Towards an ecological approach for sustainable urban planning: the case of the Brussels-Capital Region

Thesis submitted by Philip Stessens

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Abstract

In the last decades the population living in cities has substantially increased. According to the United Nations, by 2050 two thirds of the world population will be living in urban areas. Demographic pressure, through influx of residents or internal growth results in expansion and **densification of urban areas** and goes hand in hand with increased imperviousness, putting **pressure on the provision of urban green**. Urban green offers a range of direct and indirect benefits to the urban ecosystem. Green in the city reduces rainwater runoff and flooding risk while improving water quality; it improves air quality, provides natural cooling and contributes to reducing the urban heat island effect. Being the main source of contact with nature, urban green has also been shown to contribute to the physical and psychological wellbeing of urban citizens.

The environmental concern for **urban nature and re-naturing of cities** are thus at the heart of developing more **«ecological approaches to sustainable urban design and planning»**. In the framework of this research, it implies: understanding the (spatial) distribution of green space in relation to the built-up area of the city at different scale levels – the benefits they provide, their quality and proximity for urban residents – and; how to develop **diagnostic, analytical and projective capabilities** aimed at improving their (urban green) provision to address a host of sustainability challenges related to climate change, demographic growth and densification of the urban area. The research focuses on the development of **evidence-based** frameworks for planning that incorporate citizens' needs and that are built on an **interdisciplinary** foundation. With this scope and focus, this study contributes to the development of a more ecological framework for sustainable urban design and planning aimed at integrating nature in the city more effectively and in an evidence-based way.

The first part of the research focuses on the development of a **spatially explicit tool for green space quality and proximity assessment** reflecting user's perception. Application of the model in the **Brussels** context reveals that user's perception of qualities of urban green spaces such as naturalness and spaciousness can be linked to green space characteristics as described by available GIS-based data. As such GIS-based modelling allows for an extrapolation of questionnaire-based quality assessments for a selection of parks to other public green spaces. Analysis of the proximity of urban green spaces based on user's perception shows **spatial**

inequalities in green space provision, with less than 50% of Brussels' citizens having good access to small (residential and play green) and to large green spaces (city and metropolitan green). By coupling multi-scale proximity assessment with quality assessment of green spaces, it is demonstrated that nearly two third of the Brussels population has no access to high quality public green spaces. Through collaborative **research by design** workshops involving different stakeholders, indicators produced by the quality-proximity model are used to indicate and tackle problem areas. Three **alternative scenarios** for public green space development are defined. The scenario analysis demonstrates that actions to provide low-income neighborhoods with a good accessibility to public green spaces will require creative solutions, dealing with complex property and management issues, and levels of investment that go well beyond the cost of regular green space development.

The second part of the study presents a GIS- and design-based approach to **assess potential land cover change** for the Brussels-Capital Region **anticipating expected population growth**. The methodology proposed can be used to assess the impact of spatial policies and the implementation of building codes on future urban land cover. By studying the everyday processes for parcel infill and densification, and by defining a **densification process** based on the principles of **sustainable urban design** (e.g., walkable and high-density urban areas near mobility hubs, compact building typologies, preserving valuable natural areas, creative approaches to increasing the provision of urban green (green roofs, bioswales, etc.) space for water and floodscapes, etc.), two **land use evolution scenarios** are formulated; a business-as-usual and a sustainable scenario. One of the main conclusions of the case study on the Brussels-Capital Region is that densification can be deployed as a vehicle for positive land cover change and greening of the city.

Résumé

Au cours des dernières décennies, la population urbaine a considérablement augmenté. Selon les Nations Unies, d'ici 2050, deux tiers de la population mondiale vivra dans des zones urbaines. La pression démographique, due à l'afflux de population et à la croissance interne, entraîne un **étalement et une densification des zones urbaines** qui va de pair avec une étanchéification accrue des sols, ce qui exerce une **pression sur la pression sur la quantité d'espaces disponibles verdurisables**. Les espaces verts urbains offrent des avantages directs et indirects à l'écosystème urbain concernant le ruissellement des eaux de pluie, risques d'inondation, la qualité de l'air, et l'effet d'îlot de chaleur urbaine. En tant que source principale de contact avec la nature, les espaces verts contribuent également au bien-être physique et psychologique des citadins.

