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A social-ecological analysis to enhance the multifunctionality of urban greening

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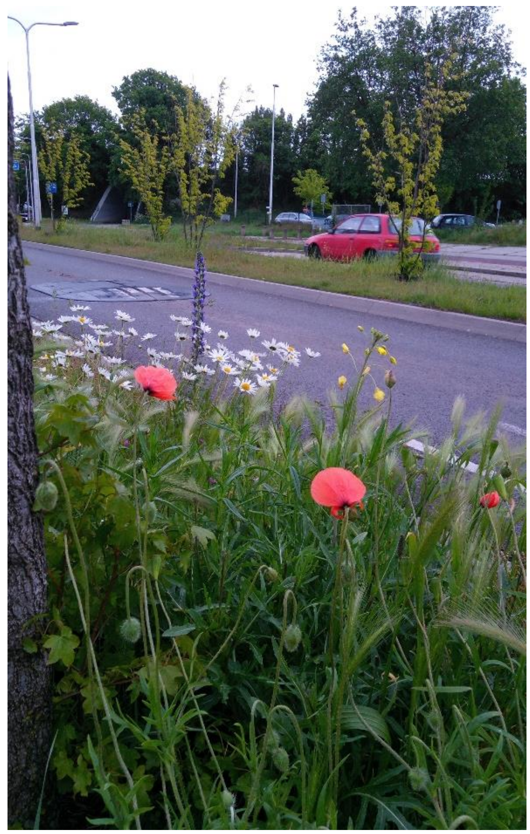

WAGENINGEN UNIVERSITY & RESEARCH

Interconnectivity of urban green space

A social-ecological analysis to enhance the multifunctionality of urban greening

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Preface and acknowledgment

During my thesis process, I was mostly working from my student room in Nijmegen. I often looked through my window while discovering, puzzling, and learning how to include both the ecological and social perspectives on UGS development into a GIS environment. I saw a lot of different birds in the trees and sometimes a squirrel jumped from one tree to another. This connection between my thesis about urban green space and nature thriving in front of me inspired me during the times of the pandemic.

My interest in urban green space comes not only from the value nature adds to my personal life but I also see so many opportunities of fostering nature to make the world a better place to live. For me, nature is the basis of life and we should take great care of not only the large national parks but also the small urban green spaces. Every square meter counts in a world in which is the consequences of climate change become more evident.

This thesis is part of the Master's program Urban Environmental Management at the Wageningen University and Research (WUR), where I followed a specialization in Geo-Information Science (GIS). I discovered a link between my thesis and the mission of the WUR: 'to explore the potential of nature to improve the quality of life'. During my thesis, I was thinking about the potential of nature to provide ecosystem services, health benefits, and climate adaptation measures. However, this potential was mainly targeted to improve the quality of life for human beings. We should not forget there are other forms of 'life' as well. When nature, including all the living organisms, is declining in quality and/or quantity, the potential of nature to deliver all its benefits decreases. Therefore, I tried to not only look at the potential that humans can receive from nature, but I found it equally important to explore the potential of improving the quality of life of nature itself.

I learned to make a lot of choices and the implications of these choices during my thesis process. When encountering problems, I learned to search for alternative ways or workarounds to still reach my goal. I learned much from the feedback fellow students provided me. I learned from the conversations with various experts in the field of ecology, spatial planning, design, landscape architecture, and climate adaptation. And most of all, I learned to better see the connections between nature and humans.

Thanks to the experts who made the effort to share their knowledge and expertise. Special thanks to Pieter Boone and Inge Kersten (municipality of Rotterdam), Ton Verhoeven and Bart Tromp (municipality of Nijmegen), Quirijn Verhoog (municipality of Amsterdam), Raymond Creemers (RAVON) and Ella Raaijmakers (municipality of Purmerend). I would like to thank my thesis supervisor Ron van Lammeren for his supervision and feedback. Last but not least, I would like to thank my parents, friends, and fellow students for their support, feedback, and encouragement.

Abstract (English)

Space is limited in urban areas to assign new locations for urban green space (UGS). UGS planners thus far have had a limited integrated perception of UGS, while its multifunctionality is essential for sustainable urban development. Also, ecological processes at multiple scales are disconnected from current UGS planning. Instead, a more integrated social-ecological approach is fundamental and a more in-depth understanding of the interrelated social and ecological system is required. Therefore, the aim of this study is to assess such interconnectivity of UGS by finding potential UGS locations and comparing these on multiple scales to detect directions for an interconnected social-ecological approach.

Four steps contributed to reaching this aim. First, interviews with three Dutch municipalities were conducted to identify the social-ecological criteria used by municipal UGS planners and designers. In the second step, these social-ecological criteria constitute the input for a GIS analysis using the municipality of Nijmegen as study area. This GIS analysis incorporates 1) a land suitability analysis, including justice and ecosystem services criteria, to investigate the potentials of social UGS connectivity (SUC), and 2) an ecological connectivity analysis, focusing on connectivity of UGS for the hedgehog, squirrel and alpine newt, to unravel the ecological UGS connectivity (EUC). The third step was to compare SUC and EUC suitability results by calculating the amount of overlap and difference on the city, district, and neighborhood scale. The last step was to evaluate the interconnected social-ecological suitability map by comparing it with the green structure of the municipality to identify where potential UGS locations overlap.

Findings resulting from the first step show that municipalities share the aims of utilizing UGS for climate adaptation, ecosystem services provision, and connecting existing UGS. It is found that municipalities' search for potential UGS locations is largely driven by limited space rather than through GIS analyses with social-ecological criteria. The second step showed that in the study area of Nijmegen, potential UGS locations based on SUC occur mainly along roads, in the city center and the west of Nijmegen, while potential locations from a EUC approach showed suitable locations for UGS in the east of Nijmegen near the forest areas and along road infrastructure. The third step resulted in locations where the EUC and SUC overlap in suitability scores (22% of the area) of which 6% received (very) high suitability scores that could be assigned as priority locations for UGS development. The interconnected social-ecological suitability map indicated road infrastructure as highly suitable to develop UGS. On a neighborhood level, the city center is very suitable from a social perspective but highly unsuitable from an ecological perspective. A few neighborhoods turn out to be both socially and ecologically highly suitable. When comparing the findings to the municipal green structure in the fourth step, one-fourth to one-third of the very high, high, and moderate suitable locations is overlapping with the municipal green structure. This shows high potential for UGS outside the current green structure.

Overall, it is difficult to integrate and compare the UGS locations from the social and ecological disciplines because they are derived from two different GIS analyses with different indicators. Nevertheless, by further developing an integrated and interdisciplinary social-ecological approach, UGS development will support the interconnectivity in aiming for sustainable urban development. This study takes a quantitative UGS approach to integrate the social and ecological perspective by using GIS analysis. This might help UGS planners to emphasize the added value for humans and other species and to reach UGS interconnectivity.

Keywords: urban green space (UGS), social-ecological, interconnectivity, land suitability analysis, ecological connectivity

Abstract (Dutch)

Ruimte is beperkt in de stedelijke ruimte. Dat maakt het moeilijk om nieuwe plekken aan te wijzen voor stedelijk groen (stedelijke groene ruimte: SGR). Stadsplanners hebben tot dusver een beperkte integrale kijk op SGR, terwijl de multifunctionaliteit van SGR juist zo belangrijk is voor duurzame stedelijke ontwikkeling. Daarbij zijn ecologische processen, op verschillende schaalniveaus, losgekoppeld in de huidige praktijk van SGR-planning. In plaats daarvan zou een integrale sociale en ecologische benadering goed zijn. Ook zouden SGR-planners baat hebben bij meer diepgaande kennis van de verbondenheid van sociale en ecologische systemen. Daarom is het doel van dit onderzoek om de verbondenheid van SGR aan te tonen. Dit onderzoek doet dat door potentiële groen-locaties te vinden op basis van zowel sociale als ecologische methoden en deze te vergelijken op verschillende schaalniveaus. Zodoende beoogt dit onderzoek een geïntegreerde sociaal-ecologische benadering te ontwikkelen.

Vier stappen droegen bij aan het bereiken van deze doelstellingen.Ten eerste zijn interviews uitgevoerd met drie Nederlandse gemeenten om sociaal-ecologische criteria te definiëren, zoals deze gebruikt worden door SGR-planners en stedenbouwkundigen. Als tweede stap zijn deze sociaal-ecologische criteria gebruikt als input voor een GIS-analyse waarbij gemeente Nijmegen als onderzoeksgebied is gebruikt. Deze stap verbond: 1) een land geschiktheidsanalyse, inclusief rechtvaardigheids- en milieu/gezondheids-criteria, om de potenties van sociale SGR connectiviteit (social UGS connectivity: SUC) in kaart te brengen, en 2) een ecologische verbondenheidsanalyse, gericht op de eekhoorn, egel en alpenwatersalamander, om de ecologische UGS verbondenheid (ecological UGS connectivity: EUC) in kaart te brengen. Als derde stap zijn deze SUC en EUC geschiktheidsanalyses vergeleken door de mate van overlap en de verschillen tussen de SUC en EUC te berekenen, op stads-, wijk- en buurtniveau. Ten slotte betrof de vierde stap een evaluatie van de geïntegreerde sociaal-ecologische geschiktheidskaart, door deze te vergelijken met de bestaande groenstructuurkaart van de gemeente Nijmegen.

De bevindingen die voortkomen uit deze stappen zijn als volgt. Uit de eerste stap volgt dat gemeenten grofweg dezelfde doelen hebben als het gaat om het gebruik van SGR ten behoeve van klimaatadaptatie, ecosysteemdiensten, en het verbinden van bestaand stedelijk groen. Hieruit wordt duidelijk dat de gemeentelijke zoektocht naar potentiële groenlocaties grotendeels gedreven wordt door ruimtegebrek, en niet door GIS analyses gebruik makend van sociaal-ecologische criteria. De tweede stap laat zien dat in Nijmegen, op basis van SUC potentiële groenlocaties veelal rondom wegen, het centrum en Nijmegen-West worden aangewezen. De EUC benadering wijst juist locaties aan in Nijmegen-Oost, nabij bos en ook rondom wegen. De derde stap leverde locaties op waar, op basis van SUC en EUC analyses, de land-geschiktheid voor 22% overlappen. 6% van het landoppervlak werd zeer hoge geschiktheidscores toegewezen, die locaties zouden aangemerkt kunnen worden als prioriteitslocaties voor groenontwikkeling met zowel sociale als ecologische functies. Ook laat de geïntegreerde sociaal-ecologische geschiktheidskaart zien dat wegen over het algemeen zeer geschikt is voor SGR-ontwikkeling. Verder lijkt, op wijkniveau, het centrum geschikt vanuit sociaal perspectief, maar is het centrum zeer ongeschikt vanuit ecologisch oogpunt. Enkele wijken zijn daarentegen geschikt vanuit beide analyses. Ten slotte laat stap vier zien dat de resultaten in de vergelijking met de gemeentelijke groenstructuurkaart slechts voor 1/4e tot 1/3e van de geschikte locaties overeenkomen. Dit laat zien dat er nog zeer veel potentie is voor SGR-ontwikkeling buiten de huidige groenstructuur.

Ter conclusie, het blijft lastig om SGR-locaties uit de sociale en ecologische benadering te integreren en te vergelijken, aangezien deze benaderingen gestoeld zijn op twee zeer verschillende GIS-analyses en verschillende criteria. Desalniettemin kan het doorontwikkelen van een geïntegreerde en interdisciplinaire sociaal-ecologische benadering erg waardevol zijn. Het kan SGR-ontwikkeling ondersteunen in het bereiken van connectiviteit en daarmee duurzame stedelijke ontwikkeling teweeg brengen. Dit onderzoek maakt gebruik van een kwantitatieve SGR benadering om sociale en ecologische perspectieven te integreren met behulp van GIS analyse. Dit kan planologen, stedenbouwkundigen en bestuurders helpen om de toegevoegde waarde van groene ruimte voor mens en dier aan te tonen en om groene verbindingen te bewerkstelligen in de stedelijke ruimte.

Trefwoorden: stedelijk groen ruimte, sociaal-ecologisch, interconnectiviteit, geschiktheidsanalyse, ecological connectiviteit

List of abbreviations

BGT………………… 'Basisregistratie Grootschalige Topografie' (Basis registration large-scale topography)
BRT………………… 'Basisregistratie Topografie' (Basis registration topography)
MSPA………………Morphological Spatial Pattern Analysis
NDFF……………… 'Nationale Database Flora en Fauna' (National Database Flora and Fauna)
PM2.5…………….Fine particulate matter
SPA………………….Spatial Pattern Analysis
UGS…………………Urban Green Space
UHI………………….Urban Heat Island
WHO……………… World Health Organization

List of figures

List of tables

Table of content

1. Introduction

This introductory chapter highlights the background of the study, the problems identified in previous research, and the knowledge gap.

1.1 Context and problem definition

Globally, the population living in cities will increase from 55% in 2018 to almost 70% in 2050 (United Nations, 2019). Europe is one of the most urbanized continents in the world with more than two-thirds of its population living in urban areas (European Commission, 2011). This share will continue to grow, also in Dutch cities (De Vries et al., 2017), and requires expansion and/or densification of urban areas. Therefore, a need for *sustainable urban development* is becoming increasingly important (Haaland & van den Bosch, 2015). This implies the "creation of both resource-efficient systems and good, engaging urban design for attractive cities with good quality of life" (p. 760). Developing sustainable cities is guided by building in a more compact manner to avoid negative effects of urban expansion and sprawl (Burton, 2000).

While this so-called *compact city* concept was adopted by planners as the most sustainable urban form, critique and negative side effects of city densification also become more evident. Assumptions assigned to the compact city, such as reduced traffic or less environmental damage, are being questioned (Williams, 2000; Neuman, 2005). One of the issues is the lack of space for urban vegetation (Brunner & Cozens, 2013). This has serious consequences as green spaces in cities play an important role by providing ecosystem services, such as reducing air pollution, preventing water run-off, absorbing the effects of noise, and mitigating the urban heat island (UHI) effect (Derkzen et al., 2015). Furthermore, urban green space provides aesthetic enjoyment and recreation while at the same time promoting health and well-being in residential areas (Groenewegen et al., 2006). All these benefits show the multifunctionality of urban green. *Urban green space* (UGS) is defined as "any vegetation found in the urban environment, including parks, open spaces, residential gardens, or street trees" (Kabisch & Haase, 2013, p. 113). Recognition of the importance of green space resulted in the need for UGS planning to improve the quality of life in urban environments (Erickson, 2012).

Furthermore, planning layouts of UGS in high-density areas often consider residents as the main object, while biodiversity and ecological processes are rarely considered in urban green space planning (Zhang et al., 2021). Isolation and fragmentation of urban green space have become increasingly profound. This also relates to the compact city, where "due to the intensive competition to use land, green spaces in compact areas tend to be small, isolated and unevenly distributed, and are precious due to their scarcity" (Jim, 2004, p. 313). Fragmentation of UGS not only decreases the health of urbanized ecosystems but also deteriorates the quality of living environments, threatening urban sustainability, especially in dense cities (Li et al., 2015).

The management of landscape connectivity has been identified as one of the most important measures to counteract the aforementioned negative impacts of habitat loss and fragmentation (Zetterberg, 2011). Habitat loss and fragmentation are the primary threats to biodiversity (Wilcove et al., 1998). An *urban green network* approach to improve landscape connectivity in compact city areas is becoming a priority in research and planning practice since urban densification started to develop (Xiu et al., 2017). The term *green infrastructure* emphasizes the crucial role of green spaces and the connections between them to support and improve sustainable development as well as enhance the functioning of urban environments (Forest Research, 2011). In response to pressure from urban development, a multi-functional approach and the combination of many different green spaces into an integrated green framework is considered suitable to improve both the ecological value of UGS and the urban environment (Uy & Nakagoshi, 2008; Li et al., 2015). However, recent research by Bekhuis et al. (2021) stated that Dutch municipalities do not apply an integral view of urban green. This means that urban green is not considered as providing multiple functions. Municipal information on urban green space is often approached from one discipline and distributed by one sector within the municipality.

1.2 Relevance

Finding potential locations for UGS to improve landscape connectivity has been researched from broadly two approaches. The first type of approach focused on benefits provided by green space (i.e., ecosystem services) and included one or more criteria in a *land suitability analysis* (e.g. Manlun (2003); Abebe and Megento (2017); Apud et al. (2020)). This multi-criteria evaluation method or multi-criteria decision-making analysis recognizes the multifunctionality of UGS. It can also include biodiversity values or environmental factors such as the ecological element threshold technique. The latter is used to know how much green area is needed for a city to maintain ecological stability (Mahmoud & Adel, 2011). Still, the aim of this rather social or anthropocentric perspective is often to maximize the benefits for humans as users. This approach is referred to as the *social urban green space connectivity* (SUC) which is defined in this thesis as the relation (i.e. connectivity) of humans with UGS.

The second approach has its origin in landscape ecology and focuses on *landscape connectivity*, which is "the degree to which the landscape facilitates or impedes movement among resource patches" (Taylor et al., 1993, p. 571). It is hard to grasp landscape connectivity as one concept for the entire landscape as different organisms or processes have different degrees of connectivity in the same landscape (Zetterberg, 2011). Landscape connectivity also depends on the spatial and temporal scales at which the property is studied. Network-based tools are often used to measure fragmentation and connectivity by including various landscape metrics (e.g. Zetterberg (2011); Li et al. (2015); Xiu et al. (2020)). For example, graph theory can be used to visualize the landscape as a network of nodes and edges (Xiu, 2017). The ability of UGSs to provide their expected benefits depends on the landscape metrics, including spatial locations, compositions, and configurations of UGS (Woldesemayat, 2021). The approach focusing on the connectivity of ecology to UGS is defined as the *ecological urban green space connectivity* (EUC) in this thesis.

While both approaches are valuable on their own, because of the interconnectivity of social and ecological systems, addressing the challenges needs an approach that integrates the multiple interlinkages and dependencies between both systems (Apud et al., 2020). By further developing an integrated and interdisciplinary approach of a social-ecological perspective, cities might become more sustainable in the future (Frank et al., 2017). A holistic social-ecological approach is fundamental and more in-depth knowledge about the interrelated social and ecological system is therefore required (Xiu et al., 2020). According to Frank et al. (2017), research on coupled human-environmental interactions so far has struggled to merge the ecological and social dimensions of urbanizations.

1.2.1 Social-ecological methods

One example to develop a social-ecological network model is by overlapping sociotope and biotope maps in graph theory (Xiu et al., 2017). Sociotope maps focus on human recreation and the social values of open spaces. However, this approach might fall short on the multifunctionality of UGS also providing a range of social-environmental benefits (i.e. ecosystem services). Consequently, it lacks partial support for stakeholders to prioritize the realization of UGS. As Kim et al. (2021) suggested, future research on suitable locations for UGS should integrate social welfare considerations, involving the many benefits for urban residents, and spatial and locational factors. This opens the way for landscape planning designs that improve UGS and its combined effects.

It is possible to perform only a land suitability analysis and include ecological factors in the suitability composition. An example of such a study is Apud et al. (2020) who included biophysical, socioeconomic, and built-environment aspects in their study. On the one hand, when the highest weights are assigned to areas lacking vegetation and biodiversity, a more socially just outcome can be achieved as spaces where people lack UGS are prioritized. On the other hand, when considering the protection of areas with high biodiversity and landscape connectivity, the highest weights should be assigned to areas nearby current vegetation and ecological areas. Therefore, as Apud et al. (2020) also highlight, green infrastructure cannot achieve all benefits at the same time and priority issues must be selected. A second example of including ecological benefits of connected green infrastructures in land suitability analysis is using the distance from current urban green areas as a criterion (Ustaoglu & Aydınoglu, 2020). However, these two examples do not take the movement of species or landscape connectivity into account, which is a prerequisite for many ecological processes and functions (Taylor et al., 1993). That is why conducting two analyses, land suitability and ecological connectivity analysis, were required in this thesis to not only show potential trade-offs but also find synergies between both the ecological and social aspects.

Previous studies also discussed and applied landscape-ecology concepts on the results produced by the land suitability analysis. An example of a first way is the study of Uy and Nakagoshi (2008), who looked at the proposed government plans to review the green structure in Hanoi and proposed a green network based on these plans. They 'applied' landscape-ecology principles in a descriptive way, not conducting a network analysis or calculating landscape metrics. A second way is using the ecological threshold method to quantify how much green area is needed for a city in terms of maintaining ecological balance (Mahmoud & Adel, 2011). Uy and Nakagoshi (2008) used this method to show how much green area should be developed in the future. However, it is not enough to use the ecological threshold method as it does not include landscape connectivity issues and where to develop UGS to enhance the green infrastructure network.

Besides using ecological factors in land suitability analysis, the opposite was done by using a land suitability map as a cost layer in the network analysis. A first potential method is shown by Giordano and Riedel (2008), who used a land suitability map as friction input in pathway analysis, connecting relevant points of interest for leisure and ecological importance. However, a limitation of this methodology was the separation of information used as factors or constraints. It would be useful to depict the results of both the ecological network and land suitability analysis to be able to see where combined results come from. A second method to integrate social factors in network analysis is to identify patches with high human recreational value and with wildlife values and use a least-cost model to identify potential linkages between these patches (Xiu et al., 2020). Still, there are more social factors that should be considered when searching for new UGS, such as environmental factors (e.g., air pollution) and justice factors (e.g., distance to public green space).

1.2.2 Multiple scales

Besides the challenge of developing an interconnected social-ecological approach, a second challenge is to include the multiple spatial scales at which UGS have different functions and values. Due to the interactions of species across scales, the ecological restoration must take place at several spatial scales (Turner, 2006). ”Any local attempts will meet little success without ensuring adequate habitat at the landscape scale” (p. 13). Also, the more social aspects used in land suitability analysis, such as access to UGS, are meaningful to apply at multiple scales. For example, green space provision per inhabitant might be high at the city level overall, masking scarcity at a neighborhood scale (Haaland & van den Bosch, 2015). Furthermore, the distribution of ecosystem services differs across scales (Ernstson, 2013). For example, where noise reduction is mainly a local effect, mitigating excessive heat also impacts city-scale temperatures.

Therefore, we need to reconcile spatial quality at the local level (e.g. variation in built environments and public spaces) to the structural effects on society as a whole (e.g. socioeconomic effects, segregation of groups) according to Berghauser-Pont and Haupt (2010). A major challenge within the management of landscape connectivity and UGS is taking spatial scales into account as these are often neglected (Borgström et al., 2006). Design and planning research rarely propose green space structures at the regional, city, and neighborhood levels comprehensively (Uy & Nakagoshi, 2008; Mahmoud & Adel, 2011). These studies do acknowledge the importance of both social and environmental benefits at all scales. However, an integrated social-ecological approach is lacking.

1.3 Research objective and questions

The aim of this research is to assess the interconnectivity of UGS by finding potential UGS locations and comparing these on multiple scales to detect directions for an interconnected social-ecological approach. This thesis will thereby respond to the multiple challenges of compact cities and fragmentation of UGS in urban environments and contribute to enhancing the green infrastructure network for all inhabitants. Doing so is quintessential, as both humans and wildlife use the urban environment, thus planning and design measures working for both groups are necessary (Xiu et al., 2020).

The following research questions will be answered to reach the research objective:

1. What social-ecological criteria are in use by municipal UGS planners and designers to find potential locations for UGS?
2. Which potential UGS locations should be prioritized based on social UGS connectivity and ecological UGS connectivity?
3. Which potential UGS locations overlap when comparing the social and ecological UGS connectivity on a city, district, and neighborhood scale?
4. To what extent do the identified potential UGS locations from a social-ecological perspective overlap with the green structure map of the municipality?

The conceptual framework in Figure 1 shows the interconnectivity of the social and ecological system elements of UGS.

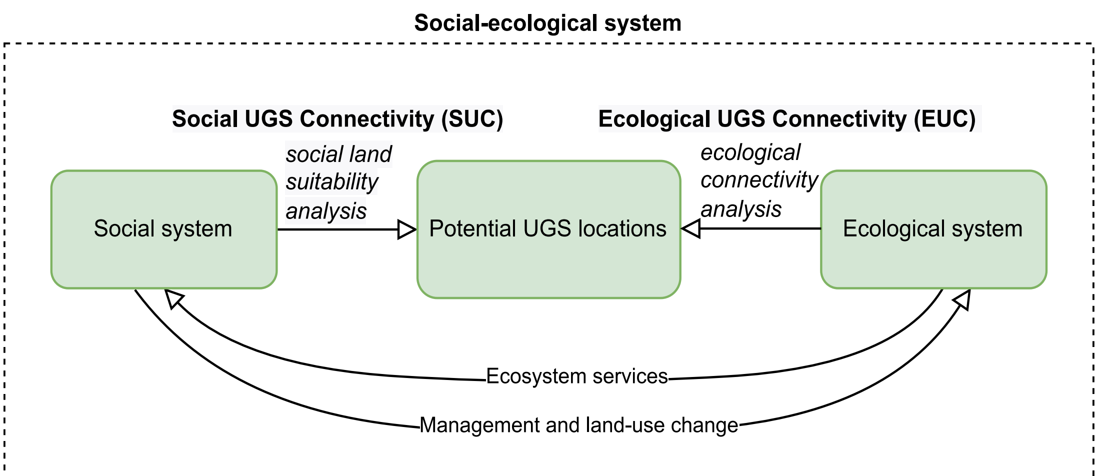


Figure 1 Conceptual model based on Resilience Alliance (2010).

1.4 Reading guide

This thesis consists of six chapters. The first chapter provides the general background to the issues studied, the research relevance, the research objective, and the research questions to reaching this objective. Chapter 2 reviews the literature from the fields of landscape ecology and landscape planning, highlights how these two are connected, and shows a social-ecological conceptual model. Chapter 3 presents the research methodology and data used. It describes per research question the approach that was used to answer the corresponding question. Chapter 4 shows the main research results to the research questions. This is followed by a discussion of the findings and methodology used in relation to the wider body of knowledge in Chapter 5. Finally, chapter 6 draws conclusions based on the answers to the research questions. The last chapter also describes the study limitations and recommendations for both policy change and future research directions.

2. Theoretical background

This chapter provides the theoretical and conceptual basis for this research. It identifies the key concepts and discusses the theories of landscape ecology and urban planning. In the last section, the theoretical model of a social-ecological system approach is explained. Urban planning is related to the social part of this system whereas landscape ecology is connected to the ecological side of this system.

2.1 Landscape ecology and ecological network

Landscape ecology is the study of structure, function, and change in a heterogeneous land area composed of interacting ecosystems (Forman & Godron, 1986). The landscape has a spatial mosaic pattern, usually represented as an ecological network, including three main elements: patches, corridors, and matrix (Forman & Godron, 1986) (Figure 2). A *patch* is described as "a non-linear surface area differing in appearance from its surroundings" (Forman & Godron, 1986, p. 83); *corridors* as "narrow strips of land which differ from the matrix on either side" (p. 123); and the *matrix* as: "a surrounding area that has a different species structure and composition" (p. 83).

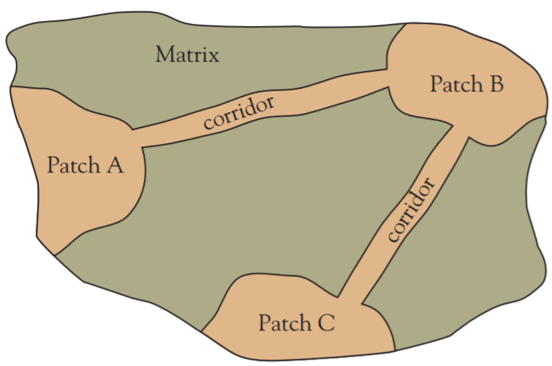


Figure 2 Mosaic landscape consisting of patches, matrix, and corridors (Barnes, 2000).

Landscape fragmentation is the alteration and destruction of the habitat, which is leading to a decreased proportion and isolation of ecologically valuable habitat patches in the landscape (Andrén, 1994). Two processes are resulting in fragmentation. First, natural causes, such as fires and volcanic eruptions, may lead to habitat disruption. Spatial structure of conversion due to human activities as a second process contributes greatly (Collinge, 1996). For example, landscape fragmentation is most evident in urbanized or otherwise intensively used regions, resulting from the development of built-up areas linked by linear infrastructure such as roads and railways (Forman, 1995). As a result of urban development, important habitats that shelter species may be divided into smaller pieces and some may even disappear (Xiu, 2017).

Connecting habitat fragments with corridors of similar habitats has long been an approach to mitigating the effects of habitat fragmentation. *Landscape connectivity* was introduced by Merriam (1984) as "the degree to which absolute isolation is prevented by landscape elements which allow organisms to move among patches". A division can be made between structural and functional connectivity. *Structural connectivity* refers to the physical composition and spatial configuration of the landscape elements, where *functional connectivity* includes the behavioral responses of organisms or processes in the landscape (Zetterberg et al., 2010). Whereas structural connectivity is based only on the spatial characteristics of a landscape without taking into consideration the movement ability of different species, functional connectivity measures are both dependent on the ecological requirements of organisms and landscape structure (Collinge, 1996).

Functional connectivity measures require information on the movement of species through the landscape. Network analysis as part of graph theory has been used for the last 20 years to deal with landscape connectivity issues. The network is often represented by a graph, which consists of a set of nodes and a set of links (also referred to as edges). The link between two nodes connects them (Zetterberg et al., 2010). The ecological network represents habitat patches as nodes and corridors as links (Xiu, 2017). This model can be used as input for least-cost-corridor modeling, referred to as cost-distance modeling, to calculate the most effective connections between nodes. This is conducted based on a cost-surface, also referred to as friction or resistance layer, representing the difficulty in traveling among various parts of a landscape (Xiu, 2017). While Rayfield et al. (2010) suggested that previous studies on cost surface are a reliable approach to represent real costs, Sawyer et al. (2011) highlighted that few studies validate or assess model sensitivity to errors in cost assignment.

Structural connectivity can be measured spatially according to the basic attributes of landscape composition and configuration using landscape metrics (Ersoy, 2015). Compositional metrics provide evidence of the abundance of certain patches (e.g., UGS), whereas configuration offers information on the geometrical characteristics of the patches (Woldesemayat, 2021). Landscape metrics include, for example, the total number of patches, the size of patches, the mean distance to nearest neighbor patch, shape index, and connectedness between patches of the same habitat. Structural connectivity measures do not require very extensive input data except for land cover and land use datasets (Ersoy, 2015).

2.2 Urban planning and green infrastructure network

While landscape ecology focuses on the functioning of resources, planning activities try to establish the appropriate use of resources (Botequilha-Leitão & Ahern, 2002). Landscape planning is the development and application of strategies, policies, and plans to create successful environments, in both urban and rural settings, for the benefit of current and future generations (Landscape Institute, 2016). The focus in this study is on urban areas as these are "hot spots that drive environmental change at multiple scales" but the pressures caused by urban areas and their expansion on the environment are beyond the city boundaries (Grimm et al., 2008). That is why urban areas are central to long-term functioning of societies and ecosystems. *Urban planning* embeds policies, regulations, and management of neighborhoods, towns, cities, and metropolitan regions involving attempts to organize social and economic relations, land use, resource distribution, and spatial morphologies (Huxley, 2009). Urban planners steer towards sustainable development by balancing three aims: environmental protection, economic development, and social equity (Campbell, 1996).

The concept of *green infrastructure* is recognized as a key approach to delivering multiple functions in landscapes providing several environmental, economic, and social benefits (Ersoy, 2015; Woldesemayat, 2021). It includes both green spaces and water bodies. There are currently as many definitions of green infrastructure as authors are working on the concept (Mell, 2010). They all share the idea of connectivity (in the form of networks), multi-functionality, and the development of better ecological, economic, and social places across a number of scales. Multifunctionality is the core idea of the green infrastructure concept since it has been realized that a landscape can deliver multiple benefits and functions at different (and/or the same) temporal and spatial scales for wildlife and people (Ersoy, 2015). The application of green infrastructure in urban planning reconnects the natural system and people by designing urban areas as living systems that are more connected with nature. In this way, green infrastructure planning is creating healthier, resilient, and sustainable urban environments (Mell, 2010).

The terms *green network* and *green infrastructure* are often used as synonyms (Forest Research, 2011; Davies et al., 2015). Still, a slight difference can be identified. Green infrastructure considers the different functions of greenspace, e.g., environmental benefits, biodiversity, and its contribution to social inclusion and sustainable development (Forest Research, 2011). Green networks put more emphasis on how these areas interconnect to form networks of greenspace and facilitate movement of people and biodiversity. However, the network component can also be integrated into the definitions of green infrastructure, as Benedict and McMahon (2002) define green infrastructure as "an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife". In order to avoid confusion and have the best of both worlds, this study uses the term *green infrastructure network* to highlight both the multifunctional and the connectivity aspects for planning UGS.

"To green the compact city is possible to a certain degree, but requires careful planning and knowledge on how ecosystem services can be provided within the compact city's limited green space area" (Haaland & van den Bosch, 2015, p. 768). The ecosystem services approach offers the consideration of multiple functions and their relation to human health and wellbeing. *Ecosystem services* are defined by the Millennium Ecosystem Assessment (2005) as "the benefits people obtain from ecosystems" (p.5). They are divided into four categories: provisioning services of products such as food and water; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling (Millennium Ecosystem Assessment, 2005). The supply of vital multiple ecosystem services makes UGS a fundamental part of sustainable urban development (Haaland & van den Bosch, 2015).

