“Connectivity of Green Infrastructures in Urban Areas: Case of Dutch cities”

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Abstract

Environmental, social and economical processes and resource use that are linked to cities are major contributors to the global climate crisis. Moreover, urban environments are also becoming increasingly vulnerable to urbanization and climate crisis-related risks. One of the most prominent climate adaptation and mitigation strategies is the development of green infrastructure (GI). The latter is a multifaceted tool that provides a wide range of ecosystem services, in turn solving and mitigating the numerous challenges that cities face. However, in order for GI to reach its full capacity, certain criteria, such as the presence of a strong ecological network within a city must be met. Despite the great potential of GI as a climate crisis adaptation, there is a lack of research assessing the connectivity and fragmentation of habitats in urban contexts. In order to fill this gap and initiate further research into the topic, this study analyzed the connectivity and fragmentation of GI in Dutch cities - Amsterdam, Groningen, Rotterdam and Utrecht. The research was conducted by reviewing relevant literature and analyzing land-use and biodiversity data. The outcomes of this study demonstrated that it is not sufficient for GI to be present, but the number and connectivity across green areas as well as its shape have paramount importance for biodiversity, and consequently, to the capacity of the ecological network to provide all the ecosystem services expected.

Introduction

Rapid urbanization is one of the most prominent development trends over the last centuries (Elmqvist et al., 2013). The trend continues today - the urban population is expected to increase by 2,5 billion city dwellers worldwide by 2050 (United Nations. Department of Economic and Social Affairs Population Division, 2019). In Europe (European Union states) alone, 74% of the population currently resides in urban areas (European Union, 2016). This causes enormous economical, societal, infrastructural, and environmental pressures from and on urban environments (Lucertini & Musco, 2020; Seto et al. 2014). Currently, urban areas are significant contributors to the climate crisis. In fact, cities consume 75% of the world's resources and account for 70% of global carbon dioxide emissions (Lucertini & Musco, 2020; Seto et al. 2014). Furthermore, cities are also prominent sites of air pollution - studies show that in some cases, e.g. European Union members exceed the World Health Organization's set values for human health protection (Sicard et al., 2020). Additionally, cities are known to generate not only air but also noise, light, and chemical pollution (De Carvalho & Szlafsztein, 2019; Brainard et al., 2004; Tirkolaee et al., 2020; Mandaric et al., 2018). Moreover, the city area is expected to reach 1,7 million km^2 by 2050 (Zhou et al., 2019). This urban sprawl has repercussions for surrounding rural, agricultural and natural areas which in turn can affect the health and the performance of these areas (Czamanski, 2008; De Carvalho & Szlafsztein, 2019). Therefore, the resource and energy use, greenhouse gas emissions, and pollution pressure that cities face, can have far-reaching consequences for the globe. Therefore, urban development is a crucial component to be addressed when tackling sustainable development and climate crisis mitigation efforts for the entire globe (Lucertini & Musco, 2020; Seto et al. 2014).

However, it is worth noting that urban areas themselves are already widely affected not only by the issues arising from urbanization such as air, noise, light, waste pollution, and management problems but also by the climate crisis itself. (Kumar, 2021; Balaban, 2012). Rising temperatures increase heat stress in densifying urban environments and amplify the urban heat island effect (Kumar, 2021; Balaban, 2012). The latter has adverse consequences for human health and heightened energy consumption, which in turn further influences resource use (Chakraborty et al., 2019). Moreover, the adverse effects of pollution and urban heat island effects are unequally distributed across the cities varying by different demographic groups (Checker, 2011; Watkins et al., 2016; Alizadeh et al., 2022; Chakraborty et al., 2019). In fact, in 72% of the cases, low-income neighborhoods were disproportionately affected by elevated heat stress exposure compared to the rest of the city neighborhoods (Chakraborty et al., 2019). Therefore, the sustainability challenges that cities currently face, not only exposes the vulnerability of urban areas to the changing climate but also amplify the social inequalities already present in urban areas.

Consequently, cities are striving to address these multifaceted and interconnected issues by adopting different climate mitigation and adaptation strategies (Kumar, 2021; Balaban, 2012; Gemeente Amsterdam, 2012; Gemeente Groningen, 2018). Some examples of them are, that cities might tackle the transportation infrastructure sustainability issues by increasing and creating a more efficient public transport system, encouraging and subsidizing fossil fuel independent transportation as well as building bike and pedestrian friendly streets in order to increase the walkability of the urban areas (Sultana et al., 2021; de Kruijf et al., 2018). Which in turn would promote more sustainable transportation behaviors from city dwellers (de Kruijf et al., 2018). Furthermore, addressing the sustainable energy transition in cities by opting for renewable energy sources and encouraging individual and community scale energy production and efficiency initiatives (F. Liu et al., 2020). One of the most prominent examples of climate mitigation strategies in urban areas is the Netherlands, the case study area of this research. With their highly developed transport infrastructure, in which trains run on exclusively renewable energy, extensive and widely bicycle infrastructure, water management, and city planning, they are a renowned example of well-integrated (urban) climate mitigation and adaptation (de Kruijf et al., 2018; Proka et al., 2018; Hölscher et al., 2019).

Furthermore, the presence of high-quality green infrastructures and other similar nature-based solutions in cities is being increasingly referred to as a multifaceted tool able to mitigate the most pressing urbanization issues in the context of climate change. (Sturiale & Scuderi, 2019; Gómez-Villarino et al., 2020; Madureira & Andresen, 2013). This takes the form of installing, implementing or adapting green infrastructure into the existing city structure. Parks, green roofs, street vegetation, and tiny forests are some of the many examples of GI in cities (Liquete et al., 2015). While Green Infrastructures (further referred to as GI) do not have a fixed definition, for the purpose and context of this paper, the definition provided by the European Commission will be used. The latter is defining GI as a part of wider ecosystem services, which bring benefits not only to the natural environment but also to the wider population by cleaning the air, climate regulation, pollination, nutrient cycling, etc. (European Commission Directorate-General for Environment, 2021; Lai et al., 2018). In the urban context, GI provides all-around benefits for the city environment, infrastructure, and resident communities (Sturiale & Scuderi, 2019; Gómez-Villarino et al., 2020; Madureira & Andresen, 2013). The existence of high-quality GI such as city parks provides services for climate crisis adaptation firstly, by storm prevision, excess water storage, which mitigates the effects of floods (Madureira & Andresen, 2013). Secondly, by cleaning cycling nutrients, cleaning the air, and providing a cooling effect which helps to combat urban challenges such as air pollution and urban heat stress (Zardo et al., 2017). Moreover, the GI provides recreational spaces which are crucial for maintaining the social and personal well-being and health of local communities (Astell-Burt & Feng, 2019; Taylor & Hochuli, 2014; Annerstedt van den Bosch et al., 2015; Hegetschweiler et al., 2017). Furthermore, the existence of GI (network) increases the biodiversity levels in urban areas, which in turn strengthens the resilience and functioning of the GI for urban areas through environmental services such as pest control and pollination to name a few (Taylor & Hochuli, 2014; Beaujean et al., 2021; Correa Ayram et al., 2015; Olds et al., 2011; van der Grift, 2005).

Nonetheless, in order for GI to reach their full potential in providing environmental services for cities, the GI needs to meet certain criteria such as green area patch size and shape, as well as establishing a continuous GI ecological network. (Zardo et al., 2017; Driscoll et al., 2013; Tischendorf & Fahrig, 2000). Connectivity of GI in cities enables species movement and dispersal which is crucial for a strong ecological network. The presence of habitat connectivity in urban environments can be manifested in many ways, but the most prominent ones being the existence of green corridors and green cover links between bigger GI patches (Beaugeard et al., 2020; Angold et al., 2006; Rudd et al., 2002). However, despite the increasingly growing popularity of the use of GI as a tool for climate adaptation and mitigation as well as the importance of the connectivity of ecological networks, there is a lack of research examining it, especially in the urban context. (LaPoint et al., 2015). Specifically, the role as well as the level that ecological connectivity plays in fostering biodiversity levels and ecosystem functioning in urban contexts. Urban GI connectivity research in the Dutch context is sadly not extensive enough as well. While there is a number of research and reports investigating the connectivity, fragmentation of habitats as well as and the existence and provision of green corridors for wildlife in other spatial contexts such as natural reserves, and agricultural areas, there is a clear lack of research in urban context (van der Grift, 2005b; Ovaskainen, 2012; Grashof-Bokdam, 1997). Therefore, this study aims to fill the gap in research and provide an informal assessment of the connectivity and fragmentation of green infrastructures in Dutch cities.

Literature review

` Cities are not only one of the major contributors to climate change, but they will also be greatly affected by it (Kumar, 2021; Balaban, 2012). Examples such as the urban heat island effect (UHI) and urban air quality degradation are prominent and visible in almost every city around the globe. (Kumar, 2021; Balaban, 2012). However, the issue of climate change in urban areas has revealed that cities nowadays are facing multi-dimensional problems which are all amplified due to climate change (Chakraborty et al., 2019; Checker, 2011; Watkins et al., 2016; Alizadeh et al., 2022; Sicard et al., 2020). Social and economic inequality infrastructures become more visible when we talk about accessibility to cleaner air, public services, transportation, and green areas within the cities (Comber et al., 2008). Studies have shown that low-income, minority neighborhoods have significantly higher levels of air and other types of pollution as well as a lack of green areas in the neighborhoods (Checker, 2011; Watkins et al., 2016). In fact, 72% of the cases, low-income neighborhoods were disproportionately affected by elevated heat stress exposure compared to the rest of the city neighborhoods (Chakraborty et al., 2019). Therefore, earlier presented green infrastructures become a crucial multifaceted tool to deal with these problems of climate crisis effect on urban environments and their communities.

Key elements and benefits of Green Infrastructures

As earlier briefly presented, green infrastructures are broadly referred to as green, often vegetation (as well as water) or other “natural” elements in the urban systems (Gómez-Villarino et al., 2020). There is a big range of different GI available for urban environments (Sturiale & Scuderi, 2019). Some are more traditional and straightforward such as parks, green squares, installing tree cover or other vegetation next to transportation corridors, and residential neighborhoods establishing community gardens. While others are less widespread and innovative such as green facades and roofs, urban forests, and tiny forests. These green elements provide crucial environmental, societal, and even technical benefits for the cities (Sturiale & Scuderi, 2019; Gómez-Villarino et al., 2020; Madureira & Andresen, 2013).

Examples of such environmental services for cities and their residents include provisionary services - resources such as wood and food production, regulatory - air, noise, and light pollution reduction, pollination, and storm protection (Madureira & Andresen, 2013). As well as cultural services such as recreational areas which increase personal and social well-being for local residents (Astell-Burt & Feng, 2019; Taylor & Hochuli, 2014; Annerstedt van den Bosch et al., 2015; Hegetschweiler et al., 2017; United Nations, 2005). For instance, urban parks and forests not only improve air quality but also contribute to local climate regulation by providing a cooling effect. In fact, a study done by Zardo and colleagues in 2017 measured the cooling capacities of green infrastructures had found that in some cases, with the right size, tree canopy coverage, and soil coverage conditions, these GI can provide an up to 3,5°C in Atlantic region and up to 6°C local temperature decrease in the Mediterranean region (Zardo et al., 2017). Moreover, green urban areas such as parks, urban forests, rooftops, and vertical gardens or vegetation can act as water level regulators and even storage during heavy rainfalls or flash floods (Liu et al., 2014). Additionally, there is an added value in harvesting the runoff water from green roofs, ponds, and lakes that act as water storage, for places with high risk and frequency of droughts and general water insecurity (Liu et al., 2014). Lastly, the existence of green infrastructures such as urban forests or parks adds benefits to the social well-being of local communities. Researchers agree that providing green, walkable and community spaces, such as parks and urban forests encourages physical activity, and social interaction and increases the mental well-being of its residents (Astell-

Burt & Feng, 2019; Taylor & Hochuli, 2014; Annerstedt van den Bosch et al., 2015; Tzoulas et al., 2007). Worth noting that a study done by Taylor & Hochuli argues for the importance of biodiversity and ecosystem functions in an urban environment as crucial components of mental and physical wellbeing in urban areas as these components are greatly intertwined and crucial for the functioning of provisionary and regulatory GI and wider ecosystem service functioning (Taylor & Hochuli, 2014). It is worth mentioning that different types of GI provide different sets of benefits, therefore there is a possibility for urban planners to include different types of GI for cities in order to diversify and expand their effects on the local environment and residents.

Connectivty

It is prominent that GI has a number of known benefits for urban areas, studies show that even relatively small urban green areas can host considerable biodiversity (Melliger et al., 2018; Iojă et al., 2014; Angold et al., 2006). Moreover, especially in the climate crisis context GI acts as a tool for climate adaptation, mitigation, and increased resident well-being. However, in order for green infrastructure to live up to its full potential, it is necessary to ensure a strong ecological network and connectivity between patches of green areas (Melliger et al., 2018) The latter is crucial for natural areas in all habitats in order to preserve and foster biodiversity levels and improve performance of other environmental services (Beaujean et al., 2021; Correa Ayram et al., 2015; Olds et al., 2011; van der Grift, 2005; Melliger et al., 2018). Firstly it is important to understand that habitat connectivity is landscape dependent. Namely, in the context of natural areas, the level of connectivity depends on the level of how the landscape facilitates or hinders the possibility of species movement between habitats and resource patches (Tischendorf & Fahrig, 2000). Similarly, Driscoll et al. introduce mechanisms through which habitat matrix qualities influence species in fragmented habitat patches. They found that the main influences come from effects associated with firstly, movement and dispersal of species in and out of the habitat patches, secondly, resource availability in the patches and lastly, the surrounding abiotic environment (see figure 1) (Driscoll et al., 2013).