Les préoccupations environnementales liées à la **nature urbaine et à la re-verdurisation des villes** sont donc au cœur du développement d'**«approches écologiques de conception et de planification urbaines durables»**. Dans le cadre de cette recherche, cela implique: de comprendre la répartition (spatiale) des espaces verts par rapport aux zones bâties de la ville à différents échelles - les avantages qu'ils offrent, leur qualités et leur proximités pour les citadins, et; de développer des moyen de **diagnostics, des analyses et des projections** visant à améliorer l'offre en espaces verts afin de relever un grand nombre de problématiques de durabilité liées au changement climatique, à la croissance démographique et à la densification de la zone urbaine. La recherche porte sur l'élaboration d'une perspective de planification **fondée sur des données factuelles** qui prennent en compte les besoins des citoyens et qui reposent sur un corpus **interdisciplinaire**. Grâce à sa portée et à son orientation, la présente étude contribue à l'élaboration d'un cadre plus écologique pour la conception et la planification urbaine durable tout en visant à intégrer la nature dans la ville plus efficacement dans une démarche scientifique.

La première partie de la recherche porte sur le développement d'un **outil spatialement explicite qui fait l'évaluation de la qualité et de la proximité des espaces verts** en reflétant la perception de l'utilisateur. La mise en application du modèle dans le contexte **bruxellois** révèle que la perception des utilisateurs quant aux qualités des espaces verts urbains, tels que la naturalité ou la notion d'espace, peut être liée à des caractéristiques d'espaces verts qui sont interprétable via des données

spatiales déjà disponibles. La modélisation, basée sur les Systèmes d'Informations Géographiques (SIG), permet donc d'extrapoler les évaluations de la qualité (basées sur des questionnaires pour une sélection de parcs) à d'autres espaces verts publics. L'analyse de la proximité d'espaces verts urbains basée sur la perception des utilisateurs montre des **inégalités spatiales** dans l'offre d'espaces verts: moins de 50% des Bruxellois ont un bon accès aux espaces verts. En associant une évaluation de proximité multi-échelle à une évaluation de la qualité des espaces verts, il est démontré que près des deux tiers de la population bruxelloise n'ont pas accès à des espaces verts publics de haute qualité. Grâce à des **exercices réalisés via des méthodes de 'research by design'** impliquant différents acteurs, les indicateurs produits sont utilisés pour désigner et offrir des solutions à des zones problématiques. Trois **scénarios alternatifs** pour le développement d'espaces verts publics sont définis pour Bruxelles. L'analyse de scénarii montre que les mesures visant à fournir aux quartiers à faible revenu une bonne accessibilité aux espaces verts publics nécessiteront des solutions créatives, abordant des problèmes complexes de propriété et de gestion, ainsi que des niveaux d'investissement allant bien au-delà des coûts classique de développement d'espaces verts.

La deuxième partie de l'étude présente une approche basée sur les SIG et la conception architecturale et urbaine pour **évaluer les changements potentiels de l'occupation des sols** dans la Région de Bruxelles-Capitale en **anticipant la croissance démographique attendue**. La méthodologie proposée peut être utilisée pour évaluer l'impact des politiques d'aménagement du territoire et des codes du bâtiment sur l'occupation des sols urbains. En étudiant les processus quotidiens de densification et en définissant un **processus de densification** basé sur les principes de la **conception urbaine durable** (zones urbaines piétonnières et des zones à haute densité à proximité de pôles de mobilité, des typologies de construction compactes, une préservation de zones naturelles de grande valeur, des espaces pour l'eau et les zones inondables, des approches créatives pour augmenter l'offre de végétation par des toits verts, des bassins d'infiltration, etc.), deux **scénarii de l'utilisation des sols** sont formulés; un scénario de statu quo et un scenario durable qui maximise l'offre en espace verts sur Bruxelles compte tenus des limitations de l'environnement bâti. L'une des principales conclusions de l'étude de cas sur la région de Bruxelles-Capitale est que la densification peut être utilisée comme un moyen de modifier positivement l'occupation des sols et de rendre la ville plus verte.