2.3 Social-ecological systems

The green infrastructure network of green spaces and water produces ecosystem services and is therefore linked to ecological principles (Niemelä, 2014). The result of green structure planning based on landscape-ecology principles (i.e., connectivity, corridors, patch arrangement, network mosaics) is a connected green infrastructure network (Mahmoud & Adel, 2011). In this way, the green infrastructure concept provides common ground for both planners, social scientists, and ecologists, and helps to build bridges between these disciplines (Niemelä, 2014). The ecosystem services flow from nature to humans (provisioning, regulating, and supporting) but equally flow from humans to nature (conservation, restoration, and cultural services) in a mutual interactive relationship. Despite the growth in interest in an ecological approach to urban planning in the past 30 years, it is not mainstream in practice (Heymans, 2019). "Humans are seen as separate from, and superior, to nature " (p. 16). In planning and designing UGS, there is a tendency to focus on site area or green-area per capita at the expense of high-level benefits such as ecosystem services. The narrow outlook could discourage adoption of ecological design (Jim, 2013).

A new urban planning paradigm is needed. As researchers have recognized that cities are dynamic, integrated, and multi-scalar systems, urban areas should be understood as human-driven ecosystems, human-environmental systems, or social-ecological systems (Wu, 2014). Urban ecological studies suggest an emerging urban sustainability paradigm including social-ecological systems. A *social-ecological system* is a

> "coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner; a system that is defined at several spatial, temporal, and organizational scales, which may be hierarchically linked; a set of critical resources (natural, socioeconomic, and cultural) whose flow and use is regulated by a combination of ecological and social systems; and a perpetually dynamic, complex system with continuous adaptation" (Frank et al., 2017).

A conceptual framework can enrich the understanding of cities as complex social-ecological systems and lead to surprising conclusions that might not have been reached without the integration in the social-ecological system approach (Grimm et al., 2013). The framework is composed of dynamic interactions between societal (social-cultural-economic template) and ecological components (biophysical template), external driving forces, and their impacts (Figure 3). The yellow highlighted concepts are related to this study. Designing and building urban areas with one ecosystem service in mind often degrades another, producing trade-offs (Bennett et al., 2009). As a result, research that addresses "the provision of multiple services and the trade-offs and synergies among them and examines the ecosystem processes that link services will lead to a better understanding of how the relationships among ecosystem services can change over time and space" (p. 1401).

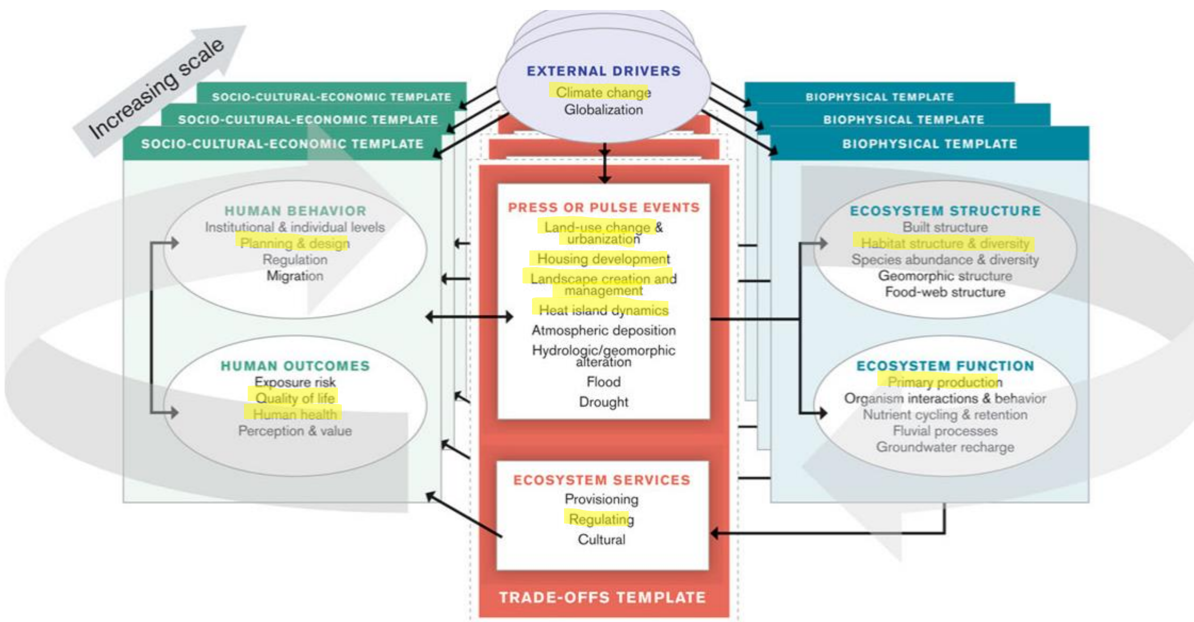


Figure 3 Conceptual framework for an urban social-ecological system to visualize human-environmental interactions on multiple spatial scales (presented in Grimm et al. (2013), who adapted it from Collins et al. (2011). The concepts highlighted in yellow are most related to this study.

The *external drivers* (Figure 3, top) are fluctuations that drive long-term change. There are also internal drivers of change: *press events* (e.g., air pollution and urban policies) and *pulse events* (e.g., droughts or housing developments) (Grimm et al., 2013). The *ecosystem structure* can include ecosystem components such as vegetation, but also the built environment, including urban infrastructure and designed ecosystems, non-native species, and biodiversity. These components interact with and control the rates of *ecosystem functions* (i.e. processes), such as nutrient cycling. These processes are in turn “inputs” to *ecosystem services* (Figure 3, right). “Notably, human decisions and behavior are the major drivers of urban ecosystem functioning” (p. 222). *Human outcomes* or responses to the ecosystem services include, for example, the risk to human health arising from extreme urban climate events or implications for environmental justice. The actions taken by people and their *behavior* often change the pulse or press events that affect ecosystem structure and function (Grimm et al., 2013).

In this research, the ecosystem structure will be identified by conducting an ecological connectivity analysis, and the more human interests of new UGS will be analyzed using a land suitability analysis. The former includes more or less the perspective of landscape ecology, referred to as Ecological UGS Connectivity (EUC) while the latter is more focused on planning green structures based on enhancing ecosystem services, referred to Social UGS Connectivity (SUC) in this study. The next chapter provides more details on the methodology.

3. Methodology

The methodology for each research question is described and an overview can be seen in the flowchart of Figure 4. The first question was answered through interviews with three municipalities and the rest of the research questions were answered by GIS analysis.

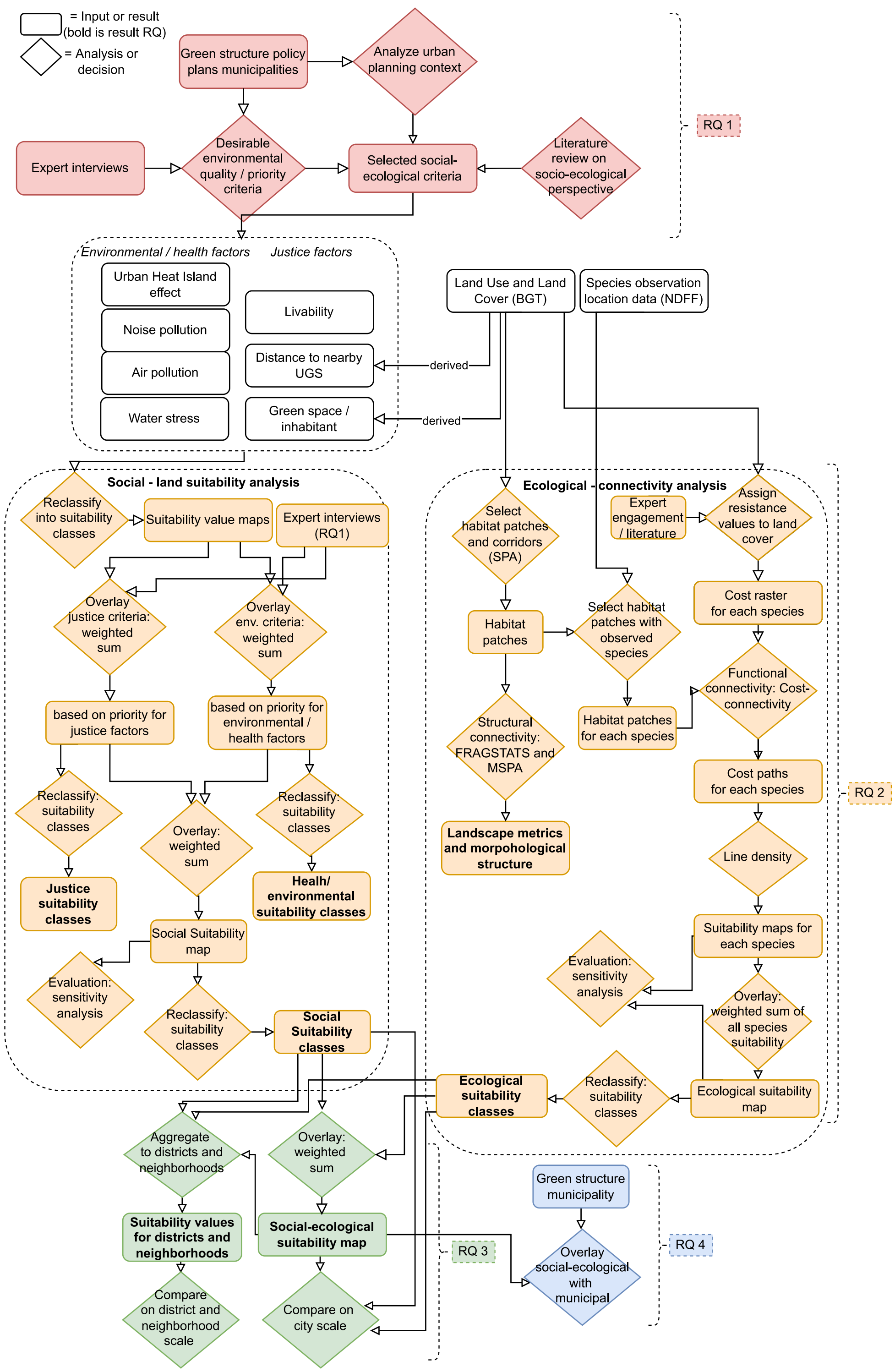


Figure 4 Methodology workflow specified for each research question.

3.1 Identifying social-ecological criteria

The first research question is *what social-ecological criteria are in use by municipal UGS planners and designers to find potential locations for UGS?* The social-ecological criteria which were used in the GIS analysis for the next research questions were identified based on interviews with municipalities.

Three semi-structured interviews with UGS designers or policymakers were conducted to gain insight into how the planning of UGS is done within the municipalities. Semi-structured interviews are useful for getting an idea about a general topic and more in-depth understanding by asking follow-up questions (Qu & Dumay, 2011). It is more reliable than unstructured interviews because a general list of topics is used for all interviews. The municipalities of Nijmegen, Amsterdam, and Rotterdam were asked for interviews as these are big Dutch cities in different provinces. Although three municipalities is a rather small representation of all the Dutch municipalities, it was considered sufficient to represent the larger municipalities. Also, a lot of answers were similar and rather a conformation of previous interviews than information being completely new or contradicting to previous interviews.

Specifically, questions were asked about how the UGS locations and green structures are selected and what priority issues or benefits UGS should address (see Appendix I for the respondents and Appendix II interview questions). Questions were formulated beforehand, but the goal of the interview was also to explore the criteria the respondents might consider themselves to be important. Follow-up questions were used when the respondent said something interesting related to social or ecological criteria. Also, specific questions were asked based on the policy documents that were used as background information. Furthermore, questions were asked related to incorporating the city-wide green infrastructure network into local neighborhood practices. The interviews were transcribed and summarized. To make sure no information was misinterpreted, the summary was sent to the respondents to comment on any misunderstandings or mistakes in the interpretation of their answers.

3.2 Study area

Based on the interviews and the policy documents available, the municipality of Nijmegen was selected for further data analysis as a study area. The municipality of Nijmegen is the largest city and municipality of the province of Gelderland and has more than 177,000 inhabitants (Municipality of Nijmegen, 2021). The municipality is divided into 9 districts and 44 neighborhoods (Figure 5). This municipality was selected because the municipality of Amsterdam and Rotterdam had already more detailed green plans than Nijmegen, which makes it more relevant for Nijmegen to allocate UGS locations. The policy documents of the corresponding municipality were analyzed to describe the context and used together with the interviews for choosing the criteria as input for further data analysis, such as determining weights in land suitability analysis.

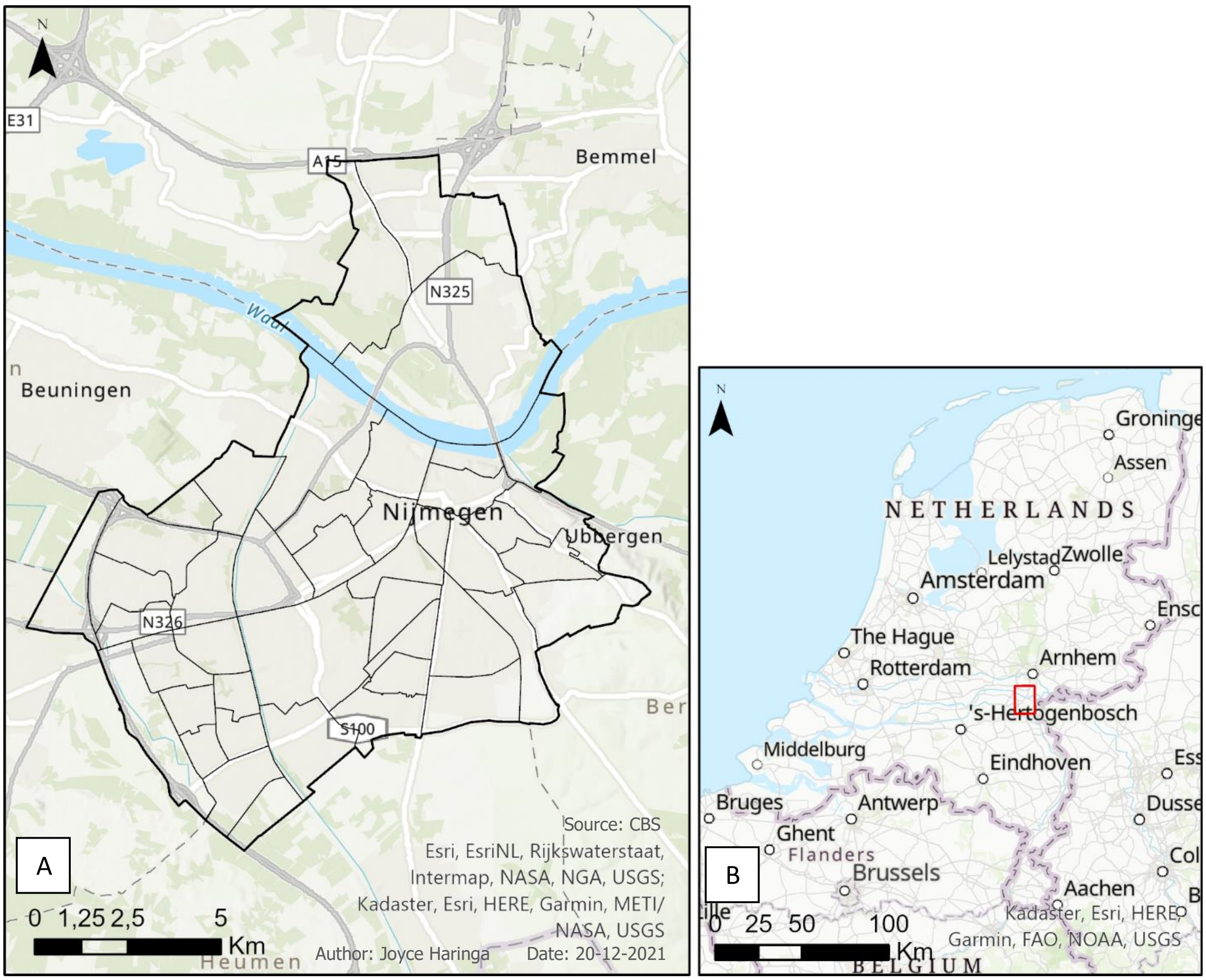


Figure 5 Municipality of Nijmegen with A) the neighborhoods and B) its location in the Netherlands.

3.3 Application in GIS analysis

To answer the second research question, *which potential UGS locations should be prioritized based on social UGS connectivity and ecological UGS connectivity?,* a land suitability analysis and ecological connectivity analysis were conducted at city scales for the municipality of Nijmegen. These two analyses used the social-ecological criteria identified in the first research question.

3.3.1 Input data

The data used for the derived criteria (see chapter 4.1) is shown in Table 1. Data representing UGS is available from various sources with different categories and characteristics (see Appendix III for more detail). From all the various data sources, two datasets of 'basisregistraties' were chosen for further investigation. These two datasets are publicly available and contain the required information about the geometry and type of green. Public green space was chosen from 'Basisregistratie Topografie' (BRT) after a comparison with the green space from BGT ('Basisregistratie Grootschalige Topografie') (see Appendix IV for more detail). Although BRT contains fewer spatial details (e.g. no single trees along roads) than BGT, the BRT dataset was chosen because it contained subclasses in the attribute tables which BGT did not. The subclasses are especially valuable for dividing UGS into different vegetation types. The fact that there is less spatial detail is an advantage for computational power in later analysis steps.

An example of the differences in geo-data for UGS is that some data does include green areas in private gardens while others only include public green space. BRT data did not include private green space. However, this was not critical for this study as this thesis focuses on enhancing the green network infrastructure and municipalities only have a direct influence on public space where they own the land. Also, private UGS can not simply substitute public UGS or the other way around as they have different functions and meanings for people (Coolen & Meesters, 2011).

Table 1 Social-ecological criteria and input data used for the GIS analysis.

Variable	Data	Data Type	Measure ment scale	Unit	Resolution	Year	Source
Neighborh oods	Neighborhoods	Polygon	Nominal	Neighborho odcodes	-	2020	CBS
UHI effect	UHI	Raster	Interval	Degrees	10 m	2017	Atlas Leefomgeving
Noise pollution	Noise all sources	Raster	Ratio	Lcum	10 m	2017	Atlas Leefomgeving
Air pollution	Fine particulate matter (PM2.5)	Raster	Ratio	Mg/m3	25 m	2019	Atlas Leefomgeving
Water stress	Water on streets after extreme rainfall	Raster	Ratio	Depth in cm	2 m	2018	Atlas Leefomgeving
Livability	Leefbaarometer 2018	Table	Ordinal	Score 1-9 (insufficient – excellent)	neighborho od level	2018	Atlas Leefomgeving
Land use	BRT	Polygon	Nominal	-	-	2021	BRT
Species observa-tions	National Database Flora and Fauna	Polygon	Nominal	-	-	2021	NDFF

3.3.2 Defining Urban Green Space

Based on the input data, UGS includes different types of vegetation: grass (grassland, heather, and graveyards), trees (deciduous, pine, mixed, griend, and poplars), agriculture (arable land, orchard, tree farmer, and fruit farmer), sand and water (ponds and lakes). 1908 hectares (33%) of the municipality of Nijmegen is considered UGS in this study. Water is considered UGS because it is not only important for the ecology of urban green systems but also highly valued for recreational and aesthetic purposes (Ustaoglu & Aydınoglu, 2020). Only lakes and ponds and watercourses smaller than 50 meters in width are included in the UGS. It did not include wider watercourses like the river as these can also be obstacles to the movement of most land animals (Zhang et al., 2021).

3.4 Social land suitability analysis - SUC

The land suitability analysis finds suitable sites for developing UGS based on multiple social criteria, including justice and health/environmental criteria. It addresses the first part of the second research question about potential UGS locations based on social UGS connectivity (SUC). Figure 6 provides the steps taken during the land suitability analysis.

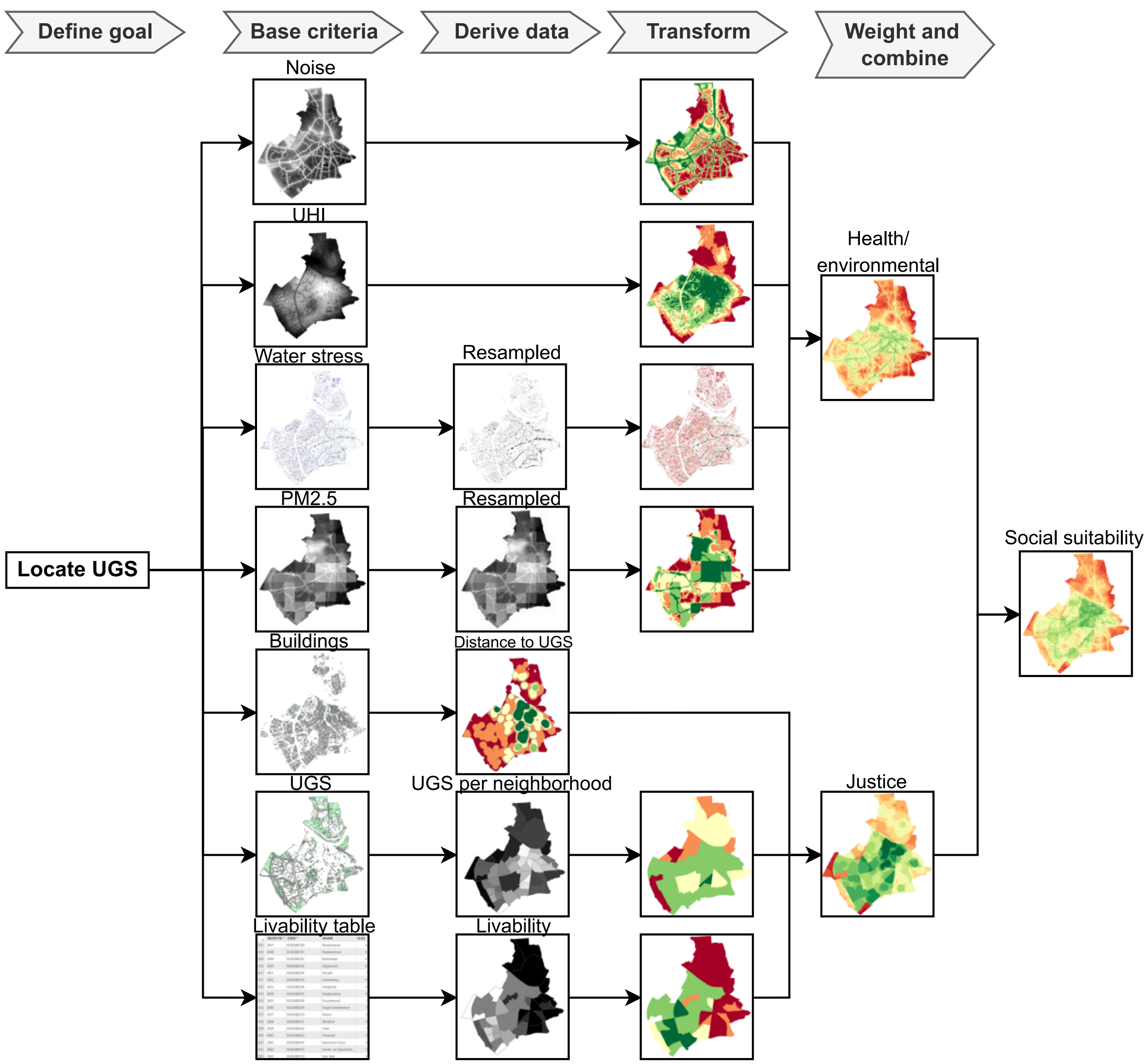


Figure 6 Process diagram of the steps to analyze suitable locations for UGS from a social perspective, based on ESRI (n.d.-d).

3.4.1 Preprocessing: social input criteria

The base criteria in Figure 6 were identified in section 3.3.1. The next steps performed in ArcGIS Pro will follow below.

Derive

Two of the seven variables were derived from the input data: *Distance to nearby UGS* and *UGS per inhabitant*. For the former variable, the buildings with an area of 10 m2 or more were selected from the BRT dataset. This threshold was used to exclude most shreds in backyards and to limit computational power. Also, the buildings were dissolved to form building blocks when they touch each other.

Then, the distance in meters was calculated for each building block to the nearest UGS of 5000 m2 or bigger using the Near tool in ArcGIS Pro. This size is in line with the green norm: 5000 m2 within 300 meter linear distance from houses (World Health Organization (WHO), 2017). As a next step, buffers were made of 300 meters around every block to assign a suitability value based on the calculated distance later on. This resulted in almost 14,000 overlapping buffers, which made computing a union impossible due to the required computational power. Consequently, the distances to UGS were classified into five classes based on the norm of the WHO before the Buffer tool was applied. The higher the distance to UGS, the more suitable it is to develop UGS within 300 meters from a house block. Therefore, a buffer area was classified as suitable for a distance of 300-325 to UGS, and as very suitable for a distance of more than 325 meters. The lower suitability classes have an interval of 100 meters to equally divide the distance ranges over the three remaining suitability classes. This classification made it possible to use the Union tool to have polygons for every separate overlapping part of the buffers. When buffers overlapped, the maximum distance class was extracted to make sure that the house blocks with the most distance (most suitable to develop green nearby) are not overlapped with houses with the least distance. This was done by adding the centroid x- and y-coordinates, calculating the maximum distance class, and using the Add Join tool to append this maximum distance class to the Union features class.

For UGS per inhabitant, the total amount of public UGS was calculated per neighborhood and divided by the total number of inhabitants in this corresponding neighborhood. A disadvantage of this method is that inhabitants can also go to green areas just outside the boundaries of their neighborhood which may be more closeby when they live on the outskirts of a neighborhood. However, it was seen as an appropriate approach because municipalities often look at the neighborhood level for the amount of green and (re)development of green.

To derive the livability score per neighborhood, the table with the livability scores was appended with Join Field based on the neighborhood codes which were in both the neighborhood scores input table and the data from CBS Neighborhoods.

Rasterize

For the rasterization, the Polygon to Raster tool was used for the vector criteria of distance to UGS, UGS per inhabitant, and livability. There are three methods how to decide what value a cell will be assigned: Cell center, Maximum area, Maximum combined area. The method Maximum area was chosen because it represents the original vector data best (see also Appendix V).

Resample

The raster datasets of air pollution (PM2.5) and water stress were resampled to a cell size of 10 meters from 25 meters and 2 meters respectively. Resampling to a lower resolution is not preferable because no new data is created on a finer scale. The accuracy is still only the size of the original resolution. This is taken into account by making no hard statements about air pollution on its own. Also, a 10 meter resolution was chosen because most input data was already having this resolution. When converting all data to 25 meters, the amount of detail in the information is partly lost. Therefore, a cell size of 10 meters was chosen.

For air pollution, the resampling techniques of Nearest neighbor, Bilinear interpolation, and Cubic convolution were tried for resampling to a coarser resolution. Nearest neighbor chooses the value of the input raster based on the value of the input raster which is the nearest to the center of the output raster cell (ESRI, n.d.-c). Bilinear interpolation bases the new value on a weighted distance of four nearest input cell centers. Cubic convolution has a similar approach as Bilinear interpolation but then with 16 nearest input cells. In the end, Nearest neighbor was chosen because this did not change the values of the cells and no smoothing effect of the edge was preferred.

For water stress, the resampling techniques Nearest neighborhood and Majority were tried as these are suitable for categorical data (see Appendix V). Majority calculates the value of the new raster based on the most popular value in a filter window of 4 by 4 cells closest to the center of the output cell. In the end, Majority was chosen because it represented the area better for the smaller areas where Nearest neighbor would have no data in the output.

Correlation input variables

The input criteria were checked for covariance to see whether the criteria have a strong spatial correlation. If this is the case, two variables might point to similar suitability values which gives these two a bigger than necessary share in the final result. That is why one of the two should be removed. Also, double criteria make the model unnecessary more complicated.

The covariance was calculated for the 7 input raster datasets after they were resampled (see Appendix VI). This was done using QGIS because this software provided the opportunity to calculate a covariance table for raster data. The plug-in called r.covar outputs the covariance/correlation matrix (GRASS GIS, n.d.). High correlation results in a high covariance value close to 1 and a low correlation between two variables result in a low covariance close to 0. When the value was 0.7 or higher, a high correlation is expected and one variable will be removed.

3.4.2 Social suitability map

Reclassify

After the preprocessing, the 7 input datasets were reclassified into categorical suitability values: very low suitability (value 1), low suitability (value 2), moderate suitability (value 3), high suitability (value 4), and very high suitability (value 5). This was done using the Quantile classification method to create classes in which each class contains the same number of records. This method is considered useful for showing rankings. However, it can also be misleading as it does not show how much difference there exists between each class. Therefore, the range for each suitability class is given in the result (chapter 4.2.1). The criteria 'distance to UGS' was classified manually on the known distance by the green norm (World Health Organization (WHO), 2017). This was done beforehand because of computational difficulties (see chapter

4.2.1). A scale of five categorical classes for suitability was chosen, ranging from very low suitability to very high suitability. Using three suitability classes was also tried (high, moderate, and low suitability) but this resulted in a map that explained not enough detail as the variation between the values was too limited. Also, more than five classes make it hard to explain and interpret the results by distinguishing the color classes.

Weighting and combine

Weights were assigned to these criteria based on the expert interviews with municipalities and the literature. Chapter 4.2.2 describes which weight division was used.

Next, a spatial overlay with the Weighted Sum tool was used twice for two different priority issues: environmental/health and justice. These two issues were identified during the literature study and interviews (see Chapter 4.1). Transforming the NoData values to 0 for Weighted Sum made it possible to have an output suitability class while one or more input raster contained NoData values. However, the disadvantage of the Weighted Sum compared to the Weighted Overlay is that the Sum tool does not convert the classes to a common measurement scale. Therefore, a reclassification based on an interval of 1 was done to compute a final land suitability map.

The approach of having priority issues is similar to the study of Apud et al. (2020), who argued that priority issues sometimes have compatible locations. It is therefore important to evaluate different possibilities to make trade-offs when possible. Also for decision-makers, it is important to show where the social land suitability map consists of. After evaluation of the difference between the two suitability maps, both maps were combined in one final suitability map by another spatial overlay.

3.4.3 Sensitivity of the results

As a final step, a sensitivity analysis was conducted to evaluate the impact of the weights and thereby the outcome of the land suitability analysis. The weights or priorities have an effect on the suitability classes ranking. Different decision makers' preferences using a set of weights impact the result of the multi-criteria decision making (Chen et al., 2010). Sensitivity analysis is often based on the variation of the weights of criteria to test whether it significantly changes the results obtained. The resulting variations for the two criteria of health/environmental and justice were used to describe the stability of the suitability classes.

One method is by investigating the stability of the suitability values by a known amount of change of the criteria weights (Chen et al., 2010). Similar to the approach of Chen et al. (2010) and Ustaoglu and Aydınoglu (2020), a series of suitability assessments was performed where each criterion weight was altered by a quarter percent and the remaining weights were changed proportionally so that all weights together add up to 100%. This means the percentage increase used in this study was 25%, 50%, and 75%. Three scenarios were made: one in which justice of green becomes more important, one in which health, environment and climate adaption becomes more important and the last one changes only the PM2.5 criterion. The justice criteria include changing the criteria of livability, distance to UGS, and UGS per inhabitant. The health/environmental criteria are PM2.5, noise, water stress, and UHI. These scenarios are related to the ambition of the municipality of Nijmegen to green 'future proof' neighborhoods, to create 'social green meeting points', and to 'make the city resilient to climate change effects' (Municipality of Nijmegen, 2020). The criterion of PM2.5 was chosen randomly from the total of the seven criteria but is nevertheless a realistic priority due to the issue for human health (World Health Organization (WHO), 2016).

3.5 Ecological connectivity analysis - EUC

The ecological connectivity analysis evaluated the current UGS and identified suitable new green spaces to enhance the green infrastructure network from an ecological perspective. It addresses the second part of the second research question about potential UGS locations based on ecological UGS connectivity (EUC).

3.5.1 Selection of species

Three animal species were included in this study: Hedgehog (West-European hedgehog, *Erinaceus europaeus*), squirrel (Red Squirrel, *Sciurus vulgaris*), and alpine newt (Alpine newt, *Ichthyosaura alpestris*). Non-flying species were selected as these have a lower dispersal ability, which makes them more likely to be affected by habitat fragmentation (Cushman et al., 2010). Furthermore, the selection of the hedgehog and squirrel was based on the prioritized species mentioned by the municipalities during the interviews. Also, the hedgehog is considered to have bad conservation status and is a rare and endangered species in Dutch urban settings (Lahr et al., 2016). Where the hedgehog prefers mostly shrubs, the squirrel is dependent on trees. A third species that was dependent on water was selected because water is considered a relevant ecological element in the ecological urban system (Ustaoglu & Aydınoglu, 2020). For this reason, the Alpine Newt was selected as this species was observed within the study area of the municipality of Nijmegen. Amphibians and water bodies are less studied and less well known (Pickett et al., 2001). The three selected species were seen as a representation of the various habitat preferences in urban areas.

Observation data for the municipality of Nijmegen was requested from the National Database Flora and Fauna (NDFF) on the 16^{th} of November 2021. The species dataset obtained from NDFF contained different shapes for the observations: point, line, area, rectangle, coordinate. The shape says something about how the observation was done. There are projects where, for example, only observations are made per square kilometer (rectangle). The size of the polygon says something about the area within which the observation was done where a bigger area represents a less precise location of the observation. Therefore, observations with an area of 200 m2 or more were not included in further analysis. These big areas were considered not accurate enough when extracting public green space based on the observation locations to come up with the species habitat patches.

3.5.1 Preprocessing: Habitat patches

A first step was to come up with UGS where at least one of the selected species was observed. A threshold of 100 meters was used because the observation points did not always intersect with the UGS locations. As a next step, a division was made between patches and corridors. The different types of green spaces can be represented in a patch-corridor-matrix model (Forman & Godron, 1986). The linear-shaped UGS are corridors and the non-linear UGS are represented as patches.

Patch and corridor separation

What will be identified as a patch or corridor depends mostly on the width of the UGS areas as corridors are linear and patches are non-linear green areas. In general, the wider the ecological corridor, the better it will be for habitat quality (Peng et al., 2017). Previous studies advocated different widths but not clarified their scientific basis. Determining a uniform width is difficult because urban ecosystems and environmental problems differ from one place to another (Peng et al., 2017). There is one document found for the Netherlands where they specified a minimum corridor width of 4 to 5 meters for urban ecological corridors (Burgerinitiatief Katwijk Smart Village, 2019). A corridor is defined by a width of 10 meters or less in this study and a patch has a minimum width of 10 meters because it is above the minimum of 5 meters and 10 meters is the spatial resolution used for the social suitability classes (see Chapter 3.4.1).

Several ways to divide the vegetated space into habitat patches and corridors have been explored in ArcGIS Pro (see Appendix VII). In the end, the tools in ArcGIS Pro were not sufficient because calculating the width of irregular polygons or raster regions was not possible. Therefore, the software of GuidosToolbox (Graphical User Interface for Description of image Objects and their Shapes) was used (Vogt & Riitters, 2017). This software was chosen because it included an easy-to-use Graphical User Interface and had good documentation.

Several morphological Image Analysis Pattern tools were available. All input GEOtiff files are in the format of foreground (value 2), background (value 1), and NoData (value 0). The Simplified Pattern Analysis 2 (SPA2) distinguishes linear/small features from coherent small foreground regions (see Figure 7). This analysis was used to distinguish corridors from patches. The input cell size was 10 meters because no further parameters could be specified and this cell size is similar to the minimal determined corridor width.

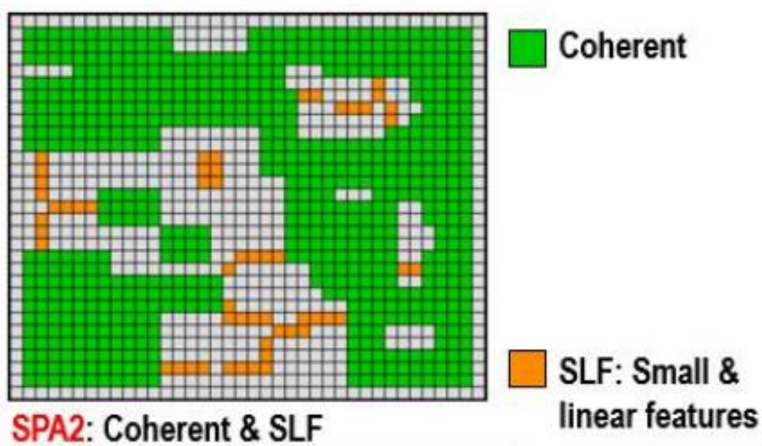


Figure 7 Simplified Pattern Analysis (SPA) including coherent areas and small/linear features (Vogt, 2017).

Polygon to Raster

For the polygon to raster transformations, there are three methods how to decide what value a cell will be assigned: Cell center, Maximum area, Maximum combined area. A cell size of 10 meters was chosen for the green area raster to meet the required computational power and align the ecological analysis with the social suitability analysis (see chapter 3.4.1). The raster transformation of the vegetated public spaces was done for the three methods to identify the differences in cell assignment (Appendix V).

Maximum area and Maximum combined area gave similar results because there were no multiple features sharing boundaries in one cell. The Cell center method is more 'filling in', while Maximum (combined) area is more often assigning values to cells where the feature has a very narrow width (Appendix V). That may be because Cell center assigns a value of a feature to the cell if the cell's center falls within the feature, whereas Maximum (combined) area assigns it when there is at least 50 percent overlap between the feature and the cell. In the end, the Cell center method was chosen because it represented the original vector dataset best.

3.5.2 Structural connectivity

As described in the theory of landscape ecology (Chapter 2.1), landscape connectivity can be divided into structural and functional connectivity. Structural means the physical landscape composition and functional includes the behavior or movement of species.

FRAGSTATS

To measure the structural connectivity, several landscape metrics were calculated in the software program FRAGSTATS based on the composition, shape, and configuration of UGS. All the habitat patches in the public UGS dataset were used as input after it was converted to raster format required for FRAGSTATS. Also, the habitat patches used by the specific species (hedgehog, squirrel, and alpine newt) were separated and used to calculate the landscape metrics. The parameter specification can be seen in Table 2.

Table 2 Parameters used in FRAGSTATS analysis.

Parameters	**Patches species**
Data format	GEOtiff
Pixel size	10 meter
Neighbor Rule	Use 8 cells neighboring rule (4 orthogonal and 4 diagonal neighbors)
Level	Patch and Class (patches of the same land cover/land use)
Search radius	100 meter

MSPA

Besides FRAGSTATS, also the software of GuidosToolbox was used to do a Morphological Spatial Pattern Analysis (MSPA) (Soille & Vogt, 2009). The analysis was used to describe the geometry and connectivity of the image components (i.e. the habitat patches). Zhang et al. (2021) also did an MSPA to show the relative proportion of the class for different areas. It provides a more intuitive basis for identifying the characteristics of the ecological network structure (Zhang et al., 2021).

An MSPA processes a binary raster image and segments the binary pattern into categories representing specific geometric features. The foreground area of a binary image is divided into seven classes: Core, Islet, Perforation, Edge, Loop, Bridge, and Branch. The processing steps described by Soille and Vogt (2009) resulted in these mutually exclusive categories as shown in Figure 8. This ecological network construction from the perspective of spatial morphological connectivity was created using the plug-in to ArcGIS from GuidosToolbox (Joint Research Center - European Commission, n.d.).

Three parameters need to be set. First, the habitat patches were assigned a value of 2, other land-use types 1, and the background 0. Secondly, the 8 neighborhood rule was selected which was similar to the FRAGSTATS analysis. Third, for the EdgeWidth several widths were tried based on the various resolutions. The spatial resolutions were 2, 5, and 10 meters. To align the division between corridor and patch with the SPA, a width of 10 meters was chosen. This resulted in an EdgeWidth of 5, 2, and 1 pixel for the resolution of 2, 5, and 10 meters respectively.

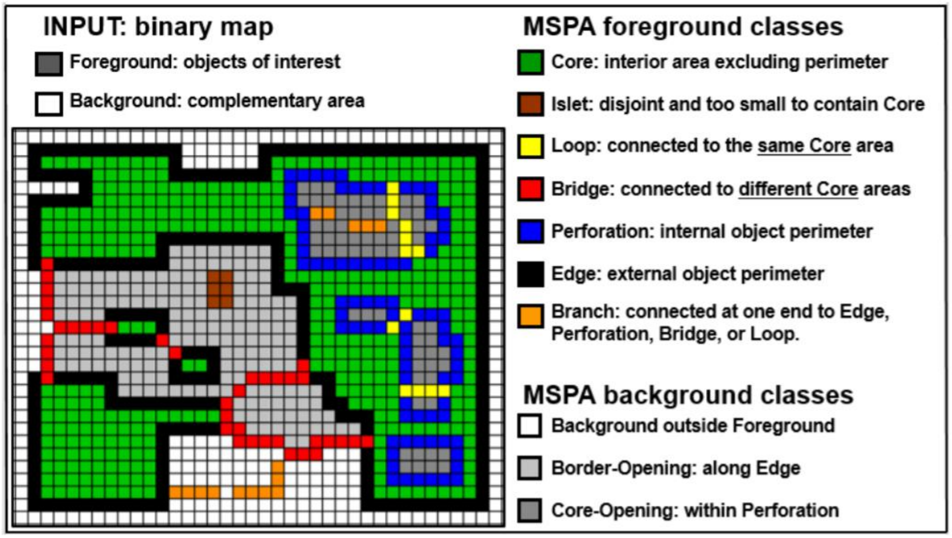


Figure 8 Overview of binary input and resulting classes from Morphological Spatial Pattern Analysis (MSPA) (Vogt, 2017).

3.5.3 Functional connectivity: Ecological suitability map

Whereas structural connectivity is more about the physical composition and spatial configurations, functional connectivity is concerned with the behavioral responses of the species (Zetterberg, 2011)

Cost raster

For the analysis of the functional connectivity, a cost surface was created for least-cost path analysis. Instead of representing the actual distance in geographical units, a cost raster indicates the costs of traveling over different land-use types. In terms of species movement from patch A to patch B, countless factors may influence these costs, such as land use, elevation, human disturbance (Xiu, 2017). In this study, the cost raster is based on land use types from the BRT dataset to reflect the ease of movement through the landscape. While elevation might be important for the dispersal of the alpine newt (personal communication, R. Creemers (RAVON), 10-01-2022), it was not included because there was no indication found for the hedgehog and squirrel. Also for human disturbance in terms of population density, no proof was found in the literature that the three selected species avoid humans. They actually live in gardens of humans.

The cost raster in this study represents the resistance in terms of dispersal of the species. The resistance depends on the selected species' preferences for certain land-use types. The costs range from 1 to 100, where 1 stands for lowest resistance and 100 means the highest resistance. Many studies have used different approaches to estimate the cost data of species dispersal, such as genetic flow and species colonization (Xiu, 2017). "Ideally, cost values should be assessed based on field and experimental data" (Rayfield et al., 2010). However, these data are difficult to collect which is why the setting of the resistance values is based on expert judgment in most cases. This study also used expert judgment and literature to assign resistance to land use types as no empirical data, such as movement data of species, was available.

Several experts were contacted via RAVON (Reptile, Amphibian & Fish Conservation Netherland) and the 'Zoogdiervereniging' (mammal association). One expert from RAVON, R. Creemers, was able to make a suggestion for the resistance values of the alpine newt. The city ecologist from the municipality of Purmerend, E. Raaijmakers, estimated the values for the hedgehog. Luckily, for the squirrel, one contacted expert was part of the study that also used resistance values (Verbeylen et al., 2003). Therefore, this study could be used as a reference for the cost values of the squirrel. No other experts could be reached as second opinions as they did not respond or felt not confident to give specific resistance values. This might indicate that it is rather difficult and/or subjective to estimate cost values for species.

Before the resistance values could be assigned to different land-use types, the BRT data had to be converted to raster to serve as input for later ArcGIS tools. Similar to the raster transformation of the habitat patches, the three classification methods Cell center, Maximum area, and Maximum combined area were tried to see the difference (Appendix V). Again, a cell size of 10 meters was used to align it with the habitat patches and social land suitability analysis. A land-use code was assigned to each land use type to distinguish the raster cells. Based on a visual as well as quantitive comparison of the three methods, Maximum area was chosen as a method because this contained the most road pixels. Linear features like roads are difficult to capture in raster cells. Therefore, most road pixels are selected. Also, roads are seen as extensive barrier for the selected species in cities (nederlandsesoorten.nl, n.d.; waarneming.nl, n.d.-b, n.d.-a).

Cost-connectivity

The Cost Connectivity tool in ArcGIS Pro was used to define the optimum network of least-cost paths. It is not used to create separate paths connecting one source habitat patch to a destination patch (Figure 9). Instead, the result is a network showing how the species can move from one region to any other region using the paths and possibly also traveling through other regions (ESRI, n.d.-b). The algorithm has 6 steps: 1) input regions and cost surface layer are identified, 2) Cost Allocation is performed to calculate for each cell the value of a particular region that can be reached with the lowest accumulated cost, 3) cost paths are created between each region and its neighboring cost region, 4) the regions and resulting paths are converted to a graph (graph theory), 5) the minimum spanning tree is determined using graph theory to connect the vertices (regions) in the most effective (least cost) way possible, and 6) the spatial representation of the regions and paths from the minimum spanning tree is mapped to an output feature class. The result of the tool might vary depending on the starting point or patch used in the minimum spanning tree algorithm, but ESRI is not clear which algorithm they used specifically for the tool.

Also, other software is available for landscape connectivity analysis, such as Linkage Mapper (e.g. Lechner et al., 2017), GFlow (e.g. Egerer et al., 2020), and Graphab (e.g. Zhang et al., 2021). It might be that such specialistic software provides more detailed options and parameters. However, not only the ease of use and having most analysis steps in ArcGIS Pro, but also not having an additional software program made the Cost Connectivity tool preferable.

Figure 9 How the Cost Connectivity tool works: input regions and a cost raster result in an output of a least-cost network over the regions (ESRI, n.d.-a).

Line density

Corridors with the most travel costs in the green network were identified based on the results of the Cost Connectivity tool. This tool gave two results: the paths between the regions based on the minimum spanning tree and all the paths to neighboring patches. In the next step, the Line Density tool was used to calculate the density of the paths (lines). The paths based on a minimum spanning tree were chosen as input for this tool because the other option (all paths to neighboring patches) also includes paths with very high costs, which are theoretically unlikely to be used by species. The costs were reclassified based on the quantile classification method to align the outcome for each species so they could be combined into an ecological suitability map.

The Line Density tool calculates the length of the line within a search distance (radius) and multiplies this by the path costs (the travel costs) (Figure 10). To take into account the dispersal distance of the three species, the alpine newt had a search distance of 200 meters, and the squirrel and hedgehog had a distance of 500 meters. The resulting output raster is then reclassified in five suitability classes similar to the land suitability analysis (very high, high, moderate, low suitability, and very low suitability).

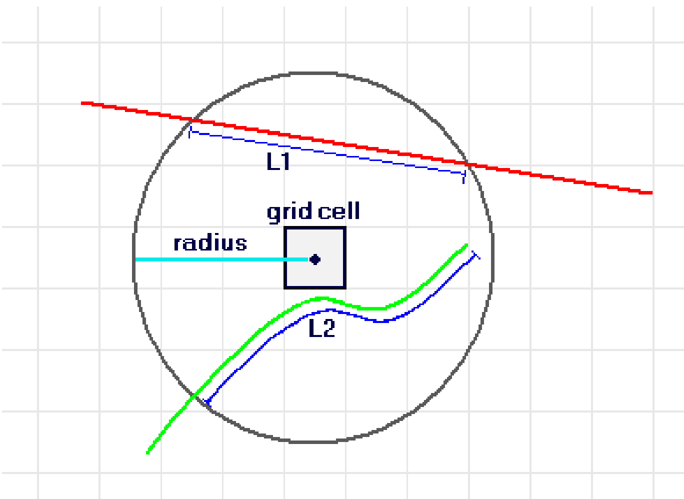


Figure 10 A raster cell and the radius used to determine the line density value for the grid cell (ESRI, n.d.-b).

3.5.4 Ecological suitability map

Integrating the individual species suitability maps into an overall ecological suitability map can be done in multiple ways. The ecological suitability map should contain the same five suitability classes as the social suitability map to compare them in the third research question (see chapter 3.4.3). Still, when to reclassify the ecological data into these suitability classes matters for the outcome. Two methods were tried. The first method performed used the Weighted Sum tool with the resulting values of the Line Density tool and then reclassified the results based on quantile into suitability classes. The second method was first reclassifying the costs of each species Line Density into the five suitability classes based on the quantile method and then performing a Weighted Sum overlay. The first method was preferred in this study because reclassifying the costs values into suitability values could imply information loss when the data is classified early in the processing steps. It was thus considered best to reclassify data in the end.

3.5.4 Sensitivity of the results

While many studies rely on expert opinion to assign costs associated with landscape features, only a few validate these costs with empirical data or assess model sensitivity (Sawyer et al., 2011). While empirical data was not available for this research, the sensitivity of the assigned costs values was assessed. Therefore, several scenarios of changes in the resistance scores were done to see how much the suitability classes changed. The change was not only assessed quantitatively but also spatially by showing the resulting suitability classes maps (Appendix IX).

The scenarios of changing resistance that were included are: 1) changing only the resistance of main roads (BRT sub-class 2.1), 2) increasing the low resistance values and decreasing the high resistance values by 25%, 50%, and 75%, and the other way around, and 3) changing the scores randomly by a percentage between -25% and 25%, -50% and 50%, and -75% and 75%. The Cost Connectivity tool does not allow to have decimal numbers as input in the cost raster. Therefore, the resistance scores were multiplied by 100 to keep the proportion similar but avoid any float numbers.

3.6 Comparison of social and ecological suitability

The third research question is *which potential UGS locations overlap when comparing the social and ecological UGS connectivity on a city, district, and neighborhood scale?* The results of the second research question, a map of social suitability classes from the land suitability analysis (SUC) and a map of the ecological suitability classes from ecological connectivity analysis (EUC), were spatially overlayed to compare the SUC and EUC.

3.7.1 Multiple scales

On the level of the municipality of Nijmegen, also called city-scale, the resolution was 10 by 10 meters. The differences and similarities were described between locations and their suitability class. This was done by computing a difference map where the change in the categorical suitability classes was calculated by using the ArcGIS Pro tool Compute Change Raster. In general, by comparing locations based on social and ecological suitability, the synergies and trade-offs could be identified for different potential UGS locations.

After priority areas were identified at a city level, the suitability classes were derived per district and neighborhood by calculating the mean suitability value of all cells within the respective neighborhood and district. This was done because zooming in and out between scales is a major advantage when discussing the planning and design of green infrastructure networks (Xiu et al., 2017). Planning and design approaches implemented at a larger scale of urban green networks affect the network in specific sites, and vice versa. The neighborhood and district scales are relevant for municipal UGS planners and designers as they often look at urban development on lower spatial scales than 10 by 10 meters.

3.7 Comparison social-ecological interconnectivity and municipal plan

The fourth research question is: *To what extent do the identified potential UGS locations from a social-ecological perspective overlap with the green structure map of the municipality?* To answer this question, the social UGS suitability (SUC) was combined with the ecological UGS suitability (EUC) to come to the final social-ecological interconnectivity map. This was done using the Weigthed Sum tool to calculate the mean suitability score. The ecological and social scores were equally weighted. To evaluate this interconnected social-ecological map, it was overlayed with the municipal map of the green structure. This data was retrieved from the municipality of Nijmegen as Web Feature Service and converted to Shapefile format.

Locations were identified that were highly suitable and overlapped the UGS decided upon by the municipality. The percentage of overlap was calculated from the social-ecological interconnectivity map with the green structure map of the municipality of Nijmegen. This was performed for the five suitability classes (very low to very high) by using the Extract by Mask tool to retrieve the suitability scores for the green structure elements. Also, the opposite – the percentage per suitability class which does not overlap the municipal green structure map - was calculated to see how much area is highly suitable outside the municipal green structure. This was performed to see how many opportunities there might be outside the existing municipal green structure.

4. Results

This chapter highlights the main findings as answers to the four research questions.

4.1 Social-ecological criteria

This section answers the first research question of what social-ecological criteria are in use by municipal UGS planners and designers to find locations for UGS. The results were collected through three interviews with the municipality of Amsterdam, Nijmegen, and Rotterdam. The semi-structured interviews resulted in the four overlapping themes and corresponding chapters: limited space, ecological areas, roads as corridors, and climate adaptation. In the end, the selected criteria will be provided. Thematic words which were most often used during the interviews are: connection(s) (52 times), trees (41), street/streets/roads (41), biodiversity (33), greening (24), water (29), climate adaptation (20), heat stress (14).

4.1.1 Limited amount of space

All representatives from the three municipalities indicated during the interviews that they want to develop more green in the neighborhoods with large amounts of paved surfaces, but due to the lack of space are limited to greening small squares or small façade or vertical gardens. “Green must be strengthened when the city becomes denser due to building more compact” (Interview municipality of Amsterdam). Furthermore, space is also limited underground as both municipalities mentioned there is not always enough space in the underground to plant trees along roadsides. Therefore, the municipality of Amsterdam suggested looking at how many squared meters are left after subtracting the space needed for functions, such as walking, cycling, cars, parking, and garbage, from the available space. Then, one can discuss which part to green and claim a budget for this. Where green on a map is placed is not based on hard numbers, but rather on knowledge and profile studies of streets where there is a certain claim for space. “Knowing where green is possible, is not databased” (Interview municipality of Amsterdam).

Space can become available during city redevelopments, such as the transformation from a car-based city to a bike and walking-friendly city. The interviewee from the municipality of Rotterdam highlighted the existing urban morphology as a critical factor on where to develop new UGS. Because the municipality owns only 40% of the land and has limited financial resources, greening the city can be done when parts of the city are restructured or redeveloped. Then, several structures or programs can be stacked, such as renewal of sewage, district heating, and giving priority to cycling and walking instead of cars. Consequently, the space which becomes available can be filled in with green. In this way, redevelopment and greening projects are combined. For example, the municipality of Nijmegen identifies where a ‘grey’ build environment can be replaced by green during projects like sewage renewal, road pavement, or district heating. Which area will be developed first is not based on specified criteria, but they look at the amount of nature or paved surface and where they can combine green development with other development projects. “Which street has priority depends on the planning of the replacement cycle of the streets” (Interview municipality of Amsterdam).

4.1.2 Ecological priority areas

Multiple criteria for ecological routes were mentioned by the interviewee of the municipality of Amsterdam. First, it was said that “an ecological connection should have enough elements for certain species, such as wood and shrubs for hedgehogs” (Interview municipality of Amsterdam). Secondly, a certain amount of robustness and size was mentioned to be important. Thirdly, the corridor should be accessible and safe for the animals. Roads and obstacles in streets were considered dangerous for crawling fauna. Therefore, the municipality of Amsterdam focuses on green space along watersides as the watersides often continue along the side of the roads under the bridge. Also, flying fauna forages often along the water. Food is seen as the fourth criterion for ecological routes. A fifth important criterion mentioned by the municipality of Amsterdam is the use of native plants. “The problem of biodiversity is mostly species being threatened because their plants are not found anymore” (Interview municipality of Amsterdam).

The municipality of Nijmegen identified current and potential green areas with high nature values based on the number of protected species and called them ‘nature pearls’, which are similar to the ‘key biotopes’ identified in Rotterdam. The municipality of Nijmegen wants to focus on animal species that are attractive to inhabitants, and which can be recognized easily in order to serve in citizen science projects. The interviewee from the municipality of Amsterdam mentioned there are several key species on certain ecological routes which are decided upon together with the urban ecologist. However, ecological knowledge about which species are living in the city is often lacking. Monitoring data is sometimes missing (for specific parts of the city) and therefore depends on expert judgment. Current research being carried out depends largely on data from the National Databank Flora and Fauna (NDFF).

4.1.3 Roads as corridors

All three municipalities indicated their focus on connecting the green structures along roads. The municipality of Rotterdam has plans to connect their identified key biotopes with the smaller green spaces via robust corridors along the roads and tramlines. The green structure plans and the main tree structure of Nijmegen are also based on the road structure to connect cultural history and green. “Some roads are already green by the side of the roads as a leftover from back in the days when the city was built, while other roads have no green or trees at all“ (interview municipality of Nijmegen). The interviewee from the municipality of Amsterdam mentioned it is difficult to implement green in some streets in the inner city. “You must not prioritize a street which has too limited chance to green while not far from it is a route which is more interesting for biodiversity”. Green in the inner city will probably be still fragmented due to the intensive use of space (Interview municipality of Amsterdam).

The focus on green space along roads as corridors is based on their linear character, which differs from the matrix (i.e. the built environment) on both sides of the corridor. “Due to the lack of space, it is necessary to combine structures of road infrastructure, green and recreation into a multifunctional public space” (Interview municipality of Rotterdam). The municipality of Amsterdam gives priority to connecting their main green structure for biodiversity. Secondly, there are green connections in the network of bicycle lanes and thirdly, green for pedestrians to make walking more pleasant and beautiful.

4.1.4 Climate adaptation

Besides the creativity needed due to the limited amount of space within the existing urban structure, all three interviews highlighted several functions of green, such as climate adaptation and the health of citizens. All municipalities mentioned similar ecosystem services: heat absorption, water retention, noise reduction, and cleaner air. However, the interviewee from the municipality of Amsterdam mentioned the outcome of their research, which was that urban green does not have a large influence on air quality and noise because of the small scale and small amount of urban green. Nevertheless, urban green influences the feeling of people. For example, if you do not see the traffic, you experience more silence. Thus, it is not all about hard numbers but also about the impact on humans.

These ecosystem services are helping to make the city more climate-proof and increase the living quality for citizens. As an illustration, the municipality of Amsterdam mentioned climate adaptation has both a physical and social aspect. “It is not only the presence of green but also the quality of staying and playing” (Interview municipality of Amsterdam). All three municipalities aim for a good living or staying quality (in Dutch: ‘verblijfskwaliteit’) of the public spaces. For example, the municipality of Nijmegen focuses on shade along walking and cycling routes and distance from houses to cool places and green. The municipality of Nijmegen incorporates a combination of green, health, biodiversity, and climate adaptation in their ambition and realization of the city. All three municipalities share the ambition for a healthy green city. Nijmegen includes this by designing green social meeting places, which can also be an ecological connection in terms of a steppingstone.

4.1.5 Selected criteria

The selected criteria based on the interview data described above can be seen in Table 3. Which datasets were used for these criteria can be found in Table 1 in the methodology (Chapter 3.3.1). The results from the interviews with the municipalities showed that the themes of living quality, health, and climate adaptation were considered the most important. The first two themes are included in the three criteria of livability score, distance to public green space, and amount of existing public green space. The livability score is based on 100 indicators in the dimensions of houses, inhabitants, amenities, safety, and physical environment. Interviewees from all three municipalities mentioned green space distance and/or distance to cool spaces as criteria. These two criteria can overlap, but if the quality of green spaces is not high (e.g. only grass), the temperature can still be high. However, data of distance to cool places was not available, which is why distance to green was calculated. Regarding the climate adaptation criteria, four ecosystem service criteria are included as health or environmental criteria.

Table 3 Social criteria derived from the interviews and classified based on two priority issues: justice and health/environment.

Domain	**Criteria**	**Unit**
Justice	Livability score	score 1-9
	Distance to public green space	meters
	Amount of existing public green space	m2/inhabitant
Health/environmental	Urban Heat Island effect (UHI)	degrees Celsius
	Particulate matter 2.5	mg/m2
	Noise pollution	dB
	Water depth by intense rainfall	cm

4.2 Social land suitability analysis - SUC

This chapter shows the results of the covariance of the input social-ecological criteria, the individual suitability criteria, the final social suitability map, the suitability maps for the justice and health/environmental criteria, and the sensitivity analysis. This contributed to answering the first part of the second research question about potential UGS locations prioritized based on social UGS connectivity (SUC).

4.2.1 Suitability criteria

The individual suitability criteria used are shown in Figure 11. This figure also indicates which range of values was used for the five suitability classes. UGS can tackle different problems and decision-makers can prioritize different issues (Apud et al., 2020). Therefore, the social analysis had two categories of criteria: justice factors and environmental/health factors (ecosystem services).

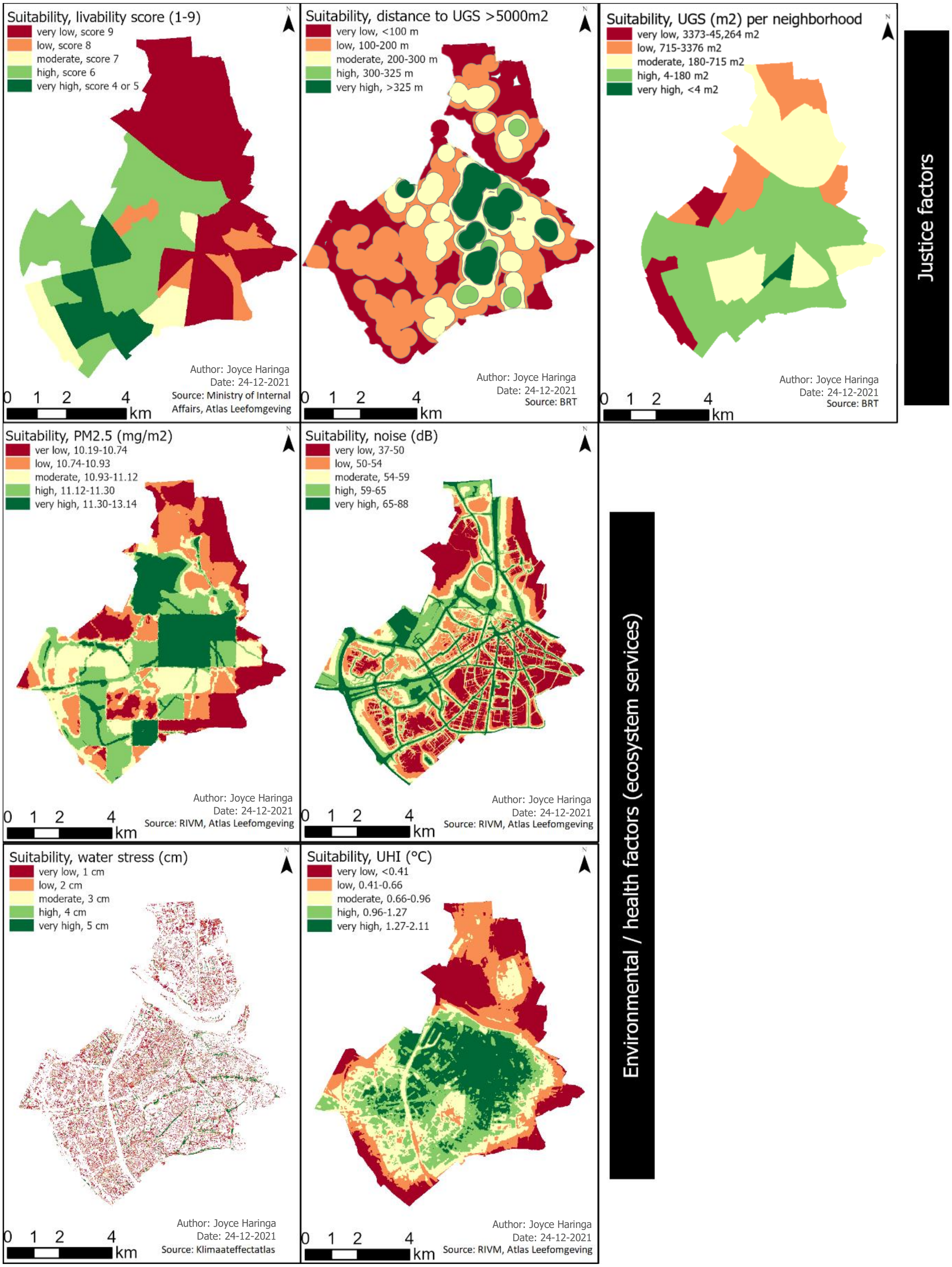


Figure 11 Individual suitability criteria classified in very high to very low suitability classes.

4.2.2 Social land suitability map

All the suitability criteria were combined by multiplying each value with its weight and summing them together. Equal weights were used because no specific important issues or rankings were mentioned or highlighted during the interview with the municipality of Nijmegen. Several important variables or criteria were mentioned. With 7 input criteria, a weight percentage of 14.29 or 14.28% was assigned. The difference of 0.01% was assumed to be negligible.

Figure 12 shows that at the edges of the municipality, there were mostly low to very low suitability values. This is mostly because it is already greener at the edges than in the more inner-city areas and because there is more pollution (noise, air) and heat in the inner-city areas. Specifically, most high to very high suitability values are in the city center and along the roads near large crossings of infrastructure.

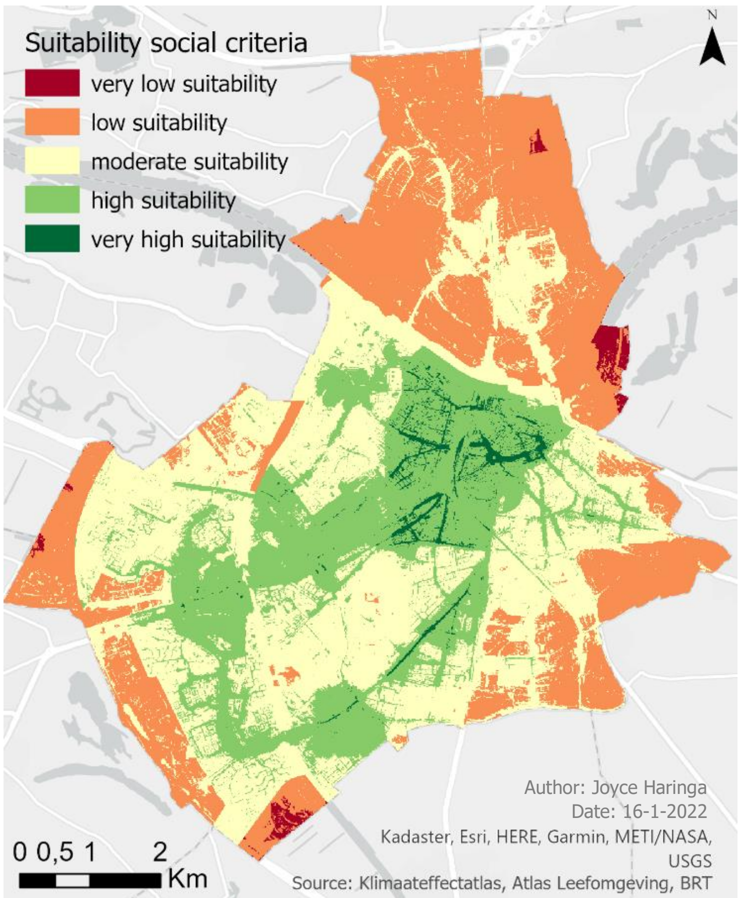


Figure 12 Social land suitability map based on justice and environmental/health criteria.

4.2.3 Justice and health/environmental suitability maps

The social suitability map of Figure 12 is derived from overlaying the two categories of the social criteria: health/environmental and justice criteria. An overlay was performed with equal weights for these criteria (Figure 13). This method is similar to the study of Apud et al. (2020), where they showed two possible priority issues that decision-makers can focus on when allocating UGS.

Figure 13 shows that the amount of detail of the resulting suitability classes was different because of the input data. For the justice criteria, two input criteria are on the neighborhood level (livability and amount of UGS per neighborhood). This makes it more difficult to compare the maps. However, it might be useful for decision-makers to see how various input datasets result in different outcomes and which two maps are combined to come to a social land suitability map.

One can see, for example, that both analyses resulted in a high to very high suitability in the city center. While the justice map (Figure 13B) has a more coarse pattern than the health/environmental one (Figure 13A), it does roughly follow the lines of the roads like the health/environmental map does. Another point is the very unsuitable neighborhood in the south and west on the justice map. These are neighborhoods where (almost) no citizens live. For this reason, it would be unsuitable for justice reasons (e.g. equal division of green).

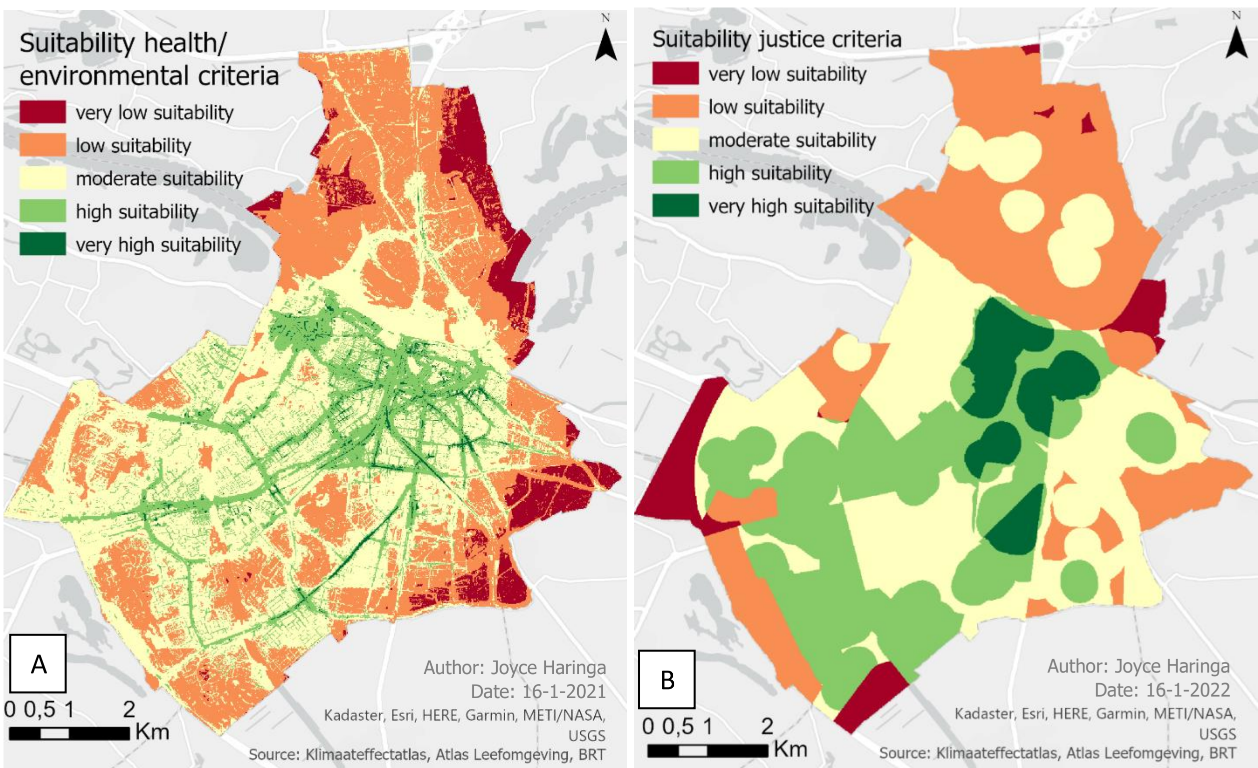


Figure 13 Suitability map of the health/environmental criteria (A) and of the justice criteria (B).

4.2.4 Sensitivity analysis

The relative change for each suitability class for the three different scenarios (justice, health/environmental, and PM2.5) with the various relative changes of weights can be seen in Figure 14.

Figure 14 Sensitivity analysis results of the changes in suitability classes for three different scenarios: justice (A), health/environmental (B), and PM2.5 (C).

Figure 14 shows that the change in suitability classes was higher in the case of the more extreme increase or decrease of the weights. Specifically, the suitability classes of 'very low' and 'very high' were more sensitive to the percentage variation of the weights than the other three suitability classes of 'low', 'moderate', and 'high'. The PM2.5 scenarios had the least variation for the 'moderate' suitability class in general for all changes in weights, whereas the justice and health/environmental scenarios had the least variation in the 'low' suitability class. When comparing the three scenarios in general, PM2.5 showed the least change and the health/environmental scenario the most.

The sensitivity analysis indicates that the larger the increase or decrease of the weights, the more the suitability classes distribution changed. A change of 25% in the three different scenarios resulted in a change between -42% and 59% in the suitability classes. For the 50% change in weights, a range between -29% and 221% was calculated, and for the 75% change, a change in suitability classes of -38% to 436%

was observed. Although the change in suitability classes distribution was rather high when changing the weights of the health/environmental or the justice criteria or one single criterion, the spatial pattern of higher suitability along roads and in the city center was still recognizable (see Appendix VIII for the spatial distribution).

4.3 Ecological connectivity analysis - EUC

Where the land suitability analysis focused on social criteria regarding the justice of green and health/environmental criteria benefiting urban citizens, the ecological analysis focused on habitat patches of the three selected animals and assessed the structural and functional connectivity. This focused on the second part of the second research question about which potential UGS locations should be prioritized based on ecological UGS connectivity (EUC).

4.3.1 Species: Hedgehog, Squirrel, and Alpine Newt

The three selected species were the hedgehog (West-European hedgehog, *Erinaceus europaeus*), squirrel (Red Squirrel, *Sciurus vulgaris*), and newt (Alpine newt, *Ichthyosaura alpestris*). The hedgehog prefers a habitat of variation of open and closed vegetation (waarneming.nl, n.d.-b). They potentially live in a mosaic of trees, shrubs, and open fields (grasslands). The squirrel lives in forests (conifer, deciduous and mixed trees), parks, and gardens as they eat the seeds from trees (waarneming.nl, n.d.-a). The alpine newt lives both on land and in the water. On land, they prefer a kind of deciduous and mixed forests (nederlandsesoorten.nl, n.d.). They reproduce in various waters as long as there are not a lot of predators like fish (personal communication, R. Creemers (RAVON), 10-01-2022).

Not all observations were within or intersecting UGS. As mentioned in Chapter 3.3.2, UGS is all public areas containing trees, grass, agriculture, and water obtained from the BRT dataset. Of the species observations, 170 of the 221 (76.9%) newt observations were within UGS, 359 of the 706 (50.8%) hedgehog observations were within UGS, and 541 of the 666 (81.2%) squirrel observations were within UGS. To include all the observations, a search distance of 100 meters was used to select also the nearby green areas where the species can (potentially) live.

The green areas were divided into patches and corridors with the Simplified Pattern Analysis (SPA) and the result for all UGS areas can be seen in Figure 15.

Figure 15 Division of UGS into Small Linear Features (SLF) and coherent areas as a result of the SPA.

4.3.2 Structural ecological connectivity

The structural connectivity was investigated by using landscape metrics in FRAGSTATS and conducting a Morphological Spatial Pattern Analysis (MSPA) in Guidostoolbox.

FRAGSTATS

After the habitat patches were identified with the SPA for the total UGS and the three selected species, several landscape metrics on the class level were calculated in FRAGSTATS (Table 4). The class includes all the habitat patches and the patches are the individual green areas. The number of patches is related to the number of observations for each species, as the UGS was selected for each species once the species was observed there. The average area per patch was derived from the number of patches and the area of the class. The hedgehog had a higher patch size than all the vegetated patches and had the highest mean patch area compared to the squirrel and newt. The lowest mean patch size for the alpine might be related to the lower movement range of the newt compared to the squirrel and hedgehog. While the mean patch area measures the surface, the mean radius of Gyration measure the mean distance within a patch. This was probably why a similar ranking occurred over the species with Gyration and mean patch area.

Table 4 Landscape metrics in FRAGSTATS (descriptions from McGarigal and Marks (1995)).

Metric (unit)	**Description**	**All vegetated patches**	**Squirrel patches**	**Alpine newt patches**	**Hedge-hog patches**
Number of patches	The number of patches in the landscape of patch type.	726	253	74	415
Class area (ha)	How much of the landscape is comprised of a particular patch type.	1694 ha	558 ha	113 ha	1142 ha
Mean patch area (ha)	A function of the number of patches in the class and total class area.	2.3 ha	2.2 ha	1.5 ha	2.8 ha
Mean Radius of Gyration (m)	Measures the average distance an organism can move within a patch before encountering the patch boundary from a random starting point.	44.6 m	46.2 m	41.8 m	48.8 m
Mean Euclidean Nearest Neighbor Distance (m)	Uses simple Euclidean geometry as the shortest straight-line distance between the patch and its nearest neighbor of the same class.	44.6 m	46.0 m	61.1 m	51.8 m
Mean Proximity Index	This index considers the size and proximity of all patches whose edges are within a specified search radius of the patch to measures both the degree of patch isolation and the degree of fragmentation of the corresponding patch type.	191.5	136.9	41.7	140.4

The average Euclidean Nearest Neighbor Distance showed that all species patches had a higher distance to the nearest neighbor patch than all the vegetated patches. The newt has to travel the most between two patches and the squirrel the least. This was remarkable because the newt has a lower movement range than the squirrel while the newt has to travel a larger distance. Another measure of patch isolation and fragmentation is the average Proximity Index. The index had no units so can only be used as a comparative index (McGarigal & Marks, 1995). The higher the index, the more isolation and fragmentation of patch distribution. One can derive from the indices in Table 4 that the newt patches were the most isolated and fragmented, followed by the squirrel and hedgehog.

MSPA

A second element of the structural connectivity analysis was the MSPA from the Guidostoolbox software (Soille & Vogt, 2009). This divided the habitat patches of all vegetation for different resolutions and the three species into 7 classes (Figure 16). In general, the core area has the largest share, followed by the edges, branches, bridges, and islets.

Different resolutions resulted in different classes for the same pixels (Figure 17). The insets in the figure show the differences. Especially when zooming in and also looking at the statistics per class, one can see the differences between the various resolutions. For example, the results showed that the lower the resolution, the fewer edges and fewer islets, but lower resolutions have more branches.

For the different species, the hedgehog had the most core areas (62.5% of the UGS patches), followed by the squirrel (56%) and the newt the least (50.6%). Core areas indicate areas of a broad movement range. The squirrel had the least islets (2%), closely followed by the hedgehog (2.4%), and the newt had the most (4.6%). Furthermore, the hedgehog had the least bridges, and the newt (5.5%) and squirrel (5.7%) almost had the same share. Bridges connect a core area to a different core area.

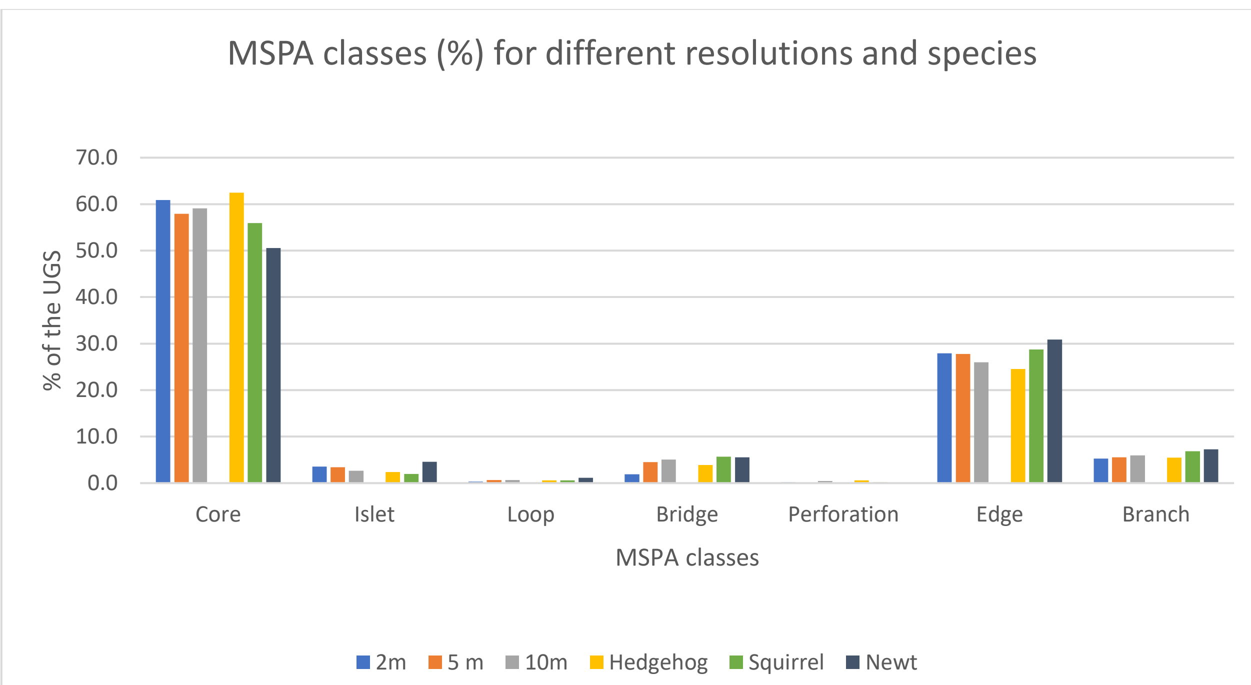


Figure 16 MSPA classes for three different resolutions and the three different species.

Figure 17 MSPA results for different resolutions: A) 2 m, B) 5 m, and C) 10 m. The legend of the MSPA classes is shown in D).

4.3.3 Functional ecological connectivity

The functional connectivity of UGS was assessed by using a cost raster in the Cost Connectivity tool and transforming the results into ecological suitability classes.

Cost surface

Table 5 below shows the resistance costs used for the cost surface. No weights were used as only land use data from BRT was used so no overlap with other data existed. The category 'other' (BRT sub-attribute 1.7) includes mainly areas around houses and other buildings. E. Raaijmakers, city ecologists, filled in the scores for the hedgehog, and R. Creemers did the same for the alpine newt. For the squirrel, no expert was found who could fill in the resistance scores. Instead, a previous study by Verbeylen et al. (2003) was used as a reference for the proportion of the scores of the squirrel. They tried 36 resistance sets and used 25 landcover types. They assigned resistance scores based on classes of landcover types. When using the highest number of classes, canals and buildings had the highest resistances scores, followed by water, roads and agriculture, then grass, then houses with gardens (included in BRT-attribute 'other'), then shrubs, then tree nursery and orchard, then houses with gardens and railroad with vegetation, then houses with gardens with trees and the forest. Main roads have higher scores than parking places because there is less traffic. In this study, grass was assigned a lower score than in the study of Verbeylen et al. (2003) because it is assumed to also include some shrubs. Sand was not a landcover category but is assigned a value of 40 in this study because pine trees grow on sandy grounds but it is not very likely that squirrels move a lot on the ground.

Table 5 Cost (resistance) values for different landcover attributes as input for the cost raster in the Cost Connectivity analysis.

			Hedgehog	**Squirrel**	**Alpine newt**
Variable	**Attribute**	**Sub-attribute**	Costs	Costs	Costs
Land use BRT	1. Terrain	1.1 Trees (deciduous, pine, mixed and griend, popular)	10	1	1
		1.2 Grass (grassland, heather, graveyard)	10	10	50
		1.3 Agriculture (arable land, orchard, tree farmer, fruit farmer)	20	50	50
		1.4 Railroad area	50	20	10
		1.5 Water constructions (dock, stone pitching)	95	70	40
		1.6 Sand	30	40	80
		1.7 Other	10	10	10
	2. Road infrastructure	2.1 Main roads (highway, main road, regional road, local road)	70	50	90
		2.2 Streets	50	30	60
		2.3 Other (walking and biking)	30	20	30
		2.4 Parking places	10	10	10
	3. Buildings		95	90	90
	4. Water	4.1 Ponds and lakes <125 meters in width	80	70	5
		4.2 Watercourse > 125 meters in width	100	100	50

Ecological connectivity suitability classes

The cost raster and the habitat patches were input for the Cost Connectivity tool. The resulting paths of all three species are shown in Figure 18A. The costs were classified based on the quantile method to make the costs of the different species comparable. The resulting map shows that mainly in the middle of the municipality, south of the river Waal there were rather high costs. This is probably because there are not a lot of large green areas and many crossings of roads. Near the boundaries of the municipality, the travel costs were in general low. This is also possibly due to more green spaces and less crossing of main roads.

The Line Density tool in ArcGIS with the costs paths as input resulted in a raster with density values for each species. These three raster layers were combined into a suitability map as shown in Figure 18B. When comparing it with the costs paths, one can see that the (very) high suitability classes were mainly on locations where there was a high density of lines and high travel costs. 52.6% and 23.4% of the paths are within the very high and high suitability area classes respectively. For the total travels costs, 32.6% and 46.7% of the costs are within the very high and high suitability classes. There are also places with no data because no species potentially traveled there between patches where they were observed. This is mainly on the northwest side near the river and the harbor.

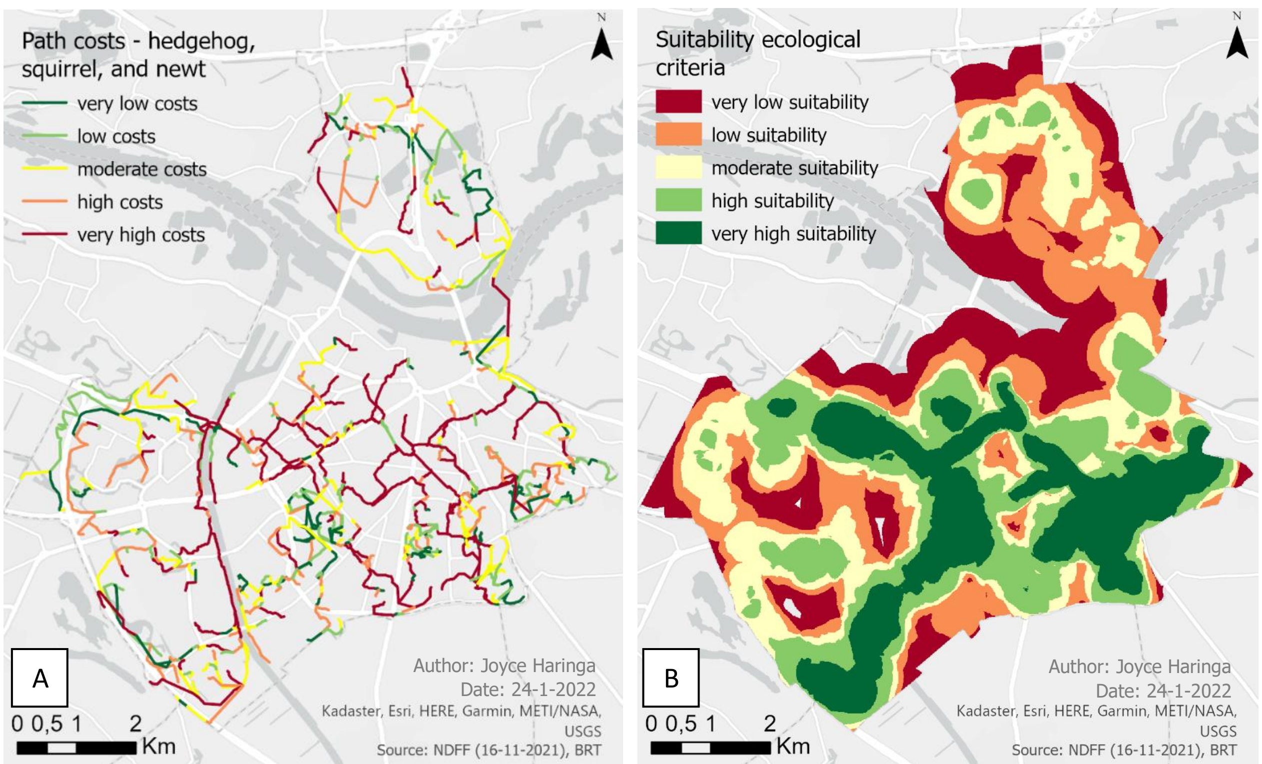


Figure 18 Cost of paths as a result of the Cost Connectivity tool (A) and ecological suitability ranges based on potential movement cost paths of the hedgehog, squirrel, and alpine newt (B).

4.3.4 Sensitivity cost raster

Three different ways of changing resistance values of the three species were tested (Figure 19). In general, the highest change in suitability scores is within a range of -7.5% to 12.2% for all species. Consequently, it was assumed that changing the weights of one species did not result in large changes in the ecological suitability map. Changing only BRT sub-attribute 2.1 (main roads) resulted in the least change in suitability classes compared to changing all the resistance values. When the resistance scores for main roads were 15 less than the baseline scenario, the hedgehog had the highest average change in very high and high suitability scores (2.3%), followed by the newt (0.8%) and the squirrel had a negative average change (-0.65%). This might be because squirrels might use trees to cross roads. See Appendix IX for more details.

Figure 19 Sensitivity of the changes in resistance scores of the hedgehog (A), squirrel (B), and newt (C). It shows the changes in suitability classes for multiple scenarios: random, BRT sub-attribute 2.1 (main roads), high and low scores.

4.4 Comparison of social and ecological suitability

This section provides results for the third research question: Which potential UGS locations overlap when comparing the social and ecological UGS connectivity on a city, district, and neighborhood scale? It does so by comparing the suitability values from the SUC and EUC approach, comparing it for different land-uses, and zooming in to the neighborhood and district scales.

4.4.1 Suitability classes

The suitability values of the SUC and EUC approach showed overlap for 22% of the study area, of which 6% are including the very high, high, and moderate suitability values (Table 6). Figure 20 shows where these locations are on the map. The darker the gray colors are in this figure, the fewer the difference between SUC and EUC, the higher chance for integration of SUC and EUC. The colored classes from red to green represent the same suitability values for SUC and EUC or one suitability class difference.

Table 6 How much area belongs to a certain EUC and SUC suitability score. The darker the color, the higher the suitability score. Orange means the same suitability score, green represents EUC suitability scores, and blue represents the SUC suitability scores.

		Area (ha)				
		EUC suitability scores				
		1	2	3	4	5
SUC suitability scores	1	12.54 (0.2%)	25.20 (0.5%)	0.92 (0.02%)	3.67 (0.1%)	11.13 (0.2%)
	2	409.72 (7.7%)	423.55 (8.0%)	411.95 (7.7%)	252.56 (4.7%)	246.02 (4.6%)
	3	248.98 (4.7%)	382.99 (7.2%)	410.15 (7.7%)	541.38 (10.2%)	501.12 (9.4%)
	4	277.74 (5.2%)	263.25 (4.9%)	212.63 (4.0%)	316.85 (5.9%)	280.55 (5.3%)
	5	36.71 (0.7%)	23.11 (0.4%)	9.26 (0.2%)	12.33 (0.2%)	11.62 (0.2%)

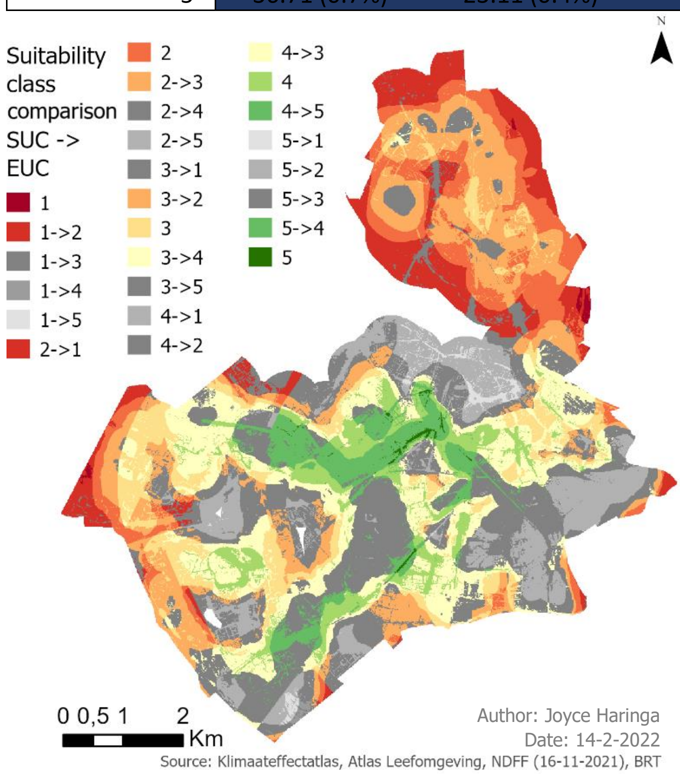


Figure 20 Comparison map between SUC and EUC suitability values. Darker gray means less difference and lighter gray means more difference. Colors classes show the same suitability value or a difference of one suitability class. The green areas show high suitability for SUC and EUC potentials.

4.4.2 Land-use suitability

The mean suitability score for each land use sub-attribute from the BRT layer was calculated (Table 7). The social-ecological mean suitability value is not simply the average of the social and ecological value as the latter two have a different spatial pattern (Figure 12 and 18B).

Table 7 shows that on average the railroad areas and streets were the most suitable in general, closely followed by other roads and tree areas. This might be because there is mainly high social suitability for noise and air pollution near roads. From the ecological perspective, roads are rather difficult to cross when species move, which makes roads highly suitable to improve as an ecological corridor. Railroad areas may be most suitable due to the high noise level from the social side. From an ecological perspective, railroad areas were less suitable than from the social perspective but UGS enhancement might still be beneficial due to relatively little human disturbance and less intensively maintained UGS along railroads.

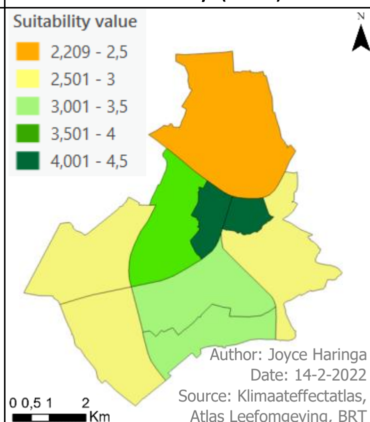
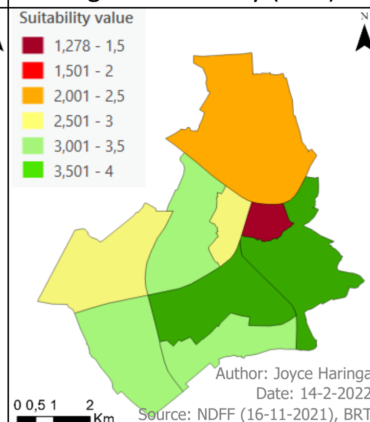
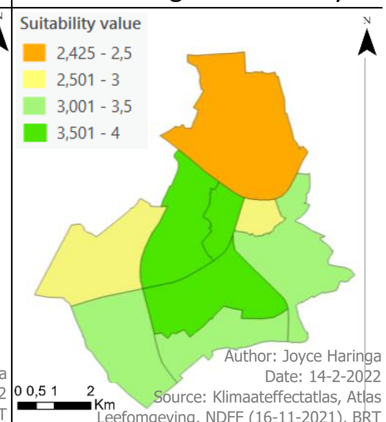
Table 7 Mean suitability scores per land-use sub-attribute from BRT data colored in a range from red (low/close to 1) to green (high suitability/close to 5).

Attribute	Sub-attribute	Mean suitability social	Mean suitability ecological	Mean suitability social-ecological
1. Terrain	1.1 Trees (deciduous, pine, mixed and griend, populars)	2.55	2.91	3.43
	1.2 Grass (grassland, heather, graveyard)	2.57	3.89	2.94
	1.3 Agriculture (arable land, orchard, tree farmer, fruit farmer)	2.1	2.96	2.09
	1.4 Railroad area	3.61	1.95	3.71
	1.5 Water constructions (dock, stone pitching)	2.58	3.18	2.03
	1.6 Sand	2.05	1.71	1.67
	1.7 Other	3.17	3.06	3.3
2. Road infrastructure	2.1 Main roads (highway, main road, regional road, local road)	3.25	2.98	3.28
	2.2 Streets	3.47	3.06	3.49
	2.3 Other (walking and biking)	3.11	3.18	3.33
	2.4 Parking places	3.21	3.18	3.39
3. Buildings		3.24	2.19	3.26
4. Water	4.1 Ponds and lakes <125 meter in width	2.39	2.6	2.72
	4.2 Watercourse >125 meter in width	2.56	1.99	2.1

4.4.3 District and neighborhood level

Contrary to previously shown maps with five suitability classes, the maps below have classes based on an interval of 0.5 (Table 8). This was done because having five classes did not show enough variance as there were often only two colors appearing on the map (see Appendix X).

Table 8 Suitability on district and neighborhood level from the perspective of the SUC, EUC, and interconnected suitability.

<table>
<tr><th></th><th>Social suitability (SUC)</th><th>Ecological suitability (EUC)</th><th>Social-ecological suitability</th></tr>
<tr><td>District level</td><td>
</td><td>
</td><td>
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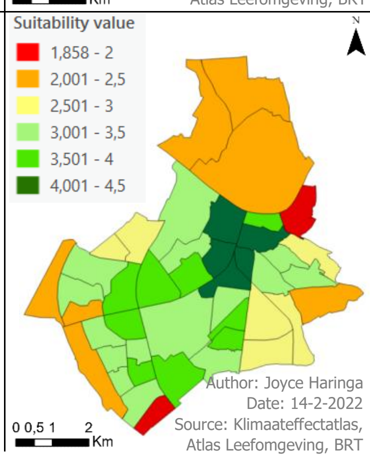
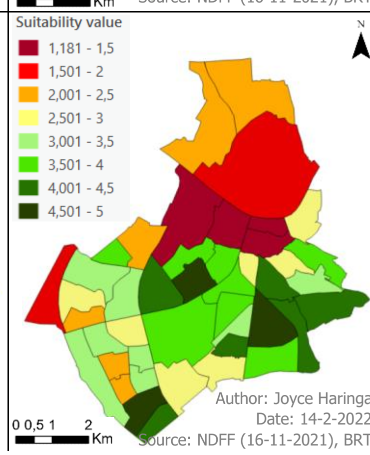
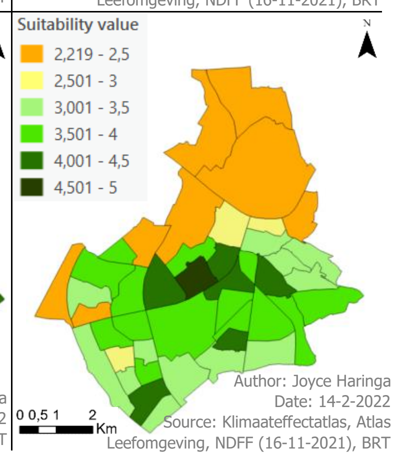
<tr><td>Neigh-borhood level</td><td>
</td><td>
</td><td>
</td></tr>
</table>

For the district level, the maps show that the three districts in the mid-west and city center of Nijmegen were the most suitable from a social perspective, while from an ecological perspective the city center was the most unsuitable and the mid-west districts were also less suitable than from the social perspective. Similar scores on the district level occurred in three of the nine districts that are located in the north, far-west, and south. The east of Nijmegen is considered more suitable from an ecological perspective. This is possible because there are forest areas outside the boundary of the municipality which could be connected to UGS in the surrounding neighborhoods.

On a neighborhood level, the variation of the districts was demonstrated. For example, the mid-west district had high and low ecological suitability scores in the corresponding neighborhoods. Specifically, close to the river Waal, there is very low suitability while there is high suitability in the same district in neighborhoods further south. This highlighted the relevance of zooming in and out between spatial scales. The social-ecological suitability values showed that the five neighborhoods in the middle of the municipality were highly suitable from a combined social-ecological approach.

4.5 Comparision of social-ecological interconnectivity and municipal green structure

This section compares the social-ecological interconnected suitability map with the municipal green structure to provide answers to the fourth research question about how much the identified potential UGS locations from a social-ecological perspective overlap with the green structure map of the municipality. First, the social and ecological suitability map will be shown. Then, an overlay with the municipal green structure map will be demonstrated.

4.5.1 Social-ecological suitability map

Figure 21 shows the interconnected social-ecological suitability map based on the average suitability score of the social suitability map (Figure 12) and the ecological suitability map (Figure 18B). It shows that almost all (very) high suitability class values are south of the river Waal. This was probably because the northern part of Nijmegen is developed in a later stage and showed lower social suitability values. Furthermore, the areas with very high suitability values were often overlapping with the main roads and crossings of main roads.

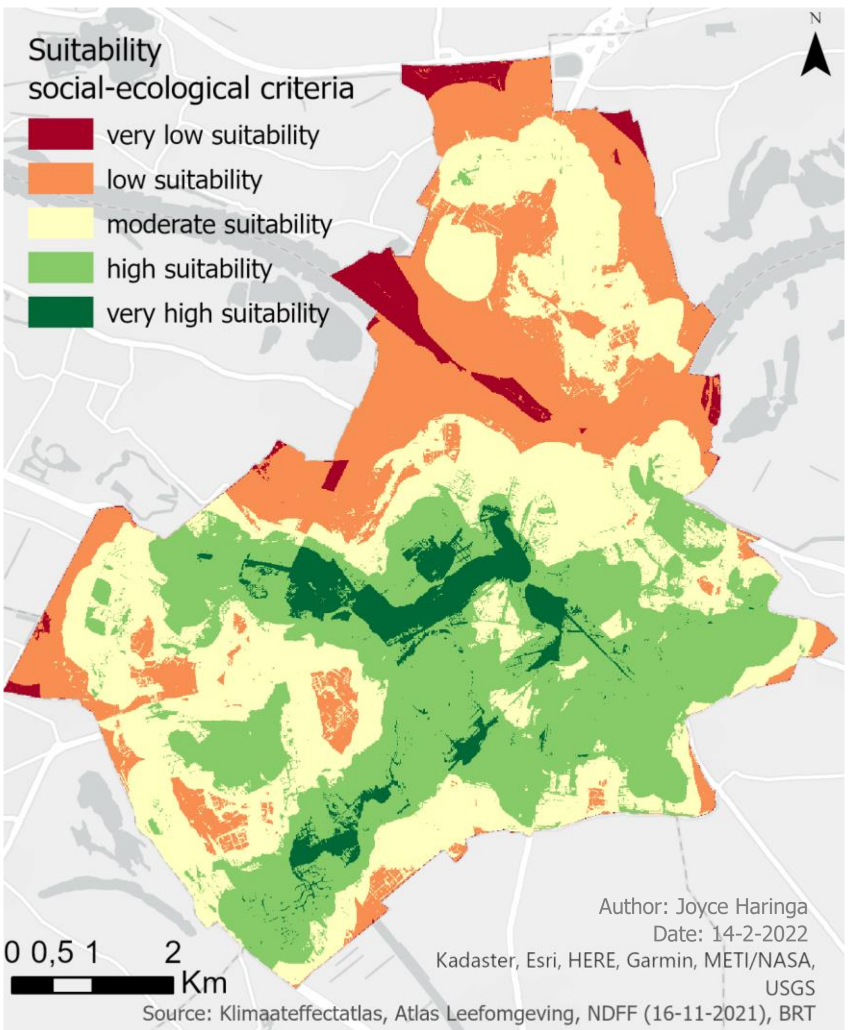


Figure 21 Social-ecological suitability map based on social UGS connectivity (SUC) and ecological UGS connectivity (EUC).

4.5.2 Municipal green structure map

The green vision or green structure maps of various municipalities come in different forms, amounts of detail, and layouts (see also Appendix XI). Some include recreational routes or movement of humans as connections and others make a division between current and future green development. Sometimes green was characterized by function or spatial scale. Also, the terms used in the legend are very diverse.

To evaluate the final social-ecological suitability map, it was compared to the map from the municipality of Nijmegen. At the time of writing, the municipality of Nijmegen had one map about their vision for a green and healthy city in their policy plan ('Omgevingsvisie') (Figure 22A). The green areas are the urban green structures, such as parks, forests, nature areas, recreation areas, and estates (Municipality of Nijmegen, 2020). The green lines form the lane structure where historical roads and main roads will become of a green character. The pink thin lines are so-called movement routes across neighborhoods for cycling and walking (Municipality of Nijmegen, 2020).

Because this policy map was not available (yet) as geo-data, it could not be used to spatially overlay it with the social-ecological suitability map in ArcGIS Pro. Instead, the green structure vector data from the municipality was used for the overlay with the social-ecological suitability classes. This geo-data differs slightly from the policy-map of Figure 22A. As shown in Figure 22B, the municipal green structure map overlapped the (very) high suitability values. Also, gaps are visible where the map colors green (high suitability) but where there is no green structure or only small linear green structures. This is mainly in-between the green structures following the main roads, where the smaller streets are located.

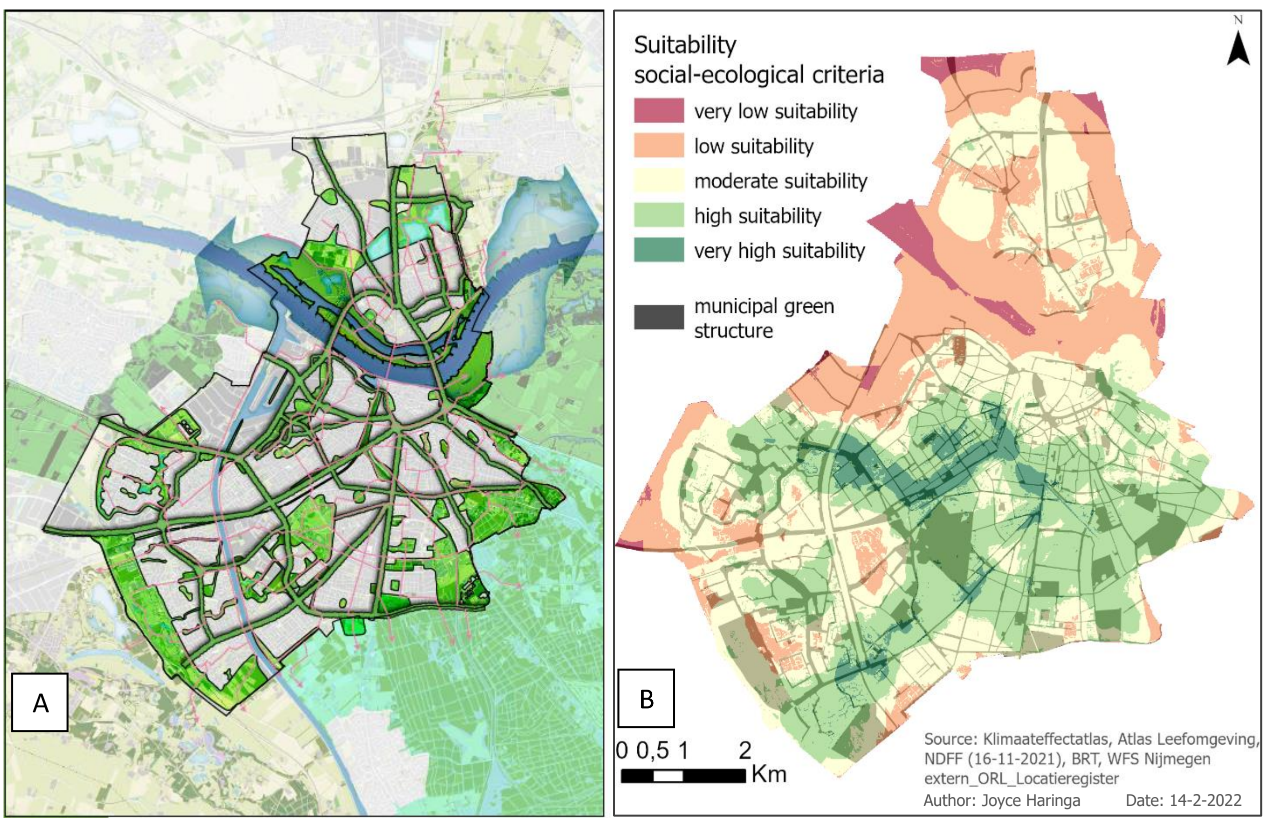


Figure 22 Green structure plan Nijmegen (Gemeente Nijmegen, 2020) (A) and an overlap of the municipal green structure data with the social-ecological suitability classes.

The map in Figure 22B, as well as Table 9, show that a large proportion of the social-ecological suitability map overlapping the municipal green structure resulted in moderate (39%) and high suitability (45%). Furthermore, 72% and 73% of the total area with, respectively, very high and high suitability is not overlapping the municipal green structure planning.

Table 9 Percentage overlap of the social-ecological suitability with the municipal green structure map (overlapping means inside).

	Total social-ecological suitability		**Social-ecological suitability overlapping the municipal green structure**			**Social-ecological suitability not overlapping the municipal green structure**		
Suitability class	Total area (ha)	Percentage of the total area of the municipality	Area of the municipal green structure (ha)	Overlapping area / total area of the municipal green structure (%)	Overlapping area / total area (%)	Area excluding the municipal green structure (ha)	Non-overlapping area / total area excluding green structure (%)	Non-overlapping area / total area (%)
1	171.91	3%	8.90	1%	5%	163.01	4%	95%
2	1385.91	24%	100.28	9%	7%	1285.63	28%	93%
3	2051.12	36%	447.92	39%	22%	1603.20	35%	78%
4	1850.37	32%	514.88	45%	28%	1335.49	29%	72%
5	304.50	5%	80.76	7%	27%	223.74	5%	73%
total	5761.58	100%	1152.47	100%		4609.11	100%	

5. Discussion

This study aimed to assess the interconnectivity of UGS by finding potential UGS locations and comparing these on multiple scales to detect directions for an interconnected social-ecological approach. This was done by conducting a social land suitability analysis (SUC) and an ecological connectivity analysis (EUC) and combining the two. This chapter discusses the main findings in relation to previous research and evaluates the research by highlighting the strengths and weaknesses. These strengths and weaknesses have an impact on the conclusions drawn in the next chapter. Therefore, alternatives for the methods used are specified that might improve future research.

5.1 Social-ecological criteria

One of the key findings of this study was the social-ecological criteria that could be used by municipal UGS planners and designers. The themes mentioned by the three municipalities were mainly about ecosystem services, climate adaptation, and quality of living and staying in the city. This suggests that ecological criteria are less used by the municipalities compared to social criteria. A study by Bekhuis et al. (2021) found similar results, who focused on an integrated approach of greening cities by Dutch municipalities. They found that several survey respondents of the municipalities mentioned that ecology is not, or too little, or only in terms of the nature laws included in municipal tender offers or contracts. The study of Zhang et al. (2021) also agrees with this finding and stated that “planning layouts of UGS in high-density areas often consider residents as the main object, while biodiversity and ecological processes are rarely considered in urban ecological space planning” (p.1).

There are many city functions using land, which results in competition for green spaces (Jim, 2004). The lack of space for green relates to the compact city concept including building more compactly to avoid negative effects of urban expansion and sprawl (Burton, 2000). This was also said during the interview with the municipality of Amsterdam: compacting is one of the ideas behind a plan for green streets. While this study is based on only three interviews with municipalities, it supports the findings of Bekhuis et al. (2021) who surveyed the same target group of Dutch municipalities. Three interviews might not be enough to generalize findings to all Dutch municipalities, especially the smaller ones as Amsterdam, Rotterdam and Nijmegen are some of the largest municipalities. Still, the findings are considered valid for the bigger municipalities as the three interviews highlighted the same key issues and issues to focus on.

A second key finding regarding the criteria was that the allocation of greening is more based on experience and knowledge than on hard data analysis. Municipalities do take both social and ecological ambitions into account when plans are made to green the city, as shown in the policy plans (‘Omgevingsvisies’). However, the findings of this study may indicate that the translation to certain social-ecological criteria as input for spatial analysis was missing to specify where to enhance UGS. It is assumed that allocating UGS is decided upon more by drawing on a table than finding locations by (GIS) analysis. Bekhuis et al. (2021) also stated that some other respondents in their study used ecology as a criterium for checking tenders or as part of their policy plans. This is partly supported by this study as it was found that municipalities do have criteria to assess projects and stated ecological ambitions such as connecting nature areas. However, no hard criteria were identified that assess the allocation of where UGS should be enhanced. This means that the first step (policy ambitions) and last step (evaluation on a project basis) include ecology, while the step in between (allocating UGS locations to locate the ambitions and priority projects) is missing ecological aspects. Bekhuis et al. (2021) also mentioned it could be particularly beneficial to prioritize greening where it is most needed. Which criteria this prioritization is currently based on is not clear from this study but the comparison of the interconnectivity map and the greening plan of the municipality could offer directions.

5.2 Social land suitability analysis - SUC

The social land suitability analysis focused on where green should be allocated given the health/environmental and justice criteria from a SUC approach. The first main finding from the social land suitability analysis was that roads appeared to be highly suitable. This was in line with the municipal green structure map and the results from the interviews. Kim et al. (2021) also highlighted the importance of small green spaces, such as roadside trees, as it is almost impossible to create new large green spaces due to the high development demand and land prices. Lahoti et al. (2019) point in the same direction by saying that "although at present the roadside green spaces are affected due to road widening and metro construction projects, these linear spaces hold a great amount of potential area to increase the total available UGS" (p.16). This potential is in correspondence with the high social suitability values for roads and streets in this study.

However, the land suitability analysis did not take into account whether greening on identified suitable locations is possible in practice. Although this study was not specifically on roadside vegetation, previous research indicated that most roads do not permit such extensive roadside tree planting because of the width, configuration, and usage (Li et al., 2005). The limited amount of space was also mentioned multiple times during the interviews but this was not fully taken into account during the social land suitability analysis. It is, therefore, possible that roads will be less suitable when more detailed data was included in this study, such as the width of streets. Still, the social suitability values overlaying the road could serve as identification of priority locations for roadside vegetation when roads are rebuilt.

Also, recreational value for cycling and walking along greenways was not included in this study as there was no data available about recreational values. A study by Giordano and Riedel (2008) used for example recreational and scenic values for the demarcation of greenways. When such recreational criteria were also included in this study, other roads might be more suitable than only the roads based on ecosystem services such as noise and pollution. Nevertheless, roads with high noise levels might become more attractive for recreation when trees are planted between a road and a bicycle lane.

A second main finding was that the social suitability map showed mainly areas in the inner city as highly suitable. A possible explanation for this comes from the study of Derkzen (2017) in which it was stated that residents in the city center of Rotterdam are offered fewer ecosystem services than those living in the urban periphery or nearby major parks. "This means that they might suffer more from heat stress, noise, air pollution, and flooding while needing to travel further in search of recreation areas" (p. 127). Similarly, Derkzen et al. (2015) also demonstrated that ecosystem service supply increases with increasing distance from the city center because central neighborhoods are the most densely built up and hence least green. Especially when the municipality of Nijmegen wants to focus on densification and being a compact city (Municipality of Nijmegen, 2020), it might be that UGS will experience increasing pressure. A recent study has already shown that densification decreases the quantity, average size, and connectivity of UGS (Balikçi et al., 2021).

While the supply is low, the demand for ecosystem services is high in the city center (Lin et al., 2021 -b). The demand for ecosystem services was taken into account by assigning high suitability values to areas that have a high UHI effect, noise level, air pollution, and water stress. The demand of residents was not taken into account specifically. Instead, municipalities were interviewed to identify criteria for the social land suitability analysis. However, no distinction in importance for the various input variables could be made based on the interviews. This is a limitation for the social land suitability analysis because it is uncertain whether equal weights represent the wishes of the municipality. The spatial distribution of suitability values changed depending on the weights for the justice and health/environmental criteria. As changes in weights affect the final result, outcomes should always be checked and corrected by a group of experts, ensuring they correspond with the current situation and priorities sought (Apud et al., 2020). M'Ikiugu et al. (2012) also used expert interviews as a way to provide priorities represented by relative weights. They used an unknown number of interviews with various experts. Using multiple experts might increase the validity of the weights when they are statistically integrated. This method has still some subjectivity in the order of weighting but the final weights are relatively precise and scientific (Manlun, 2003). Also, other methods could have been applied, such as an analytical hierarchy process of a pairwise comparison matrix (Abebe & Megento, 2017; Apud et al., 2020) or the fuzzy model (Giordano & Riedel, 2008). Although this could have improved the weighting of the suitability values, it was outside the focus of this study.

Furthermore, this study tried to be transparent about potential different issues or functions which UGS can serve. It did so by showing the spatial distribution of the input suitability values (Figure 12) and the two different priority issues (health/environment and justice, Figure 13) before combining them in a final social suitability map. This might be helpful to show policymakers and stakeholders that UGS multifunctionality cannot always be successful at achieving all the benefits at the same location. As Apud et al. (2020) indicated, stakeholders must evaluate different possibilities to make trade-offs when possible. Besides, the input suitability values also showed the neighborhood without input data, in this case for the livability score (4 of the 44 neighborhoods were missing data). This might influence the reliability of the suitability scores in these neighborhoods. However, the influence of this missing data is considered limited in the final social-ecological suitability map because there are also 6 other input variables for the social perspective and this social side is only 50% when it is combined with the ecological suitability values.

5.3 Ecological connectivity analysis - EUC

The discussion for the EUC approach is divided into two chapters to discuss the structural and functional connectivity.

5.3.1 Structural connectivity

The results from the structural connectivity analysis showed that the newt habitat patches were the least connected followed by patches of the hedgehog and squirrel. A possible explanation for this might be that amphibians, such as salamanders, require the adjacency of aquatic and terrestrial environments for their life cycle (Bennett, 2003). Salamanders are considered more habitat specialists and have a lower dispersal ability than the hedgehog and squirrel. An alternative clarification for the lower structural connectivity of the newt compared to the hedgehog and squirrel is that there are fewer observations of the newt. Lahr et al. (2016) also mentioned that there are not sufficient observations for amphibians in the Netherlands to back up their conclusions. It is possibly more difficult to observe and determine an alpine newt than a squirrel or hedgehog. This means that the landscape metrics used to say something about the structural connectivity is highly dependent on the observations from NDFF. It would therefore be better to compare connectivity of habitat patches for one species over time due to landscape changes than to compare patches of different species.

The MSPA used for structural connectivity showed the distribution of MSPA classes for different spatial resolutions, of which the smallest resolution of 2 meters was considered most suitable because it showed the most detail. A similar ranking of the MSPA classes occurred compared to Zhang et al. (2021) who also used the 8 neighbors rule but a width of 15 meters instead of 10 meters and conducted a case study in Shanghai. The largest share in their study was of core areas, followed by edges, islets, branches, bridges, loop, and perforation. In this study, islets and branches were switched places compared to the latter ranking. Because Shanghai might not be comparable with the landscape of Dutch municipalities, the MSPA could be improved if the classes are compared to other Dutch municipalities to say something about the structural connectivity. Another way to make use of the MSPA results is to compare the landscape over time. Regarding the spatial resolution, it is comparable with the study of Lin et al. (2021 -a) which showed that core areas first decreased or increased from 30 to 10 meters resolution and then increased from 10 to 1 meter resolution. Although the study of Lin et al. (2021 -a) used different resolutions than this study (1, 5, 10 meters), it is in correspondence as it showed the same pattern. Besides the core, also the bridge areas play an important role in migration and landscape connectivity. The proportion of bridge areas increased with higher resolution (Lin et al., 2021 -a), while in this study it decreased. This shows that MSPA is sensitive to changes in spatial resolution. The effects of spatial grain should be taken into account as such differences are critical for decision making in UGS planning and management (Lin et al., 2021 -a)

5.3.2 Functional connectivity

Regarding the functional connectivity, one of the main results was that there is not high suitability observed in the city center. This is in line with Ersoy (2015) who claimed that connectivity is the lowest in city centers where buildings and hard surfaces dominate and affect the movement of species. Together with the fact that this city center surface was assigned high costs, this resulted in low suitability to increase ecological connectivity in the inner city. A shortcoming of the approach to calculating the least costs paths was the subjectivity of the cost raster based on expert knowledge. There was no empirical data behind the cost resistance values and the costs were not validated with empirical data. This introduced uncertainty and bias in the resulting connectivity routes (Ersoy, 2015). However, it was considered the best option when empirical data is not available. Future research can improve cost values based on expert knowledge by combining results from multiple experts.

A second main finding from the functional connectivity was that roads resulted in high costs and have therefore high ecological suitability to enhance UGS along roads. This is in line with Ersoy (2015) who concluded that roadside vegetation represents a very high potential to support the movement of species. A possible explanation is that roads form barriers to the movement of wildlife (Jim, 2013). This suggests that transforming roads to ecological corridors or greenways can improve the ecological network extensively. However, a potential weakness of least-cost modeling is whether species choose to use the ideal paths. Real low-cost corridors in the landscape for an organism would be the optimal movement routes, but for particular species, this does not always apply since they cannot be guaranteed to use the effective paths for their movement (Xiu, 2017). Nevertheless, least-cost paths predictions are confirmed to be of good use for stakeholders, especially for urban contexts (Balbi et al., 2019). A feasible improvement of the least-cost path model would be to show the multiple routes for possible movement through the landscape. However, it was only possible to calculate a corridor between two patches and not for all the patches within the used software of ArcGIS Pro.

While the resistance values based on expert opinions might not be considered the best method, the sensitivity analysis showed that the suitability classes varied between -7.5% and 12% when changing the resistances values by 25, 50, and 75%. This indicates that the classes were robust as the variation was low. Also, the spatial distribution of the ecological suitability classes changed only very slightly (Appendix IX). This is probably because the ecological suitability map is constituted of multiple species suitability maps. While only a minority of the researchers quantitatively assessed the sensitivity of model-selected paths to different cost schemes, it is important because the analysis heavily depends on cost schemes used (Sawyer et al., 2011). Possible trade-offs exist between suitability scores for the selected species when the resistance score for a certain land-use type changes. For example, making water more suitable for the newt might have different consequences for the squirrel and hedgehog. It was hard to make correlations between the sensitivity scenarios for the three species per suitability class because the baselines of the species include different resistance scores and have a different number of observation points.

A last point of discussion for the ecological connectivity results was the selection of three species. The hedgehog, squirrel, and alpine newt were selected to represent different habitat preferences. Yet, not all habitats are taken into account, such as species dependent on flowers. One can question to what extent the preferences of the selected species are considered as the surrogacy of other species (Ersoy, 2015). On the one hand, it was suggested to include as many species as possible instead of only one or a small number of species (Baguette et al., 2012). On the other hand, Cushman (2006) advocated using species-level information to be able to reliably predict species-environment relationships. This study of Cushman (2006) about amphibians showed that among the amphibian species there are large differences in terms of their habitat requirements. However, this species-specific ecological knowledge is often lacking.

5.4 Comparision of social and ecological suitability

The most similar locations resulting from a comparison between social and ecological suitability values were the roads, which had a high suitability score for both SUC and EUC approaches. Green infrastructure networks use network connectivity as a tool for integrating the ecological and social functions jointly, rather than separately for ecology (green corridor) and recreation (greenways) (Xiu, 2017). Roads are not only barriers to wildlife (Jim, 2013) but are also increasingly forming problems for humans in terms of heat, noise, and air pollution (Forman et al., 2003). This suggests it might be a win-win situation to focus on the green networks to support the movement of people and biodiversity (Forest Research, 2011). According to Xiu (2017), these locations that can fulfill multiple values and functions are crucial to balance different interests of humans and other life forms in urban environments. Still, human and ecological interests are always in conflict (Xiu, 2017). An example is that certain species will not use roads as ecological corridors because they avoid roads or degraded habitats (Van Der Ree et al., 2015). Thus, while roads might be a win-win situation for both humans and non-humans, there remains conflict in interests.

The main difference on the neighborhood and district level between the social and ecological suitability locations was assessed by calculating the mean suitability value on the corresponding spatial scales. The implication is that the spatial variation within these areas is not taken into account. However, it is assumed to match the approach of the municipalities well as they often have neighborhood management plans. The higher resolution map (10 meters) can be used after selecting a priority neighborhood. The main difference was that the city center was most suitable from a social perspective but the least suitable from an ecological perspective. This is probably because of the lower amount of UGS and higher distance to UGS as Kabisch et al. (2016) suggest that UGS in inner-city areas are lower due to population density. However, giving priority to the city center to develop UGS could be read as a trade-off as the city center is not a priority for ecological connectivity. The latter is only true for the species used in this study as the city center might be a potential habitat for other species like birds. A similar trade-off was also described in the study by Ernstson (2013), saying that spreading trees evenly would be good to distribute the ecosystem service but would be a bad option seen from an ecological perspective in terms of landscape connectivity.

Although the objective of this thesis was to find and assess *potential* UGS locations, existing UGS locations were not excluded from the final social-ecological suitability map. Consequently, the high suitability values also overlapped with existing green spaces. Not only finding new locations to extend the green infrastructure network, but also enhancing existing UGS is considered essential (Haaland & van den Bosch, 2015). The highly suitable locations overlapping existing UGS could be seen as a location to enhance the quality of existing green space, both from a social and ecological perspective. When UGS locations are overlapping with high SUC and low EUC suitability values or vice versa, the UGS location can be transformed or developed to either a more ecological or social function when the suitability values differ much. This might help UGS planners and designers to adopt certain functions or types for UGS.

While there are differences and similarities between suitable locations for ecological and social values, it is necessary to enhance UGS from a multi-functional angle. So far, no study has been identified that combined a social perspective and ecological perspective using a land suitability analysis and ecological connectivity analysis. Other suitability studies utilized the ecological factor threshold method to quantify how much green area is necessary to maintain an ecological balance in urban areas (Zhang et al., 2007; Uy & Nakagoshi, 2008). However, this does not take the connectivity into account, which is considered one of the most important measures to counteract habitat fragmentation (Zetterberg, 2011). Also, a 'minimum' threshold amount of green might not be universally applicable to all species and all ecosystems (Fischer & Lindenmayer, 2007).

What is new compared to previous studies is that this study used multiple analyses (land suitability and ecological connectivity) to come to the interconnectivity of both the social (SUC) and ecological (EUC) perspectives. In general, the importance of integrating ecological and social systems to form interdisciplinary research to ensure sustainable urban development has been widely recognized (Niemelä, 2014). The different research methods are considered one of the obstacles in interdisciplinary studies. This was also experienced when comparing results from the social and ecological analysis because the analyses are from different disciplines using different (GIS) methods. Specifically, the transformation from costs paths into suitability classes resulted in buffer-like patterns whereas the social suitability showed a more fine-grain pattern. Nevertheless, it is considered a valuable step to come to a methodology that integrates multiple perspectives and functions of UGS. Integration of the ecological approach with a suitability analysis was also suggested by Ustaoglu and Aydınoglu (2020). This thesis contributed to the social-ecological system approach (Figure 3) by developing a GIS model to include both the ecological structure (structural connectivity), ecological functions (functional connectivity), and human outcomes (justice and health/environmental factors). Human behavior was to some extent included in the interviews by discussing the planning and design.

5.5 Comparison of social-ecological interconnectivity and municipal green structure

While the majority of municipal green structure map appeared to be moderately or highly suitable (40 and 43% respectively), more than 70% of the very high and high suitable area was located outside the municipal green structure. This might indicate that the municipality is to a limited extent prioritizing UGS locations based on the social-ecological criteria used in this study's GIS analysis. There might be multiple reasons for this high percentage. First, it might indicate that the municipal green structure map does not cover a high proportion of the total area of the municipality. This might be because the municipal green structure map is not detailed enough. An indication for this is that green structure covers the entire road and not only the roadsides. It could be that roadside vegetation is only possible on one side of the street but the municipal green structure map does not indicate this. Also, when the municipal green structure map is based on, for example, green spaces of more than 100 square meters or areas more than 10 meters wide or long, it is not in line with the social-ecological suitability map that has a resolution of 10 meters. Thus, a more detailed municipal green structure map is necessary for the future.

5.6 General limitations GIS analysis

There are three points of discussion that account for both the SUC and EUC, which are the main three limitations of the GIS analysis.

The first point of discussion is that private UGS was not included in the scope of this thesis because it focuses on municipalities and their green structure plans which have to do with the public space. Still, private gardens are valuable for both ecological value by providing species with additional habitat and social value for humans in terms of, for example, leisure (Brunner & Cozens, 2013). Including private UGS, such as gardens, might add additional insights for SUC. Lin et al. (2015) highlighted that in deprived neighborhoods, UGS is often less available while in these places residents rely more heavily on public UGS due to the lack of private greenery. While the study of Lin et al. (2015) was conducted in the context of Sydney, it might be possible that the same is occurring in Dutch cities. In the end, exclusion of private UGS was not considered a big limitation as Coolen and Meesters (2011) concluded that private gardens cannot simply be substituted by public green space in the Netherlands. It would be more important to acknowledge the difference between public and private UGS when both are included in studies to address challenges in green space planning under densification processes (Haaland & van den Bosch, 2015).

Secondly, as this study addressed UGS with a quantitative approach, it did not take into account specific UGS vegetation and quality. Critics of such an approach, like Hunter and Luck (2015), would say to rather focus on the quality of greenspace to examine the role of green space in delivering social-ecological value. In the future, more detailed datasets, such as intensity of management, nature-friendly shores, or attractiveness to visit, could serve as input for either the social suitability values or the ecological cost resistance values. This data would be most beneficial to strengthen the ecological connectivity analysis as it is now based on broad BRT classes which possibly do not represent the complex reality. An example given by the expert who helped define the resistance values for the hedgehog is that the hedgehog prefers shrubs and gardens but can not access these because of the fences. An example for the newt is that they prefer water without fish and water surrounded by habitat which is not intensively maintained. Unfortunately, this amount of detail could not be included as data was lacking.

A third general point for the GIS analysis is that it was limited by the boundaries of the municipality but ecological – and to a lesser extent social – processes are not limited by this boundary. For the social variables, this mainly implied distance to UGS per house block. When a large distance would be calculated for a house block with UGS just outside the boundary of the study area but within the specified distance, it would be incorrectly assigned as suitable to develop UGS. This effect is assumed to be low because there are only two high suitability circles cut off by the boundary of which only the one in the north has UGS outside the boundary (Figure 11). From the ecological perspective, as identified by Egerer et al. (2020), external landscape features outside the research area may influence connectivity flows. There were boundary effects in this study for the cost connectivity calculations as paths had to follow the boundary of the map (Figure 22). This effect will be more prominent when large habitat patches are present close to the edge of the study area. In this case, the forest at the east side of the municipality is assumed to have a boundary effect. Therefore, it would be advisable to include such large potential habitat patches just outside the study area in future studies or to also include a regional approach besides the municipal (city), district and neighborhood scales.

6. Conclusions and recommendations

This final chapter draws conclusions based on the answers to the research questions which were discussed in the previous section. It also provides recommendations for municipal practices and future research directions.

6.1 Key findings

This study contributed towards a GIS workflow for allocating potential UGS locations on multiple scales by applying an interconnected social-ecological approach. The first research question about the criteria used by the municipal UGS planners and designers showed that they do not solely base the allocation of UGS locations on (GIS-) data analysis. Hence, they do not have a strict list of social-ecological criteria. Consequently, the criteria used in this study were derived from the municipal ambitions mentioned during the interview. The municipal policy plans include ambitions related to UGS, such as climate adaptation measures, improving living quality and health, and connecting existing UGS. When a project is realized in the city, biodiversity criteria are used to assess such a project. However, allocating priority locations for UGS as a step in between the ambitions and realization was not primarily based on data analysis with specific criteria. This study specifically contributed to this gap between the municipal ambitions and the realization of urban development projects.

The second research question identified the suitability of UGS locations from a social (SUC) and ecological (EUC) perspective by conducting a land suitability analysis and an ecological connectivity analysis respectively. In general, the SUC perspective resulted in high suitability for locations in the city center and along roads while the EUC perspective showed highly suitable locations in the middle of Nijmegen and along roads. The third research question compared the UGS suitability from the SUC and EUC perspective on different spatial scales. On neighborhood level, the most striking differences in the suitability of UGS locations occurred in the city center. This is an indication of the discrepancy between social values and ecological interests, in this case, those of the newt, hedgehog, and squirrel. Potential win-win locations for UGS development are found along roads as they appeared to be highly suitable from both social and ecological perspectives. Altogether, the two analyses are both considered essential because landscape fragmentation is one of the most important identified issues for urban sustainability. Together with the identified benefits of UGS for humans, UGS could become a priority in the scarce amount of urban space.

The fourth research question, concerning the overlap of the identified potential UGS locations from a social-ecological perspective with the green structure map of the municipality, showed that the majority of the allocated green structure is moderately or highly suitable. Moreover, there is high potential outside this green structure as more than 70% of the very high and high suitable locations do not overlap the municipal green structure map. This indicates that the green structure map of the municipality is not elaborated enough (yet). Although municipalities already acknowledged the importance of green along roads on their maps for biodiversity, recreational values, and climate adaptation, the results highlighted which roads are most suitable and should therefore receive priority in future city development. Whereas the existing municipal green structure map focuses more on main roads, also smaller streets within the neighborhoods seem highly suitable. It can thus be concluded that most of the municipal green structure overlaps the highly suitable UGS locations but also a large part of the highly suitable areas is located outside this municipal green structure.

While allocating UGS with digital models may not be optimal due to a model's incapacity to capture all uncertainties and circumstances, it is considered a useful instrument for decision-making. This is because the GIS workflow can be used as a first step to identify priority locations for UGS development based on defined municipal ambitions. When these results are used in practice, it strengthens the claim of UGS in the competition of space by showing the multifunctionality of UGS. In this way, it exceeds the rather sectoral thinking that is currently still common for UGS planning and designing. By further development of an interconnected and interdisciplinary social-ecological approach to UGS planning, cities might become more sustainable. All in all, this study responded to the multiple challenges of compact and sustainable cities and contributed to enhancing the green infrastructure network for all its inhabitants.

Furthermore, the methodology used in this study can be applied to other Dutch municipalities and regional scales. The weights for the social priority issues (e.g. social justice or health) as well as the input of ecological species and their resistance values can be modified. Besides changing existing values, also new input criteria could be added that were not available for this study. These can include more practical data, for instance on underground utilities or soil, or social criteria, such as valuable recreational locations. The methodology could also be used outside the context of the Netherlands but this requires new input data, as the data used in this study is solely focused on the Netherlands.

6.2 Recommendations for future research and practice

This section provides five recommendations based on the results and analysis of this thesis, for both municipal practice change as well as for further research about social-ecological GIS analysis and UGS planning.

6.2.1 Highlight multifunctionality of UGS

The first recommendation for municipal practices is to make use of a GIS model like proposed in this study as a step between the formulation of ambitions and the realization of UGS. This not only fosters sector-exceeding and area-oriented collaboration, but it could also help to exemplify that green should receive a higher priority from multiple perspectives, such as ecology, health, environmental and social justice, and livability. Showing the need for UGS development from several perspectives and combining these can help decision-makers and stakeholders to prioritize locations for planning, designing, and maintaining UGS.

This thesis not only showed locations for UGS based on the integration of the SUC and EUC but also highlighted the differences between these two. Where there are differences between social and ecological values of UGS, municipalities should indicate which functions UGS development aims for. When a location is only suitable from the SUC perspective, green could focus more on green recreation places for citizens or climate adaptation measures. When a location is only suitable from the EUC perspective, green should be more focused on ecological species preferences and high biodiversity values. When geodata is combined to prove that UGS development on a certain location is necessary from multiple perspectives, it increases the likelihood of finding (financial) support for a greening project.

An implication of using the outcomes of this thesis in practice is that the allocation of UGS should not be solely based on this GIS analysis. UGS should also be determined according to a locally appropriate place-based situation, such as the interests of different stakeholders. Suitability maps, which encompass the different priority issues of social justice, environment/health, and ecology can serve as information to show different perspectives on UGS development to different stakeholders. Hence, it can guide the planning process of UGS. The social-ecological interconnectivity map should be analyzed carefully in case it is used for policymaking and requires the participation of stakeholders and decision-makers.

6.2.2 Species and private gardens

Researchers should also take into account private gardens in future studies as this was not done in this study. Researchers should beware of substituting the loss of public UGS by trying to increase private UGS as these have different functions. Nevertheless, private UGS can be included besides public UGS. A first step would be to include private UGS into a spatial dataset. Currently, the BRT or BGT do not include private UGS. Secondly, future research should keep in mind the differences in the amount of vegetation in private space, as private gardens vary from fully paved to great amounts of green. Therefore, a suggestion is to conduct research on private UGS on a small scale first, for example on a neighborhood scale.

For studying the ecological perspective of UGS (EUC), observation and movement data are extremely relevant. When private gardens will be researched, citizen science can be an approach to gather observation data of species in private UGS. This can be an addition to the NDFF dataset on which this thesis is based. The NDFF dataset combines observations from different databases, both single observations and more structural observation methods. Still, the observations are just an estimation of the species' presence. Green areas where a certain species is not observed at one moment in time do not mean the species is not present there at another time.

Not only more observations but also other animal species which are not included in this research, such as fish, insects, or birds, should be included in future research. Not only the more familiar species, such as hedgehogs, should be taken into account but also species that are less familiar yet vital for urban ecosystems. Every species has different preferences and is in its way valuable in an urban ecosystem. This study showed that the alpine newt has the lowest connectivity of its habitat patches. Therefore, aquatic species, such as salamanders, should be one of the focus species for future research. Future research can use and build on the GIS workflow used to research ecological suitability as it is possible to add other and more species.

6.2.3 Roads as greenways and ecological corridors

When UGS planners and designers decide to focus on greening roads, developing roadside green should also aim to provide multiple functions. This could make the claim for developing green stronger in the case of spatial competition. An example would be to introduce bioswales which are also ecologically interesting habitats when planted with wild and native species. These bioswales also serve multiple ecosystem services such as removing pollutants and increasing stormwater infiltration (Prudencio & Null, 2018). Smaller streets, which are currently not often featured in the municipal green structure, are also highly suitable on the social-ecological map. A more detailed municipal green structure map is needed that includes more detail on where greening is possible. Specific locations should be considered along roads where UGS development is feasible, instead of marking the entire road including the driving lanes as green spaces on a map. In streets where space is limited, the municipality could also encourage citizens to green their gardens.

Municipal UGS planners and designers should take into account that roads can still be a barrier to less mobile species such as amphibians. Hence, wildlife crossing including underpasses (ecotunnels or eco-friendly culverts) and overpasses (ecological bridges) should be implemented where species mortality is high or where the habitats are highly fragmented. Identifying relevant locations for the creation of new wildlife crossing should take into account a multi-scale and multispecies perspective. For example, species have different preferences in vegetation and difference in dispersal distance. Besides constructing new wildlife crossings, current infrastructure can also be upgraded to serve as an ecological corridor. For example, under the viaducts along the Maas-Waal canal in Nijmegen, vegetation strips stop just in front of the bridge (see Appendix XII). These viaducts can be upgraded to ecoducts by including, for example, a tree stumps wall (in Dutch: 'strobbenwal') along the walls. This way, the enhancement of ecological connectivity goes hand in hand with nature along roads and bicycle and pedestrian paths.

A suggestion for future research would be to solely focus on the movement of cyclists and pedestrians, for example for recreation, and combine this with the movement of species. This would be valuable to show where along the roads synergies could be created. The recreational value of roads in terms of green would provide insight into potential recreational greenways. When movement data of different species are combined, overlapping areas can be identified as win-win locations to develop UGS. This approach for urban green networks is context-dependent and requires a range of local knowledge.

6.3.4 Landscape fragmentation

Greening roads should also take into account connections to adjacent or nearby larger UGS to make vegetated road corridors function as part of urban green infrastructure networks. This will contribute to decreasing UGS fragmentation. Nowadays, municipalities focus largely on green providing several ecosystem services as a benefit for their citizens and on green for climate adaptation. They should not forget that landscape fragmentation and biodiversity has an effect on the provision of these services. This dependence was also shown in the conceptual model of the social-ecological system (Figure 3). Landscape fragmentation, as well as biodiversity, are included in the 'ecosystem structure' element of this figure. When biodiversity declines with landscape fragmentation (Fischer & Lindenmayer, 2007), ecosystem service supply is also likely to be lost. Landscape connectivity should therefore be the basis of designing UGS.

This study only calculated the landscape metrics for each habitat class, but future research could include landscape metrics on patch level to assess structural connectivity of individual green patches. An example is given in Figure 23, where the proximity index to other UGS patches is calculated per UGS patch. This shows the degree of isolation and fragmentation per patch. The landscape metrics could be included in future spatial analysis, such as a suitability analysis. To make research on functional and structural connectivity more robust in the future, it could include expert knowledge on 'potential' habitat patches instead of only the patches where the species is present. This might represent the complex ecological reality in a better way than solely focusing on species observations.

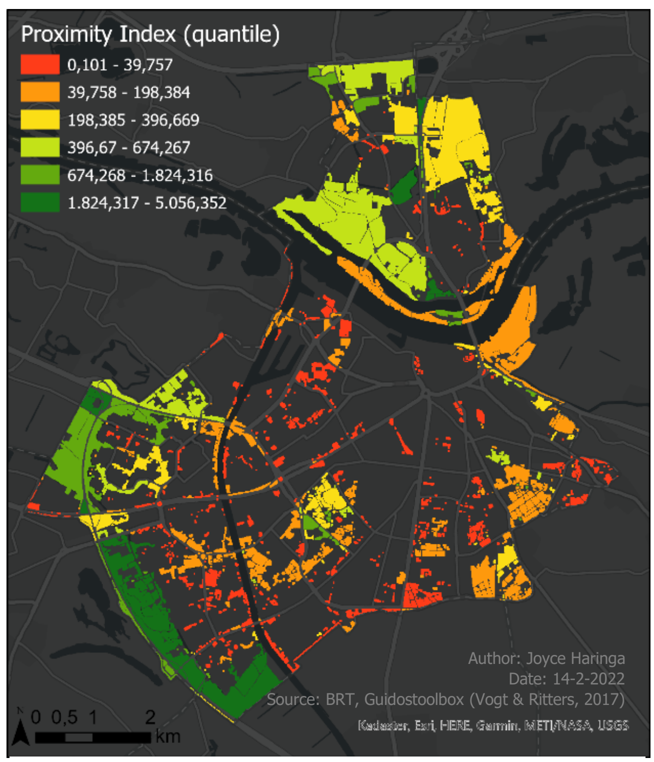


Figure 23 Proximity Index per habitat patch calculated in FRAGSTATS.

6.3.5 Third dimension

Although trees have great value for climate adaptation, there is not always space for trees. Therefore, UGS planners and designers should focus more on shrubs and herbs where space is limited. A narrower roadside planting strip of 1 meter could already serve the growth of small shrubs and herbs. Also, when space is limited under the ground because of underground utilities like pipes and cables, shrubs and herbs could provide a solution as these are less deep-rooted. Citizens should be aware of the multifunctionality of UGS by providing information on the multiple benefits of UGS. For example, rose beds not only provide nectar for insects but also esthetic value because of the flowers and food provision through the rosehip. This demands more detail in planning and assessing UGS by including, for example, which types of UGS vegetation serve which social and ecological functions.

Lastly, this research focused on suitability above ground but also mentioned that underground space is important to consider. Underground infrastructure, such as cables and pipes, are often mapped. However, there is a lack of knowledge on soils and soil quality in urban areas. Therefore, future research should focus on mapping the urban soil. Soil maps of cities can help in prioritizing functions for UGS. For example, where soils are highly water-permeable, it is more suitable to develop a bioswale than soils that are not that pervious. Also, not only the underground can be used as ecological corridors for the movement of species (underpasses) but also overpasses can be included. This asks for adding the third dimension of height into future ecological least-cost path analysis.

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Appendices

Appendix 0: Table of content zip file

1. Documentation of what is where in the zip file (Word)
2. Thesis report (Word, pdf)
3. Midterm presentation (Powerpoint)
4. Final presentation (Powerpoint)
5. GIS-input data (folder)
6. Resulting maps (folder with PNGs)
7. ArcGIS models (folder)
8. Interview data (folder)
    a. Municipality of Rotterdam (Word)
    b. Municipality of Amsterdam (Word)
    c. Municipality of Nijmegen (Word)
    d. Municipality of Rotterdam (Word)
    e. Municipality of Amsterdam (Word)
    f. Municipality of Nijmegen (Word)
9. EndNote library (folder)
    a. Endnote Library (Endnote Library)
    b. Endnote data (PDF)
10. Literature overview (Excel)
11. Calculations/tables (Excel)

Appendix I: Respondents and interview questions

Table 10 Interview respondents of the three municipalities of Rotterdam, Nijmegen, and Amsterdam.

Municipality	Respondent	Function within municipality
Rotterdam	Pieter Boone	Strategisch landschapsarchitect (strategical landscape architect)
	Inge Kersten	Strategisch landschapsarchitect (strategical landscape architect)
Nijmegen	Ton Verhoeven	Beleidsadviseur Groen en Klimaatadaptatie (policy adviser green and climate adaptation)
Amsterdam	Quirijn Verhoog	Designer Public space – Space and Sustainability (Ontwerper Openbare Ruimte - Ruimte en Duurzaamheid)

Introduction

1. First of all, can you tell something about yourself?

Current green plans and maps:

2. What kind of role does green and nature play in municipal plans, like the 'Omgevingsvisie'?
3. How are the green structure maps made?
    a. Which analysis / methods / research?
    b. By whom / which departments?

Criteria:

4. Which criteria have priority when pointing to locations for greening?
    c. Which social / human-oriented criteria?
    d. Which ecological / species-oriented criteria?
        i. Are there certain plant or animal species that are important when designing a green infrastructure network?
5. Which criteria have priority?
    e. For example, livability, walking distance to green space, air pollution, noise pollution, UHI effect, amount of existing green.

Scales

6. In policy documents like the 'Omgevingsvisie', maps are often made on a city-scale. How will the municipality work out these green arrows on a neighborhood scale?
    a. I.e. how will the green arrows be locally implemented?

Appendix II: Interview answers

Table 11 Interview questions and corresponding summarized answers of the three municipalities.

Question / subject	**Municipality of Rotterdam**	**Municipality of Nijmegen**	**Municipality of Amsterdam**
About the respondent	Strategical landscape architect	Policy adviser green and climate adaptation	Designer public space
Role of green in municipal plans?	Guide about public space including sustainability and biodiversity. Toolkit for biodiversity: what type of corridor or stepping stone? Types and definition of green structure. Green plans are the basis for prioritizing green development.	Main tree structure for connections. The old guide did not include biodiversity. Biodiversity plan for the protection of species and ecological connections. Climate adaptation plan for climate-proof neighborhoods. And health and movement of citizens.	Guide Puccini on how to design streets and squares. Green structure lines are used for profile studies with a toolbox of measures.
Making process of green structure maps (e.g. analysis/methods /research and who/which departments)?	Ecological research on key species in key habitats. Maps made by different departments. Ecologists make a map with key nature areas, for example.	Maps of the underground, green, water, nature history, archeology will be overlapped to see where is space suitable. This is not one product yet. Sometimes, ecological knowledge is not present and expert judgment is used instead.	Where is which amount of green possible to make priorities clear. No hard numbers, more knowledge, and profile studies. Based on where the space is available, a budget will be calculated. Maps made by the department of space and sustainability.
What is important when designing green (infra)structure?	Green along riversides for humans and animals. Current green structure and how the city is historically grown and designed (morphology). Green along roads next to canals ('singels'). Cultural heritage / protected spaces difficult to include more green.	Green along roads and water: combination with cultural-historical value and already green along part of the roads, but some roads have limited amount of green (not many trees).	Green along canals and quays. Cultural heritage / protected spaces are not always suitable for radical greening. Priority for biodiversity, the second is bicycling, third is walking.
Pressure on space	Urbanization: which potential for (current) green?	In small streets, trees can not be placed sometimes. Maybe	In which streets is space for greening: depends on the spatial profile including the many

	There is much gain between the facades and buildings. Space can become available when wide streets become smaller because less car-focused.	smaller trees are possible. Car parking space conflicts with green development. There is space left in the city when you think in layers. Underground is not always enough space. Project developers do not have all the freedom anymore to only build buildings, but they should also build a good environment.	functions located (pressure on using space) → physical space criteria. Find parallel streets where there is more space. Car parking space in the inner city can be transformed to green when car use is reduced. Housing development pressure: houses sometimes developed where green is not interesting. Compacting the city: green should be compensated with the money earned for housing development.
Social / human criteria?	Climate proof: urban heat island effect, water storage; Walking distance to cool place. Green along routes for recreation (biking and walking); Attractive green; Experience of green, quality of staying/living; Noise reduction; air quality; The physical and mental health of inhabitants; green for food; the amount of green in neighborhoods.	Climate proof: heat stress and water storage; Green social meeting places playgrounds; green norm (5000 m2 within 300 meters); walking distance to cool places; shade along with bike- and pedestrian routes; Particulate matter and CO_2 absorption; The physical and mental health of inhabitants; the amount of existing green/paved surface in neighborhoods.	Climate proof neighborhoods: heat stress, rainproof; Network of routes for walkers and bicycles with green; Green on city-scale not much influence on air and noise pollution, but more on the feeling of pollution and the impact on humans; Green which is beautiful and attractive to stay/recreate/play; Walking distance to cool places: place benches and trees on paved surface.
Ecological / species criteria	Connecting the main green-blue structure with key habitat areas; biodiversity.	Connecting green structures; fauna passage; key habitat areas based on the amount of protected species.	Connections between islands main green structure (biodiversity); size and quality of green; type of green; streets as barriers; passage along

			canals and watersides; native plant species
Specific species to take into account?	Current research on species development in key habitats to prioritize in policymaking.	Protected and important species. Species that are suitable for petting (‘aaibaar’), engaging, and easy to recognize for citizen science.	Crawling, swimming and flying species (bats, insects). Species depend on the route, e.g. squirrel or grass snake. Protected species
Spatial realization of broad maps on city level to neighborhood level?	Priority when planning restructuring/renovation from different sectors coincides.	There will be an implementation program for the policy goal of ‘green healthy city’ with strategic projects. Select neighborhoods based on where replacement or renovation is needed. Small green development can go on its own. There will be neighborhood (management) plans zooming in on parts of the city to see what should be where. Main green structures should counteract the development only focused on building houses.	When a project will be realized, the green structure map shows the green assignment/task which should be realized. Priority realization is based on the planning of renovation or replacement of streets.
Finance	Prioritizing project which cover multiple sectors (e.g. heat storage, roads and sewage) because not enough money for all projects.	Underground measures for trees along roads cost a lot of money but make sure the tree can become old due to the right growing conditions. When development is framed from both tree plan, green plan, and biodiversity plan, more money can be available.	To receive money, a project is examined based on certain criteria, e.g. is it interesting enough for biodiversity (i.e. big enough, quality, ecosystem services).

Appendix III: Possible geo-data UGS

Table 12 Possible geo-data for UGS locations and their characteristics.

Dataset	**Type**	**(Sub)class UGS / raster value**	**Private UGS (yes/ no)**	**Resolution**	**Source**
LGN2020	Raster	Water, Infrastructure, Urban (semi-)built-up areas, Bare soil in built-up areas	No	5 m	WUR database
BGT	Polygon	Water, vegetated terrain ('begroeid terreindeel')	No	-	Basisregistratie Grootschalige Topografie
BRT	Polygon	Terrain (deciduous, pine, mixed and griend, populars, grassland, heather, graveyard, arable land, orchard, tree farmer, fruit farmer, dock, stone pitching, sand, other)	No	-	Basisregistratie Topografie
Green map Composite of trees, shrubs, and low vegetation (see below)	Raster	% green	Yes	10 m	Atlas Leefomgeving
a. Trees b. Shrubs c. Low vegetation	Raster	a. % trees > 2.5 m b. % shrubs < 2.5 m c. % low veg. < 1 m	Yes	10 m	a, b, c: Atlas Leefomgeving
Groenmonitor	Raster	NDVI 0-1		10 m	Satellietdataportaal
a. Tree (Dominant Leaf Type 2018) b. Tree cover density % c. Grassland cover	Raster	Broadleaved or coniferous 0-100% Grassland or non-grassland		10 m 10 m 10 m	Land.copernicus.eu

Appendix IV: BRT or BGT

Land use and land cover data is available from BRT ('Basisregistratie Topografie') or BGT ('Basisregistratie Grootschalige Topografie'). BRT is a digital topographic map on different scales from 1:10.000. BGT is a largescale digital map with a precision of 20 cm with a lot of detail. When choosing one or the other dataset for land cover and land use data including green space, there are differences in how the data is divided into attribute categories.

BGT has no subcategories in its attribute table. Therefore, the vegetated terrain of BGT was further divided by combining it with the green map including trees of 2.5 meters or higher, shrubs between 1 and 2.5 meters, and grass (low vegetation) lower than 1 meter. When a raster cell of 10x10 meter contained more than 50% of one of the three vegetation types, a cell was considered the most of a certain vegetation type when it was also the maximum value compared to the other two vegetation types (sub-attribute 1.1 until 1.3 in Table 1). When one vegetation has the highest percentage and this number is between 20 and 50%, it was divided into sub-attributes 1.4 until 1.6. It was also possible that public green space contained not much vegetation for certain cells. Therefore, a distinction was made between bare vegetation (when all vegetation types were between 1 and 19%) and no vegetation (when all vegetation types were 0%).

To compare the datasets on a quantitative scale, the surface area per (sub-)attribute was calculated for the transformed raster layers (see Table 13). Similar raster transformations were applied for BGT and BRT: maximum area and 10 meter resolution. The green highlighted attributes are considered UGS and the associated surface area is also shown in green. The surface area was also calculated for the UGS in vector format. What is striking, is the difference between the raster and vector surface area of UGS in the BGT dataset. This is probably due to single trees in the vector dataset which were not included in a 10 meter raster cell. This difference in level of detail between both datasets can be seen in Figure 24.

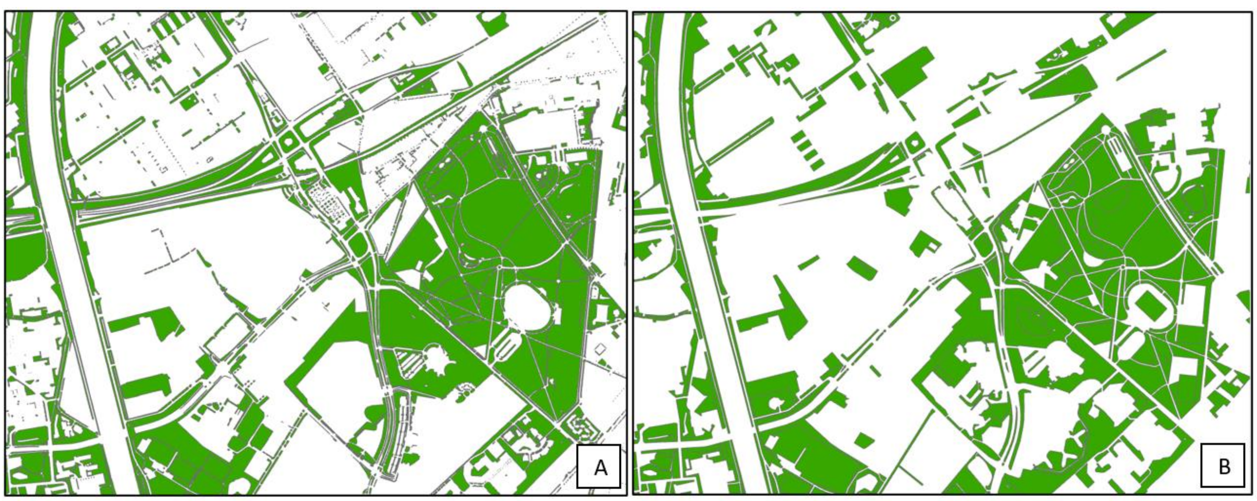


Figure 24 Data of UGS from A) BGT and B) BRT.

Table 13 BGT and BRT data comparison.

Variable	Attribute	(Added) sub-attribute	Surface	% of total pixels
Land cover BGT raster	1. Vegetated terrain (incl. river and ditch side) 14,441,700 m2 UGS (raster) 17,665,722 m2 (vector)	1.1 Most trees and trees > 50%	4,274,300 m2	7.4%
		1.2 Most grass and grass > 50%	5,401,700 m2	9.4%
		1.3 Most shrubs and shrubs > 50%	16,700 m2	0.03%
		1.4 Most trees and trees 20-50%	525,300 m2	0.9%
		1.5 Most grass and grass 20-50%	1,797,500 m2	3.1%
		1.6 Most shrubs and shrubs 20-50%	57,100 m2	0.1%
		1.7 Bare vegetation (trees, shrubs and grass between 1-19%)	3,355,100 m2	5.8%
		1.8 No vegetation (sum trees, shrubs and grass is 0%)	2,861,000 m2	5.0%
	2. Roads (incl. traffic island)		9,910,400 m2	17.2%
	3. Buildings (incl. walls and built constructions)		7,287,200 m2	12.7%
	4. Water		5,782,900 m2	10.0%
	5. Bare terrain		16,336,600 m2	28.4%
Total surface			57,605,800 m2	100%
Land cover BRT raster	1. Terrain 18,121,200 m2 UGS (raster) 19,082,059 m2 (vector)	1.1 Trees (decidious, pine, mixed and griend, populars)	4,320,800 m2	7.5%
		1.2 Grass (grasland, heather, graveyard)	12,308,100 m2	21.4%
		1.3 Agriculture (arable land, orchard, tree farmer, fruit farmer)	1,291,400 m2	2.2%
		1.4 Railroad area	430,600 m2	0.7%
		1.5 Water constructions (dock, stone pitching)	105,800 m2	0.2%
		1.6 Sand	200,900 m2	0.3%
		1.7 Other	18,866,700 m2	32.7%
	2. Roads	2.1 Main roads (highway, main road, regional road, local road)	2,372,400 m2	4.1%
		2.2 Streets	3,245,600 m2	5.6%
		2.3 Other (walking and biking)	1,461,900 m2	2.5%
		2.4 Parking places	390,500 m2	0.7%
	3. Buildings		7,081,700 m2	12.3%
	4. Water	4.1 Ponds and lakes	1,011,800 m2	1.8%
		4.2 Watercourse	4,536,500 m2	7.9%
Total surface			57,624,700 m2	100%

Appendix V: Pre-processing extra information

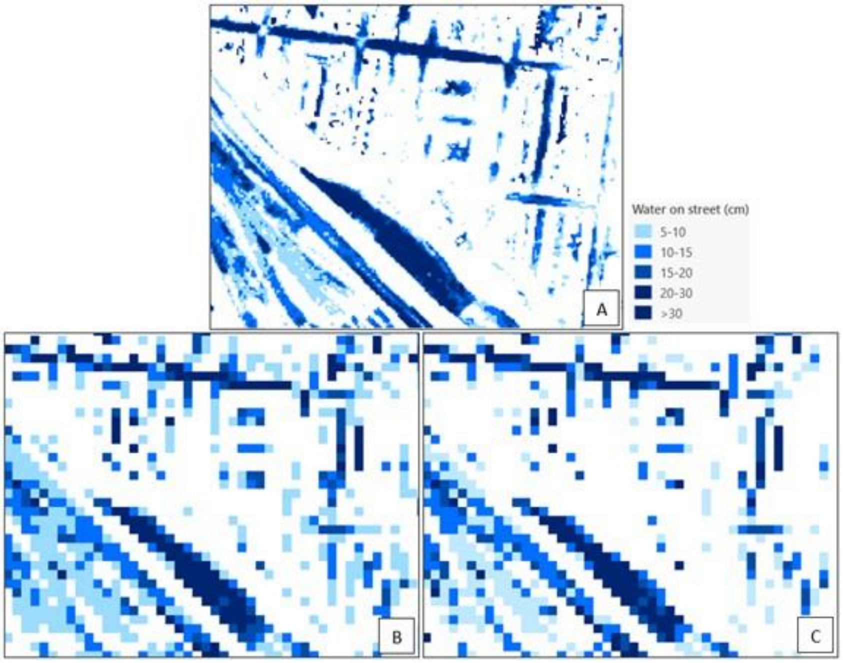


Figure 25 Resample techniques for water stress. A) Original data of approximately 2 meter cell size. B) Resampled using majority to 10 meters. C) Resampled using nearest neighbor to 10 meters.

Figure 26 Polygon to raster transformation of UGS with Cell center method and Maximum (combined) area compared for two different sites. The left images show the raster data (A) and (C), and the right shows the vector data (B) and (D).

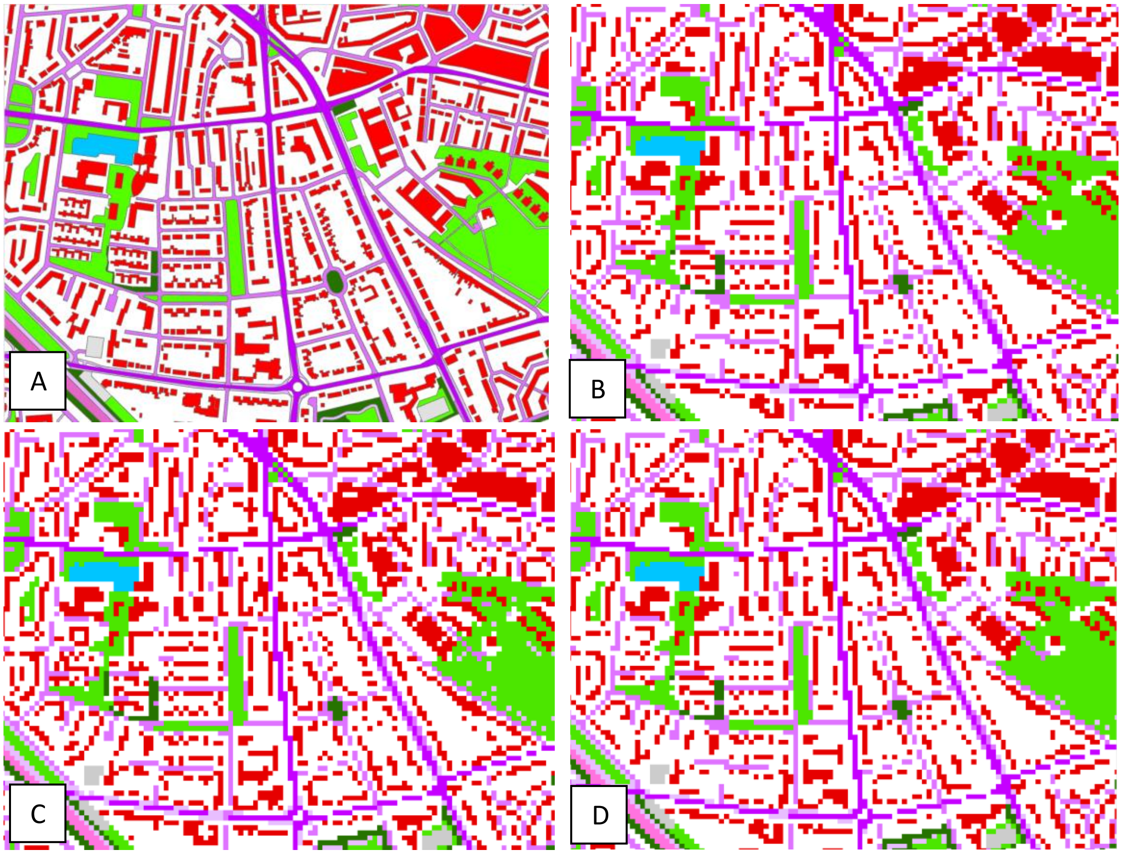


Figure 27 Polygon to raster transformations of BRT data: A) original vector data, B) maximum area classification, C) cell center classification, and D) maximum combined area classification.

Appendix VI: Covariance matrix

A covariance matrix was produced to see whether input criteria Only UHI ~ PM2.5 and UHI ~ distance to green space approach the target value of 0.7. However, because both do not exceed this threshold, all 7 variables are kept as input for the model.

Table 14 Multicollinearity of all input variables.

	Green/inh	livability	UHI	PM2.5	Distance to green	Water	Noise
Green/inh	-	0.012584	-0.28638	-0.12925	-0.32573	-0.04031	0.114028
livability	0.012584	-	-0.37792	-0.44065	-0.0161	0.032754	-0.15742
UHI	-0.286377	-0.377915	-	0.615046	0.6046	0.056712	0.181004
PM2.5	-0.129252	-0.440653	0.615046	-	0.411395	0.051412	0.293426
Distance to green	-0.325725	-0.016100	0.6046	0.411395	-	0.059939	0.028451
Water	-0.040308	0.032754	0.056712	0.051412	0.059939	-	0.042786
Noise	0.114028	-0.157424	0.181004	0.293426	0.028451	0.042786	-

1
0.75
0.5
0.25
0
-0.3
-0.5
-1

Appendix VII: ArcGIS Pro tools to divide features based on their width

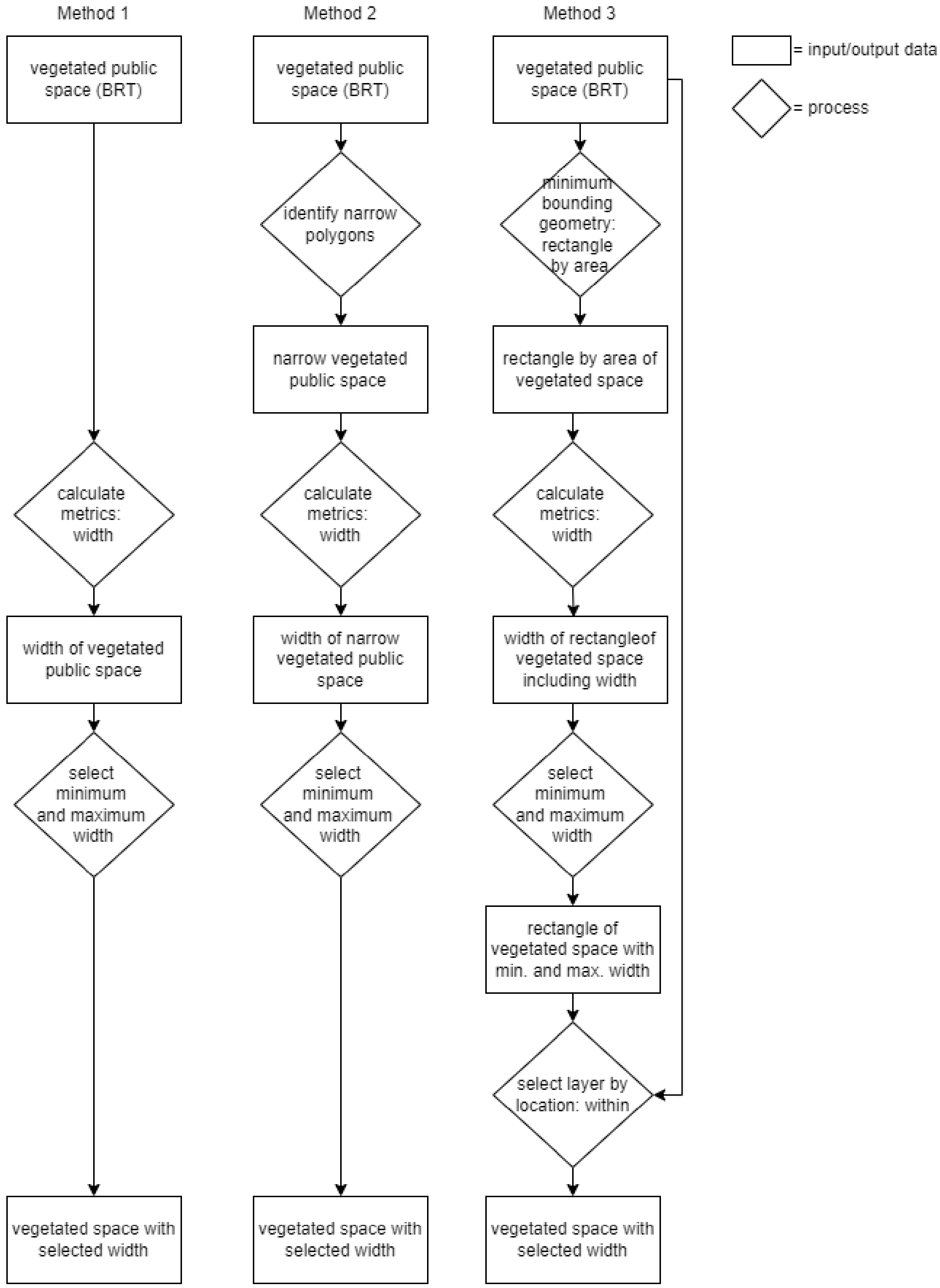


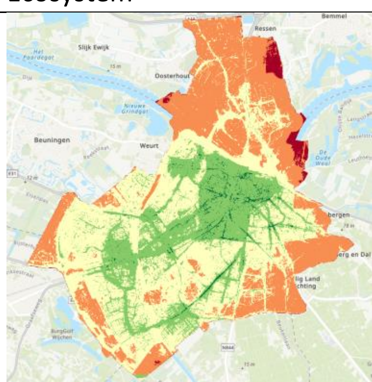
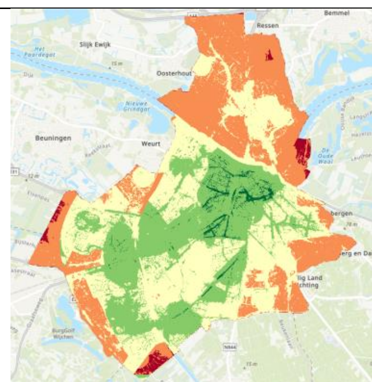
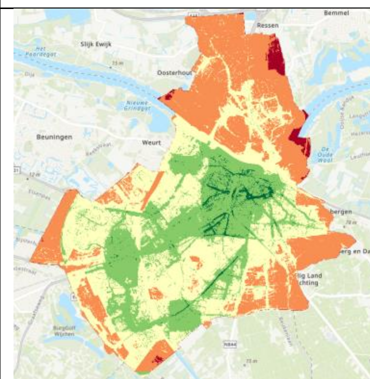
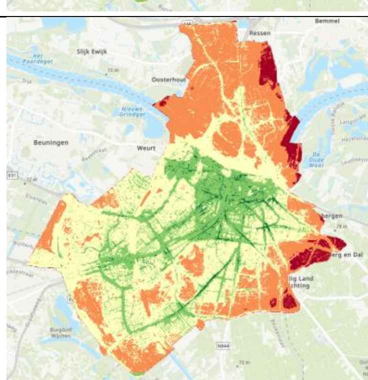
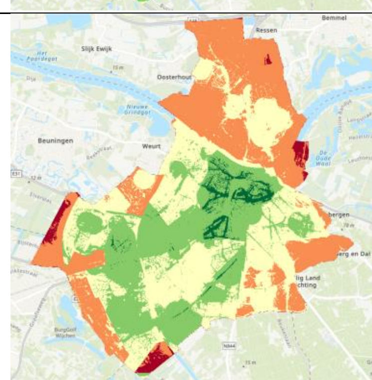
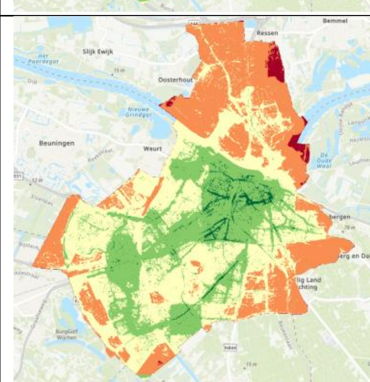
Figure 28 Methods to divide habitat polygons into patches and corridors in ArcGIS Pro.

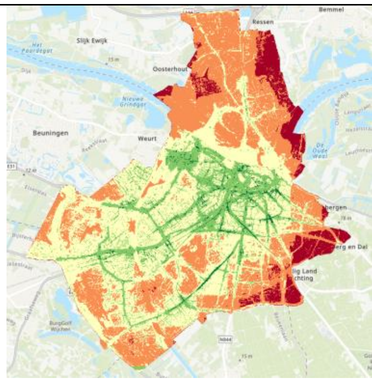
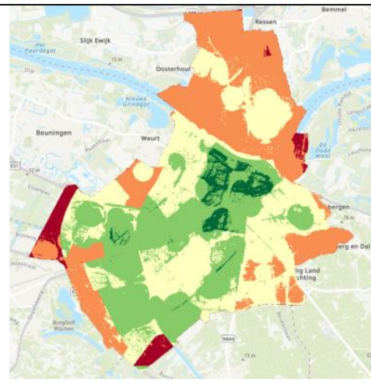
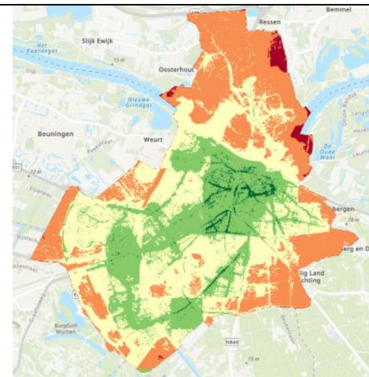
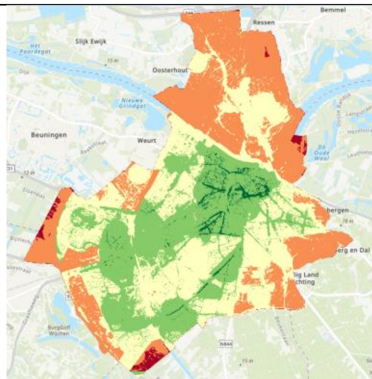
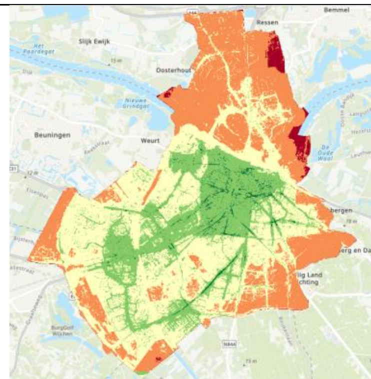
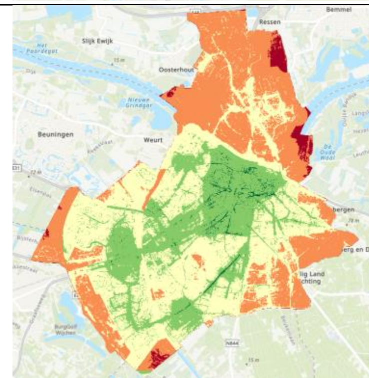
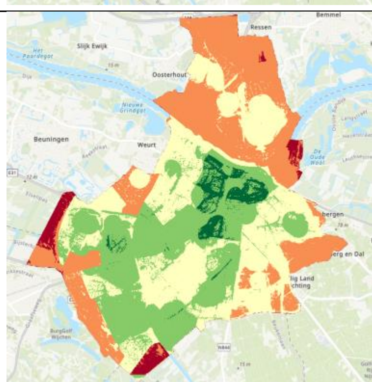
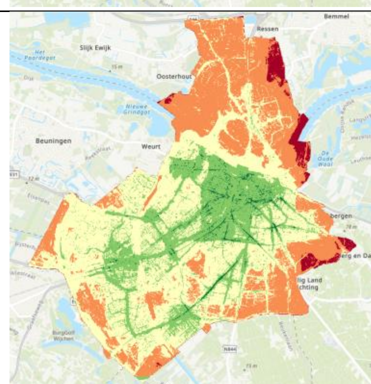
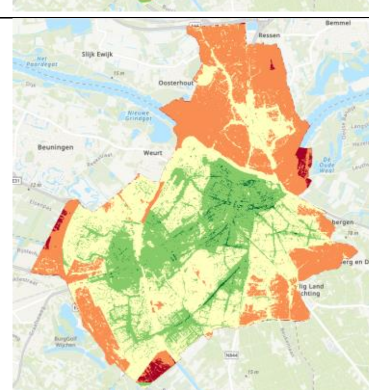
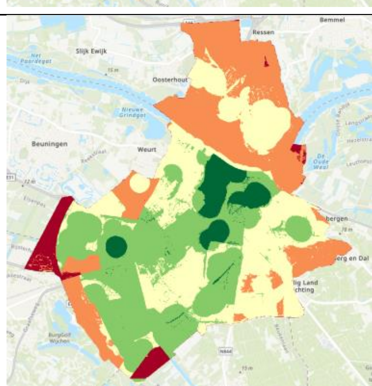
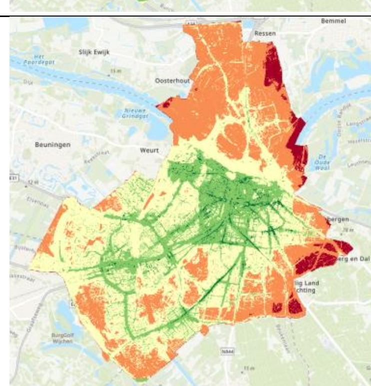
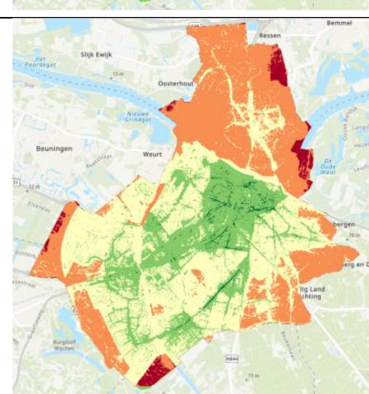
Appendix VIII: Sensitivity Land Suitability Analysis

Table 15 For the three different scenarios (PM2.5, justice, and ecosystem), the new weights, number of pixels, and relative difference compared to the baseline scenario are calculated.

	-75%			-50%			-25%			0%	+25%			+50%			+75%		
	pm2.5	justice	ecosystem	pm2.5	justice	ecosystem	pm2.5	justice	ecosystem	base	pm2.5	justice	ecosystem	pm2.5	justice	ecosystem	pm2.5	justice	ecosystem
	New weights																		
Livability	16.07	3.57	28.57	15.48	7.15	23.81	14.88	10.72	19.06	14.28	13.69	17.86	9.52	13.09	21.44	4.77	12.5	25	0
Distance to UGS	16.07	3.57	28.57	15.48	7.15	23.82	14.88	10.72	19.05	14.29	13.69	17.87	9.52	13.09	21.44	4.77	12.5	25	0
UGS per inhabitant	16.07	3.57	28.57	15.48	7.14	23.81	14.88	10.72	19.05	14.29	13.69	17.87	9.52	13.09	21.44	4.77	12.5	25	0
PM2.5	3.58	22.32	3.58	7.14	19.64	7.14	10.72	16.96	10.71	14.28	17.86	11.6	17.86	21.43	8.92	21.42	25	6.25	25
Noise	16.07	22.32	3.57	15.48	19.64	7.14	14.88	16.96	10.71	14.28	13.69	11.6	17.86	13.1	8.92	21.42	12.5	6.25	25
Water stress	16.07	22.32	3.57	15.47	19.64	7.14	14.88	16.96	10.71	14.29	13.69	11.6	17.86	13.1	8.92	21.42	12.5	6.25	25
UHI	16.07	22.33	3.57	15.47	19.64	7.14	14.88	16.96	10.71	14.29	13.69	11.6	17.86	13.1	8.92	21.43	12.5	6.25	25
	Number of pixels per suitability class																		
very low	14866	20877	21932	7654	15515	15712	10810	9214	6253	10830	8145	7894	9214	7845	10730	20639	7929	18756	41367
low	190841	184646	154838	182511	178225	169503	187087	184677	180124	186809	183845	177865	183460	176209	177809	182420	181451	167764	201043
moderate	234476	249557	182850	239133	254426	196999	235067	243782	212631	233489	227979	219955	244757	231294	206862	253989	228678	196223	239594
high	129068	110598	180745	139162	118787	171945	136314	130118	165951	137283	144616	159734	130338	148942	165404	108851	146588	171431	85210
very high	5596	9169	34482	6387	7894	20688	5569	7056	9888	6436	10262	9399	7078	10557	14042	8948	10201	20673	7633
	Relative difference compared to baseline scenario (equal weights)																		
very low	37%	93%	103%	-29%	43%	45%	0%	-15%	-42%	0%	-25%	-27%	-15%	-28%	-1%	91%	-27%	73%	282%
low	2%	-1%	-17%	-2%	-5%	-9%	0%	-1%	-4%	0%	-2%	-5%	-2%	-6%	-5%	-2%	-3%	-10%	8%
moderate	0%	7%	-22%	2%	9%	-16%	1%	4%	-9%	0%	-2%	-6%	5%	-1%	-11%	9%	-2%	-16%	3%
high	-6%	-19%	32%	1%	-13%	25%	-1%	-5%	21%	0%	5%	16%	-5%	8%	20%	-21%	7%	25%	-38%
very high	-13%	42%	436%	-1%	23%	221%	-13%	10%	54%	0%	59%	46%	10%	64%	118%	39%	58%	221%	19%

Table 16 Spatial distribution of the social suitability scores from the land suitability analysis for three different sensitivity scenarios: ecosystem, justice, and PM2.5.

	Ecosystem	Justice	PM2.5
+25%			
+50%			

+75%			
-25%			
-50%			
-75%			

Appendix IX: Sensitivity Ecological Connectivity Analysis

Table 17 New resistance values for the three different situations: random change, change of BRT class 2.1 (main roads), and change of low and high scores.

							Hedgehog resistance								
BGT	Random +-75%	Random +-50%	Random +-25%	2.1=55	2.1=60	2.1=65	Baseline	2.1=75	2.1=80	Low scores +25%, high scores -25%	Low scores -25%, high scores + 25%	Low scores +50%, high scores -50%	Low scores -50%, high scores + 50%	Low scores +75%, high scores -75%	Low scores -75%, high scores + 75%
1.1	13.3	8.1	11.7	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
1.2	2.8	14.2	11.8	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
1.3	30.4	26.4	24.2	20	20	20	**20**	20	20	25	15	30	10	35	5
1.4	39	57	57.5	50	50	50	**50**	50	50	37.5	62.5	25	75	12.5	87.5
1.5	28.5	105.45	83.6	95	95	95	**95**	95	95	71.25	118.75	47.5	142.5	23.75	166.25
1.6	11.1	36.6	29.7	30	30	30	**30**	30	30	37.5	22.5	45	15	52.5	7.5
1.7	5.2	14	8.6	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
2.1	32.2	73.5	54.6	**55**	**60**	**65**	**70**	**75**	**80**	52.5	87.5	35	105	17.5	122.5
2.2	32	62	50	50	50	50	**50**	50	50	37.5	62.5	25	75	12.5	87.5
2.3	38.7	39.9	29.7	30	30	30	**30**	30	30	37.5	22.5	45	15	52.5	7.5
2.4	15.7	7.4	7.8	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
3	149.15	127.3	74.1	95	95	95	**95**	95	95	71.25	118.75	47.5	142.5	23.75	166.25
4.1	101.6	101.6	66.4	80	80	80	**80**	80	80	60	100	40	120	20	140
4.2	25	110	123	100	100	100	**100**	100	100	75	125	50	150	25	175

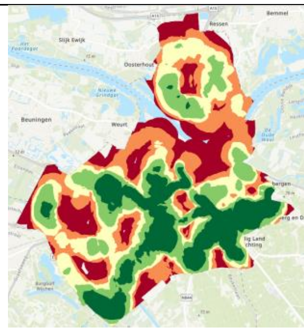
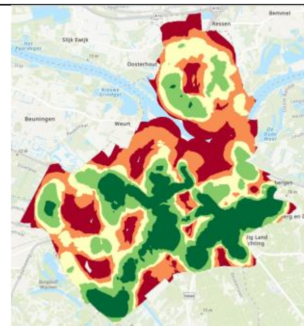
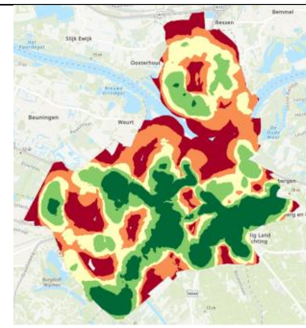
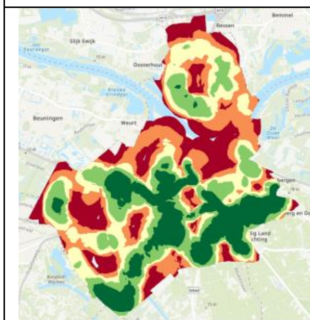
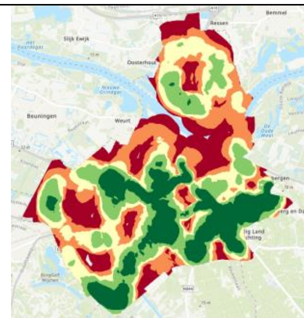
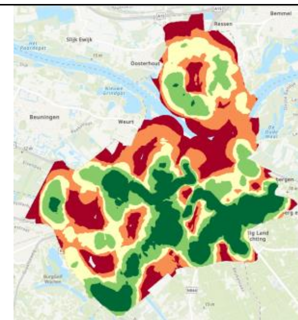
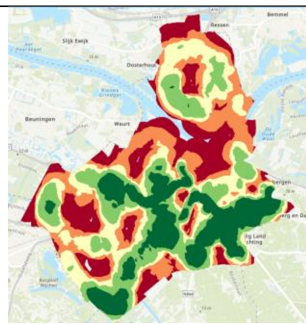
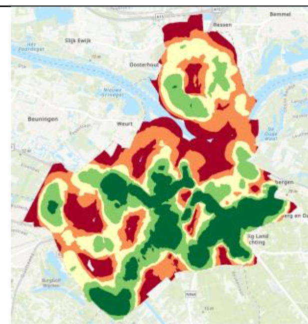
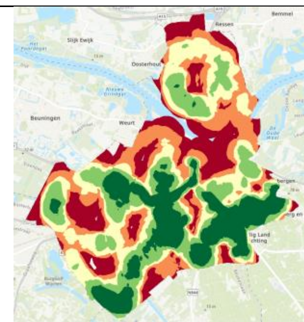
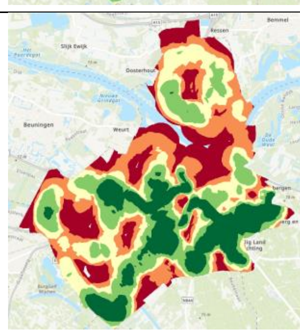
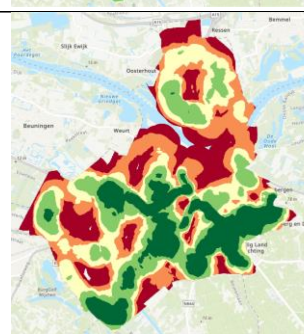
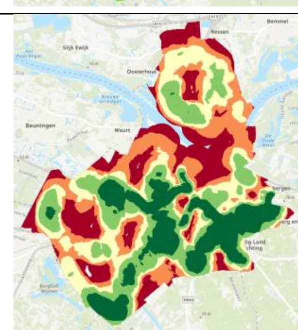
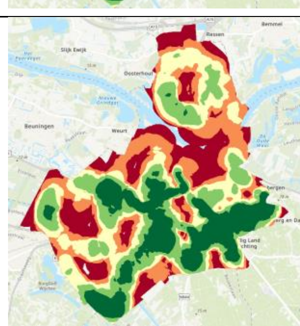
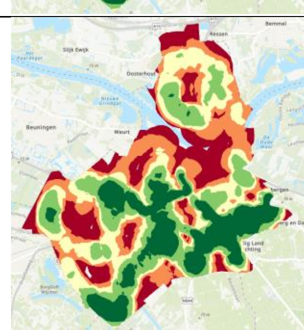
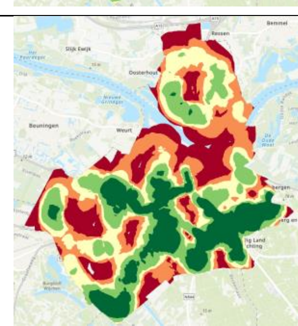
							Squirrel resistance								
BGT	Random +-75%	Random +-50%	Random +-25%	2.1=35	2.1=40	2.1=45	Baseline	2.1=55	2.1=60	Low scores +25%, high scores -25%	Low scores -25%, high scores + 25%	Low scores +50%, high scores -50%	Low scores -50%, high scores + 50%	Low scores +75%, high scores -75%	Low scores -75%, high scores + 75%
1.1	1.14	0.84	0.79	1	1	1	**1**	1	1	1.25	0.75	1.5	0.5	1.75	0.25
1.2	7.5	9.4	9.2	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
1.3	76.5	47.5	49.5	50	50	50	**50**	50	50	37.5	62.5	25	75	12.5	87.5
1.4	21.2	25.6	16	20	20	20	**20**	20	20	25	15	30	10	35	5
1.5	77	91	76.3	70	70	70	**70**	70	70	52.5	87.5	35	105	17.5	122.5
1.6	66	34	48.4	40	40	40	**40**	40	40	30	50	20	60	10	70
1.7	15.1	10	8.5	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
2.1	85.5	64	43.5	**35**	**40**	**45**	**50**	**55**	**60**	37.5	62.5	25	75	12.5	87.5
2.2	51.9	21.9	27.6	30	30	30	**30**	30	30	37.5	22.5	45	15	52.5	7.5
2.3	13	16.8	18.4	20	20	20	**20**	20	20	25	15	30	10	35	5
2.4	17.2	5	10	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
3	71.1	58.5	75.6	90	90	90	**90**	90	90	67.5	112.5	45	135	22.5	157.5
4.1	69.3	82.6	78.4	70	70	70	**70**	70	70	52.5	87.5	35	105	17.5	122.5
4.2	41	104	113	100	100	100	**100**	100	100	75	125	50	150	25	175

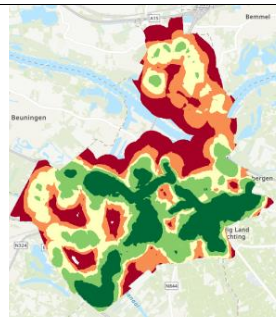
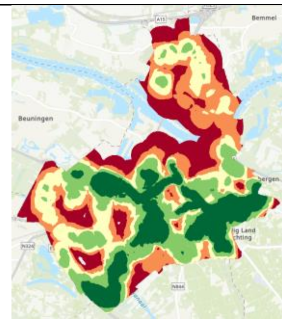
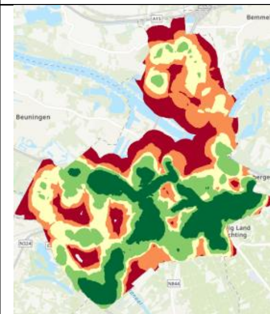
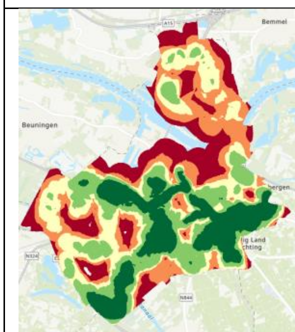
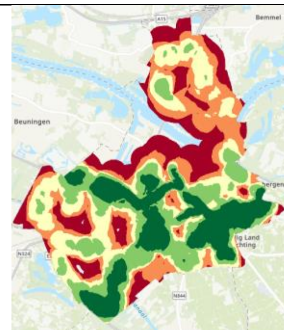
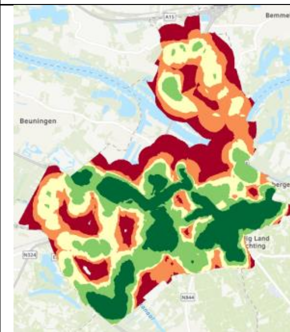
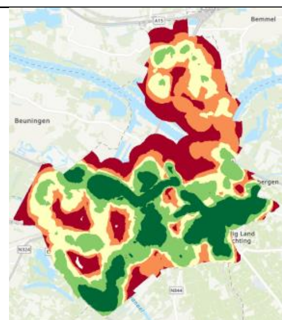
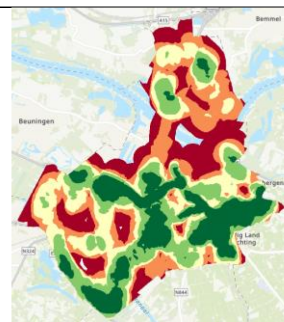
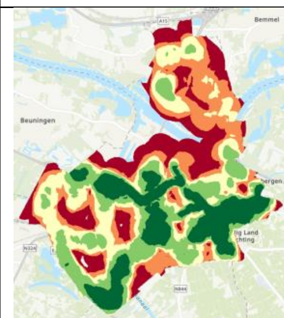
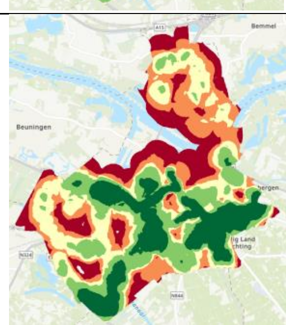
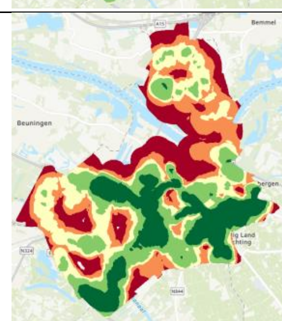
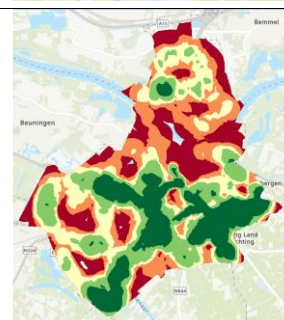
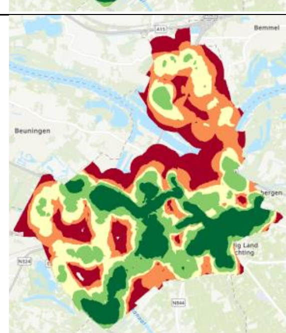
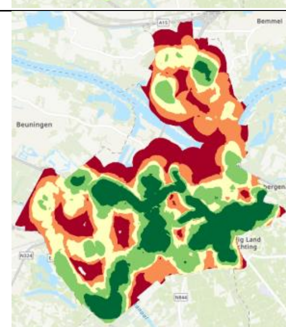
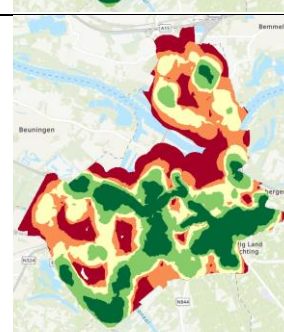
							Newt resistance								
BGT	Random +-75%	Random +-50%	Random +-25%	2.1 = 75	2.1 = 80	2.1 = 85	Baseline	2.1 = 95	2.1 = 100	Low scores +25%, high scores -25%	Low scores -25%, high scores + 25%	Low scores +50%, high scores -50%	Low scores -50%, high scores + 50%	Low scores +75%, high scores -75%	Low scores -75%, high scores + 75%
1.1	1.68	0.81	1.07	1	1	1	**1**	1	1	1.25	0.75	1.5	0.5	1.75	0.25
1.2	18.5	43	45.5	50	50	50	**50**	50	50	37.5	62.5	25	75	12.5	87.5
1.3	44	57.5	60	50	50	50	**50**	50	50	37.5	62.5	25	75	12.5	87.5
1.4	10.8	7.9	12.4	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
1.5	15.2	55.6	48	40	40	40	**40**	40	40	50	30	60	20	70	10
1.6	72	57.6	95.2	80	80	80	**80**	80	80	60	100	40	120	20	140
1.7	8.2	14.8	9	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
2.1	35.1	94.5	103.5	**75**	**80**	**85**	**90**	**95**	**100**	67.5	112.5	45	135	22.5	157.5
2.2	22.8	65.4	50.4	60	60	60	**60**	60	60	45	75	30	90	15	105
2.3	38.7	25.8	24	30	30	30	**30**	30	30	37.5	22.5	45	15	52.5	7.5
2.4	10.3	8.6	12.5	10	10	10	**10**	10	10	12.5	7.5	15	5	17.5	2.5
3	65	69	119	100	100	100	**100**	100	100	75	125	50	150	25	175
4.1	53	45.5	39.5	50	50	50	**50**	50	50	37.5	62.5	25	75	12.5	87.5
4.2	2.95	5.6	4.75	5	5	5	**5**	5	5	6.25	3.75	7.5	2.5	8.75	1.25

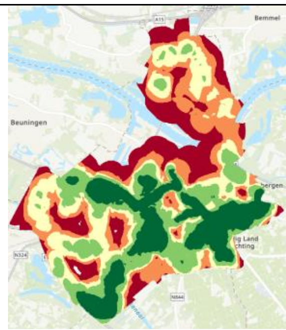
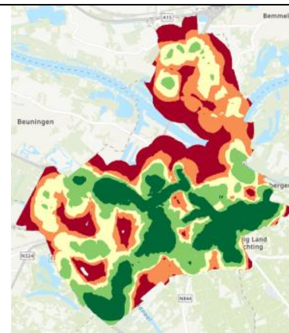
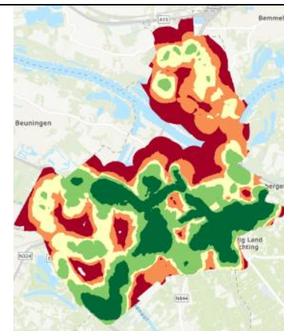
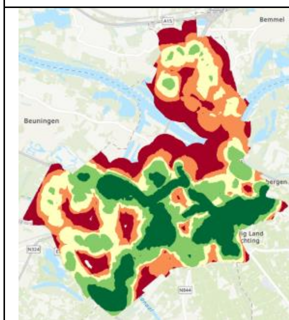
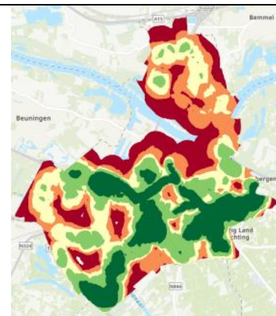
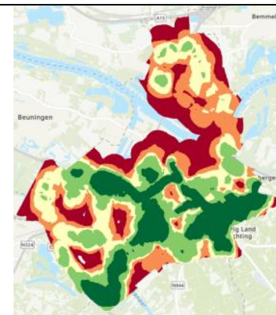
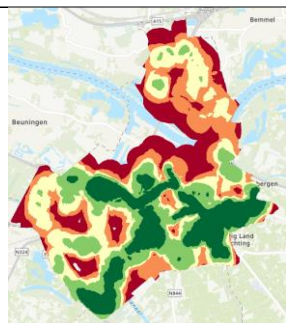
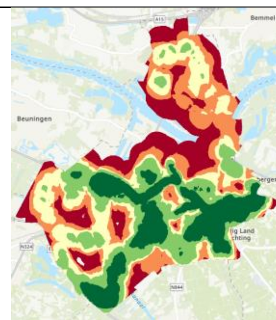
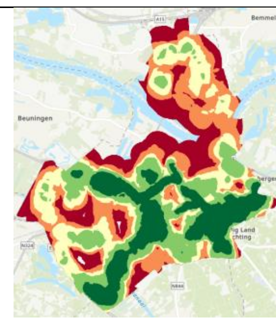
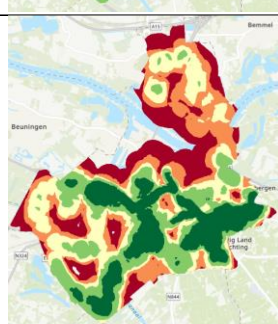
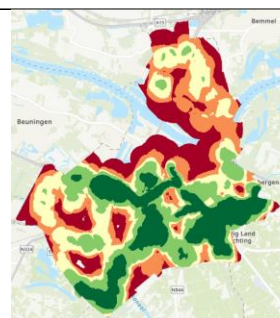
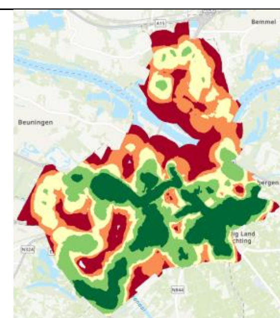
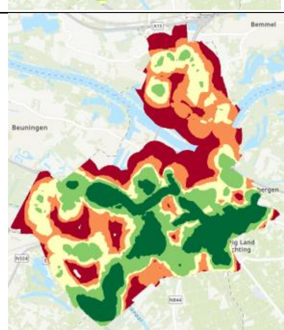
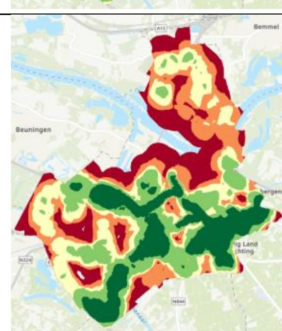
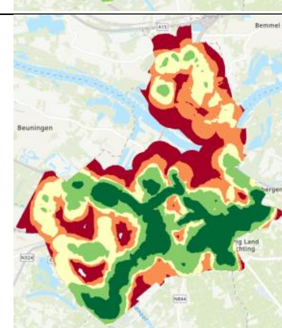
Table 18 Change of suitability classes for the three species (hedgehog, squirrel, and newt) for the species suitability and ecological suitability. The sum means the sum of the absolute percentages.

								Change hedgehog								
	Random +-75	andom +-50	andom +-25	2.1 = 55	2.1 = 60	2.1 = 65	**Baseline**	2.1 = 75	2.1 = 80	Low +25%, high -25%	Low -25%, high + 25%	Low +50%, high -50%	Low -50%, high + 50%	Low +75%, high -75%	Low -75%, high + 75%	
very low	101657	102978	102193	104490	101953	104369	**104358**	104149	104134	101260	104118	101780	104678	102074	111131	
low	107598	104870	104079	102534	106753	103307	**106589**	106670	106719	107761	103827	105935	105893	105442	110370	
moderat	106344	107256	105905	104863	103528	107683	**105694**	106405	103061	105107	104195	106615	105164	103814	113621	
high	103815	107736	104221	105594	104186	104900	**103273**	102342	103031	102870	104073	104506	105179	106757	110963	
very high	101707	102910	104202	103198	103903	100420	**100765**	101119	103734	103287	104527	101147	102292	102462	107582	
sum	521121	525750	520600	520679	520323	520679	520679	520685	520679	520285	520740	519983	523206	520549	553667	sum
very low	-2.6%	-1.3%	-2.1%	0.1%	-2.3%	0.0%	**0.0%**	-0.2%	-0.2%	-3.0%	-0.2%	-2.5%	0.3%	-2.2%	6.5%	23.5%
low	0.9%	-1.6%	-2.4%	-3.8%	0.2%	-3.1%	**0.0%**	0.1%	0.1%	1.1%	-2.6%	-0.6%	-0.7%	-1.1%	3.5%	21.7%
moderat	0.6%	1.5%	0.2%	-0.8%	-2.0%	1.9%	**0.0%**	0.7%	-2.5%	-0.6%	-1.4%	0.9%	-0.5%	-1.8%	7.5%	22.8%
high	0.5%	4.3%	0.9%	2.2%	0.9%	1.6%	**0.0%**	-0.9%	-0.2%	-0.4%	0.8%	1.2%	1.8%	3.4%	7.4%	26.6%
very high	0.9%	2.1%	3.4%	2.4%	3.1%	-0.3%	**0.0%**	0.4%	2.9%	2.5%	3.7%	0.4%	1.5%	1.7%	6.8%	32.2%
sum	5.6%	10.9%	9.0%	9.4%	8.5%	6.9%	0.0%	2.2%	6.0%	7.5%	8.7%	5.5%	4.8%	10.1%	31.7%	
								Change of ecological suitability when hedgehog changes								
very low	107315	106842	100329	106457	101042	100914	**104358**	106298	100542	105564	100181	104962	104526	105122	109520	
low	107350	108827	110245	110993	109596	110561	**106589**	109190	110669	111573	110492	110070	108756	104127	119597	
moderat	111270	108143	107559	106919	113184	106616	**105694**	105341	106851	110217	111174	110333	110197	113155	114267	
high	107223	107442	108929	105862	106863	110940	**103273**	107275	109611	106582	107905	105176	109796	105441	113063	
very high	101096	108069	105952	102878	102430	104078	**100765**	105011	105436	99174	103219	102279	102144	105639	110125	sum
very low	2.8%	2.4%	-3.9%	2.0%	-3.2%	-3.3%	**0.0%**	1.9%	-3.7%	1.2%	-4.0%	0.6%	0.2%	0.7%	4.9%	34.7%
low	0.7%	2.1%	3.4%	4.1%	2.8%	3.7%	**0.0%**	2.4%	3.8%	4.7%	3.7%	3.3%	2.0%	-2.3%	12.2%	51.3%
moderat	5.3%	2.3%	1.8%	1.2%	7.1%	0.9%	**0.0%**	-0.3%	1.1%	4.3%	5.2%	4.4%	4.3%	7.1%	8.1%	53.2%
high	3.8%	4.0%	5.5%	2.5%	3.5%	7.4%	**0.0%**	3.9%	6.1%	3.2%	4.5%	1.8%	6.3%	2.1%	9.5%	64.2%
very high	0.3%	7.2%	5.1%	2.1%	1.7%	3.3%	**0.0%**	4.2%	4.6%	-1.6%	2.4%	1.5%	1.4%	4.8%	9.3%	49.6%
sum	12.98%	18.08%	19.68%	11.91%	18.21%	18.61%	0.00%	12.72%	19.35%	14.89%	19.77%	11.58%	14.14%	17.04%	44.03%	
								Change squirrel								
	Random +-75	andom +-50	andom +-25	2.1 = 35	2.1 = 40	2.1 = 45	**Baseline**	2.1 = 55	2.1 = 60	Low +25%, high -25%	Low -25%, high + 25%	Low +50%, high -50%	Low -50%, high + 50%	Low +75%, high -75%	Low -75%, high + 75%	
very low	59432	60406	61665	61122	60829	60755	**59088**	58900	58991	58602	59935	60165	61439	60748	64509	
low	61744	63380	64675	61938	64659	64019	**63555**	63605	63524	62388	63857	61506	63906	63355	64722	
moderat	61726	63323	63053	62712	60941	61251	**62333**	61990	61655	64025	61379	63327	62887	62020	67319	
high	64019	62334	60641	63242	62435	63067	**62684**	62832	63523	62451	63546	62792	61635	62701	65645	
very high	61458	60626	59817	60876	61037	60816	**62230**	62515	62149	61507	61107	61455	60320	60182	65208	
sum	308379	310069	309851	309890	309901	309908	309890	309842	309842	308973	309824	309245	310187	309006	327403	sum
very low	0.6%	2.2%	4.4%	3.4%	2.9%	2.8%	**0.0%**	-0.3%	-0.2%	2.8%	1.4%	1.8%	4.0%	2.8%	9.2%	38.9%
low	-2.8%	-0.3%	1.8%	-2.5%	1.7%	0.7%	**0.0%**	0.1%	0.0%	0.7%	0.5%	-3.2%	0.6%	-0.3%	1.8%	17.2%
moderat	-1.0%	1.6%	1.2%	0.6%	-2.2%	-1.7%	**0.0%**	-0.6%	-1.1%	-1.7%	-1.5%	1.6%	0.9%	-0.5%	8.0%	24.2%
high	2.1%	-0.6%	-3.3%	0.9%	-0.4%	0.6%	**0.0%**	0.2%	1.3%	0.6%	1.4%	0.2%	-1.7%	0.0%	4.7%	18.0%
very high	-1.2%	-2.6%	-3.9%	-2.2%	-1.9%	-2.3%	**0.0%**	0.5%	-0.1%	-2.3%	-1.8%	-1.2%	-3.1%	-3.3%	4.8%	31.1%
sum	7.8%	7.2%	14.4%	9.7%	9.2%	8.2%	0.0%	1.6%	2.8%	8.2%	6.6%	8.1%	10.2%	6.9%	28.5%	
								Change of ecological suitability when squirrel changes								
very low	101284	106395	99435	104622	106016	106009	**106076**	105712	105731	106088	105932	106965	106191	100657	106084	
low	112337	111567	111883	107840	108693	108433	**109024**	108796	108734	112219	108543	111256	108932	113368	109319	
moderat	106526	104126	112379	105391	106291	106711	**105597**	105448	104892	104902	110254	107507	111330	112454	115588	
high	108484	108488	107139	109970	108351	108393	**107471**	107606	110519	107968	105327	107034	104437	105702	108164	
very high	104189	102506	102267	105286	103758	103563	**104941**	105547	103233	101932	103053	100367	102126	100782	106230	sum
very low	-4.5%	0.3%	-6.3%	-1.4%	-0.1%	-0.1%	**0.0%**	-0.3%	-0.3%	-0.1%	-0.1%	0.8%	0.1%	-5.1%	0.0%	19.5%
low	3.0%	2.3%	2.6%	-1.1%	-0.3%	-0.5%	**0.0%**	-0.2%	-0.3%	-0.5%	-0.4%	2.0%	-0.1%	4.0%	0.3%	17.8%
moderat	0.9%	-1.4%	6.4%	-0.2%	0.7%	1.1%	**0.0%**	-0.1%	-0.7%	1.1%	4.4%	1.8%	5.4%	6.5%	9.5%	40.1%
high	0.9%	0.9%	-0.3%	2.3%	0.8%	0.9%	**0.0%**	0.1%	2.8%	0.9%	-2.0%	-0.4%	-2.8%	-1.6%	0.6%	17.5%
very high	-0.7%	-2.3%	-2.5%	0.3%	-1.1%	-1.3%	**0.0%**	0.6%	-1.6%	-1.3%	-1.8%	-4.4%	-2.7%	-4.0%	1.2%	25.9%
sum	10.10%	7.29%	18.16%	5.31%	2.96%	3.83%	0.00%	1.40%	5.72%	3.83%	8.78%	9.46%	11.13%	21.20%	11.61%	
								Change newt								
	Random +-75	andom +-50	andom +-25	2.1 = 75	2.1 = 80	2.1 = 85	**Baseline**	2.1 = 95	2.1 = 100	Low +25%, high -25%	Low -25%, high + 25%	Low +50%, high -50%	Low -50%, high + 50%	Low +75%, high -75%	Low -75%, high + 75%	
very low	14415	13109	13742	13544	13392	13392	**13392**	13550	13383	13550	13513	13323	13306	13427	14064	
low	15262	14229	14172	13977	14276	14276	**14281**	13924	14218	13765	14337	13989	14241	13801	14212	
moderat	15073	13794	13660	14079	14068	14068	**14064**	13634	13836	13423	14134	13611	14088	13608	14382	
high	14992	14082	13717	13716	13527	13527	**13520**	13907	13934	13756	13788	13498	13857	13868	14023	
very high	14891	13391	13350	13408	13373	13373	**13379**	13606	13733	13198	13326	13250	13641	13323	13576	
sum	68641	68724	68636	68636	68605	68641	68636	68621	69104	67692	69098	67671	69133	68027	70257	sum
very low	7.6%	-2.1%	2.6%	1.1%	0.0%	0.0%	**0.0%**	1.2%	-0.1%	1.2%	0.9%	-0.5%	-0.6%	0.3%	5.0%	23.3%
low	6.9%	-0.4%	-0.8%	-2.1%	0.0%	0.0%	**0.0%**	-2.5%	-0.4%	-3.6%	0.4%	-2.0%	-0.2%	-3.3%	-0.5%	23.2%
moderat	7.2%	-1.9%	-2.9%	0.1%	0.0%	0.0%	**0.0%**	-3.1%	-1.6%	-4.6%	0.5%	-3.2%	0.1%	-3.2%	2.3%	30.7%
high	10.9%	4.2%	1.5%	1.4%	0.1%	0.1%	**0.0%**	2.9%	3.1%	1.7%	2.0%	-0.2%	2.4%	2.6%	3.7%	36.6%
very high	11.3%	0.1%	-0.2%	0.2%	0.0%	0.0%	**0.0%**	1.7%	2.6%	-1.4%	-0.4%	-1.0%	2.0%	-0.4%	1.5%	22.9%
sum	43.9%	8.6%	7.9%	5.0%	0.2%	0.2%	0.0%	11.3%	7.8%	12.4%	4.2%	6.9%	5.5%	9.8%	13.0%	
								Change of ecological suitability when newt changes								
very low	105951	105896	110632	106453	105195	105195	**105195**	106737	106785	108094	107786	105533	108308	109543	109056	
low	113176	119055	114930	116123	115906	115906	**115906**	116435	115891	112022	119411	113608	116791	115260	117384	
moderat	117620	114665	112093	111584	111113	111113	**111113**	111515	111887	114803	114957	114894	114562	110121	113999	
high	109281	109579	111493	111606	111404	111399	**111399**	111349	110434	111017	109814	113265	111727	111058	111342	
very high	109148	105981	106028	109410	111558	111563	**111563**	109140	110179	109240	103208	107876	103788	109194	103395	sum
very low	0.7%	0.7%	5.2%	1.2%	0.0%	0.0%	**0.0%**	1.5%	1.5%	2.8%	2.5%	0.3%	3.0%	4.1%	3.7%	27.0%
low	-2.4%	2.7%	-0.8%	0.2%	0.0%	0.0%	**0.0%**	0.5%	0.0%	-3.4%	3.0%	-2.0%	0.8%	-0.6%	1.3%	17.5%
moderat	5.9%	3.2%	0.9%	0.4%	0.0%	0.0%	**0.0%**	0.4%	0.7%	3.3%	3.5%	3.4%	3.1%	-0.9%	2.6%	28.2%
high	-1.9%	-1.6%	0.1%	0.2%	0.0%	0.0%	**0.0%**	0.0%	-0.9%	-0.3%	-1.4%	1.7%	0.3%	-0.3%	-0.1%	8.8%
very high	-2.2%	-5.0%	-5.0%	-1.9%	0.0%	0.0%	**0.0%**	-2.2%	-1.2%	-2.1%	-7.5%	-3.3%	-7.0%	-2.1%	-7.3%	46.8%
sum	13.00%	13.22%	11.94%	3.92%	0.01%	0.00%	0.00%	4.50%	4.33%	11.85%	17.86%	10.69%	14.09%	8.01%	14.92%	

Table 19 Spatial distribution of the ecological suitability scores for different sensitivity scenarios (2.1, random, and high/low scores) for the three species (newt, squirrel and hedgehog).

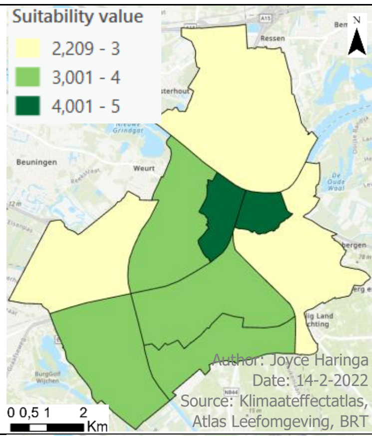
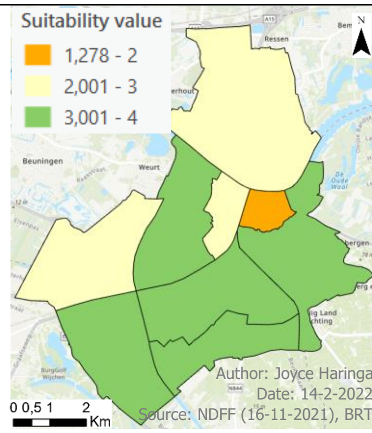
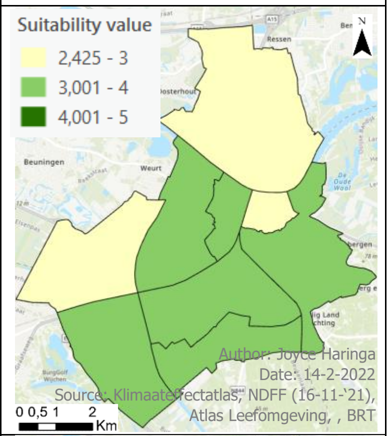
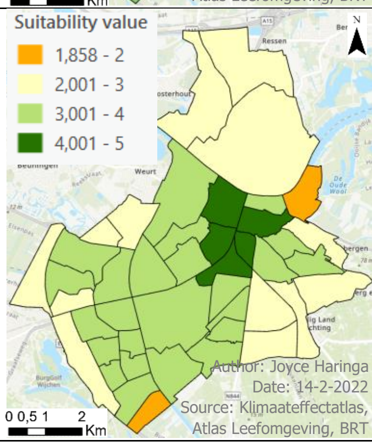
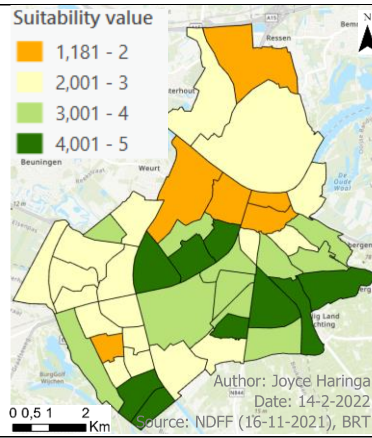
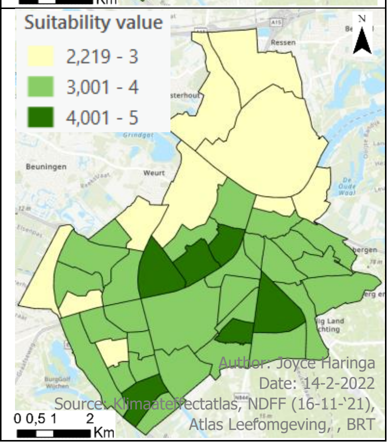
Newt	Baseline (2.1= 90):	2.1= 75	2.1= 80
Change score of BGT subclass 2.1 (main roads)			
	2.1= 85	2.1= 95	2.1= 100
			
	X= 25%	X= 50%	X= 75%
Random +- X:			
Lowest scores -X, highest scores +X:			
Lowest scores +X, highest scores -X:			

Hedgehog	Baseline (2.1= 70):	2.1= 75	2.1= 80
Change score of BGT subclass 2.1 (main roads)			
	2.1= 65	2.1= 60	2.1= 55
			
	X= 25%	X= 50%	X= 75%
Random +- X:			
Lowest scores -X, highest scores +X:			
Lowest scores +X, highest scores -X:			

Squirrel	Baseline (2.1= 50):	2.1= 55	2.1= 60
Change score of BGT subclass 2.1 (main roads)			
	2.1= 45	2.1= 40	2.1= 35
			
	X= 25%	X= 50%	X= 75%
Random +- X:			
Lowest scores -X, highest scores +X:			
Lowest scores +X, highest scores -X:			

Appendix X: District and neighborhood with five suitability classes

Table 20 Suitability scores from the social, ecological, and social-ecological perspectives for district and neighborhood level.

	Social	Ecological	Social-ecological
District			
Neigh-borhood			

Appendix XI: Green vision map of different municipalities

Figure 29 Green structure plan Amsterdam (Municipality of Amsterdam, 2012)

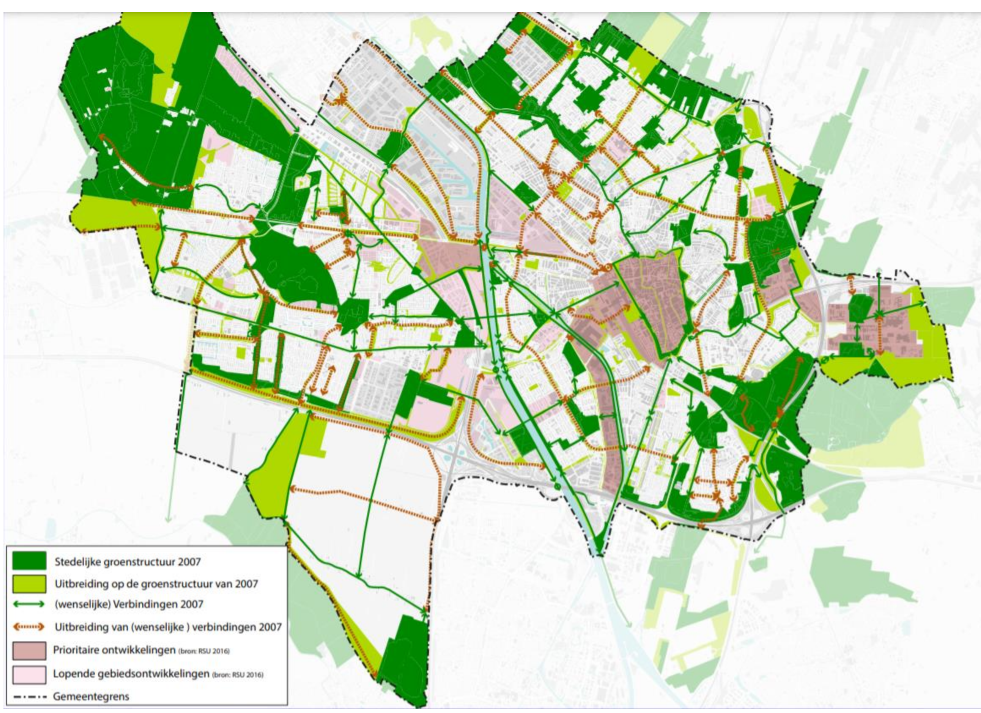


Figure 30 Green structure plan Utrecht (Municipality of Utrecht, 2018)

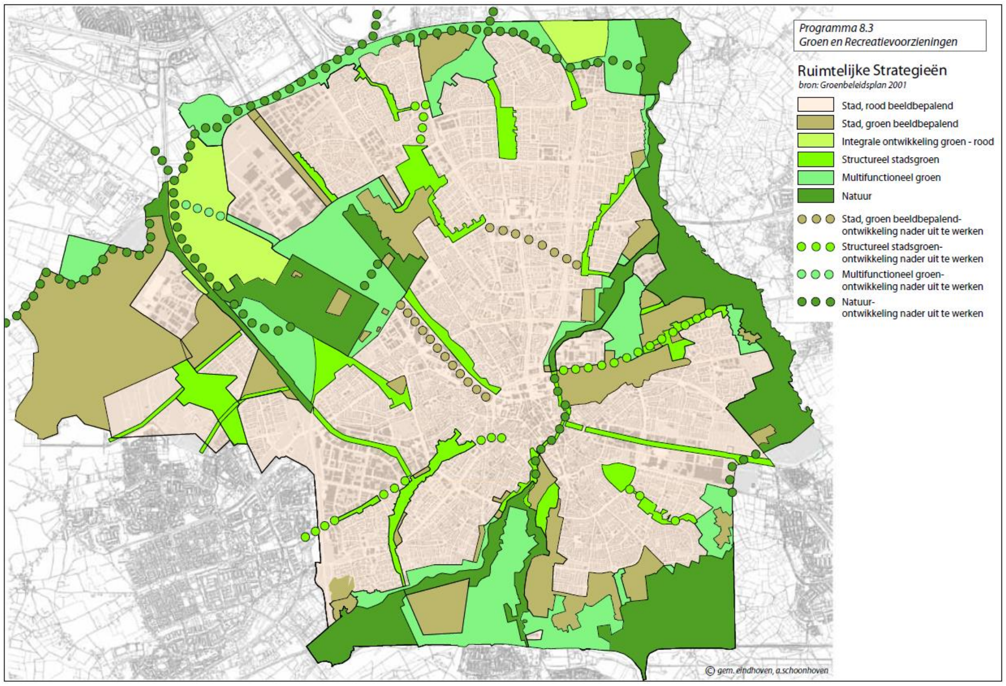


Figure 31 Green structure plan Eindhoven (Municipality of Eindhoven, 2020)

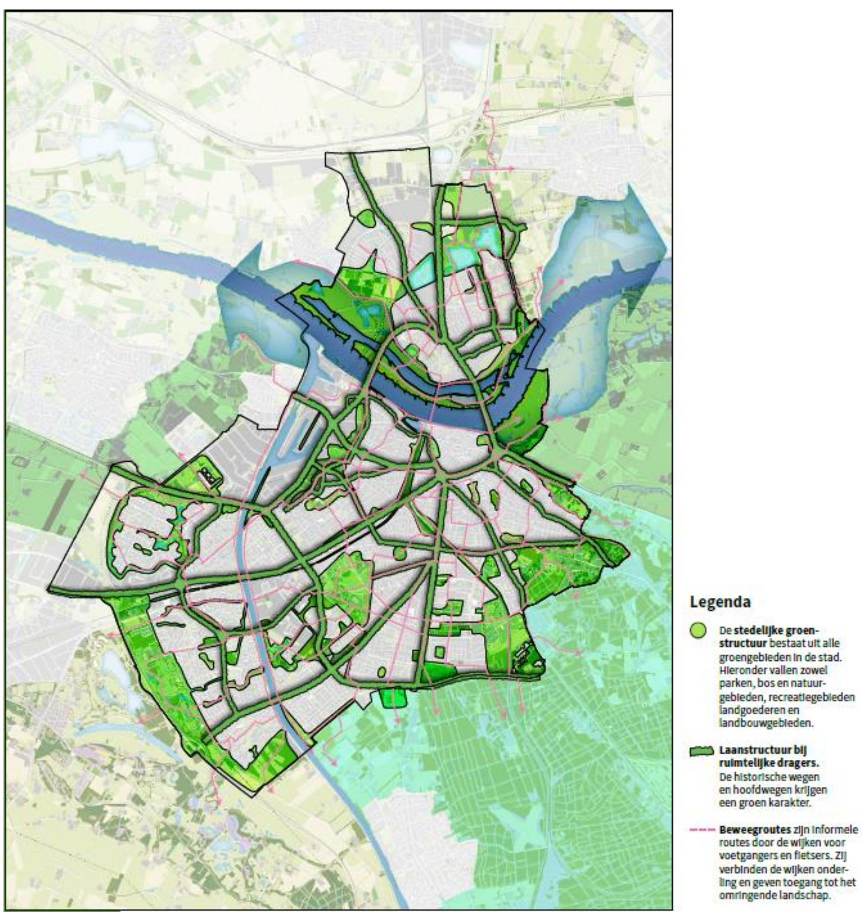


Figure 32 Green structure plan Nijmegen (Municipality of Nijmegen, 2020)

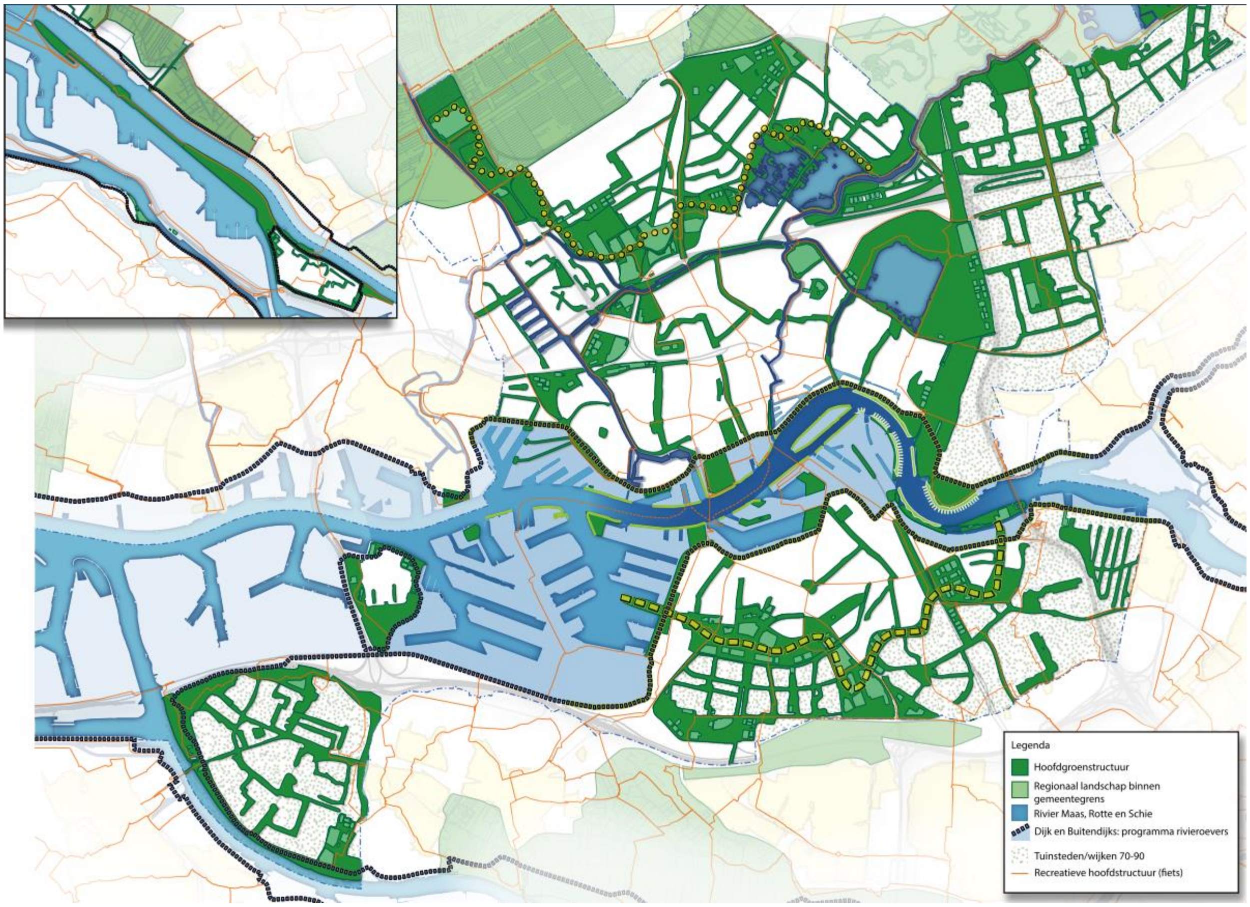


Figure 33 Ambition green structure municipality of Rotterdam (Municipality of Rotterdam, 2021).

Appendix XII: Roads as ecological corridors

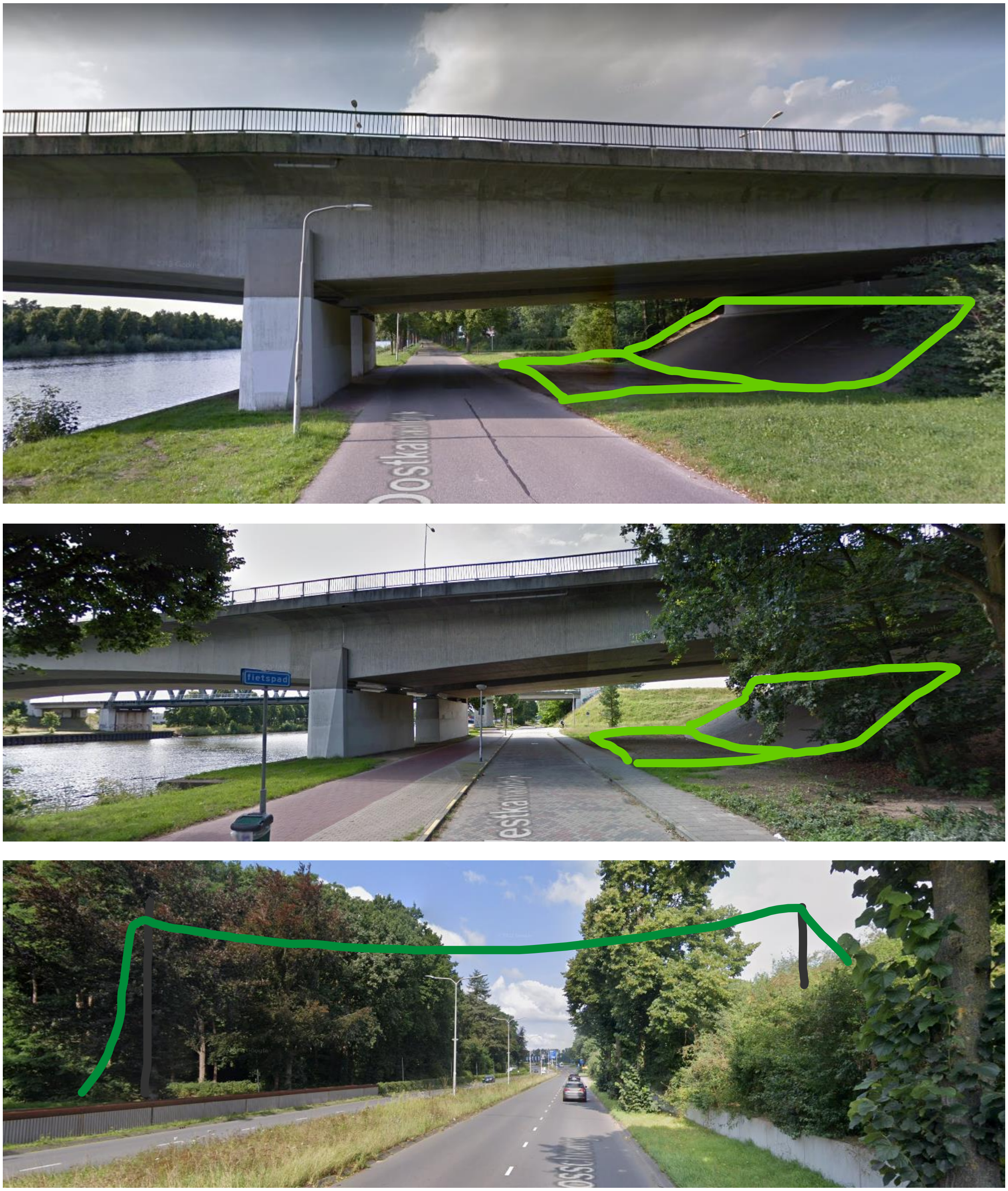


Figure 34 Suggestions for enhancing roads as ecological corridors in Nijmegen.