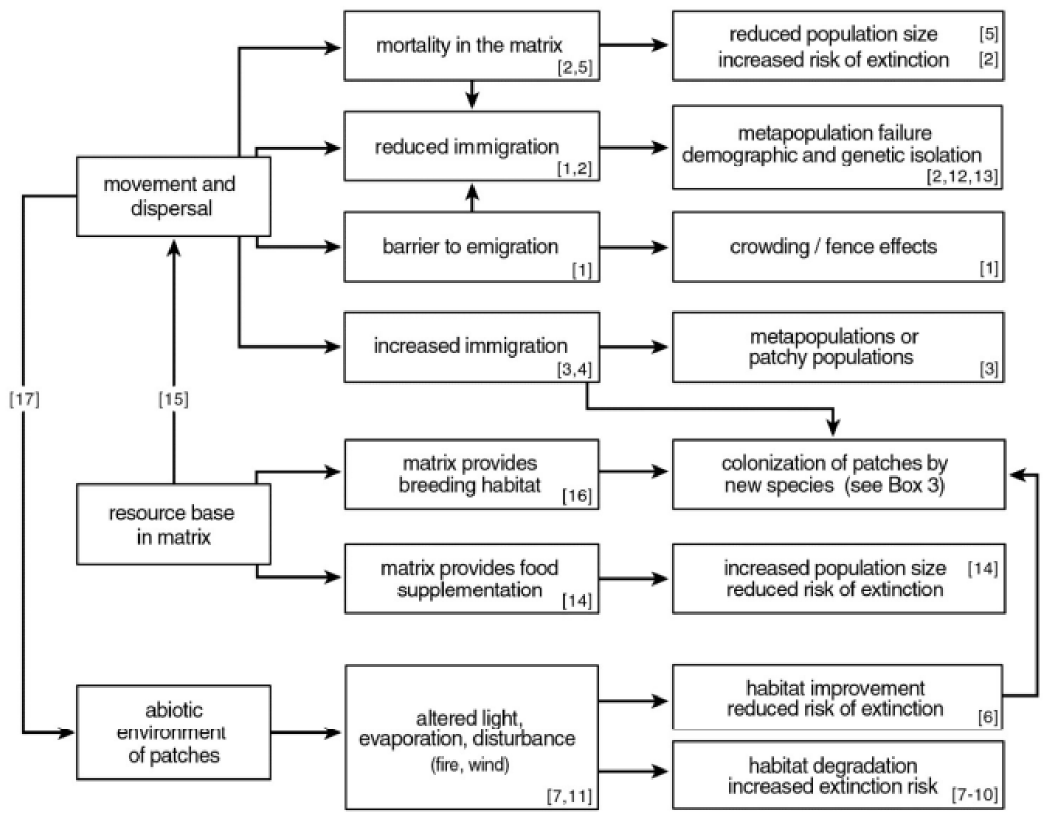

Figure 1 Flow diagram of the mechanisms through which changes in the habitat matrix affect ecological networks (Driscoll et al. 2013).

Urban ecosystems function in the same principle - studies show that nature can thrive, and thus provide us with valuable ecosystem services, if certain habitat conditions are met (Beaugeard et al., 2020; Angold et al., 2006; Rudd et al., 2002). A study by Beaugeard et al. has found that local urban biodiversity richness is highly benefited from the presence of green areas, proximity to the edge of the urban center, and the proximity to a green corridor. This goes in line with previously presented Driscoll et al. findings. The presence of resource-rich green areas in urban contexts provides species with food and breeding habitats. Moreover, habitat patches with their edges next to contrasting, in this case urban, abiotic environments are exposed to air, noise, and light pollution which negatively impacts the species living in that area (Driscoll et al., 2013). Lastly, movement and dispersal availability depend on the proximity to a green corridor (Beaugeard et al., 2020; Driscoll et al., 2013; Rudd et al., 2002). In fact, Beaugeard et al. note that the presence of green corridors has significantly affected the presence of even rare species in the urban study area (Beaugeard et al., 2020). The significance of green corridors goes in line with the research outcomes of Rudd et al., moreover, the author stresses that "Creating corridors using the connectivity analysis is much more effective than randomly selecting links. The results of the analysis indicate the value of a network of backyard habitat, boulevards, and utility rights-of-way to provide a matrix of corridors." (Rudd et al., 2002). The latter shows, that urban green habitat corridors can have many different forms, including earlier discussed GI such as urban parks, green streets, and community gardens. Even considerably small green areas can amplify the connectivity and multifunctionality within an urban ecological system (Iojă et al., 2014; Melliger et al., 2018). An example of the latter was observed by Iojă et al. in their case study in Bucharest examining the multifunctionality of green space in public schools. They have found that even these relatively small green areas "acting as steppingstones for species flow" as well as provide social benefits such as outdoor classrooms, recreation, and leisure spaces for the local residents (Iojă et al., 2014). Therefore, creating an ecological network and increasing GI connectivity within an urban area is one of the best tools to deal with environmental and social well-being challenges that cities encounter today.

Urban GI agendas

With cities all around the world facing climate crisis-induced environmental and social challenges, there are numerous frameworks and development strategies being proposed and implemented (Mansur et al., 2022). From global institutions like the United Nations, national governments, or through local community initiatives, cities have shifted their efforts to focus on development strategies that include and account for nature in cities. Increasingly, environmental services and GI are becoming central tools for climate change adaptation and mitigation efforts. However, these green urban development strategies often fail to account for social inequalities that occur within cities, and through non-equitable green development plans even further social and economical inequalities (this is a very important and pressing issue, however, due to the scope of this paper for more information please read Checker, 2011). Furthermore, despite clear scientific support and evidence for the importance of GI connectivity in all spatial contexts, urban developers are only starting to include it in the green (re)development national and municipal agendas.

The focus of this paper, Dutch cities are no exception. Despite the Netherlands being a seeming leading example of climate change adaptation in energy and transportation sectors, their GI and habitat connectivity are getting less attention. While there are several studies showcasing habitat fragmentation problems and efforts to increase connectivity in natural and agricultural areas, GI and habitat connectivity in urban contexts have received little to no attention (van der Grift, 2005b; Ovaskainen, 2012; Grashof-Bokdam, 1997). Therefore, in order to get a comprehensive analysis of GI connectivity in the case cities of Amsterdam, Groningen, Eindhoven, and Utrecht, a brief description of published green infrastructure and specifically habitat connectivity, development agendas, and goals will be presented below. The agendas that cover targets up to and including 2018 will be used in order to be consistent with the available satellite data (from 2018).

Case study cities and their GI agendas

Amsterdam

In 2011, the city council of Amsterdam published a structural vision "Amsterdam 2040: economically strong and sustainable". As a part of the environmental vision of the latter development plan, the "Ecological vision" report focusing on ecology, biodiversity and green connectivity was developed (Gemeente Amsterdam, 2012). The latter development plan underlines that it drifts from previous GI development strategies, as it also focuses on environmental sustainability for local flora and fauna, and not only as recreation spaces for Amsterdam inhabitants (Gemeente Amsterdam, 2012). This marks an important shift, as it requires additional attention towards establishing and strengthening the infrastructure required for fostering biodiversity in a functioning ecological network for species movement and dispersal. The city council (see Figure 2) proposes the vision of the GI connectivity and addresses the fragmentation issues by pointing out bottleneck areas (Gemeente Amsterdam, 2012). The city council strives to realize it by firstly, establishing the latter in the policy level - any construction plans must take into account the existing and potential GI network as well as bottleneck areas and include them into the development structure (Gemeente Amsterdam, 2012). Moreover, the city council identified the most important (by the size of the available green area) GI patches - Amsterdamse Bos, the Schinkelbos, the areas in the Gardens of West, Geuzenbos and Spaarnwoude. It strives to connect these large green areas to the existing GI within the city in order to allow for species to move in and out of the city safely (Gemeente Amsterdam, 2012).

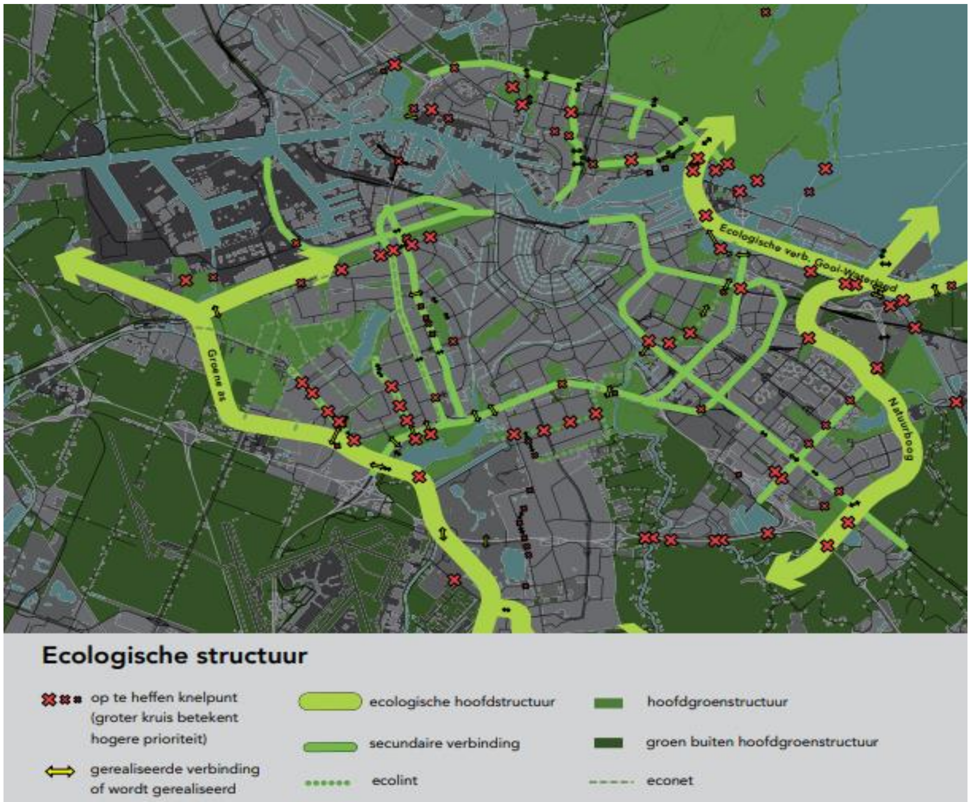

Figure 2 Ecological structure proposal from Amsterdam as recorded in Structural Vision Amsterdam 2040 p. 6. Ecological structure [of Amsterdam]: Bottlenecks (the larger the cross means higher priority); Connections in development; Main ecological network; Secondary links; Main GI; Green areas outside of main GI.

Groningen

In 2018 as part of the Greenplan Groningen (dutch - *Groenplan Groningen*) development plan focuses on planning and developing physical environments of Groningen. The agenda covers multiple disciplines such as urban growth and housing, economic development, community health, sustainable energy transition, climate-proof, and livable Groningen (Gemeente Groningen & Strootman Landshapsarchitecten, 2020). The latter includes implementing greening initiatives such as extending the tree cover (planting 1000 trees a year) and implementing 30 000sq/m of new green areas by creating and repurposing currently unused (gray infrastructure) space (Gemeente Groningen & Strootman Landshapsarchitecten, 2020). Moreover, in collaboration with residents municipality launched a "Groningen climate-proof" initiative by encouraging (and subsidizing) citizens, private and business entities to invest in climate adaptation - green roofs, green facades, planting and adoption of trees and tiny forests in private and public areas, preserving rainwater and public and private urban garden initiatives (Gemeente Groningen, 2018). Furthermore, the municipality aims to not only plant more, but also more diverse plant species in order to increase the biodiversity and resilience of GI in the city (Gemeente Groningen & Strootman Landshapsarchitecten, 2020). With the help of these initiatives, the municipality strives to strengthen the ecological network in Groningen which would provide direct benefits for flora, fauna, local residents as well as climate adaptation. In the Greenplan Groningen report from the municipality, they have identified the main ecological structure in the urban system as well as places where key species cannot pass due to the lack of green infrastructures or designated green corridors (Figure 3) (Gemeente Groningen & Strootman Landshapsarchitecten, 2020).

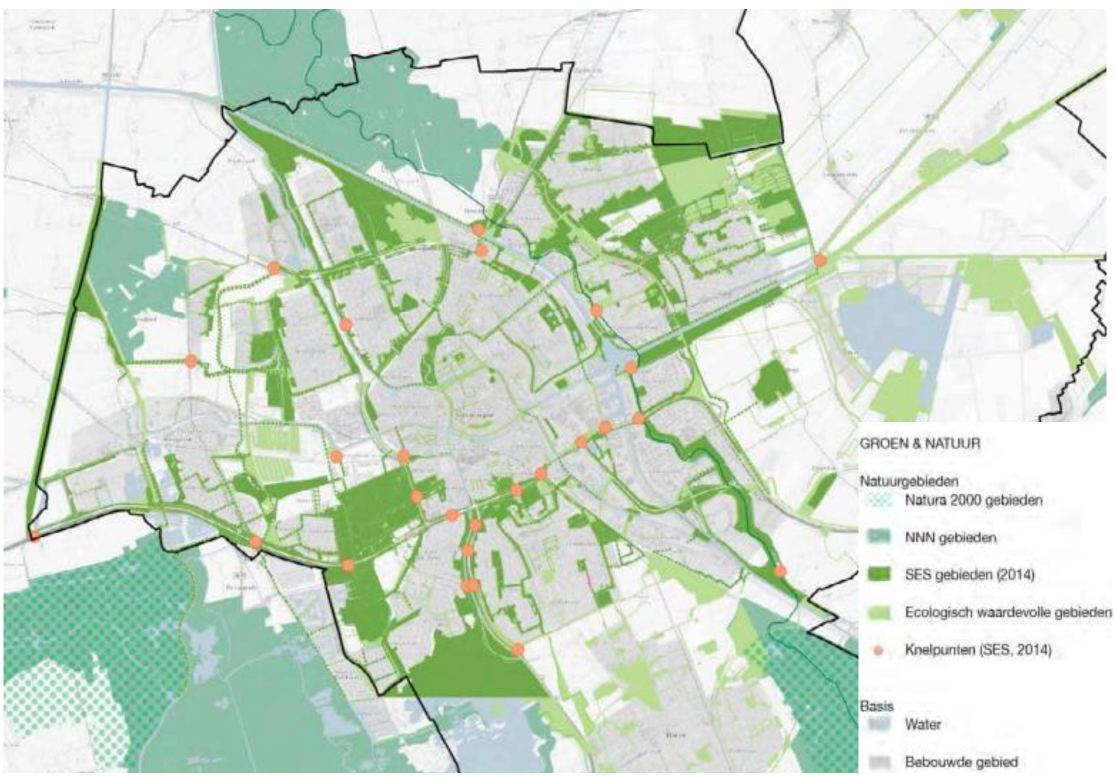

Figure 3 Image adapted from "Greenplan Groningen" development plan, "Ecologische hoofdstructuur binnen de gemeente", p27

Snapshot from the latter “Greenplan Groningen” showing the ecological networks under different reserve jurisdictions, moreover, the Starting from the top - Natura 2000, NNN (Dutch National Nature resevrve) areas, SES (Urban ecological structure) areas, Ecologically valuable areas, Bottleneck (areas that fragment the ecological network and hinder species movement), water areas, gray infrastructure.