Samenvatting

In de laatste decennia is de bevolking in steden aanzienlijk toegenomen. Volgens de Verenigde Naties zal tegen 2050 twee derde van de wereldbevolking in stedelijke gebieden wonen. Demografische druk, door instroom van bevolking of interne groei resulteert in **expansie en verdichting van stedelijke gebieden** en gaat hand in hand met een afdichting van de grond, waardoor de **voorziening van stedelijk groen onder druk komt te staan**. Stedelijk groen biedt een scala aan directe en indirecte voordelen voor het stedelijk ecosysteem. Het vermindert regenwaterafvoer en overstromingsrisico's terwijl de waterkwaliteit wordt verbeterd. Het verbetert de luchtkwaliteit, zorgt voor natuurlijke koeling en draagt bij aan het verminderen van het stedelijk hitte-eilandeffect. Als belangrijkste bron van contact met de natuur voor inwoners draagt stedelijk groen ook bij aan fysiek en psychologisch welzijn.

De **stedelijke natuur en vergroening van de stad** staan dus centraal in de ontwikkeling van meer **«ecologische benaderingen van duurzaam stedenbouwkundig ontwerp en stedenbouw»**. In het kader van dit onderzoek houdt het in: inzicht in de (ruimtelijke) verdeling van groene ruimten in relatie tot het stedelijk gebied op verschillende schaalniveaus - de voordelen die ze bieden, hun kwaliteit en nabijheid voor inwoners - en; hoe **diagnostische, analytische en projectieve capaciteiten** te ontwikkelen die gericht zijn op het verbeteren van de voorziening (van stedelijk groen) om een groot aantal duurzaamheidsuitdagingen aan te pakken met betrekking tot klimaatverandering, demografische groei en verdichting van het stedelijk gebied. Het onderzoek richt zich op de ontwikkeling van en '**evidence-based**' kader voor planning dat op een **interdisciplinaire** manier rekening houdt met behoeften van inwoners. Met deze 'scope' en focus draagt deze studie bij tot de ontwikkeling van een meer ecologisch kader voor duurzaam stedenbouwkundig ontwerp en planning gericht op een effectievere en meer 'evidence-based' integratie van natuur in de stad.

Het eerste deel van het onderzoek richt zich op de ontwikkeling van een **ruimtelijk expliciete tool voor de beoordeling van kwaliteit en nabijheid van publieke groene ruimten** die de perceptie van de gebruiker weerspiegelt. Toepassing van het model in de **Brusselse** context laat zien dat perceptie van kwaliteiten zoals natuurlijkheid en ruimtelijkheid kan worden gekoppeld aan groene ruimte-karakteristieken zoals beschreven door beschikbare GIS data. Zodoende biedt GIS modellering een mogelijkheid tot extrapolatie: van enquête-analyse van een selectie van publieke groene ruimten naar een interpretatie van het gehele studiegebied. Analyse van de nabijheid van stedelijke groene ruimten op basis van de perceptie van de gebruiker toont de **ruimtelijke ongelijkheden** in de voorziening, waarbij minder dan 50% van de Brusselaars een goede toegang hebben tot kleine (woon- en speelgroen) en tot grote groene ruimten (stads- en metropolitaan groen). Door het koppelen van multi-scale nabijheidsbeoordeling met kwaliteitsbeoordeling van groene ruimten, wordt aangetoond dat bijna twee derde van de Brusselse bevolking geen toegang heeft tot openbaar groen van hoge kwaliteit. Door middel van collaboratieve '**research by design**' workshops waarbij verschillende belanghebbenden zijn betrokken, worden geproduceerde nabijheids-kwaliteits-indicatoren gebruikt om probleemgebieden aan te wijzen en aan te pakken. Er worden drie **alternatieve scenario's** voor ontwikkeling van publieke groene ruimte gedefinieerd. De scenario-analyse toont aan dat acties om buurten met een laag inkomen te voorzien van een goede toegankelijkheid van publieke groene ruimten creatieve oplossingen vereisen die te maken hebben met complexe vastgoed- en beheerskwesties, maar ook met investeringsniveaus die veel verder gaan dan de kosten van doorsnee groene ruimteontwikkeling.

