Compact nature for compact cities

Graduation Report by Menno de Roode

Final Graduation Report

Title:
Compact nature for Compact cities

Subtitle:
Towards an urban nature network in streets and on buildings that enhances ecological values and well-being, a Rotterdam case study

Faculty and department:
TU Delft Faculty of architecture and the built environment | Department of Urbanism

Course:
AR3U100 Graduation Lab Urbanism Studio - Urban Ecology & Eco-Cities

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Date:
July 2021

Delft University of Technology

Department of Urbanism

Urban Ecology Graduation Lab


Image by Tsuneo Yamashita

Why should one have to *visit* the park, shouldn't the city *be* the park?

after Beatley, 2017. p. 29 in
Handbook of biophilic city planning and design

Abstract

As cities are getting denser and larger, space for conventional green features is diminishing. Cities without green alienate people from nature, deteriorate ecological systems and directly harm personal well-being. Limited open areas and many sealed surfaces in today's cities raise the need for a renewed green space approach that fits in an increasingly dense and compact urban landscape; an approach in which green space is not limited to large open spaces at ground level, but one where greenery is truly integrated with built structures. The concept of compact urban green space (CUGS) is introduced in this study to refer to green space compatible with this approach. Too often, current CUGS on buildings and in small spaces solely serves aesthetic purposes and is treated as mere (architectural) decoration. This attitude results in pragmatic but disconnected interventions with little added value to ecology and well-being.

This study puts forward that urban planners and landscape architects should embrace these new and unconventional green spaces, because, when planned and designed from a larger social-ecological perspective, compact urban green space can functionally solve several urban challenges simultaneously while also improving ecological quality and human well-being. This graduation project explores the qualitative aspects of small green spaces that result in major improvements in ecological resilience and personal well-being. It is concluded that CUGS can provide quality for people and nature. E.g. by encouraging stewardship of local communities and allocating space for natural processes.

A pattern language approach is used to better understand the relations between a variety of CUGS patterns across different scales. Novel CUGS patterns, such as rooftop landscapes, bioreceptive building envelopes and topographic building blocks are tested in the spatial and ecological context of Rotterdam. The resulting spatial framework for the city centre guides the development of future CUGS. A design experiment performed in the neighbourhood of the Wijnhaven Eiland shows that multidimensional green structures and networks can improve well-being and ecological resilience in Rotterdam when they add value at different scale levels and are fundamentally integrated into the design of the city.

Keywords: Compact urban green space; ecological resilience; well-being; Rotterdam; urban ecology

Compact Urban Green Space

Transferable design conclusions. Compact Urban Green Space should...

Fig. 1. Graphical abstract with transferable design conclusions for the design of compact urban green space..

Preface

This report is the direct result of a full year graduation project in the Urban Ecology and Ecocities lab of the TU Delft. Though, the foundation of it had already been laid long before I started writing. During my Bachelor of Landscape Architecture in Wageningen, I learnt how fragile the natural environment is. I also learnt that we, as people, very much depend on this fragile system and also benefit from spending time in a natural environment. This made me wonder:

"If spending time in a natural environment is so beneficial to humans, then why do cities, where most of the world's population lives, not look like natural environments at all?".

During a half year-long exchange programme in Singapore, I was repeatedly amazed by how prominent urban green space was integrated into the built environment. After another half-year of internship at ECHO Urban Design, I was introduced to the complexity associated with spatial development, but also with the ambition of many clients to make their urban projects greener. A worldwide pandemic finally gave me the time to start a large green project in my student room and construct a green living wall.

This altogether formed the motivation for me to better understand the relationship between people and nature, and urban and nature. Besides theoretical research, this report also contains practical experiments and results.

I would like to thank Dries, Ivan and Aik from Ebben Nurseries for providing space on their green roof to conduct experiments. I also thank Marco Roos from Naturalis and Stéphanie Scholtes for their support in setting up and performing the measurements on this rooftop. And finally, I could not have done this without my mentor team. My main mentor Nico Tillie has connected me to these and many other inspiring people. Remon Rooij and Marc Ottele helped to elaborate my research further with their knowledge, motivational feedback and critical questions.

Please enjoy reading this report and do not hesitate to contact me for a further discussion or to pose a question.

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Glossary

The definitions of concepts referred to in this thesis are given in the list below.

Compact city is an urban planning model that steers for condensed urban development, as opposed to spread-out development. This results in little open space in the city. The urban structures in compact cities are not monotonous but are diverse in function and form. Lastly, the scale of the streets, buildings and open spaces is small and fine-grained (Neuman, 2009). The definition is further explained in the theory and methodology chapters.

Ecology is the study of relationships between living organisms and their physical environment. This is not limited to 'natural' environments and species, but also includes humans and urban environments. This knowledge helps to understand the benefits of ecosystems for human life. See also: urban ecology.

Ecology, urban is the section of ecology that focuses on the relationships between living organisms (especially non-human), and the urban environment and humans. It is uncommon to treat humans as part of the living organisms, as the study that explores the relationship between humans and their environment is considered environmental psychology.

Ecosystem is the whole set of groups of species that live together and their interactions with the environment.

Greenery is used in this thesis to refer to either single plant species (e.g. trees, shrubs) or vegetation structures (e.g. forests, meadows).

Nature is a concept that is open to many interpretations. While the concept is often associated with untouched wilderness and wildlife (the opposite of humans), this is referred to as the classical view. In this thesis a broader definition is used: a co-evolutionary view. Nature is seen as something that includes humans. This view advocates that a balanced interaction between society and nature leads to mutual benefits. Conflicts between society and nature may happen and are accepted, as long as neither suffers serious damage or threats to the other's existence. This means that ecological qualities, such as ecological resilience, should be maintained (TUDelft, n.d.). In this view, the structures and cities humans have created may also be seen as a natural feature that provides habitat for people.

Resilience, ecological is the ability of an ecosystem to recover from disturbances. The definition is further discussed in the theory chapter.

Urban green space consists of all the vegetation, soil and water structures in a city. Traditional urban green space in cities includes features such as parks, brownfields, street trees, canals and open water.

Urban green space, compact (CUGS) is a renewed concept of urban green space that focuses on urban green space that is spatially compatible with the compact city. This means that the green space does fit in small open spaces, or has a limited footprint at the ground level. Green spaces on buildings, such as green roofs and green walls are an example of compact urban green space.

Well-being in this thesis is used as an indicator that describes someone's quality of life. Since this is influenced by many aspects, the aspects are limited to the ones that have a strong relationship with spatial design and ecology. These are health, social development, and belonging (Ecocity Builders, 2020). The definition is further defined in the theory and methodology chapters.

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Image by ANP

01

Introduction

As cities are getting denser and larger, space for conventional green features, such as parks, is diminishing. Cities without green alienate people from nature, deteriorate ecological systems and ultimately harm our own well-being. Limited open areas and many sealed surfaced in today's compact cities raise the need for a renewed green space paradigm that fits in an increasingly dense urbanized landscape. A paradigm in which green space is not limited to large open spaces at ground level, but one where greenery is truly integrated with built structures. Yet, too often greenery in cities and on built structures is treated as mere architectural decoration and serves only aesthetic purposes, ignoring its potential to mitigate many of the urban challenges we face today.

Problem field

Global

Currently, already 4.9 billion people live in an urban area, more than half of the world's population (see Fig. 2). As this number is projected to increase to 6.7 billion in 2050, a considerable amount of urban development can be expected in the coming years (United Nations, 2018).

Benefits related to urban areas are well-documented and are a consequence of the density of people and their social and economic networks. Examples include increased economic productivity, information and knowledge spillovers, diverse social networks, and cost-sharing of infrastructures and services (Ciccone and Hall, 1993; Cervero, 2001; Montgomery et al., 2013, pp. 40–42).

Besides advantages, disadvantages related to urbanization are also well-described and seem to largely concern issues related to environmental degradation and decreased human well-being.

The effect of urban development on natural systems should not be underestimated. Of all human activities, urbanisation has been appointed as the largest cause of habitat loss, resulting in high extinction rates among local biodiversity (McKinney, 2002). Globally, over 30% of this biodiversity has already gone extinct (see Fig. 3). This ecological destruction threatens the existence of all life on earth, including ours (WWF, 2020).

The relation between urban form and ecological impact is complex and repeatedly debated (Neuman, 2005; Artmann, Inostroza and Fan, 2019). Yet, consensus exists regarding the role of the city size and physical footprint. Large cities that are spread out into the landscape have a larger negative impact on the environment than condensed cities. This is one of the main arguments used in favour of compact development. Furthermore, compact development promotes a sustainable lifestyle by creating support for (less resource intensive) shared transportation options and walkable neighbourhoods (Jenks, Burton and Williams, 1996). Because of these advantages, compact development is encouraged by local, national and international institutions (e.g.: UN-Habitat, 2015; Gemeente Rotterdam, 2018; Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2020).

However, compact development comes at a cost. With higher building densities and fewer open spaces, liveability is jeopardized. Dense urban environments are known to trigger mental stress responses, while physical stresses ensue from the urban climate which tends to be polluted and hot (Jim, 2004; Adli, 2011; Russo and Cirella, 2018). Neuman refers to this as the compact city paradox, which describes the trade-off between the liveability and sustainability of cities (Neuman, 2005).

To understand the origin of these stresses, we need to look at the concept of *biophilia*, which was coined by Eric Fromm in 1973. Biophilia can be defined as the inherent affection humans have towards natural environments. This affection is a result of evolution in the past millennia, in which humans have evolved to adapt to and thrive in a natural environment (Beatley, 2017). On the time scale of human existence on earth, the urban environment has been around for a very short time. This can be clearly seen in Fig. 2, in which the percentage of the urban population is plotted against time since the beginning of the Holocene. Since then, our mind and body have not changed much in a period in which the living environment has changed drastically (Kellert and Calabrese, 2015). Hence, an urban environment devoid of the natural elements to which we have evolved will eventually fail in fulfilling human needs. Hence, it is widely acknowledged that green space should be incorporated into the urban fabric (Russo and Cirella, 2018).

> **"A major task for modern cities is to become more compact and dense, but at the same time foster closer connections to nature."**
> **(Beatley, 2017, p. 2)**

Unfortunately, the inherent characteristics of compact cities make the implementation of conventional green space not always possible. This challenge has not been unnoticed as pocket parks, green roofs and walls, and other small green features are given more and more interest by architects and developers in developed countries. Although some earlier studies refer to it (Tillie et al., 2012, 2018), the potential contribution to urban quality and the mitigation of urban challenges by new compact urban green typologies remains largely unexplored from an urban ecological planning and design perspective. This results in disconnected implementations of these features that mainly treated as add-ons to existing architecture and do not contribute much to ecological sustainability and human well-being (Jim, 2004). Furthermore, the harsh growing environment on buildings and the lack of knowledge often results in a vegetation selection based on pragmatic choices, rather than its contribution to ecology and well-being (Langemeyer et al., 2020). Nevertheless, novel urban green spaces, particularly those making use of the vertical

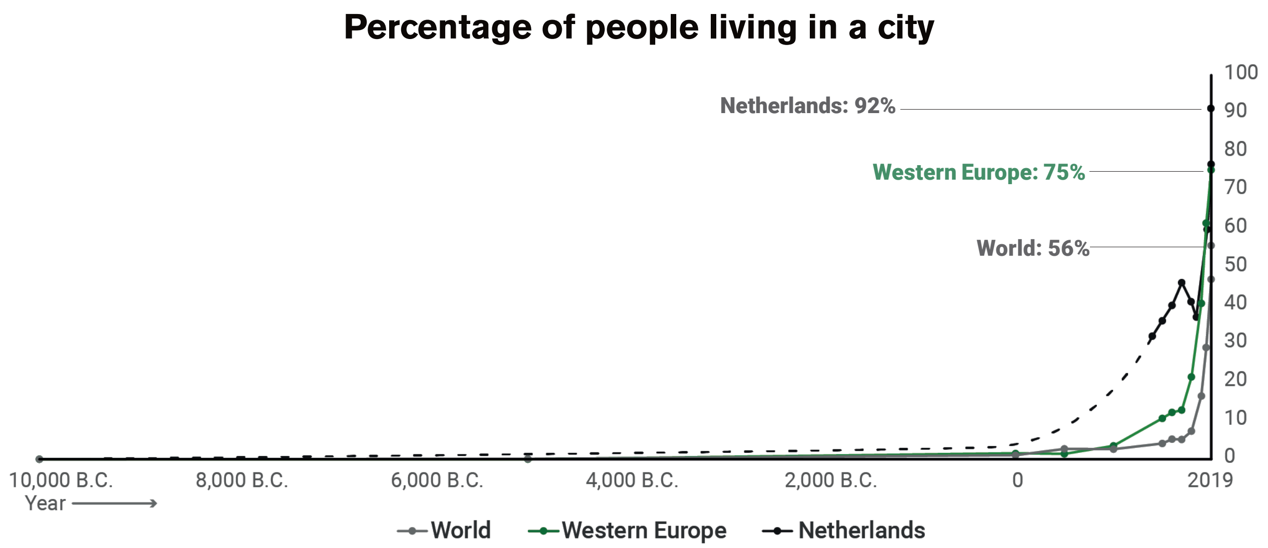


Fig. 2. The development of the urban population as percentage of the total population since the beginning of the Holocene illustrates living in an urban environment is a relatively new phenomenon. Data sources for figures are included in the reference chapter.

dimension, have a large potential to contribute to more liveable and ecologically sustainable cities due to their spatial compatibility with the compact city paradigm.

Throughout this thesis, the term *compact urban green space (CUGS)* will be used to group these green spaces. The definition is elaborated in the next chapter. The aim of this thesis is to explore the potential contribution of these compact urban green space types in improving personal well-being and ecological sustainability in the context of the compact city. It will do so by approaching them from an urban ecological planning and design perspective. Since both ecology and urban planning and design are context specific, a case study will be used to illustrate the concepts and to demonstrate the results. The Dutch city of Rotterdam fits this research well, as this city is steering towards compact development. Moreover, the city is not afraid to adopt progressive ideas and embrace new technologies. The next section introduces the city of Rotterdam in the context of this research.

> "What is often considered and belittled as "green architectural decoration" is however an important element in our built environment which must not be underestimated."
> (ARUP, 2016, p. 7)

Rotterdam

Over 650,000 people live inside the municipal borders of Rotterdam, making it the second-largest city in the Netherlands. Fig. 6 shows the location of the municipality, close to the North Sea and crossed by the river Maas. Rotterdam is located in an estuary, a natural biotope that generally holds large a large diversity of wildlife. However, after the urbanisation of this area and the large scale interventions in the landscape that followed, the remaining native biodiversity is now estimated at 14% of the original situation (CLO, 2016).

The city of Rotterdam has a rich history in which the harbour has always played an important role. It was founded in the 13th century as a port city and managed to grow to a large trade hub in the Dutch Golden Age (around 1600). Even today, the harbour remains the largest in Europe. Past harbour expansions still dictate the current urban development, as former docks and quays are redeveloped into housing areas.

The city suffered from substantial damage during the Second World War, in which the urban centre got completely destroyed. Modernistic urban planning principles emerged before the war were embraced to accelerate the reconstruction process. This led to a separation of functions and the construction of more spacious and green neighbourhoods around the centre (Tillie et al., 2016).

In 1985 a new strategy was adopted to move towards a compact city. This plan aimed to densify and diversify the monotonous modernistic centre. The construction of tall

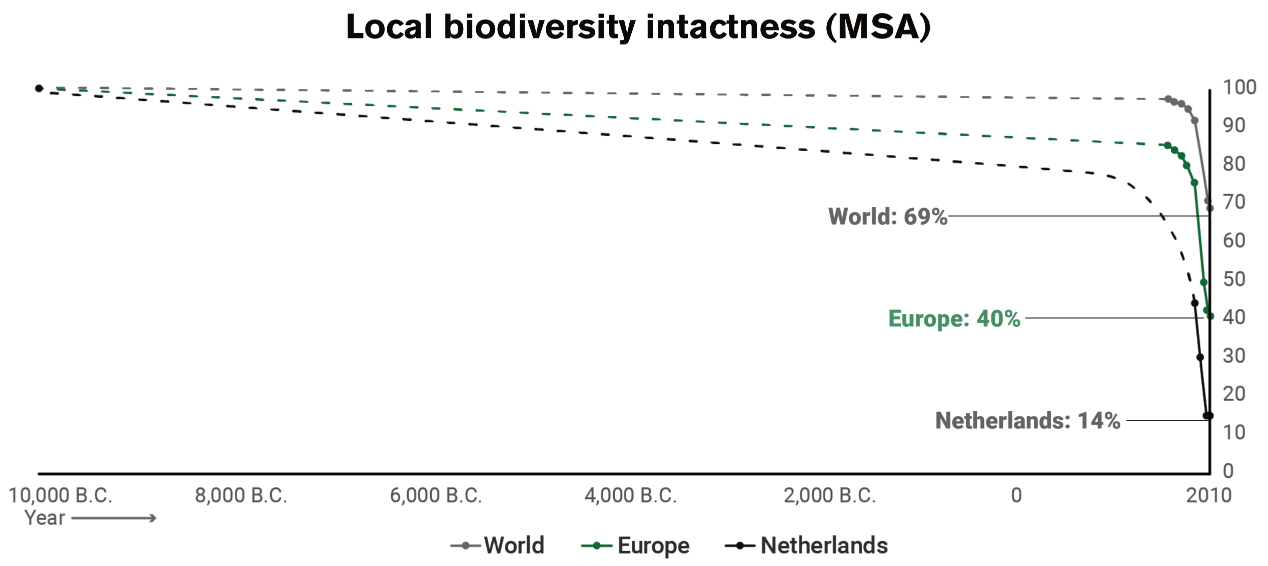


Fig. 3. Local biodiversity, estimated using the Mean Species Index (MSA), has declined rapidly in the past decades. Data sources for figures are included in the reference chapter.

buildings was allowed, which was later combined with the obligation of improving the public space at the ground level of the building. This compact form of development is still encouraged today (Laar et al., 2004; Gemeente Rotterdam, 2018). Fig. 7 shows a morphological cluster analysis based on parameters such as building volume, the surface area of the building envelope and green and water amounts. This analysis was performed for a heat stress study and clearly shows, when ordered by the surface area of the building envelope, compactness in Rotterdam (Van der Hoeven and Wandl, 2015). The most compact cluster lies in de centre and is indicated by a dotted black line. Since this thesis focuses on operating in compact urban environments, the analysis and design throughout the report are confined to this area. Please note that the next chapter, theory, goes further into depth on the definition of compact development.

As mentioned before, compact development comes at a cost. Rotterdam suffers severely from the urban heat island effect, resulting in temperatures in the city that are up to 8ºC hotter during heat waves when compared to the rural area. Due to the lack of green space, more than 30% of the inhabitants are not able to visit a cool place during such a heatwave (Gemeente Rotterdam, 2020). While Rotterdam has relatively much green space per person (115m²), the city scores badly when the accessibility, quality and distribution of green is taken into account. Of all 72 European cities ranked in the HUGSI green city index, Rotterdam takes 70th place, the lowest of all included Dutch cities (HUGSI, 2020). Green space in the city is predominantly confined to well-manicured geometric shapes that consist of a monoculture of species. Fig. 4 shows a typical image of such a space. As a result, the city has faced many insect and disease outbreaks in the past. The die of off infected elm (*Ulmus spp.*) and chestnut trees (*Castanea spp.*), just as the rise of the itchy oak processionary (*Thaumetopoea processionea*) caterpillar can be attributed to the monotonous planting schemes (Gemeente Rotterdam, 2009).

However, Rotterdam has ambitious plans to increase the green space in the city. This will be a challenge, as the ambition is to simultaneously add 50.000 dwellings — Rotterdam currently has 300.000 dwellings — will make the city even more dense (Gemeente Rotterdam, 2018). In 2019 a greenification plan was published with the aim to add 20ha of urban green space, of which 6-8ha on rooftops. An additional program solely focused on the activation of rooftops was also introduced, just as subsidies for private parties to foster green roof development. All green roofs qualify for such a subsidy, regardless of the type and amount of vegetation. One of the focal points in this greenification strategy is the development of green space close to people's homes, which makes the use of compact urban green space incredibly relevant (Gemeente Rotterdam, 2019a; Gemeente Rotterdam, 2019b).

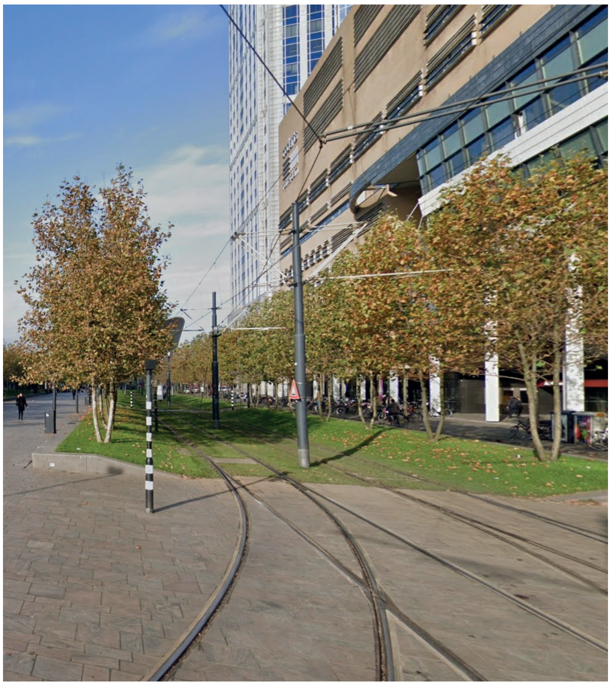


Fig. 4. Green space in Rotterdam is predominantly confined to well-manicured monocultures, attracting pests and contributing little to ecological sustainability (Jim, 2004).

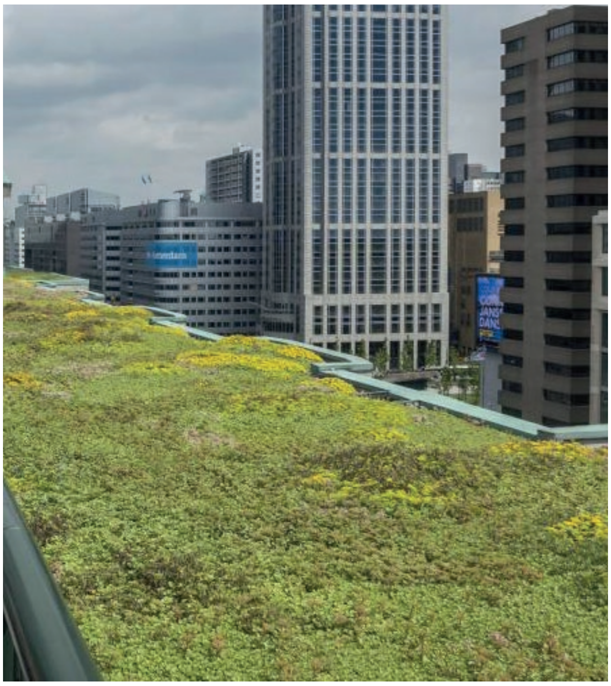
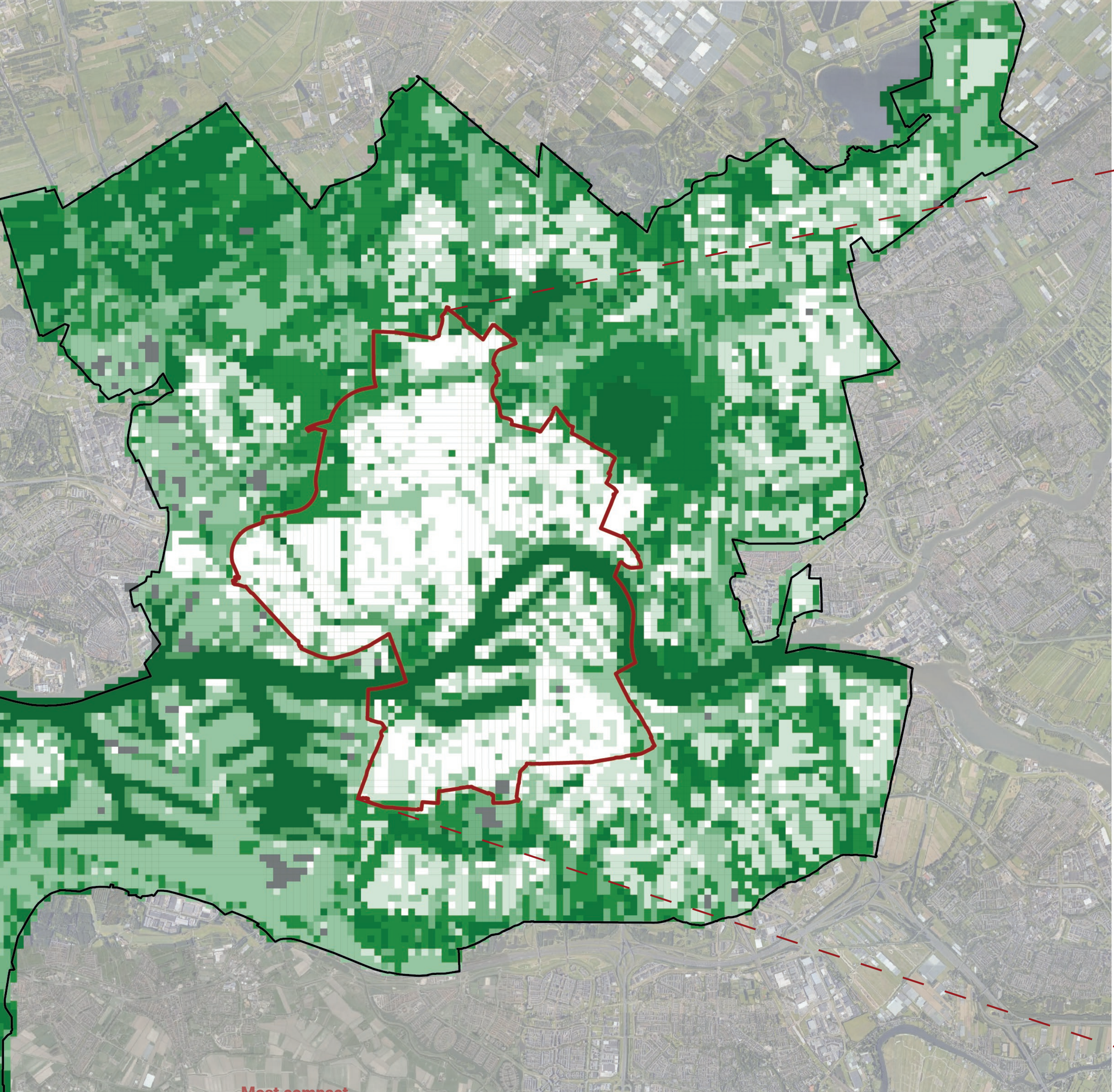


Fig. 5. Green rooftops often consist of solely exotic sedum species that offer little to no value to native insects and birds (Madre et al., 2013).

Fig. 6. Rotterdam is located in an urbanised river delta landscape. The city is situated close to The Hague and Amsterdam. The harbours, which are part of the municipality, stretch out towards the North Sea.

Fig. 7. Compactness of different areas in Rotterdam. A clear 'compact cluster' can be distinguished in the city centre. The research in this thesis will be limited to this area, indicated by a red line. Figure adapted from Van der Hoeven and Wandl (2015).



Most compact

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
Building envelope	8136m²/ha	4269m²/ha	1261m²/ha	1139m²/ha	732m²/ha	663m²/ha	136m²/ha	23m²/ha
Pavement	0.59	0.58	0.80	0.39	0.36	0.37	0.09	0.06
Vegetation (LAI)	350	557	249	1014	262	1056	2074	27
Surface water	2%	4%	3%	7%	54%	8%	8%	96%

Municipal border

Compact cluster

N

2km

Fig. 8. Even though being already compact, a lot of densification sites appointed by the municipality are located around the centre of the city. Most are easily accessible by public transport. The area is served by an extensive public transportation network, consisting of metro, train, tram, watertaxi and bus lines.

Unfortunately, a larger vision for green space that also includes green on buildings has not yet been developed, as green ambitions consistently exclude built structures. There is a need for a framework that does not only addresses the quantity of green space but also provides guidelines for improving the quality. This includes defining a spatial-ecological structure to control the proliferation of green projects that would otherwise be disconnected and of little value for improving well-being and ecological sustainability, such as the green rooftop in Fig. 5 (page 16).

Research aim

This research aims to explore new relationships between the urban and natural environment and between people and nature. This requires three main paradigm shifts. Firstly, we need to move beyond just recreating the look and aesthetics of nature in urban environments towards recreating the whole system, or ecosystem. This is referred to as resilient ecosystems in this thesis. The concept will be further explored and defined in the next chapter. Secondly, the effect of nature on human well-being has to be acknowledged as a complex system consisting of both positive and negative interactions. In the next chapter, this relationship is discussed thoroughly. And thirdly, the spatial dichotomy between urban form and natural environments should be mitigated. Novel compact urban green spaces, particularly those integrated into built structures, may be able to provide a new hybrid form of nature that will improve the liveability and ecological sustainability of cities.

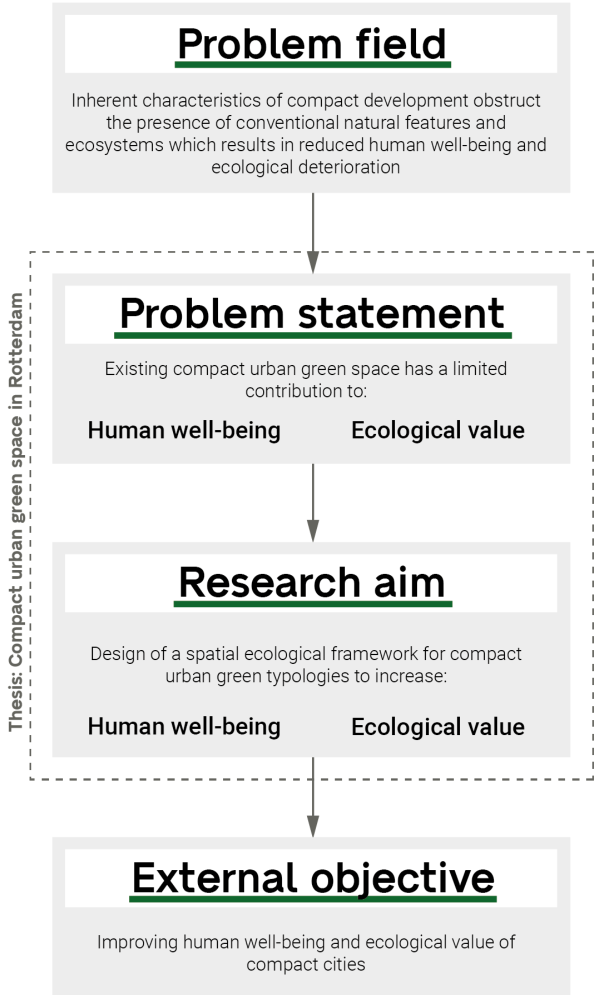


Fig. 9. Position of the research.

Therefore, the external objective of this research is to increase the value of these compact green typologies regarding human well-being and ecology. The research itself contributes to this objective by better understanding the relationship between individual compact urban green spaces and their potential to reinforce each other. This can only be achieved when compact urban green space is approached throughout a variety of scales. On these scale levels, guidelines to improve their impact and quality will be defined. A spatial-ecological framework will guide future developments of compact urban green space types in Rotterdam.

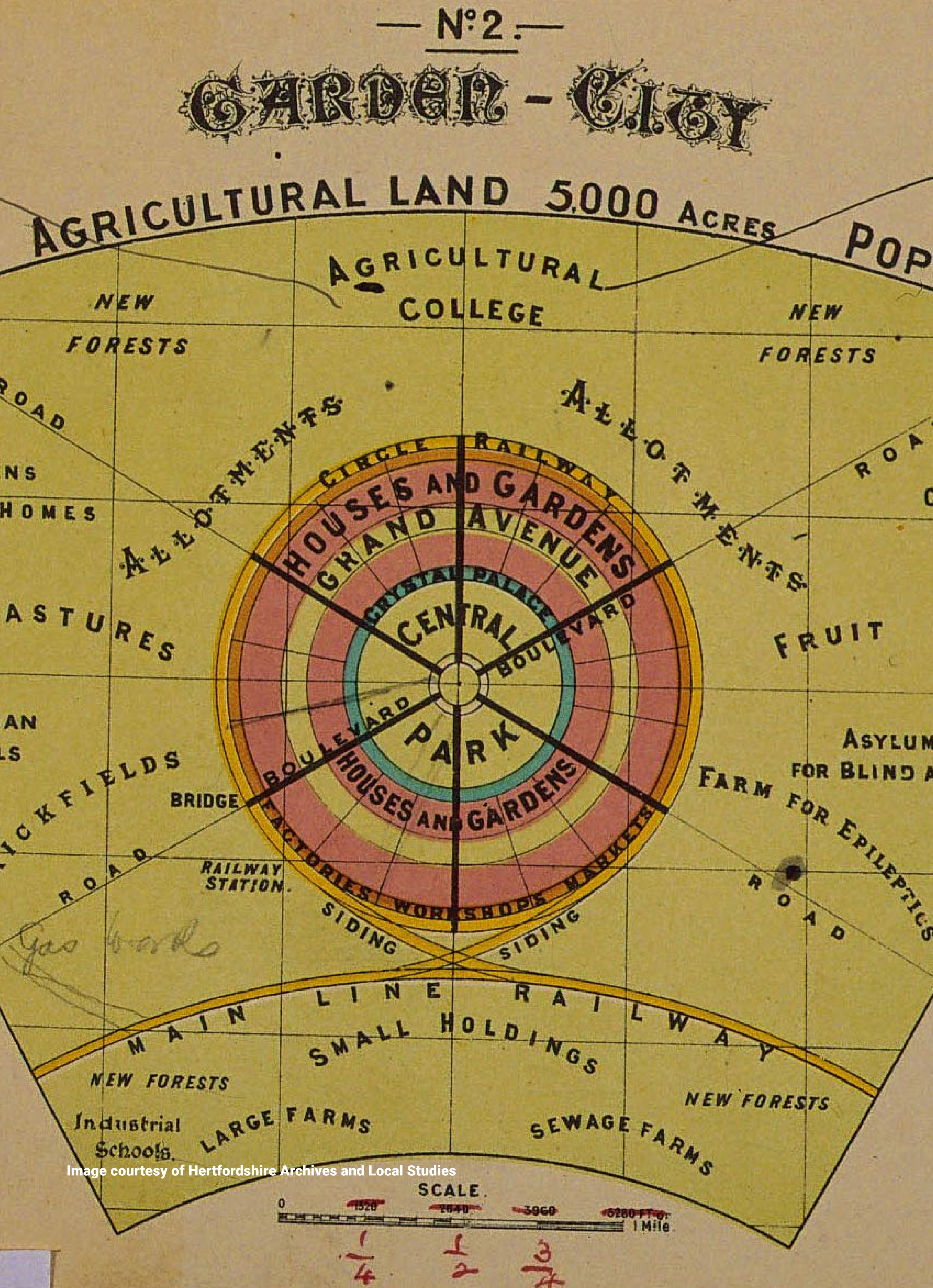
Fig. 9 positions this research within the problem field and external objective. Since the aim of this research is to provide an overview of design guidelines and a spatial ecological structure for the city of Rotterdam, the research question that will guide this research is:

"What framework can be used to guide the development of *compact urban green space* in Rotterdam that addresses both the quality, in terms of well-being and ecology, as well as the spatial-ecological structure?"

Definitions used in this question are embedded into a theoretical framework which is discussed in the next chapter. Chapters 4 and 5 further explore and analyse these themes in the context of Rotterdam.

The output of this research consists of two main elements. First, a *pattern language* approach is used to compile an overview of desirable compact urban green space patterns. The approach is, just as the other methods used in this thesis, elaborated in chapter 3. The pattern study itself can be found in chapter 6. Second, a spatial ecological framework for the use of these patterns in Rotterdam is designed, which can be found in chapter 7. Both elements are tested by a design experiment in the Wijnhaven Eiland in Rotterdam, also presented in chapter 7. The spatial design will demonstrate how abstract theoretical principles can be applied and tailored to the local contextual conditions. Additionally, the experiment provides a concrete example of how the compact urban green space in the city might look like and function.

Finally, the research question is answered and a conclusion is given in chapter 8. A reflection in the same chapter reflects on the results. The final framework (consisting of both the pattern study and spatial-ecological structure for Rotterdam) will also be evaluated on the transferability to other compact cities.



— Nº 2. —
GARDEN - CITY
AGRICULTURAL LAND 5,000 ACRES
POP
AGRICULTURAL COLLEGE
NEW FORESTS
NEW FORESTS
ROAD
ALLOTMENTS
ALLOTMENTS
ALLOTMENTS
NS
HOMES
ROAD
C
PASTURES
FRUIT
AN
LS
ASYLUM FOR BLIND A
FARM FOR EPILEPTICS
CKFIELDS
BRIDGE
ROAD
RAILWAY STATION.
ROAD
CIRCLE RAILWAY
HOUSES AND GARDENS
GRAND AVENUE
CRYSTAL PALACE
CENTRAL PARK
BOULEVARD
BOULEVARD
BOULEVARD
HOUSES AND GARDENS
FACTORIES
WORKSHOPS
MARKETS
SIDING
SIDING
Gas works
MAIN LINE RAILWAY
SMALL HOLDINGS
NEW FORESTS
NEW FORESTS
Industrial Schools.
LARGE FARMS
SEWAGE FARMS
SCALE.
0
1320
2640
3960
5280 FT or 1 Mile
1/4
1/2
3/4

02

Theoretical framework

The relation between urban and natural environments has influenced many landscape architects and urban planners throughout history. This chapter explores how historical urban-nature paradigms have led to compact city planning, dives further into the concepts of *ecological sustainability* and *well-being* and relates the discussed paradigms and concepts to compact urban green space.

From garden city to city in nature

The best-known example of the integration of nature into cities has to be Ebenezer Howard, who ought to define a new planning model in which the qualities of suburban villages were combined with the conveniences of urban living. In his influential book the Garden Cities of To-morrow, he argues that *"[h]uman society and the beauty of nature are meant to be enjoyed together"* (Howard, 1902., p. 17). More recently, modernistic urban planners such as Le Corbusier aimed to address urban liveability issues by letting in more light and air. This was achieved by placing large building blocks into an urban landscape of green open spaces. The city of Rotterdam has several neighbourhoods that were designed with these modernistic principles in mind. This can be seen in Fig. 10 (page 24). Most of them were constructed right after the Second World War. Unfortunately, the implementation of these modernistic concepts often did not yield the urban qualities their founders had envisioned. The large buildings and open areas allocated for greenery lost connection with the human scale and resulted in unpleasant spaces and resource-intensive urban-sprawl (Jenks, Burton and Williams, 1996).

Moreover, at the time these concepts were developed, the understanding of the environmental relevance of greenery and ecology was not at the level it is today. Urban green space was only valued on aesthetics which resulted in geometric and well-manicured grass fields with limited contribution to ecological sustainability (Jim, 2004). Furthermore, the increased awareness of the changing climate and the depletion of the earth's non-renewable resources put sustainability forward as one of the main urban design principles (Jenks, Burton and Williams, 1996; Neuman, 2005).

Previous attempts to include green space into cities often resulted into poor urban quality or unsustainable urban sprawl

These paradigm shifts resulted in a new dominant urban planning concept that had to address both social and environmental sustainability: the compact city. The compact city model distinguishes itself from previous planning models in the sense that it is focused on the preservation of green space outside the city boundaries, as opposed to the inclusion of green space into the city itself. Green belts around cities were established

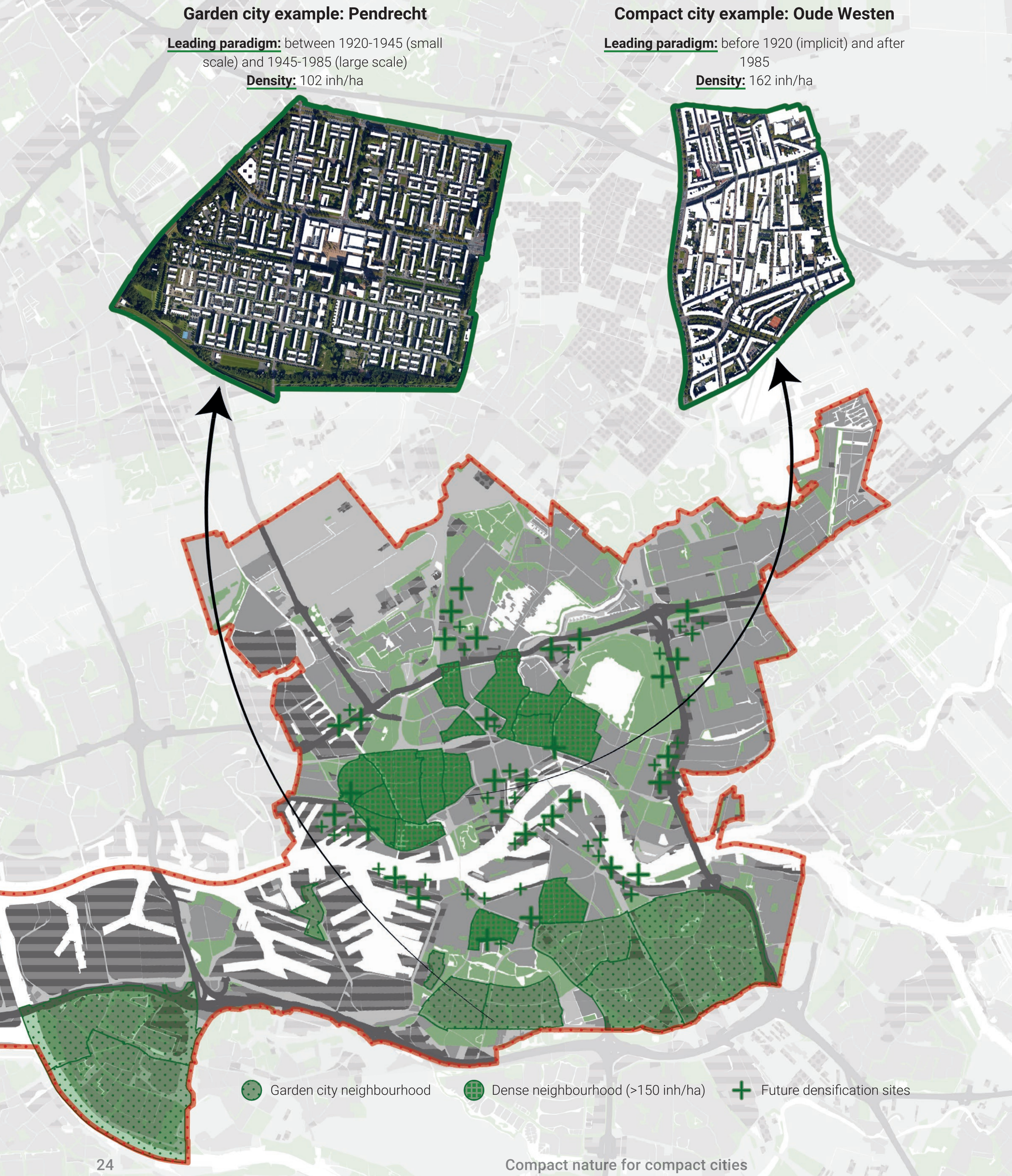


Fig. 10. Different planning paradigms throughout history have led to a variety of urban fabrics and the resulting space for nature in Rotterdam. Currently, the municipality of Rotterdam is aiming for compact development. That means open space in future neighbourhoods will look less like Pendrecht (left) and more like Oude Westen (right)

to prevent urban agglomerations to merge further and allow for recreation for city dwellers. There is no single accepted definition of the compact city, but Neuman (2005) does list some common characteristics of compact development. These characteristics include high residential and employment densities, a mixture of land uses, fine-grained urban fabric, high degrees of street connectivity and low open-space ratio. Hence, it should be noted that compact development does not equal high-density development, as it includes additional aspects such as scale and diversity. Nevertheless, the high amount of impervious surfaces and low open-space ratio results in the loss of green space and a decline in well-being.

Increasingly more scientific evidence on the positive effects of greenery on human well-being led to a different view on urban green space and nature. Natural features began to be acknowledged as important elements that should be part of our daily routines, as they help us to distress, focus and be productive. This understanding led to a view of urban green spaces beyond something that you plan a visit to. Rather, urban green spaces should be physically and visually close to people (Beatley, 2017). Examples can be found in Singapore's greening vision that shifted from 'Garden city' to 'City in a garden', to 'City in nature' today (NParks, 2020a). Similarly, Melbourne's Urban forest strategy aims to create a city in a forest (City of Melbourne, 2016). This new paradigm requires the integration (or rather an amalgamation) of urban green spaces and the compact urban fabric. The term compact urban green space (CUGS) aims to cover all the (often unconventional and new) green typologies that fit in dense and compact urban environments and contribute to this integration. There is no clear boundary between greenery that is compact and greenery that is not. CUGS commonly has a small footprint and can be found at the transition between private buildings and public spaces, characterized by its close proximity to living or working spaces. It can be directly seen or reached from indoors and does not require a planned visit. It is not limited to the ground level greenery and includes green on buildings in the form of skyparks, green façades, planted rooftops and green balconies. In fact, the vertical dimension and green space on buildings are essential in greening compact cities. Therefore, this report mainly focuses on those compact green spaces above ground level. Since city dwellers have the most frequent interaction with CUGS (by definition), CUGS has large potential to improve well-being and liveability. The next section discusses the relationship between well-being, liveability and CUGS.

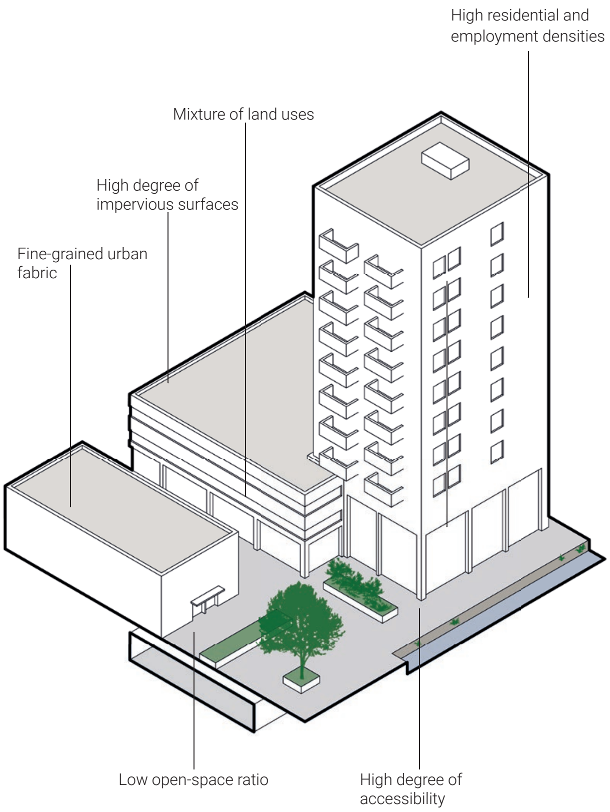


Fig. 11. Characteristics of compact cities as described by Neuman (2005).

Compact urban green space and well-being

While there is no consensus on the definition of liveability,

Aspects of well-being (Ecocity Builders, 2020)	Described relation of reduced well-being and urban areas
Health	
Physical	Described relation of reduced well-being and urban areas
Mental	Increased stress, noise pollution, schizophrenia, Addictive disorders (Ulrich et al., 1991; Gruebner et al., 2017)
Social development	
Education	-
Safety	Increased crime (Laub, 1983)
Recreation	Reduced outdoor recreation in urban green spaces (Russo and Cirella, 2018)
Belonging	
Social	Social isolation (Gruebner et al., 2017)
Spatial	-

Table 1. Aspects of well-being that are negatively influenced by urban environments.

the concept is often associated with similar terms like quality of life, well-being and *"desire to live in a certain place"* (Khee Giap, Wing Thye and Aw, 2014). The definition by Kennedy and Buys combines all aspects into a coherent explanation:

> *"[Liveability is] the well-being of a community and represents the characteristics that make a place where people want to live now and in the future" (Kennedy and Buys, 2009, p. 2).*

Hence, liveability derives from the relation between well-being and space. It consists of both quantitative and qualitative aspects. In this report, the concept of liveability is narrowed down to well-being indicators, as defined by the Ecocity standard Well-being/Quality of life (Ecocity Builders, 2020). These indicators form a framework that can be grouped into health, social development and belonging. Some studies also present indicators as mobility, housing availability and employment. This research does not address these aspects because their relationship with urban green space is less pronounced (Kennedy and Buys, 2009). Additionally, as Neuman correctly notices: *"Liveability is not only a matter of form, it is also a matter of personal preference"* (Neuman, 2005, p. 16). Hence, well-being indicators will differ depending on personal and cultural preferences.

Many aspects of well-being in cities can be related to urban green space and nature. Reduced well-being is therefore often associated with high building densities or lack of green spaces (Jenks, Burton and Williams, 1996; Russo and Cirella, 2018). Table 1 gives an overview of well-being aspects that are negatively influenced by urban environments.

Engagement with nature positively affects well-being. The inherent attraction humans tend to have towards nature can be explained with the theory of biophilia (Beatley, 2017). This theory hypotheses that due to thousands of years of living and evolving in a natural environment, humans evolved to feel comfortable in it.

Aspects of well-being (Ecocity Builders, 2020)	Compact urban green related to ecosystem services	Compact urban green related ecosystem disservices
Health		
Physical	Temperature regulation of green roofs and walls (Alexandri and Jones, 2008; Stav and Lawson, 2011); Green facades reduce air pollution (Radić, Dodig and Auer, 2019)	(Pollen) allergies caused by vegetation; Air quality; VOC by vegetation; Diseases spread by animals (Von Döhren and Haase, 2015)
Mental	Stress reduction of green facades (Elsadek, Liu and Lian, 2019); Stress reduction of small green roofs (Mesimäki, Hauru and Lehvävirta, 2019); Green facades reduce noise pollution (Radić, Dodig and Auer, 2019)	Anxiety caused by plants and animals (Von Döhren and Haase, 2015)
Social development		
Education	Green facades have an educational value (Radić, Dodig and Auer, 2019)	
Safety	Green facades have a positive effect on crime reduction (Radić, Dodig and Auer, 2019)	Structural damage to walls by vertical vegetation (Chen et al., 2020); Crime increase in poorly maintained green spaces, natural forces can cause structural damage to buildings and infrastructures (Von Döhren and Haase, 2015)
Recreation	Recreational value of small green roofs (Mesimäki, Hauru and Lehvävirta, 2019)	Protected nature areas restricts other usages (Von Döhren and Haase, 2015; Langemeyer et al., 2020)
Belonging		
Social	Community driven skyrise greenery (Oh, Richards and Yee, 2018)	
Spatial	The role of nature and gardening in placemaking (Brook, 2003)	Undesired 'weeds' as a result of spontaneous growth (Chen et al., 2020); Plants can block views (Von Döhren and Haase, 2015)

Table 2. Value of compact urban greenery related to the well-being framework.

In 2005 the Millennium Ecosystem Assessment popularized the benefits of nature to humans by collectively referring to them as ecosystem services (Millennium Ecosystem Assessment, 2005). Since then, ecosystem services became part of the planning and design objectives of cities. They are still the most important motivation for incorporating natural ecosystems into the urban fabric. Some researchers take this implementation a step further and advocate for cities completely designed around natural systems, so-called biophilic cities (Beatley, 2017; Tan, 2019). However, care should be taken to not overly romanticize nature. Urban environments may be completely designed around the needs of humans, but natural environments are not centred around human needs. Real nature can be a hostile place to live. This notion led to the rise of the concept of ecosystem disservices. Ecosystem disservices harm human well-being (Von Döhren and Haase, 2015).

Ecosystem services and disservices related to CUGS

Larondelle and Haase (2013) conclude that when properly planned and designed, small green features in dense urban areas can provide similar, or even more numerous, ecosystem services when compared to green in rural areas (Larondelle and Haase, 2013). This suggests that CUGS can positively affect well-being. Likewise, a study on small green roofs in Helsinki found that these features can have recreational and restorative benefits for residents when accessibility and aesthetic is paid attention to. Currently however, the experienced quality of green roofs is not enough addressed by urban planners. Participatory methods such as co-design give more insights into the wishes of local users (Mesimäki, Hauru and Lehvävirta, 2019).

Generally, vertical greenery is often included too late into the building process, resulting in a selection of plant species based on pragmatic choices, as opposed to their contribution to well-being. A more bottom-up approach, such as community-led corridor greening with potted plants, allows residents to pick plants that provide the ecosystem services that they need (Oh, Richards and Yee, 2018). This approach evidently requires people to be educated on this subject, but might be an effective way to enhance social and spatial belonging.

Compact urban greenery can also increase well-being by contributing to health. Significant decreases in stress and improvements in comfortable feelings were found when participants looked at a vegetated wall in comparison with a regular building wall (Elsadek, Liu and Lian, 2019). Similarly, An extensive literature review by Radic et al. (2019) shows that vertical greenery increases thermal comfort, decreases air pollution and offers educational and safety benefits (Radić, Dodig and Auer, 2019). The scale of these effect depends on the climate, the amount and type (leaf size) of vegetation and the type of vertical greening system. Green walls are more effective in reducing temperature than green roofs, but a combination results in the largest reduction (Alexandri and Jones, 2008; Stav and Lawson, 2011). On the other hand, accessible green roofs are deemed more valuable for recreation as opposed to inaccessible natural roofs or green walls (Langemeyer et al., 2020).

Since ecosystem services and disservices are closely connected, it can be expected that compact green features also provide ecosystem disservices, such as invoking allergic reactions, inducing fear or damaging infrastructures (Von Döhren and Haase, 2015). Table 2 provides an overview of the discussed ecosystem services and disservices in relation to the well-being framework.

Compact urban green space and ecology

The concept of ecosystem services stresses that natural processes do not operate independently from one another. Rather, they require a healthy ecosystem of natural features, events and networks to be sustained. Furthermore, several ecosystem disservices are associated with malfunctioning ecosystems (Von Döhren and Haase, 2015). Scientific knowledge on how these natural ecosystems behave in urban environments is young and far from complete. Nevertheless, it is clear that urban ecosystems are complex and adaptive systems formed by an interplay between human and natural processes that happen everywhere around us (Alberti, 2008).

A healthy and stable ecosystem can support human and ecosystem functions simultaneously. Different approaches exist in describing well-functioning ecosystems. The Millennium Ecosystem Assessment used the term supporting ecosystem services for characteristics of healthy ecosystems that do not directly contribute to well-being but rather support other ecosystem services (Millennium Ecosystem Assessment, 2005). Other definitions are found in the field of (urban) ecology, such as ecological resilience or ecological sustainability (Alberti, 2008). Ecological resilience was defined by Peterson et al. as:

> *"Ecological resilience is a measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures*

to a different set of processes and structures." (Peterson, Allen and Holling, 1998, p. 10)

In other words, ecological resilience refers to the degree to which an ecosystem can sustain itself over time, especially after changes and disruptions from outside the system. An ecosystem that can reorganise itself after these changes and disruptions is resilient. Examples of external disruptions include extreme weather events, the introduction of pests or the changing climate. Ecological resilience is a requirement when coping with these, and other unforeseen challenges (Peterson, Allen and Holling, 1998). Thus, a resilient ecosystem is by definition sustainable. Building on Neuman's (2005) sustainability theory, at least three essential characteristics of ecological resilience can be defined. Resilient ecosystems are biodiverse, consist of species that fit in space and time and have a high carrying capacity. These three concepts form the foundation of an ecological framework for compact urban green space.

Biodiversity is the most well-known aspect of healthy and resilient ecosystems. This thesis limits itself to biodiversity at the species level because this is the most documented form of biodiversity in urban areas. However, biodiversity does also refer to diversity in habitats and genetic diversity. The exact relationship between species richness and ecological resilience is still not completely understood. Researchers agree on the fact that more species result in more stable ecosystems, but not all models describe this relationship as completely linear. As species perform all different ecological functions, stability also depends on which species are present. Some have a larger impact on the ecosystem (driver species) than others (passenger species) (Peterson, Allen and Holling, 1998). Ecological resilience also increases when different species operate at different scales and when different species have slightly overlapping functions (Peterson, Allen and Holling, 1998).

If different plant species are used CUGS, space itself becomes a source of biodiversity, as well as an attractor of various fauna, such as insects and birds (Radić, Dodig and Auer, 2019). The 10-20-30 theory by Santamour can be adapted to suit CUGS. This guide was originally established to foster urban tree diversity and states that the plant assortment should not include more than 10% of plants from the same species, 20% of the same genus and 30% of the same family (Santamour, 1990, p. 57). A target that was easily met with community-driven sky-rise greening, as found by the same study mentioned before. Researchers reported a high plant diversity of 124 species/ha. Larger corridors correlated to more potted plants and higher diversity, as well as corridors with more sunlight. Unfortunately, the majority of species (82%) were not native in the area (Oh, Richards and Yee, 2018). Native species contribute more to ecological resilience than exotic species. This can be explained by the notion of fitness.

Fitness as a concept gained popularity after its inclusion in the works of the famous naturalist Charles Darwin. He noticed species that suited the environment have the highest chance of survival (Darwin, 1859). This is well summarised by Neuman, who describes fitness as: *"an evolutionary process marked by the mutual interaction between species and environment. It involves adaptation over time—a fit between organism and habitat" (Neuman, 2005, p. 18).* Hence, the concept of fitness includes the aspect of time and adaptation. It also stresses that a resilient ecosystem is context-specific. Furthermore, environmental adaptation is an ongoing process. There are many examples of species that are currently evolving to novel species by adapting to the new urban environmental conditions, such as insects that evolved to not get distracted by urban light pollution and birds that sing louder to combat urban noise (Schilthuizen, 2019).

Fitness in CUGS is best achieved by creating opportunities for natural processes to 'design'. For instance, spontaneous growth of plants can be encouraged on vertical surfaces. The advantage of spontaneous growth is that species that survive, fit well in the environmental context and thus need little maintenance. Species that grow on building walls are often originating from rocky habitats, such as cliffs and stones. Walls resemble these habitats, which results in many species growing in mountainous regions doing well in cities (Lundholm and Marlin, 2006). In urban areas that are situated in mountainous environments, this strategy can be effective to raise biodiversity with local species. For instance, spontaneous flora on walls in Chonqing consisted of 90% of native species (Chen et al., 2020). However, this number can be expected to be lower for cities that are not situated in mountainous habitats. Furthermore, there is a discrepancy between connecting to local ecology and selecting species that do well in urban environments. The use of local soils on rooftops is another strategy to attract more local biodiversity (Brenneisen, 2017). Yet, habitats on rooftops and walls are considered less valuable than ground habitats, as they attract common (generalist) species (Williams, Lundholm and Scott Macivor, 2014). Habitats on roofs and walls are small and disconnected, failing to provide the capacity for rare species.

Carrying capacity is a concept from the field of ecology. It refers to the maximum population density at a specific place and time. This carrying capacity depends on the available resources such as food, shelter and nesting places. A high carrying capacity reflects a productive ecosystem that provides resources to sustain large and stable populations (Miller and Spoolman, 2011). Good connectivity and conservation of resources can raise the carrying capacity of the ecological system as a whole. This is especially relevant for urban environments, as human development creates isolated patches of habitats that individually do not have the resources to sustain a stable population. Fragmentation of habitat causes specialized and uncommon species to go extinct, causing more common and often exotic species to dominate. This is a common phenomenon in cities (Dramstad, Olson and Forman, 1996; Godefroid and Koedam, 2003). Hence, larger patches of habitat generally have a higher value when compared to smaller patches, suggesting that the limited spatial footprint of compact cities indeed can reduce the negative impacts of urban development on biodiversity outside the city. Carrying capacity is a popular concept in qualifying ecological sustainability as it is easily measurable (Neuman, 2005).

Compact urban green spaces can raise the carrying capacity by contributing to a larger ecological network. On the city scale, they can form corridors between patches of high biodiversity (Jim, 2013). For instance, a comprehensive network of "nature ways" along streets in Singapore permeates deeply into the city and connects biodiverse areas. The small green spaces are designed to "replicate the natural structure of forests as far as possible" and to bring nature close to the residents (NParks, 2020b).

Even though these concepts were described separate from each other, the discussed examples illustrate they are closely related and sometimes even overlap. Compact urban greenery that contributes to ecological resilience therefore addresses all three aspects. Table 3 presents the discussed research in the ecological framework.

Conclusion

The current paradigm of compact development raises the need for new urban green spaces that fit in an increasingly more urbanized landscape. Compact urban green space (CUGS) is spatially compatible with compact development but does not always contribute to urban quality. Urban planners need to pay more attention to the quality of these features and not only to the quantity (Russo and Cirella, 2018). Additionally, CUGS should not be standalone interventions but contribute to a larger green network tailored to local needs.

The presented theoretical frameworks in this chapter illustrate how to assess the quality of these features on well-being and ecological value. The parameters for well-being (health, social development and belonging) and ecological resilience (biodiversity, fitness and carrying capacity) sometimes overlap (ecosystem services), but can also conflict (ecosystem disservices). This introduces a new paradox, describing the complex relationship between ecosystems and human well-being.

Ecosystem disservices can be mitigated by the engagement of local communities and education on the value of nature. For instance, spontaneous growth of vegetation improves ecological resilience but can result in ecosystem disservices when not valued for its contribution to biodiversity. Also, community-driven initiatives might be a solution to improve ecological resilience while also increasing social and spatial belonging. This requires an urban greening vision that engages the local community as well as public and private sectors (Jim, 2004).

The anthropocentric nature of cities asks for a hybrid solution, where ecology is managed in such a way that it contributes to well-being. This will result in novel typologies and habitats that have not yet been researched. Still, the discussed studies illustrate that with proper planning and design, compact urban green space can increase well-being in compact cities while also improving ecological values

Characteristic of ecological resilience	Addressed by
High biodiversity	Community driven skyrise greenery (Oh, Richards and Yee, 2018); Planting of diverse flora (Santamour, 1990)
Fitness	Spontaneous wall vegetation (Chen et al., 2020); Use of local soils on roofs (Brenneisen, 2017)
High carrying capacity	Network of green spaces (Jim, 2004; NParks, 2020b)

Table 3. Value of compact urban greenery related to the ecological resilience framework.

Image courtesy of author

03

Methodology

Being an Urbanism graduation project, methods in this thesis continuously shift between research-oriented and design-oriented. This chapter relates methods and approaches to research aims and outcomes. First, the theory of chapter 2 is used to construct a conceptual framework. Thereafter, the methodological framework elaborates on the methods that will be used and links these to sub-research questions and desired outcomes. Finally, research limitations and ethical considerations are discussed and a conclusion is given.

Conceptual framework

The conceptual framework (Fig. 12) shows the relation between the different concepts used in this research. This relationship is based on the definitions and theoretical research in the theory chapter. The definitions are also recapped below.

There is no single accepted definition of the **compact city,** but Neuman (2005) does list some common characteristics of compact development. These characteristics include high residential and employment densities, a mixture of land uses, fine-grained urban fabric, high degrees of street connectivity and low open-space ratio. Hence, it should be noted that compact development does not equal high-density development, as it includes additional aspects such as scale and diversity. Nevertheless, the high amount of impervious surfaces and low open-space ratio results in the loss of green space and a decline in well-being. Rotterdam is an example of a compact Dutch city. The compact city paradigm has guided planning decisions since the publication of the Binnenstadsplan in 1985 (Laar, Van Jaarsveld and Klaassen, 2004).

While there is no consensus on the aspects that influence **human well-being**, the concept itself is often associated with quality of life. Liveability is also related to well-being and derives from the relation between well-being and spatial characteristics (Kennedy and Buys, 2009, p. 2). In this research, well-being indicators as defined by the Ecocity standard Well-being/Quality of life (Ecocity Builders, 2020) are used. These indicators can be grouped into health, social development and belonging. Some studies also present indicators as mobility, housing availability and employment. This research does not address these aspects because their relationship with urban green space is less pronounced (Kennedy and Buys, 2009). Additionally, as Neuman correctly notices: "*Liveability is not only a matter of form, it is also a matter of personal preference*" (Neuman, 2005, p. 16). Hence, well-being indicators will differ depending on personal and cultural preferences. The relation between well-being and ecology can be found with the concept of ecosystem services and ecosystem disservices. Ecosystem services are ecological processes that improve human well-being, while ecosystem disservices are ecological processes that harm human well-being (Millennium Ecosystem Assessment, 2005; Von Döhren and Haase, 2015).

Ecological resilience refers to the degree to which an ecosystem can sustain itself over time, especially after changes and disruptions from outside the system. An ecosystem that can reorganize itself after these changes and disruptions is resilient (Peterson, Allen and Holling, 1998). Ecological resilience can also be used to indicate the health and functioning of an ecosystem. An urban ecosystem that is resilient supports both human and ecological functions simultaneously (Alberti, 2008).

The concept of **compact urban green space (CUGS)** aims to cover all the (often unconventional and new) green typologies that fit in dense and compact urban environments. There is no clear boundary between greenery that is compact and greenery that is not. CUGS commonly has a small footprint and can be found at the transition between private buildings and public spaces, characterized by its close proximity to living or working spaces. It can be directly seen or reached from indoors and does not require a planned visit. In this thesis, the concept is divided into three categories: ground-level greenery (such as small street planters, street trees and pocket parks), vertical greenery (such as green façades) and elevated vertical greenery (such as skyparks, planted balconies and green roofs) The vertical dimension and green space on buildings are essential in greening compact cities (Beatley, 2017). The current relationship between CUGS and human well-being and ecological resilience is very weak. Other aspects are prioritized, such as technical feasibility, aesthetics or marketing value (Langemeyer et al., 2020).

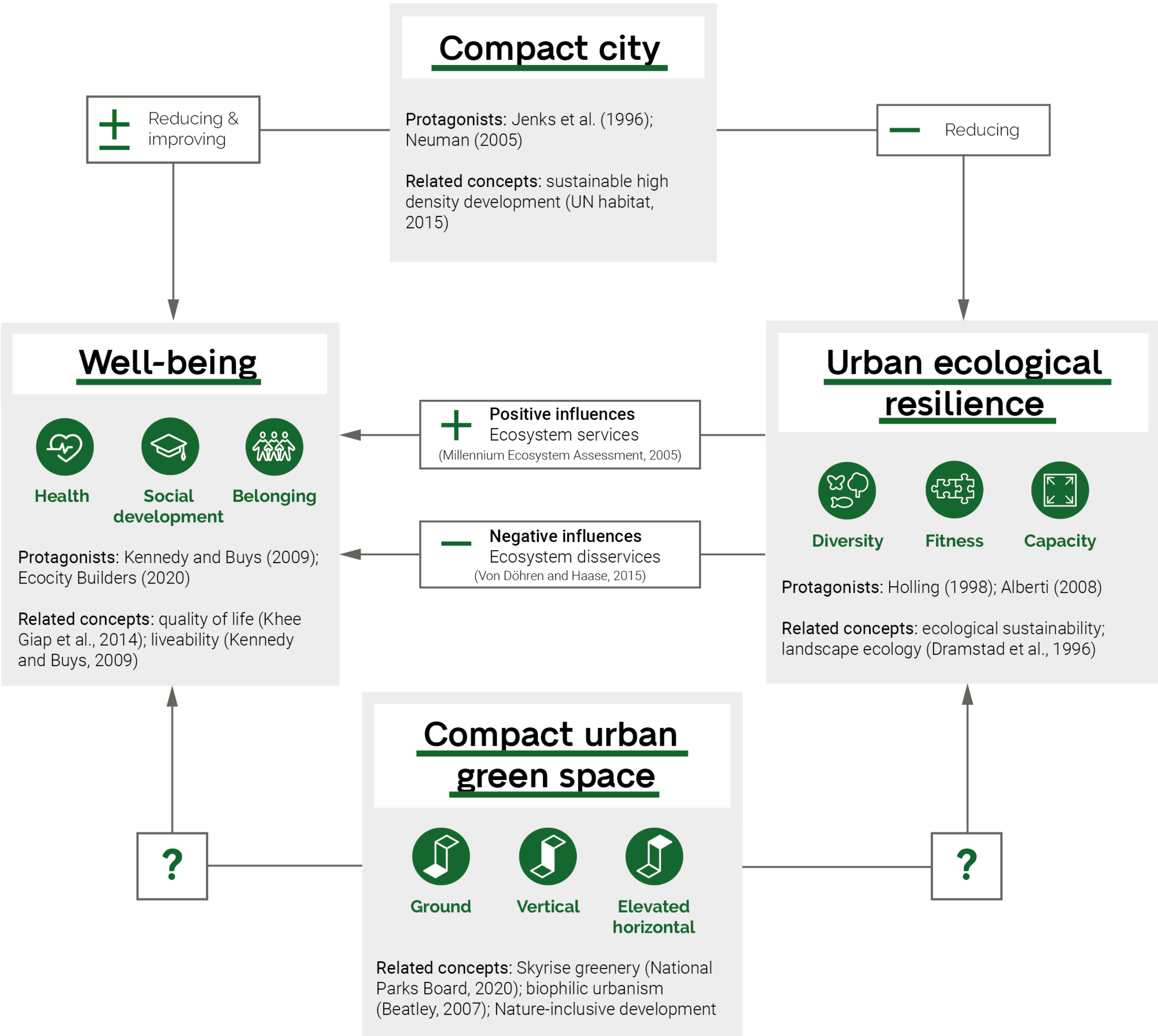


Fig. 12. The conceptual framework illustrates the relation between the concepts used in this research.

Research approach

The research approach is illustrated in Fig. 13. This section will elaborate on the methods and outcomes. As mentioned in the introduction, the main research question is:

"What framework can be used to guide the development of compact urban green space in Rotterdam that addresses both the quality, in terms of well-being and ecology, as well as the spatial-ecological structure?"

This question is divided into four sub research questions. Each question requires a different set of methods to reach the desired outcome. The advantages and limitations of methods used in this research are elaborated in Table 4 (page 36). For each sub question the methods and desired outcomes are discussed below. Sub research question 1 and 2 share the same methodology and are thus discussed together.

1. "How could compact urban green space improve ecological resilience in Rotterdam?"

2. "How could compact urban green space improve well-being in Rotterdam?"

These research questions are analytical and will provide knowledge on (1) the ecological context and opportunities of Rotterdam and (2) the well-being related challenges and opportunities. The question combines aspects that are theoretical and general and aspects that are local and site-specific. Literature research is used for the theoretical part. Both scientific peer-reviewed papers and professional literature are used.

Methods used for the context-specific analysis include mapping of ecological data and well-being challenges, a policy analysis of municipal documents and field visits. The questions are answered in the form of design principles and a spatial conclusion map depicting challenges and opportunities.

3. "Which compact urban green space patterns contribute to ecological resilience and well-being?"

This question is design-oriented and will be answered by an overview of possible compact urban green space patterns. Relations between patterns are explored with the use of a pattern approach. This approach, coined by Christopher Alexander (1977), orders complex phenomena by dividing them into comprehensible patterns at different scale levels. It also gives insight into the relations between those patterns. The result is a pattern language that does not only provide design guidelines, but also acts as a communication tool.

The patterns are based on the principles from the first two sub-research questions together with an analysis of reference cases. The theoretical framework is used to evaluate the typologies on ecological and well-being value. Additionally, a collaboration with the Ebben Tree Nursery allows for a rooftop experiment that tests the suitability of (a selection) of patterns. More information about the experiment and the preliminary results can be found in chapter 6. Methods used for the experiment include data collection (via sensors) and field observations.

4. "What spatial vision and strategy can be used to guide the development of the compact urban green space patterns in Rotterdam?"

This research question has both analytical and design oriented-elements. It ties the outcomes of the previous research questions together into one coherent spatial ecological vision for the city of Rotterdam. The vision is elaborated and tested with the use of a design experiment of the Wijnhaven Eiland in the same city.

Both the vision and the design experiment are used to test and develop the patterns further. The analytical part of this research question concerns the actor analysis, which will give more insight into the position and ambitions of

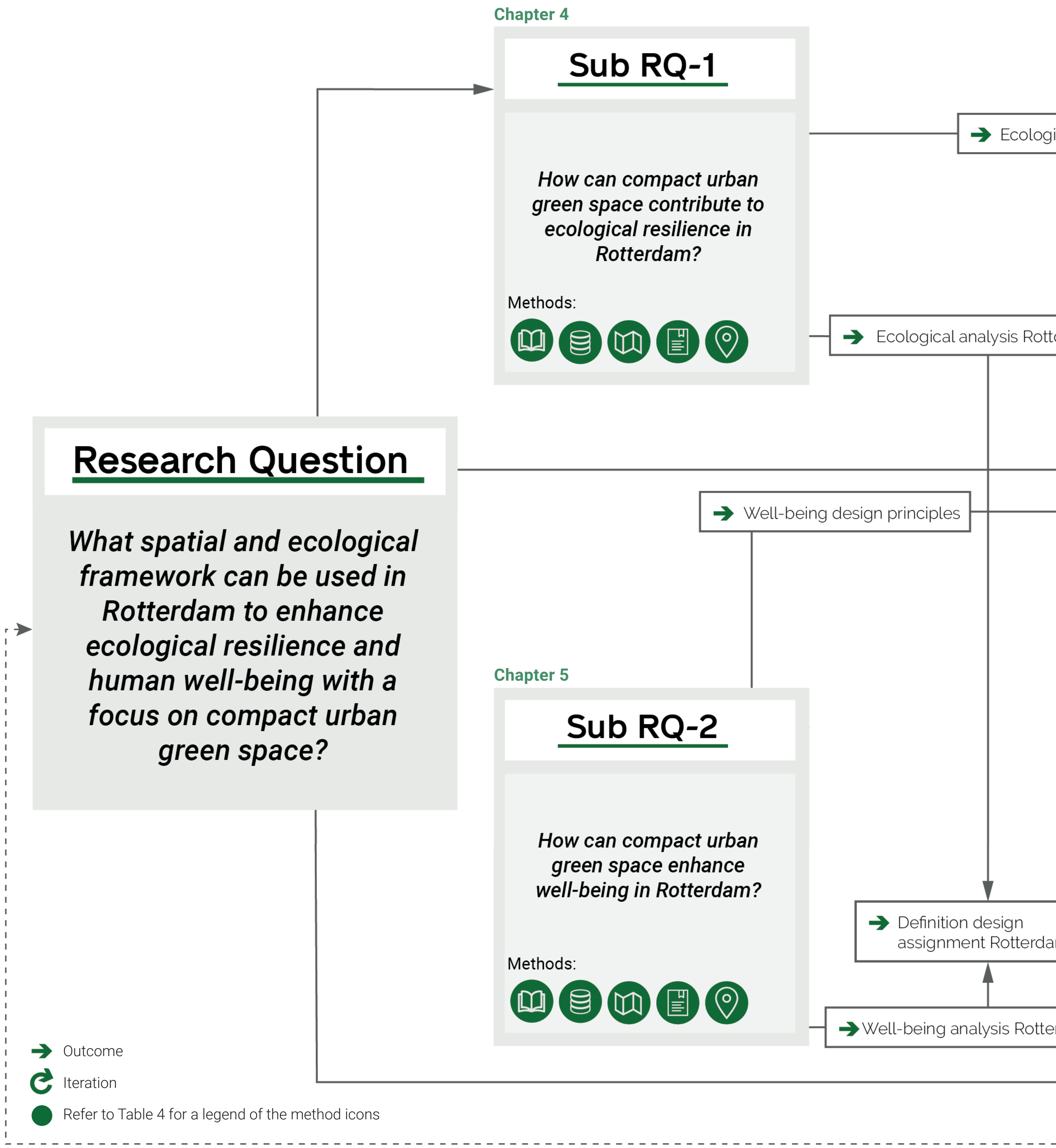
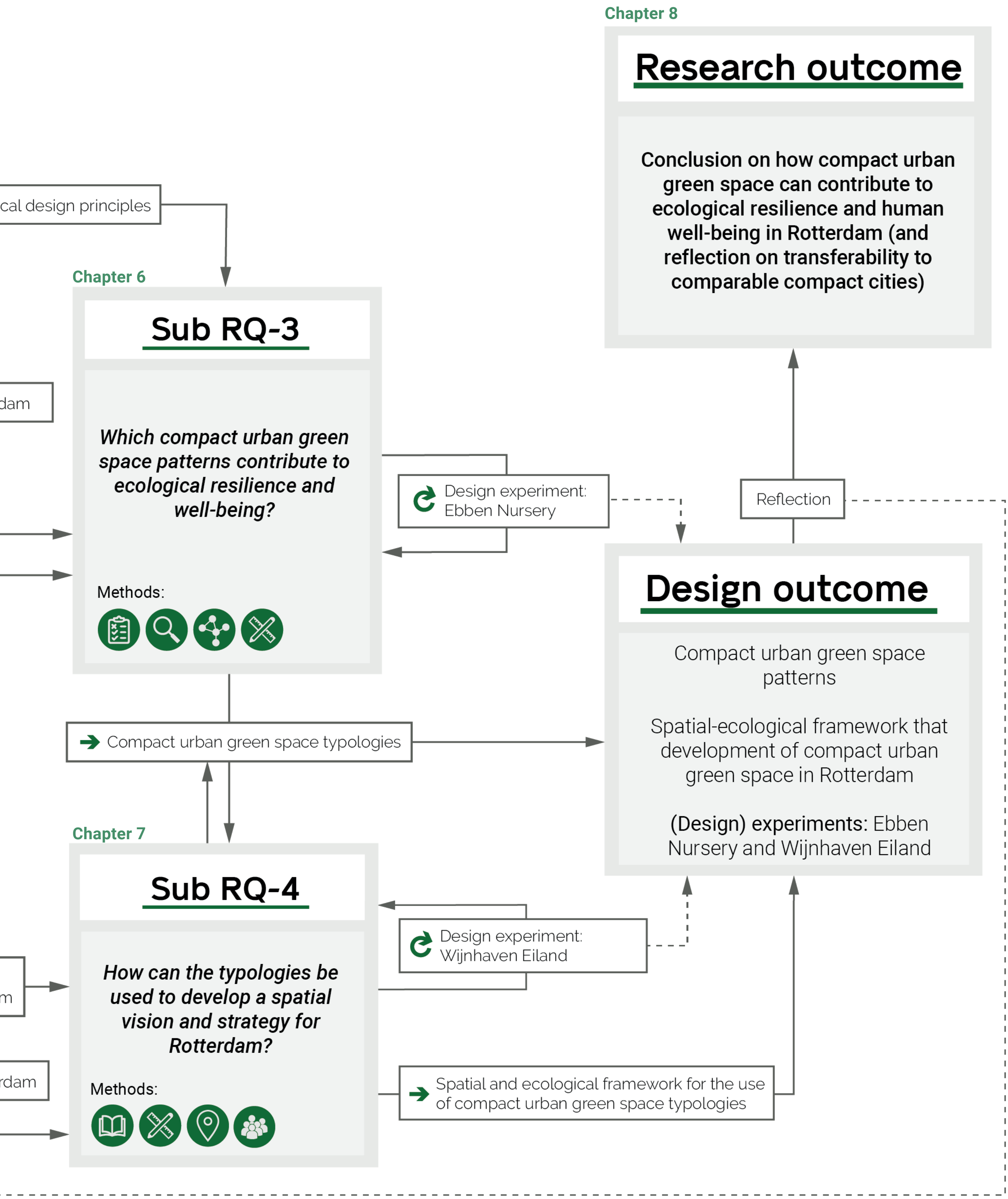


Fig. 13. The research framework shows the relation between the research questions, methods and outcomes.


Chapter 8
Research outcome
Conclusion on how compact urban green space can contribute to ecological resilience and human well-being in Rotterdam (and reflection on transferability to comparable compact cities)
cal design principles
Chapter 6
Sub RQ-3
dam
Which compact urban green space patterns contribute to ecological resilience and well-being?
Methods:
Design experiment: Ebben Nursery
Reflection
Design outcome
Compact urban green space patterns
Spatial-ecological framework that development of compact urban green space in Rotterdam
(Design) experiments: Ebben Nursery and Wijnhaven Eiland
Compact urban green space typologies
Chapter 7
Sub RQ-4
How can the typologies be used to develop a spatial vision and strategy for Rotterdam?
Methods:
m
rdam
Design experiment: Wijnhaven Eiland
Spatial and ecological framework for the use of compact urban green space typologies

Method	Advantages	Limitations
Mapping	Mapping of existing and future conditions and phenomena makes it possible to relate theories to spatial context and to reveal complex spatial patterns.	Mapping is subjective and provides an incomplete perspective on reality. This can be mitigated by combining maps of different scales (temporal and spatial) and themes.
Field visit	During a field visit existing structures and processes can be observed. It is a method that directly engages with the reality and allows for the discovery of phenomena that are not well-documented in literature or other media.	Field visits might provide a superficial and incomplete image. Not all phenomena are noticeable during one field visit and it remains a snapshot of a complex and dynamic reality. This can be mitigated by proper preparation and performing multiple field visits.
Policy analysis	This method gives an perspective of existing ambitions and opinions of policy makers on a certain topic. With this knowledge the research can be linked to topics that are currently relevant.	While created by democratically chosen parties, policy documents may be biased and do not reflect opinions of all people on a certain matter.
Literature research	Literature is easily available and covers a wide variety of topics. It is therefore an effective way to obtain information. Using scientific literature has the additional advantage of being peer-reviewed.	Not all knowledge is documented in literature. Using merely this method for the acquiring knowledge will result in an incomplete picture. Information in literature can also conflict. A critical attitude is required to review literature on its reliability.
Test by design	Testing theoretical principles in a spatial context gives insight in the relevance of these theories. Furthermore, a design can provide a new perspective on a theory.	Since designing is a complex skill, this value of this method also relates to the competence of the designer. Furthermore, spatial design is context specific. Hence, this method can only reveal if a theory is relevant for the tested place.
Design evaluation	Evaluation of a certain design on a specific theory tells something about the performance of that design.	In order to evaluate, an evaluation framework is required. The quality of the evaluation directly relates to the quality of this framework. Depending on the assessment criteria the evaluation might be subjective. This can be mitigated by the use of clear and measurable criteria. However, this is not always possible.
Typology study	A typology study (pattern language approach in this case) orders complex phenomena into comprehensible pieces. It also gives insight in the relations between those pieces.	Classifying real world situations into typologies requires some simplification. This can lead to over-simplified problems, or generic solutions that are not applicable to real world cases.
Reference case analysis	Examining other cases where similar challenges were solved with design interventions serves as inspiration and gives insight in which interventions work and which do not.	Not all designs are transferable to other locations. Care should be taken to not ignore contextual influences such as culture and climate.
Data collection and analysis	Collection and analysis of large amounts of data reveals patterns and relationships would otherwise be hard (or impossible) to find.	The quality of data (source, accuracy, actuality) influences the value of this method. Furthermore, data always represents a selection of reality (mainly the quantitative part), which can give an incomplete image.
Actor analysis	An actor analysis shows the position of involved actors. Furthermore, it reveals the existing power structure and gives insight in who should be addressed to foster change. Information can be obtained by talking to actors individually or by acquiring their positions and opinions from representative organisations.	Many actors are involved in projects that take place in the urban environment. Care should be taken to provide a balanced and inclusive overview of actors. Especially actors that are vulnerable and less pronounced might be overlooked.

Table 4. Methods used in this research and their advantages and limitations.

different actors.

Finally, all the outcomes will be combined to form a conclusion that answers the main research question. A reflection on the outcomes goes into the transferability of the results for other compact cities.

Limitations

As shown in Table 4, each method has its own limitations. To mitigate these limitations, multiple different methods should be combined. However, this is not always possible as some data or information is only accessible to obtain with the use of one specific method. In these cases, care should be taken to critically assess whether available information represents the larger phenomenon.

The field of urban ecology is relatively young and many urban ecological processes cannot be explained by humans. Moreover, humans will likely never completely understand all the natural processes that happen around them, and thus can never completely design these processes in a way they would happen in 'true nature'.

Additionally, well-being is not an objective term. This will make it difficult to make claims on well-being that will be acknowledged by all. Nevertheless, there are still many aspects on which there is consensus in the scientific community. For instance, well-being related to physical health is much more objective than well-being related to social belonging.

Finally, the outcomes and quality of this research are also subject to time constraints. Hence, sometimes practical choices will have to be made such as narrowing down definitions to make sure the project is feasible to complete within a year.

Conclusion

There is a knowledge gap on how compact urban green space can contribute to ecological value and human well-being. This research addresses that knowledge gap with the use of a case study in Rotterdam. The concepts of ecological resilience, compact city, well-being and compact urban green space play a major role in the understanding of this complex challenge. Since some of these concepts, mainly ecological resilience and well-being, are complex and partly subjective, the research outcome should not dictate one single answer. Rather, the result should be a spatial ecological framework that guides development and actions of actors (both human and nature) in a direction that improves the quality of life in the compact city for all.

The use of different methods during this research (triangulation) mitigates biases and increases the validity of the outcomes. Nevertheless, results should always be subjected to a critical review. This is done by constantly evaluating and testing the results. Furthermore, as the performance of a design is highly context-specific, the case study in Rotterdam allows it to be tested in a spatial context. To increase the societal and scientific relevance of the outcomes, these results are used to form transferable design conclusions on how compact urban green space can contribute to well-being and ecological resilience in other compact cities. With this knowledge, human well-being and the ecological value of compact cities can be improved.

Image courtesy of author

04

Ecological analysis

This chapter addresses the first sub research question of *"How can compact urban green space contribute to ecological resilience in Rotterdam?"*. To answer this question, a spatial-ecological analysis of Rotterdam is performed, as well as a literature study on urban ecology in the Dutch context. The combination of these methods of inquiry results in a set of design principles for compact urban green space tailored to the Rotterdam context.

Urban ecology and design

An ecological system can be divided into two aspects: the abiotic and biotic part. In the city, the abiotic part of the ecosystem is formed by the urban structures and the urban climate on the small scale, and the regional climatic conditions on the large scale. Nutrients (such as nitrogen oxides in the air) are also part of the abiotic component of urban ecosystems. The biotic component is made up of all living species, from bacteria, mosses, plants and algae to birds, fish and mammals. Both parts react to each other: a certain set of environmental variables (abiotic) creates the right growing conditions for vegetation, but vegetation growth (biotic) can also influence the urban climate, e.g. by cooling it.

A spatial design can both influence biotic and abiotic conditions. The abiotic system is often a result of the spatial structure and the resulting micro-climate, while the influence on the biotic system is generally limited to the vegetation that is planted.

Biotopes

The city of Rotterdam has an ecologically interesting location as it is situated at the end of the Rhine Muise river delta. This results in a variety of alternating landscape types that interact with each other and form many habitats for species. Both terrestrial and aquatic biotopes will be discussed in this ecological analysis. While terrestrial biotopes are the most relevant for green space on built structures, the combination of aquatic and terrestrial biotopes is what makes the natural system in and around Rotterdam unique.

While some of the biotopes might look natural, all are heavily influenced by human management. Fig. 14 shows the spatial distribution of the six biotopes around Rotterdam. The biotopes are discussed on the next page.

Fig. 14. Terrestrial landscape biotopes around Rotterdam

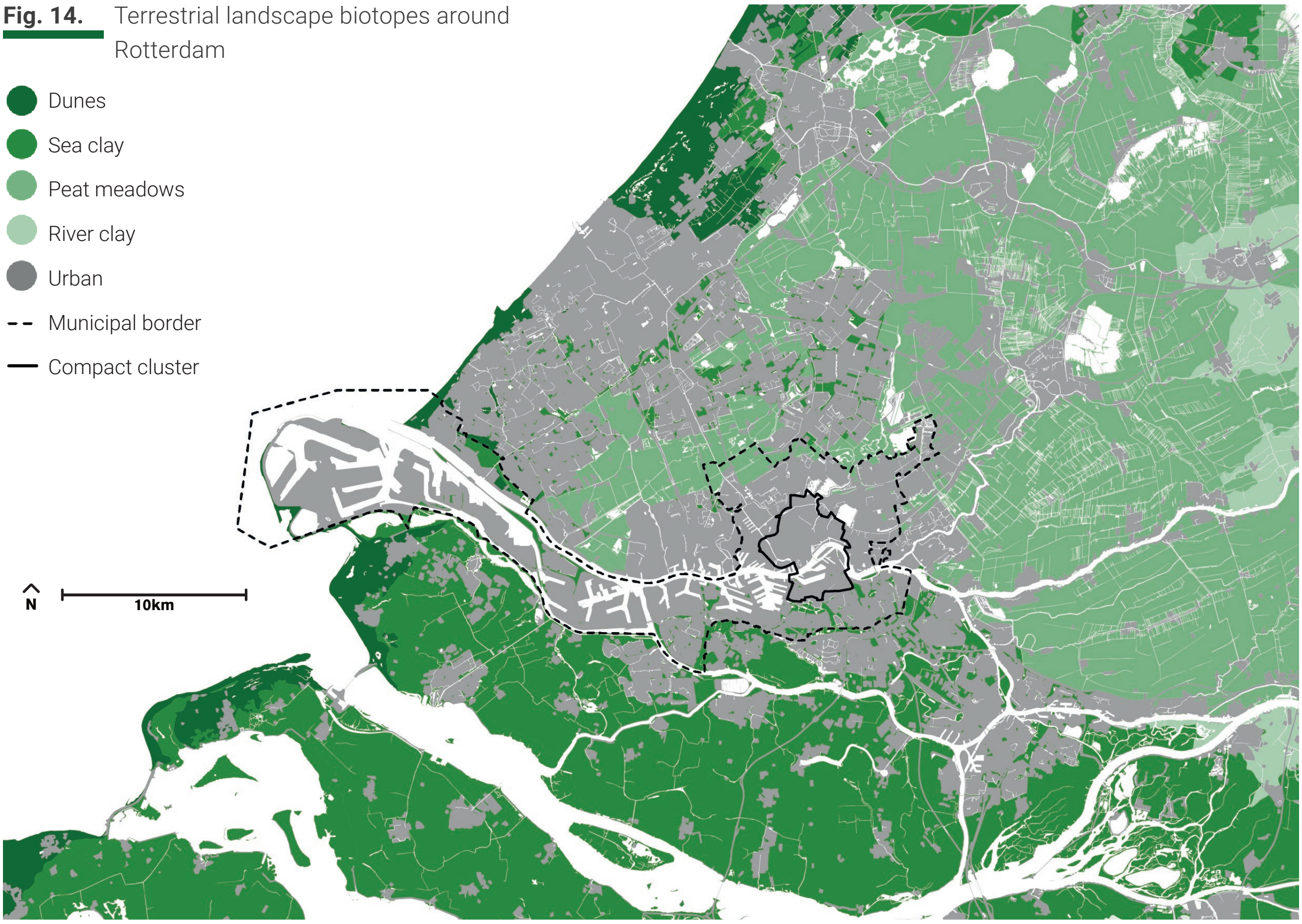
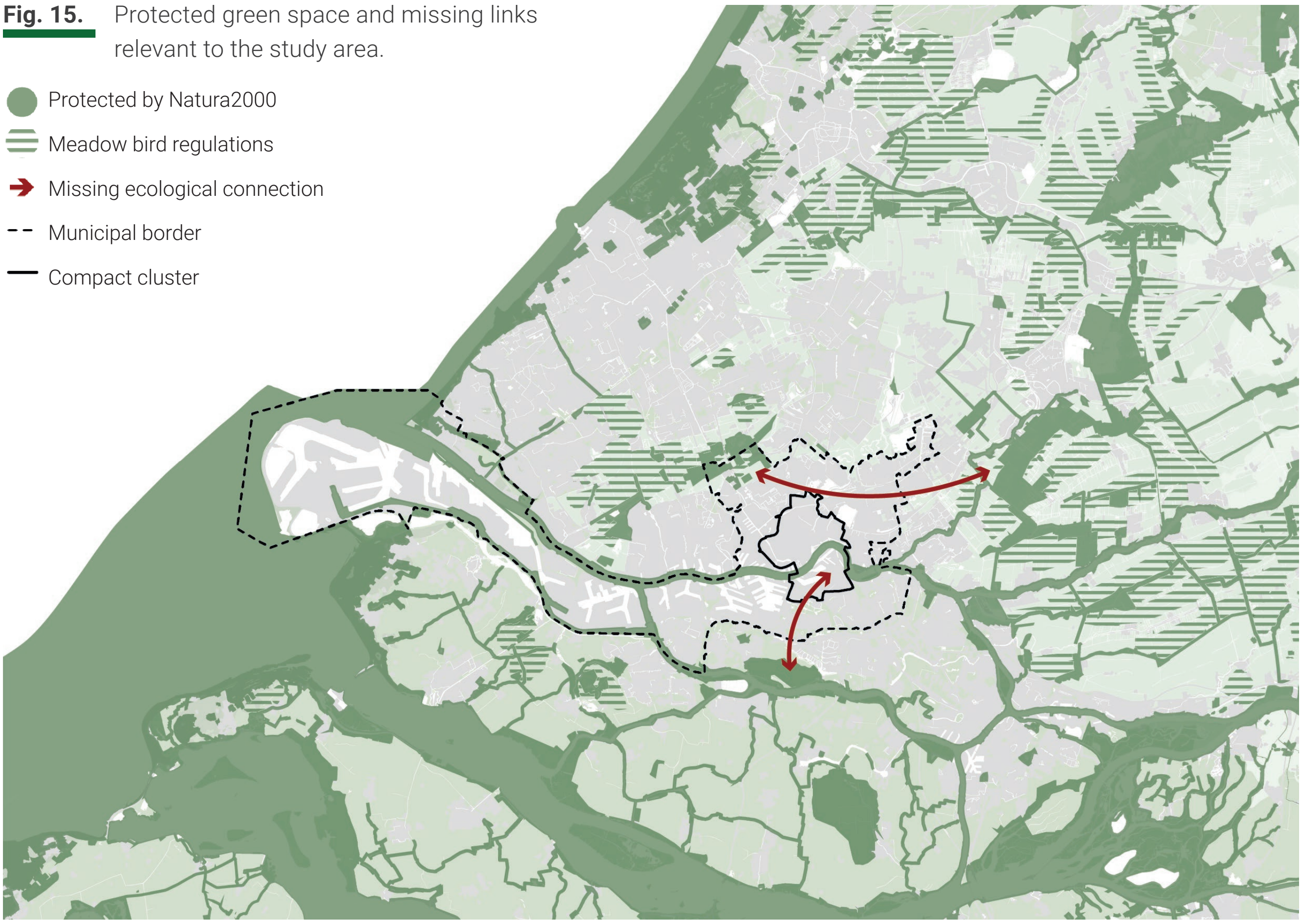
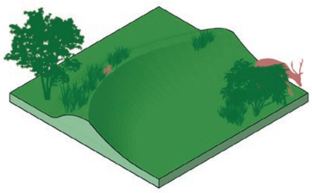


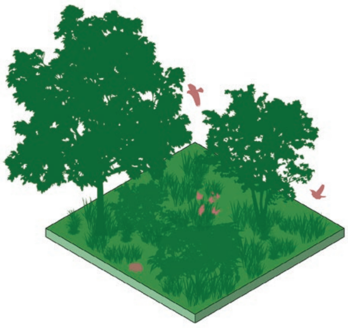
Fig. 15. Protected green space and missing links relevant to the study area.





Sandy dunes

This biotope separates the sea from the land and is characterized by dunes that are formed as a result of fine sand deposition by the wind. Dynamics of the sea and the wind continuously change the appearance of the landscape and form new habitats. The relatively high degree of protected areas of this biotope can be attributed to its role in coastal defence. Species that thrive here have adapted to events of droughts, occasional salt floods and strong winds with sand.

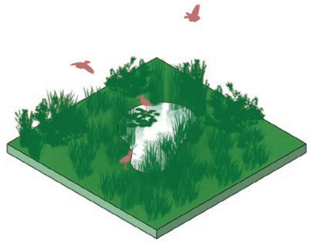


Sea clay polders

The sea clay landscape as we know it today are the remains of a dynamic lake and creek system once influenced by the sea. Land reclamation practices have transformed the lakes into fertile clay ground below sea level. In open areas, similar meadow birds are found as in the peat meadows, such as the Lapwing (*Vanellus vanellus*) and the Black-tailed godwit (*Limosa limosa*). Intensive agriculture in this biotope has led to a decline in bird species (Schaminee et al., 2010).

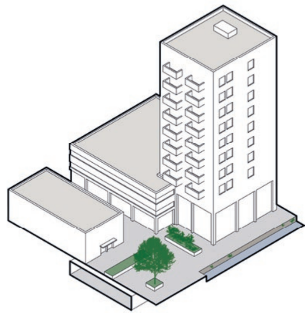
River clay floodplains

Green space in the floodplains is subjected to a strict maintenance regime, as its play an essential role in maintaining water safety. This results in landscapes that are deliberately kept open, allowing them to quickly absorb excessive river discharge. The protected areas are characterised by a occasional Blackthorn (*Prunus spinosa*) and Hawthorn (*Crataegus spp.*). Areas not subjected to mowing or grazing change into riparian forests (Schaminee et al., 2010).



Peat meadows

Characterised by its flatness, this biotope consists of open grasslands and fresh water lakes and ditches. The unprotected areas are heavily managed for agricultural purposes. This resulted in the disappearance of bog peat and subsidence of the land. Most of this biotope is located below sea level. The protected areas attract many (semi) aquatic bird species, such as the Tundra swan (*Cygnus columbianus bewickii*), and the Widgeon (Mareca penelope).



Urban fabric

The urban biotope is the most novel biotope. It has environmental characteristics similar to relatively warm and stony biotopes. This is why many species originating from mountainous biotopes do well in cities, such as the Rock pigeon (*Columba livia domestica*) and the Common swift (*Apus apus*). As the defined study area falls completely within the urban biotope, this biotope will be further explored in the next section.

The urban biotope

Cities are probably the least associated with nature. Yet, the urban fabric offers many habitats for a wide variety of species, from plants to fungi and animals (Vink, Vollaard and de Zwarte, 2017).

Species that thrive in the urban environment have either been introduced by humans or have naturally dispersed themselves into cities. Fig. 18 shows that the lack of green in many compact cities cannot completely be attributed to the harsh growing conditions. In fact, many plant communities thrive in the warm and stony urban environment. These species, which were generally not planted by humans but a result of spontaneous growth, have evolved to fit in environmental conditions that are found in cities and thus are extremely resilient. Though often considered undesired, these “weeds”, form an important part of the urban biotope.

Lithophytes (plants that grow naturally on stony surfaces and rocks) dominate in dense urban environments. They disperse via small seeds (or even smaller spores), that easily adhere to small cracks in rocks. Hence, wall texture is the first variable that influences the potential vegetation. Besides wall texture, moisture and nutrients are important too. Moist environments, located at the base of walls and in joints between pavements provide suitable growing conditions for ferns and shrubs (Chen et al., 2020).

Most spontaneous urban vegetation consists of pioneer species. Intensive management of urban structures and green spaces hampers natural development towards more stable climax vegetation structures. Unfortunately, there is still little research on the possibilities of climax vegetation in urban environments. Climax communities found in natural environments with similar growing conditions, such as the Alps in Fig. 16 or the Zhangjiajie mountains in Fig. 17, may show us what the true potential of spontaneous urban vegetation can be.

Fig. 16. Tree growth in the Alps illustrates that harsh stony growing conditions do not necessarily prohibit plant growth, as certain species have evolved to overcome those challenges.

Fig. 17. The landscape of Zhangjiajie has, besides wetter summers, a comparable climate to Rotterdam and thus shows us how climax urban vegetation in Rotterdam might look like.

The lack of green in many compact cities cannot completely be attributed to the harsh growing conditions. In fact, many vegetation communities thrive in the warm and stony urban environment.

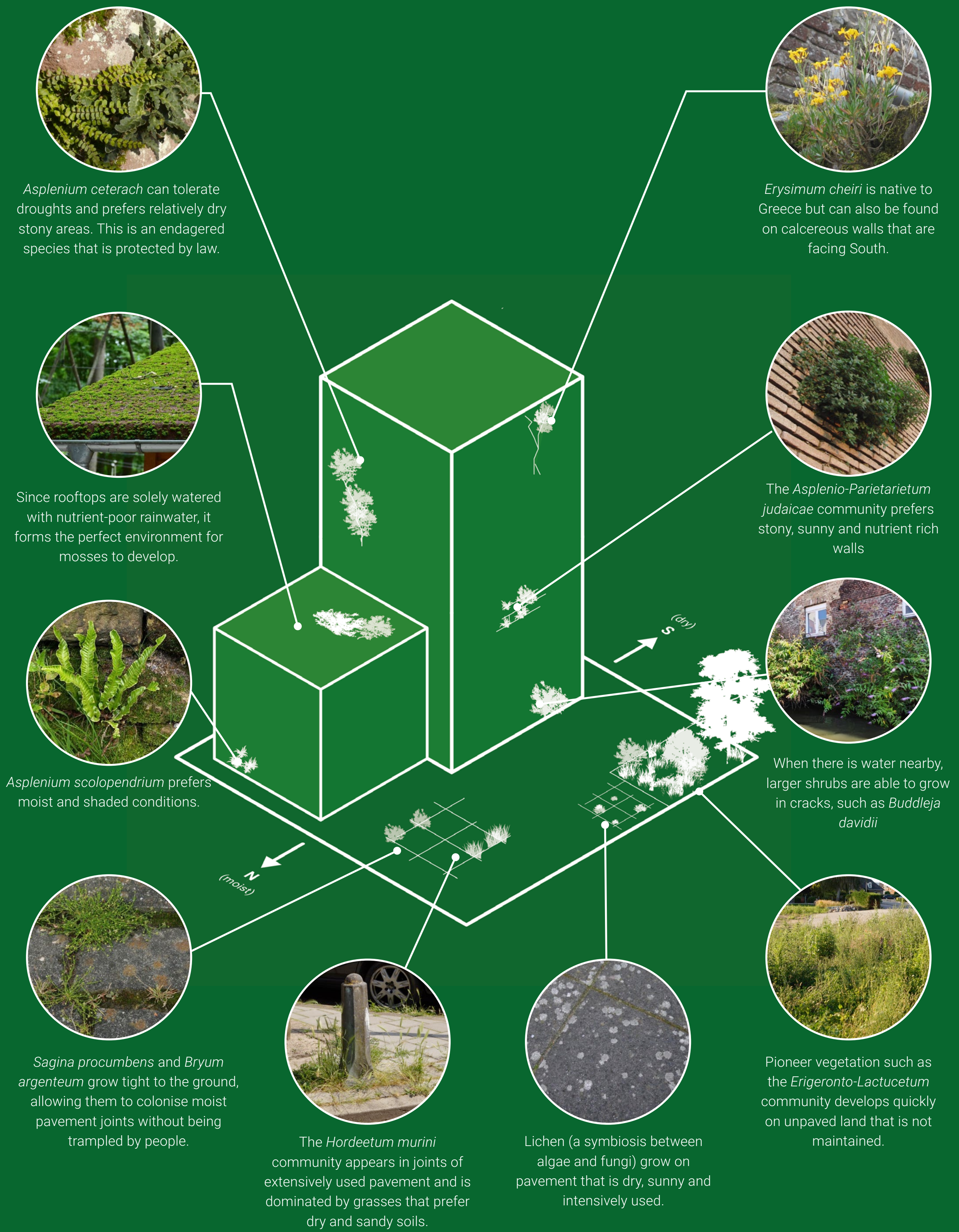


Fig. 18. What grows where? Images by Floravannederland.nl

Urban habitats

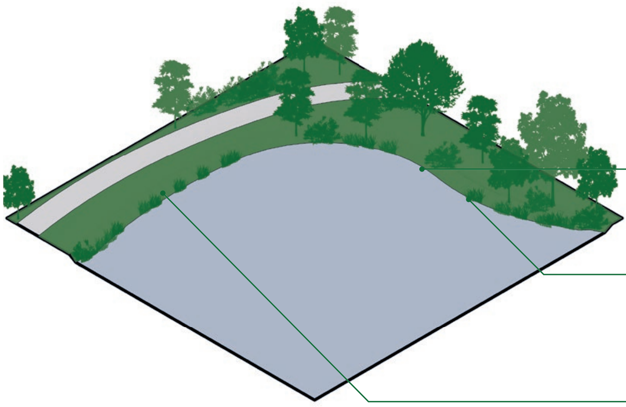
The variety of forms and structures in the urban environment result in different habitats that each attract different species.

Blue habitats

The aquatic and semi-aquatic habitats in Rotterdam can be divided into three main types: large water bodies, water ways that make up the water network, and the tidal River Maas. The habitats are illustrated below, and located on the map of Rotterdam in Fig. 19. Especially the tidal River Maas is of international importance when it comes to biodiversity conservation.

Large water bodies

Large water bodies close to green space are not common in the compact cluster in Rotterdam. The Kralingse Plas (North east of the cluster), some water bodies in Het Park and around the Blijdorp area fall into this type. Waterbodies that have green space nearby attract many species, and are most valuable when there is a gradual transition from water to land.



A gradual transition between water and land encourages the growth of aquatic plants.

The **Mute swan** (*Cygnus olor*) likes to nest in quiet places on land next to large water bodies, such as islands.

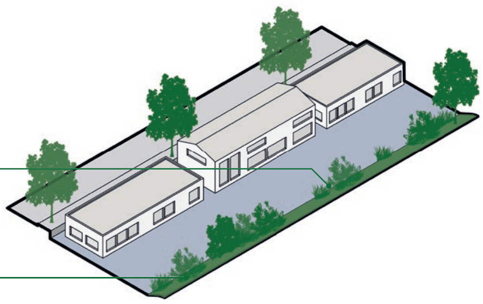
The **Great Crested Grebe** (*Podiceps cristatus*) prefers to build a nest far from the shore, and thus needs large water bodies.

Water network

A few main water structures cross the compact cluster, such as the Schie Canal and the historic river Rotte. The Singels in Rotterdam are also part of this network.

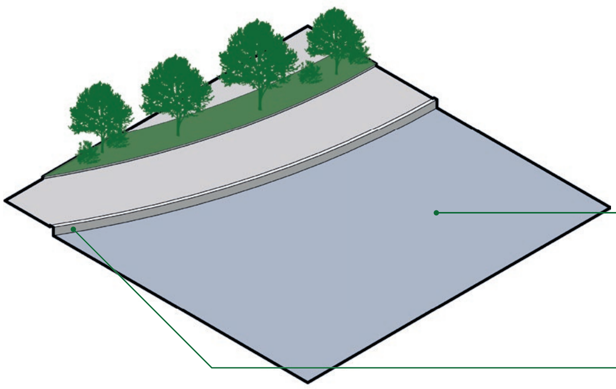
The **Eurasian Reed Warbler** (*Acrocephalus scirpaceus*) prefers reed domiated habitats.

The **Wild duck** (*Anas platyrhynchos*) nests in banks vegetated with aquatic plants.



Tidal river

The most notable water structure in the city is the brackish River Maas. The water level of this river fluctuates 150cm twice a day as a result of tidal influences. The river is part of the European Natura2000 network.



The **European eel** (*Anguilla anguilla*) uses the tidal river as a connection between sea and fresh water where they grow up.

Epifytic ferns, such as **Asplenium** (*Asplenium spp.)* grow in the cracks of old moist quay walls.

Fig. 19. Aquatic and semi-aquatic habitats in Rotterdam

Green habitats

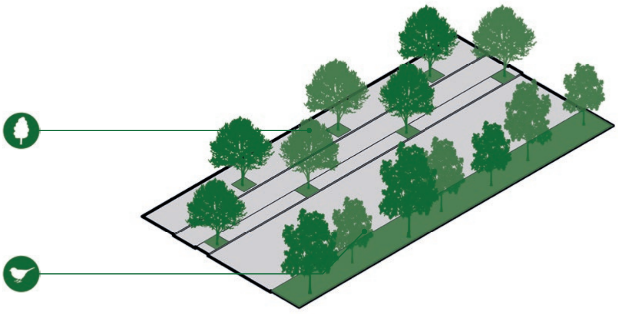
Vegetation in the city creates habitats on land. Fig. 20 shows vegetation structures in Rotterdam, divided into free-standing trees, shrubs and grass. The illustrations below discuss three elements of the primary green structure of Rotterdam.

Tree-lined streets

Streets lined with trees from an important aspect of the ecological network of Rotterdam. Tree lined-streets consists mostly of a single tree species, which has resulted into the spread of tree diseases in the past (Gemeente Rotterdam, 2009).

Because of its tolerance against paved surfaces, **Plane trees** (*Platanus spp.)* are often planted along streets. The tree is exotic and provides little value for insects and other species.

Large old trees attract birds like, the **Short-toed Treecreeper** (*Certhia brachydactyla)* and the **Common Chiffchaff** (*Phylloscopus collybita*)



Parks

Parks, but also forested graveyards, sport parks and allotment gardens, are generally biodiversity hot spots. Trees in these areas are allowed to fully mature, increasing their ecological value. Parks located on the fringes of cities attract more species than parks surrounded by urban structures.

The **Tawny Owl** (*Strix aluco)* nest in old and hollow trees. Young trees and shrubs attract birds like the **Garden Warbler** (*Sylvia borin*) and the endangered **Icterine Warbler** (*Hippolais icterina*).

The **Gray Heron** (*Ardea cinerea*) needs tall trees close to water to breed.

Dry and diverse ribbon

Road and rail networks are constructed on raised construction sand, which creates a specific habitat for species that prefer a dry and sunny environment.

Large trees that bear fruits, such as **Hazel** (*Corylus spp.*), **Common beech** (*Fagus sylvatica*) and **Chestnut** (*Castanea spp.*), attract the **Red squirrel** (*Sciurus vulgaris*).

The **European hedgehog** (*Erinaceus europaeus*) uses continues shrubs to migrate between habitats.

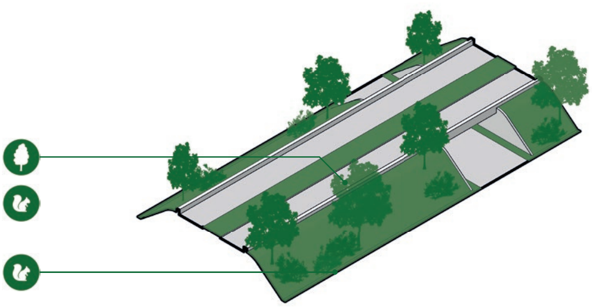
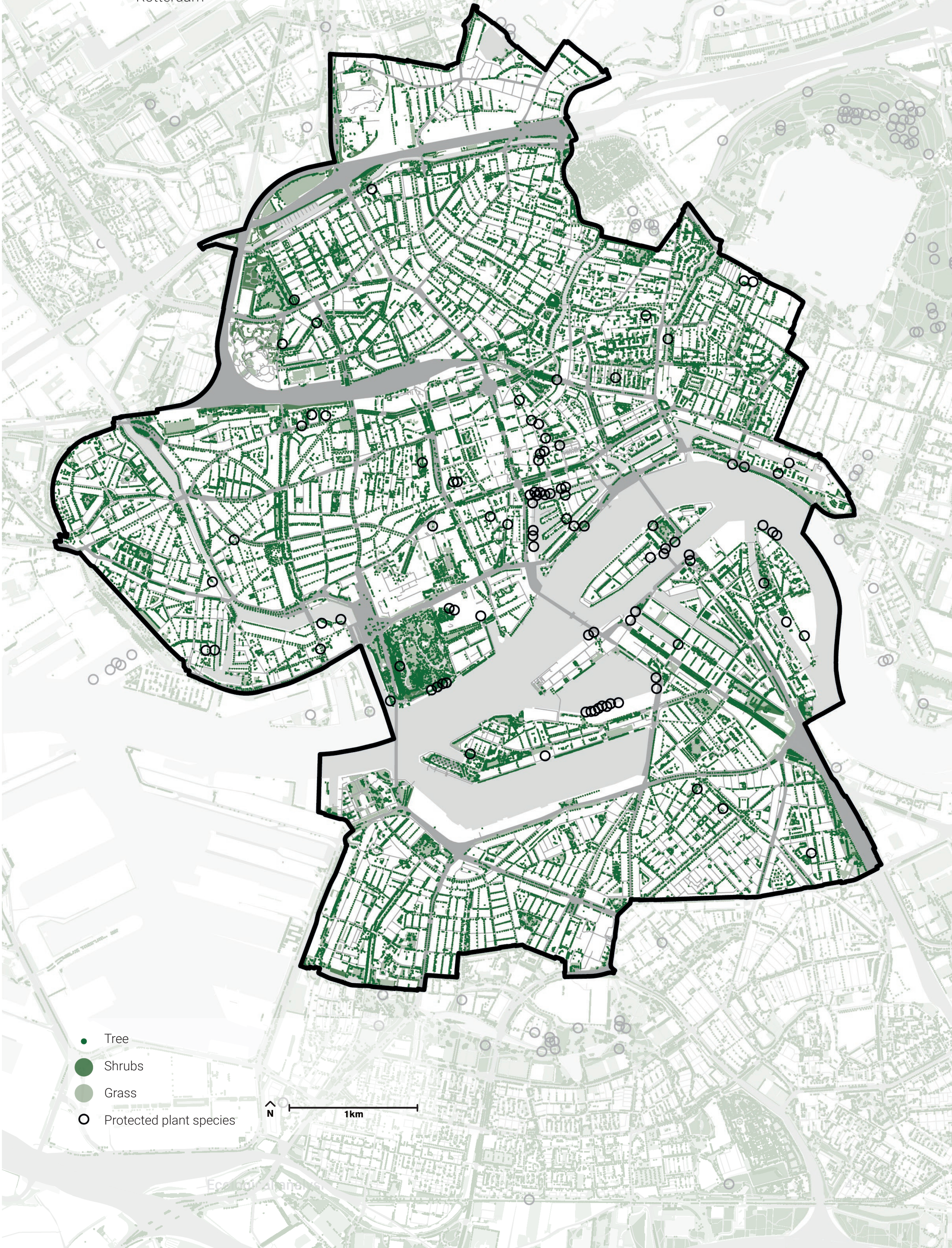
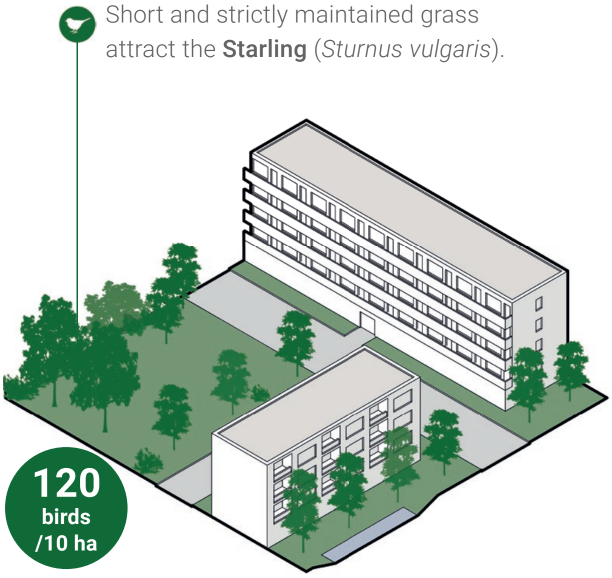


Fig. 20. Green habitats and vegetation structures in Rotterdam



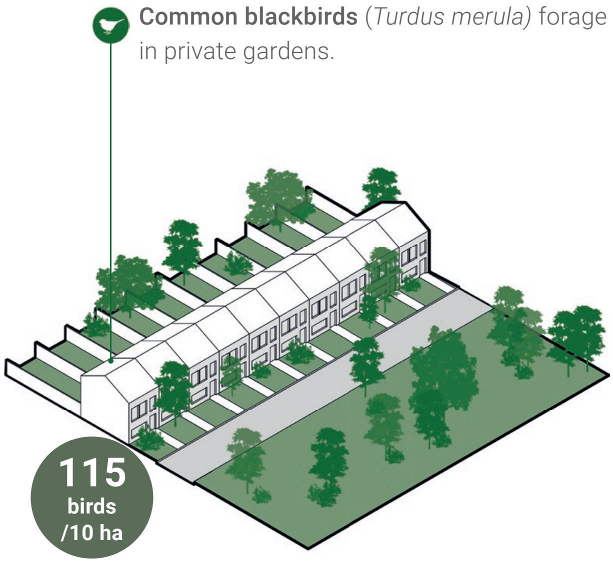
Gray habitats

Built structures in the city itself also create habitats for species. The urban form of a neighbourhood largely influences the biodiversity and type of species that occur area (Kooijmans, 2009). In the compact cluster of Rotterdam four main neighbourhood types can be distinguished, modernistic apartments, garden village, historic row houses and renewed centre. The types are shown on the map in Fig. 21 and illustrated below.



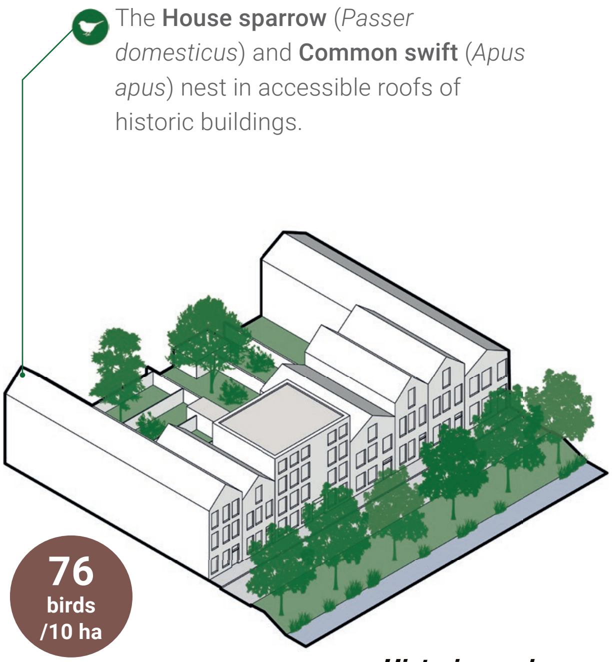
Modernistic apartments

Road and rail networks are constructed on raised construction sand, which creates a specific habitat for species that prefer a dry and sunny environment.



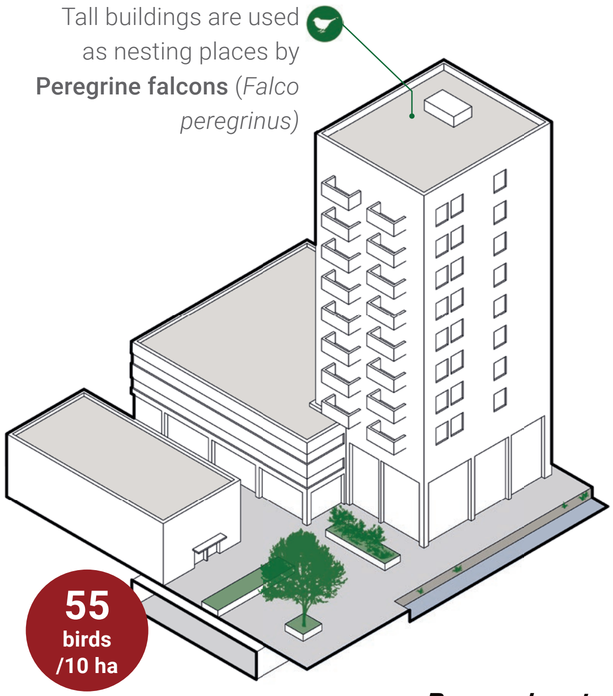
Garden village

Road and rail networks are constructed on raised construction sand, which creates a specific habitat for species that prefer a dry and sunny environment.



Historic row houses

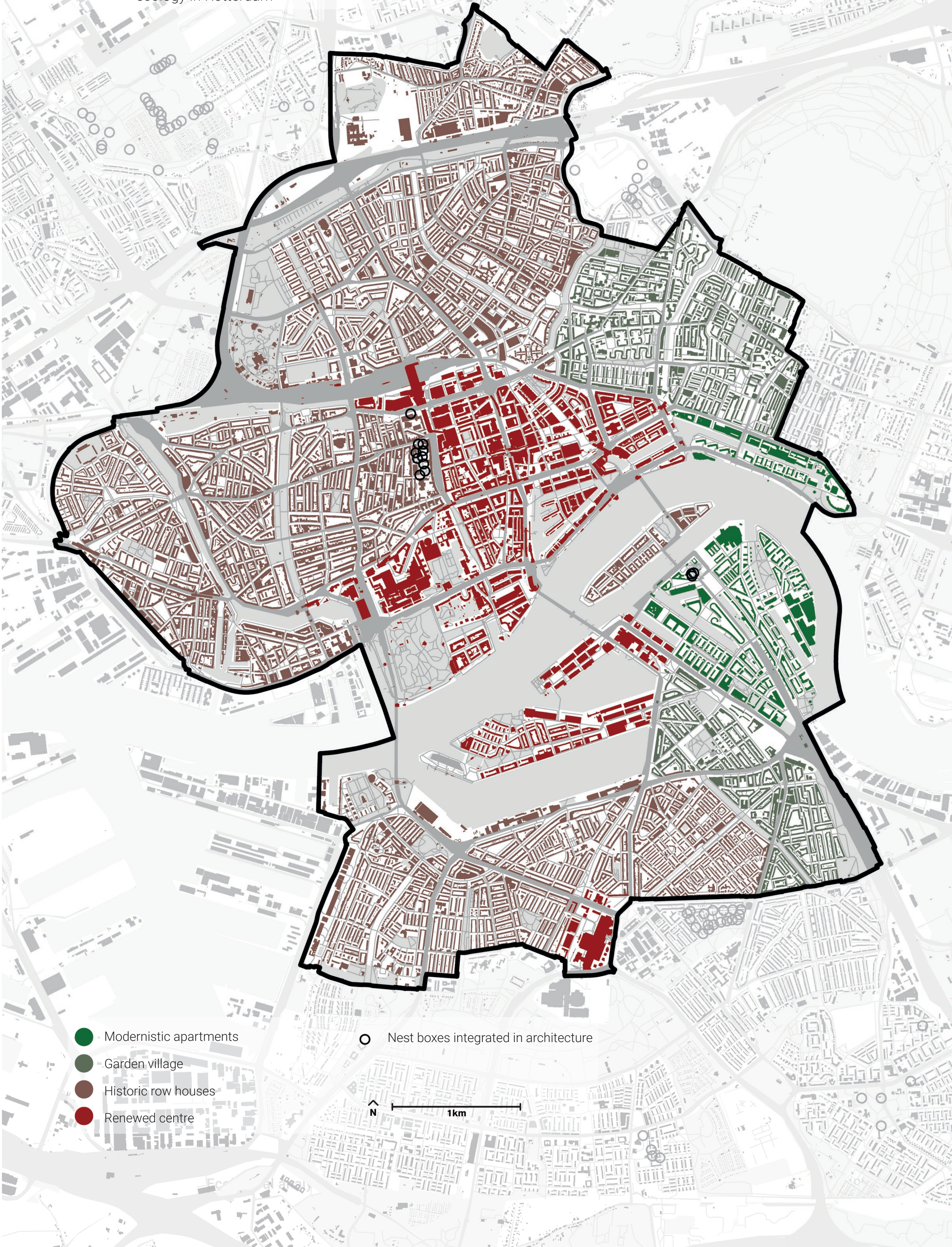
Road and rail networks are constructed on raised construction sand, which creates a specific habitat for species that prefer a dry and sunny environment.



Renewed centre

Road and rail networks are constructed on raised construction sand, which creates a specific habitat for species that prefer a dry and sunny environment.

Fig. 21. Neighbourhood typologies relevant for urban ecology in Rotterdam



Conclusion

Rotterdam is situated in a river delta, a diverse location where multiple biotopes interlace. Given its distinctive environmental characteristics, the urban environment can be considered as a separate biotope on itself. This biotope has environmental characteristics that differ from the biotopes around it and thus attracts additional and different species. The urban biotope is hotter, has more relief and consists of much more stony materials when compared to its environment.

To answer the sub research question of "How can compact urban green space contribute to ecological resilience in Rotterdam?", the current ecological system of the city and its surrounding landscape should be understood.

Compact urban green space can increase ecological resilience in Rotterdam by increasing the carrying capacity, biodiversity and fitness of the current ecological system

Currently, the city acts as a barrier that curbs species interaction of the surrounding biotopes. North of the river Maas, an East-West connection is missing that connects the peat meadows. South of the river, a missing North-South connection results in fragmented clay landscapes. Also within the city the high biodiversity zones are highly fragmented, which can be seen in Fig. 22. CUGS could create corridors that facilitate species movement between those high biodiversity zones and between different biotopes outside the city. To create the carrying capacity of the system even further, CUGS could add new habitats in the city by using a reverse greenification approach: green surface area is the standard, and sealed surfaces are only used when absolutely necessary.

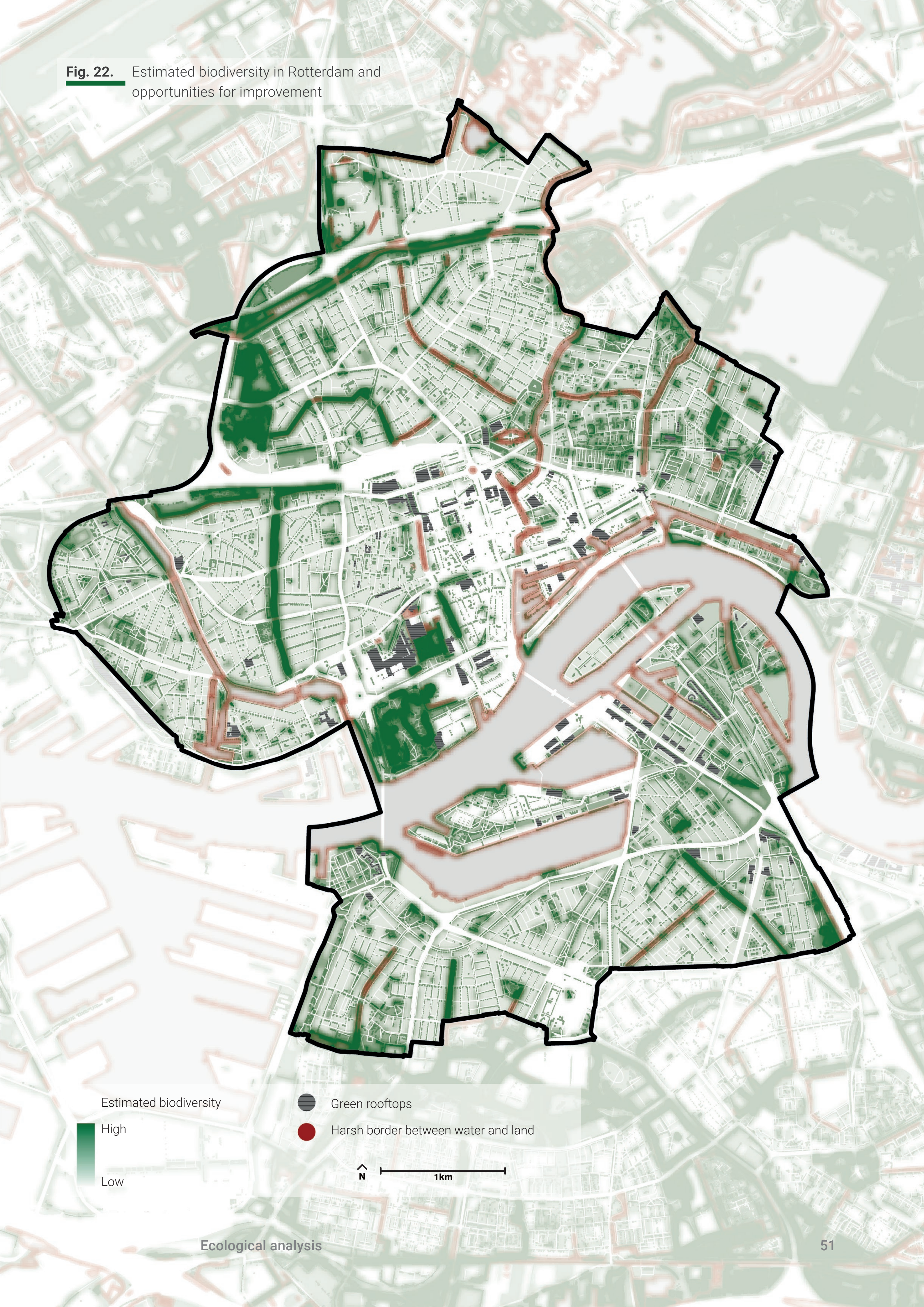
Biodiversity also increases ecological resilience and thus should CUGS attract a variety of species at locations that currently are low in biodiversity. The map in Fig. 22 combines the different habitat maps and shows the estimated biodiversity in Rotterdam. High biodiversity is predicated in green space directly next to water bodies and large clusters of diversely vegetated planters (bosplantsoen). Open grass fields, infrastructure and the urban centre neighbourhood on the other hand are estimated to be low in biodiversity.

Approaches to increase biodiversity can be linked to the existing spatial (green) structure. The diversity of urban form across neighbourhoods in Rotterdam forms a good starting point to achieve different urban habitats that attract a variety of species. For instance, the many river banks and harbour docks in the city offer an opportunity to attract species of the river and clay landscape biotope, while the open grass fields of the Modernistic garden villages offer opportunities to provide habitats for species found in peat meadows. Biodiversity also increases with habitat size, which stresses the importance to connect small patches of CUGS into larger areas.

The last aspect discussed in this thesis of ecological resilience is fitness. CUGS contributes to this aspect by being inviting to two groups of species. Firstly, native species that are already present in the surrounding biotopes should feel encouraged to visit the city. This can be achieved by designing the greenery of CUGS in such a way that it is similar to the greenery found in the biotopes outside the city. Second, new (non-native) species that are attracted by the environmental conditions of the urban biotope should be welcomed too. Because we do not know how this new urban biotope will develop itself, not all green features of CUGS can be designed. Specific areas of CUGS can be allocated where human intervention is limited and where natural processes are allowed to naturally develop a resilient new urban biotope.

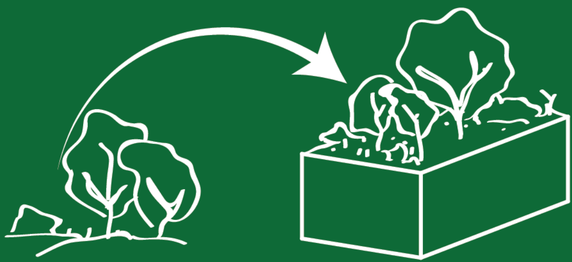
Based on this conclusion, design principles have been developed to increase ecological resilience in Rotterdam, illustrated in Fig. 23 (page 52). These principles are combined with the principles to increase well-being (see next chapter) and form the basis of the development of the compact urban green space patterns in chapter 5.

Fig. 22. Estimated biodiversity in Rotterdam and opportunities for improvement

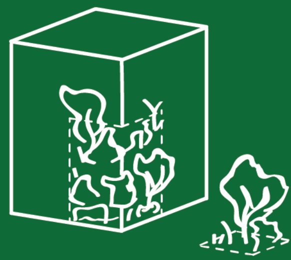


Design principles to increase ecological resilience in Rotter

Fitness

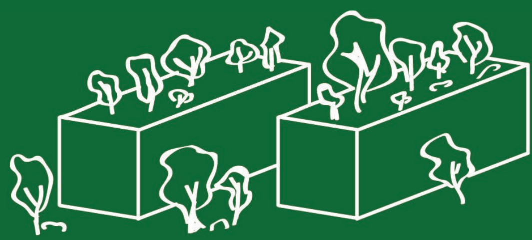


Replicate natural biotopes (peat, dunes, clay, river) in CUGS, but recognize the new urban biotope as a habitat too.



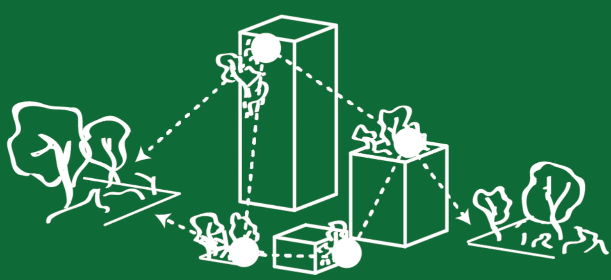
Do not design complete ecosystems but design conditions for natural processes and allocate areas where human intervention is limited.

Biodiversity

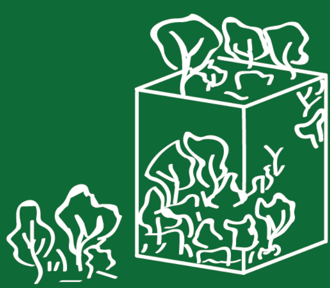


Use the diversity of the urban form to create different urban habitats. Habitat types (related to biotopes) are linked to neighbourhoods.

Carrying capacity



CUGS forms stepping stones in an ecological network that connects large urban green areas and protected nature outside the city

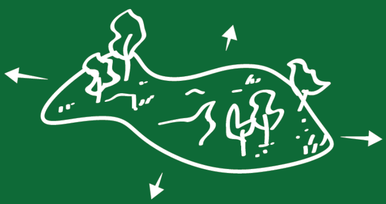


Reverse greenification: completely vegetated is the starting point, only use pavement and uncovered structures when absolutely necessary

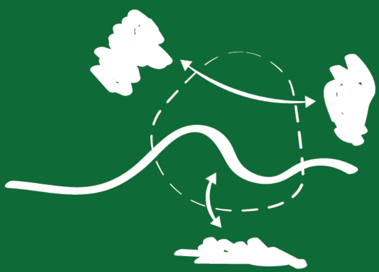
Fig. 23. Design principles to increase ecological resilience

rdam

Diversity of flora and vegetation structures of existing and future green space



Large green areas are preferred over small ones



Improve species connectivity between separated habitats outside the city


Image courtesy of Ossip van Duivenbode and Walter Herfst

05

Well-being analysis

Human well-being is strongly related to nature. This chapter explores that relation by elaborating the concepts of ecosystem services and ecosystem disservices in the spatial context of Rotterdam. Simultaneously, an analysis of policy documents that address well-being in Rotterdam gives insight into the challenges and ambitions at the city scale. The research question "How can compact urban green space enhance well-being in Rotterdam" is answered in this chapter.

Human-nature interaction

As mentioned in the introduction, humans are inherently attracted to nature, which gives the natural environment a lot of potentials to contribute to well-being. But it is not just the presence of nature that positively affects one's well-being. Beatley stresses the importance of interaction with nature.

These human-nature interactions are referred to as biophilic interactions by Beatley. Previous studies describe diversity in interactions and make a distinction based on type of environment (such as urban green, water bodies, wilderness), type of exposure (visual, physical, images, mental), and time of exposure (Bratman, Hamilton and Daily, 2012). The presented classification for CUGS can be used to define the type of environment and has a strong correlation to the type of exposure.

> A biophilic city is not just a city that has lots of nature in and around it [...]. It is also the engagement with, the enjoyment of, the celebration of that nature. (Beatley, 2017, p. 25)

CUGS and interaction

Compact urban green space has the potential to evoke many biophilic interactions, as the spaces are located close to people. The type of compact urban green space poses limitations and opportunities for interaction. Three types can be distinguished: ground level, vertical and raised horizontal. For each type, the potentials are discussed briefly on the next page.

Ground-level
Urban green space on the ground level is usually easily accessible. This means they can provide both visual and physical interaction. As visual interaction generally concerns viewing from a window indoors (people spend most of their time indoors), the proximity and visibility from indoors will define this interaction.

Vertical
Vertical greenery is, unlike horizontal greenery, not accessible. Vertical greenery on the ground floor may be possible to touch, but greenery above reach prevents any form of physical interaction. However, its verticality greatly increases the visibility of this type of green. In a dense city where open space is scarce, vertical surfaces have the potential to foster visual biophilic interactions.

Raised horizontal
Raised greenery on buildings, such as on rooftops is not visible from the street level. Hence, visual interactions are limited to those located above the green feature. The accessibility of these green features depends on the design and private decisions, as most buildings will be privately owned.

Perceived ecosystem services and disservices are strongly dependent on the type and time of interaction with nature. Fig. 25 and Fig. 26 illustrate an example of ecosystem services and ecosystem disservices. The sections on the next pages further explore specific ecosystem services and disservices related to the three well-being aspects.

Additionally, well-being data for the centre of Rotterdam is analysed and spatially presented to get an overview of the challenges and opportunities related to well-being in the city.

Well-being in Rotterdam

In this thesis, well-being is divided into three aspects: health, social development, and belonging. These aspects can be further divided into sub-aspects, as can be seen at Fig. 24. These aspects, among others, are mentioned by the Ecocity Standards as indicators of well-being (Ecocity Builders, 2020). It is worth noticing that well-being is personal, which means there is no one-fits-all solution. Even though well-being the indicators and their weight differs depending on personal preferences, general conclusions can be drawn for the well-being of a group. The next pages discuss these conclusions and relate them with the agenda of the municipality of Rotterdam.

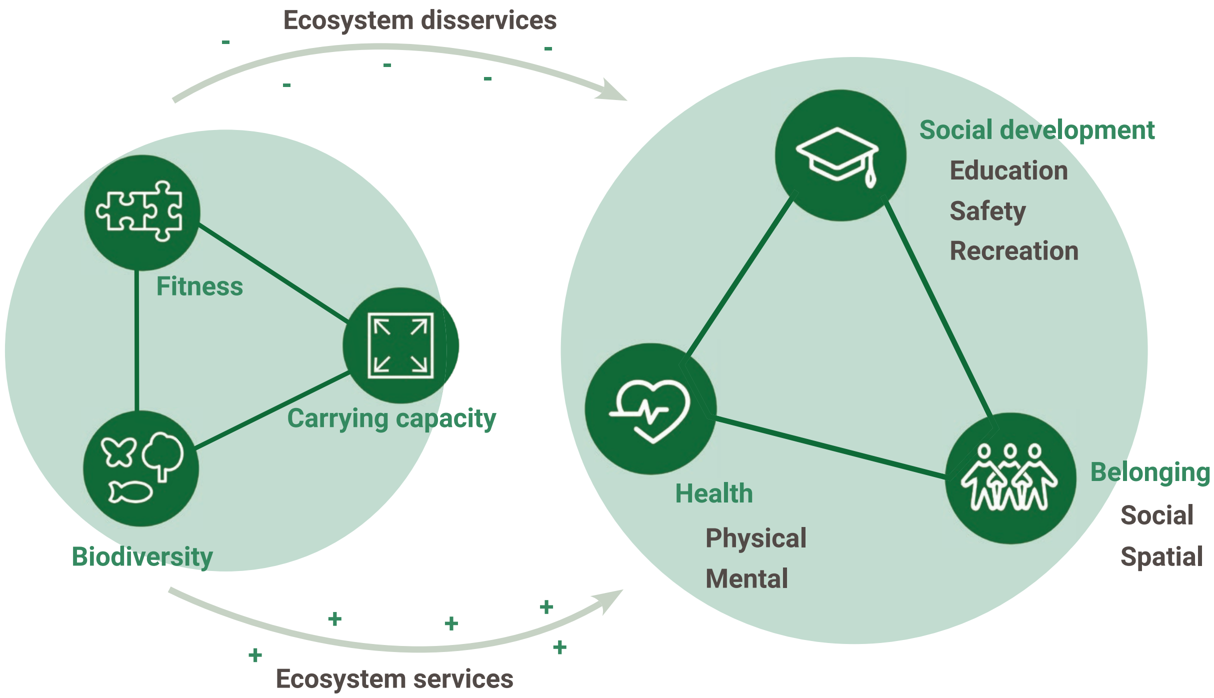


Fig. 24. The aspects and sub-aspects for well-being used in this research are influenced by ecosystem services and ecosystem disservices

Fig. 25. Ecosystem services improve human well-being

Fig. 26. Ecosystem disservices reduce human well-being.

Health

Heat stress reduces physical health in Rotterdam. The urban heat island in and around the city results in temperatures that get up to 8°C hotter than the rural surroundings during a heatwave. There are insufficient cooling areas, as over 30% does not have access to a cool space close to home. Moreover, the severity and frequency of heatwaves are expected to increase due to climate change. To mitigate heat stress, greenification of the public space is proposed, as well as creating more green roofs and façades (Gemeente Rotterdam, 2020b).

Air pollution also reduces physical health and improving the air quality is on the municipal agenda. However, measures are focussed on reducing the sources of the pollution (i.e. discourage car usage), and less on improving air quality with vegetation. A logical decision since curbing emissions is likely more effective than purifying polluted air afterwards.

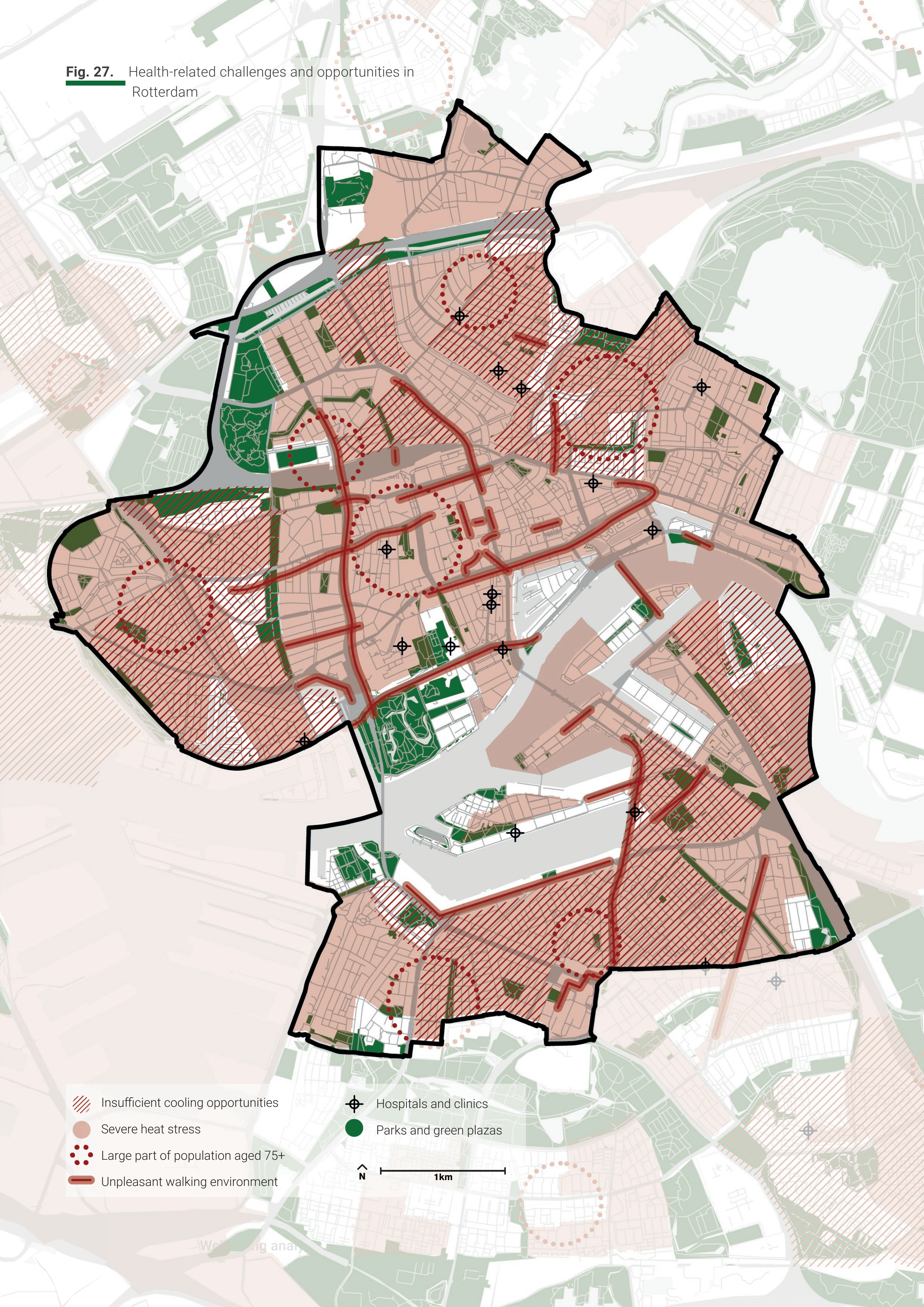
The municipality gives special attention to the improvement of physical health by walking. Although indirect, a green environment has a large influence on walkability and can thus help to achieve a more walkable city. Research under the inhabitants of Rotterdam, carried out by the municipality itself, showed that a green environment was the second-largest motivation for people to walk, after the availability of walking paths. Walking is also mentioned as a measure to improve mental health (Gemeente Rotterdam, 2020a). As mentioned in the theory chapter, green space in general is very effective in reducing mental stress, which is likely an issue in Rotterdam given its attention-demanding urban environment (Ulrich et al., 1991).

The map in Fig. 27 shows the most pressing health challenges for Rotterdam.

	Ecosystem services	Ecosystem disservices
Physical health	**Reduce temperature** Vegetation has been proven to be effective in cooling down both surface and ambient temperatures. The magnitude of the effect depends on leaf size and amount of vegetation, which can be measured with the Leaf Area Index (LAI). Green façades are more effective in cooling then green roofs (Alexandri and Jones, 2008; Stav and Lawson, 2011).	**Evoke allergies** Plants and animals can evoke allergic reactions. The severity of the allergy depends per person and species. However, some species are known to trigger allergic reactions for large groups of people, such as the hairs of the **Oak Processionary** (*Thaumetopoea processionea*) and the pollen of **Birch** trees (*Betula sp.*).
	Increase air quality Vegetation can increase air quality, but the magnitude of this effect is small (Radić, Dodig and Auer, 2019).	**Reduce air quailty** Vegetation can reduce air quality by releasing VOCs (Von Döhren and Haase, 2015).
		Spread of diseases Animals and plants may carry diseases and facilitate the spread of them (Von Döhren and Haase, 2015).
Mental health	**Reduce stress** Views of nature and being in a green environment reduces stress. This effect has also been proven for green façades and accessible small green roofs (Elsadek, Liu and Lian, 2019; Mesimäki, Hauru and Lehvävirta, 2019).	**Induce anxiety** Specific plants and animals might induce anxiety in certain cultures or for certain individuals (Von Döhren and Haase, 2015).
	Reduce noise pollution Green facades reduce noise pollution. (Radić, Dodig and Auer, 2019).	

Table 5. Ecosystem services and disservices related to health.

Fig. 27. Health-related challenges and opportunities in Rotterdam



Social development

Social development is divided into three sub-aspects: recreation, safety and education. The map in Fig. 28 shows the most pressing challenges regarding social development and ecosystem services on the map. The red zone marks the area in which there is no park (above 1ha) within 300m. This guideline is recommended by the World Health Organisation (Annerstedt van den Bosch et al., 2016).

The map also highlights the neighbourhoods with a safety index below average. This index is computed by the municipality of Rotterdam with the use of data on theft, violence and vandalism reports (Gemeente Rotterdam, no date d). Greenery may reduce crime, but this effect is not always easily measurable. Furthermore, greenery can also induce crime when it is not maintained well. Because of this ambigious relationship, compact urban green space is not used in this research to reduce crime. Nevertheless, it would be very interesting to further research the effect CUGS has on crime rates.

	Ecosystem services	Ecosystem disservices
Education	**Educational value** Green façades have an educational value (Radić, Dodig and Auer, 2019).	
Safety	**Reduce crime** Green façades have a positive effect on crime reduction (Radić, Dodig and Auer, 2019).	**Increase crime** Crime increase in poorly maintained green spaces (Von Döhren and Haase, 2015). **Cause demage** Structural damage to walls by vertical vegetation (Chen et al., 2020); natural forces can cause structural damage to buildings and infrastructures (Von Döhren and Haase, 2015).
Recreation	**Recreational value** Sometimes the environment is the source of recreation, while other times the green environment facilitates recreational activities. Accessibility is in the second case very important. Hence, vertical greenery is less suitable for recreation. The recreational value of small green spaces will depend on the facilities available in this green space, but there is research pointing out that even small accessible green roofs can have a recreational value (Mesimäki, Hauru and Lehvävirta, 2019).	**Restrict usage** Protected nature areas restricts other usages (Von Döhren and Haase, 2015; Langemeyer et al., 2020)

Table 6. Ecosystem services and disservices related to social development.

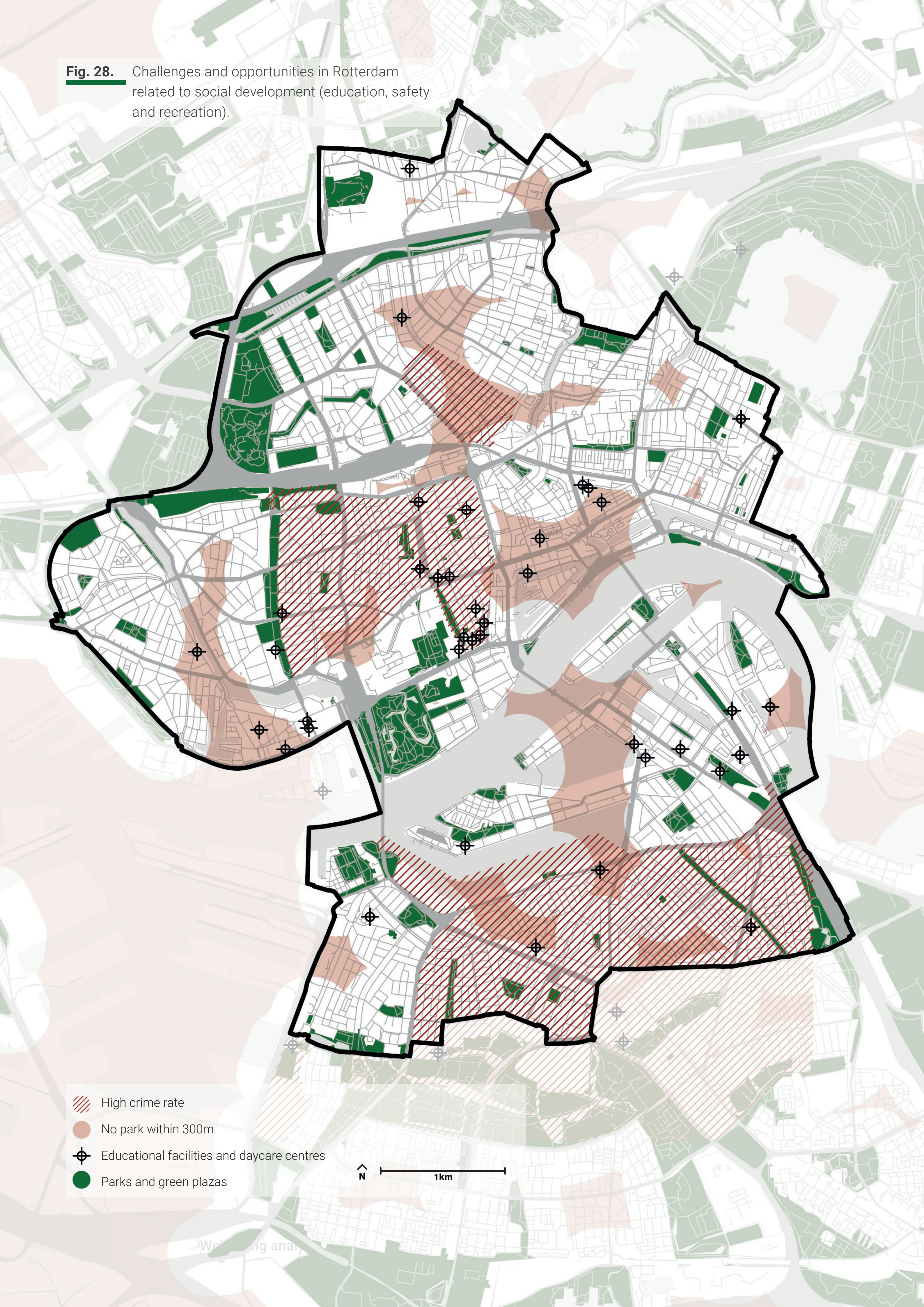


Fig. 28. Challenges and opportunities in Rotterdam related to social development (education, safety and recreation).

Belonging

Belonging can be divided into social and spatial belonging. Social belonging refers to the feeling of being part of a group, while spatial belonging relates to placemaking and feeling part of a space. The municipality measures belonging using data such as the time before people move to a different place and the participation in social activities. This score was used to create the map in Fig. 29. Urban green space, and especially CUGS given its proximity to people's homes, can increase belonging. The municipality of Rotterdam has programmes to encourage facade gardening and the adoption of tree planters. Facade gardening is only possible on wide sidewalks, as the width of the sidewalk always has to be 1.80m or wider (Gemeente Rotterdam, no date b).

In the dense urban fabric of the city, there is not always space for a private or communal garden. This is mainly an issue in the centre of the city. Compact urban green space could mitigate this by providing space for gardening activities.

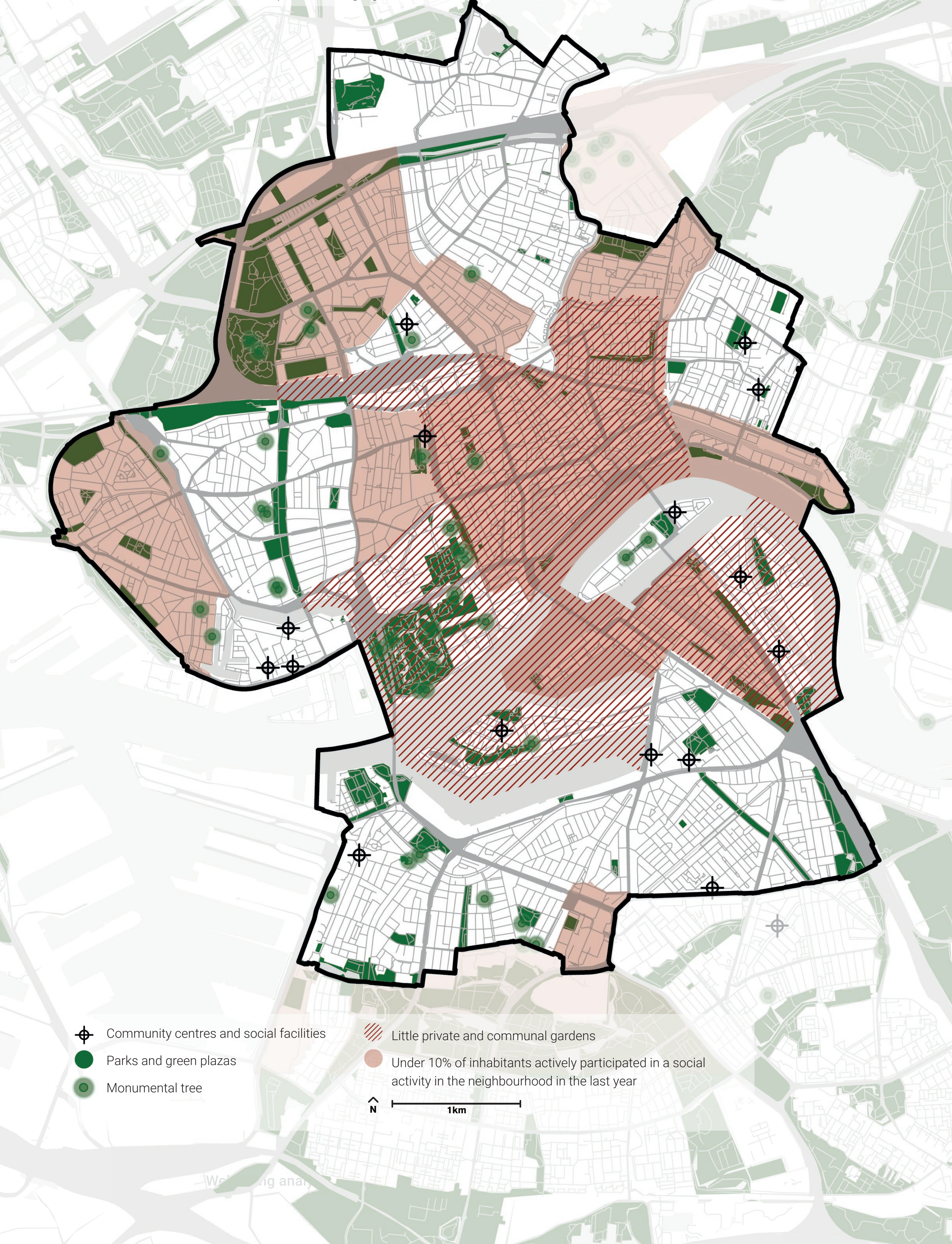
Belonging may be the most difficult aspect of well-being to address, because of its subjective nature. While some people may feel at home in a green environment surrounded by plants, others get irritated by the uncontrolled aspects of it, such as leaf litter and weed development. Therefore, compact urban green space will contribute the most to belonging when people can exert influence on its appearance and are allowed to change the space to their liking.

CUGS can also increase belonging by giving identity to a neighbourhood and by becoming monumental. This is a process that takes time.

	Ecosystem services	Ecosystem disservices
Social	**Facilitates interaction** Community driven gardening or greening can facilitate social interaction and enhance social belonging (Oh, Richards and Yee, 2018).	
Spatial	**Increase sense of place** Nature and gardening can be used as a tool for place making (Brook, 2003).	**Reduce control** The promoted strategy of allocating space for natural processes can be perceived as unwanted and reduce spatial belonging. For instance the undesired 'weeds' that result from spontaneous growth (Chen et al., 2020). **Block views** Plants can block views, especially if they are not maintained (Von Döhren and Haase, 2015).

Table 7. Ecosystem services and disservices related to belonging.

Fig. 29. Challenges and opportunities in Rotterdam related to social and spatial belonging.



Conclusion

Green space and ecological processes have a strong relationship with well-being. While some effects are directly measurable and predictable (such as temperature regulation, air quality improvement), others are more ambiguous and less easy to predict (crime reduction, stress reduction). Additionally, the subjective nature of personal well-being further complicates the equation. For instance, even though research has shown that gardening can increase both social and spatial belonging (Oh, Richards and Yee, 2018; Brook, 2003), there are plenty of people who prefer to refrain from gardening activities and get frustrated by the development of spontaneous vegetation, belittling it as 'weeds'. Hence, cultural and personal preferences should not be underestimated.

The spatial and policy analysis in this chapter combined with the theoretical framework of ecosystem services and ecosystem disservices provide an answer the sub research question *"How can CUGS improve well-being in Rotterdam?"*.

Compact urban green space increases well-being when it mitigates ecosystem disservices and creates ecosystem services that address prevailing challenges of a specific area

Firstly, the potential improvement depends on the type and accessibility of CUGS, which is different for ground level, elevated and vertical features. Interaction can result in both positive and negative effects. Hence, one should steer to maximise the positive ecosystem services, while minimizing the negative ecosystem disservices.

Second, the value of the potential ecosystem services offered by CUGS depends on the challenges present at a specific location. The spatial analysis of Rotterdam revealed several challenges that could be mitigated by ecosystem services provided by CUGS. These challenges are shown on the map in Fig. 30 and will be briefly explained below.

People in Rotterdam severely suffer from the urban heat island effect. Compact urban green space can provide **cooling** at locations where currently too little cool spots are available. The cooling effect will be most effective when the green features are located close to the people.

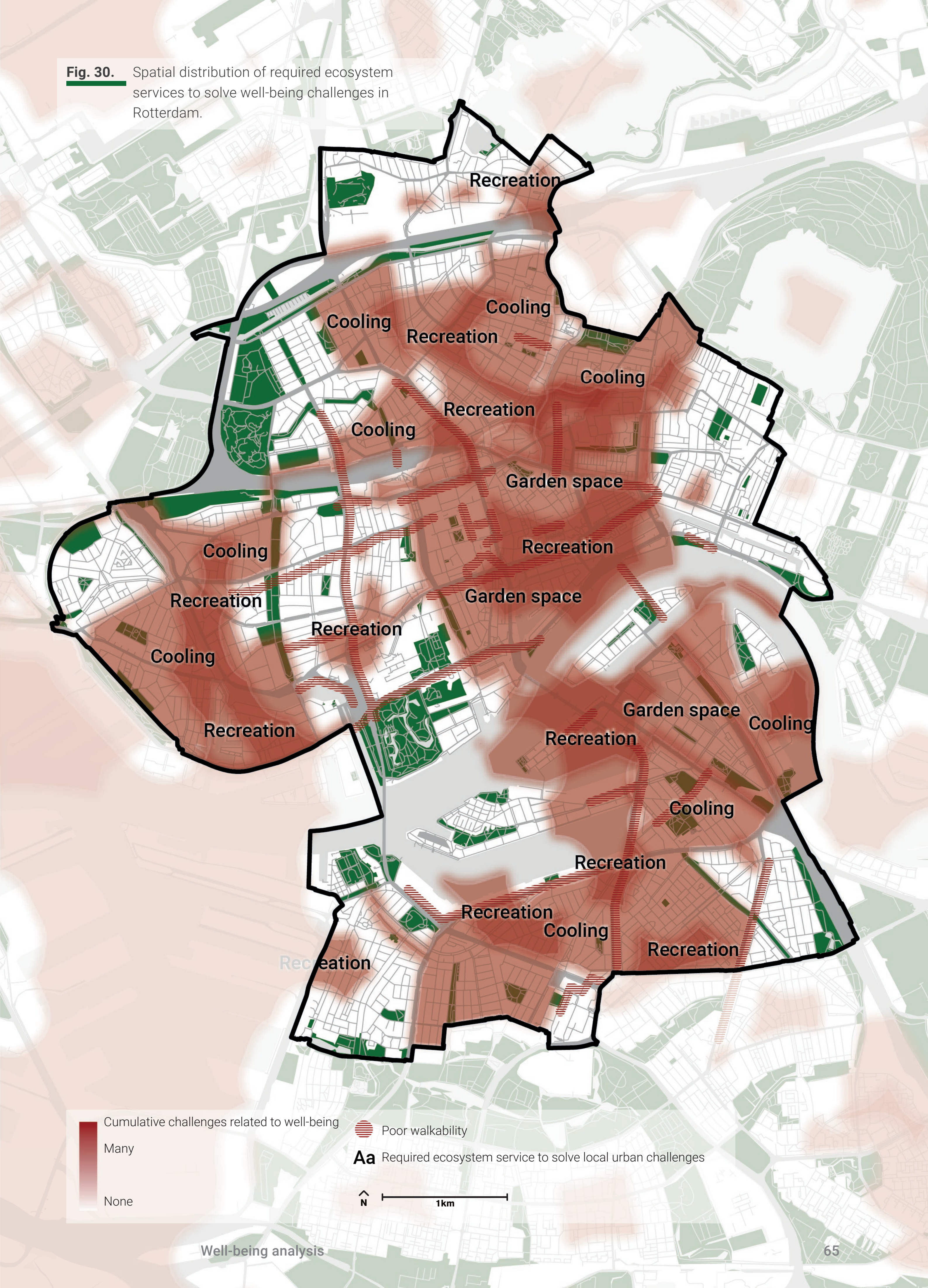
Not all people in the city have access to a park in their neighbourhood. Compact urban green space can provide **recreation** possibilities at locations where open space is scarce. It is important that the green features are accessible.

Many road networks in Rotterdam are perceived as unpleasant to walk on. Greenery, provided by compact urban green space improves walkability as it creates a pleasant outdoor environment. Walkable networks decrease the need for car usage and therefore can **improve air quality**. Furthermore, walking is also associated with numerous **improvements of physical and mental health**. Compact urban green space contributes to walkability by being visible, accessible and connected.

Many dwellings in Rotterdam do not have sufficient garden space. By providing a **place for gardening**, CUGS can increase both spatial and social belonging. Space for bottom-up initiatives and encouragement of participation in the design, construction and maintenance of CUGS is required to involve local communities. CUGS can also increase belonging by giving identity to a neighbourhood and by becoming monumental. This is a process that takes time.

Based on these conclusions, design principles for CUGS that increases well-being have been developed and are illustrated in Fig. 31 (page 66). The design principles form the foundation of the CUGS patterns in the next chapter.

Fig. 30. Spatial distribution of required ecosystem services to solve well-being challenges in Rotterdam.

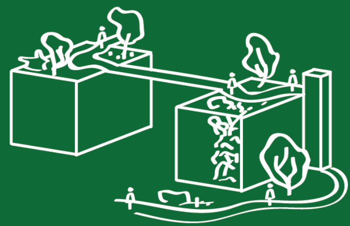


Design principles to increase well-being in Rotterdam

By maximising ecosystem services and minimizing ecosystem disservices

Health

Link interactions and type of CUGS to spatial distribution of health challenges: cooling vegetation at hot places and visible restorative vegetation around medical facilities



Use of green along existing pedestrian networks and creation of new (elevated) pedestrian networks to promote walkability

Social development

CUGS is preferably accessible (or visible for vertical greenery) from the ground level public space

CUGS provides facilities that support recreational and educational activities such as walking paths, benches, sport fields, outdoor classrooms and playgrounds

Belonging

Increase belonging by citizen engagement and empowerment during the planning, design, construction and maintenance phases of CUGS

Mitigation of ecosystem disservices by providing information on the value of nature

Fig. 31. Design principles to increase well-being in Rotterdam.

Mitigate ecosystem disservices by avoiding specific species that cause nuisance

Mitigation of ecosystem disservices by a stricter maintenance regime on CUGS in crime sensitive areas

Mitigation of ecosystem disservices by the design of clear boundaries to fend off greenery at undesirable locations


Image courtesy of The Athenaeum

06

Compact urban green space patterns

This chapter explores patterns of compact urban green space at different scale levels. Relations between different patterns are explained. The link between the patterns and the improvement of well-being and ecological resilience is discussed. This will answer the research question of: *"Which compact urban green space typologies contribute to ecological resilience and well-being?"*.

A pattern language approach is used to organise all kinds of different green space types. This method, developed by Christopher Alexander (1977), identifies reoccurring problems and proposes a pattern to solve those problems. It also approaches individual patterns as accumulations of other patterns, which makes it possible to better understand their relationship. This methodology results in a network of patterns at different scale levels. Patterns get a place in this network because they consist of other (smaller)patterns and because they are embedded in other (larger) patterns. For instance, Green street (21) consists of patterns such as Open pavement (5), Adopted planter (10) and Urban tree (6). On the other hand, Green street is embedded in the patterns Multi-level pedestrian network (29) and Wildlife corridor (31). This methodology is illustrated in Fig. 32.

Pattern atlas

Those patterns are collected in a pattern atlas, which can be seen in Fig. 33 and can be downloaded as a separate document. This atlas starts with patterns at the smallest scale and moves gradually to larger patterns. For each pattern a problem statement is given that justifies its relevance. Scientific and professional literature is used to further understand the problem and solution. An image on the left page illustrates how the pattern could look like and a schematic drawing on the right page explains the working principle. The image and schematic drawing are mere examples of the spatial manifestation of a pattern and not a blueprint or one-fits-all solution. The social, spatial and ecological context should in the end impose the form. Some green space patterns are divided into

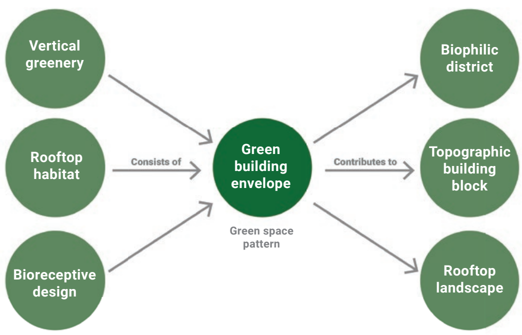


Fig. 32. Patterns relate to each other at different scale levels.

sub-patterns, to demonstrate this variety. For instance, Rooftop habitat (15) has been divided into Marsh (15a), Herbaceous (15b), Brownfield (15c) and Forest (15d). These and other examples are grounded into the context of the Dutch city of Rotterdam, which makes the atlas notably relevant for well-developed Western European cities.

Scoring

Patterns are evaluated on two topics: their contribution to well-being and ecology. An 0-5 score system based on the theoretical framework and the previous chapters is used for this. Ecology has been divided into three aspects (biodiversity, fitness and carrying capacity). The same goes for well-being, which contains the aspects of health, social development and belonging. For each type, icons are used to refer to a certain score:

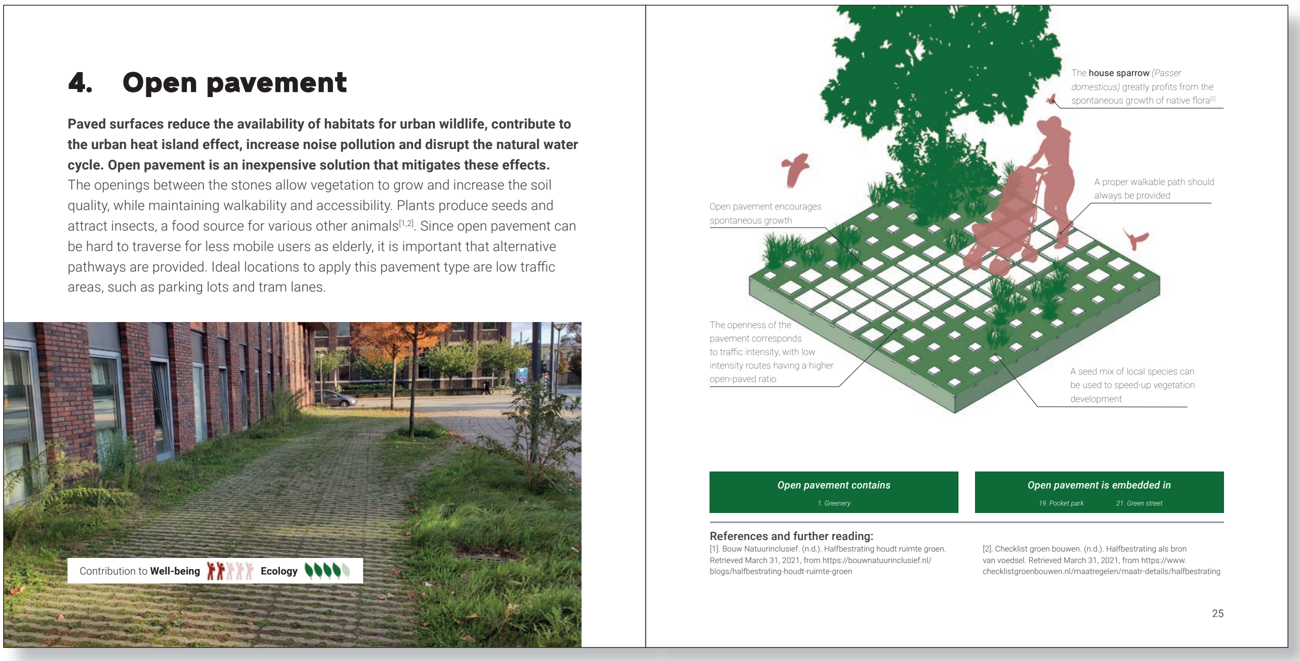
Ecology

	No added value
	Weak contribution to one of the three aspects
	Scientifically proven strong relationship with improvement of one of the aspects
	Scientifically proven strong relationship with improvement of two aspects
	Scientifically proven strong relationship with improvement all three aspects
	Improvement of all three aspects and attracts endangered and vulnerable species

Well-being

	No added value
	Weak contribution to one of the three aspects
	Scientifically proven strong relationship with improvement of one of the aspects
	Scientifically proven strong relationship with improvement of two aspects
	Scientifically proven strong relationship with improvement all three aspects
	Improvement of all three aspects and also inclusive, especially for vulnerable groups

The two scores combined provide a clear picture of the value of a specific green space type on its own. This value will substantially increase when a green type is embedded into larger types. Hence, one should always strive to achieve larger types by combining smaller ones.



4. Open pavement

Paved surfaces reduce the availability of habitats for urban wildlife, contribute to the urban heat island effect, increase noise pollution and disrupt the natural water cycle. Open pavement is an inexpensive solution that mitigates these effects. The openings between the stones allow vegetation to grow and increase the soil quality, while maintaining walkability and accessibility. Plants produce seeds and attract insects, a food source for various other animals[1,2]. Since open pavement can be hard to traverse for less mobile users as elderly, it is important that alternative pathways are provided. Ideal locations to apply this pavement type are low traffic areas, such as parking lots and tram lanes.

Open pavement contains

1. Greenery

Open pavement is embedded in

19. Pocket park *21. Green street*

References and further reading:

[1]. Bouw Natuurinclusief. (n.d.). Halfbestrating houdt ruimte groen. Retrieved March 31, 2021, from https://bouwnatuurinclusief.nl/blogs/halfbestrating-houdt-ruimte-groen

[2]. Checklist groen bouwen. (n.d.). Halfbestrating als bron van voedsel. Retrieved March 31, 2021, from https://www.checklistgroenbouwen.nl/maatregelen/maatr-details/halfbestrating

25

Fig. 33. The pattern atlas describes all patterns and shows how they are related.

Pattern field

Since all patterns contribute to the formation of larger patterns and also exist of smaller patterns, a pattern field can be drawn to show this relationship. This pattern field is shown in Fig. 34. Patterns are ordered by scale; with the smallest patterns on the left. The pattern field offers valuable information in two ways, depending on the direction it is read. First, it can be used to de-construct complex patterns into smaller comprehensible patterns. For instance, if one were to construct a rooftop habitat, the field shows the patterns it should contain. On the other hand, the pattern field can also be used to view opportunities to move from smaller patterns to larger patterns that have more impact. For the rooftop habitat, this means one is able to see the next development that could be initiated with the construction of a rooftop habitat.

Overview of all patterns

The next pages are meant to present the diversity of compact urban green space patterns. For a complete overview of the patterns, as well as more substantiation of their relevance, refer to the atlas.

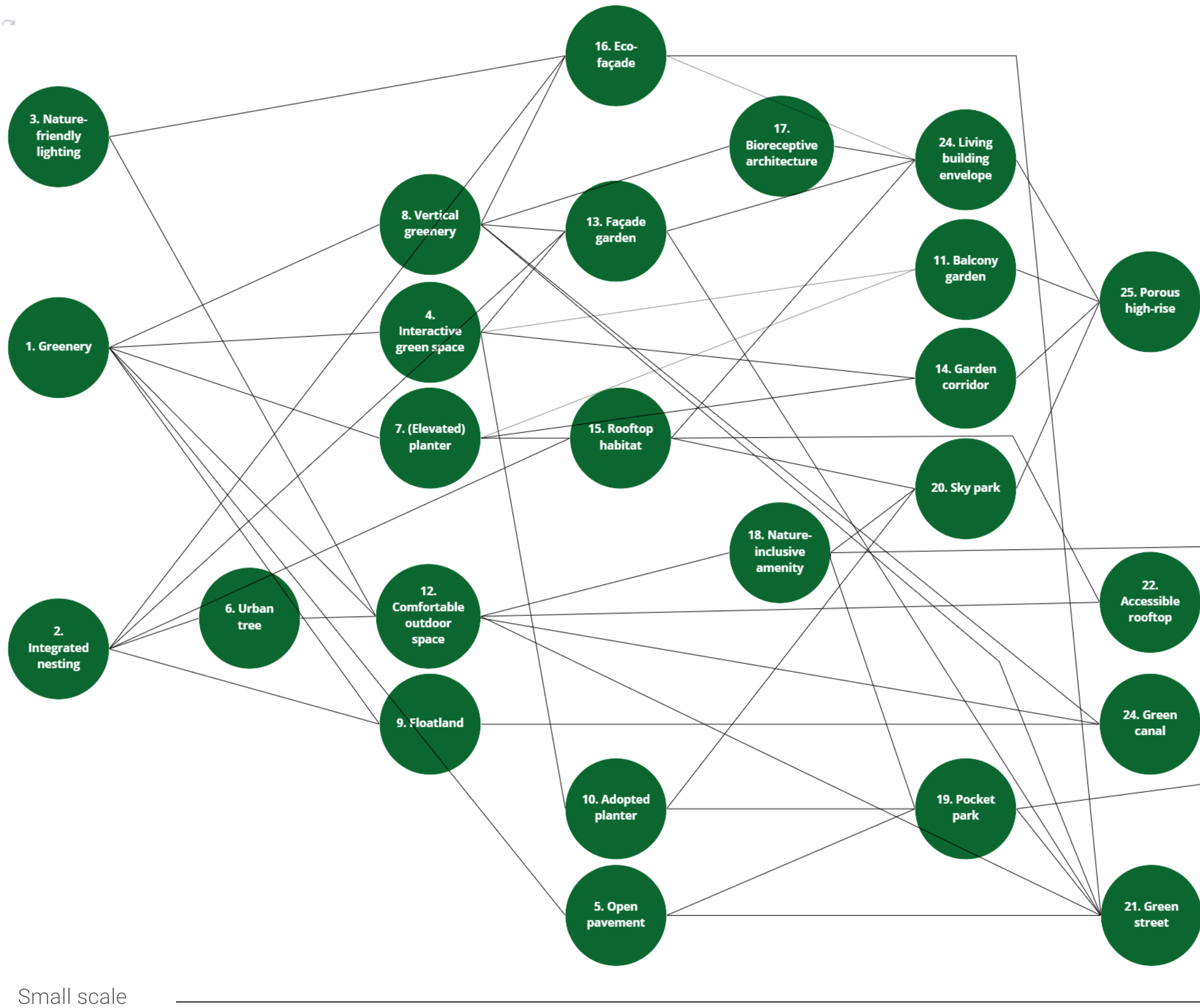
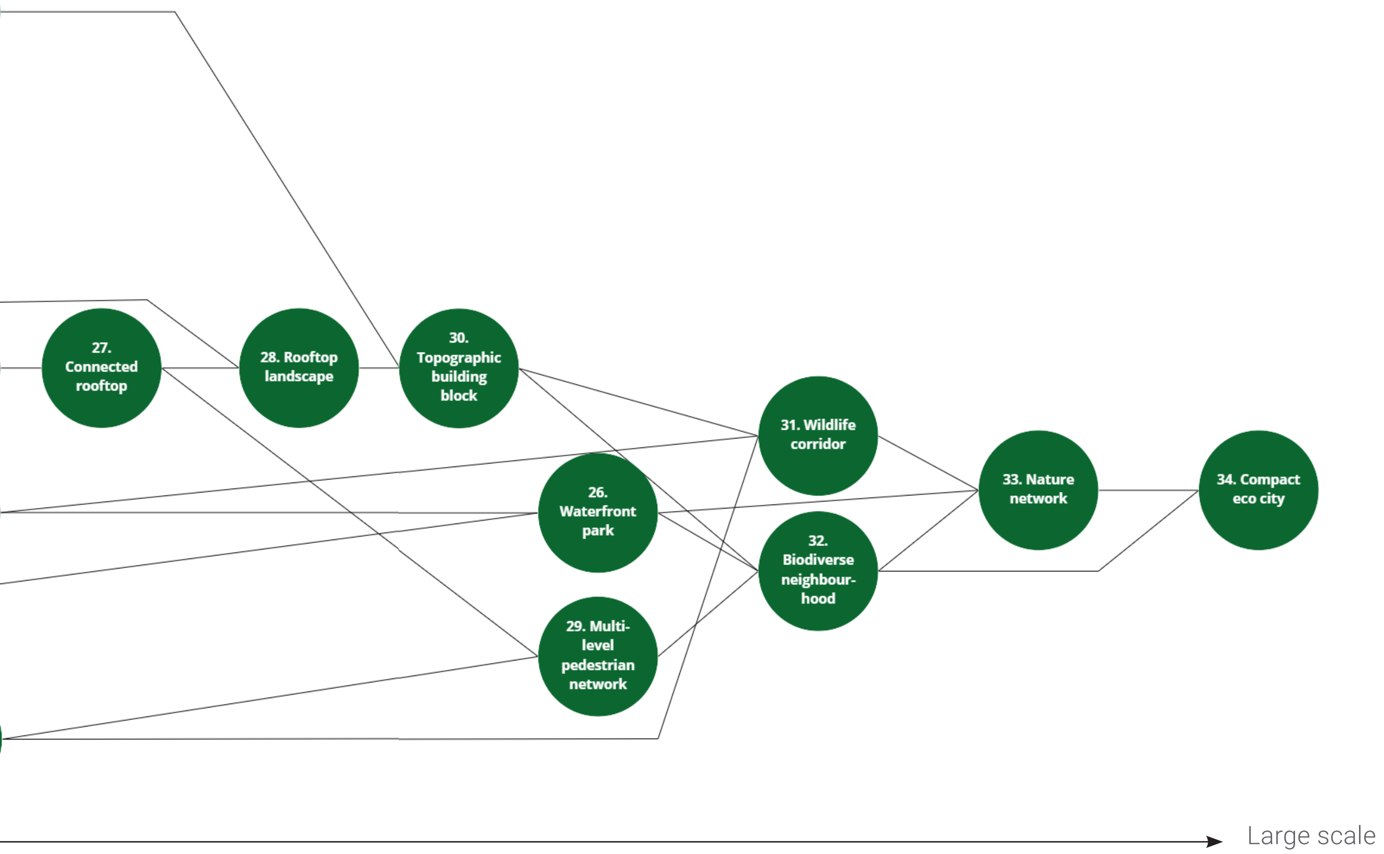
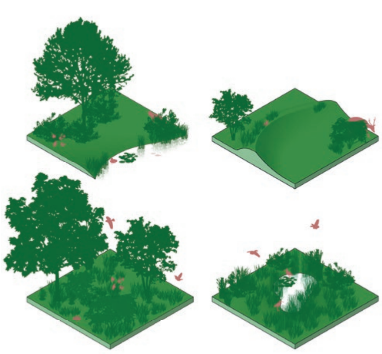


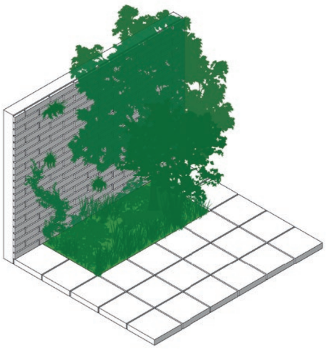
Fig. 34. Relations between patterns are shown in a pattern field.


27. Connected rooftop
28. Rooftop landscape
30. Topographic building block
31. Wildlife corridor
26. Waterfront park
32. Biodiverse neighbour-hood
29. Multi-level pedestrian network
33. Nature network
34. Compact eco city
Large scale

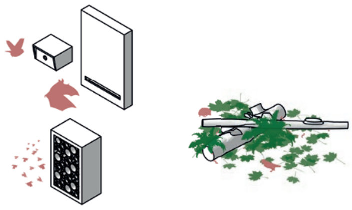
Patterns at object scale



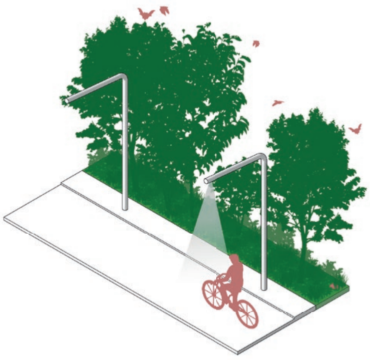
1a. Greenery (nature-based)



1b. Greenery (spontaneous)



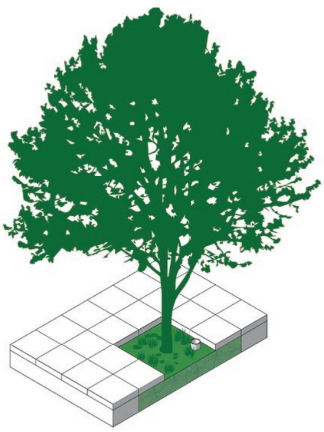
2. Integrated nesting



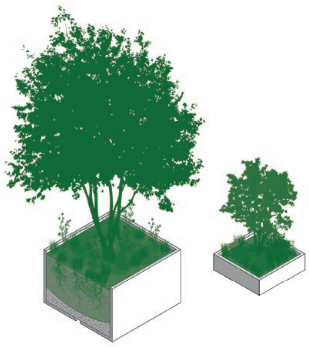
3. Nature-friendly lighting

4. Interactive green space

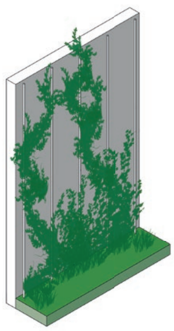
5. Open pavement



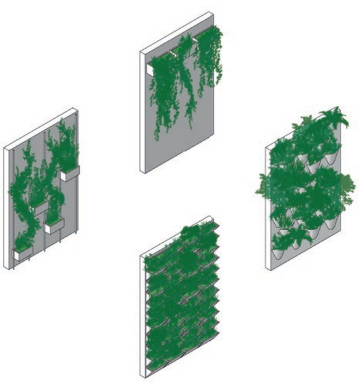
6. Urban tree



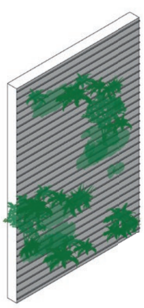
7. (Elevated) planter



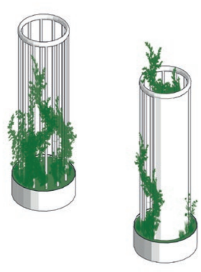
8a. Vertical greenery (green facade)



8b. Vertical greenery (living wall)

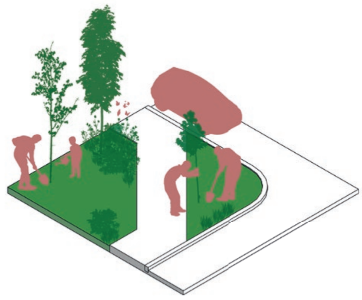


8c. Vertical greenery (bioreceptive)



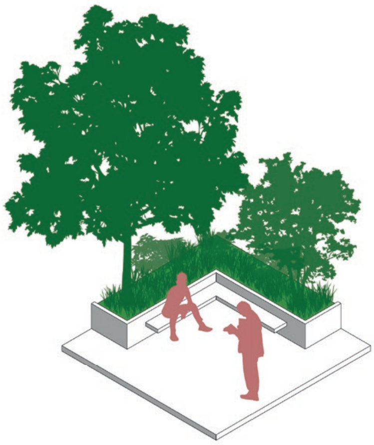
8d. Vertical greenery (structure)

9. Floatlands

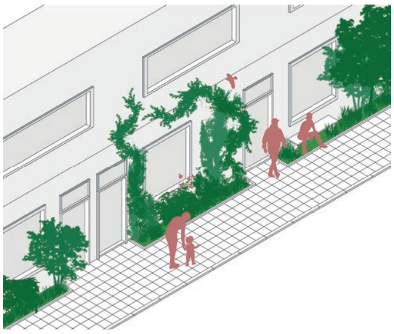


10. Adopted planter

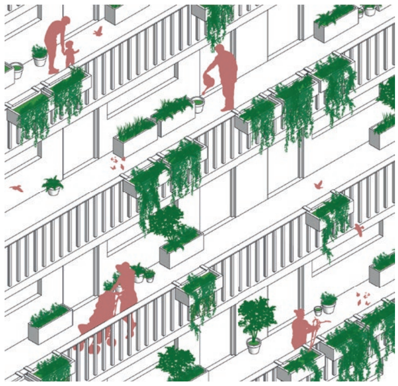
11. Balcony garden



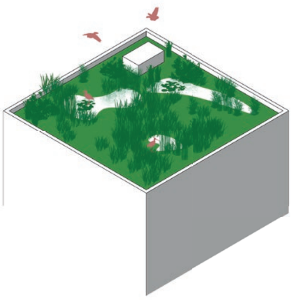
12. Comfortable outdoor space



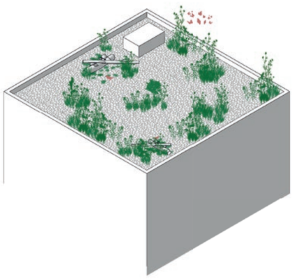
13. Facade garden



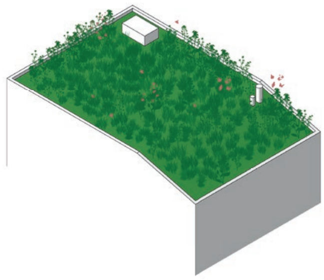
14. Garden corridor



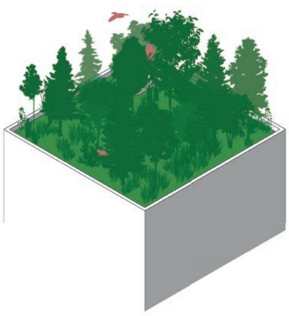
15a. Rooftop habitat (marsh)



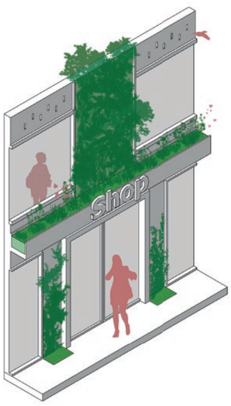
15b. Rooftop habitat (brown field)



15c. Rooftop habitat (herbaceous)

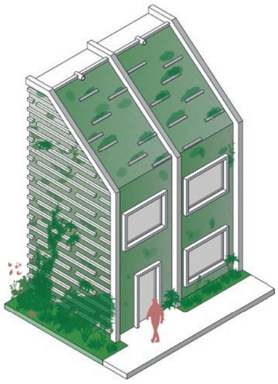


15d. Rooftop habitat (forest)

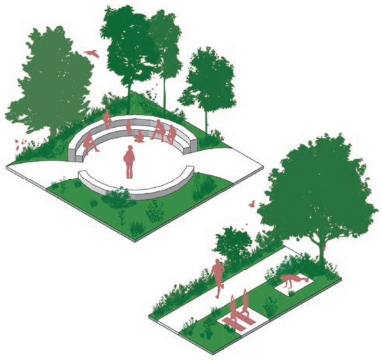


16. Eco-facade

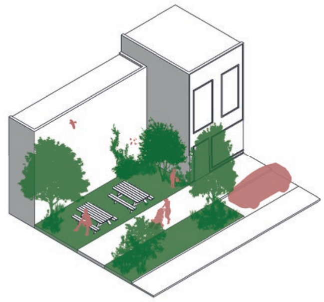
Patterns at building and street scale



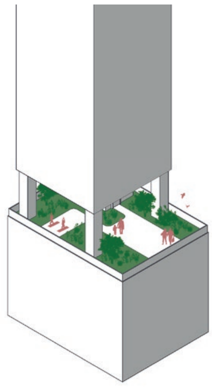
17. Bioreceptive design



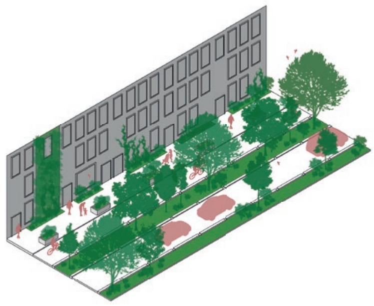
18. Nature-inclusive amenity



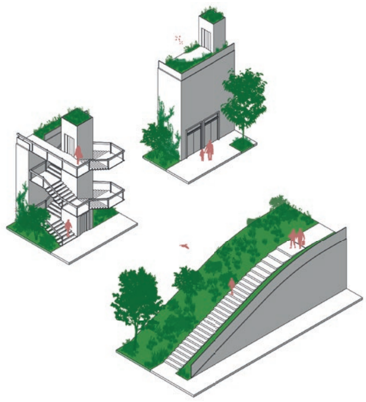
19. Pocket park



20. Sky park

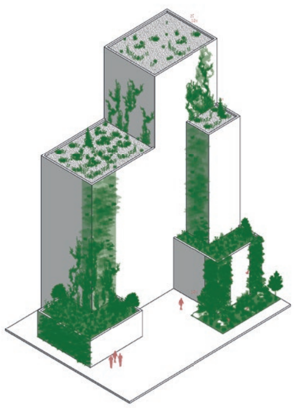


21. Green street

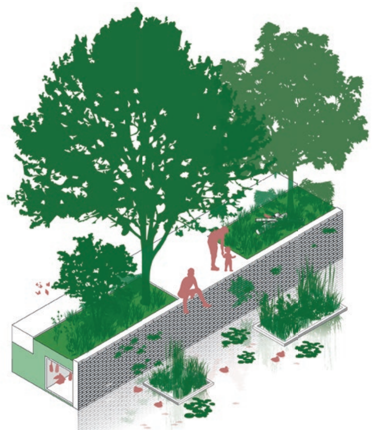


22. Accessible rooftop

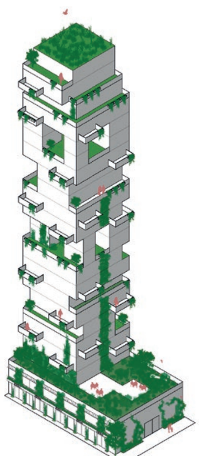
23. Living building envelope



23. Living building envelope

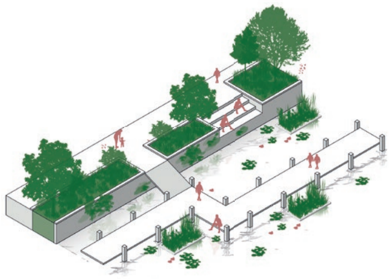


24. Green canal

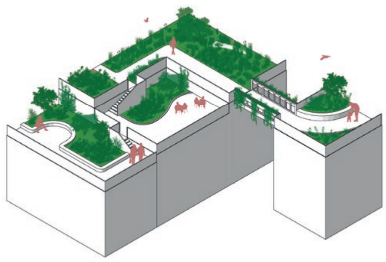


25. Porous high-rise

Patterns at block and park scale

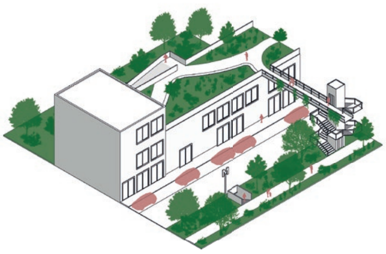


26. Waterfront park

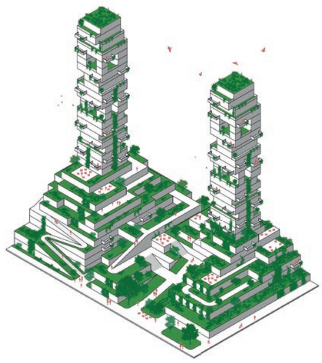


27. Connected rooftops

28. Rooftop landscape

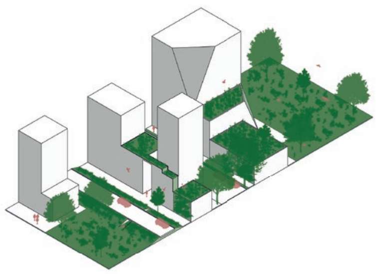


29. Multi-level pedestrian network

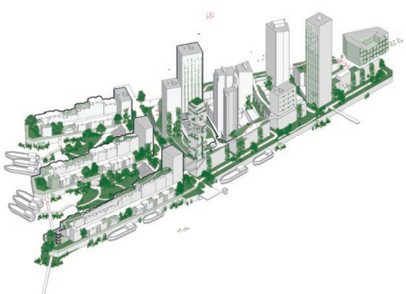


30. Topographic building block

Patterns at neighbourhood scale

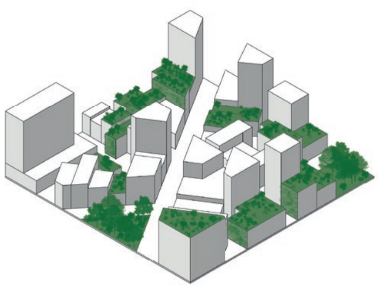


31. Wildlife corridor

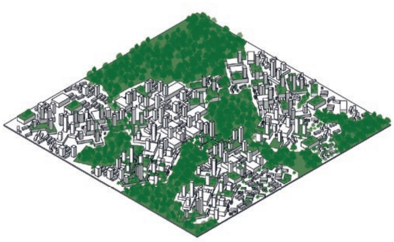


32. Biodiverse neighbourhood

Patterns at city scale



33. Nature network



34. Compact eco city

Rooftop habitat pattern experiment

Part of this thesis is a physical experiment on the rooftop of Ebben Nurseries. In this experiment, vegetation growth and the development of insect populations are measured on rooftop plots and ground plots. This data has been collected and processed together with Stéphanie Scholtes (Bsc. Biology) and gives more insight into the ecological value of rooftop habitats.

Methods and materials

The experiment takes place in Cuijk, the Netherlands. Four plots of 3x3 metres were created of which three plots are located on a rooftop (17m above ground level) and one plot on the ground. Each plot was prepared the same, with the only variables being the substrate the location of the plots (roof and ground level). Each plot contains two pitfall traps in the soil and one adhesive strip on one of the tree branches to capture insects. Additionally, pictures were used to estimate the overall ground vegetation cover percentage. Fig. 36 gives an overview of the setup and used measuring tools. Measurements were taken three times and include the total insects found per plot that were trapped in the past three days.

The plots on the rooftop consist of an aggregate with a soil type and a lightweight material. The soil types used differ per plot:

- Plot 1 (roof, vulkaterra): Coarse mineral substrate 0-32 mm particle diameter. This is currently the standard for roof substrates.
- Plot 2 (roof, vulkagazon): Fine mineral substrate 0-6 mm, enriched with compost.
- Plot 3 (roof, local clay): Local soil (fine clay).
- Plot 4 (ground, local clay): Local soil (fine clay).

Vegetation was introduced with the planting of one tree (Cornus mas) per plot, nine locally sourced sods with herbaceous plants and a seed mix of local flowers.

Results

A total of 411 insects representing 10 families were count during the three surveys. Most insects have been found in the reference plot at the ground level (206). This plot also had a higher diversity of species. There was no significant difference in the biodiversity between the different plots on the roof. This can be seen in the graph in Fig. 37. Refer to the appendix for a detailed graph of the number of insects and families per plot per measurement.

There were major differences in vegetation development between the three rooftop plots. During the first measurement, a vegetation cover percentage of 0-5% was observed for all plots. However, after 46 days, the differences in coverage were significant. The rooftop plot with local soil had a far higher vegetation coverage when compared to other plots. This can be seen at the graph in Fig. 37 and on the images in Fig. 38.

Conclusion

It can be concluded that the biodiversity on the rooftops was significantly less when compared to the ground level plot. There was no difference noticed between roof substrate types. However, the substrate does matter when it comes to vegetation development. The rooftop plot with local clay soil showed the most active vegetation growth, followed by the ground level plot. A possible explanation for the low coverage on the ground level plot is that animals may have eaten the seeds of the local flower mix, resulting in less vegetation cover.

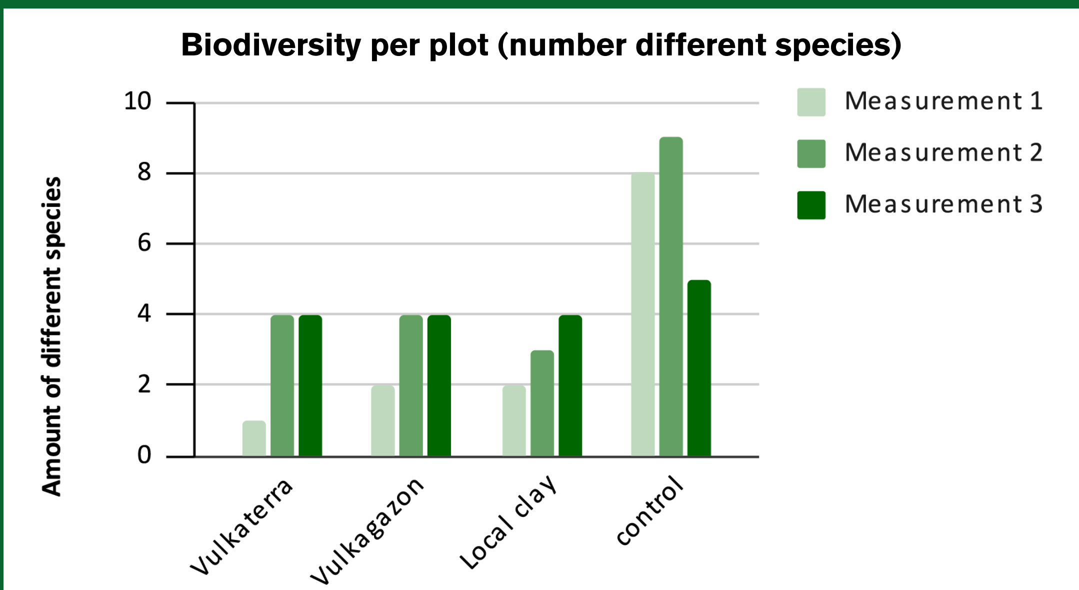


Fig. 35. Biodiversity per plot

Fig. 36. Experimental setup of plots and measuring tools: adhesive tape (above) and pitfall traps (below).

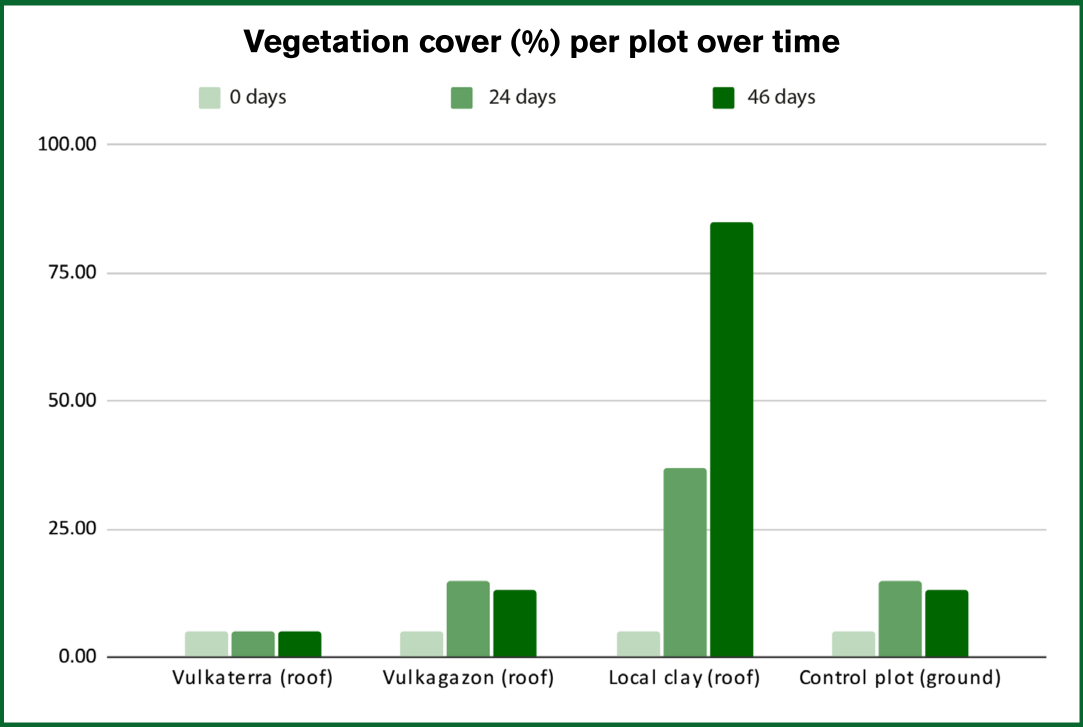


Fig. 37. Vegetation cover per plot

Fig. 38. Vegetation cover per plot (images)

Conclusion

The compact urban green space pattern atlas provides an answer to the sub research question of “Which compact urban green space patterns contribute to well-being and ecological resilience?”.

Patterns of green space can be identified at different scale levels. Ideally, large patterns consist of smaller patterns, and smaller patterns contribute to larger patterns. The atlas shows that patterns occurring at a larger scale are able to make more impact. However, they also require more resources and planning to be implemented.

The pattern language method clearly shows why the relationship between patterns is so important. For instance, a large topographic building block covered with exotic vegetation is of little value, just as a single isolated patch of native, nature-based greenery.

Compact urban green space will be much more contributing when it is an integral part of the (architectural) design. Simple greenery add-ons used for window-dressing fail to comply with many of the described patterns and thus should be avoided.

The contribution of compact urban green space towards well-being and ecology increases when it adds value at multiple scale levels

The patterns in the atlas are a (well thought out) selection of the many patterns of CUGS. The collection of patterns can be amended or changed based on new perspectives and research results.

Not all patterns are straightforward to implement. Some patterns can be easily integrated into existing structures, such as vertical greenery, while others require a more substantial approach, such as rooftop landscapes.

The experimental rooftop habitat pattern does emphasize the importance of local environmental conditions and clearly shows that using local soils does improve the vegetation cover on rooftops. It can be expected that this will eventually result in a higher biodiversity of animals. Unfortunately the experiment look not place long enough to test the effect of vegetation on the long-term.

While developed with the context of Rotterdam in mind, the use of the patterns is not limited to the city alone. Cities that deal with comparable challenges can use the same patterns to solve these, yet the spatial manifestation of a pattern might be different. The real value of the patterns is largely dependent on the spatial manifestation of a pattern and how well it fits in the context. That is why the next chapter provides a framework for the use of the presented patterns in Rotterdam, based on the spatial analysis performed in the chapters before.

Image courtesy of Joep Boute

07

Framework for Rotterdam

The urban green space patterns that were developed in the previous chapter illustrate principles and concepts for green space. In reality, these patterns have to be embedded into the spatial and ecological context of a place. This chapter illustrates how these patterns could be used to construct a spatial ecological framework for the city of Rotterdam, resulting in the answer to the research question: "How can the patterns be used to develop a spatial vision and strategy for Rotterdam?". The framework is elaborated by a design experiment in which different scenarios are tested in the Wijnhaven Eiland. The experiment in this neighbourhood shows the spatial quality and practical challenges that arise when the conceptual patterns are implemented. Furthermore, it provides a concrete example of how compact urban green space in Rotterdam could look like and function.

Results from the previous chapters have shown that for both ecology and well-being it can be valuable to not completely plan and design everything, but to also leave space for spontaneous processes and bottom-up initiatives. This framework does provide that space, while simultaneously presenting clear guidelines and a spatial structure that can improve ecology and well-being in Rotterdam.

The concluding maps of the ecological analysis and the well-being analysis for Rotterdam form the basis for the spatial structures that are proposed.

The constructed framework consists of five key points, each addressing a different subject. These points are summarized next to the framework which is illustrated in Fig. 39 (page 85). The key points are also discussed below.

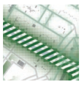
1. An ecological network connects and creates high biodiversity areas

The ecological analysis of Rotterdam revealed that zones of higher biodiversity are highly fragmented. Connecting these zones with Wildlife corridors (31) to form a Nature network (33), will result in more resilient ecosystems and stable populations. The two water ways of the Schie and the Rotte in the North of Rotterdam form the perfect starting point for the realisation of these corridors. The South has less pronounced water ways. Nevertheless, the existing green waterways of the Hillevliet and the Lange Hilleweg can act as corridors that connect the inner city with the landscape around it. The main structure, consisting of the water network, is augmented with Green streets (21) and connects to biodiverse neighbourhoods (32), such as the Wijnhaven Eiland. The patterns relevant for this point are shown in Fig. 41 (page 86). Since the scale of this point exceeds private developments, the municipality of Rotterdam should take the lead in the realisation of the network. With top-down imposed regulations and subsidies for greenery on buildings and spaces that are part of the network, private parties can be encouraged to contribute too.

1. An ecological network connects and creates high biodiversity areas

 Existing ecological corridor and high biodiversity areas

 Ecological improvement of current green areas

 New ecological corridors

 Main rivers and canals connect greeny in the centre to the landscape outside the city

2. Densification projects serve as green injections for the neighbourhood

 New urban development improves well-being and ecological quality of surrounding neighbourhood

3. New parks make innovative use of under-used spaces

 Activation of river front through water-based park

 Pocket park

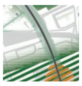
 New development combined with rooftop parks

 Planned green project (part of 7 stadsprojecten program)

4. Green routes connect parks with public transport and improve walkability

 Green route through existing streets

 Metro station

 Walkable and accessible elevated route

 Train station

5. Invite community to be stewards of greenery and bring green space close to home

 Local projects encourage depaving and green streets

 Educational facilities and community centres catalyse green initiatives

 Activation of flat rooftops

Fig. 39. The spatial-ecological framework for Rotterdam

This point also includes the improvement of the quality of existing green spaces. Opportunities for ecological improvement include diversification of the planting schemes and a transition towards (designed) nature-based greenery (1a) and appointed areas for spontaneous greenery (1b). Improvements of green space for well-being can be done by creating comfortable outdoor environments (12) and encouraging citizen interactions with the green space (4).

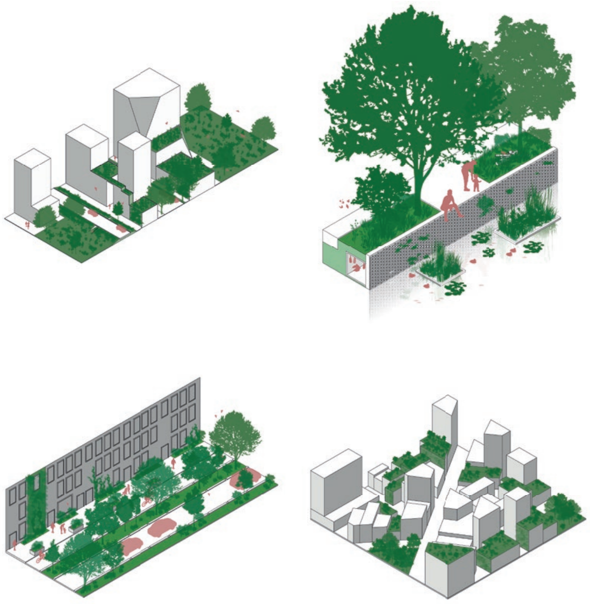


Fig. 41. Patterns used to create ecological corridors and an ecological network of green spaces.

2. Densification projects serve as green injections for the neighbourhood

The patterns in the pattern atlas demonstrate that new buildings can improve the ecological and spatial quality of the neighbourhood. Structural challenges make the implementation of intensive green features, such as rooftop landscape (28) and bioreceptive design (60) hard to implement in the existing building stock. Integrating these patterns in new buildings is more realistic and can result in new innovative design typologies, such as porous high-rises (25) and topographic building blocks (30). Therefore, current densification locations in Rotterdam serve as potential green hotspots for the surrounding area.

Regulations and guidelines for new development can be set up by the municipality together with urban designers, architects and ecological experts. Patterns that can be used to achieve this are shown in Fig. 40.

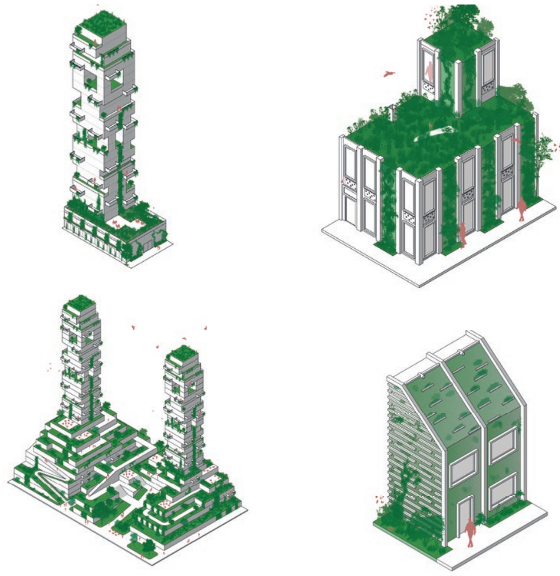


Fig. 40. Green densification injection patterns

3. New parks make innovative use of under-used spaces

Due to densification of the centre of Rotterdam, open space is scarce. Yet, the well-being analysis has shown that there are still many areas in the city that do not have sufficient outdoor recreation possibilities. Clever use of the available space can make it possible to realise parks in these areas. New development zones can, besides serving as a green injection, also include private rooftop parks (20) and public rooftop landscapes (28). Additionally, transformation of the waterways into green canals (24) offers the opportunity to develop recreational space on the water in the form of waterfront park (26), combined with ecological restoration of the aquatic ecosystem. Currently the municipality already has such

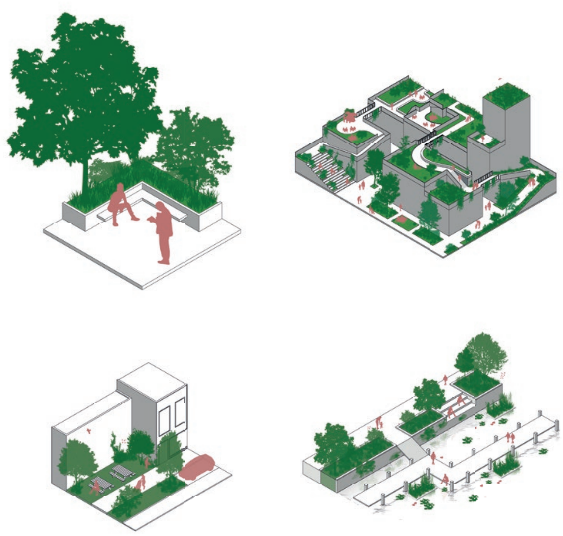


Fig. 42. Patterns that add outdoor recreation possibilities to under-used spaces.

plans for the Rijnhaven (Gemeente Rotterdam, no date b), but the analysis has shown that other areas would also benefit a similar transformation, such as the Coolhaven and adjacent Schie canal and the Wijnhaven. Pocket parks (19) can further be developed in areas in need for green recreation. These patterns are shown in Fig. 43.

4. Green routes connect parks with public transport and improve walkability

Even compact urban greenery takes up space in the city, which is scarce. Reducing the car dependency in the inner city while at the same time improving pedestrian connectivity and public transportation gives this space. Multi-level pedestrian networks (29) improve this walkability, just as using trees to create comfortable outdoor space (12) for green routes along streets that are currently car-dominated and perceived as unpleasant. The network aims to connect public transport nodes to green areas.

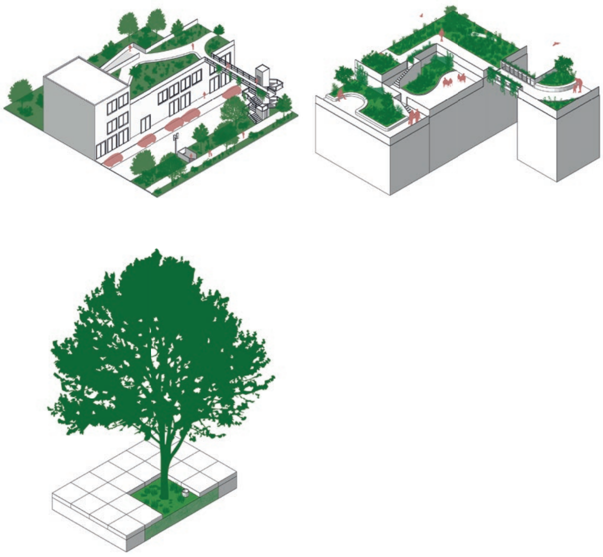


Fig. 43. Patterns that increase walkability

5. Invite community to be stewards of greenery and bring green space close to home

The well-being analysis has revealed the importance of green space close to people's homes. Community driven green space projects, such as facade gardens (13), rooftop habitats (15) and balcony gardens (11) can solve challenges such as the urban heat island effect and at the same time foster social interaction among people. The locations indicated in the framework for the depaving and green streets programmes are currently lacking sufficient green outdoor space to cool down during heat waves. It is therefore important that these locations are given priority in the realisation of green space close to

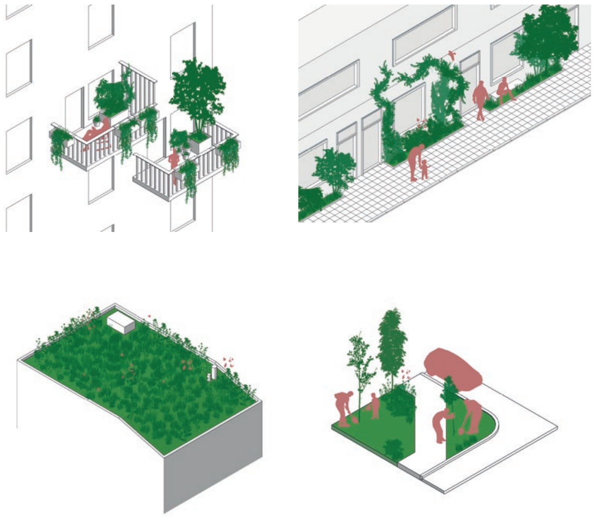


Fig. 44. Patterns that bring green space close to people

home. Patterns that could be used to bring the greenery close to home are shown in Fig. 44.

Nature types

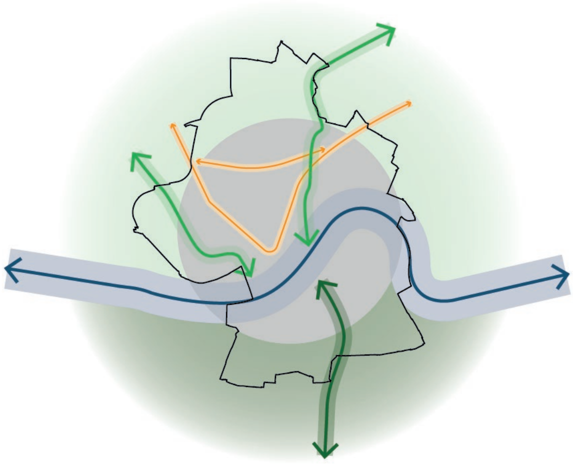
In the vision the term 'greenery' is used to refer to both terrestrial and aquatic habitats. As explained in the urban ecology analysis, there is a lot of variety in the type of habitat that is formed by greenery, depending on the vegetation used, environmental conditions and other factors. The illustration in Fig. 46 shows the desired types of habitats that the green space of the vision should contribute to. These habitats can be grouped into five main nature types, which are discussed below. It should be noted that this map applies to greenery on the ground level. Green space above ground level is subjected to different environmental parameters and will this be less related to native nature types. This is further explained in the Wijnhaven Eiland experimental design section.

Peat meadows & singels

This nature type consists of habitats that relate to the natural peat polders and meadows North of the city. The terrestrial areas are characterised by a large diversity of grasses, wildflowers and occasionally some shrubs. Trees are less common in this type. Water plays an important role is in this type. The water table is high throughout the whole year and there are many river banks and floatlands available. Species typical for these habitats are the flowering rush (*Butomus umbellatus*). In the vision this nature type is introduced into the city along the waterways that stretch out from the centre to the landscape around it.

Dry forests and large ponds

This nature type consists of habitats that are currently



Tidal river and alluvial forests

Peat meadows and singles

Floodplains and creeks

Dry forests and large ponds

Urban structures and canals

Fig. 46. Schematic representation of the target nature types for compact urban green space at ground level.

mainly found in the large parks around Rotterdam. These areas are characterised by tall and mature trees and large shrubs. The large ponds attracts amphibians such as the common newt (*Lissotriton vulgaris*). Other species prefer the shade of dense forests in this type, such as the red wood ant (*Formica rufa*). The vision aims to connect these regions and also aims to introduce this nature type to new urban development.

Tidal river and alluvial forests

Perhaps the most characteristic nature type of Rotterdam is the tidal river and the adjacent alluvial forests. The river Maas forms the most important structure. The connected harbours have the potential to reinforce this nature type with the development of tidal parks. Species characteristic for the tidal river and alluvial forests are the beaver (*Castor fiber*) and the critically endangered europeaan eel (*Anguilla anguilla*).

Floodplains and creeks

The meadows in the South of Rotterdam are much dryer when compared to the meadows North of Rotterdam. In these former floodplains species such as the Stoat (*Mustela erminea*) can be found. The creeks and ditches in this nature type also function as corridors that enable movement of species between the Maas and the Oude Maas in the South.

Urban structures and canals

As mentioned before, the dense urban centre can be seen as a new nature type that shares characteristics with mountain ranges. Species typical for this type are ferns that grow on canal and building walls and animals that originate from stony habitats, such as the pigeon (*Columba livia*).

Fig. 45. The ecological structure of the framework connects well to the surrounding landscape

Connection to the surroundings

The map in Fig. 45 illustrates that the framework for Rotterdam connects well to the surroundings. The framework itself also provides new wildlife corridors that were formerly missing. This mainly concerns the East-West connection in the North and the North-South connection in the South.

Implementation framework

The main structure of the framework is visible in Fig. 50. Blue arrows indicate the existing natural features in the city that could be used in the ecological structure. The black arrows are the currently missing connections between those natural features. Together, the arrows show the primary ecological structure. This structure is extended by a secondary structure, indicated with narrow green bands. A network that consists of multiple ecological corridors and habitats is more resilient, as it alternative corridors are available in case the main structure is facing disturbances that interrupt the structure.

The realisation of the structure will be more difficult in some areas than in others. Fig. 48 shows some of the possible projects that could result from the framework in a matrix. It can be seen that not all projects have an equal priority, as some are more important than others. Additionally, the complexity varies too. Projects with many actors and required large investment are rated more complex to realise than projects with little actors and at smaller scales.

The illustration in Fig. 50 also shows these complexities in a map. Besides complexities, there are also opportunities. The ecological analysis has shown that green spaces close to existing high biodiversity zones perform better and attract more species. Projects that are located in those zones have been indicated on the map. The map also shows large rooftop clusters with rooftops that are elevated less than 15m. These rooftops have the most potential in attracting insects (MacIvor, 2016). Lastly, locations where already new development is planned are indicated. These locations offer possibilities to include some of the more difficult larger patterns, such as topographic building blocks and rooftop landscapes. These patterns are more difficult to realise in existing buildings.

The map in Fig. 50 could be combined with a policy framework that provides guidelines and regulations on the amount of greenery that is required in each development.

A variety of methods can be used to persuade actors in realising compact urban green space. The type of method depends on the willingness of the actor to cooperate and the phase the framework is in (see also phasing). This willingness can be categorised with the diffusion of innovation model by Rogers (1995). This model is shown in Fig. 47.

In the first phase, information on the development and possibilities of compact urban green space could be shared and promoted. This can kick-start the first projects by the group that is most willing to cooperate: the innovators. To also convince early adopters and the early majority, subsidies can be used. These subsidies do no only have to come from the municipality, but can also be paid by other parties that profit from more greenery in the city. For instance, a Dutch insurance company is already promoting green (roof) development as this results in better overall health of their clients and reduces claims for damages (Interpolis, n.d.).

To persuade the last and most difficult groups, stricter regulations can be developed. The experiments with the development of compact urban green space in the first phases can help to define these regulations. An example of such regulations is the green plot ratio that is used by the Urban Redevelopment Authority of Singapore (Urban Redevelopment Authority, 2017). This metric is used to not only quantify green space as a percentage of the total plot size, but can also be combined with qualitative aspects. For instance, urban development along the primary

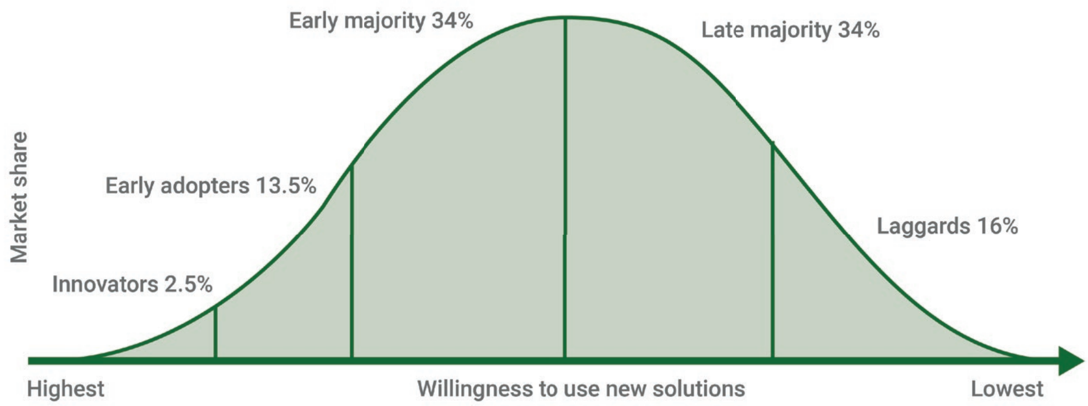


Fig. 47. Diffusion of innovation by Rogers (1995) categorizes actors in their willingness to use a new solution.

network could be forced by the municipality to have a green plot ratio of at least 100%. Qualitative aspects may be added to this guideline with the introduction of weights. E.g. green space that is accessible counts double, just as green space that provides space for natural processes. On the other hand, green space that only consists of a few vegetation species may count only for half of its size. The design principles that were presented in this thesis in the well-being and ecology chapter can be used for this.

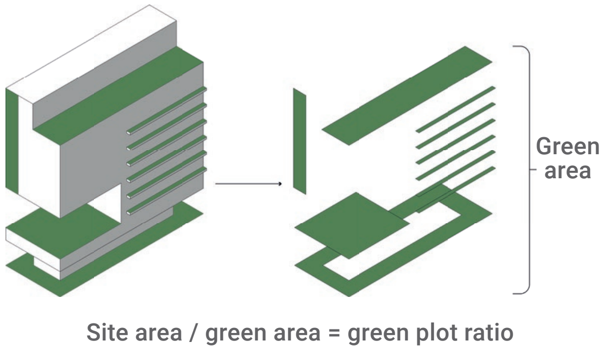


Fig. 49. Green plot ratio can be used to quantify compact urban green space and set regulations accordingly.

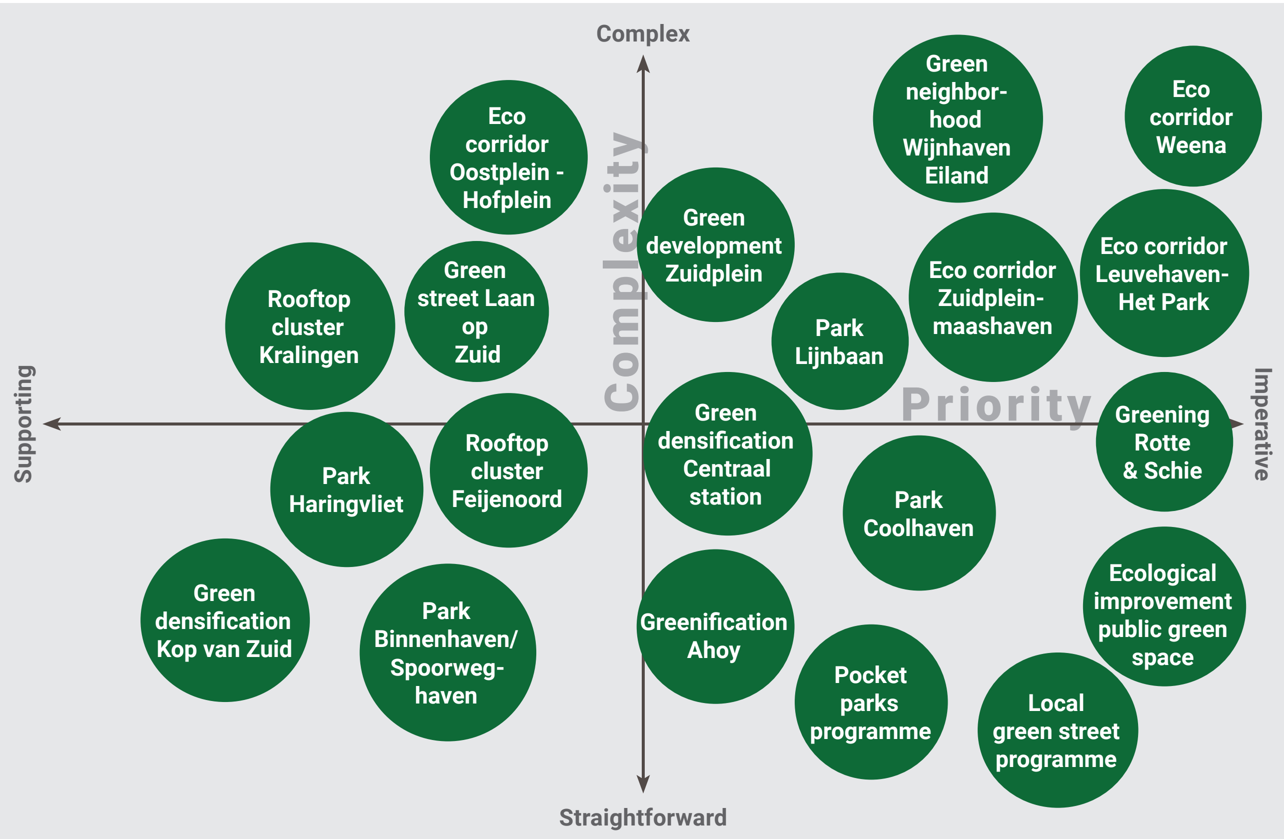


Fig. 48. Complexity-priority matrix of projects

Fig. 50. Opportunities and challenges in realizing the ecological structure

Strategy and phasing

First phase

Projects that are crucial for the development of the vision, but also relatively straightforward to implement are realised first. In this phase the availability of information is key to encourage innovators and early adopters to start with the development of compact urban green space. This phase includes:

- Diversification of existing green spaces: move towards nature-based greenery (1a) and allocate areas for spontaneous greenery (1b).
  Involved actors: owners of green space (municipality, businesses, housing corporations, house owners)

- Invite community of neighbourhoods suffering by severe heat stress (indicated in Fig. 51) to green facades, rooftops and streets.
  Involved actors: municipality together with local community organisations. actors: citizens of Rotterdam

- Setting up of a platform to collect and distrubute information on the development of compact urban green space.
  Involved actors: innovators and green businesses.

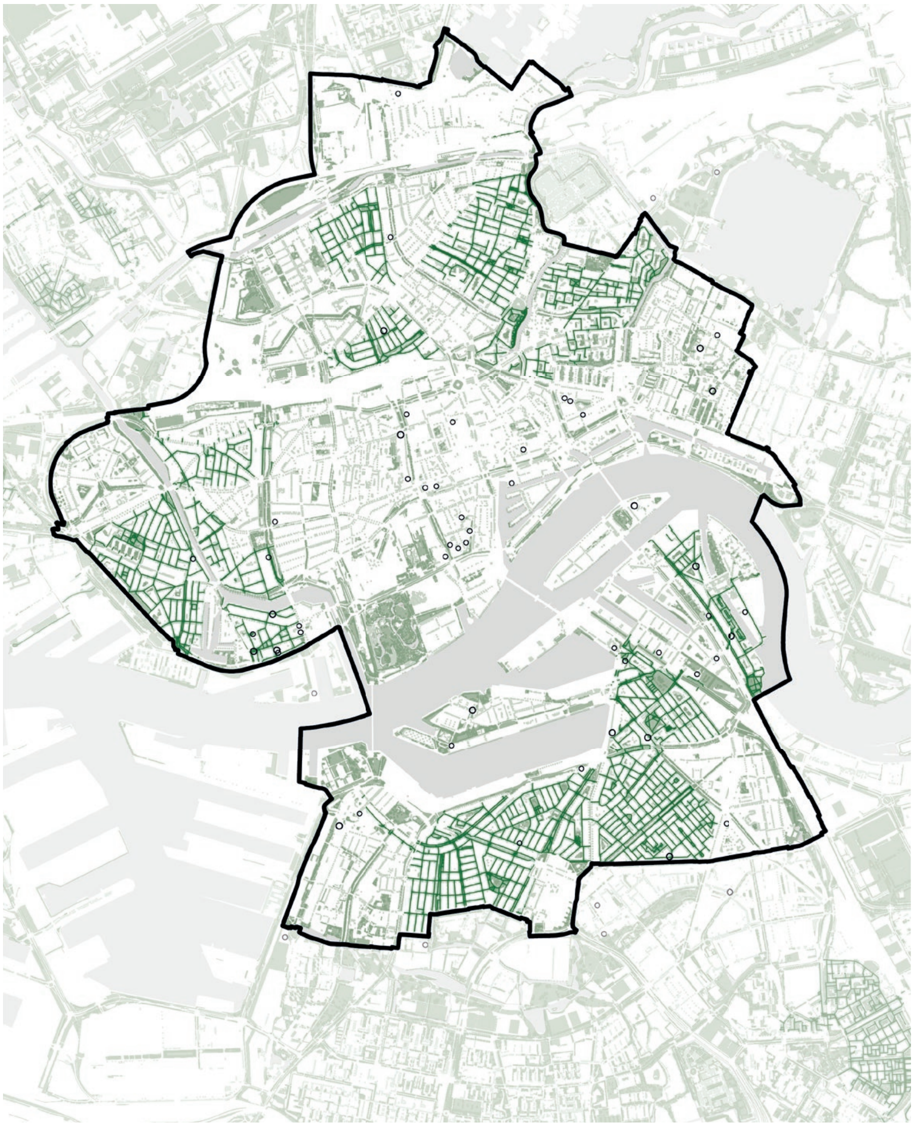


Fig. 51. Phase 1, small scale initiatives and qualitative improvement of green space

Phase 2

Phase 2 elaborates and expands the projec
there is still some expirimentation. A conso
development of green space provides sub
phase includes:

- Diversification of green space has
  Building greenery is used to enhance
  clusters close to high biodiversity
  habitats. See Fig. 52 for clusters
  Involved actors: owners of rooftops, n

- Formation of a consortium that can pr
  Involved actors: insurance companies

- Increase rooftop accessibility and con
  programmes that have become feasib
  Involved actors: local businesses, buil

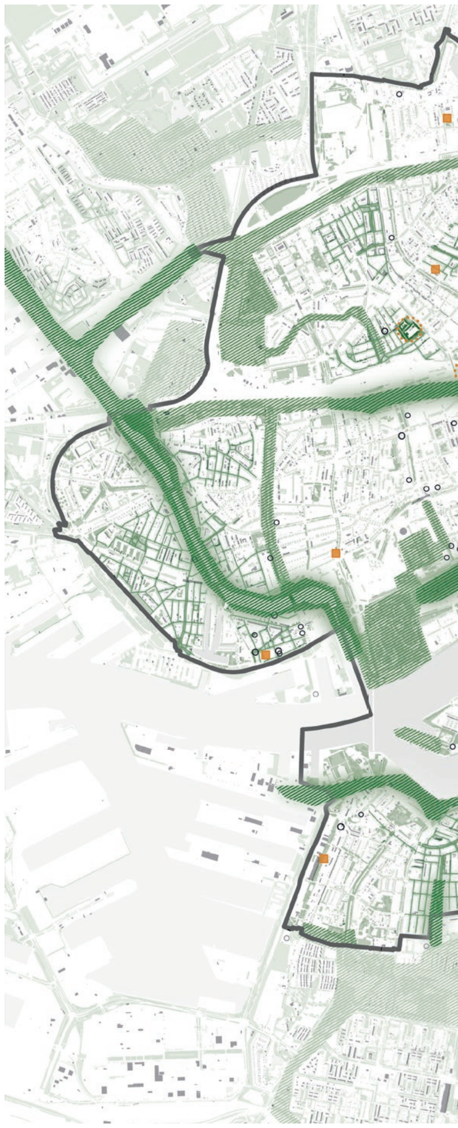


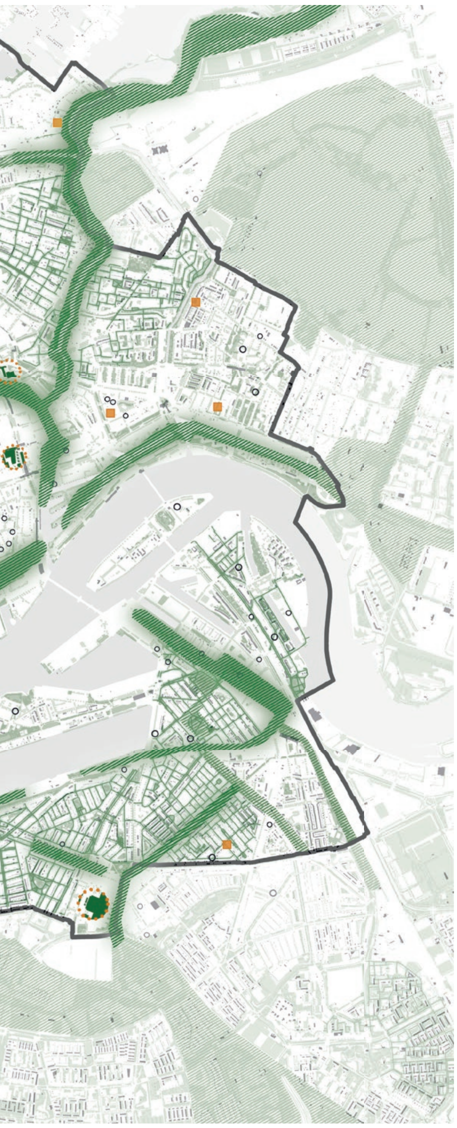
Fig. 52. Phase 2, ecological corridors, roof

cts and initiatives of phase 1. In this phase ortium of actors that has benefits from the sidies to persuade the early majority. This

created new valuable green corridors. e and extent the corridors. Large rooftop y areas are transformed into rooftop (>250m²) with low elevation (<15m). municipality, green roof businesses

rovide subsidies
, municipality, other involved stakeholders

nectivity. Start of the first green injection le due to subsidies.
ding owners, municipality



ftop projects and pioneering experiments

Phase 3

Experiments of phase 2 are used to establish new greenification techniques. Green corridors form a network and connect high biodiversity areas (both parks and biodiverse neighbourhoods) to protected nature reserves outside Rotterdam. A green plot ratio that addresses quality and quantity of green space is introduced to persuade the late majority and laggards. Developing compact green space has become the standard.

- Activated rooftops are connected and form rooftop landscapes that are well-connected to the public space at the ground level. A pedestrian network connects new and existing parks with public transportation and is integrated into the connected rooftop structure.
- Green densification injections use the lessons learnt from the experiments and are now mandatory for new developments. The 100% green plot ratio policy is applied to new buildings and renovations along the ecological corridors.
- There is space for spontaneous development of vegetation and for bottom-up initiatives led by citizens that make the city greener.

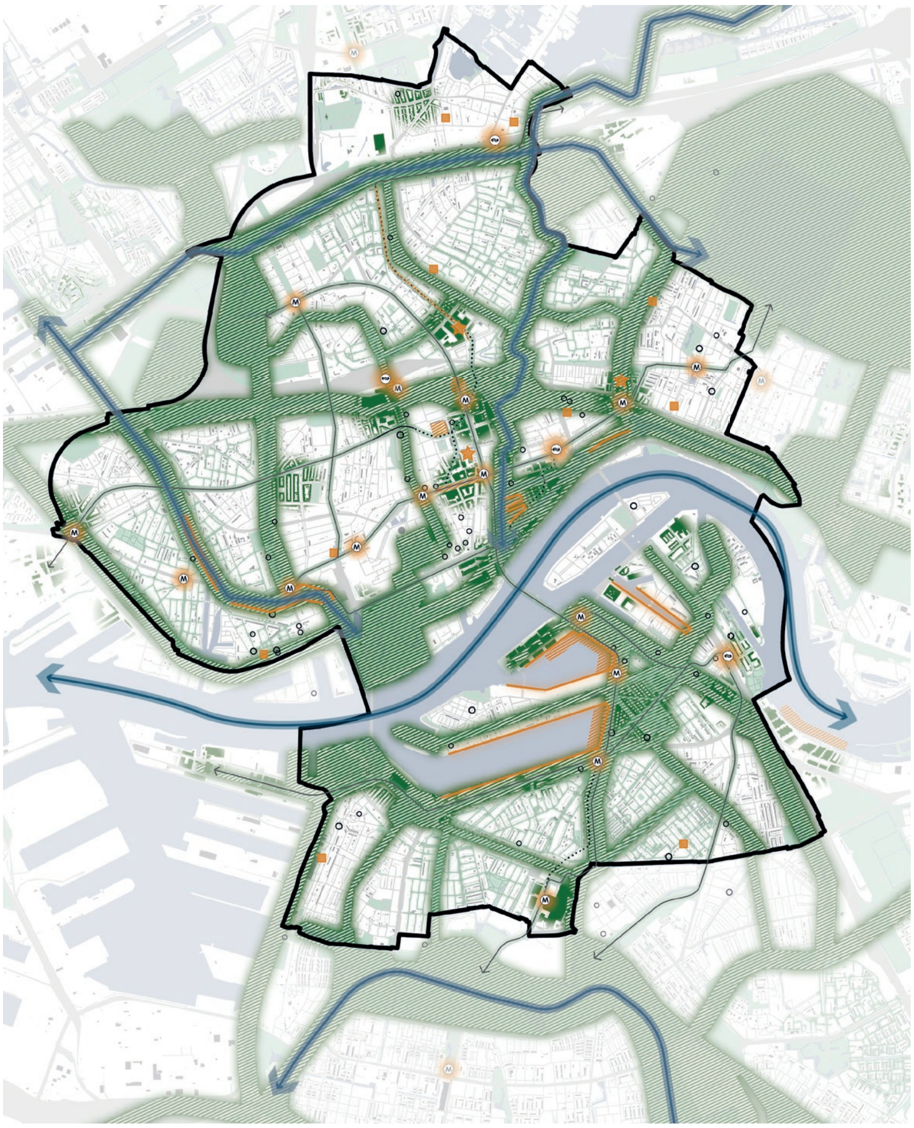


Fig. 53. Phase 3, resilient ecological structure and green neighbourhoods

Design experiment Wijnhaven Eiland

In this section, the Wijnhaven Eiland in Rotterdam is used for an experimental design that tests both the developed compact urban green space patterns and the framework for Rotterdam.

The Wijnhaven Eiland is located in the historic city triangle of Rotterdam. After all of the buildings were destroyed during the Second World War, the centrality of the island quickly prove to be an attractive location for new development. Initially, offices and industrial buildings were developed during the reconstruction of the centre according to modernistic principles. Currently, these buildings are rapidly getting replaced by high-rise apartments that fit into the current compact city development vision. The island is a perfect example of a dense and compact urban area without space for conventional green spaces. Fig. 54 shows some of the challenges and opportunities the island is facing.

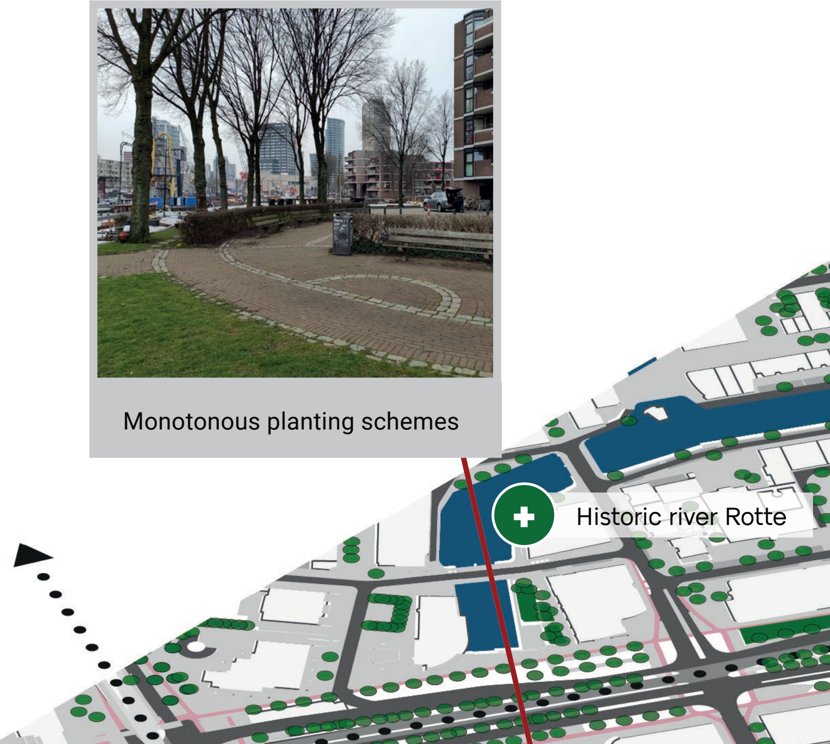
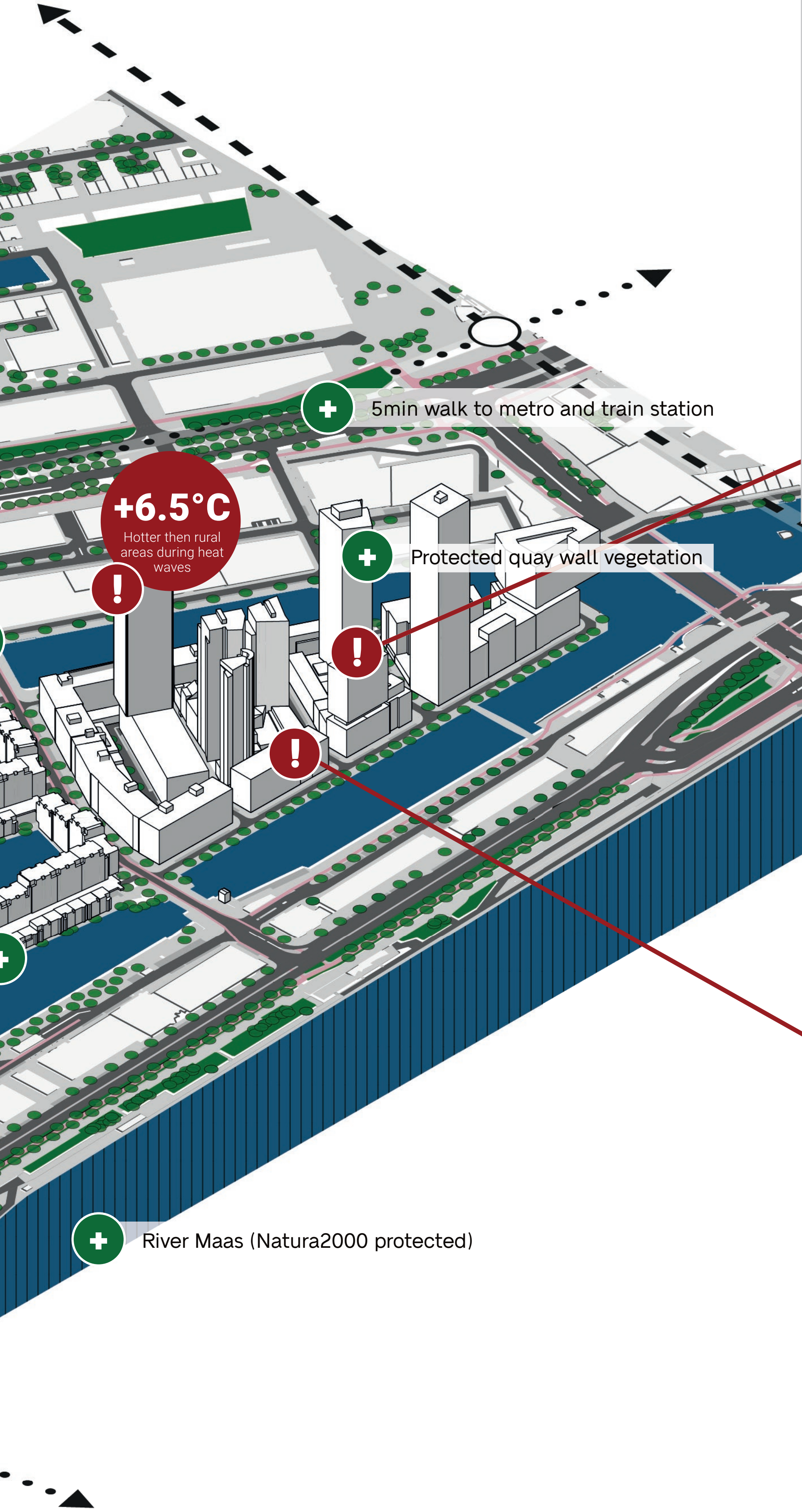


Fig. 54. Wijnhaven Eiland




Streets completely devoid of green space


Disconnected proposed building greenery. Image courtesy of Stebru

Applied pattern: living building envelope

Instead of the conventional practice of selecting one target habitat, multiple habitats can be aimed for when green space is approached in a multidimensional manner. This is similar to the natural distribution of habitats in mountainous regions, which can often be correlated to elevation. Habitats should be chosen in such a way that they are compatible with the environmental conditions of the urban fabric. Habitats are in the first place locally-inspired (see Fig. 46), but can also be more exotic when the urban environmental conditions do not meet the requirements of local habitats. The reference biotopes suitable for the Wijnhaven environmental conditions are shown in Fig. 56.

Different compact urban green space patterns can be used to create the different reference biotopes. This is shown in Fig. 55.

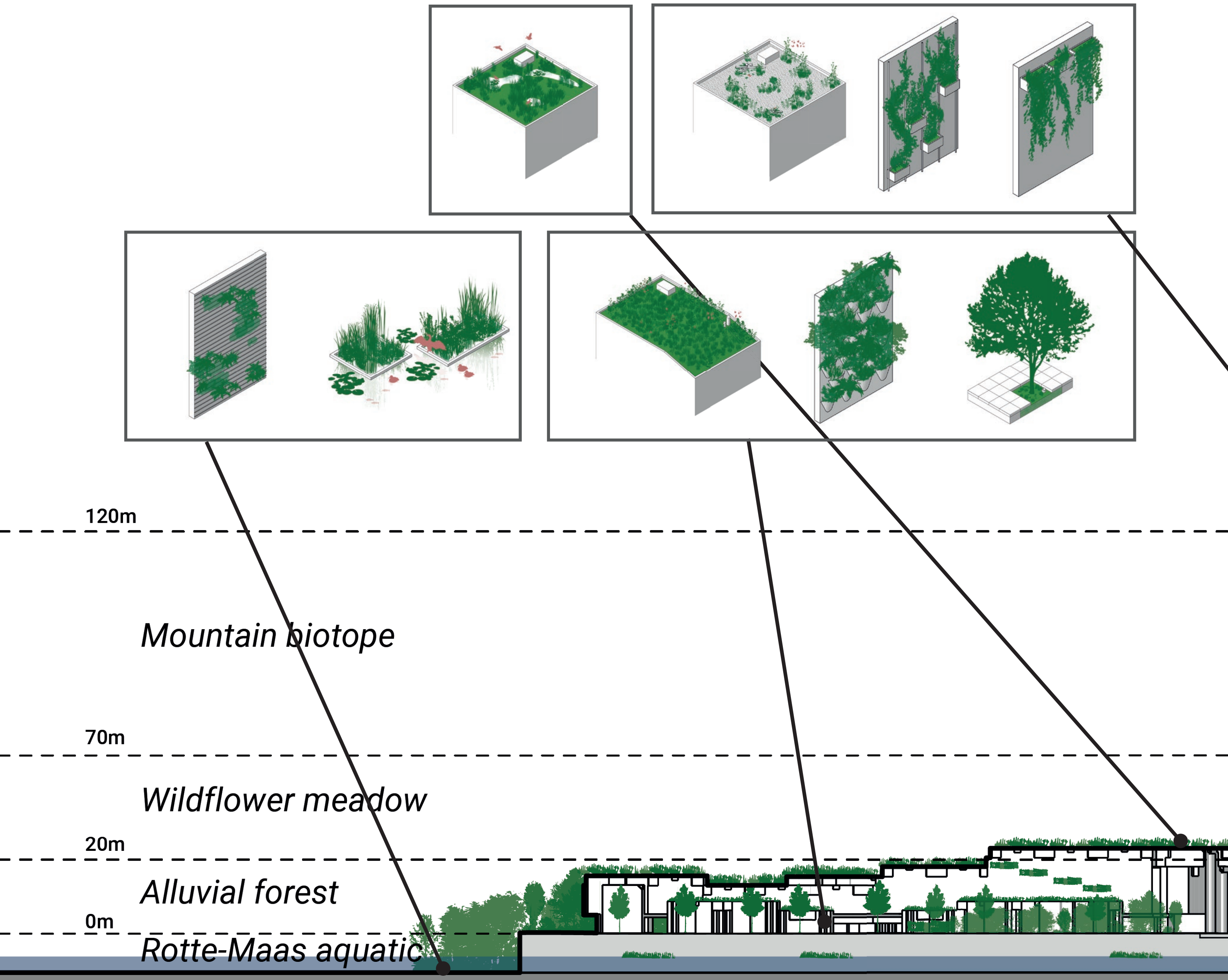


Fig. 55. Layered urban ecology concept and matching compact urban green space patterns

Fig. 56. Reference biotopes

70-120m Mountain biotope

The harsh environmental conditions at these heights such as strong winds and extreme temperatures are only tolerated by species originating from mountenous areas.

Reference biotope: European mountain ranges

Ambassadors: Peregrine falcon *(Falco peregrinus), Alpine swift (Tachymarptis melba)*

10-70m Wildflower meadow

Rooftops just over 10m are still visited by insects and thus can be used to attract insects. Since placing trees at these hights becomes resource intensive, wildflower meadows can be created that provide food and shelter for insects and birds and profit from the sun that reaches these roofs.

Reference biotope: Wildflower meadows

Ambassador: Blue rock thrush *(Monticola solitarius)*

0-10m Alluvial forest

Larger trees require more moisture and are not feasible on tall buildings. At the ground level a forest provides many additional benefits such as shade for people and habitat for many species.

Reference biotope: Oude Maas (Natura2000)

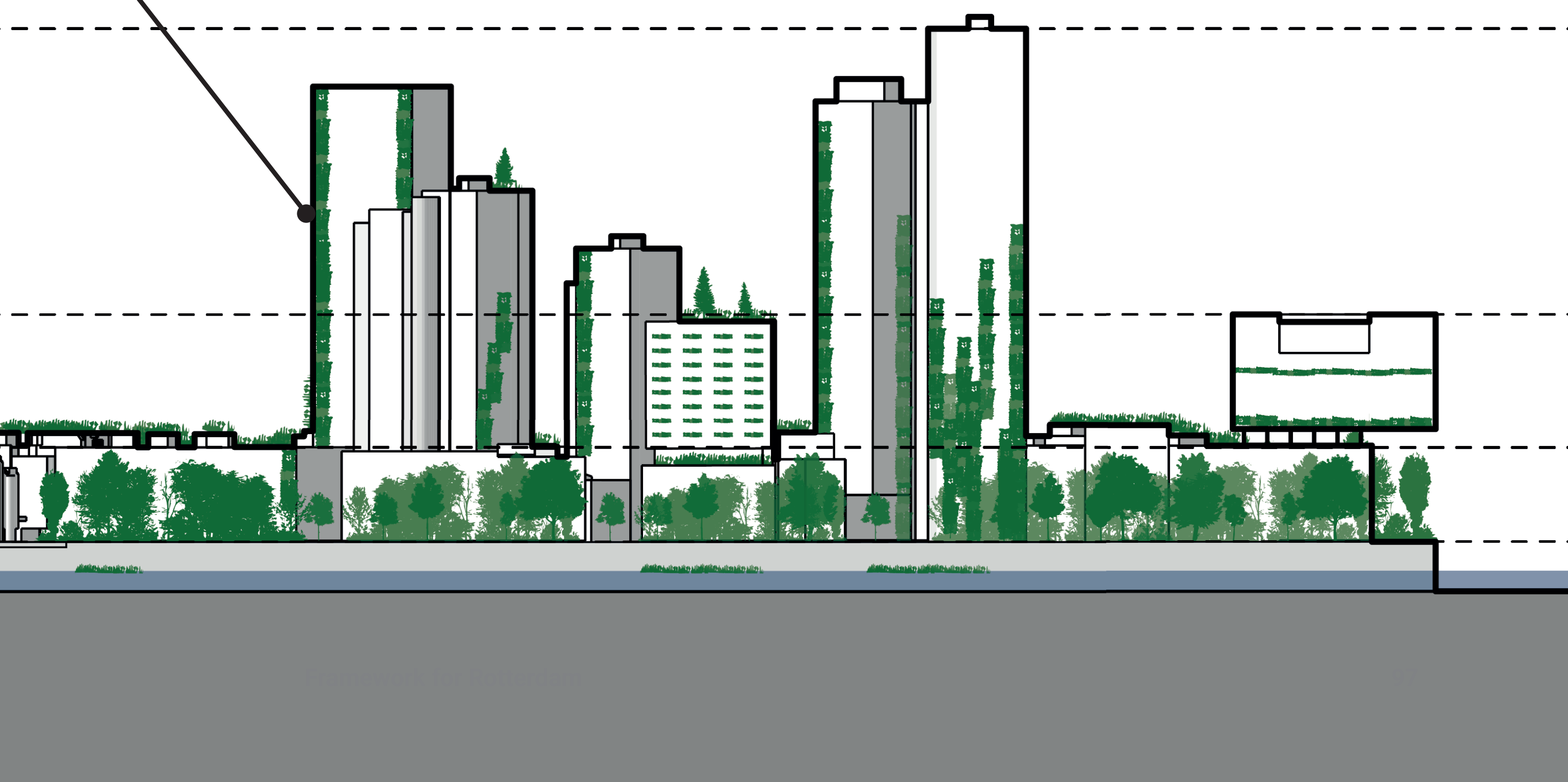
Ambassador: Poplar admiral *(Limenitis populi)*

<0m Rotte-Maas biotope

The aquatic biotope should connect to the existing Rotte and Maas biotope. Ecological value can be enhanced by reintroducing tidal forces.

Reference biotope: Oude Maas (Natura2000)

Ambassador: European eel *(Anguilla anguilla)*



Applied pattern: biodiverse neighbourhood

The biodiverse neighbourhood pattern does not only adds greenery to the neighbourhood, it also aims to transform the complete island into a publicly accessible park. The rooftops and a tidal park in the harbour attract residents from the whole of Rotterdam. Rooftops are connected together and form a rooftop landscape with space for various amenities.

Parking spaces are partly replaced by sharing car facilities and road networks make place for a green park at the street. Redeveloped building blocks form topographic buildings and connect green at the street with the rooftop park. Cafés, shops and other businesses located on the island are encouraged to participate in the development of the park, and can greatly profit from the new space for rooftop amenities such as outdoor gyms, terraces, lounges and playgrounds.

This altogether results in a new iconic green project that may even be a new tourist attraction in Rotterdam.

A top down view of this design can be found in the appendix 6.4. Fig. 58 and Fig. 59 show a visualisation of this neighbourhood.

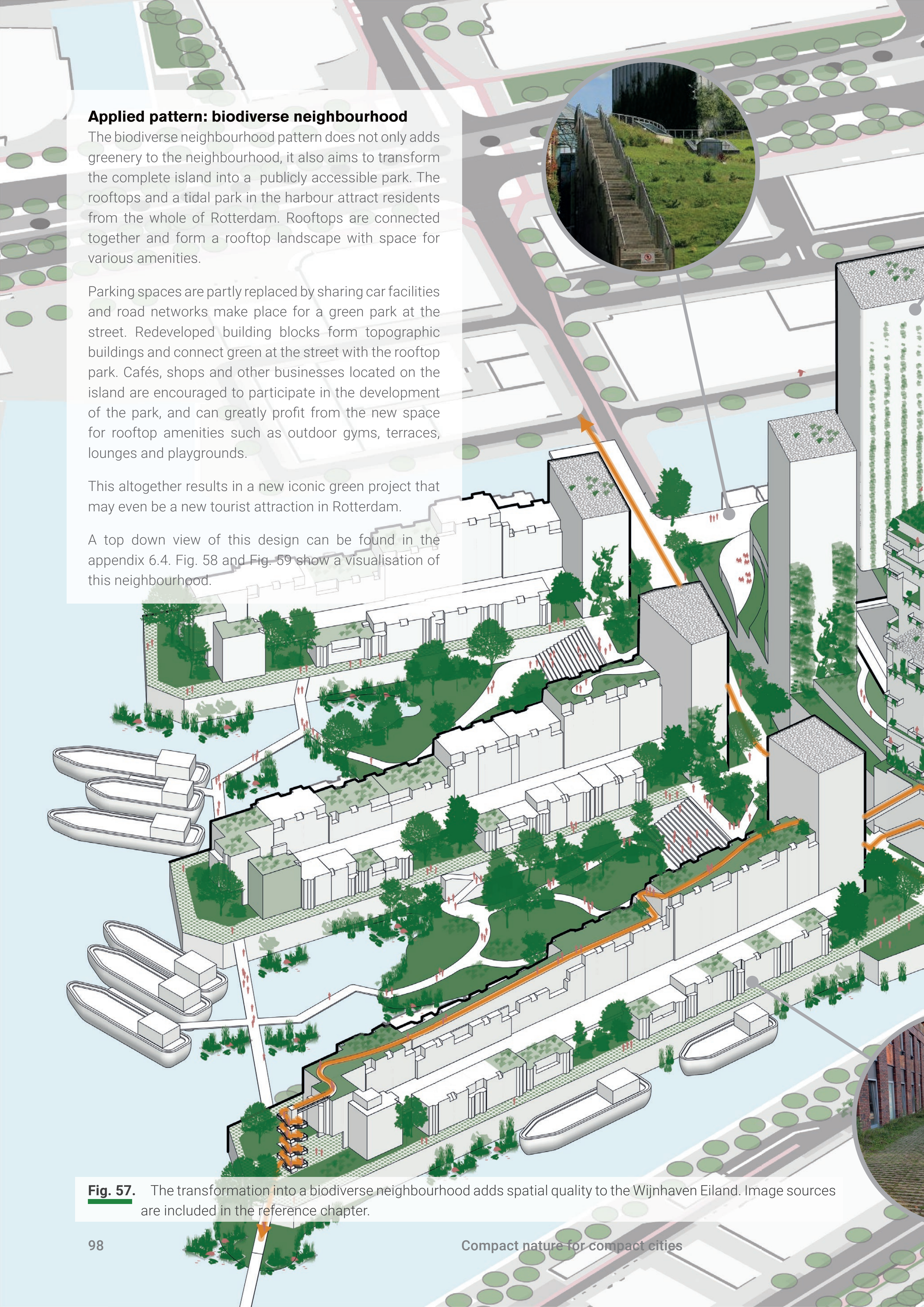


Fig. 57. The transformation into a biodiverse neighbourhood adds spatial quality to the Wijnhaven Eiland. Image sources are included in the reference chapter.

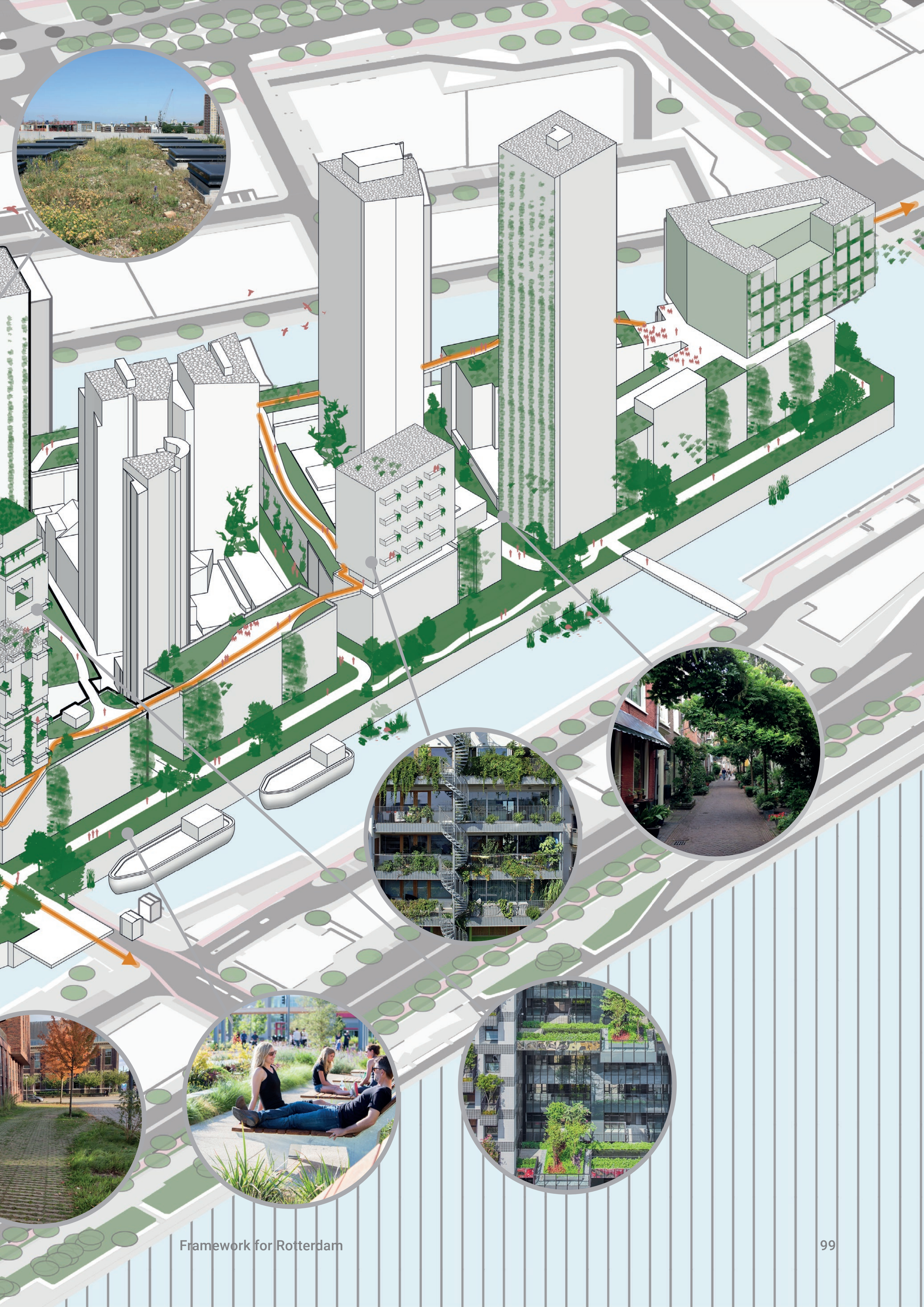


Fig. 58. A rooftop cafe that is part of the rooftop landscape

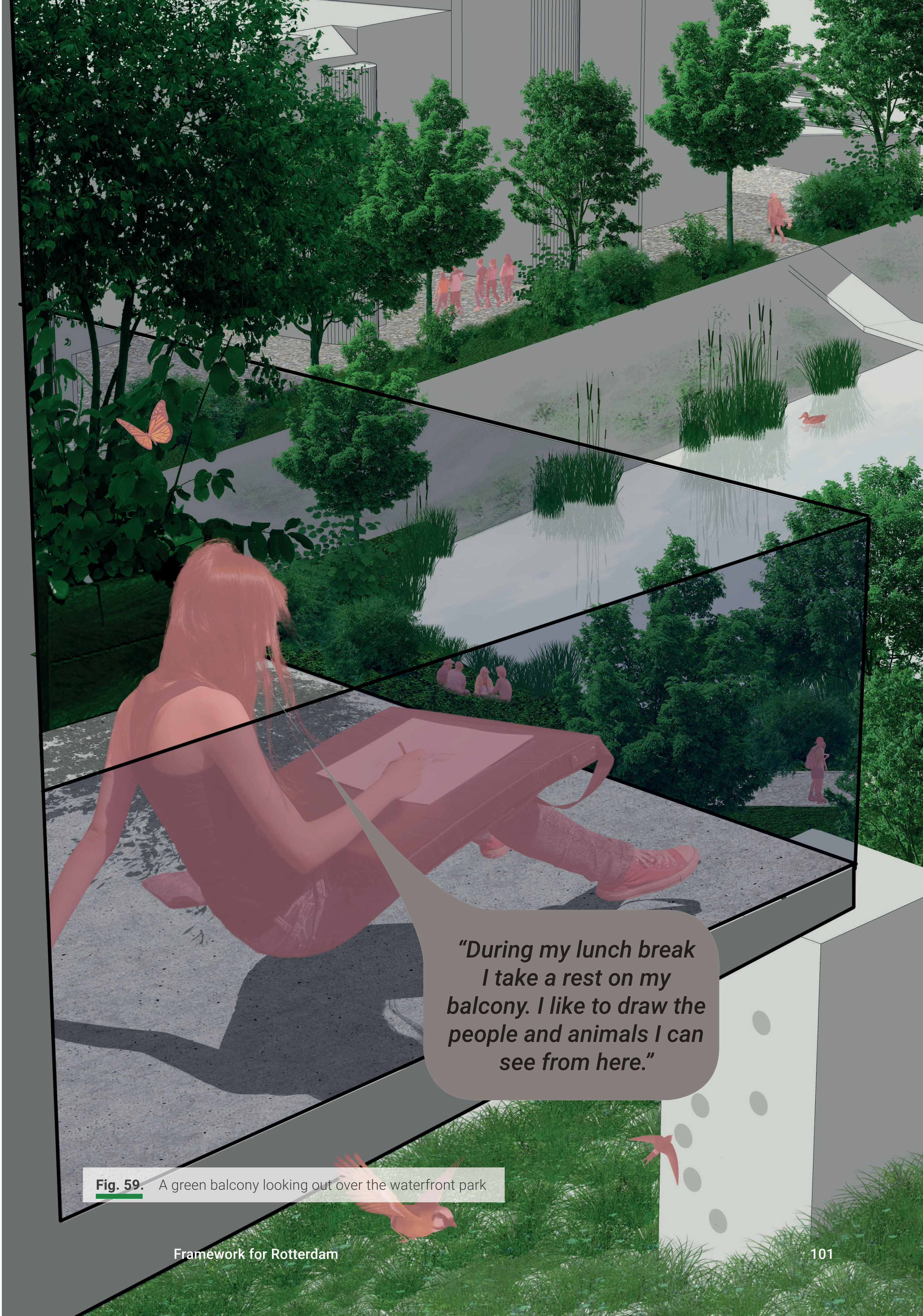


Fig. 59. A green balcony looking out over the waterfront park

Conclusion

The presented framework and design experiments answer the sub research question of *"What spatial vision and strategy can be used to guide the development of the compact urban green space patterns in Rotterdam?"*. It can be concluded that the development of compact urban green space should be integrated and connected to existing initiatives. Hence, the framework is not a novel blueprint for the city. Rather, it builds on and connects existing qualities. The spatial structure provided by the framework is fixed, but the spatial elaboration will be a result of the many actors involved in the process. The patterns included in the framework prevent proliferation of green projects that add little value to the city by providing development guidelines.

Greenification of existing structures and spaces can be difficult, especially when compact urban green space concerns built structures. It is therefore important that new developments take on a role of providing qualitative green features for their surroundings.

It is essential that new developments take on a leading role in providing qualitative green features that improve their surrounding

The municipality has a principal role in initiating the projects. Eventually, private developers and local communities are encouraged to use the compact urban green space patterns to add quality to the city. The framework should be implemented in different phases. Each phase correspond to a certain planning instrument that encourages actors to get involved.

The design of the Wijnhaven Eiland gives two examples of this strategy. It shows that even in dense and compact areas green space can still add quality to the city, in the form of ecological improvement and increased well-being. It also shows that the addition of greenery results in a variety of benefits that are not limited to ecological improvements.

In the next chapter, a main conclusion is given that is based on the separate conclusions of each chapter.

Image courtesy of Author

08

Conclusion and reflection

Conclusion

Rotterdam is, just as other compact cities, facing serious challenges related to well-being and ecology. Urban green space can mitigate many of these challenges. As compact development remains the dominant planning paradigm, the notion of urban green space should be amended to include compact urban green space.

The main research question of *"What framework can be used to guide development of compact urban green space in Rotterdam that addresses both the quality, in terms of well-being and ecology, as well as the spatial-ecological structure?"* can be answered by combining the answers of the sub-research questions.

Compact urban green space can increase ecological resilience in Rotterdam by increasing the carrying capacity, biodiversity and fitness of the current ecological system. Concrete, this means the green space provides habitats for and facilitates movement of species that already exist in the area and new species that fit well in the urban environment.

Regarding the design of urban ecological systems there are roughly two options which are promising to realize. First, environmental conditions around green space can be altered to resemble the natural environment outside the city. This yields in habitats for native species and mitigates the homogenisation of species in cities worldwide. Second, non-intervene zones can be designed where natural processes such as succession are allowed to take place. This will yield in a new type of resilient urban ecosystem. There are still little examples of the potential of novel ecosystems adapted to the urban environment. Further research and experiments will need to be done before we can truly estimate the value of urban ecosystems. Little is known about the possible climax stadia these systems could achieve, but this likely resembles that of warmer mountainous regions.

> **Little is known about the possible climax stadia of urban ecological systems, but it will likely show similarities with systems of warmer mountainous regions**

Compact urban green space can also improve well-being when it mitigates ecosystem disservices and creates ecosystem services that address prevailing challenges of a specific area. In the case of Rotterdam, compact urban green space could reduce the urban heat island effect, improve walkability, add recreational spaces and increase space for gardening and other outdoor activities.

Addressing both ecology and well-being requires proper planning and design. The relation between well-being and ecology is complex and varies depending on personal and cultural preferences. Some conclusions drawn are more ambiguous than others, and as many benefits concern indirect external effects, the direct relation is not always clear and predictable. It should be noted that the majority of research on benefits of nature for well-being concentrates on the positive effects of vegetation, while the majority of research about urban ecology focusses on the larger living organisms, such as birds. This mismatch makes it harder to link urban ecology to well-being, as both parties are talking past each other. People concerned with well-being and greenery may be missing the larger picture of the ecosystem that is required to sustain green space. People interested in urban ecology perhaps have difficulties to understand that not every citizen is waiting for more uncontrollable animals in the city.

Most research about the benefits of nature for well-being focusses on vegetation, while urban ecology tends to have a bias towards (larger) living organisms

Nevertheless, both reference projects and previous research shows that nature in cities can improve the spatial quality and contributes to a comfortable environment. The pattern atlas is a collection of these examples, and stresses that the value of compact urban green space for well-being and ecology increases when it improves the aspects at multiple scale levels.

The benefits of green space are not always clear and predictable. Nevertheless, both reference projects and previous research show that nature in cities can improve the spatial quality and contributes to a comfortable environment

The city is a place where many different interests interlace. Especially in densely built urban environments, it can be hard to make space for greenery and allow natural processes to occur. The competition for space and interests makes it attractive to implement easy solutions, but in the case of compact urban green space, these are not always valuable.

A clear framework can provide guidance and prevent a proliferation of green projects. The framework for Rotterdam illustrates that the spatial-ecological structure is a result of the existing ecological qualities and biodiversity zones. Urban green space does add quality in many ways to the city and does not have to be limited to large open areas. When buildings become an essential part of the green structure, new opportunities to tackle urban challenges arise. Not all compact urban green space patterns can be added afterwards to existing buildings. It is therefore important that new developments take the role of providing qualitative green space for the city seriously, and fundamentally integrate compact urban green space into the design.

Since the challenge of adding green into dense urban environments is incredible relevant to many other cities, it may be strategic for Rotterdam to start quickly and take on the lead. Rotterdam can serve as an example city to show how qualitative green space can be added to existing compact cities. This can be a clever strategy to achieve a head start and anticipate on the current developments and demand for qualitative compact green space in many developed cities.

Rotterdam has the potential to set an example for other compact cities by showing that green space can not only solve urban challenges but also adds quality to the city for people and nature

Reflection

Societal relevance

Increasing green space in cities and restoring native ecosystems is extremely relevant to the society. Besides the well-being related benefits discussed in this thesis, the performance natural ecosystems can also be directly linked to supporting human life. From the oxygen we breathe to the food we consume and the materials we use; it is all produced by a functioning ecosystem. Hence, it is of vital importance that we protect and value these ecosystems. This is currently not the case, as the WWF clearly stated in its latest living planet report: “The findings are clear: our relationship with nature is broken" (WWF, 2020). The results are especially apparent in cities, where most of the world's population lives (United Nations, 2018). However, in these same cities there is an enormous opportunity to use natural ecosystems to mitigate the challenges. Furthermore, what makes green space and ecosystems in cities interesting is the potential for people to interact with it. This thesis aimed to illustrate that this interaction can increase the quality of life in urban environments.

The Coronavirus pandemic demonstrates the importance of accessible green space close to home. In a time where people crave for the outdoors and the natural environment to escape their stresses, green space close to home has never been more important. It also reveals that compact urban development results in both positive and negative effects. The positive effect is that there is plenty of unbuilt green space around the city to enjoy, while the downside can be found in the lack of green space in the city.

Financial and political feasibility

While the relevance of compact urban green space is great for society as a whole, the costs of greening dense cities can be high for private parties, making large interventions infeasible. As benefits of green space in cities are often external, it is hard to estimate their financial value. Luckily, large institutions and companies that do profit from these benefits (municipalities, insurance companies) have begun to recognize the value of green space and also promote the usage and construction of it (Gemeente Rotterdam n.d.a; Interpolis n.d.). This is a very promising business model that can contribute to future green cities.

This thesis did limit the benefits of green space to just two aspects: well-being and ecology. This definitely helped in telling a clear story, but can also be dangerous. There are so much more advantages of using greenery. To create political support for these interventions it is important to point out synergies with other challenges that the municipality is working on. The development of compact urban green space contributes to many other goals of the municipality. For instance the compatibility with climate adaptation. Green rooftops can temporarily store water, relieving the stress of the sewage system after a heavy downpour. Unpaved areas allow water to infiltrate, relieving the system even further (Resilio, n.d.).

Danger of greenwashing

When it comes to sustainability there is always the danger of greenwashing. Greenwashing is defined as "a form of marketing in which green values are deceptively used to persuade the public that an organization's products, aims and policies environmentally friendly." (Wikipedia, 2021). It is not uncommon for businesses to misuse compact urban green space to disguise their environmental impact. Similarly, the environmental footprint of a concrete skyscraper is not all of a sudden diminished when the facade is covered by plants. It should therefore be noted that using compact urban green spaces to improve urban quality does not grant one with the permission to harm the environment in other ways. Also, the use of compact urban green space cannot be an excuse to replace existing areas with high biodiversity. Green roofs for instance, are not as valuable as ground level habitats (MacIvor et al., 2011). Furthermore, the addition of a few green roofs does not replace large amounts of lost green space, as was found in a remote sensing study in Amsterdam (Giezen, Balikci and Arundel, 2018).

> "The 40,000 m² of green roofs is a drop in the bucket towards compensating the 3 million m² of green space lost over the previous decade or so"
> (Giezen et al., 2018. p. 11)

Hence, these features should be an addition to the green space in and around cities. When used correctly, they can facilitate compact development, which further limits the negative impact of cities on biodiversity (McKinney, 2002).

Research methods

In this thesis both research and design are used as methods to gather data and to draw conclusions. The analysis of the first chapters was mainly executed using deductive reasoning. The advantage of this method is that the concluding principles, based on the analysis, are scientifically sound and backed up by research data. The disadvantage however, is that these principles are also very generic and not directly applicable to construct the framework for Rotterdam.

In the design of the framework, the method of mapping spatial data proved to be the most useful. The selection of spatial data that had to be mapped was based on the analysis of both scientific literature and policy documents by the municipality, resulting into well-founded maps. This way of inductive reasoning (based on the deductive theory) has resulted into the final framework that could answer the main research question. The disadvantage of basing the framework mostly on available spatial data is it may ignore informal structures and data which have not been mapped yet. This is a limitation of this research, all the more because due to the pandemic site visits and contact with local communities had to be limited.

A large part of the framework is the atlas with green space patterns. These patterns were created using a pattern language approach, coined by Christopher Alexander (Alexander, 1977). This method was very helpful in organising many small ideas and interventions into a larger and interconnected framework. It also helped me to understand relations between patterns and to explore ideas at different scale levels without losing the overview. Since the pattern language approach aims to identify general patterns, I found it hard to illustrate the possible variety a pattern can have based on the context it is embedded in. To combat this problem, some patterns were described using multiple spatial examples, such as the rooftop habitat. The approach does still not completely justify the diversity of possible solutions to a pre-defined problem. Furthermore, spatial, social and cultural context are often simplified for the sake of creating an easy to understand pattern. The advantage of this is that it has resulted into a pattern atlas with very comprehensible patterns. These can be used as a communication tool as well as a tool to further explore and expand the pattern study.

In the beginning I had anticipated to also include data collected from an on-site rooftop garden experiment at an external company. Unfortunately, the planning and realisation of this experiment took more time than expected, resulting in a very short time span to conduct measurements. While the results are certainly not useless, the data from the experiment did ultimately not influence any of my design decisions.

Scientific relevance and transferability of the results

As compact development remains the most dominant planning paradigm (see UN-Habitat, 2015; Gemeente Rotterdam, 2018; Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2020), research should be conducted on possibilities to include green space without compromising on compactness. This knowledge contributes to reinforcing the compact city theory by making the model more valuable for both people and nature.

Urban ecology is a young field, but its research output is growing incredibly fast. Unfortunately, much research data on novel green spaces such as green roofs and walls is limited to single elements and this makes it also difficult to predict what will happen when multiple elements are combined. The compact urban green space patterns and the vision in Rotterdam are based on a lot of assumptions and research of small scale elements. Nevertheless, there is scientific consensus on the effects that these patterns can achieve when used at larger scale levels and for complete cities (Beatley, 2017).

The two outcomes of this research (the pattern atlas and the spatial-ecological framework for Rotterdam) have different transferability. As the patterns in the pattern atlas are largely generalised, these are very well transferable to other compact cities. The spatial manifestation of a pattern might be different, depending on cultural and spatial context, but the working principle remains the same. The framework for Rotterdam is less transferable to other cases, as this framework is based on the specific challenges present in Rotterdam. The method used to construct this framework can be transferred, but the framework itself is highly context-specific.

As this whole research has been set up to fit in the context of compactly developed urban environments, the results may less suitable for cities that are spread out. In those cases, there are simply other (more cost-effective) interventions to introduce green in the urban fabric, such as large parks and wide green streets.

Ethical considerations

Because of its desirability, urban green space is often associated with the increase in housing prices and gentrification. This is a serious issue for two reasons. Firstly, cities in general are coping with raising housing prices, as the available housing stock fails to meet the demand. Adding green space in cities and thus making them more attractive will likely reinforce this trend. This contributes to the increase of the housing prices. The second issue is that neighbourhoods that currently house low-income groups are often the same neighbourhoods that lack green space and experience issues regarding well-being. In such a case, simply adding green will not solve well-being problems of existing community but might make it worse, by increasing housing prices. Therefore, equal distribution of the benefits of green space should be aimed for. However, this can be hard to achieve in practice and requires governmental interference.

The subjectivity and complexity of the topics of ecology and well-being also raises the question whether it is even possible (and desirable) for the designer alone to address these issues successfully. Nature itself is a complex concept that knows many interpretations. When the designer has to design and create nature, the origin of the nature will always be determined by human decisions. Especially in cities where space is at a premium, it will be hard to completely surrender to nature. Furthermore, this approach will likely also not result in a contribution to well-being, as ecosystem disservices can dominate.

The other end of the spectrum, completely planning out and steering natural development is also undesired, as this will limit natural processes and result in artificial ecosystems. Furthermore, knowledge on creating natural ecosystems is very limited. We will likely never completely understand the functioning and composition of nature, let alone be able to artificially recreate it.

This same trade-off can be described for well-being. Only imposing top-down interventions fails to take into account the individual needs and preferences of people, but relinquish total control will result in a untenable situation. That is why the outcome of the research is a vision, and not a master plan. With the engagement of actors and a steering approach, instead of a dictating approach, the design becomes much more valuable. This holds both for people, in the form of co-design and participatory trajectories, and for nature, in the form of creating opportunities for natural processes to occur.

It is difficult, if not impossible, to value ecology and nature on itself by not taking into account its value for people. Ecology and nature remains a social construct defined by humans. For instance, the tendency is to favour native biodiversity over non-native biodiversity. Yet, non-native biodiversity sometimes performs better in a novel ecological system, such as that of the urban environment. In fact, by fitting better in the environment, non-native species were able to dominate native species and are now much more resilient. Humans also tend to value the quality of nature on its physical appearance. However, a healthy and resilient ecosystem does not always have to be pretty or comfortable look at. Depending on the environment, it can be vegetation growing through pavement, mosses taking over a wall or a decaying bird.

The role of the designer is to create conditions for the ecological processes that yield the ecosystem that is deemed desired (by people). A resilient ecosystem is preferred, as this is the most stable and able to sustain itself. But designing conditions for an ecosystem inherently means a human-centered approach is used to create nature. We have to acknowledge that the main motivation for greening cities arises from human needs. But we also have to acknowledge that without a resilient ecosystem, humans would not be able to live on earth at all.

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List of figures

Appendix

6.1 Urban population and biodiversity (MSA) table

This table with percentages was created to visualise the urban population graph. The sources used for the data are included in the list of figures.

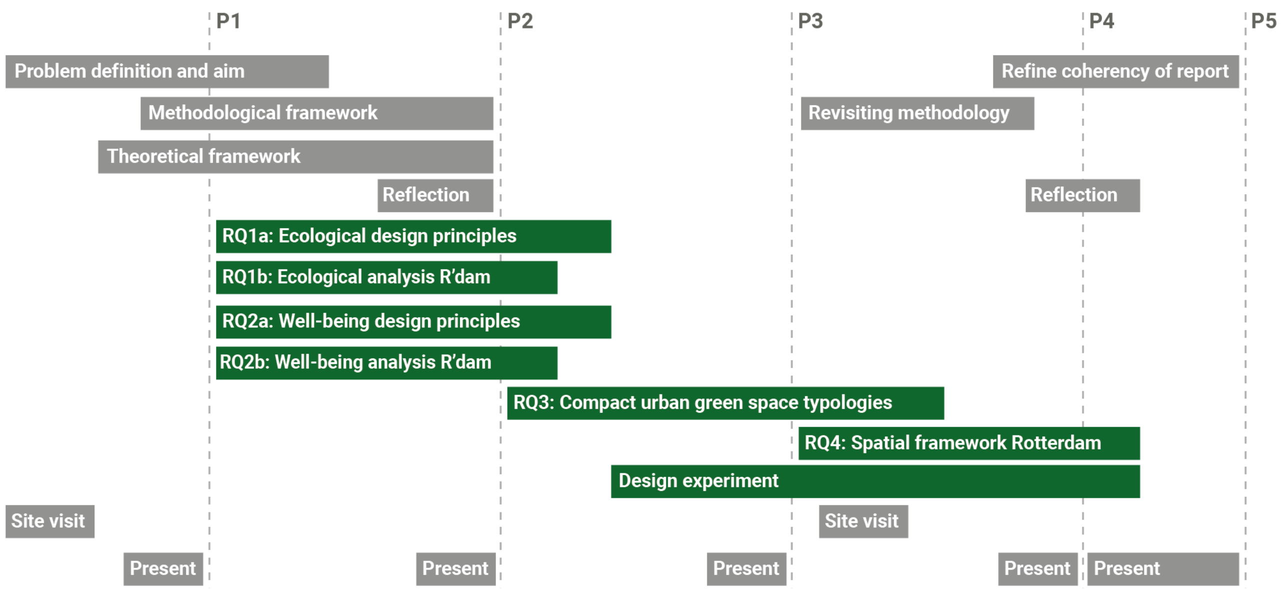
Urban population:

Year	-10000	-5000	0	500	1000	1400	1500	1600	1700	1795	1800	1849	1900	1950	1960	2000	2019
World	0	0,1	1	2,7	2,6		4,1	5,2	5,1		7,3		16,4	29,1		46,8	55,7
W. Europe	0	0	1,5	1,4	3,5		10,6	12,2	12,8		21,4		40,6	61,5		75,3	74,7
Netherlands						32	36	40	46	41		37			59,8	76,8	91,9

Mean species abundance:

Year	-10000	1700	1750	1800	1850	1900	1950	1970	1990	2000	2010
World	100	97	96	96	94	91		77		70	69
Europe	100	85	84	82	79	75		48		41	40
Netherlands	100					44	26		14	14	14

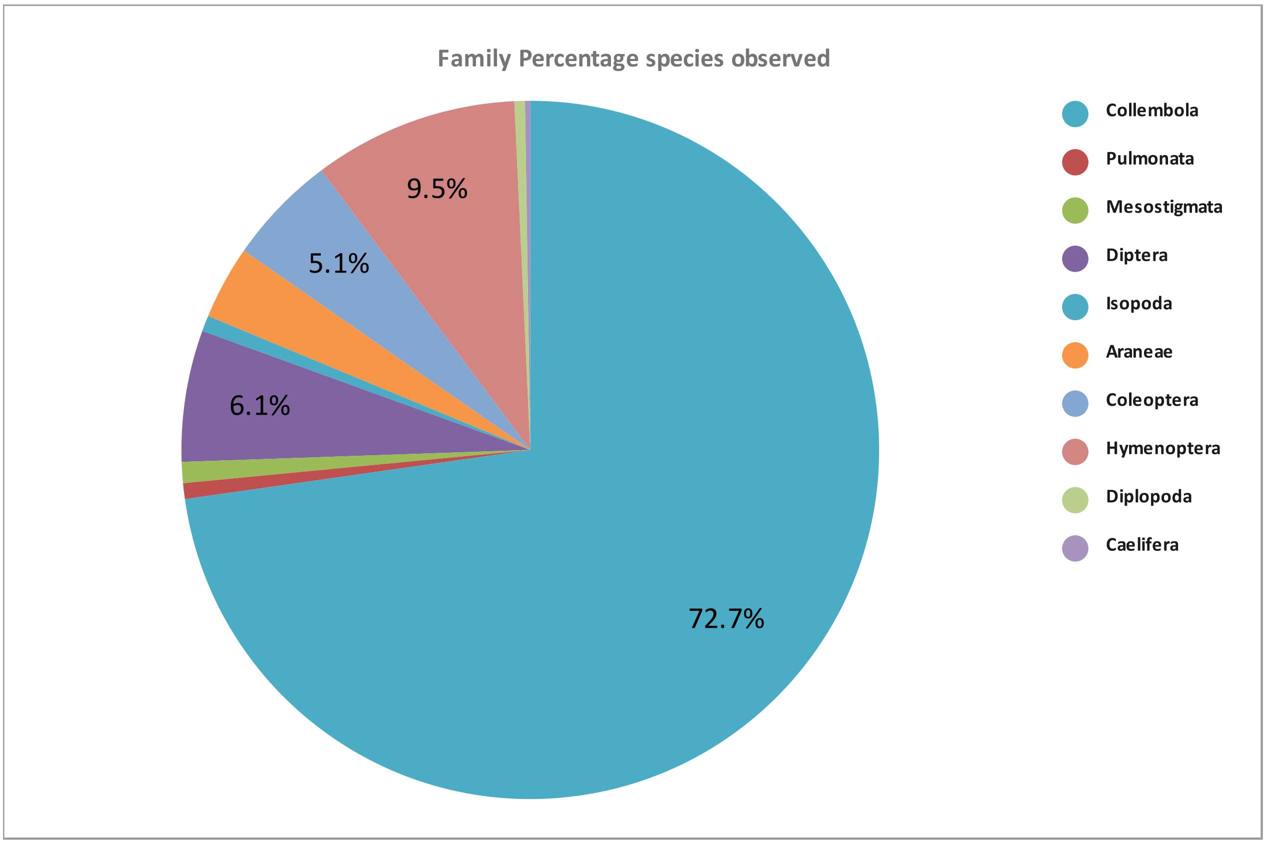
6.2 Time planning



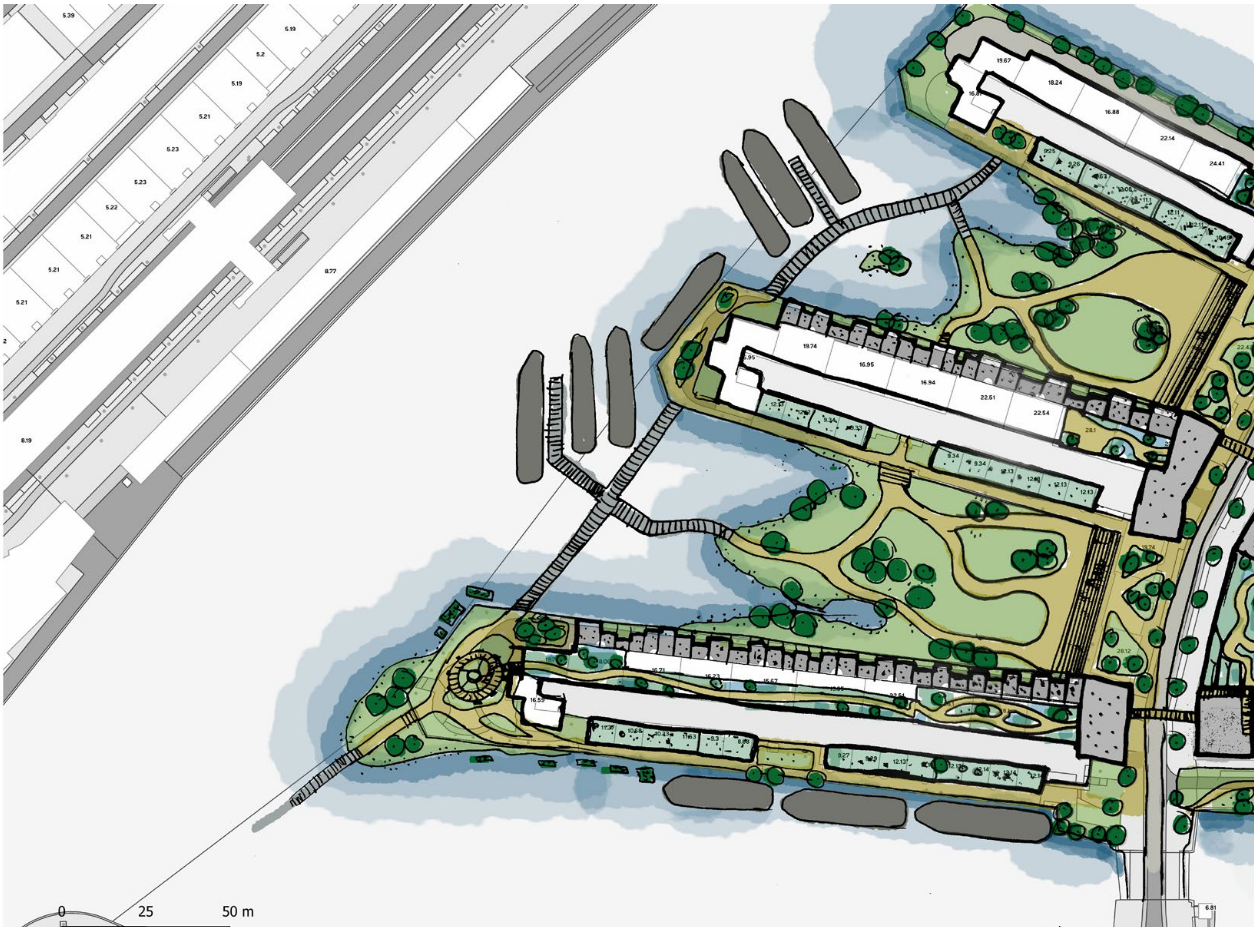
6.3 Additional data rooftop experiment

Count percentage of species

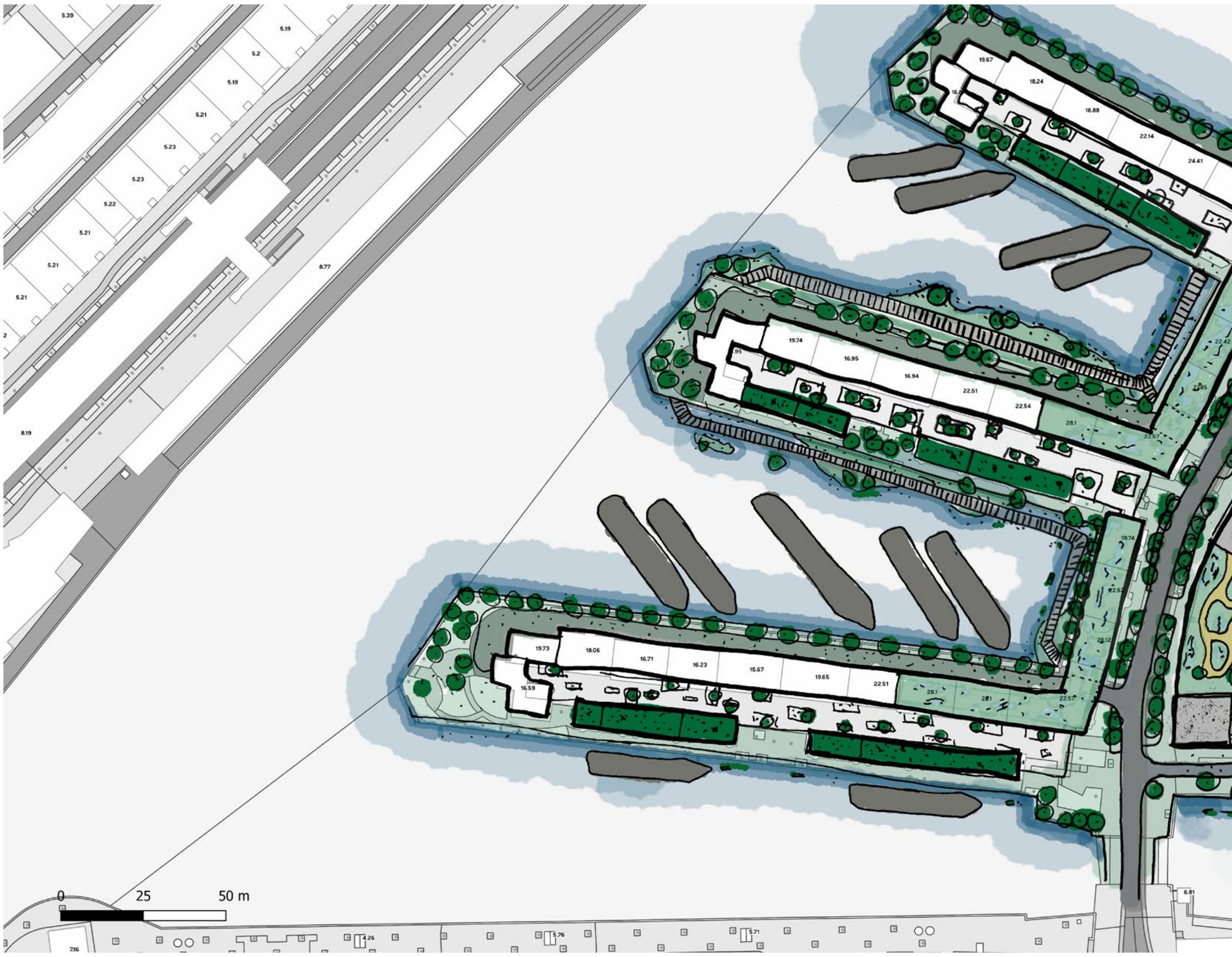
Insect	Count	Percentage (incl. groui	Count (excl. ground)	Percentage
Collembola	299	73%	164	80%
Pulmonata	3	1%	1	0%
Mesostigmata	4	1%	4	2%
Diptera	25	6%	17	8%
Isopoda	3	1%	1	0%
Araneae	14	3%	7	3%
Coleoptera	21	5%	1	0%
Hymenoptera	39	9%	9	4%
Diplopoda	2	0%	1	0%
Caelifera	1	0%	1	0%
Total	411		206	



6.4 Spatial design Wijnhaven Eiland 'Urban nature reserve' scenario



6.5 Spatial design Wijnhaven Eiland 'City in a Park' scenario

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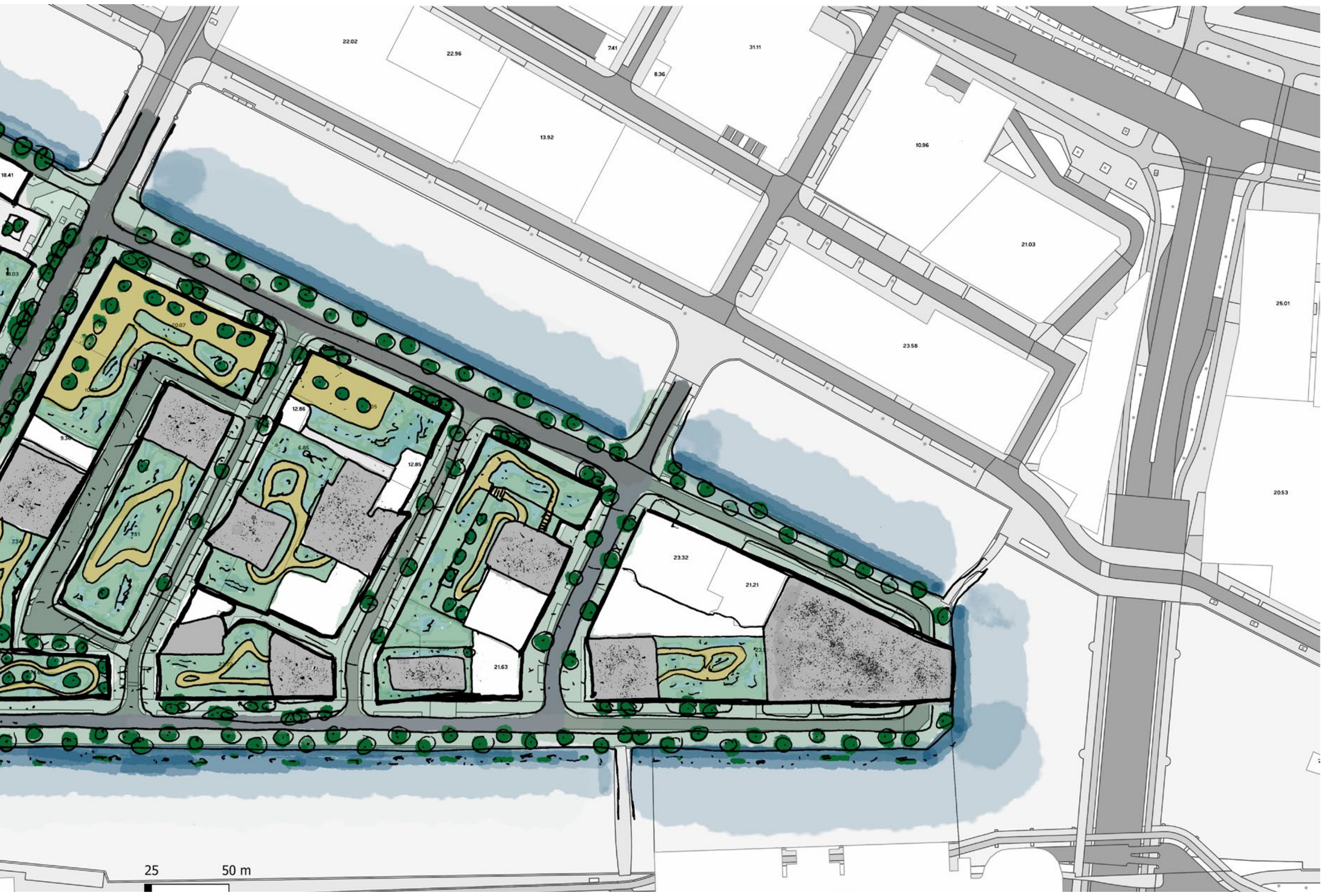
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