Based on this current green network assessment map in the city (Figure 3), the municipality strives to not only eliminate the bottleneck regions but also create a more robust ecological network by connecting and densifying existing GI in the city as well as bridging the urban ecological network to more rural areas of the municipality (Gemeente Groningen & Strootman Landshapsarchitecten, 2020). Moreover, collaborating with local residents with earlier described individual initiatives. With this plan the municipality strives to provide an extensive network and foster species movement, dispersal and higher biodiversity levels, thus creating a more livable and climate-proof city for its residents.

Rotterdam

In 2018, the municipality of Rotterdam as a part of the college targets 2018-2022 has released an environmental program “Rotterdam goes green” and since then more than 20ha of greenery have been added to the public spaces such as streets and squares (Gemeente Rotterdam, 2022). While this initiative has been very successful, it was the only environmental goal in the college targets 2018-2022 (Gemeente Rotterdam, 2018; Gemeente Rotterdam, 2022). Moreover, there was a lack of concreteness of where, how, and why the green areas will be added. In contrast with the Amsterdam, Groningen, and Utrecht municipalities, Rotterdam has (seemingly) failed to present not only a publicly accessible display of more concrete measures that were taken in order to reach this goal as well as propose a long-term strategy for the GI as a network development in Rotterdam.

Utrecht

In 2018, the municipality of Utrecht evaluated and updated the earlier developed green structure plan (Green structure plan 2007 - 2016) for the 2017-2030 period. In it, the municipality stressed the inevitable urban population growth and thus the urgent need to strengthen the ecological network within the city. The efforts from the earlier GI development plan were clearly seen and evaluated - the outward green area expansion connecting the city and rural areas was realized by adding a total of 620ha of green space around the city. Moreover, by planting more trees the tree count within the city has grown to 160 000. It is worth mentioning that the municipality focused on planting native trees in order to increase the resilience and biodiversity of native ecosystems. Furthermore, the municipality developed a “Green web” network focused on identifying the connectivity and fragmentation addressing bottleneck spots in the ecological network of the city. To inform the latter they presented a map showcasing the current, development stages and potential GI that would improve and strengthen the ecological network in Utrecht (Figure 4). Overall, the municipality presented a green structure plan that primarily focuses on the expansion of GI in the city by improving neighborhood greenery (encouraging local residents to participate in these initiatives), securing, strengthening, and diversifying tree structures in the city as well as implementing roof and facade greenery projects.

Figure 4 Image adapted from Gemeente Utrecht, 2018 "Status of green structure implementation in the city" p18.

Light green - existing, dark green - in development, purple - future developments (Green Web program).

Methods

The aim of this study is to look at the coverage, connectivity, and fragmentation of green infrastructures in Dutch cities. Additionally, this study explores the correlations between the (successful) implementation of nature-based solutions for climate adaptation in cities and higher connectivity and biodiversity levels. This research project was completed in several stages.

Firstly, a review of relevant literature and similar studies was done in order to gain a deeper understanding of the subject, available methods, existing discussions, and gaps in knowledge. This was done by reviewing and analyzing peer-reviewed articles retrieved from Smart Cat, Google Scholar, and ResearchGate. The latter was done by using keywords such as *habitat connectivity; fragmentation; green infrastructures; urban areas; Netherlands; biodiversity*. Furthermore, in order to gain recent historical and additional background knowledge, a review of sustainability achievements, strategies, and agendas from selected case study cities - Amsterdam, Groningen, Rotterdam, and Utrecht was done using publicly available municipality-issued reports and agendas. The agendas that cover targets up to and including 2018 will be used in order to be consistent with the available satellite data (from 2018).

Secondly, cities for the case studies were chosen. This was done by reviewing several Dutch cities such as Amsterdam, Eindhoven, Groningen, Leeuwarden, Maastricht, Nijmegen, Rotterdam, The Hague, Utrecht and Wageningen. The cities were placed in a table (see Tables 1 and 2) together with a set of criteria markers. The latter include - the name of the city; size (SqKm); population size, population density (if available from literature review), main economic flows, number of or distance to the nearest airports; types of nature-based solutions (if available from literature review) and density of green areas (if available from literature review). Based on the criteria above and the variation between variables such as population density, size, and main economic flows Dutch cities Amsterdam, Groningen, Rotterdam, and Utrecht were chosen and investigated further (see Tables 1 and 2).

Name	Size (sqkm)	Population size	Population dens	Main economic flows
Amsterdam	219.32 km2	1,558,755	5,214/km2	financial and business capital
Eindhoven	88.92 km2	337,487	2,643/km2	Techonolgy and industry (phillips)
Groningen	197.96 km2	216,655	1,246/km2	Hospitality, a couple production companies, gas mining
Leeuwarden	255.62 km2	108,254	516/km2	Basically offices
Maastricht	60.12 km2	277,721	2,171/km2	Manufactoring and offices
Nijmegen	57.63 km2	168,840	3,329/km2	University, hospital and offices
Rotterdam	324.14 km2	1,273,385		Port, shipping
The Hague	286.31 km2	883,720	6,523/km2	Service-oriented
Utrecht	99.21 km2	489,734	3,807/km2	Institutions
Wageningen	32.36 km2	38,774	1,275/km2	

Table 1

Main economic flows	Number or distai	Types of nature	Density of green areas	
financial and business capital	Schipol	https://maps.amsterdam.nl/klimaatadaptatie/?LANC		
Techonolgy and industry (phillips)	Eindhoven (8km from city centre)			
Hospitality, a couple production companies, gas mining	8.9km to neares	Tiny forests ...		
Basically offices	5km to Military airport			
Manufactoring and offices	10km			
University, hospital and offices	9km	https://theses.ubn.ru.nl/bitstream/handle/12345678		
Port, shipping	5.6km	http://www.urbanisten.nl/wp/wp-content/uploads/UE		
Service-oriented	20km	Tiny forests, tiles<greenery (https://resilientthehagu		
Institutions	47km	Tiny forests		

Table 2

In order to calculate habitat connectivity and fragmentation in chosen cities, the satellite data collection and analysis stage followed. Firstly, publicly available land cover data were extracted from satellite data of selected cities, at Copernicus Urban Atlas 2018 (European Union, Copernicus Land Monitoring Service 2018). Satellite data gathered in 2018 was used, as it is the most recent available data. Secondly, QGIS software (QGIS Development Team, 2020) was used to further investigate relevant data. The latter includes cropping city boundaries to contain only the urban core of the selected cities in order to focus on the urban green infrastructure connectivity while reducing the effect of rural areas surrounding the city. Furthermore, the next step was reclassifying land-use classes and existing GI into 4 different classes for each city. This was categorized in line with European Commission's established GI definitions. Thus, the classification was done as follows -

- *Class 1 - gray areas* which include categories of the continuous urban fabric of varying density. Moreover, sports and leisure areas were associated with the gray area category because of their variability in supporting ecosystem services and habitat connectivity.
- *Class 2 - green areas* which included green urban areas, forests, herbaceous vegetation associations, and wetlands.
- *Class 3 - agriculture areas* included arable land, permanent crops, pastures with complex, and mixed cultivation patterns, and orchards.
- *Class 4 - water* - was dedicated to water bodies such as ponds, lakes, rivers, canals, and seas.

To measure percentage cover across the cities, polygon (hexagon) grids of 1000 meters by 1000 meters, covering the urban core area were created and the land class coverage per polygon was calculated (see figure 6).

Furthermore, data was rasterized and landscape structure analysis was performed using GRASS GIS (GRASS Development Team, 2020) and R (R Core Team, 2020). The former was used to calculate fragmentation using patch metrics. The program used a four-neighbor algorithm to calculate edge density and mean patch size. Moreover, a calculation of the number of patches and the shape index was performed. The results from this analysis were presented in a table corresponding to the data from each city (see table 3). Following that, analysis in R using the *grainscape* package to calculate landscape connectivity was performed. Here the minimum planar graph (MPG) was plotted to find the links showing the shortest paths between the perimeters of the patches that are on the resistance surface. To complement MPG, patch grain of connectivity (GOC) and Voronoi tesselation were plotted (see appendix 2). Furthermore, an MPG using the characteristics of nodes and links was plotted for each city. These plots represent the links between nodes, which are scaled up to represent the area of GI that they represent (see figure 8).

Next to GI node size, connectivity, and fragmentation in urban areas, biodiversity data were analyzed and included in the later statistical calculations in order to compare the effect of GI patch size and connectivity on the level of observed biodiversity levels in cities. Publicly available data for this part of the analysis were retrieved from the "Global Biodiversity Information Facility" website (GBIF.org 2022). For this research, we used occurrence data from species classes: amphibia, arthropoda, aves, mammalia, plantae, and reptilia. The downloaded data covered species occurrence records from 2017 - to 2021 in CSV format from Amsterdam, Groningen, Rotterdam, and Utrecht cities. Furthermore, the data was uploaded into QGIS. Here, the earlier created polygon (hexagon) grids of the size of the urban core regions of each city were used in order to calculate the level of biodiversity (per species) occurrences per polygon per city.

Lastly, after gathering all the necessary data, statistical analyses in R were conducted. Firstly, the land class - gray infrastructure, GI, agricultural areas, and water areas cover percentage per city per polygon was calculated and visualized using a violin plot (see figure X). Furthermore, despite the low number of study sites (4), a principal component analysis (PCA) was performed using earlier generated data on edge density, mean patch size, patch number, and shape index per city (see figure 9). Moreover, a PCA analysis was also performed using biodiversity data per species amphibia, arthropoda, aves, mammalia, plantae, and reptilia) (see figure 10). This with the aim of exploring the distribution of the cities across these variables in terms of, patch metrics and biodiversity separately. Furthermore, logistic regression was performed using the percentage of GI cover per polygon, from previously calculated land class cover percentage data, and species biodiversity count per polygon data. In order to reduce the effect of sampling bias (Hughes et al., 2020) of the GBIF data in the analysis, the biodiversity data was transformed to presence-absence data (1 or 0). Where biodiversity variable with a count of species occurrence (only more than 5 occurrences per polygon were included) per polygon was classified as presence and polygons with less than 5 occurrences were classified as absences. The latter graphs were plotted using categories and their probability of occurrence in accordance with the green area cover (GI) percentage per polygon (see graphs 11,12,13 and 14). The categories were divided and categorized based on their movement ability and method as followed - birds (aves), plants (plantae), artrhopoda (arthropoda) and other species (amphibia, mammalia, reptilia). This with the aim of differentiating groups of species by their use of GI in terms of mobility (connectivity) and home range (patch characteristics).

Results

Land-class distribution

The aim of this study is to look at the connectivity and fragmentation of GI in Amsterdam, Groningen, Utrecht and Rotterdam urban centers. As a first step, the land-use class visualization (see Methods) was created (See Figure 5).

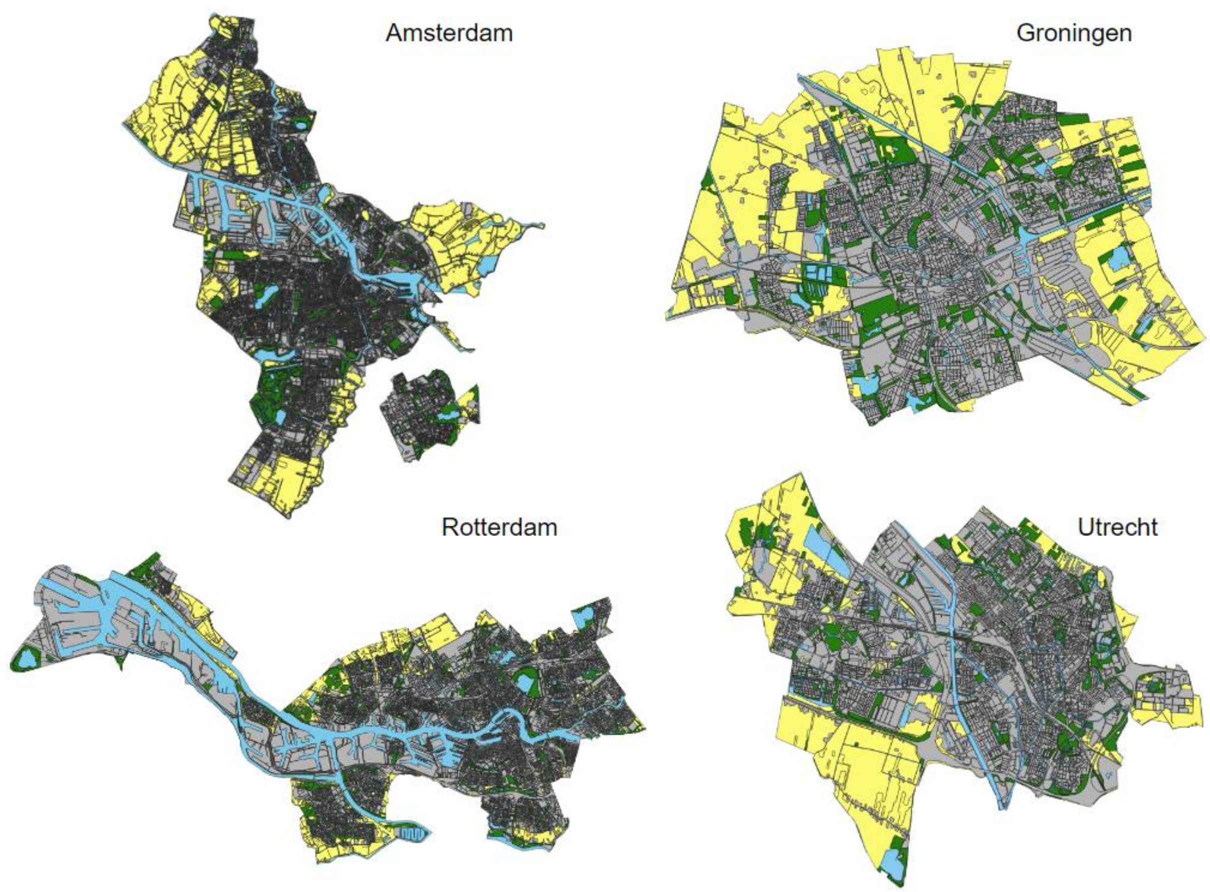

Figure 5 Land use classification within the urban centers of the case study cities. Built infrastructure marked as gray; GI marked green; Agriculture areas marked as yellow; Water areas marked as blue.

One can immediately see the disproportion of built infrastructure (gray areas) and the rest of the land use classes. This can be easily explained by the typically seen built infrastructure and population density in urban cores and as one moves outwards from the city center, more diverse land-use classes start to emerge such as bigger water bodies and agriculture designated areas. However, even from this visual one can see that GI represents a very small margin of the urban core area. In order to understand and identify it, the cities were divided into polygon (hexagon) grids and a violin plot measuring the percentage of GI cover per city per polygon was created (See

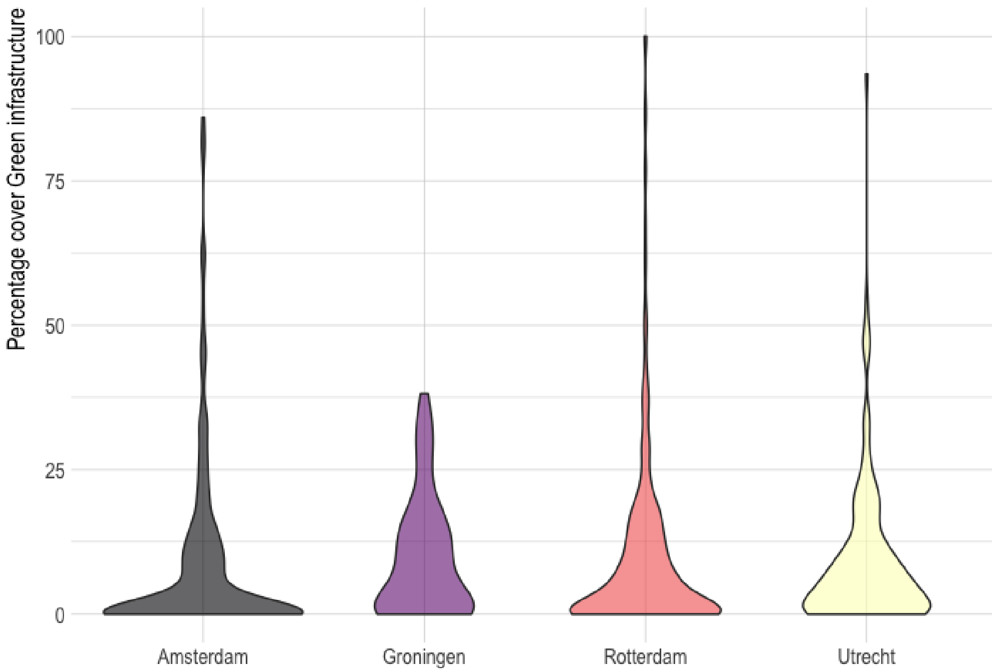

Figure 6 Violin plot showing the percentage cover of GI in polygons

Figure 6)

When looking at the percentage GI cover per polygon (Figure 6) all of the case study cities had a similar distribution at the lower parts of the plot - all cities had the majority of their GI cover occurring below 12% of the area per polygon. A notable exception is Amsterdam, which had the majority of its GI cover even below 7% per polygon. Further on, Rotterdam had a number of polygons that were almost 100% covered by GI. This was the highest score, followed by Utrecht and Amsterdam with ~90% and ~85% respectively. Thus, this shows that these cities have several patches fully covered with green areas, however, the biggest majority of GI patches do not cover big parts of the polygons. The latter was not visible in the prior maps, however, it might have an influence on the levels of connectivity and biodiversity levels in the cities. Furthermore, Groningen, compared to the other cities, had a unique distribution of GI across polygons. Just like other cities, it had the majority of GI cover less than 12% of the polygon area, however, the highest concentration of green areas per polygon was just above 35%. This means that there were no polygon patches that covered 100% or at least half of the area per polygon across the urban core of Groningen.

Patch metrics

The next step was to calculate the patch metrics by city including edge density, mean patch size, patch number, and shape index (see table 7). Further on, from table 7, we can see that Rotterdam has the highest patch number (1158) and mean patch size (3.016), followed by Amsterdam, with a patch number of 924 and mean patch size of 2.927. Additionally, Utrecht had 541 patches, while Groningen had 399. The mean patch size of these two cities was 1.671 and 2.296 respectively. It is worth noting that while Utrecht has 142 more patches than Groningen, the latter's mean patch size was bigger. Lastly, the shape index of patches shows the complexity of the patch shape. Higher shape index numbers are associated with more complex shapes of patches (which is undesirable). Rotterdam has the highest shape index of 53.891, followed by Amsterdam with a shape index of 49.984. Groningen and Utrecht had the lowest shape indexes of 34.257 and 32.391 respectively. For a more in-depth analysis of edge density and visualization of the latter for each city please refer to appendix 1.

City	Edge denisty	Mean patch size	Patch number	Shape index
Amsterdam	384.456	2.927	924	49.984
Rotterdam	364.738	3.016	1158	53.891
Groningen	452.746	2.296	399	34.257
Utrecht	430.870	1.671	541	32.391

Figure 7 Patch metrics of the four case study cities. Patch size is provided in meters

Characteristics of nodes (weight)

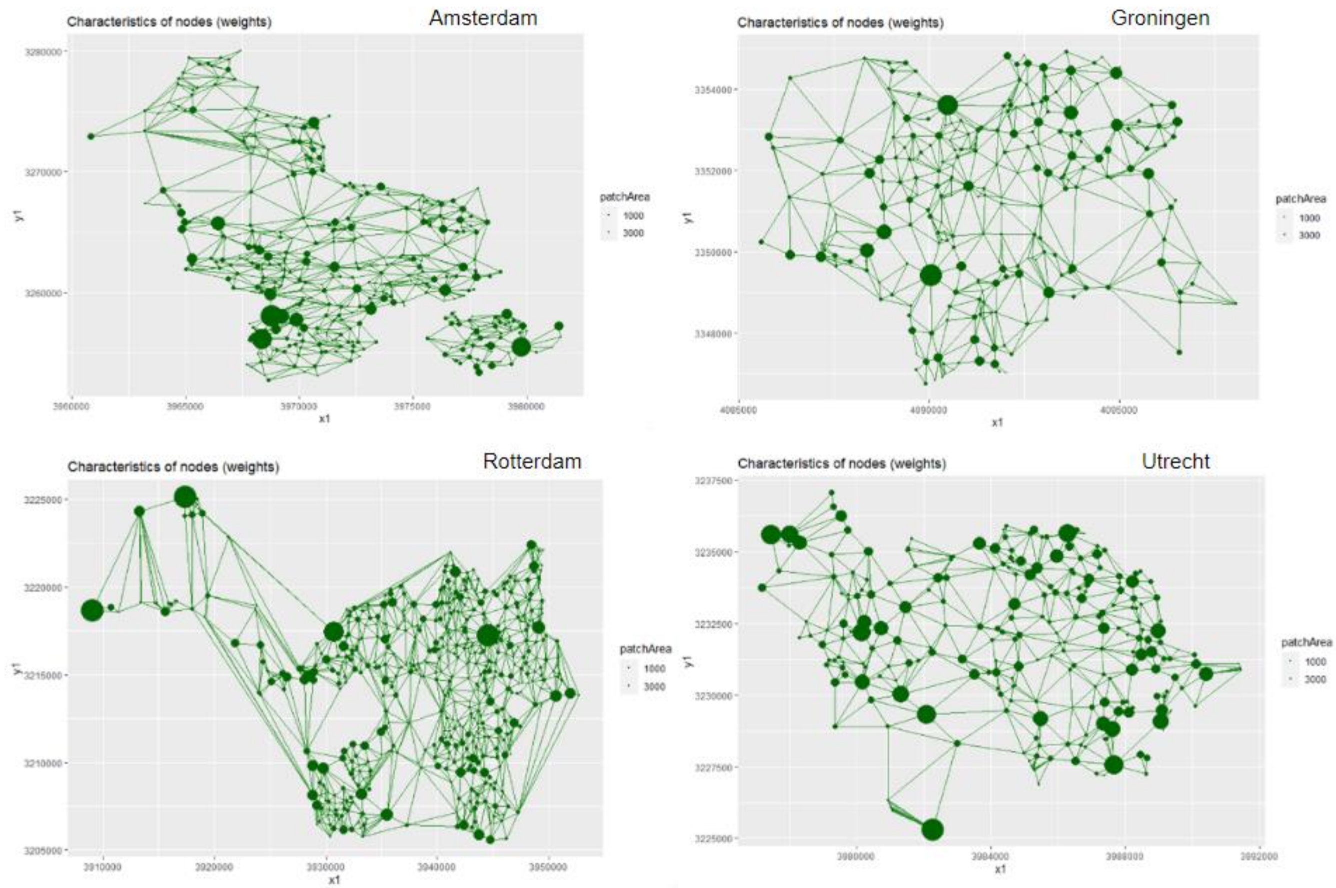

Figure 8 Complete ecological network with the shortest paths between the nodes - GI patches. Node size on the plot corresponds to the size of the patch area of GI.

The next step in connectivity analysis was to model the characteristics of nodes within the ecological networks of the case study cities (See image 8). For this study, the nodes equate to the scale of the GI patch area that each node represents.

The ecological network plots (Figure 8) further demonstrated, in line with the previously presented patch metrics findings, the size distribution across nodes and the distance of the majority of small nodes to a larger node. From visual analysis, it can be assumed that Amsterdam as well as Rotterdam have no more than 4 larger patches, while Groningen appears to only have up to 2 larger GI nodes. Utrecht on the other hand, does not seem to have significantly larger patches, but rather they are scattered quite evenly throughout the ecological network in the city. However, the latter could not be applied for Amsterdam and Rotterdam. The former seems to have most of its GI nodes, moreover, worth mentioning that those also happen to be the biggest ones, concentrated in the South-west of the city. On top of that, the North-west part of the city has a relatively small number and size of nodes, which creates a less dense and fragmented network. Furthermore, while Rotterdam has a higher node count, they are mostly concentrated towards the north of the city. Moreover, the North-west of the city seems to have fever patches, which makes the GI connectivity in the area more fragmented. Utrecht and Groningen on the other hand, have a quite uniform and evenly distributed network of GI nodes and patches, which in turn create an extensive ecological network.

Principal component analysis

For the purpose of this study, two Principal Component Analysis (PCA) were performed. Firstly, one with the distribution of patch metrics variables such as shape index, patch size, patch number and edge density across case study cities (see Figure 9). This particular PCA showcases a trend between bigger patch sizes and higher patch number mainly determined by Rotterdam metrics, while shape index and edge density are negatively correlated across cities. The PCA suggests that Rotterdam has a high patch size and number, while Utrecht has the lowest values. Meanwhile, Amsterdam has a high shape index, while the edge density is low. Groningen, on the other hand, has mirrored Amsterdam's metrics with high edge density and low shape index.

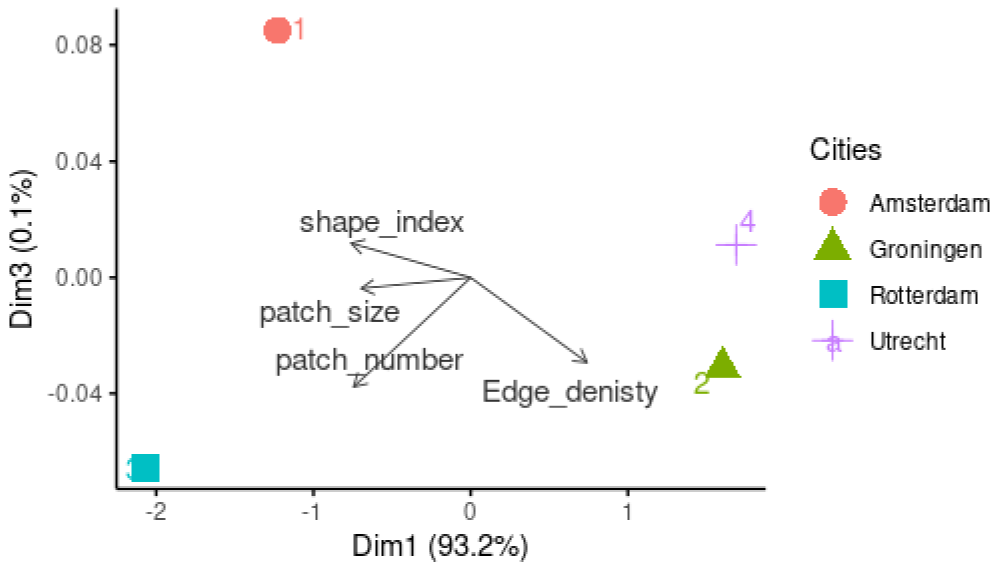

Figure 9 Principal component analysis (PCA) visualization of the first two principal components of the matrix of cities and its landscape metrics.

In the second PCA analysis, the first dimension accounted for 80.5% of the variation (Figure 10). In this case, the different biodiversity variables, as well as case study cities, were included (see figure 10). This plot draws positive correlations between the presence of mammalia, reptilia, amphibia, arthropoda and birds (i.e. aves), and plantae species. In terms of the distribution of the cities across the species diversity spectrum, Groningen and Utrecht seem to have higher diversity of all species while Amsterdam has lower presence of mammalia and reptilia species, and Rotterdam has lower amphibia, arthropoda and bird species.

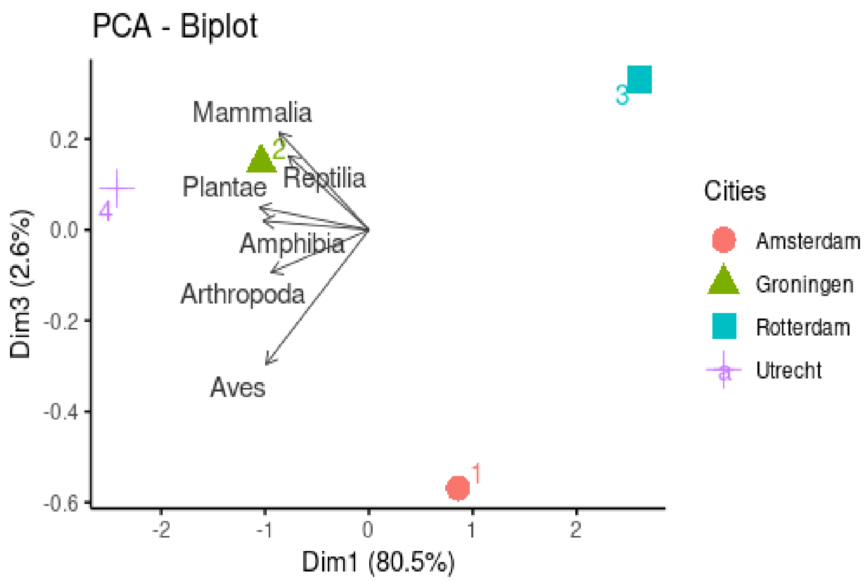

Figure 10 Principal component analysis (PCA) visualization of the first two principal components of the matrix of cities and its biodiversity.

Logistical Probability Regressions

Lastly, as the final step of GI connectivity analysis, logistical probability regressions were plotted to visualize the probability of different types of biodiversity variable categories occurring within each city. The biodiversity categories were divided based on their types of movement and home range within the ecological network of the city. It is important to note that each city has a different percentage of maximum green area cover per polygon, which has been showcased in the violin plot earlier (see figure 6), thus the PCA x axis includes the maximum percentage corresponding to each city - Amsterdam and Utrecht having above the maximum 75% coverage per polygon, while Groningen has a maximum of 40% and finally Rotterdam reaching full 100%.

The first logistical probability regression (Figure 11) focused on the probability of plantae variable occurrence in relation to the percentage of GI cover. In general, the regressions for all case study cities show an upward trend - the higher the green cover, the higher the probability of plant occurrence in the polygon for all cities. However, there is also variability among the regressions. Namely, the Rotterdam's line steadies, and the increase keeps at a low rate before even reaching the 0.50 mark (0,007; p < 0,001). While Groningen and Utrecht have nearly exponentially growing curves, the Amsterdam curve has a steady growth all throughout the regression and has statistical significance (0,029; p < 0,0001). However, it is worth noting that, Utrecht's curve starting point already begins above the o.50 mark, while Groningen's above the 0.25 mark. Nevertheless, they both reach the highest probability of plant occurrence at the same speed, and Groningen had a statistically significant result (0,194; p < 0,0001), while Utrecht did not (0,055; p < 0,001)

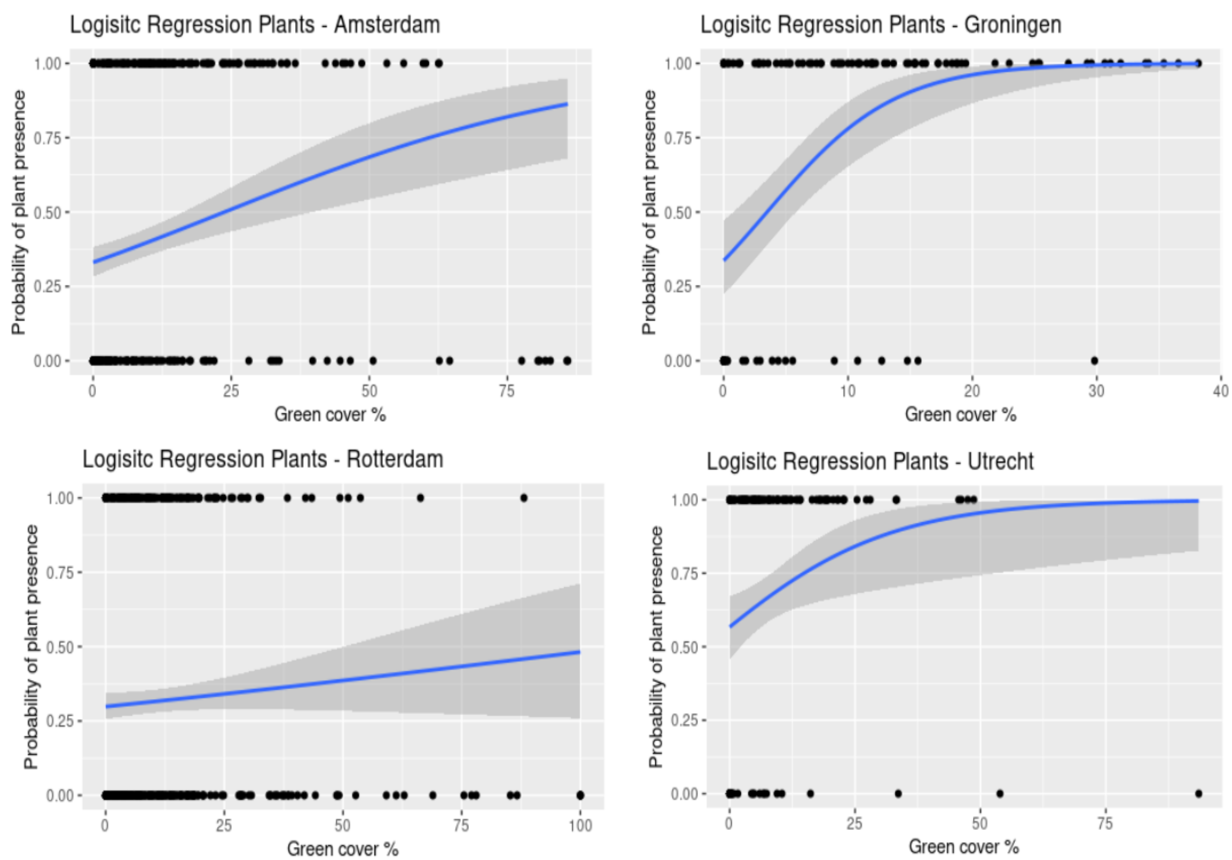

Figure 11 Graphs of the prediction using logistic regression of the presence of plant species as determined by GI cover percentage per city. Amsterdam (top left), Groningen (top right), Rotterdam (bottom left) and Utrecht (bottom right).

The second set of logistic regressions explored the probability of arthropoda species occurrence in relation to the percentage of GI cover per polygon (see image 12). These regressions show that Amsterdam and Utrecht have the lowest probability of arthropoda species occurrence

(0,004; p < 0,001). In fact, for Utrecht, the probability even lowers with the higher percentage of GI cover (0,015; p < 0,001). Rotterdam shows a steady increase, but no statistical significance, in arthropoda species occurrence with higher GI coverage (0,021; p < 0,001). Groningen on the other hand has the steepest increase in the occurrence of arthropoda from all of the case study cities and has a statistically significant result (0,193; p < 0,0001).

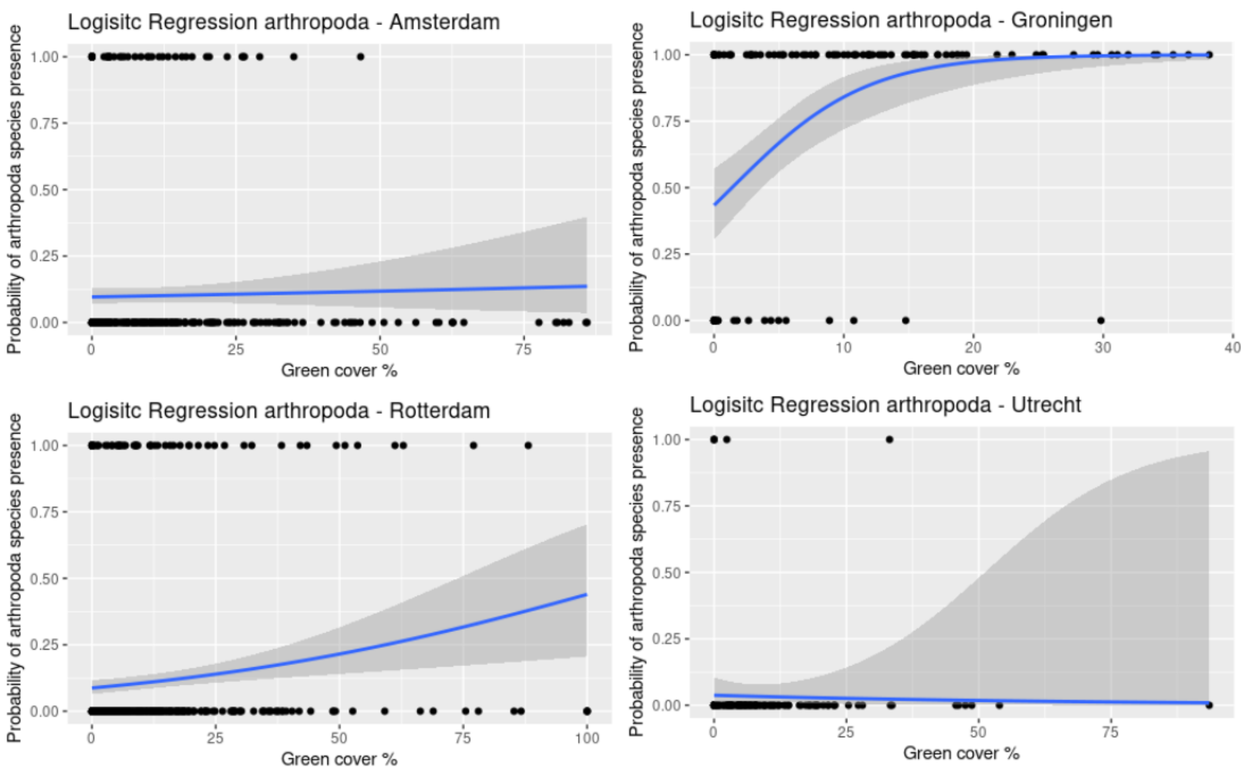

Figure 12 Graphs of the prediction using logistic regression of the presence of arthopoda species as determined by GI cover percentage per city. Amsterdam (top left), Groningen (top right), Rotterdam (bottom left) and Utrecht (bottom right).

The third set of logistic regressions explored the probability of bird (aves) species occurrence in relation to the percentage of GI cover per polygon (see figure 13). Similarly to the previous plot (see figure 12), Utrecht had the lowest and even declining occurrence possibility with an increasing percentage of the green cover (-0,015; p < 0,001). Moreover, the Rotterdam curve as well stays at a pretty steady incline, however, never reaches the 0.50 mark (0,012; p < 0,001). Groningen once again has the steepest curve incline and statistical significance of bird occurrence probability (0,010; p < 0,0001) in relation to the percentage of GI cover. Meanwhile, Amsterdam experiences a similar curve growth rate as Rotterdam, however, its starting point was higher than the latter, and it surpassed the 0.50 mark (0,011; p < 0.001).

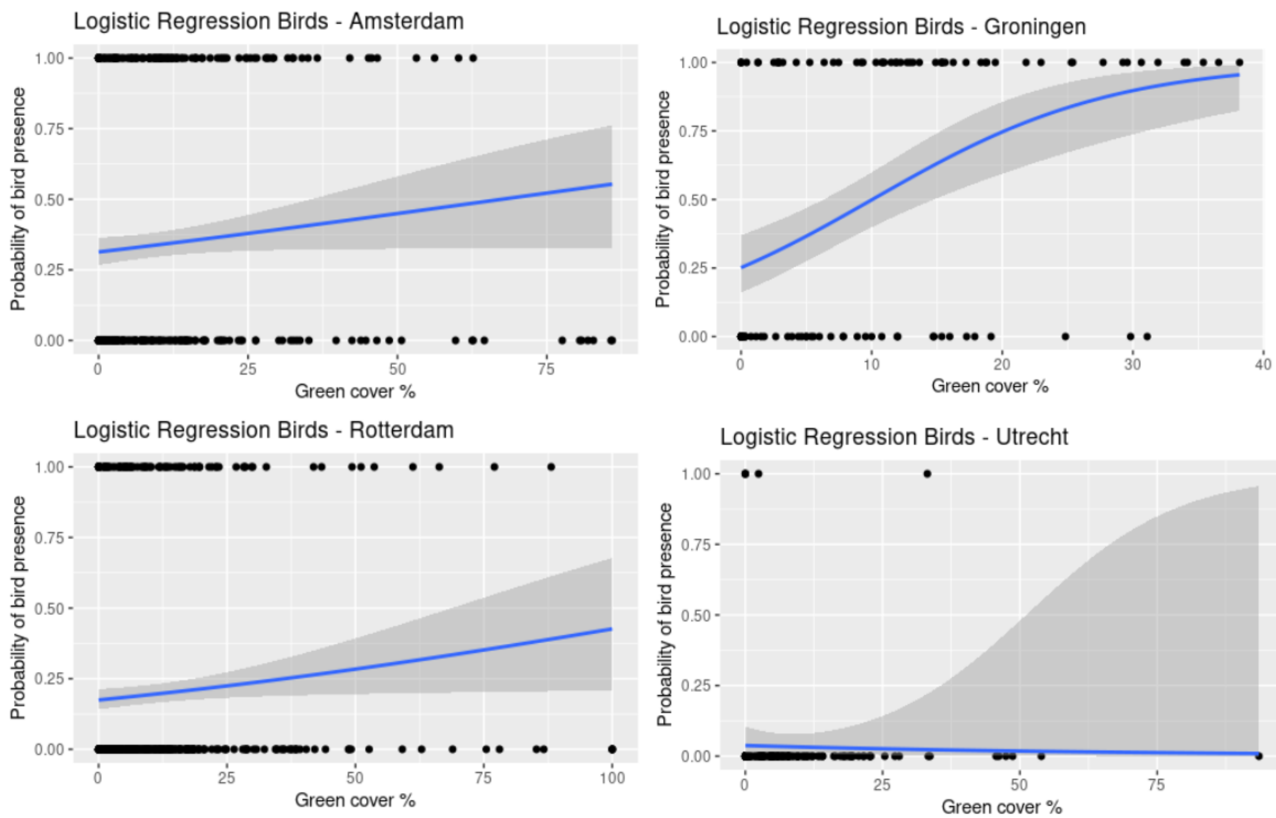

Figure 13 Graphs of the prediction using logistic regression of the presence of bird species as determined by GI cover percentage per city. Amsterdam (top left), Groningen (top right), Rotterdam (bottom left) and Utrecht (bottom right).

The fourth, and the last set of logistic regressions (see figure 14) explored the probability of the other - amphibia, mammalia and reptilia species occurrence in relation to the percentage of GI cover per polygon (see image 14). Here, Amsterdam, Rotterdam and Utrecht plots show very none or very low correlation to the probability of the other (amphibia, mammalia and reptilia) species occurrence in relation to the percentage of GI (0,008; p < 0,001 ; -0,034; p < 0,001 and 8,361; p < 0,001 respectively). However, while Groningen had the steepest curve incline, it still did not have statistically significant results (0,033; p < 0,001).

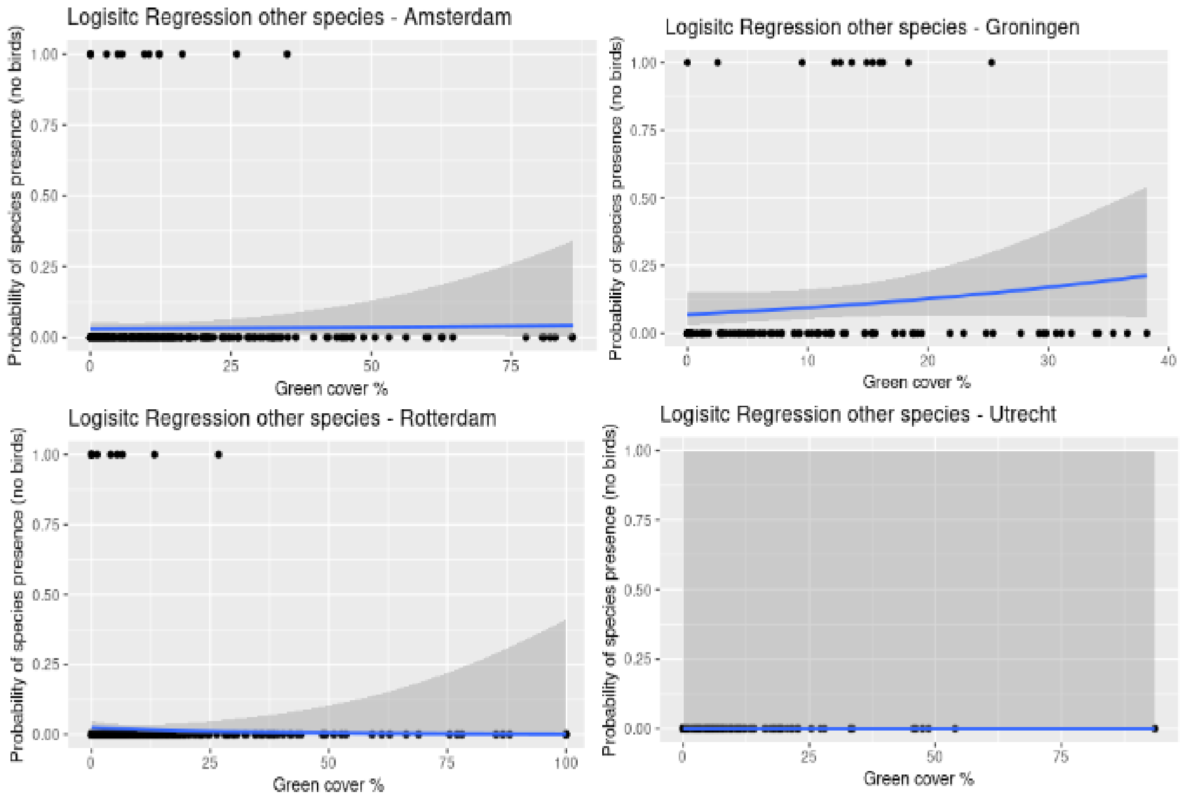

Figure 14 Graphs of the prediction using logistic regression of the presence of reptile, amphibian and mammal species as determined by GI cover percentage per city. Amsterdam (top left), Groningen (top right), Rotterdam (bottom left) and Utrecht (bottom right).

Discussion

This research aimed to assess the connectivity and fragmentation of green infrastructures (GI) in four dutch cities namely, Amsterdam, Groningen, Rotterdam and Utrecht in relation to its effect on the biodiversity levels in the cities. Moreover, the current study intended to draw links and windows of opportunities for the case study cities based on their official GI and ecological network agendas, as well as relevant literature, and the examined connectivity and biodiversity level data analyses. This research was done by analyzing available satellite land-use data as well as biodiversity data. Ultimately, the data analysis has shown a striking difference between connectivity and fragmentation of green infrastructures as well as biodiversity levels in case study cities.

Firstly, the satellite data analysis has shown that the urban core of Amsterdam had the second highest number of green area patches as well as the mean size of said GIs. This, in accordance with literature, would imply favorable conditions for biodiversity to flourish (Melliger et al., 2018; Beaugeard et al., 2020) Additionally, in some cases the green area cover reached up to 85% coverage per polygon, while the majority of GIs were scattered across the city in relatively smaller patches. However, the node weight analysis has shown that these green areas are not evenly distributed across the city. In particular, the historical center of the city as well as its North-West region, had significantly lower count of patches and ecological network connectivity. This hinders the dispersal of species across habitats and thus provides adverse effects for biodiversity (Beaugeard et al., 2020). Moreover, green areas in Amsterdam had a one of the highest shape indexes, which is unfavorable for harboring biodiversity, especially in urban environments, as the habitat patches are more exposed to the influence of the abiotic environment such as light, noise and air pollution (Driscoll et al., 2013). Furthermore, the biodiversity level analysis performed shows that Amsterdam percentages of green cover has a negative effect on of mammalia and reptile species. In addition, a more detailed biodiversity analysis shows that while the presence of Amsterdam’s GI infrastructure did increase the biodiversity of plant species, there was no significant increase in the occurrence of birds, arthropods, amphibians, mammals and reptile species. Therefore, while the initial patch metrics analysis might have shown the favorable conditions for robust ecological network and high biodiversity levels, the high shape index, and scattered green area patches with inconsistent connectivity, had a major negative effect on the biodiversity levels in Amsterdam. Therefore, having considered the latter, and looking back at Amsterdam's structural vision it becomes clear that increasing connectivity in the city is one of the most important objectives in order to create a robust and strong ecological network within a city (Gemeente Amsterdam, 2012). Thus, the removal of existing bottlenecks together with the current high patch count and area might exponentially increase the biodiversity richness as well as overall ecosystem functioning in the city.

Further on, the land-use and GI cover percentage analysis in Groningen had shown that the green areas in the urban core of the city are distributed more evenly - the majority of the GI had covered less than 25% of the polygon area, however the highest GI patch cover percentage did not exceed 35% (see violin plot). This suggested that Gronigen had a pretty well distributed network of smaller GI patches. The latter was confirmed by investigating the patch metrics table. In fact, it has shown that Groningen had the lowest count of patches as well as the second smallest mean patch size area. This would therefore suggest unfavorable conditions for biodiversity, as size and resource availability are important factors for rich biodiversity (Driscoll et al., 2013). On one hand, when looking at the ecological network depicted in the node weight characteristic map, it can be seen that most of Groningen's patches, despite their size, are pretty evenly distributed and thus support the connectivity of GI (Melliger et al., 2018). Moreover, Groningen had one of the lowest shape indexes. On the other hand,Groningen appeared to have the highest diversity of all species compared to the other cities.. More importantly, when looking at the correlation between the green cover percentage in relation to the probability of biodiversity presence, Groningen had a high statistical significance with the birds, plants and arthropods species. It is important to note that Groningen had the highest and most frequent correlations with high biodiversity levels. Thus, this shows that while Groningen did not have the presence of a large number and size of GI patches, the interplay between ecological network connectivity and shape index has highly positively influenced the presence of biodiversity. Further on, when looking back at the GreenPlan of

Groningen it becomes clear that since the GI patch size and number are harder to increase in a densely populated city, in the development plan they are tapping into one of their opting to strengthen their main current biodiversity provision asset - ecological network. The Greenplan Groningen, therefore, aims to reduce the number of bottlenecks and increase connectivity by expanding its green corridors.

Rotterdam's GI cover percentage, as well as patch metrics, were similar to that of Amsterdams. In particular, the results have concluded that Rotterdam had the highest patch numbers and mean patch size. Moreover, Rotterdam's percentage of GI patch cover per polygons was the highest among all the case study cities. This, once again should act as a predictor of high biodiversity levels (Driscoll et al., 2013). However, when looking at the negative shape index as well as node weight characteristics, it becomes apparent that, just like previously for Amsterdam, it does not necessarily mean that there is a consistent ecological network in place. The results of which can be clearly seen in the biodiversity level analysis. PCA plot, as well as logistical probability regressions, show that Rotterdam GI has a negative effect on the presence of biodiversity, and especially for bird species. Moreover, when looking at the (seeming) lack of strategic and targeted development strategies and interventions in Rotterdam, it becomes clear that there was a lost opportunity to improve the ecosystem services by creating a strong ecological network. The inspiration could be drawn from Amsterdam, which, just like Rotterdam already has a high number and size of GI patches. However, identifying the bottleneck areas and improving on habitat connectivity by strategic GI development would be the next step for both cities.

Lastly, satellite data analysis has shown that together with Amsterdam and Rotterdam, Utrecht had instances of one of the highest percentages of GI cover per polygon. However, unlike the former cities, Utrecht's patch number was second to last, while its mean patch size was the smallest among all of the case studies. Moreover, the PCA plot shows a negative correlation between the latter variables. This would, therefore, once again suggest low biodiversity levels (Driscoll et al., 2013). However, when looking at the node weight characteristic analysis, visually it seems that Utrecht might have a quite uniformly distributed network of nodes, which would suggest an ecological network. The analyses confirm the latter, Utrecht, together with Groningen has high biodiversity. However, when looking at the biodiversity analysis by category, it can be seen that while Utrecht has a similar growth curve as Groningen, the former does not show statistical significance. It is worth noting that, the other two logistical probability graphs, while they showed low correlation with the presence of biodiversity categories in relation to the green area cover, but the confidence interval being so wide might signal a biodiversity sampling bias limitation (see Limitations). Therefore, it was not possible to have any preliminary conclusions of the habitat connectivity and patch metrics analyzes in relation to biodiversity. However, it is worth mentioning that similarly to Amsterdam and Groningen, Utrecht had developed a green structure plan. In it, one of the main targets for the city is to strengthen the ecological network connectivity in the city. This goes in line with Groningen's strategy to target the habitat connectivity goals, as their patch size and numbers are already significantly lower. Therefore, by increasing the amount of green corridors, they could provide a more hospitable environment for the biodiversity to thrive or at least move throughout the city which in turn would benefit the ecosystem services and local communities as well.

In sum, the results of the analysis show that while it seems that while the patch size and number might be important, the presence of habitat connectivity and shape index of GI patches were also advantageous. It is clear that presence and interplay between all of the latter components are crucial for biodiversity richness, especially in an urban area (Melliger et al., 2018; Driscoll et al., 2013; Beaugeard et al., 2020). However, in the case of Groningen, the presence of a comparably strong ecological network that consisted of relatively smaller GI nodes as well as the presence of a positive patch shape index, seems to have majorly influenced the biodiversity richness in the city. Therefore, such green development strategies that target specifically the establishment and strengthening of the ecological network, especially when it is based on the assessment of the current ecological network state, might be one of the most effective strategies to increase biodiversity levels and strengthen the ecosystem services that GI provide.

Limitations and further research

However, it is important to mention limitations of this research. Firstly, the most recent satellite land use data was recorded in 2018, therefore the rest of the analysis has been conducted from the 2018 timeline - the biodiversity data collection included as well as records from older (published up to and including 2018) city development plans. Therefore, while this study still has valuable contributions to the field, it is important to replicate this analysis with more up-to-date data. Moreover, as mentioned earlier, while it was strived to be accounted for, the biodiversity data still had clear signs of observational bias due to inconsistent sampling. This could especially be observed when looking at Utrecht data analysis. Furthermore, this study would have benefited from more site-specific literature sources and examples of similar studies, as the research in the ecological network and habitat connectivity in urban environments in Dutch socio-economic as well as environmental is clearly lacking. Lastly, further site-specific research is needed in order to understand how and what kind of GI affects biodiversity in the cities.

Conclusion

In conclusion, the aim of this research was to assess the connectivity and fragmentation of green infrastructures in Amsterdam, Groningen, Rotterdam and Utrecht in relation to biodiversity levels. In sum, from the results of the literature review as well as data analysis on connectivity and biodiversity levels in the case study cities have provided the first connectivity analysis of Dutch cities and shown the importance of such analyses to understand the state of ecological networks, as well as its ability to provide ecosystem services in cities. This research has presented evidence of the importance of GI for biodiversity as expected, but more importantly, it has demonstrated that the number, size of patches is and a favorable shape index (e.g. small edge to core ratio per patch) greatly impact biodiversity and thus the functioning of ecological networks in cities. Therefore, while it is crucial to conduct more extensive research on this topic, this study contributes to the field as a steppingstone for further studies on habitat connectivity in urban areas.

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Appendix 1

Edge distance analysis

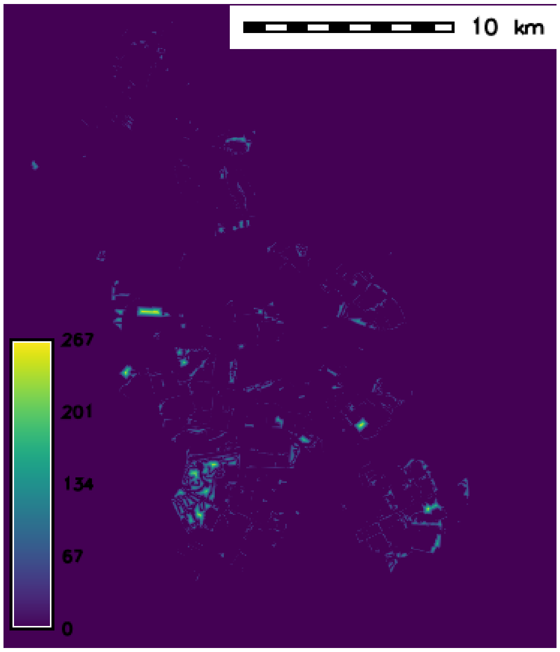


Figure X. Amsterdam Heatmap of the distance from the patch edge to its center in meters, a visualization of a city map using the latter bar color coding, and a scale bar in kilometers.

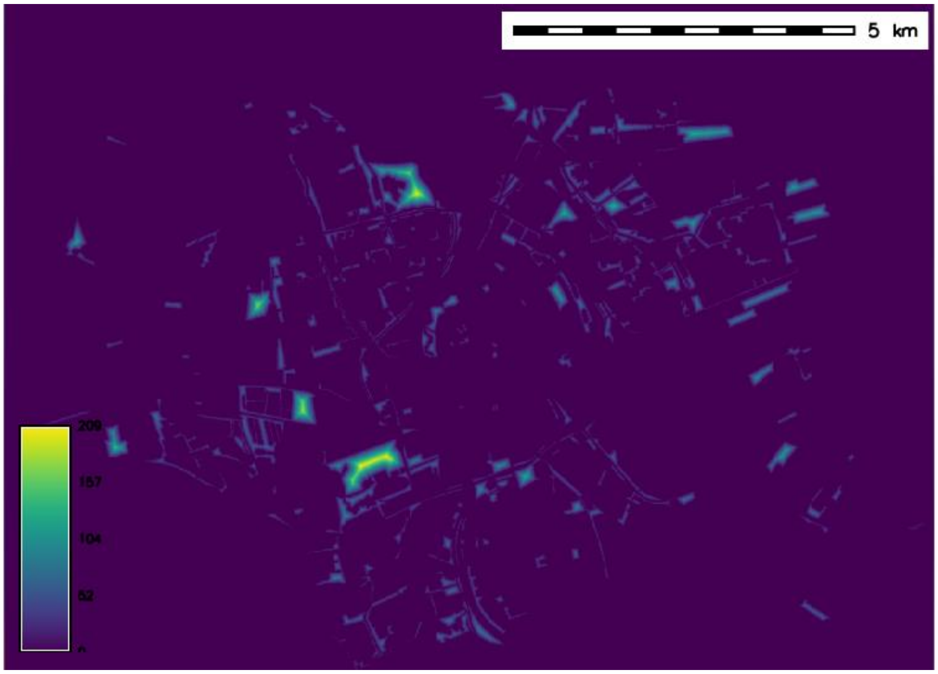


Figure X. Groningen Heatmap of the distance from the patch edge to its center in meters, a visualization of a city map using the latter bar color coding, and a scale bar in kilometers.

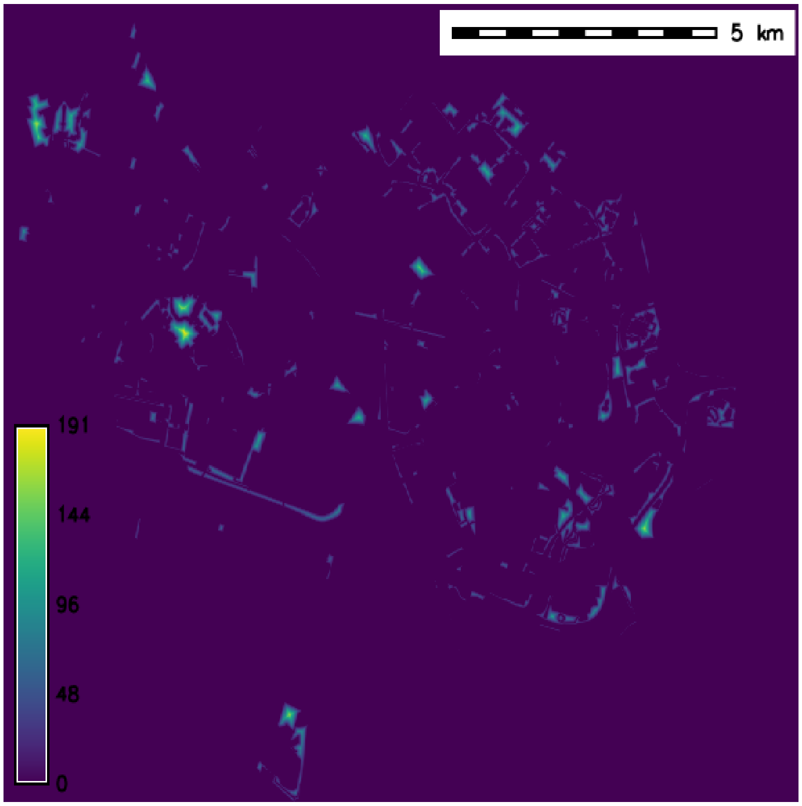


Figure X. Utrecht Heatmap of the distance from the patch edge to its center in meters, a visualization of a city map using the latter bar color coding, and a scale bar in kilometers.

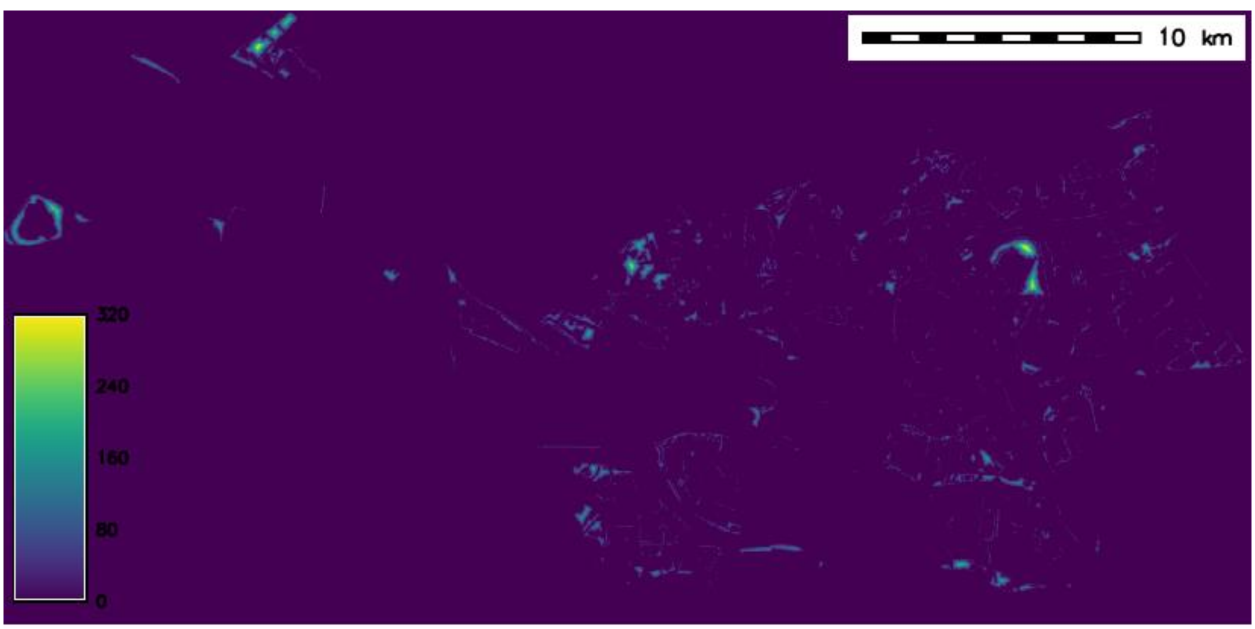
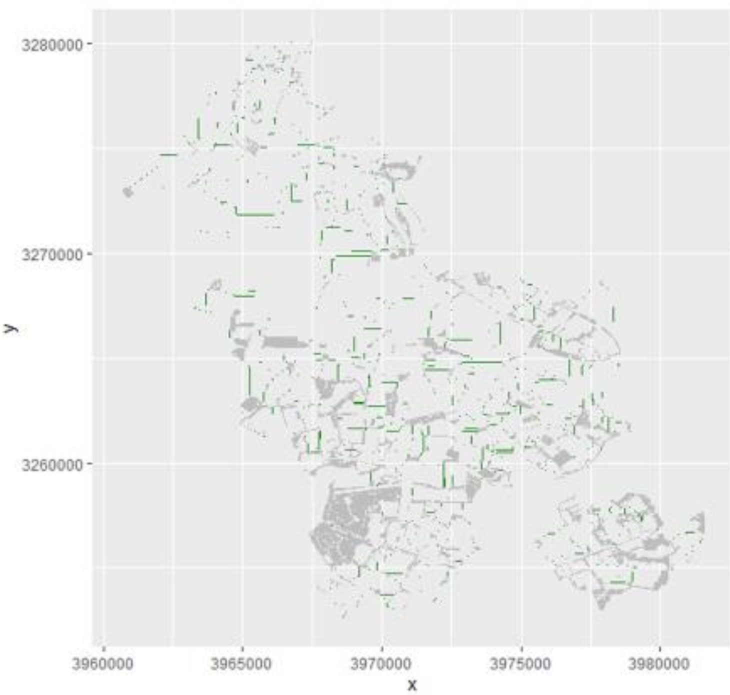


Figure X. RotterdamHeatmap of the distance from the patch edge to its center in meters, a visualization of a city map using the latter bar color coding, and a scale bar in kilometers.

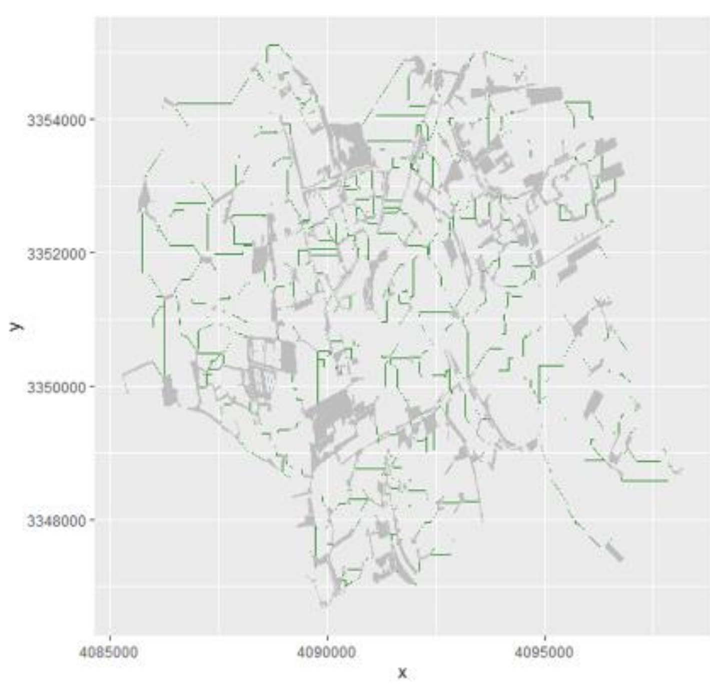
Appendix 2

Minimum planar graph (MPG)

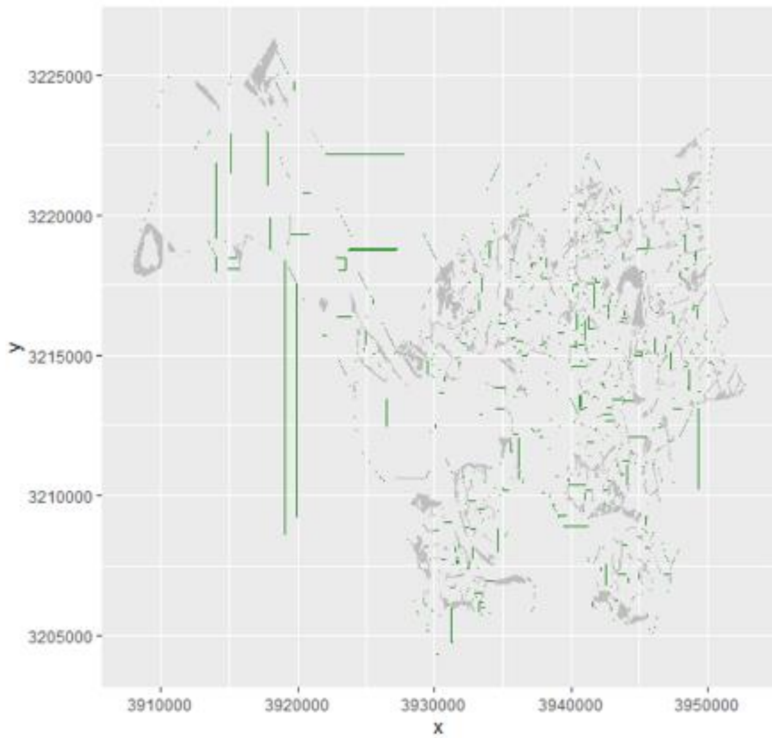
Amsterdam



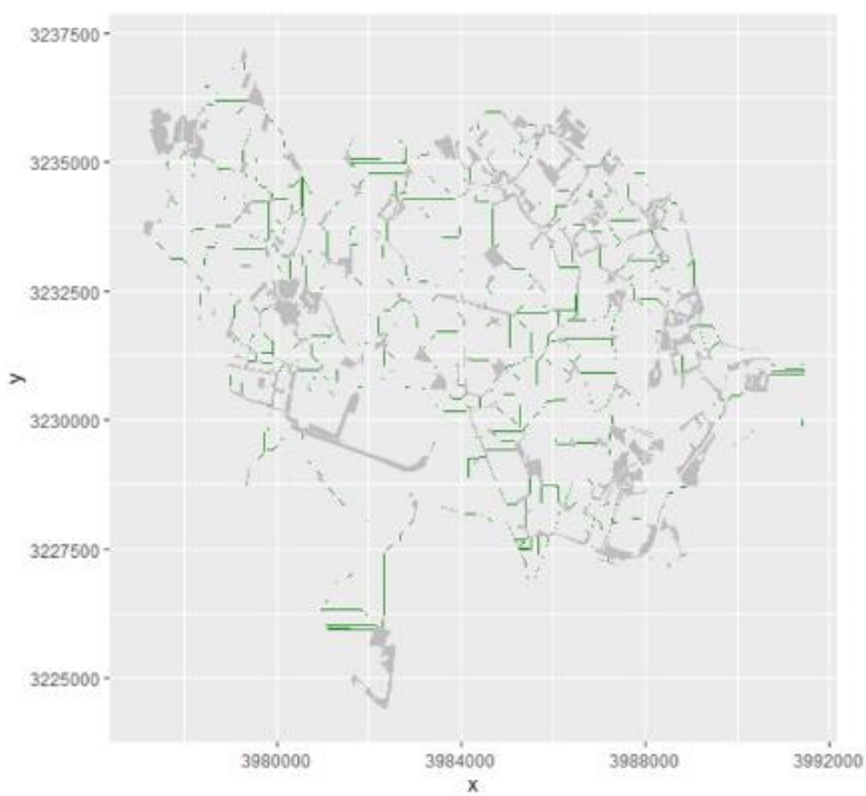
Groningen



Rotterdam

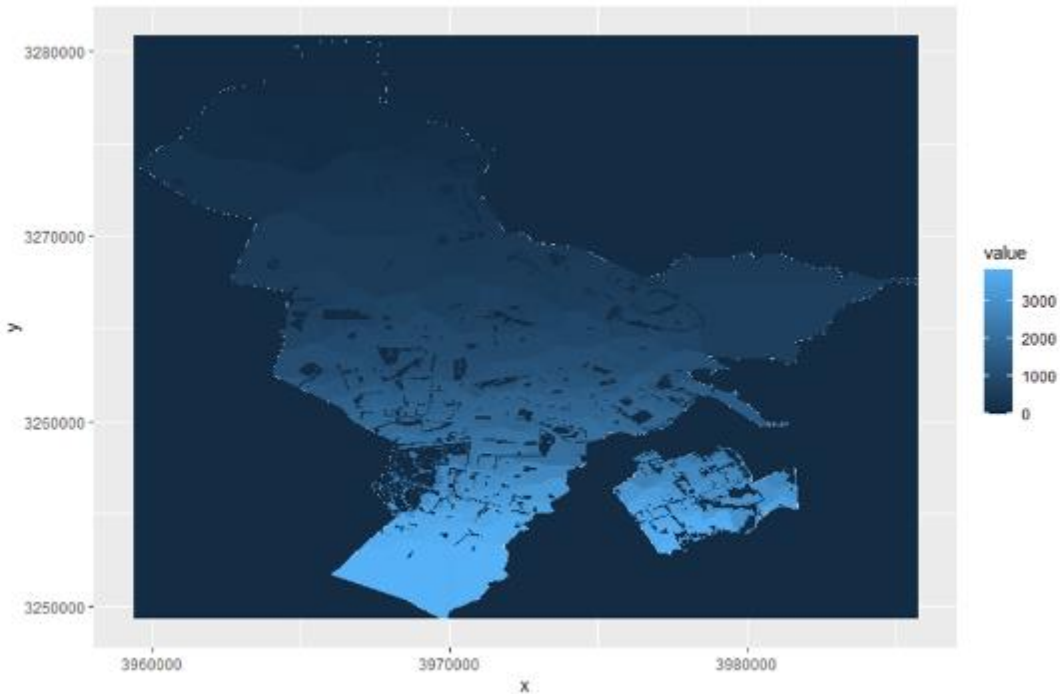


Utrecht

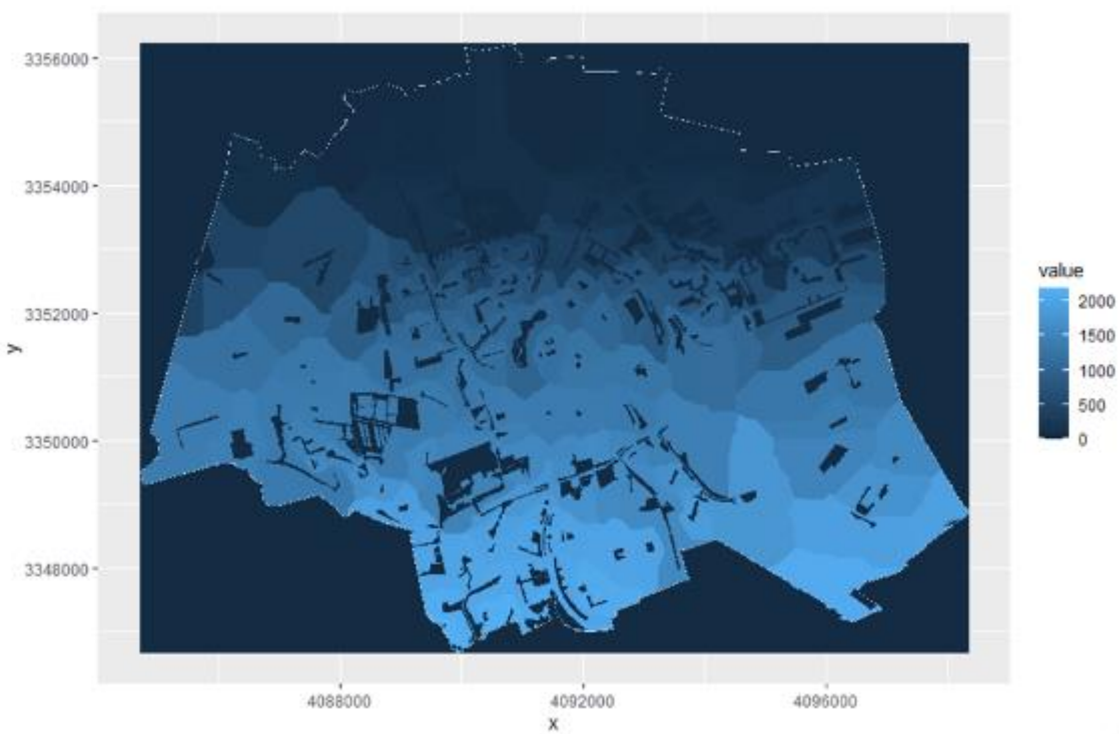


Voronoi tessellation

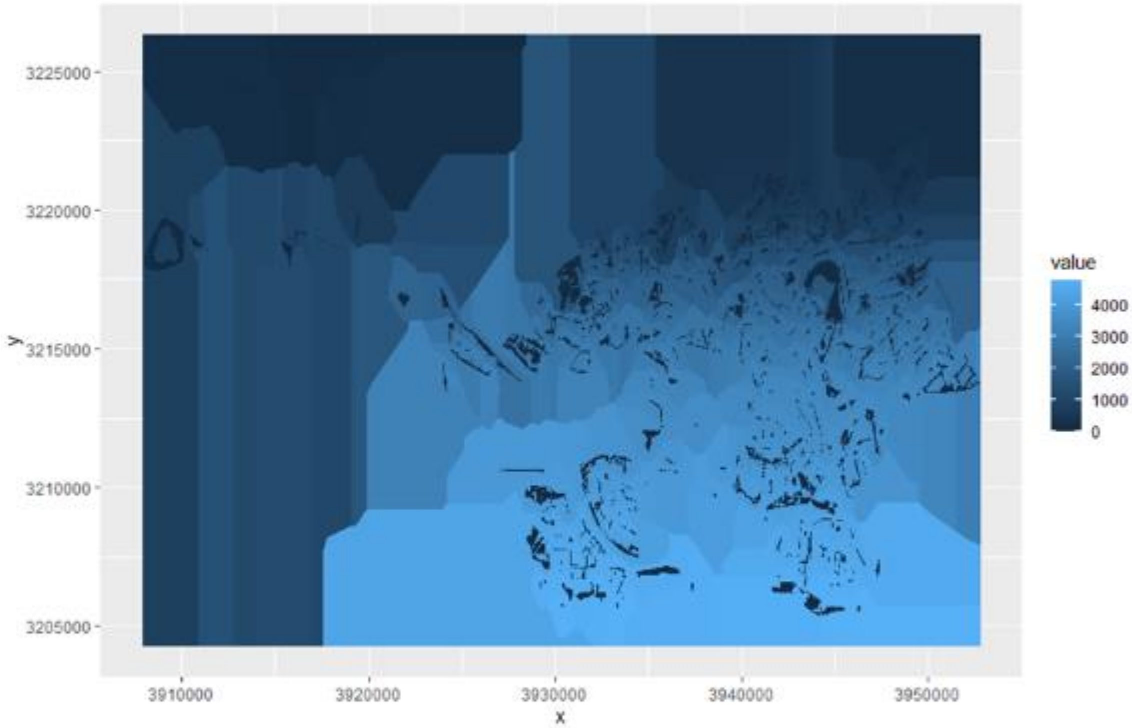
Amsterdam



Groningen



Rotterdam

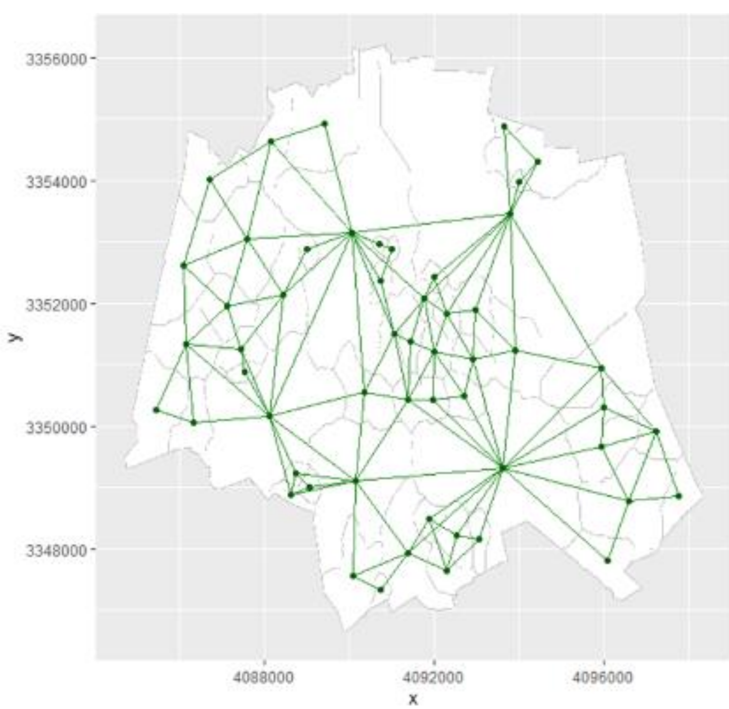


Utrecht

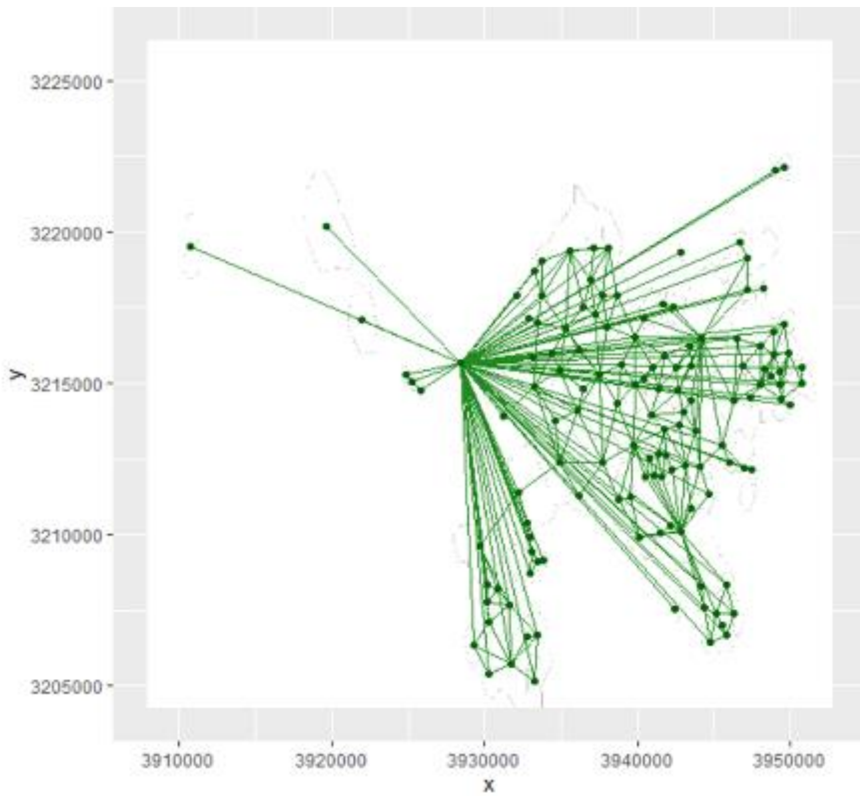
Patch grain of connectivity (GOC)

Amsterdam

Groningen



Rotterdam



Utrecht