Het tweede deel van de studie presenteert een GIS- en ontwerp-gebaseerde benadering om **mogelijke veranderingen in landbedekking** voor het Brussels Hoofdstedelijk Gewest te beoordelen, **anticiperend op verwachte bevolkingsgroei**. De voorgestelde methode kan worden gebruikt om de impact van ruimtelijk beleid en de bouwvoorschriften op bodembedekking te evalueren. Door de business-as-usual processen voor het opvullen en verdichten van percelen te bestuderen en door een **verdichtingsproces** te definiëren op basis van de principes van **duurzaam stedenbouwkundig ontwerp** (bijvoorbeeld toegankelijke en dichtbevolkte stedelijke gebieden nabij mobiliteitshubs, compacte gebouwtypologieën, behoud van waardevolle natuurgebieden, ruimte voor water en overstromingsgebieden, creatieve benaderingen om het aanbod van stedelijk groen te verbeteren – groene daken, wadi's, enz.), worden twee **scenario's voor landgebruikevolutie** geformuleerd; een business-as-usual en een duurzaam scenario. Een van de belangrijkste conclusies van de casestudy over het Brussels Hoofdstedelijk Gewest is dat verdichting kan worden ingezet als een vehikel voor positieve veranderingen in landbedekking en vergroening van de stad.

Publications and (conference) presentations

Peer-reviewed publications

Stessens, P., Khan, A. Z., Huysmans, M., & Canters, F. (2017). Analysing urban green space accessibility and quality: A GIS-based model as spatial decision support for urban ecosystem services in Brussels. Ecosystem Services, 28, 328-340. doi: https://doi.org/10.1016/j.ecoser.2017.10.016

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1 Introduction

1.1 Research context

How can we define urban green space quality in a way that reflects the way urban citizens value public green spaces? How can we incorporate information on the quality and provision of urban green in evidence-based tools for planners, and how can such tools assist policy makers, key actors and stakeholders in taking better informed planning and policy decisions? And finally, how can we evaluate the impact of future planning and policy scenarios on urban land-cover characteristics that affect regulatory ecosystem functions (e.g. water and urban climate regulation)? These general questions frame the work that is being presented in this manuscript with the ambition to contribute towards more ecological approaches for sustainable urban planning that are scientific and evidence-based. As such, the work is situated on the crossroads of several disciplines (landscape architecture, civil engineering, urban design and planning, and geography) related to urban resilience and urban environmental quality.

1.1.1 *Focus of the research*

Planning has evolved from a traditional system that involves closed processes based on regulation, to the provision of more strategic frameworks, which involve a larger number of decision units; from managing growth to sustainable development (Albrechts and Alden 2001). Within the broader transition to sustainable development, a main trajectory exists that concerns ecology and the re-naturing of the city. The interest in nature and ecological approaches in contemporary urbanism is evidenced by the proliferation of manifestoes and discourses – such as landscape urbanism (Waldheim 2006) or ecological urbanism (Mostafavi and Doherty 2016). Such manifestos have advocated the dawn of a new age of rethinking urbanism, but are mostly normative, theoretical, or design thinking based. For cities to tackle their challenges, a participative, interdisciplinary and evidence-based approach is needed. This research aims to contribute to the ongoing rethinking of urban design and planning, by emphasizing the need for including evidence-based approaches addressing the role of nature in the city in urban planning practices. This work focuses on urban green and on the potential of spatial analysis and modeling in GIS, statistical analysis, citizen participation through public inquiry (surveys and questionnaires), and stakeholder involvement in research-by-design and scenarios development as methodological approaches for supporting evidence-based planning. The thesis investigates how to mobilize these different approaches to bring the natural and the urban in a closer synergy and contribute to the building up of a more ecological framework for sustainable urban design and planning.

1.1.2 *An ecological approach to sustainable urban design and planning*

The environmental concern for urban nature and re-naturing cities is at the heart of developing more ecological approaches to sustainable urban design and planning. The environmental design disciplines (architecture, urban design, planning, landscape architecture) have an important role in developing such approaches in the quest for sustainability. They have contributed to the environmental crisis by wastefulness of space and resources, but can also be an effective agent for positive change (Buchanan 2008). Most of these approaches are conceptualized in the framework of sustainable urbanism - a comprehensive definition of which was given by Camagni (1998) as "a process of synergetic integration and co-evolution among the great subsystems making up a city (economic, social, physical and environmental), which guarantees the local population a non-decreasing level of wellbeing in the long term, without compromising the possibilities of development of surrounding areas and contributing by this towards reducing the harmful effects of development on the biosphere". Sustainable urbanism envisions, on the one hand, "walk-able and transit-served urbanism integrated with […] high-performance infrastructure" (Farr 2011), while on the other hand, density and human access to nature are considered as the core values of sustainable urbanism (Roggema 2016). It involves increasing sustainability through density, integrating transportation and land use, linking humans to nature by providing walk-to open spaces, neighborhood storm water systems and waste treatment, etc. (Farr 2011). It is seen as a responsive form of urbanism, where human impact on the natural system is mitigated and (climate) adaptation includes natural processes (Farr 2011). For the New Urban Agenda, adopted by the United Nations Conference Habitat III in 2016, sustainable urbanization includes equity and social justice and is considered as a powerful tool for sustainable development (UN General Assembly

2016). Among the various approaches, strategies and agendas for sustainable urbanism, we can discern multiple points of views, emphasizing various dimensions of sustainability related to urbanization and urban systems. While recognizing the importance of these various dimensions, the **scope** of this research, which seeks to contribute to the development of an 'ecological approach to sustainable urban design and planning' implies: understanding the (spatial) distribution of green spaces in relation to the built-up area of the city at different scale levels – the benefits they provide, their quality and proximity for urban residents – and; how to develop diagnostic, analytical and projective capabilities aimed at improving urban green provision to address a host of sustainability challenges related to climate change, demographic growth and densification of the urban area. With this scope, the main focus of this study is thus on urban green.

1.1.3 *Urban green*

The absence of a shared definition of urban green is a barrier to the generalization of empirical studies (Le Texier, Schiel et al. 2018). In this study, urban green is defined in the broadest possible sense, from private backyard plants to small public and non-public green spaces, to larger parks and urban forests. The 'urban' part in the definition points to its proximity to humans and the idea that this green and these green spaces are part of the urban ecosystem, which is "a complex, constituted by the biological (e.g. plants, animals) and physical components (e.g. soil, water, climate) of a natural ecosystem, along with human populations, their cultural and societal relations, and infrastructure, and environmental alterations stemming from human decision making" (Pickett and Rafferty 2011). As such, the natural features interact with altered material fluxes (e.g. less infiltration, pollution) and human values. Urban green is part of multiple conceptual frameworks, e.g. green infrastructure (Tzoulas, Korpela et al. 2007), urban forestry (Konijnendijk 2003), urban ecosystem services (Elmqvist, Fragkias et al. 2013), and is instrumental in nature-based solutions. The intention in this work, however, is not to subscribe to a predisposed framework. Urban green 'spaces' are in this work considered as spatial realms, which a person can enter, and which mostly have natural features. They can be close to wild nature, or have a cultivated, ornamental appearance. Public urban green spaces are the publicly accessible sub-category of these, whether they are subject to opening times or not.

When the focus in this study is on purely physical aspects (not related to human values or biological characteristics), urban green may also refer to green land cover, which e.g. includes gardens, green roofs, or street green. Now the definition begs the question: why does urban green matter and how is it related to the challenges of today's cities?

1.2 Problem statement
— The importance of urban green and its role in urban planning and policymaking

In the last decades the world population has become more urban. According to the United Nations, by 2050 two thirds of the world population will be living in urban areas (UN 2012). