other types of vegetation were rarely examined in this regard. It could be assumed that the reason why trees were researched the most often is that only trees can cause the most nuisance in urban landscape due to their size but this does not necessarily cancel out other disservices that could be associated with other types of green infrastructure. For example, no literature presented disservices of green façades while, according to the commissioning party, people are often worried that greenery will damage the wall cladding or that unpleasant insects can enter the house. Perhaps, more research on disservices and ways to avoid them could make other types of vegetation, particularly on building surfaces, more attractive and "understandable" for residents.

The fourth question posed many uncertainties, again related to the shortage of sufficient research. There was indeed a lack of literature that presented a practical approach to green infrastructure design. Regarding general design principles, it was not apparent initially how a principle such as connectivity can be achieved in practice so further analysis was conducted to investigate this principle on a smaller scale for a single type of urban green infrastructure. Overall, there was a sufficient literature available on the spatial arrangement of vegetation but not on structural traits, especially for vegetation other than trees. For that reason, many assumptions had to be made based on the existing knowledge of trees, such as that tall trees can store more water, therefore, tall shrubs and tall grass can also store more water. While such assumptions might not have resulted in accurate predictions of the performance of other types of vegetation, they certainly could lay a foundation for the further research.

Finally, the approach in the Netherlands was investigated though literature research and interviews. Similar to the previous question, there was a shortage of research conducted in the Netherlands on green infrastructure design and no publication was found that explicitly focused on the multifunctionality of green infrastructure. All publications on green infrastructure design were mainly focused on climate adaptation. In addition, certain limitations were also encountered during interviews. Firstly, it was a challenge to find interviewees due the scheduling problems or language barrier. Secondly, all interviewees had a different expertise, so different sets of questions were prepared to each interviewee. For that reason, the obtained results were highly inhomogeneous and often lacked any crossovers between different interviews. This made it challenging to adequately analyze the results and group them accordingly. In addition, only one interviewee could share thoughts on the multifunctionality of green infrastructure, while other two interviewees were not very familiar with this concept. Nevertheless, such diversity of interviews helped to get a broader idea of the green infrastructure development in the Netherlands.

Overall, all sub-questions from the research phase were answered and even expanded upon, as more types of green infrastructure were taken into analysis. The main issue that was encountered was related to the lack of sufficient available research, but it was possible to overcome this issue by making assumptions based on the existing knowledge. All assumptions presented throughout the report need to be tested, which could potentially give a direction for the further research.

6.2. Discussion of the design phase

The gathered information during the research phase was rather extensive, so it created a challenge to filter out this information and group it in the way that could be useful and understandable for the reader. Therefore, the decision was made to create three stages that could be followed in a logical order.

Throughout the design phase, one main issue was encountered that was related to the quantification of the design recommendations. The research results mainly included general recommendations, such as that a green roof on a low building is more attractive for biodiversity than on a tall building. However, it did not seem clear how low the building must be to be qualified as attractive or not attractive for biodiversity. Thus, as a result, the guideline included only general recommendations for green infrastructure design, which need to be investigated further based on a specific situation. This limitation could also give a direction for the further research.

Nevertheless, the guideline met all design requirements drafted during the design phase. It was organized in way that it captures all relevant information, which can assist in decision making during the design process.

6.3. Discussion of the validation phase

Finally, during the validation phase, several limitations were encountered that are discussed below.

Firstly, the guideline does not include information on existing rules and regulations in the Netherlands on tree placement, while such information is crucial and should be considered in the design process. Sweco provided maps that inform about the possible locations for trees in the case study areas, based on the national regulations (such as that a tree should have a minimum distance from a residential building, for example) and a tree size. Deviating from these maps would have produced inaccurate results that do not match reality, therefore, maps were carefully analyzed throughout the application process and used for choosing the exact locations for trees. This made it challenging to apply the recommendations on spatial arrangement of trees as in most cases, trees could be located only in a fragmented manner where the space allowed it. The same applied to low and medium vegetation: while continuous planting would have been more beneficial, it was not possible to do so due to spatial constraints. However, vegetation on building surfaces could be implemented according to the guideline.

In order to create more space for vegetation, it would be, perhaps, necessary to sacrifice existing grey infrastructure. For example, having only one sidewalk along the road instead of two sidewalks on both sides of the road can already greatly increase the possibility of implementing more greenery. Similar could be applied to car parking: less parking spots would lead to more space for vegetation in streets but also, perhaps, lead to other benefits, such as promotion of alternative types of transport. Careful analysis of the urban areas is needed to locate possible locations where grey infrastructure can be replaced with green without hindering accessibility or causing other nuisances.

In addition, the analyzed locations included streets that were not homogeneous in their geometry, which made it unfeasible to accurately measure the height-to-width ratio of a street. All analyzed streets did not form canyons but rather, consisted out of detached houses with many openings in between, through which the wind can freely travel. This also posed a question as to what exactly qualifies as a street canyon. While the height-to-width ratio seemed important, it was not clear how long the street should be to be qualified as a canyon and how large the openings between buildings can be to maintain the same microclimate on a street level. In addition, the guideline only included recommendations on symmetric street canyons, while in the case study, streets were rather asymmetric with buildings of varied height on both sides of the road. Since urban landscape is highly inhomogeneous, it is important to further investigate factors, other than height-to-width ratio, that can have an impact on the performance of vegetation in streets.

Moreover, regarding the preparation phase, software was used that can simulate shadows produced by buildings throughout the day. While simulations provided useful insights into shade formation, the program lacked vertical data in the studied area, so all buildings were shown with the same height. This limitation led to inaccurate results that do not match reality, so several assumptions had to be made during validation. In addition, the program lacked information on the existing vegetation in the area, so shade produced by existing trees was challenging to predict, which also led to several assumptions. More advanced software is needed that would include vertical information of objects, including trees. For instance, information on size of the crown and height of the tree can be extremely useful in shadow mapping, especially for urban areas.

Finally, in the last step of the preparation phase, underground utilities were analyzed based on the maps provided by Sweco. While these maps proved to be useful to locate utilities and distinguish them, information on the depth of the utilities was lacking. This information is important as soil volume is an important information when choosing a suitable type of vegetation. Further development of software's that include vertical distance to utilities can assist when choosing appropriate ground vegetation, which would greatly help to avoid any nuisances. In addition, soil quality was not taken into consideration in the guideline, while such information is also necessary when choosing a type or specimen of vegetation (such as drought-resistant species, for example).

To conclude, the guideline was proved to be useful particularly during the preparation phase and for choosing vegetation based on the structural traits. Recommendations on spatial arrangement were hardly used, except the recommendation that trees should be located away from each other for a better ventilation. It can be assumed that the guideline can be followed more accurately when applying it in a developing area, rather than developed, however, this needs to be tested in practice.

7. Conclusion and recommendations

Last chapter presents conclusion and recommendations for further research, based on the discussion.

7.1. Conclusion

This study investigated the topic of urban green infrastructure, with the focus on its benefits for human health, climate adaptation, and biodiversity, and attempted to translate existing scientific knowledge into usable and practical design guidelines. Overall, it can be concluded that the objective of this study has been reached and the developed guideline presents steps on how the multifunctionality of green infrastructure can be achieved.

Primary research has uncovered the complexity of green infrastructure and shown that all types of ground vegetation and vegetation on building surfaces are able to deliver multiple benefits. Nevertheless, much of the existing research specifically focused on trees, therefore, many assumptions had to be made in order to fill in the knowledge gaps. Assumptions were not unfounded, however, and were based on the existing scientific knowledge. Regarding the design approach, the method was developed that considers multiple design factors, such as the location, structural traits and spatial arrangement of five types of urban green infrastructure. The method is partially based on the existing model called GIST (Green Infrastructure Space and Traits), where multifunctionality was assessed based on the priority locations and structural characteristics.

The compiled guideline includes extensive information of green infrastructure design, which can assist urban planners in decision making process. Steps including preparation, selection of vegetation based on desirable structural traits and location, selection of the spatial arrangement of vegetation, and the maintenance and application of the general recommendations on green infrastructure design, both on street and neighborhood levels, were included in the guideline.

The application of the guideline in Arnhem has shown that implementing green infrastructure in the existing urban environment is a challenging task, as many spatial constraints, including from infrastructure, both green and grey, are present. Such limitations made it unfeasible to accurately follow the guideline, as recommendations on spatial arrangement could not be fully implemented as vegetation could be planted only in places where space, both on-and-underground, allowed it. Nevertheless, the guideline was useful for the selection of vegetation and during the preparation phase.

Overall, the design guideline can be used by practitioners where the future development is planned, as the guideline provides steps on how to uncover multifunctionality of green infrastructure specifically for such cases. The guideline is not tied specifically to any location and could assist during the decision making of the green infrastructure design where the future development is intended to take place. It can be concluded that developing around green infrastructure would lead to unlocking more benefits of green infrastructure, compared to implementing green infrastructure in a dense urban landscape.

7.2. Recommendations

Overall, based on the discussion, several recommendations can be given for the further research. First, more research is required to fill in the knowledge gaps on vegetation other than trees. Research is particularly needed into vegetation on building surfaces (green roofs and walls) and its benefits, as such vegetation will be getting more relevant in the future due to the densification of cities.

Secondly, further research is needed into additional factors affecting the performance of vegetation in streets. It has been shown the height-to-width ratio is an important factor but length of a street, for example, or the asymmetry of a street could be other factors that affect the microclimate in street canyons. Moreover, performance of urban green infrastructure in other public spaces, such as city squares, could be investigated.

Furthermore, soil quality is another factor that requires more attention. Since the health of vegetation is highly dependent on the soil condition, it is important to investigate what soil is preferable for chosen vegetation. Perhaps, the guideline could be expanded with the recommendations on species based on the soil characteristics.

Next, since less frequent maintenance is sometimes more beneficial (such as that increasing the height of grass), it could be investigated how this approach can be made more attractive for residents. Thus, increasing the attractiveness of less frequent maintenance to private stakeholders could be another recommendation for the further research.

Finally, there is a need for tools that can accurately measure the depth of the utilities and map shadows of urban vegetation.

As of now, research into vegetation on building surfaces should be prioritized due to the increasing density of urban landscape.

8. References

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Appendix A: Microclimate in street canyons

Street canyon is characterized by a road and buildings on both sides. Street canyons often have their own microclimate due to the restricted flow of air and shaded inner surface. In literature, three types of street canyons are often distinguished: wide canyon, medium canyon, and deep canyon (Kumar et al., 2019; Norton et al., 2015). Each type of a street canyon is characterized by a specific height-to-width ratio, as can be seen below:

- H/W[6] ≥ 2: narrow street canyon
- 0.5 < H/W < 2: medium street canyon
- H/W ≤ 0.5: wide street canyon

Performance of green infrastructure in street canyons is dependent on the geometry of a street, however, other factors, such as orientation to the sun and wind direction were also showed relevant. Orientation to the sun is particularly relevant when examining the necessity of greenery to shade the canyon (Norton et al., 2015), while wind direction is important for both the cooling the area downwind (Norton et al., 2015; Sodoudi et al., 2018) and dissipating the air pollution caused by vehicles (Kim et al., 2015).

Regarding orientation to the sun, East-West (E-W) oriented canyons receive longer hours of sun than North-South (N-S) canyons, therefore, shading in E-W oriented canyons is considered more important (Ali-Toudert & Mayer, 2006). Wind also contributes to cooling if it blows parallel to green belts (Sodoudi et al., 2018) and not restricted by obstacles, which could be buildings or dense vegetation (Lenzholzer, 2015). Designing for multifunctional green infrastructure in street canyons might be challenging and many trade-offs might occur. For example, while wind is beneficial overall for mentioned benefits, it can also cause nuisance for pedestrians and cyclists, especially in deep canyons where high-speed winds can be generated, so slowing down the wind by using green infrastructure might be considered as an option. In addition, streets are rarely homogeneous and buildings on both sides of the road might be of different height and shape, which can also have an effect on the microclimate. As it is challenging to consider every possible scenario, more generic recommendations are provided that can be tailored depending on the situation.

A.1. Narrow street canyons

In deep street canyons, the air exchange between the air within the canyon and ambient air outside it can be quite limited (Kumar et al., 2019; Norton et al., 2015). Because of that, only certain types of green infrastructure are recommended in deep canyons. For instance, trees are generally not recommended in deep canyons as they can trap pollutants under their crowns and therefore lead to deterioration of air quality on the street level (Kumar et al., 2019). In addition, tall buildings shade the canyon themselves, so planting trees might not be necessary for shading (Ali-Toudert & Mayer, 2006; Norton et al., 2015). However, it applies mostly to N-S oriented canyons, while E-W oriented canyons will receive a lot of sun even with the height-to-width ratio of H/W = 4 (Ali-Toudert & Mayer, 2006). Additional shading via overhead façades might be needed in such canyons. Regarding other types of vegetation, wall vegetation is considered as the most suitable type of green infrastructure for deep street canyons, as it directly shades the building, captures pollutants that move along the street and reduces internal reverberation of the sound between buildings.

[6] H refers to the height of the buildings and W to the horizontal distance between the buildings.

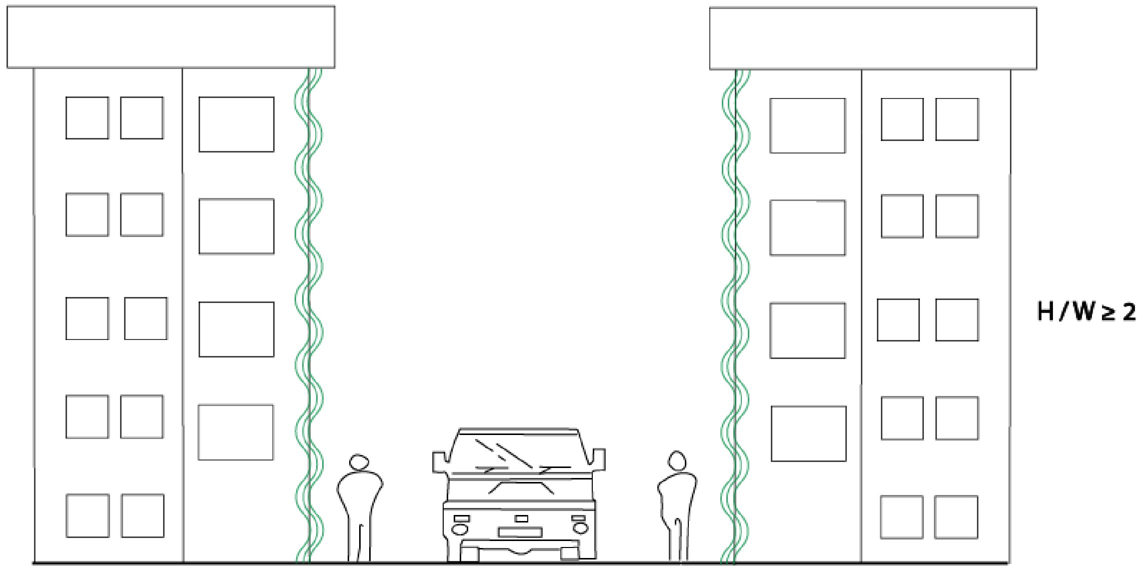


Figure 10: Narrow street canyon

A.2. Medium street canyons

As the height/width ratio decreases, the air exchange improves, so more types of green infrastructure can be used, in addition to wall greenery. Medium vegetation can be implemented in such canyons, which can contribute to additional cooling via evapotranspiration, capturing pollutants and absorbing sound frequencies. It is uncertain whether implementing trees in such canyons would be beneficial or detrimental, as one the one hand, such canyons would be more exposed to the sun and could potentially benefit from additional shading but the air exchange would still be limited, as Kumar (Kumar et al., 2019) pointed out. Careful considerations should be made beforehand whether trees can be implemented in such canyons.

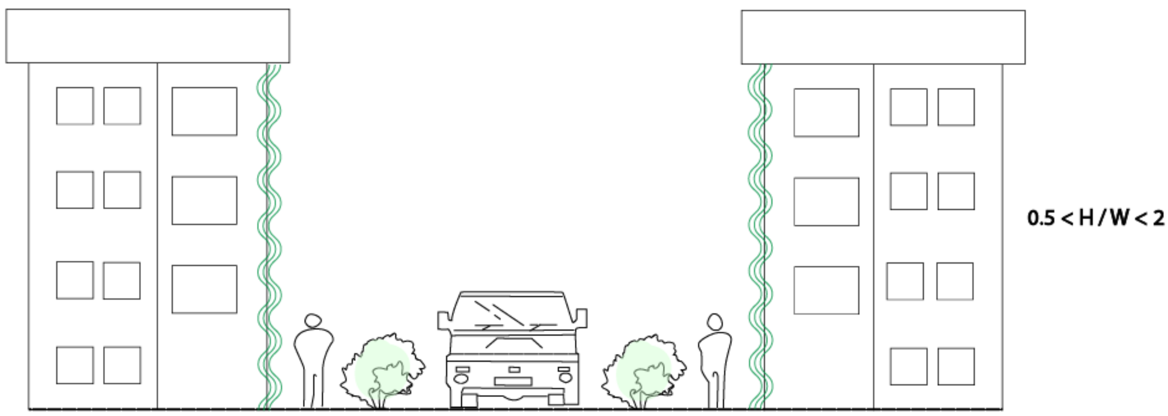


Figure 11: Medium street canyon

A.3. Wide street canyons

Finally, wide street canyons experience the highest solar exposure, so increased plant coverage is recommended. Wall greenery in combination with ground vegetation could produce the largest cooling effect and deliver other benefits, such as improving air quality and reducing noise pollution. Whether the canyon is N-S or E-W oriented, such canyon will most likely benefit from tall and dense trees from a better shading (Ali-Toudert & Mayer, 2006), however, for air pollution trees with lighter crowns are more preferred (Kumar et al., 2019).

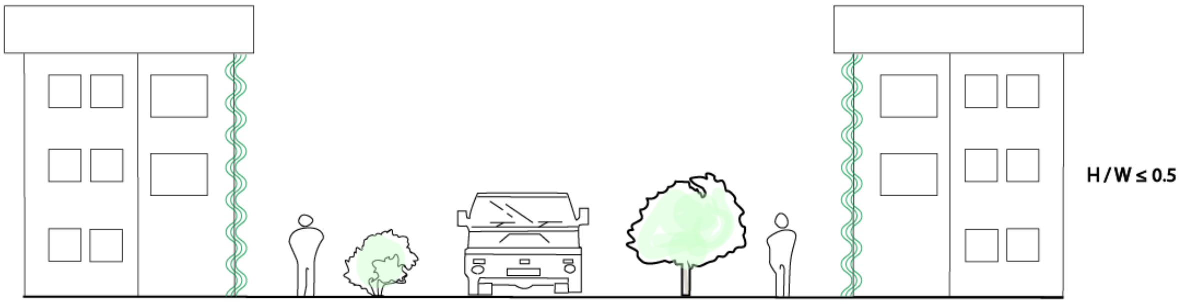


Figure 12: Wide street canyon

A.3. Summary on street canyons

Overall, as it was shown in the analysis, it is challenging to reach consensus on whether implementing trees would be beneficial in street canyons. While trees can provide shade and cool the air via evapotranspiration, they can also worsen the microclimate by trapping heat and pollutants under their crowns. As a preliminary conclusion, it can be suggested that trees with lighter crowns can be implemented in medium, E-W oriented street canyons and for wide street canyons, larger trees with denser crowns can be planted if they are spaced generously away from each other for a better ventilation (Norton et al., 2015). For wide canyons, trees can be implemented on both sides of the road (Norton et al., 2015) and in medium canyons, trees should preferably be planted only on the windward side (Kumar et al., 2019). Other types of vegetation, such as grass, green roofs and green walls can be used regardless of the geometry of a canyon, while shrubs should be prioritized in medium and wide street canyons.

Appendix B: Ranking of green infrastructure

In the following sub-section, types of green infrastructure are compared based on their ability to deliver benefits. It should be noted that due to a lack of a sufficient comparative research, many assumptions had to take place during ranking, therefore, the ranking does not qualify to be called purely scientific. In addition, performance of individual green infrastructure elements can depend on other factors, such as location and species. Moreover, it is important to mention that performance of green infrastructure is compared from a pedestrian perspective.

Overall, it can be concluded that trees perform the best at delivering benefits as shown in Table 1. Regarding physiological health benefits, trees performed the best simply due to the largest leaf mass and height, which allows trees to effectively filter large amounts of air pollutants, block noise and provide thermal comfort via two processes, evapotranspiration and shading. It was relevant to distinguish small and large trees, as performance would vary between them. Small trees were overall ranked lower than large trees for all benefits, and their performance could be somewhat compared to shrubs and hedges. Despite the fact that the increased tree canopy was associated with the increase in physical activity amongst residents, it was assumed that short-mown grass performed better in terms of promoting physical activity, simply due to the fact that grassed areas provide soft ground, which is attractive for exercising and leisure.

Shrubs were ranked third in terms of their ability to reduce air pollution and provide thermal comfort as shrubs have a similar structure to small trees, however, no literature was found that examined a connection between presence of shrubs and physical activity, so the field was left blank. Shrubs, however, were ranked the same as large trees and higher than small trees for noise pollution as one, shrubs have a dense structure throughout its height (which is an important factor for effective noise absorption) and second, trees, especially when they mature and become larger, can skip more noise through the understory, as lower branches can die due to insufficient sunlight provision (Dobson & Ryan, 2000). Grassed areas could contribute to noise pollution mitigation by muting some frequencies of the sound, however, the effectiveness was assumed to be smaller compared to shrubs, due to a lower leaf mass. For the same reason, grassed areas were ranked lower than shrubs for air pollution mitigation. Meadows could be more beneficial overall compared to short-mown grasses due to more diverse and taller plants, however, meadows were ranked lower than short-mown grasses for promotion of physical activity.

Green roofs were ranked lower for air pollution mitigation than shrubs and trees as green roofs are not directly exposed to the on-ground sources of pollution, therefore, their usefulness for pedestrians is uncertain. Similarly, green roofs could contribute to noise pollution mitigation but not much on the pedestrian level, as green roofs only absorb noise that comes from above. Intensive green roofs could be more beneficial overall than extensive green roofs, as intensive type can accommodate all types of ground vegetation.

In comparison, green vertical systems performed better than green roofs in terms of increasing thermal comfort for pedestrians, as one, such systems shade the heat-absorbing walls, two, they can cool the air via evapotranspiration on the pedestrian level and three, green vertical systems insulate buildings from all sides, which keeps people inside the building cooler in hot periods and warmer in cold periods. Regarding noise pollution, living walls were ranked higher than green façades as living walls can have more diverse and complex vegetation and higher than green roofs as most of the noise pollution sources are present on the ground level. Similarly, living walls can improve the air quality more than green façades and extensive green roofs. Ability of both green vertical systems and green roofs to promote physical activity remains uncertain due to insufficient research, so correspondent fields were left blank.

Psychological well-being posed less uncertainties, as psychological benefits were mostly derived from the presence of green infrastructure in general and less from the specific abilities related to individual types of green infrastructure. However, comparison still could be made with the trees ranked first as trees are simply the most visible type of urban green infrastructure in the city landscape. Short-mown grass and meadows were ranked the same for the stress reduction and positive emotions, as people could benefit psychologically from exercising on a short-mown grass and by looking at meadows. However, short-mown grass was ranked last for cognition and attention, as these benefits come mainly from direct visual exposure to green infrastructure, which might not be the case for low grass. Shrubs, on contrary, performed better than grassed areas in terms of improving cognition and attention as shrubs are generally more visible. Extensive green roofs were ranked the lowest for delivering all psychological benefits simply due to the fact that green roofs are often not in the direct view of pedestrians. Intensive green roofs were ranked one point higher, as taller roof vegetation could be more visible. Green façades were ranked as high as intensive green roofs due their visibility, and living walls were ranked higher than green roofs and green façades as living walls might stand out more due to their complex vegetation.

Climate adaptation benefits also posed some uncertainties. Trees were ranked the highest among all types of green infrastructure for mitigating urban heat islands, again due to their ability to shade and cool the area via evapotranspiration. Shrubs were ranked the same as living walls, as both types of vegetation can cool the air via evapotranspiration and thereby increase thermal comfort for pedestrians. Extensive green roofs, short-mown grass and green façades were ranked the lowest as such vegetation is less complex compared to others, which limits its ability to cool the area. Intensive green roofs were ranked a point higher due to a more complex and diverse vegetation, however, as it was discussed in section 3.2.2, the cooling effect of green roofs primarily comes from evapotranspiration, and for pedestrians' effect would be negligible. Regarding flood regulation, all types of vegetation were ranked in similar fashion, besides green roofs: both intensive and extensive green roofs were shown to be very effective at reducing runoff. Green roofs and green façades had no effect on drought regulation, and it can be assumed that both could even worsen the situation, as ground would receive less moisture.

Finally, trees were ranked first for contributing to biodiversity conservation and enhancement as many insects and birds can use trees for shelter, nesting materials and breeding. Shrubs were ranked lower than trees but higher than grassed areas and all types of vegetation on building surfaces. Meadows had more value to biodiversity than short-mown grass, and intensive green roofs could house more diverse vegetation and thereby attract more species. Living walls could also be more beneficial to biodiversity than green façades due to a larger variety of plants that could be installed, which explains the ranking.

Appendix C: Analysis of structural and spatial characteristics

C.1. Trees

Starting with climate adaptation, large trees with large leaves performed best against urban heat as they were able to provide the most shade in the urban areas (Tran et al., 2020; Wang et al., 2021). In addition, high density of the crone as well its size also played significant role in urban cooling, as these traits directly lead to the greater light attenuation (Wang et al., 2021). In addition, large plants are able to cool the surrounding area more effectively via evapotranspiration (Lundholm et al., 2015; R. Zhang, 2020). However, trees with dense crowns can trap heat in urban canyons, which can have a negative effect on the microclimate (Norton et al., 2015). One study demonstrated that tall trees cool the surface less via shading, therefore, shorter trees could be more beneficial (Helletsgruber et al., 2020). It has been suggested that having a variety of species would perform best against the urban heat island (Wang et al., 2021).

Besides structural characteristics, spatial configuration of trees highly affects the ability of trees to cool to area. Norton (Norton et al., 2015) examined spatial arrangements of trees only in street canyons, which occupy the most space in urban landscape (Norton et al., 2015). As it was mentioned earlier, trees with dense structure can provide the most shade, however, they can also trap heat under their canopy. In order to allow ventilation in urban canyons and thereby let solar radiation to escape, it was proposed to locate trees away from each other, so that they do not from a continuous canopy. Locating trees parallel to the wind direction would be beneficial for cooling the area downwind, while locating trees perpendicular to wind direction would block the wind and thereby reduce the cooling effect (Sodoudi et al., 2018). Regarding the location of trees, Norton suggested to avoid locating trees in deep and medium street canyons as ventilation in such canyons is already restricted. However, locating trees in wide urban canyons is recommended (Norton et al., 2015).

Concerning stormwater reduction and drought regulation, trees can be also very effective. Physical traits such as leaf area, crown density and crown size have a large impact on the ability of a tree to intercept rainfall (Berland et al., 2017; Marapara et al., 2021). Broadleaf trees can capture more rainfall on leaf surfaces, however, conifers are considered more effective at storing water due to the very dense canopy of needle leaves (Marapara et al., 2021). Small trees have a limited capacity to capture stormwater, but they can still help to reduce runoff by infiltrating rainfall in the soil. Implementing tree pits in urban areas is considered as an effective measure to capture rainfall but also contribute to replenishing groundwater stores (Berland et al., 2017).

Regarding the flood and drought regulation, it is proposed to locate greenery in areas where the impervious area is large (Marapara et al., 2021; Tran et al., 2020) and where the runoff coefficient is high (Tran et al., 2020). No literature was found on trees specifically, however, it can be suggested that since trees can intercept rainfall and absorb it via infiltration in the soil, locations where impervious surface is dominating could be appropriate for trees.

Regarding human health benefits, several structural characteristics are important to consider. First, trees are able to capture PM and gaseous pollutants, however, the performance varies greatly between species. Filtering ability of trees primarily depends on the crown size, crown density, leaf size and leaf structure (Kumar et al., 2019). Larger trees can capture more particles than smaller trees and more pollutants are trapped by larger leaves (Kumar et al., 2019). Regarding the structure of the leaf, hairy and rough surfaces are considered as the best filters for capturing particulate matter (Beckett et al., 2000; Clapp, 2014; Kumar et al., 2019). Conifers perform best because of the dense structure of the canopy and hairy needle leaves (Beckett et al., 2000; Clapp, 2014). In addition, conifers are evergreen species, meaning that they filter pollutants all year long (Beckett et al., 2000; Clapp, 2014). Species that emit high amounts of volatile organic compounds (VOC's) should be avoided (Barwise & Kumar, 2020; Grote et al., 2016; Kumar et al., 2019). Moreover, trees can act as a noise barrier. Here, traits such as density and size of leaves, branches and foliage are the crucial factors that determine the success of blocking the noise (Cameron & Blanuša, 2016; Dobson & Ryan, 2000). In addition, young and middle-aged tree belts perform the best against noise pollution, as lower branches of taller and more mature deciduous trees might become dry and fall down as they do not receive enough light, which allows noise to travel more easily through the tree understory (Dobson & Ryan, 2000).

Similar to spatial arrangement of trees for heat reduction, air pollution can be avoided by following the same principles. Tall trees with large canopies can prevent pollution dispersion, therefore it is recommended to avoid locating such trees in deep street canyons, where mixing with ambient air is restricted (Barwise & Kumar, 2020; Kumar et al., 2019). Regarding wide canyons, planting trees is encouraged, however, distance between trees is still should be large enough to allow the flow of air and locating trees as close to the source of pollution is recommended (Kumar et al., 2019). Concerning noise pollution, trees can act as an effective noise barrier if placed appropriately. First, trees can create a visual barrier between the human and the source, thereby reducing human's perception of noise (Cameron & Blanuša, 2016; Dobson & Ryan, 2000). Secondly, dense canopy of trees is recommended when the goal is to reduce the noise pollution in the certain area, therefore, locating trees close to each other would produce the best effect (Cameron & Blanuša, 2016; Dobson & Ryan, 2000). Thirdly, the green noise barrier should be wide enough to absorb noise the most effectively. Combination of tree species is recommended to ensure that gaps between trees are filled (Dobson & Ryan, 2000).

Regarding psychological health, trees are the most effective when they are in the close vicinity to residential buildings. Views from the home or office are desirable to help with attention restoration and positive emotions (Joung et al., 2015; Martínez-Soto et al., 2013). In addition, increased number of trees in the area led to more physical activity among residents, according to a few studies (Eichinger et al., 2015; Larsen et al., 2009). Structural traits such as colorfulness and availability of flowers were shown to be aesthetically pleasing (Cameron & Blanuša, 2016).

Trees also effectively support urban biodiversity by providing shelter, nesting materials and food (Hails & Kavanagh, 2013; Wood & Esaian, 2020). The most influential design factor affecting the species population is species richness, followed by structural layering and complexity. Regarding structural traits, trees should provide fruits and/or flowers to attract various insects, which, in turn, would attract birds. Diversity in planting is important as different types of insects and birds feed off different fruits and nectar from different flowers. In addition, planting diverse vegetation will make it likely that plants do not flower and fruit at the same time of the year, which will ensure an all-year-round provision of food. Diversity in planting also increases resiliency of green infrastructure to various pests and diseases (Worsley, 2018). Spatial configuration of trees is also quite important: it is recommended to locate trees close to each other, as this will ensure that birds and other species do not have to spend too much time and energy to travel between food sources (Hails & Kavanagh, 2013).

			Structural traits of trees	**References**	**Spatial arrangement of trees**	**References**
Human health	Physiological benefits	Reduced air pollution	- Crown size + - Leaf size + - Roughness of leaves + - Crown density + - Seasonal independence + - VOCs - - Species richness +	(Barwise & Kumar, 2020; Beckett et al., 2000; Clapp, 2014; Grote et al., 2016; Kumar et al., 2019; Tran et al., 2020)	- Trees should be located away from each other. - Planting in wide canyons is recommended. - Locating close to the source of pollution is recommended.	(Barwise & Kumar, 2020; Kumar et al., 2019)
		Reduced noise pollution	- Density of branches, leaves and foliage + - Leaf size + - Seasonal independence +	(Cameron & Blanuša, 2016; Dobson & Ryan, 2000)	- Trees should form a visual barrier between the noise and the hearer. - Planting as close to the source of noise as possible is desirable. - Planting densely is recommended.	(Cameron & Blanuša, 2016; Dobson & Ryan, 2000)
		Temperature comfort for people	- Crown size + - Leaf size + - Plant height + - Crown density + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Wang et al., 2021; R. Zhang, 2020)	- Higher tree cover in the area is desirable. - Trees should be planted close to parallel to the wind direction.	(Norton et al., 2015; Sodoudi et al., 2018; Tran et al., 2020; Wang et al., 2021)
		Promotion of physical activity	**N/A**		- Higher tree cover in the area is desirable. - Proximity of trees to residential buildings is recommended.	(Eichinger et al., 2015; Larsen et al., 2009)
	Psychological benefits	Reduction of stress	- Colorfulness + - Species richness + - Availability of flowers +	(Cameron & Blanuša, 2016; Joung et al., 2015; Martínez-Soto et al., 2013; Todorova et al., 2004)	- Proximity of trees to residential buildings is recommended. - Trees should be visible by residents.	(Joung et al., 2015; Martínez-Soto et al., 2013)
		Cognition and attention	- Species richness +	(Behe et al., 2005; Filazzola et al., 2019)	- Proximity of trees to residential buildings is recommended. - Trees should be visible by residents.	(Joung et al., 2015; Martínez-Soto et al., 2013)
		Positive emotions	- Colorfulness + - Species richness + - Availability of flowers +	(Cameron & Blanuša, 2016; Joung et al., 2015; Martínez-Soto et al., 2013; Todorova et al., 2004)	- Proximity of trees to residential buildings is recommended. - Trees should be visible.	(Joung et al., 2015; Martínez-Soto et al., 2013)
Climate adaptation	Temperature regulation	Mitigation of urban heat islands	- Crown size + - Leaf size + - Plant height + - Crown density + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Wang et al., 2021; R. Zhang, 2020)	- Higher tree cover in the area is desirable. - Trees should be located away from each other. - Planting in areas with high surface temperature is recommended.	(Norton et al., 2015; Tran et al., 2020; Wang et al., 2021)
	Water management	Flood regulation	- Crown size + - Leaf size + - Crown density + - Species richness + - Seasonal independence +	(Berland et al., 2017; Marapara et al., 2021; Tran et al., 2020)	- Locating trees where the impervious area is large, and the runoff coefficient is high is recommended.	(Marapara et al., 2021; Tran et al., 2020)
		Drought regulation	**N/A**		- Locating trees where the impervious area is large is recommended.	(Marapara et al., 2021; Tran et al., 2020)
Biodiversity	Biodiversity conservation and enhancement	Habitats for species	- Species richness + - Colorfulness + - Availability of flowers and fruits +	(Hails & Kavanagh, 2013; Wood & Esaian, 2020)	- Dense planting of trees is recommended.	(Hails & Kavanagh, 2013)
		Permeability for migrating species	**N/A**		- Dense planting of trees is recommended.	(Hails & Kavanagh, 2013)

Table 4: Structural and spatial traits of trees

C.2. Green open spaces

Overall, there was a limited available literature on both structural and spatial characteristics of urban grasslands, therefore, several assumptions were made that will be presented here.

First, concerning structural characteristics, ability of urban grasslands to mitigate heat is assumed to be mostly dependent on the plant height as it was pointed out by several authors that this trait is linked with the capacity to store more water on plant surfaces (Lundholm et al., 2015; Vijayaraghavan, 2016; R. Zhang, 2020), which, in turn, affects an evapotranspiration rate. Norton (Norton et al., 2015) pointed out that urban grasslands cool the air the most effectively via evapotranspiration if they are irrigated properly (Norton et al., 2015). In addition, replacing a fraction of pavement with grasslands would help to contribute to the reduction of the temperature in cites as there will be less heat-absorbing surfaces (Tran et al., 2020). Regarding placement of grasslands, it was suggested to have accessible green open spaces, as they can serve as “cool” islands during extreme heat episodes. In addition, placing green areas upwind would be more beneficial if hot areas are located downwind (Norton et al., 2015). Regarding drought and flood mitigation, plant height also played an important role as the taller the plant, the more water it can intercept (Lundholm et al., 2015; R. Zhang, 2020). Locations with high impermeable surfaces are the most appropriate locations and should be prioritized (Tran et al., 2020). In addition, to alleviate flooding, height differences withing the landscape could be used in advantage by placing green strips downstream where the water flows (VHG).

Concerning human health, availability of larger open green areas in the vicinity could lead to the increase in physical activity amongst residents (Ayala-Azcárraga et al., 2019). Moreover, availability of meadows with diverse perennials could have a psychological benefit to people (Lindemann-Matthies et al., 2010; Todorova et al., 2004), especially if meadows have blue or white flowers (VHG). However, it can be assumed that the taller the grass, the less likely that people would exercise as it is less convenient, therefore, the diversity of species and the plant height are the most influential structural traits of urban grasslands. Regarding other benefits for human health, grass has a potential to reduce noise pollution. No examined literature included empirical evidence of the effectiveness of the grass to absorb noise, however, it was pointed out in one study that the greatest noise absorption occurs at the ground level (Dobson & Ryan, 2000). Soft vegetation cover absorbs the noise, rather than reflects it, thus placing grass rather than pavement could be considered beneficial for this benefit. Regarding air pollution, capacity of urban grasslands to absorb pollutants remains uncertain. However, diversity of species, as well as plant height could potentially be important attributes that affect the ability of grasses to capture pollutants, as these traits are generally positively linked to this benefit. In addition, it is reasonable to assume that locating grass densely and combining it with other types of vegetation such as trees and hedges would produce the best effect.

Finally, urban grasslands can have a great value to biodiversity. Structural characteristics mainly affect the richness habitat of urban grasses and include the plant height, diversity of plants and colorfulness (Klaus, 2013; Mollashahi et al., 2020; Norton et al., 2019; Tran et al., 2020), while spatial characteristics mainly affect the ability of species to move withing the landscape (Mollashahi et al., 2020; Salomaa et al., 2017) . Species that have low-dispersion capabilities are very sensitive to the increase in distance between green areas. For instance, it was pointed out that the distance between green areas should not exceed a few meters to allow such species to move within the landscape (Mollashahi et al., 2020). For species with high dispersal capabilities such as bees and birds, distance could be larger, however, availability of other vegetation around also plays a significant role. Green facades and green roofs can offer an additional stepping stones for many species (Collins et al., 2017; Hop & Hiemstra, 2013). Thus, locating green areas close to each other will ensure structural and, perhaps, functional connectivity of green areas in the city. Tall grass can shelter more species, including birds and various insects, and planting wildflowers and various perennials would make it more attractive for insects (Klaus, 2013; Mollashahi et al., 2020)

			Structural traits of grassed areas	References	Spatial arrangement of grassed areas	References
Human health	Physiological benefits	Reduced air pollution	- Plant height + - Species richness +	(Kumar et al., 2019)	- Grass is recommended in all types of street canyons and open road scenarios.	(Barwise & Kumar, 2020; Kumar et al., 2019; Norton et al., 2015)
		Reduced noise pollution	- Plant height + - Species richness +	(Dobson & Ryan, 2000)	- Grass should be planted as close to the source of noise as possible.	(Cameron & Blanuša, 2016; Dobson & Ryan, 2000)
		Temperature comfort for people	- Plant height + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Vijayaraghavan, 2016; R. Zhang, 2020)	- Accessibility and proximity of green areas is recommended.	(Norton et al., 2015; Tran et al., 2020)
		Promotion of physical activity	- Plant height - - Species richness -	**N/A**	- Accessibility and proximity of green areas is recommended.	(Ayala-Azcárraga et al., 2019)
	Psychological benefits	Reduction of stress	- Colorfulness + - Species richness + - Availability of flowers +	(Cameron & Blanuša, 2016; Lindemann-Matthies et al., 2010; Todorova et al., 2004)	- Accessibility and proximity of green areas is recommended.	(Joung et al., 2015; Martínez-Soto et al., 2013)
		Cognition and attention	- Species richness +	(Young et al., 2020)	- Grassed areas should be visible.	(Joung et al., 2015; Martínez-Soto et al., 2013)
		Positive emotions	- Colorfulness + - Species richness + - Availability of flowers +	(Cameron & Blanuša, 2016; Lindemann-Matthies et al., 2010; Todorova et al., 2004)	- Grassed areas should be visible.	(Joung et al., 2015; Martínez-Soto et al., 2013)
Climate adaptation	Temperature regulation	Mitigation of urban heat islands	- Plant height + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Vijayaraghavan, 2016; R. Zhang, 2020)	- Placing grassed areas upwind of hot areas produces the best effect.	(Norton et al., 2015; Tran et al., 2020; Wang et al., 2021)
	Water management	Flood regulation	- Plant height + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Vijayaraghavan, 2016; R. Zhang, 2020)	- Locating trees where the impervious area is large, and the runoff coefficient is high is recommended.	(Marapara et al., 2021; Tran et al., 2020)
		Drought regulation	**N/A**		- Locating trees where the impervious area is large, and the runoff coefficient is high is recommended.	(Marapara et al., 2021; Tran et al., 2020)
Biodiversity	Biodiversity conservation and enhancement	Habitats for species	- Species richness + - Colorfulness + - Availability of flowers + - Plant height +	(Klaus, 2013; Mollashahi et al., 2020; Norton et al., 2019; Tran et al., 2020)	- Proximity of green areas (not exceeding a few meters) is desirable for grassland species.	(Mollashahi et al., 2020)
		Permeability for migrating species	**N/A**		- Proximity of green areas (not exceeding a few meters) is desirable for grassland species.	(Mollashahi et al., 2020)

Table 5: Structural and spatial traits of grassed areas

C.3. Shrubs and bushes

Similar to green open spaces, there was a scarcity of literature about structural and spatial characteristics about hedges. First, regarding heat stress reduction, hedges could cool the area via evapotranspiration, so leaf size, density of the foliage and thickness could be potential structural characteristics to consider, as these traits were associated with higher evapotranspiration rate for trees. Height of bushes could also play a role for evapotranspiration (R. Zhang, 2020) and for shading, however, considering that roadside bushes are usually +-2m (Kumar et al., 2019), shading effect would be negligible compared to trees. In addition, hedges are not likely to trap heat due to their height and structure, therefore, it can be assumed that locating hedges in a continuous manner in areas with the high heat stress could be an appropriate solution. In similar fashion hedges could be planted for the stormwater capture and for groundwater replenishment.

Hedges can also provide some health benefits for people. For instance, hedges are considered as very effective at capturing pollutants due to their dense structure (Blanusa et al., 2019). Moreover, height of the hedge and its thickness are also important traits not to be neglected (Kumar et al., 2019). In addition, similar to trees, rough and complex leaves were shown to be effective at capturing air pollutants (Blanusa et al., 2019). Regarding spatial arrangement, locating hedges in a continuous manner is proved to be the most effective measure to absorb pollutants. Hedges are especially valuable when the goal is to reduce exposure of cyclists and pedestrians to the air pollution (Kumar et al., 2019). Unlike trees, hedges are recommended to plant in medium street canyons and wide street canyons and for open road scenarios, hedges work best with trees (Kumar et al., 2019). Similar to trees, shrubs can emit VOCs, so species that produce low amounts of VOCs should be prioritized (Blanusa et al., 2019). Hedges can also contribute to the reduction of noise pollution. Structural traits such as density of branches and foliage, thickness and seasonal independence are all lead to the better noise absorption (Blanusa et al., 2019; Dobson & Ryan, 2000). To maximize the noise absorption by using hedges, it is recommended to plant hedges in a continuous manner as close to the source of noise as possible. In addition, planting hedges with trees and grass produces the best effect (Dobson & Ryan, 2000).

Colorfulness and diversity of species of shrubs contribute to the psychological health of people (Blanusa et al., 2019). No literature was found on the spatial arrangements of hedges to maximize psychological benefits of shrubs, however, It can be assumed that planting hedges in the close proximity to buildings could be beneficial for stress reduction and positive emotions.

Shrubs add a great value to urban biodiversity. Similar to trees, shrubs provide shelter, food and nest sites for birds, insects and mammals. Diversity appeared to be the most important factor that would ensure the fruit and flower availability throughout the year. In addition, physical continuity of shrubs was an important spatial criterion for biodiversity enhancement (Blanusa et al., 2019; Hails & Kavanagh, 2013).

			Structural traits of shrubs	References	Spatial arrangement of shrubs	References
Human health	Physiological benefits	Reduced air pollution	- Plant height + - Seasonal independence + - Roughness of leaves + - Density + - Thickness + - Species richness +	(Barwise & Kumar, 2020; Kumar et al., 2019)	- Planting shrubs as close to the source as air pollution as possible is recommended. - Planting shrubs in a continuous manner is recommended.	(Barwise & Kumar, 2020; Kumar et al., 2019; Norton et al., 2015)
		Reduced noise pollution	- Plant height + - Seasonal independence + - Density + - Thickness + - Species richness +	(Cameron & Blanuša, 2016; Dobson & Ryan, 2000)	- Planting shrubs as close to the source as noise pollution as possible is recommended. - Planting shrubs in a continuous manner is recommended.	(Cameron & Blanuša, 2016; Dobson & Ryan, 2000)
		Temperature comfort for people	- Plant height + - Leaf size + - Density + - Thickness + - Species richness +	(Blanusa et al., 2019; Lundholm et al., 2015; Tran et al., 2020)l	- Increasing the fraction of shrubs in the area is recommended.	(Norton et al., 2015; Tran et al., 2020)
		Promotion of physical activity	**N/A**		**N/A**	
	Psychological benefits	Reduction of stress	- Colorfulness + - Species richness + - Availability of flowers +	(Blanusa et al., 2019; Cameron & Blanuša, 2016; Todorova et al., 2004)	- Shrubs should be visible by residents (if possible, from buildings)	(Joung et al., 2015; Martínez-Soto et al., 2013)
		Cognition and attention	- Species richness +	(Young et al., 2020)	- Shrubs should be visible by residents (if possible, from buildings)	(Joung et al., 2015; Martínez-Soto et al., 2013)
		Positive emotions	- Colorfulness + - Species richness + - Availability of flowers +	(Blanusa et al., 2019; Cameron & Blanuša, 2016; Todorova et al., 2004)	- Shrubs should be visible by residents (if possible, from buildings)	(Joung et al., 2015; Martínez-Soto et al., 2013)
Climate adaptation	Temperature regulation	Mitigation of urban heat islands	- Plant height + - Density + - Thickness + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Vijayaraghavan, 2016; R. Zhang, 2020)	- Planting shrubs in a continuous manner is recommended. - Planting in areas with high surface temperature is recommended.	(Norton et al., 2015; Tran et al., 2020; Wang et al., 2021)
	Water management	Flood regulation	- Plant height + - Density + - Thickness + - Species richness +	(Lundholm et al., 2015; Norton et al., 2015; Tran et al., 2020; Vijayaraghavan, 2016; R. Zhang, 2020)	- Locating shrubs where the impervious area is large, and the runoff coefficient is high is recommended.	(Marapara et al., 2021; Tran et al., 2020)
		Drought regulation	**N/A**		- Locating shrubs where the impervious area is large, and the runoff coefficient is high is recommended.	(Marapara et al., 2021; Tran et al., 2020)
Biodiversity	Biodiversity conservation and enhancement	Habitats for species	- Species richness + - Colorfulness + - Availability of flowers + - Availability of fruits and nuts + - Plant height +	(Klaus, 2013; Mollashahi et al., 2020; Norton et al., 2019; Tran et al., 2020)	- Proximity of shrubs to each other is recommended.	(Mollashahi et al., 2020)
		Permeability for migrating species	**N/A**		- Proximity of shrubs to each other is recommended.	(Mollashahi et al., 2020)

Table 6: Structural and spatial traits of shrubs

C.4. Green vertical systems

Density of foliage and leaf size in façade greenery are the most common traits that were referred to across the literature about heat stress reduction (Cameron et al., 2014; S. Sheweka & Magdy, 2011) and thickness for insulation (S. M. Sheweka & Mohamed, 2012). Regarding installation, walls with high solar exposure would be the best locations for façade greenery and dark colored walls need to be prioritized over light-colored walls. Façade greenery can provide a cooling effect via evapotranspiration and therefore locating green facades next to pedestrian walkways would increase the comfort (Norton et al., 2015). Green vertical systems also have capacity to capture some of the rainfall, thereby reducing flood risks (S. Sheweka & Magdy, 2011). No literature was found on the structural characteristics of green facades for flood reduction, so it is assumed that size of leaves, and the density of the foliage could also contribute to the effectiveness of stormwater capture. Furthermore, it is assumed that living walls can be more effective for improving thermal comfort and capturing rain than green façades, owning to a more diverse vegetation and availability of the substrate. Regarding drought, façade greenery does not have a direct effect on it, unless the water seeps in the soil.

Façade greenery is also an attractive option for capturing pollutants. Density was the most important trait that was observed for effective air pollution mitigation (Abhijith et al., 2017). Façade greenery trap pollutants that move along the sides of the buildings and according to Kumar, façade greenery are encouraged in all types of street canyons, regardless of their geometry (Kumar et al., 2019). Regarding noise absorption, green façades can be used to reduce internal reverberation between buildings in street canyons and reduce the street noise up to 3dB (Wong et al., 2010). Thus, locating green facades to reduce noise and air pollution is generally can be considered as a good option regardless of the geometry of a street. Density and thickness were relevant structural traits for noise absorption (Wong et al., 2010). Green facades can also deliver some psychological benefits to people. For instance, according to the experimental study, people were feeling less stressed and felt more positive emotions when they were looking at the wall covered with green rather than a bare wall (Elsadek et al., 2019). For that reason, it can be assumed that covering more walls with green facades could be beneficial.

Concerning biodiversity conservation and enhancement, proximity of façade greenery to other types of vegetation is crucial. Façade greenery can serve as stepping stones for many species, so ensuring close distance between various green infrastructure elements would support biodiversity more effectively. Finally, living walls are considered as more attractive to wildlife than green façades again due to a more diverse vegetation (Collins et al., 2017; Mayrand & Clergeau, 2018).

			Structural traits of green vertical systems	References	Spatial arrangement of green vertical systems	References
Human health	Physiological benefits	Reduced air pollution	- Density + - Roughness of leaves + - Thickness + - Species richness +	(Abhijith et al., 2017; Kumar et al., 2019) VHG	- Installing façade greenery in all street canyons is recommended.	(Kumar et al., 2019)
		Reduced noise pollution	- Density + - Thickness of foliage + - Substrate thickness +	(Wong et al., 2010)	- Installing façade greenery in all street canyons is recommended.	(Wong et al., 2010)
		Temperature comfort for people	- Density + - Thickness + - Species richness +	(Cameron et al., 2014; S. M. Sheweka & Mohamed, 2012; S. Sheweka & Magdy, 2011)	- Installing green façades on sun-exposed walls and dark walls should be prioritized. - Installing façade greenery adjacent to pedestrian walkways is recommended.	(Norton et al., 2015)
		Promotion of physical activity	**N/A**		**N/A**	
	Psychological benefits	Reduction of stress	- Colorfulness + - Species richness + - Availability of flowers +	(Cameron & Blanuša, 2016; Todorova et al., 2004)	- Façade greenery should be visible (if possible, from buildings).	(Elsadek et al., 2019)
		Cognition and attention	- Species richness +	(Young et al., 2020)	- Façade greenery should be visible (if possible, from buildings).	(Elsadek et al., 2019)
		Positive emotions	- Colorfulness + - Species richness + - Availability of flowers +	(Cameron & Blanuša, 2016; Todorova et al., 2004)	- Façade greenery should be visible (if possible, from buildings).	(Elsadek et al., 2019)
Climate adaptation	Temperature regulation	Mitigation of urban heat islands	- Density of foliage + - Thickness +	(Cameron et al., 2014; S. Sheweka & Magdy, 2011)	- Installing green façades on sun-exposed walls and dark walls should be prioritized. - Increasing the green wall coverage in the area is recommended. - Installing façade greenery when the space for on-ground vegetation is limited is recommended.	(Norton et al., 2015)
	Water management	Flood regulation	- Species richness + - Leaf size + - Density of foliage + - Thickness + - Substrate thickness +	**N/A**	- Installing façade greenery when the space for on-ground greenery is limited is recommended.	**N/A**
		Drought regulation	**N/A**		**N/A**	
Biodiversity	Biodiversity conservation and enhancement	Habitats for species	- Species richness + - Colorfulness + - Availability of flowers and fruits +	(Collins et al., 2017; Mayrand & Clergeau, 2018)	- Proximity of façade greenery to other types of vegetation is recommended.	(Collins et al., 2017; Mayrand & Clergeau, 2018)
		Permeability for migrating species	**N/A**		- Proximity of façade greenery to other types of vegetation is recommended.	(Collins et al., 2017; Mayrand & Clergeau, 2018)

Table 7: Structural and spatial traits of green vertical systems

C.5. Green roofs

According to Norton, to maximize the cooling effect, green roofs should be places on low and large buildings. In addition, placing green roofs in case there is no on-ground space for trees could be considered as a good option as well (Norton et al., 2015). According to one study, the cooling effect of green roofs becomes negligible for pedestrians if the height of the building exceeds 60m. Locating green roofs upwind would be beneficial for cooling hot areas downwind (G. Zhang et al., 2019). It has been pointed out that intensive green roofs can provide a higher cooling effect (Norton et al., 2015) and better insulation to the building (Castleton et al., 2010). Regarding structural traits, since green roofs can accommodate all types of ground vegetation, same recommendations as for ground vegetation can apply, just adding a thickness of the substrate layer. Regarding flood mitigation, no examined literature included recommendations on placing green roofs, however, since green roofs have a capacity of absorbing a good portion of rainfall, locating green roofs in places where there is a limited space for on-ground greenery could be beneficial. Similar to heat stress reduction, intensive green roofs can be more beneficial, owning to a more diverse vegetation and a thicker substrate layer that can store more water (Vijayaraghavan, 2016). Regarding drought mitigation, locating green roofs is not generally recommended if the goal is to replenish groundwater stores.

Green roofs can deliver some health benefits as well. First, green roofs can help with noise reduction if properly located. It is recommended to install green roofs on low-rise buildings as this way, green roofs will be exposed to the direct urban noise (Berardi et al., 2014; Vijayaraghavan, 2016). Structural traits such as leaf size and thickness of the substrate affect how much noise is absorbed (Suszanowicz & Kolasa-Więcek, 2019). In addition, dense structure of the plant is also relevant (Dobson & Ryan, 2000), as it was shown in the discussion of trees and shrubs. Concerning air pollution, locating green roofs where they can catch a lot of wind is the best solution to ensure a flow of clear air in the neighborhood (VHG). Intensive green roofs are considered as more effective for improving air quality owning to the fact that intensive green roofs can accommodate more diverse vegetation, such as trees and shrubs (Filazzola et al., 2019; Vijayaraghavan, 2016). People can also benefit psychologically by looking at roofs. Views from the office building or from anywhere else could help with attention restoration, stress reduction and for stimulating positive emotions (Oberndorfer et al., 2007; K. J. H. Williams et al., 2019). In addition, it could be assumed that installing green roofs on low buildings is more beneficial for mental well-being as this way, green roods could receive a higher visual exposure. Intensive green roofs are also more pleasing to look at compared to extensive green roofs (Oberndorfer et al., 2007; Vijayaraghavan, 2016).

Finally, green roofs have a great value for biodiversity. However, the higher the building, the less species use the green roof, therefore, placing green roofs on low buildings will produce the better effect. In addition, availability of other types of green infrastructure can positively affect green roof biodiversity (N. S. G. Williams et al., 2014).

			Structural traits of green roofs	References	Spatial arrangement of green roofs	References
Human health	Physiological benefits	Reduced air pollution	- See structural traits of trees, shrubs and grass		- Installing green roofs where they can catch a lot of wind is recommended.	VHG
		Reduced noise pollution	- Substrate thickness + - See structural traits of trees, shrubs and grass	(Vijayaraghavan, 2016)	- Installing green roofs on low buildings is recommended.	(Berardi et al., 2014; Vijayaraghavan, 2016)
		Temperature comfort for people	- Substrate thickness + - See structural traits of trees, shrubs and grass	(Castleton et al., 2010)	- Installing green roofs on low and large buildings is recommended. - Installing green roofs upwind of the hot areas is recommended.	(Hop & Hiemstra, 2013; Norton et al., 2015; G. Zhang et al., 2019)
		Promotion of physical activity	**N/A**		**N/A**	
	Psychological benefits	Reduction of stress	- See structural traits of trees, shrubs and grass		- Green roofs should be visible by residents (if possible, from buildings). - Green roofs should be installed on low buildings.	(Oberndorfer et al., 2007; Vijayaraghavan, 2016)
		Cognition and attention	- See structural traits of trees, shrubs and grass		- Green roofs should be visible by residents (if possible, from buildings). - Green roofs should be installed on low buildings.	(Oberndorfer et al., 2007; Vijayaraghavan, 2016)
		Positive emotions	- See structural traits of trees, shrubs and grass		- Green roofs should be visible by residents (if possible, from buildings). - Green roofs should be installed on low buildings.	(Oberndorfer et al., 2007; Vijayaraghavan, 2016)
Climate adaptation	Temperature regulation	Mitigation of urban heat islands	- See structural traits of trees, shrubs and grass		- Installing green roofs upwind of the hot areas is recommended. - Installing green roofs when the space for on-ground vegetation is limited is recommended. - Increasing the fraction of green roofs is recommended.	(Norton et al., 2015; G. Zhang et al., 2019)
	Water management	Flood regulation	- Substrate thickness + - See structural traits of trees, shrubs and grass		- Installing green roofs when the space for on-ground vegetation is limited is recommended.	**N/A**
		Drought regulation	**N/A**		**N/A**	
Biodiversity	Biodiversity conservation and enhancement	Habitats for species	- See structural traits of trees, shrubs and grass		- Installing green roofs on low and large buildings is recommended. - Installing green roofs in proximity to other vegetation is recommended.	(N. S. G. Williams et al., 2014)
		Permeability for migrating species	**N/A**		- Installing green roofs on low and large buildings is recommended. - Installing green roofs in proximity to other vegetation is recommended.	(N. S. G. Williams et al., 2014)

Table 8: Structural and spatial traits of green roofs

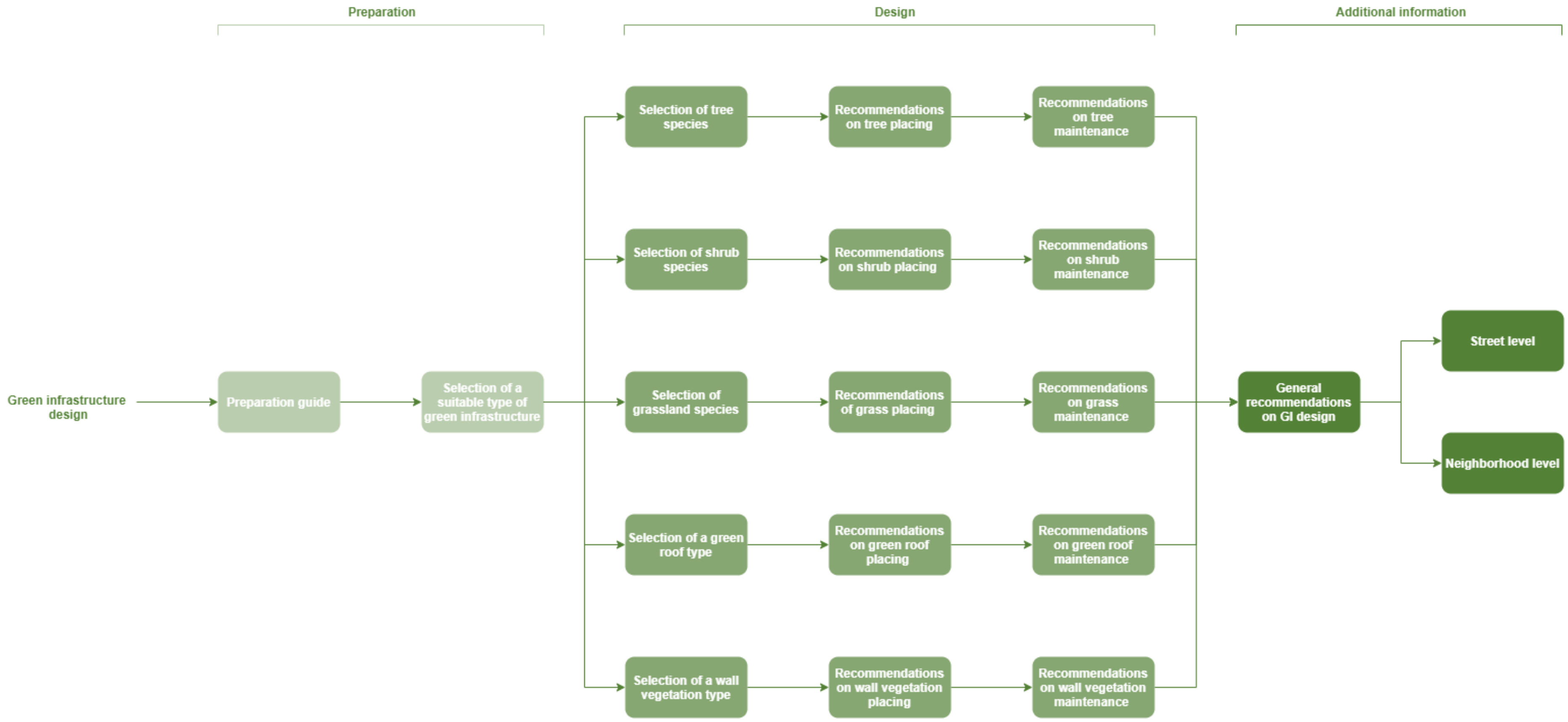
Appendix D: Design guideline

In the following section, the design guideline is presented. The structure of the guideline is as follows: first, in the preparation stage, several recommendations are given on preparing for the planting of green infrastructure. Recommendations vary from measuring the height-to-width ratio of a street to investigating the underground utilities. As a second part of the preparation stage, guideline on street canyons is provided, the goal of which is to inform about recommended types of urban green infrastructure in different types of streets.

Secondly, after determining a suitable type of green infrastructure, the design stage begins, which consists out of three sub-stages. First, guidelines on structural traits of all types of ground vegetation and vegetation on building surfaces are provided, the aim of which is to assist in selection of appropriate species. Second, recommendations on spatial arrangement of green infrastructure elements are provided and finally, recommendations on maintenance are given.

Thirdly, in the last stage, general recommendations are provided on how to design with green infrastructure both on the street and neighborhood level.

The graph below presents a structure of the guideline:



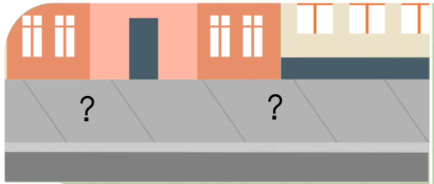
Preparation
Design
Additional information
Green infrastructure design
Preparation guide
Selection of a suitable type of green infrastructure
Selection of tree species
Recommendations on tree placing
Recommendations on tree maintenance
Selection of shrub species
Recommendations on shrub placing
Recommendations on shrub maintenance
Selection of grassland species
Recommendations of grass placing
Recommendations on grass maintenance
Selection of a green roof type
Recommendations on green roof placing
Recommendations on green roof maintenance
Selection of a wall vegetation type
Recommendations on wall vegetation placing
Recommendations on wall vegetation maintenance
General recommendations on GI design
Street level
Neighborhood level

D.1. Preparation stage

D.1.1. Preparation guide

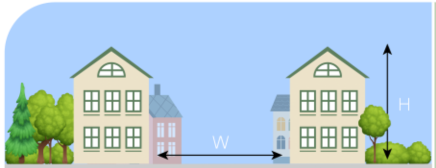
P.G.1 Identify existing green infrastructure in the area

- Existing GI (even isolated) is beneficial and should be utilized[1]
- Existing GI can enhance structural and functional connectivity[2]



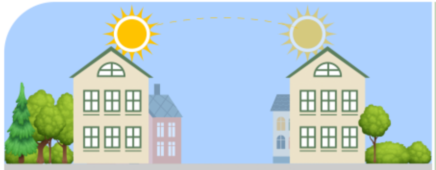
P.G.2 Identify possible locations for GI

- Possible locations for green infrastructure could include areas dominated with impermeable surfaces[3]. Sweco developed a tool for identifying useleless pavement that can be replaced by green infrastructure[4]



P.G.3 Measure height to width ratio of a selected street[5]

- Performance of green infrastructure is influenced by the geometry of a street

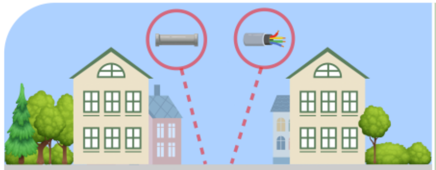


P.G.4 Determine orientation towards the sun[5]

- Orientation towards the sun is relevant for assessing the neccessity of vegetation to shade the street canyon

P.G.5 Determine wind direction[6]

- Wind direction is important for effective heat dissipation and air pollutant dispersal



P.G.6 Investigate underground utilities

- Ground vegetation (especially trees) require sufficient space for growth underground

Preparation Guide (P.G)

[1] Maitenance of existing GI is more cost efficient compared to planting new GI. For more information, see recommendations on maintenance

[2] Existing GI can be used to connect isolated patches of green, which would benefit biodiversity. For more information, see general recommendations on GI design

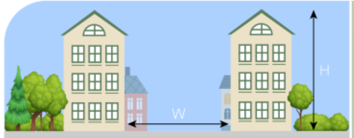
[3] Highly impermeable surfaces are likely to contribute to urban heat island effect and urban floods

[4] A pavement qualifies as useless if it meets one the following critera: 1) A pavement 3m wide or more; 2) Paved playgrounds; 3) Urban paved art

[5] For more information, see information sheet on street canyons

[6] For more information, see guideline T.P (Tree placement) and general recommendations of green infrastructure design

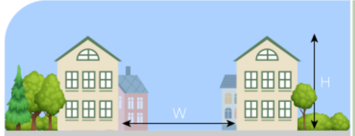
D.1.2. Guideline on street canyons



Deep street canyon (H/W >= 2)

- Mixing of air inside the deep canyon and outside it is restricted, which can negatively affect the air quality on the street
- Tall buildings can shade the canyon so vegetation might not be required for shading

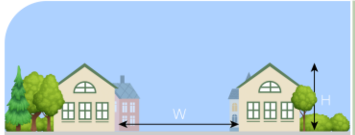
Tall vegetation (Trees)	✗[1]
Medium vegetation (Shrubs)	✗
Short vegetation (Grass)	✓
Green roofs	✓
Green vertical systems	✓



Medium street canyon (0.5 < H/W < 2)

- Mixing of air inside the medium canyon and outside it is better than of deep canyons, however, it is still limited
- Medium canyons have a higher sun exposure, so vegetation might be recommended to shade the canyon

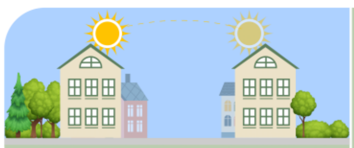
Tall vegetation (Trees)	✗[2]
Medium vegetation (Shrubs)	✓
Short vegetation (Grass)	✓
Green roofs	✓
Green vertical systems	✓



Wide street canyon (H/W <= 0.5)

- Mixing of air inside the wide canyon and outside it is close to unrestricted, which positively affects the air quality
- Wide canyons have the highest sun exposure, so vegetation is highly recommended to shade the canyon

Tall vegetation (Trees)	✓
Medium vegetation (Shrubs)	✓
Short vegetation (Grass)	✓
Green roofs	✓
Green vertical systems	✓



Sun exposure of street canyons

- Canyons that face East-West receive longer hours of sun exposure compared to North-South oriented canyons, therefore, shading East-West canyons should be a priority
- Trees is the only type of ground vegetation, which is able to provide thermal comfort for pedestrians via shading

Should the chosen street canyon be prioritized for tree planting?

Wide street canyon[3]	E-W oriented canyon →	Yes
	N-S oriented canyon →	Yes
Medium street canyon	E-W oriented canyon →	Yes, but under a certain condition[4]
	N-S oriented canyon →	No
Narrow street canyon	E-W oriented canyon →	No[5]
	N-S oriented canyon →	No

Street canyons

[1] Trees can cause the most nuisance is street canyons by trapping pollutants from vehicles under their crowns and storing heat released by impermeable surfaces. For more information on locating trees in street canyons see checklist "Should the chosen street canyon be prioritized for tree planting?" and guideline T.P (Tree placement)

[2] Exclusions apply, for more information see checklist "Should the chosen street canyon be prioritized for tree planting?"

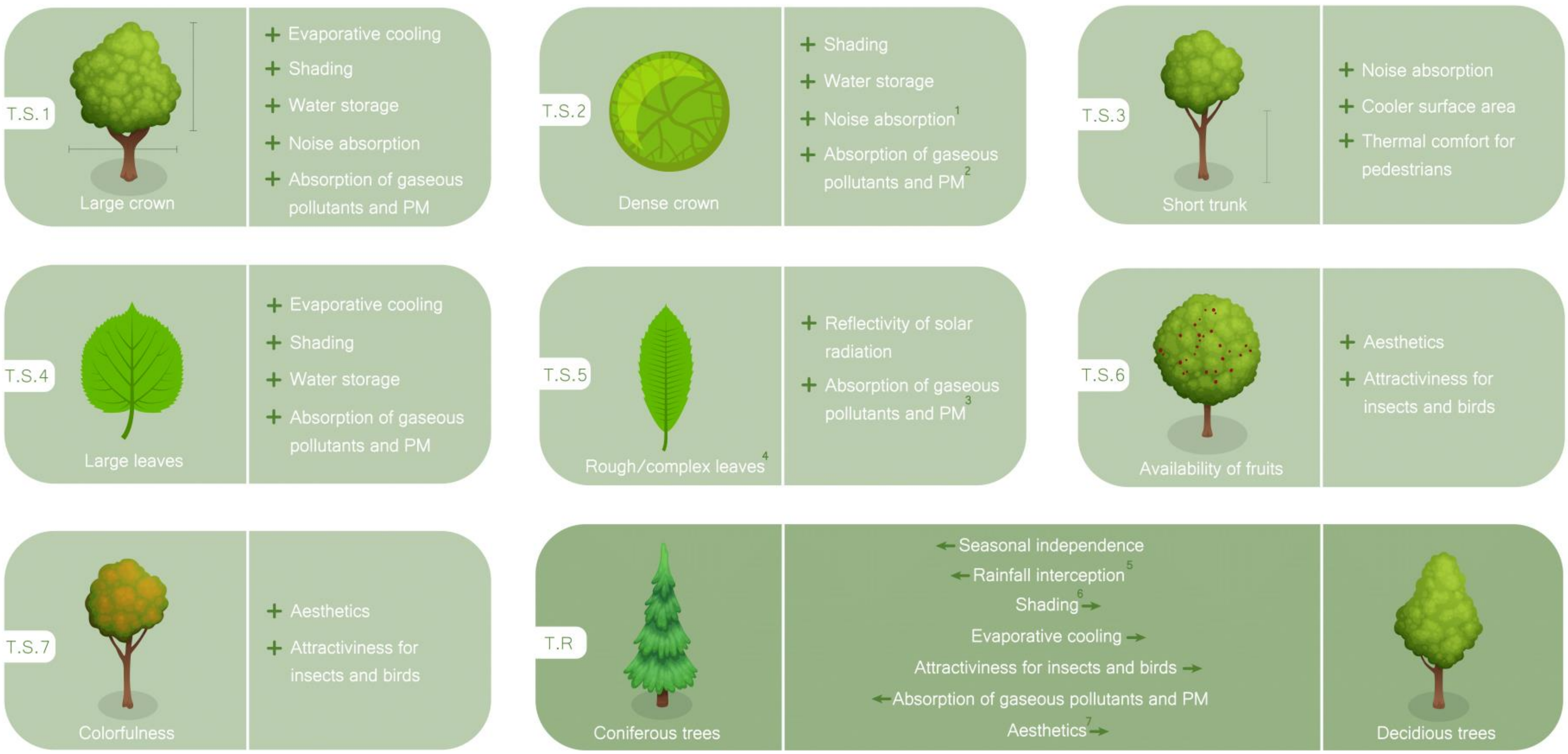
[3] Trees can be planted on both sides of the road for effective shading, however, if the traffic intensity on the street is high, planting only on the windward side might be more preferable

[4] Trees should be more compact and have lighter crowns to avoid trapping air pollutants and heat on the street level. Trees should be planted preferably only on the windward side

[5] Even if the N-S oriented deep canyon has a ratio of H/W = 4, it will recieve a lot of sun, therefore, additional shading might be required (from overhead facades, for example)

D.2. Design stage

D.2.1. Structural traits of trees



Trees Structural (T.S)
Trees Recommendation (T.R)

[1] Density of leaves, branches and foliage is important

[2] Porosity of 10-20% is regarded as the best one for PM removal

[3] Roughness is particularly importnat for capturing PM

[4] Waxy or hairy leaf surfaces are the best for capturing air pollutants

[5] Conifers can capture 10-20% more rainfall compared to decidious trees

[6] Conifers shade as well, however, as a drawback, they can block sun in winter

[7] Traits such as availability of flowers and colorfulness, which are associated with positive emotions, can belong only to decidious trees

D.2.2 Spatial arrangement of trees

T.P.1 Trees should form a discontinious canopy[1]

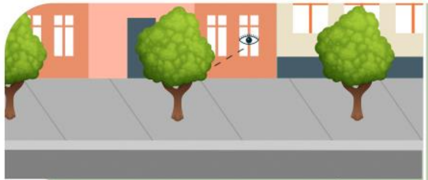
+ Improved pollutant dispersion on a street level
+ Dissipation of heat on a street level
+ Space for growth for individual trees

T.P.2 Trees should be planted close to the road[2]

+ Increased pollutant absorption
+ Increased sound absorption capacity

T.P.3 Trees should be planted close to parallel to the wind direction[3]

+ Improved pollutant dispersion on a street level
+ Dissipation of heat on a street level
+ Cooling the area downwind



T.P.4 Trees should be visible by residents[4]

+ Reduction of stress
+ Improved cognitive abilities
+ Stimulation of positive emotions

Trees Placement (T.P)

[1] Such configuration imroves a flow of air along the street

[2] The highest absorption of both air pollutants and noise occurs at the source

[3] Wind can contribute to removing heat and pollutants under the crowns of street trees. If the vegetation is perpendicular to wind, it can block the airflow and reduce the positive effect significantly

[4] Trees should be visible (if possible, from buildings as well). Views on greenery from office buildings or schools, for instance, is highly recommended for attention restoration

D.2.3. Maintenance of trees

	Maintenance activities	Maintenance intensity[1]	
 Coniferous trees	• Watering • Pruning • Sanitation • Fertilization	• Plant maintenance Low — High	• Coniferous trees are able to thrive in less nutrient soil and do not need constant pruning compared to decidious trees
 Decidious trees	• Watering • Pruning • Sanitation • Fertilization	• Plant maintenance Low — High	• Decidious trees are more sensitive to the soil quality and therefore require more frequent fertilization（especially because fallen leaves, that provide nutrients to the tree, are often being removed for aesthetic purposes） • Pruning is needed to remove dead branches and leaves, or to train a tree to develop a certain shape and form

General recommendations

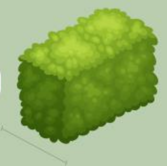
- Occasional pruning of trees is desirable to provide sufficient light to other types of ground vegetation, such as shrubs and grass
- Fallen leaves provide an important source of nutrients to the tree, opt for a less frequent maintenance
- Proactive（consistent）maintenance is more cost efficient compared to a reactive one（when the issue occurs）
- Sanitation several times a year is desirable to minimize the risks of pests and diseases
- Formational pruning（at the early stages of a tree）if more cost efficient compared to pruning a mature tree

Maintenance of trees

[1] Maintenance intensity is characterized by frequency and complexity of maintenance activities

D.2.4. Structural traits of shrubs

S.S.1



Thick structure

- Water storage
- Noise absorption
- Absorption of gaseous pollutants and PM

S.S.2

Dense structure

- Water storage
- Noise absorption[1]
- Absorption of gaseous pollutants and PM[2]

S.S.3

Tall plant

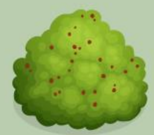
- Noise absorption
- Water storage
- Absorption of gaseous pollutants and PM

S.S.4

Rough/complex leaves[4]

- Reflectivity of solar radiation
- Absorption of gaseous pollutants and PM[3]

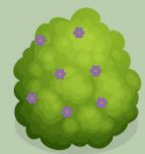
S.S.5



Availability of fruits and nuts

- Aesthetics
- Attractiveness for insects and birds

S.S.6



Colorfulness

- Aesthetics
- Attractiveness for insects and birds

S.R

Coniferous shrubs

← Seasonal independence

← Rainfall interception[5]

Evaporative cooling →

Attractiveness for insects and birds →

← Absorption of gaseous pollutants and PM

Aesthetics[7] →

Decidious shrubs[8]

Shrubs Structural (S.S)

Shrubs Recommendation (S.R)

[1] Density of leaves, branches and foliage is important

[2] Porosity of 10-20% is regarded as the best one for PM removal

[3] Roughness is particularly important for capturing PM

[4] Waxy or hairy leaf surfaces are the best for capturing air pollutants

[5] Conifers can capture more rainfall compared to decidious shrubs

[6] Conifers shade as well, however, as a drawback, they can block sun in winter

[7] Traits such as availability of flowers and colorfulness, which are associated with positive emotions, can belong only to decidious shrubs

[8] Besides flowers, ability of decidious shrubs to change their leaf colour makes them attractive

D.2.5. Spatial arrangement of shrubs

S.P.1 Shrubs should be planted in a continious manner

+ Increased pollutant absorption
+ Increased sound absorption capacity[1]
+ Increased stormwater retention[2]
+ Improved structural connectivity[3]

S.P.2 Shrubs should be planted close to the road[4]

+ Increased pollutant absorption
+ Increased sound absorption capacity

S.P.3 Shrubs should be visible by residents[5]

+ Reduction of stress
+ Improved cognitive abilities
+ Stimulation of positive emotions

Shrubs Placement (S.P)	[1] Dense planting is recommended for the most effective noise pollution mitigation [2] This, in turn, will increase evapotranspiration rate of shrubs, which can improve thermal comfort of pedestrians [3] Structural (physical) connectivity of green elements in the landscape is important for biodiversity enhacement. For more informantion, see general recommendations on green infrastructure design [4] The highest absorption of both air pollutants and noise occurs at the source [5] Trees should be visible (if possible, from buildings as well). Views on greenery from office buildings or schools, for instance, is highly recommended for attention restoration

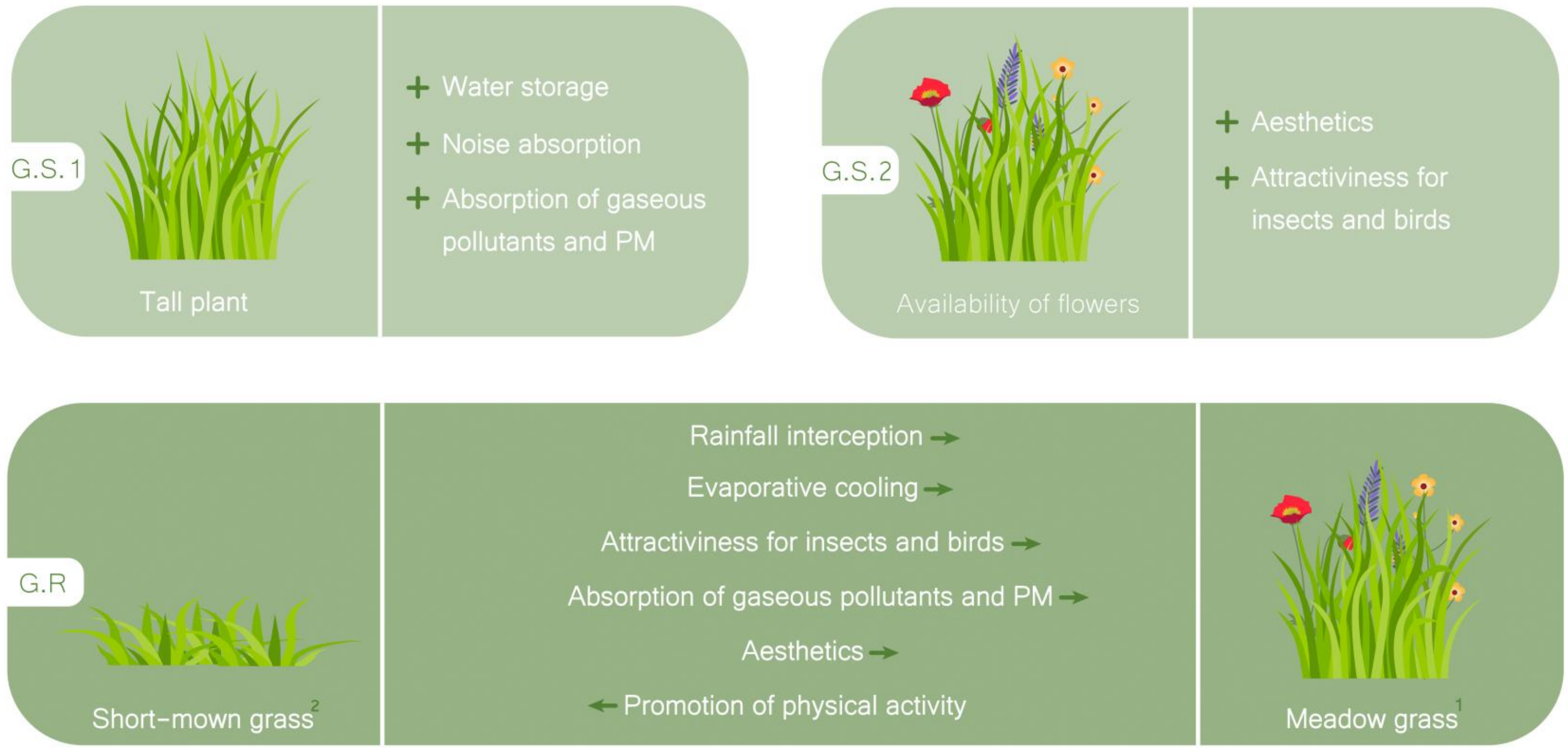
D.2.6. Maintenance of shrubs

	Maintenance activities	Maintenance frequency[1]	
 Coniferous shrubs	• Watering • Pruning • Sanitation • Fertilization	• Plant maintenance Low — High	• Coniferous shrubs are able to thrive in less nutrient soil and do not need constant pruning compared to decidious trees
 Decidious shrubs	• Watering • Pruning • Sanitation • Fertilization	• Plant maintenance Low — High	• Decidious shrubs are more sensitive to the soil quality and therefore require more frequent fertilization

Maintenance of shrubs

[1] Maintenance intensity is characterized by frequency and complexity of maintenance activities

D.2.7. Structural traits of grass



Grass Structural（G.S）
Grass Recommendation（G.R）

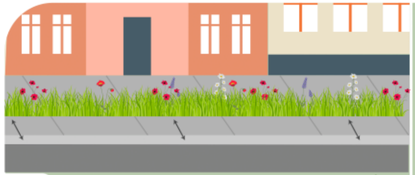
[1]Meadow grass is characterized by a taller grass with a variety of perennials

[2]While meadow grass is more beneficial overall, short-mown grass, which can be found in many urban parks, is very attractive for exercise and leisure

D.2.7. Spatial arrangement of grass

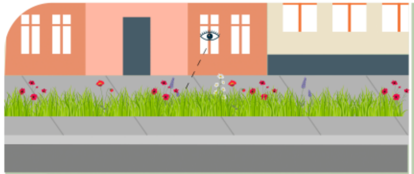
G.P.1 Grass should be planted in a continious manner

+ Increased pollutant absorption
+ Increased sound absorption capacity[1]
+ Increased stormwater retention[2]
+ Improved structural connectivity[3]



G.P.2 Grass should be planted close to the road[4]

+ Increased pollutant absorption
+ Increased sound absorption capacity



G.P.3 Grass should be visible by residents[5]

+ Reduction of stress
+ Improved cognitive abilities
+ Stimulation of positive emotions

Grass Placement（S.P）	[1] Even slightly vegetated soil is always better as it absorbs low frequencies of the sound while paved surfaces reflect any projected noise [2] This, in turn, will increase evapotranspiration rate of grassed areas, which can improve thermal comfort of pedestrians [3] Structural（physical）connectivity of green elements in the landscape is important for biodiversity enhacement. For more informantion, see general recommendations on green infrastructure [4] The highest absorption of both air pollutants and noise occurs at the source [5] Grassed areas should be visible（if possible, from buildings as well）. Views on greenery from office buildings or schools, for instance, is highly recommended for attention restoration

D.2.8. Maintenance of grass

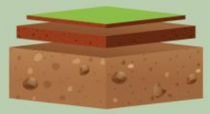
	Maintenance activities	Maintenance intensity[1]		General recommendations
 Short-mown grass	• Watering • Weeding • Mowing • Fertilization	• Plant maintenance Low High	• Short-mown grasses require frequent mowing (for example, it is done every 2-3 weeks in countries such as UK) • Frequent irrigation and fertilization is also a norm, which is demanding both economically and ecologically	• Opt for a less frequent maintenance of grassed areas to develop a meadow type grass • While maintenance intensity of meadow grasses is lower, they are more attractive to biodiversity, more effective at capturing stormwater and provide higher aesthetical value to people
 Meadow grass	• Watering • Weeding • Cutting	• Plant maintenance Low High	• Meadow grass does not require frequent maintenance once it is established and it operates as a self-sustained plant community	

Maintenance of grass

[1] Maintenance intensity is characterized by frequency and complexity of maintenance activities

D.2.9. Structural traits of green roofs

Gr.S.1



Thick substrate layer

+ Water storage
+ Noise absorption
+ Insulation

Gr.S.2

See guidelines on structural traits of ground vegetation[1]

Gr.R

Extensive green roofs

Water storage →
Evaporative cooling →
Attractiviness for insects and birds →
Absorption of gaseous pollutants and PM →
Aesthetics →
Noise absorption →
Insulation →

Intensive green roofs[2]

Green roof Structural（Gr.S）
Green roof Recommendation（Gr.R）

[1] Green roofs（particularly intensive green roofs）can accomodate all types of ground vegetation

[2] While intensive green roofs are more beneficial in every aspect, they are considerably more expensive to install and maintain. In addition, structural load of intensive roofs is significantly larger than of extensive green roofs, which increases a chance of a roof failure（such as leakage）

D.2.10 Spatial arrangement of green roofs

Gr.P. 1 Green roofs should be installed on low and large buildings[6]

+ Increased sound absorption capacity[1]
+ Thermal comfort via evapotranspiration[2]
+ Improved air quality on a pedestrian level[3]
+ Increased stormwater retention
+ Increased value for biodiversity[4]

Gr.P. 2 Green roofs should be visible by residents[5]

+ Reduction of stress
+ Improved cognitive abilities
+ Stimulation of positive emotions

Green roof Placement (Gr.P)

[1] Sound absorption effect is the most prominent on roofs of low buildings, as they are exposed to the direct urban sound field (noise from rail, for example)

[2] Cooling effect of green roofs decreases with the height of the building

[3] This applies only if a green roof can catch a lot of wind

[4] High wind speeds makes green roofs on taller buildings less accessible for insects

[5] Green roofs should be visible (if possible, from buildings as well). Views on greenery from office buildings or schools, for instance, is highly recommended for attention restoration

[6] Green roofs on tall buildings would also be beneficial for captuing stormwater and thereby reducing runoff on the ground level

D.2.11. Maintenance of green roofs

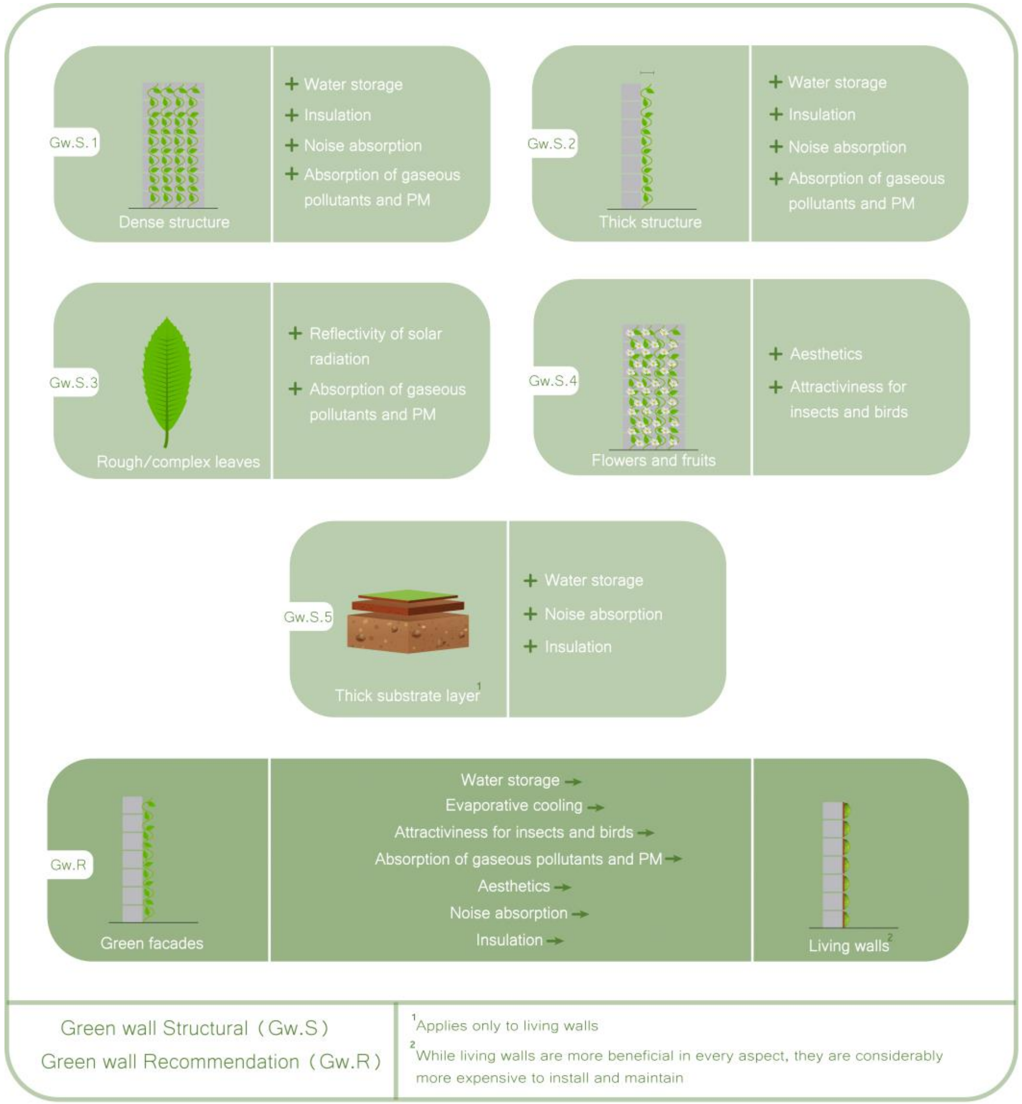
	Maintenance activities	Maintenance intensity[2]	
 Extensive green roofs	• Drainage check • Substrate check • Fertilization • Watering • Weed removal	• Roof structure maintenance Low High • Plant maintenance Low High	• Common extensive roof vegetation includes drought-resistant species, such as sedum, which do not require irrigation • Due to the light-weight structure of extensive green roof, no structural improvements to the building is required
 Intensive green roofs	• Drainage check • Substrate check • Fertilization • Watering • Weed removal • + Maintenance requirements for ground vegetation[1]	• Roof structure maintenance Low High • Plant maintenance Low High	• Intensive green roofs can accomodate all types of ground vegetation, therefore, more frequent and complex maintenance is required • Due to the heavier weight of intensive green roof, structural improvements to the building might be neccesary

Maintenance of green roofs

[1] For more information, see maintenance of trees, shrubs and grass

[2] Maintenance intensity is characterized by frequency and complexity of maintenance activities

D.2.12. Structural traits of vertical green systems



D.2.13. Spatial arrangement of vertical green systems

Gw.P. 1 Green vertical sustem should be installed wher possible

+ Shading the building surface[1]
+ Thermal comfort via evapotranspiration[2]
+ Absorption of pollutants moving along the street
+ Reduction of internal reverberation of the sound
+ Insulation
+ Enhancing structural connectivity[3]

Gw.P.2 Green vertical sustems should be visible by residents[4]

+ Reduction of stress
+ Improved cognitive abilities
+ Stimulation of positive emotions

Green wall Placement (Gw.P)

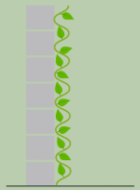
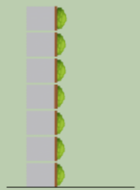
[1] Walls with high sun exposure and dark wall should be prioritized

[2] For a higher effect, green vertical systems should be installed adjacent to pedestrian paths

[3] Connectivity is important for biodiversity enhacement. For more information, see general recommendations on green infrastructure

[4] Green vertical systems should be visible (if possible, from buildings as well). Views on greenery from office buildings or schools, for instance, is highly recommended for attention restoration

D.2.14. Maintenance of vertical green systems

	Maintenance activities	Maintenance intensity[1]	
 Green facades	• Watering • Trimming • Cladding renovation • Inspection of cables/trellis	• Wall structure maintenance Low — High • Plant maintenance Low — High	• Climbing species, such as ivy, can attach themselves to the wall by themselves or via additional support, such as cables • Main maintenance activity is trimming, which is required to avoid damage to the wall
 Living walls	• Watering • Irrigation system check • Cladding renovation • Replacement of panels • Replacement of wall plants	• Wall structure maintenance Low — High • Plant maintenance Low — High	• Living walls are very complex structures that can accomodate a wide variety of plants • Frequent maintenance is neccesary to not only preserve plants but also preserve the structure, which consists of panels, substrate and irrigation pipes

Maintenance of vertical green systems

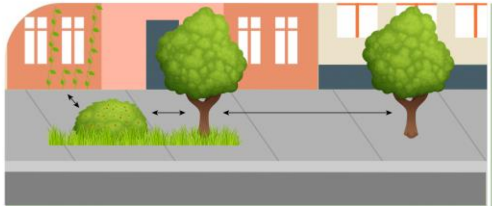
[1] Maintenance intensity is characterized by frequency and complexity of maintenance activities

D.3. Additional information

D.3.1. General recommendation on green infrastructure design (street level)

A street should accomodate diverse vegetation

+ Better overall performance of green infrastructure[1]
+ Resiliency to pests and diseases
+ More effective support of biodiversity[2]



Street vegetation should not be isolated

+ Improved structural[3] and functional[4] connectivity

Recommendations to avoid nuisances

- Vegetation does not produce undesirable shadow
- Vegetation does not obstruct views, both for drivers and people inside the buildings
- Vegetation with high pollen load is not located next to vulnerable locations, such as schools and hospitals
- Vegetation that produces a lot of plant litter（leaves, branches, twigs, honeydew）is not located next to pedestrian paths and parkind lots
- Vegetation that produces low amounts of VOCs is prioritized[5]
- Native species are prioritized to increase attractiviness for animals

General recommendations on green infrastructure design（street level）

[1] Diversity of planting increases the number of structural traits that lead to different benefits. For example, different plants absorb different air pollutants

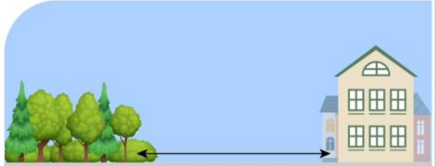
[2] Diversity in planting makes it likely that plants do not flower at the same time of the year, thereby ensuring the provision of food for insects and birds all year long

[3] Structural（physical）connectivity is required for creating ecological corridors within which species can disperse（grassland species have low dispersion capabilities, not exceeding a few meters）

[4] Functional connectivity should be assessed based on the studied species（birds and bees do not require physical connectivity, however, green elements should not be located more than 500m apart and preferably, with food sources in between）

[5] VOCs（volitile organic compounds）decrease air quality and harm human health. VOCs are produced by some species of trees and shrubs

D.3.2. General recommendations of green infrastructure design (neighborhood level)

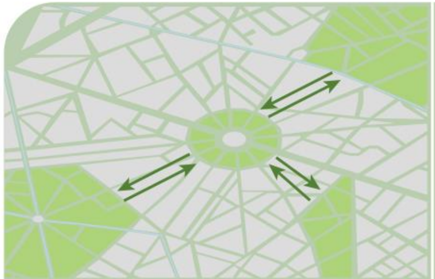


Green areas should be located in proximity to residential areas

+ Increased possibilities for physical activity and leisure
+ Thermal comfort for residents[1]

Neighborhoods should have open[2] green corridors[3]

+ Exchanging and mixing with the ambient air and thereby improving air quality
+ Cooling the areas downwind



Larger green patches should be connected with each other via green corridors[4]

+ Improved structural[5] and functional[6] connectivity

General recommendations on green infrastructure design (neighborhood level)	[1] According to the climate adaptation strategy of Arnhem, green “cool” zones must be present within 250m from any residential building [2] Vegetation should not close off neighborhoods completely and have openings to allow the movement of wind through the streets [3] Green corridors refer to linear elements than link natural habitats [4] Urban parks should be connected to green corridors for a higher cooling effect (the cooling effect of a park can reach 1.5km in the area) [5] Structural (physical) connectivity is required for creating ecological corridors within which species can disperse (grassland species have low dispersion capabilities, not exceeding a few meters). In addition, green corridors can allow people to travel safely between parks via bicycle paths, for example [6] Functional connectivity should be assessed based on the studied species (birds and bees do not require physical connectivity, however, green elements should not be located more than 500m apart and preferably, with food sources in between)

Appendix E: Application of the guideline

In the following section, the design guideline is applied to a case study area. Application of the guideline follows a step-by-step process, starting with the preparation phase, followed by the design phase and finally, additional recommendations are provided for a street and neighborhood green infrastructure design, as described in Appendix D: Design guideline.

The preparation phase includes a number of recommended steps when first approaching a green infrastructure design. Overall, there are six steps that are performed in order, where the first two steps, namely investigating existing green infrastructure and selecting appropriate locations for green infrastructure placement, are considered as more general steps, which are not tied to any specific location just yet. The remaining four steps, that are measuring height-to-width ratio of a street, determining orientation to the sun and wind direction, and investigating underground utilities, are performed when the specific location has been selected.

Thus, as a first step, the existing vegetation in Presikhaaf III is mapped. Existing vegetation includes low, medium and tall ground vegetation (grass, bushes and trees respectively) and can be seen in Figure 13.

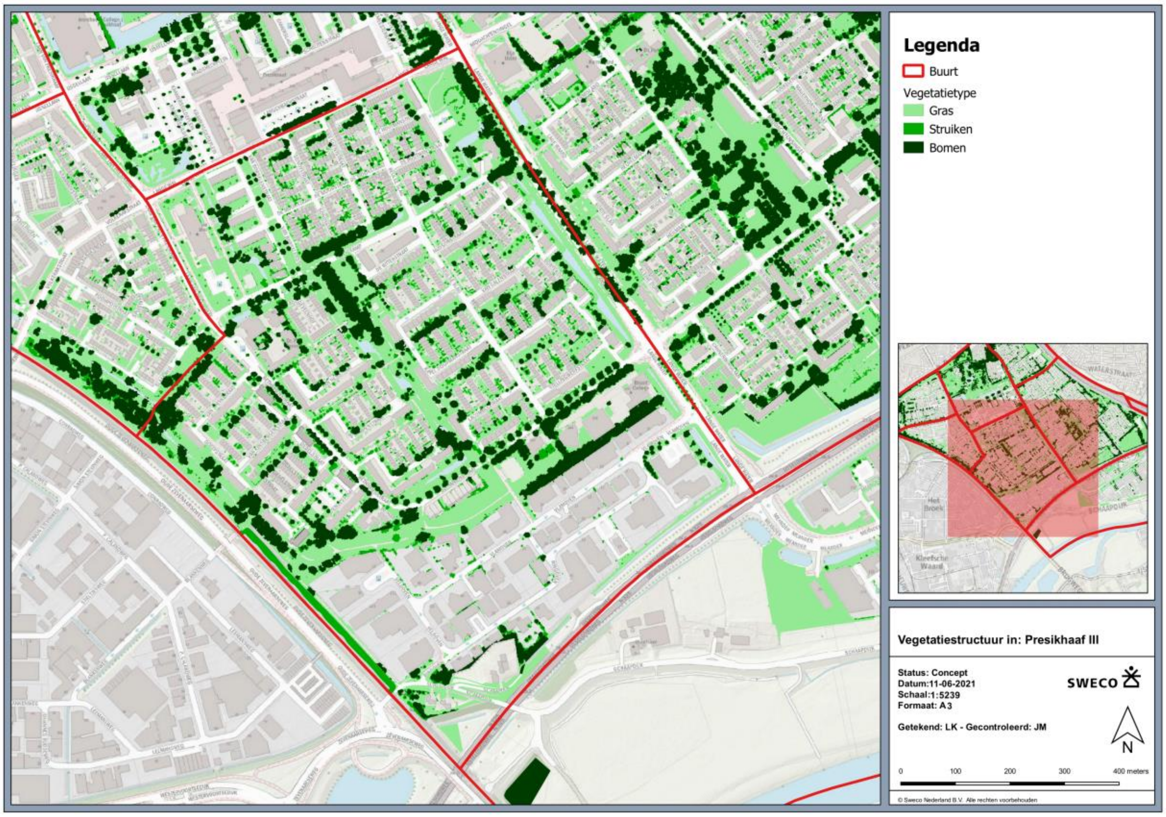


Figure 13: Vegetation in Presikhaaf III

It can be seen that Presikaaf III is dominated by low vegetation and the majority of tall vegetation is concentrated in the central part of the neighborhood and in the north-east of the business park. Medium vegetation can be found throughout the neighborhood forming fragmented patches., as a first impression, available green infrastructure is scarce and quite fragmented, while the business park in the south lacks any kind of green infrastructure, besides grass forming a boundary around it and seldomly a tree that can be seen within the business park area.

As a next step, appropriate locations for green infrastructure need to be chosen. According to the guideline, areas dominated by impervious materials could be potential locations for green infrastructure planting, as such areas could contribute to heat island effect and urban flooding. According to Klimaateffectatlas, developed by KNMI, 50-60% of Presikhaaf III is dominated by paved surfaces, which is a considerable amount of paving which could potentially be reduced. In order to assist in selection of appropriate locations for green infrastructure, Sweco has developed a tool called “useless pavement”, which provides information on areas with unnecessary pavement that could be replaced with green infrastructure. Business area on the south lacks information on useless pavement as the majority of space there is private, therefore, according to the commissioning party, it created a challenge to accurately identify useless pavement. The map with useless pavement can be seen below:

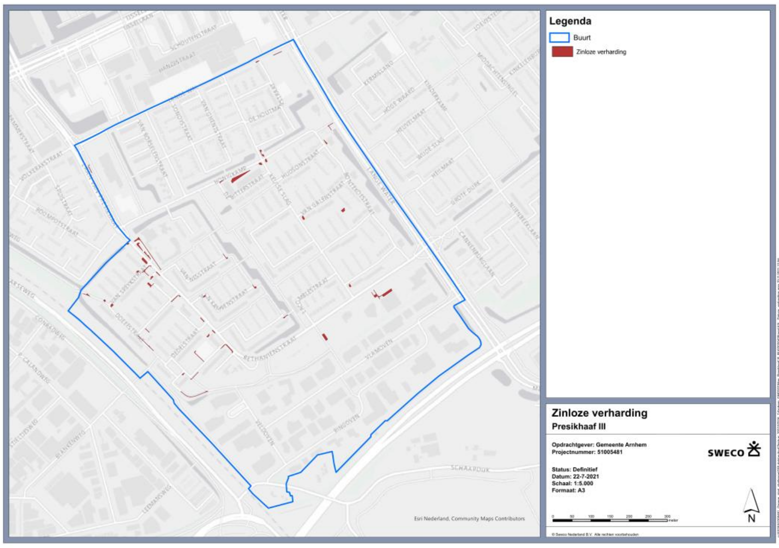


Figure 14: Useless pavement in Presikhaaf III

Besides useless pavement map, Sweco provided maps that display possible locations for large, medium and small trees (category 1, 2 and 3 respectively), and buildings that can be covered with green roofs. Possible locations for trees are determined based on the laws and regulations in regard to tree placement, such as that a tree should have a minimum distance from a residential building, for example. All maps can be found in Appendix F: Data on green infrastructure in Presikhaaf III.

In addition, Klimaateffectatlas, which displays various climatic conditions in Dutch cities, included maps such as the heat island map, showing the difference in temperature between the built-up areas and surrounding green areas. Heat island map for Presikhaaf III can be seen below:

Figure 15: Heat island map (Presikhaaf III is shown with red boundaries)

Besides heat island map, Klimaateffectatlas also included water related maps. The first map informs about the maximum water depth that can occur in case of intense precipitation, such as 70mm in 2-hour time period.

Figure 16: Maximum water depth in Presikhaaf III

The second map shows infiltration opportunity in Presikhaaf III in order to reduce flood probabilities. Infiltration opportunities are assessed based the various characteristics of soil and sub-soil.

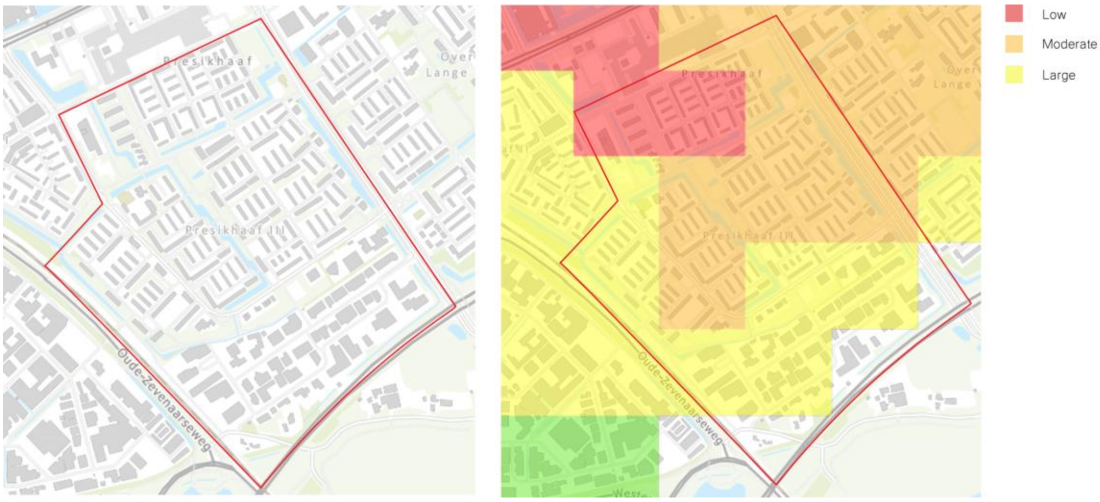


Figure 17: Infiltration opportunity in Presikhaaf III

Thus, based on the Klimaateffectatlas data and maps provided by Sweco, several locations for green infrastructure could be chosen. Overall, two locations were selected where the prognosed water depth and temperature were high, as well as the area covered with useless pavement. These locations will be referred to as case area 1 and 2 respectively.

E.1. Case area 1

The first location is a supermarket area located along Honigkamp, as shown in Figure 18. Chosen location was labeled as dark orange with the temperature difference of 1,6-1,8 C compared to the surrounding unbuilt areas, as illustrated in Figure 15. Due to the shortage of green infrastructure, this location is not attractive for biodiversity and trees, located next to buildings, are unlikely to considerably improve the microclimate in this area due to their small size and isolation.

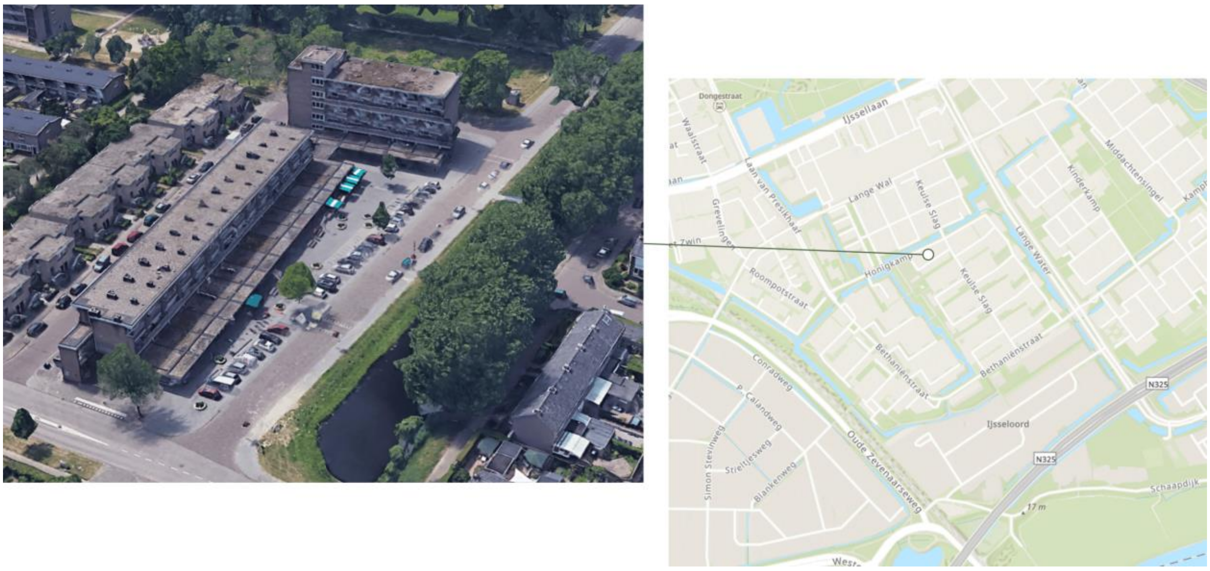


Figure 18: Case area 1

The figure below shows a schematic of the case area 1. Illustration is up to scale and oriented accordingly. Existing green infrastructure is mapped using Google Earth and vegetation map shown earlier.

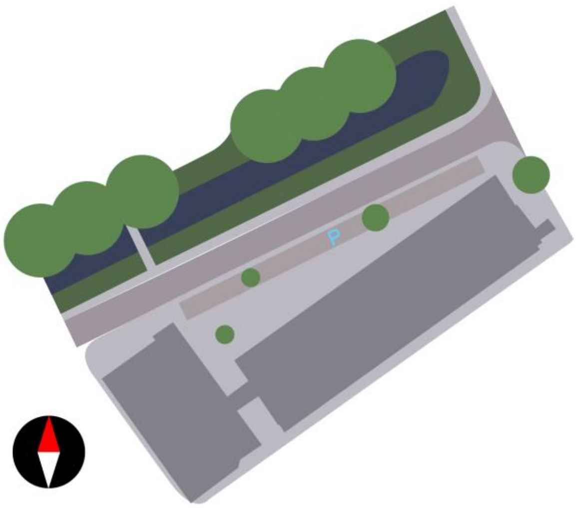


Figure 19: Schematic of case area 1 (dark green – grass and shrubs, light green – trees)

According to useless pavement map provided by Sweco, this location has a good potential for green infrastructure placement, as it has wide pavement and flat large roofs, that could be covered with green. As it is mentioned in the guideline, pavement qualifies as useless if it is 3 meters wide or more. Useless pavement is shown in the Figure below:

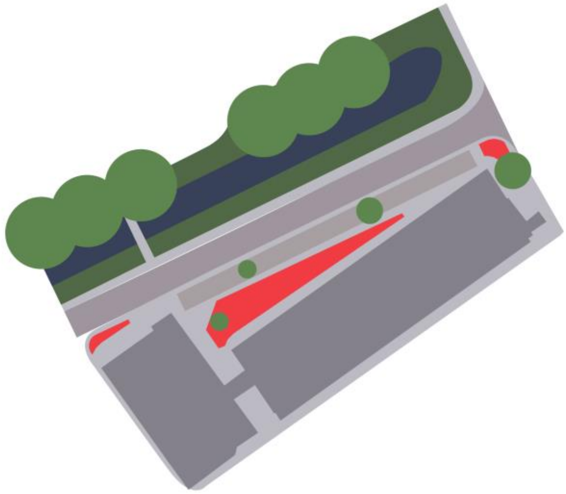


Figure 20: Useless pavement in case area 1

In addition, according to maps provided by Sweco, there are three locations suitable for trees of three categories. These locations are shown below:

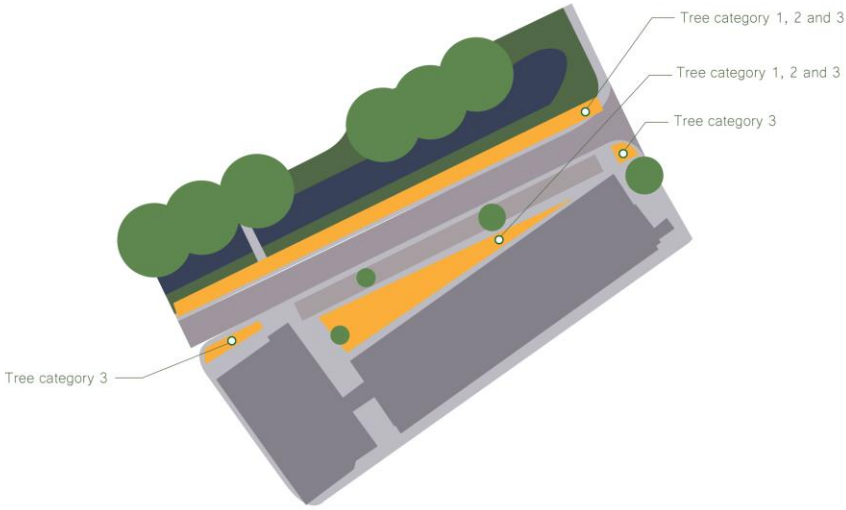


Figure 21: Tree categories in the case area 1

E.1.1. Preparation phase

According to the guideline, next steps include measuring height-to-width ratio of the street, determining orientation to the sun and wind direction. However, the street does not qualify to be called a street canyon as buildings are present only on the one side of the road, therefore, measuring height-to-width ratio is irrelevant in this case.

As the next step, orientation to the sun is determined in order to assess the necessity of trees to shade the canyon. On the first image in Figure 22, sun path can be seen, with the orange and dark orange lines representing sunrise and sunset respectively. Following the sun path from the sunrise to the sunset, it could be determined that the canyon receives 4 hours of direct sun light during the day. However, this information does not suffice to assess whether trees are needed to provide shade as buildings themselves could shade the street. For that reason, shadow simulator was used to analyze the shade pattern throughout the day. Second image of Figure 22 displays shadows produced by buildings at 15:00. It should be noted that the simulator selected the default height of 15m for buildings, as it lacks information on vertical measurements in the chosen area, which poses a limitation, as buildings are lower than 15m. In addition, simulator analyzes shade during the mid-summer, and it does not take into account shade produced by existing vegetation.

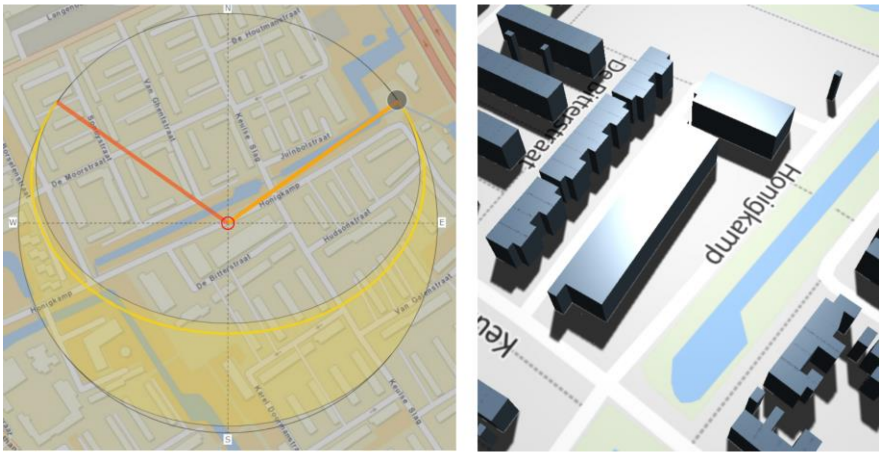


Figure 22: Sun exposure of the case area 1

According to the simulation results, the paved area in front of the buildings is shaded sufficiently till noon, after which this area is getting increasingly more exposed to the sun throughout the day. Since both buildings are lower than 15 meters, it could be assumed that the paved area could be exposed to the sun even longer. As a preliminary conclusion, the street would benefit from additional trees located on both sides of the road to shade the pedestrian paths and in the afternoon (16:00-20:00), shade sun-exposed walls of both buildings.

In the next step, wind pattern is analyzed. According to the annual weather statistics, the predominant wind direction in Arnhem is from south-west, as it can be seen in figure below:

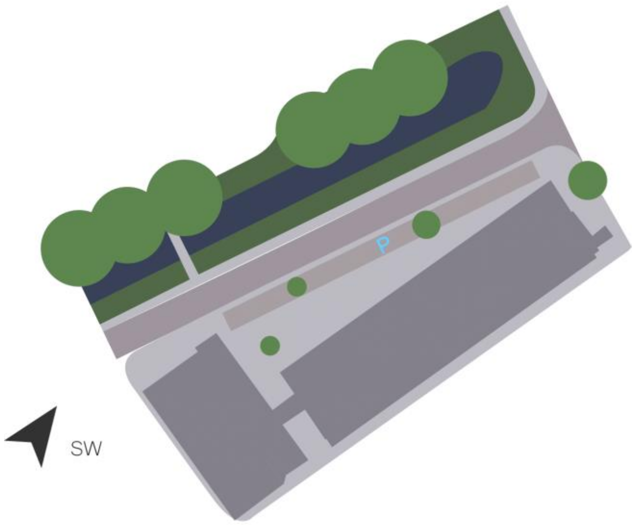


Figure 23: Wind direction in the case area 1

Buildings are located in the way that they might slow down the wind and therefore, reduce the cooling effect of vegetation located in immediate proximity of both buildings.

As a last step, underground utilities are mapped:

Figure 24: Underground utilities in the case area 1

Overall, the street could accommodate all types of ground vegetation and vegetation on building surfaces. In the design phase, it is elaborated on the structural and spatial traits of vegetation.

E.1.2. Design phase

In the design phase, recommendations on both structural and spatial traits of green infrastructure are given. Starting with trees, possible locations are shown below:

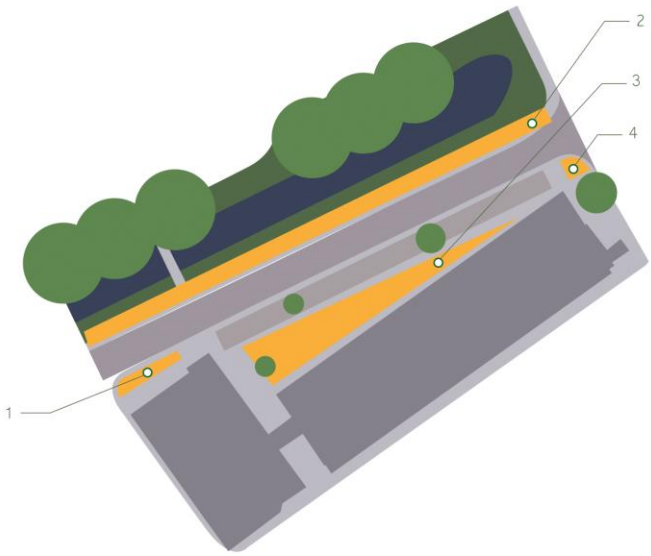


Figure 25: Possible locations for trees in case are 1

Starting with location 1, two trees of category 3 could be located there. Since such trees are unlikely to provide a lot of shade, it is important that they can at least contribute to cooling downwind, therefore, it is important to locate trees away from each other to improve a flow of wind.

Regarding location 2, trees of category 2 are recommended for two reasons. Firstly, this location includes a lot of underground utilities, therefore, larger trees are more likely to cause nuisance due to more extensive root system. Secondly, since the predominant wind direction is south-west, pollutants produced by vehicles passing the road will disperse in that direction, which can get trapped downwind in location 2 in case of dense vegetation, which will lead to the decreased air quality on the street. Perhaps, smaller trees with lighter crowns could be more beneficial in this location to let pollutants freely move downwind to get captured by dense trees on the other side of the canal. Traits such as large leaves would also be beneficial particularly for shading the pedestrian path stretching along the road. A variety of trees, both deciduous and coniferous could be located in this location.

Regarding location 3, trees of category 1 would be the most beneficial since such trees are able to provide the most shade. Besides shading the pedestrian paths and parking lots, such trees will be able to shade the wall of a building in the afternoon (16:00-20:00), which can potentially reduce costs for cooling in summer time. On the contrary, small existing trees in location 3 do not reach the necessary height to sufficiently shade upper floors of the building. Deciduous trees could be more preferable as coniferous trees can block the sun in winter. According to the maps provides by Sweco, there is a possibility to locate three large trees in location 1. Regarding spatial arrangement, trees should be located away from each other to primarily have space for growth.

Finally, location 4 can accommodate only one tree of category 3. No specific recommendations can be given in regard to structural traits, besides that, perhaps, it would be more beneficial to have a coniferous tree for a year-long provision of benefits, such as rainfall capture.

In addition to trees, other types of ground vegetation could be implemented in all locations, such as shrubs and grass. Primary goal of shrubs and grass is to make this location more attractive for biodiversity and improve a functional connectivity with vegetation in both sides of the road to assist in species dispersal. Meadow-type grass and compact shrubs that produce fruits could make this location considerably more attractive for insects and birds. Planting continuously along the road is preferred to reduce the paved area as much as possible and deliver other benefits, as mentioned in the guideline.

Finally, roofs of the buildings, since they are flat, could be covered with green infrastructure as well. Intensive green roofs would be preferable overall but extensive green roofs could be more feasible to implement, as they do not require much maintenance and the building would not require any structural improvements to sustain the load. Both buildings have a large roof surface area, therefore, green roofs would be highly beneficial particularly with capturing large amounts of rainfall. Green façades could also be implemented to shade the sunny side of the building in the afternoon.

Thus, improvements to the case area 1 are show below:

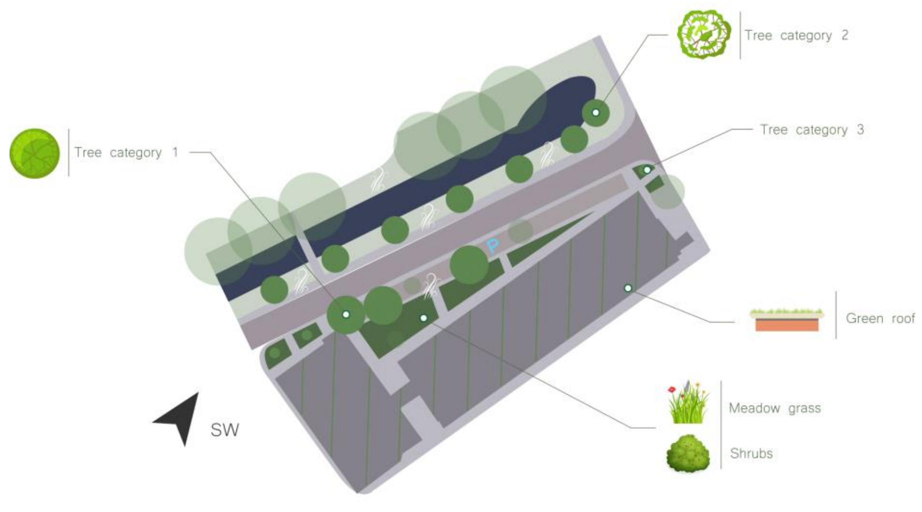


Figure 26: Added green infrastructure in case are 1 (existing vegetation is shown in transparent green)

E.2. Case area 2

Second case area is located on the south-western side of Presikhaaf III as shown in Figure 27. This area includes streets Van Speykstraat, Van Kinsbergenstraat and part of the street Doeffstraat. According to the heat island map, this area experiences a temperature difference of 1,4-1,8 C compared to unbuilt surrounding areas. In addition, according to the water depth map, this area can experience up to 30 cm increase in water level in case of heavy precipitation. However, there is a large opportunity for infiltration, according to Figure 16.

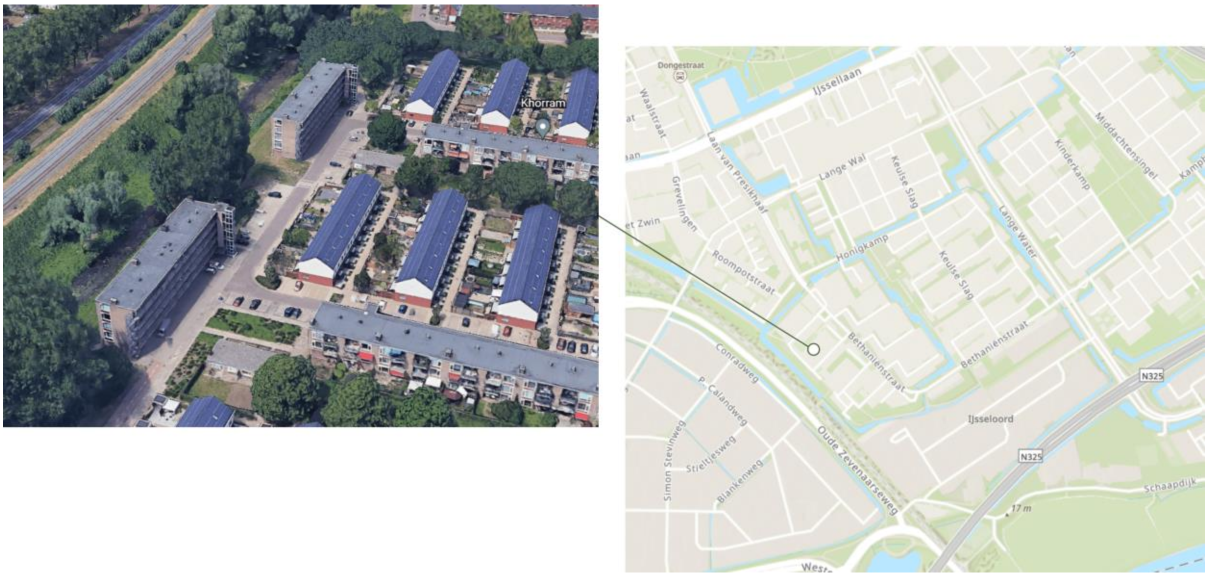


Figure 27: Case are 2

Schematic of the case area 2 is demonstrated below. Again, the map was reproduced as accurate as possible using images from Google Earth and vegetation map from Figure 13. Vegetation in private gardens was not taken into account, as the guideline is applicable for public areas only.

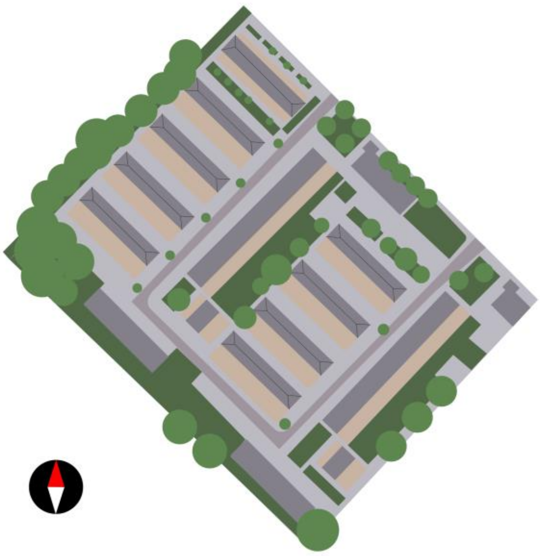


Figure 28: Schematic of the case are 2 (Orange – private areas, dark green – grass and shrubs, light green – trees)

Similar to case area 1, this location also includes flat roofs and useless pavement, which can be utilized for green infrastructure planting. Map showing locations with useless pavement can be seen below in red:

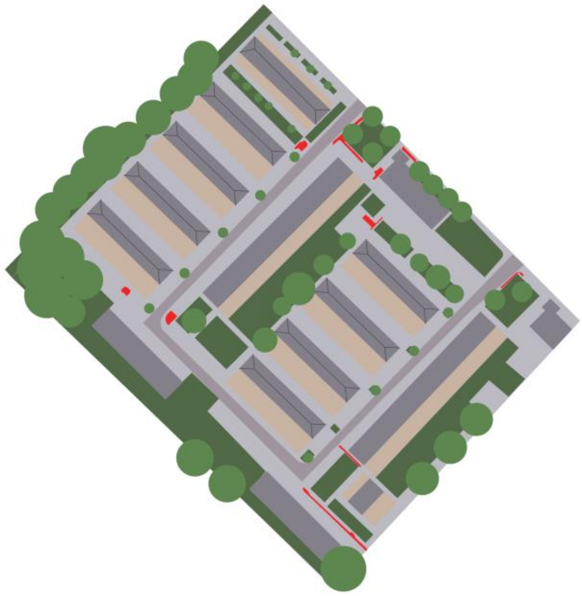


Figure 29: Useless pavement in case area 2

In addition, the map below presents possible locations for trees of category 1, 2 and 3 based on the information provided by Sweco:

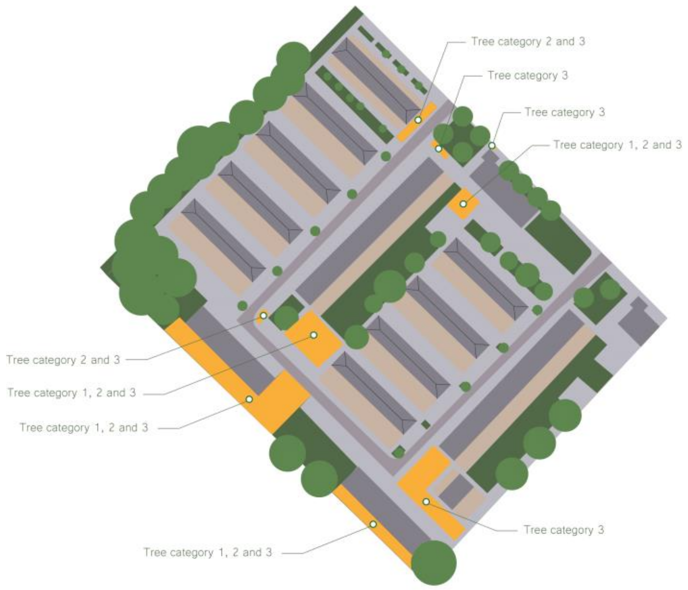


Figure 30: Categories of trees in case area 2

E.2.1. Preparation

After investigating the existing green infrastructure, the height-to-width ratios of the streets need to be determined, according to the guideline. However, in this case, streets are not homogeneous and they do not form closed canyons, therefore, measuring the height-to-width ratio does not seem possible.

As the second step, orientation to the sun is determined. For clarity, streets Van Kinsbergenstraat, Doeffstraat and Van Speykstraat were labeled as A, B and C respectively, as it is shown in the image below:

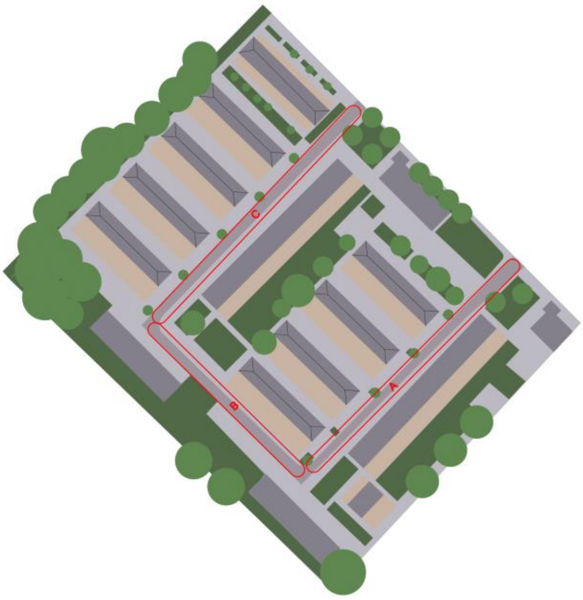


Figure 31: labeled streets in case area 2

Streets labeled A and C have the same layout, therefore, they can be analyzed together. The first image in Figure 32 displays the sun path, while second and third images show the shadow formed by buildings at 10:00 and 18:00 respectively.

Figure 32: Sun exposure of case are 2

According to the simulation results, both streets A and C receive 3 hours of direct sun exposure during the day (14:00-17:00), while from the sunrise until 14:00 both streets receive shade by apartment buildings stretched along the southern side of both streets and from 18:00 until sunset streets are shaded by buildings located perpendicularly to the road on the opposite side. However, since simulator uses default height of 15m for all buildings, produced results are not accurate as height of buildings on both streets does not exceed 8m. Thus, both streets could receive longer hours of sun exposure during the day.

Street B is exposed to the sun till 13:30, after which it receives sufficient shadow by the apartment building located along the street. In addition, trees located to the right of the apartment building, as shown in Figure 21, can also contribute to shading the street in the afternoon. Apartment building appears to be exactly 15m tall, which results in an accurate prediction of the shadow formation.

As a preliminary conclusion, apartment buildings located along the streets A and C can shade streets more effectively due to their position compared to buildings located perpendicularly to the road. Thus, it could be assumed that no additional vegetation might be needed for shading the pavement next to apartment buildings, while on the other side of the road, vegetation is needed to assist buildings in shading the street, especially in the afternoon. However, trees have already been implemented in a continuous manner on both streets A and C, so no further improvement in this regard can be made. Regarding street B, additional vegetation is needed mainly to provide shade in the morning, so trees located on the opposite side of the road could be beneficial for that reason.

In the next step, wind direction is determined. As it was explained during the analysis of the case area 1, average weather statistics was used to determine a predominant wind direction, which is south-west, as shown in the figure below:

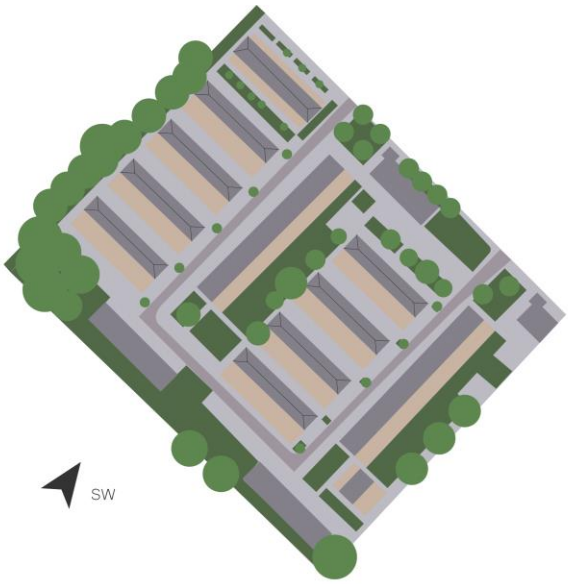


Figure 33: wind direction in case area 2

Overall, it can be seen that trees located in streets A and C can contribute to cooling downwind as they are located close to parallel to the wind direction. Same would apply for effective downwind dispersion of pollutants produced by vehicles. However, apartment buildings located on the street B might slow down the wind, so it is important that newly planted vegetation does not restrict the wind any further.

Finally, in the last step, underground utilities are mapped and can be seen below:

Figure 34: Underground utilities in case area 2

Overall, there is a potential to increase the fraction of green in the case area 2 and it is elaborated during the design phase on structural and spatial characteristics of vegetation.

E.2.2. Design phase

In the following phase, recommendations on both structural and spatial characteristics of vegetation are provided. Firstly, useless pavement can be replaced with at least low and medium vegetation, while tall vegetation can be planted in designated locations illustrated in Figure 17.

First, recommendations on trees are provided. Again, possible locations for trees are shown below:

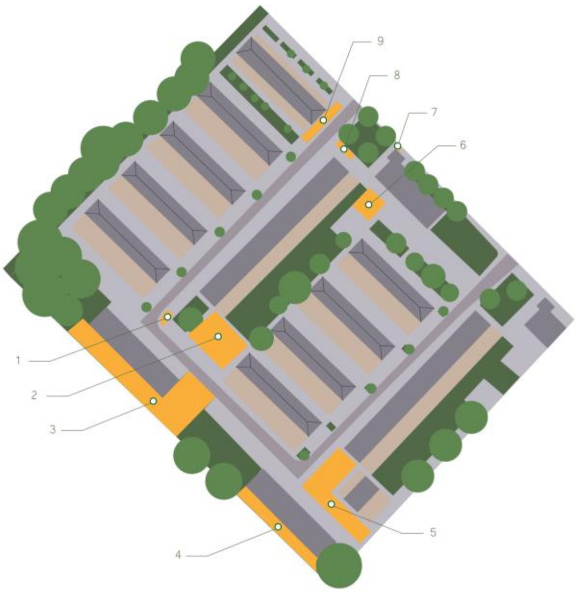


Figure 35: Possible locations for trees in case area 2

Starting with location 1, it was mentioned earlier that trees of categories 2 or 3 can be planted here. Since the apartment building located along the street B blocks the wind, the cooling effect of any tree located in this location would be produced primarily via shading. Perhaps, compact tree of category 3 would be more suitable for this location as one, there is already a larger tree next to it that can sufficiently shade the surrounding area and two, larger tree could cause nuisance as there are electrical cables located on the corner. Both deciduous and coniferous trees could be suitable for location 1.

Location 2 has more space for trees, both on ground and underground. As it was mentioned earlier, trees planted in this location could potentially shade the street B until 13:30 in the afternoon. Trees should be large enough to cast a shadow on the street so it could be assumed that trees of categories 1 and 2 are more appropriate for this location. According to the maps provided by Sweco, there is a possibility to plant one tree of category 1 or three trees of category 2. Perhaps, trees of category 2 would be more beneficial as it would be possible to plant diverse species, which would make this location more attractive for biodiversity and residents. Regarding the spatial arrangement, trees should be located as far from each other as possible to avoid hindering the air flow, since there is an opening for the wind to the right of the apartment building on the street B.

Location 3 presents even more opportunity for tree planting. The primary goal here would be to shade the sunny side of the apartment building from 14:00 until late afternoon. Thus, trees of category 1 would be more preferable in this location to sufficiently shade south-western side of the building in summer. Deciduous trees would be more preferable in order to avoid blocking sun in winter and traits such as dense crown and large leaves would be the most preferable. Same recommendation would apply to location 4. Regarding southern wall of the apartment building, it does not require a lot of shading as it exposed to the sun only till noon, therefore smaller trees of category 2 could be planted here. Smaller trees would be preferable here also because of thermal pipe located next to the southern wall of the building. Again, it is important to locate trees in this location away from each other to allow the downwind cooling. Perhaps, lighter crowns of trees would be better to improve the flow of air.

In location 5, only trees of category 3 are recommended according to the Figure 17. According to the maps provided by Sweco, it is possible to plant eleven trees in this location. A combination of deciduous and coniferous trees would be preferable in this location, both for aesthetics purposes and resiliency. No specific recommendations regarding structural traits or spatial arrangement could be made.

Location 6 could accommodate all types of trees but, perhaps, trees of category 1 or 2 would be more beneficial to increase thermal comfort via shading, especially due to a presence of a playground located to the south-west of location 6. Due to the location of the electrical cable, smaller tree of category 2 is recommended.

Locations 7 and 8 can only accommodate one and two trees of category 3 respectively. Planted trees could be both deciduous and coniferous.

Finally, in location 9, two trees of category 2 and three trees of category 3 can be planted. Perhaps, smaller trees of category 3 are more suitable as this location has many underground utilities.

Now, regarding low and medium vegetation, it can be planted instead of useless pavement and existing grasslands can be turned into meadow grasses to improve aesthetics and make them more attractive to biodiversity. In addition, flat roofs could be covered with green mainly to reduce flood probabilities. Unfortunately, in streets A and C no other improvements could be made in order to reduce flood risks, however, as a possible solution, pavement utilized for parking lots could be made permeable, so that rainwater can infiltrate into the soil. Thus, improvements are shown in the image below:

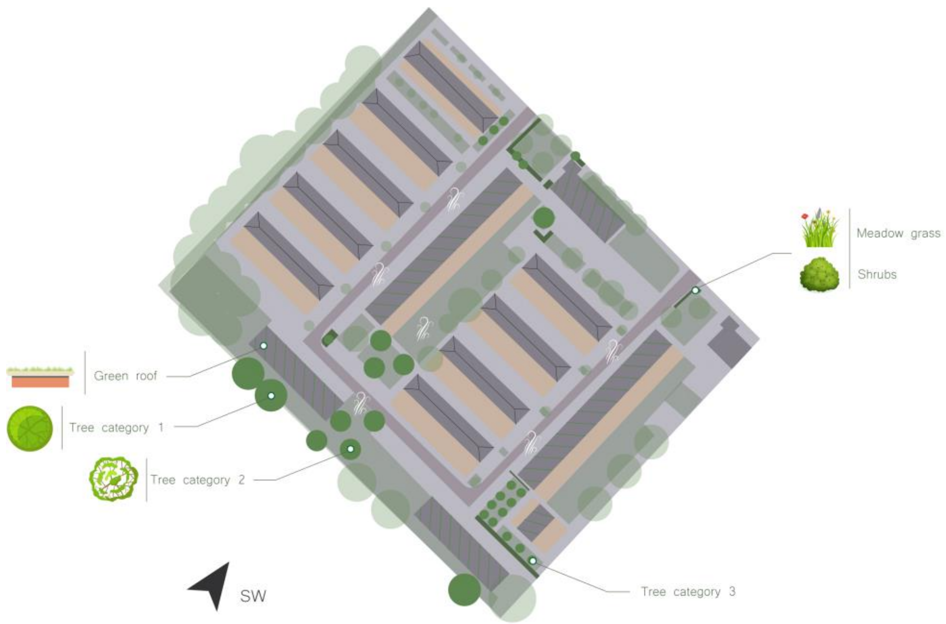


Figure 36: Improved situation in case area 2 (existing vegetation is labeled as transparent green)

E.3. Conclusion for the validation

Overall, the guideline was utilized to increase the fraction of green in two locations in Presikhaaf III. Since the guideline was applied in built up areas with existing infrastructure, both green and grey, it made it challenging to accurately follow the guideline. Main reasons included the lack of space and inhomogeneous street design. In addition, benefits were mainly described from a climate adaptation perspective due to the lack of relevant information on existing biodiversity and residents' well-being. The guideline proved to be useful during the preparation phase and in selection of species but not in choosing the appropriate configuration in space, as vegetation could be located mainly where the space, both on-ground and underground, allowed it.

Appendix F: Data on green infrastructure in Presikhaaf III

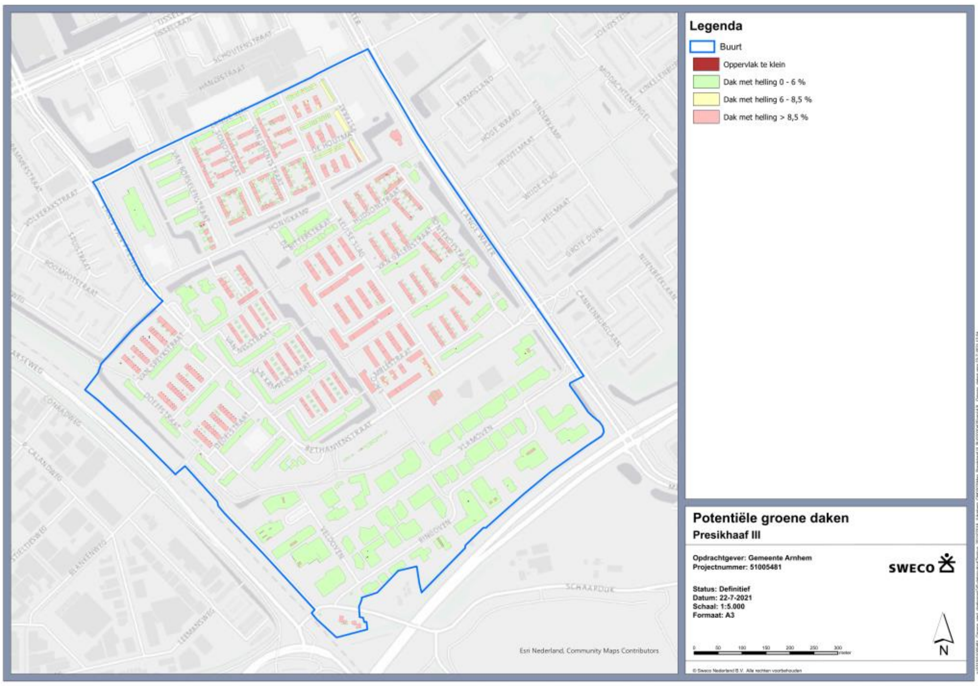


Figure 37: Flat roofs

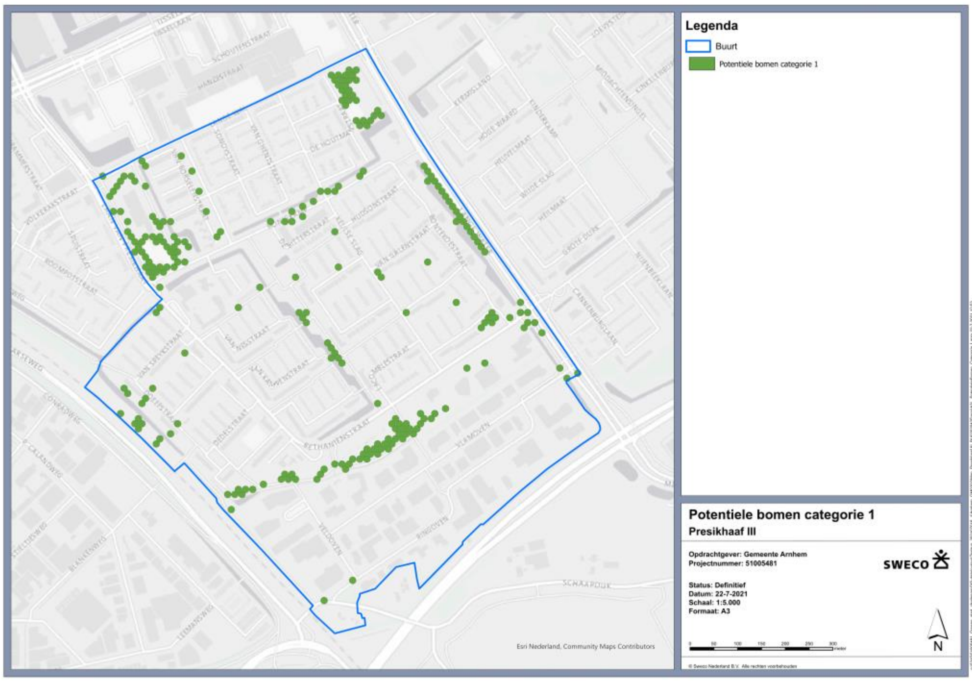


Figure 38: Trees of category 1

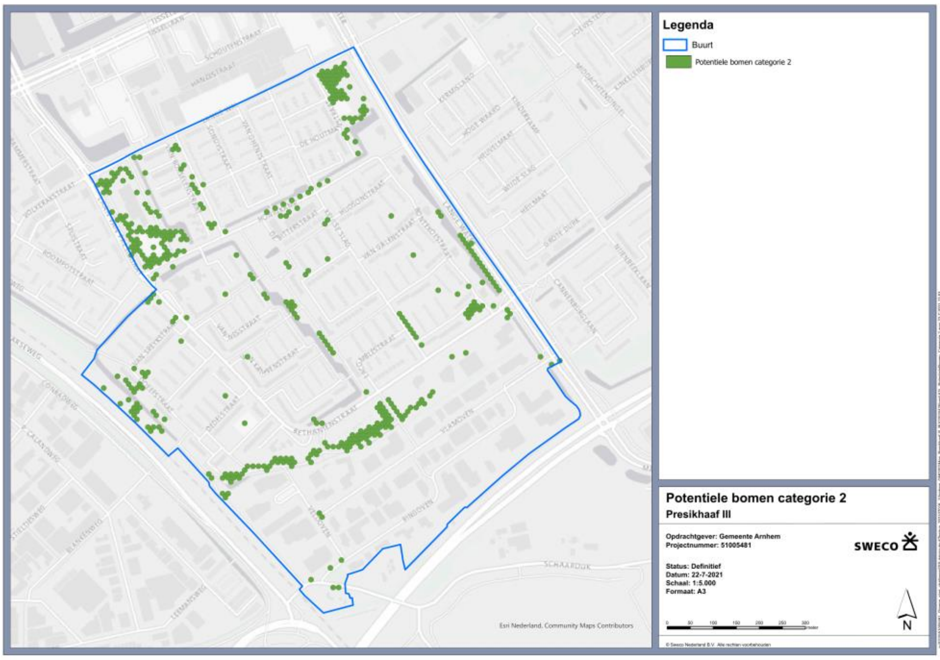


Figure 39: Trees of category 2

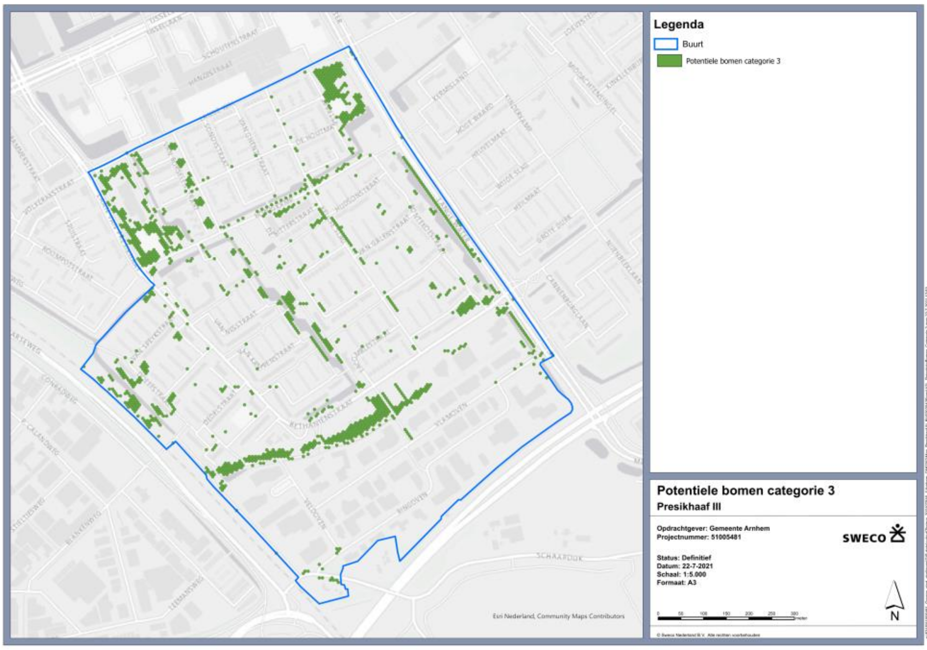


Figure 40: Trees of category 3

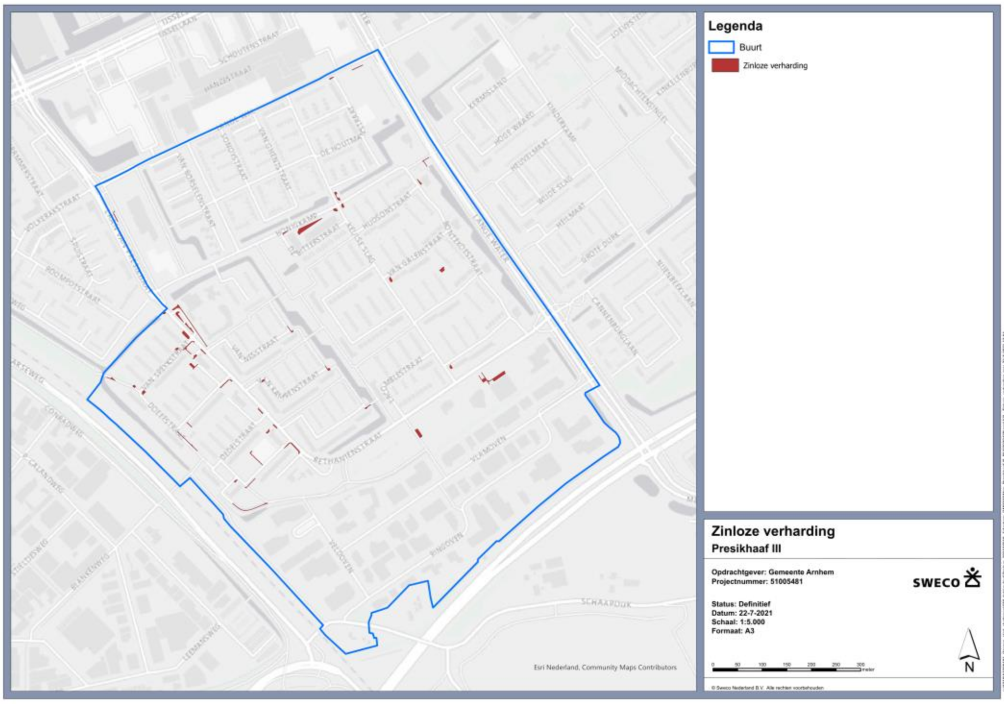


Figure 41: Useless pavement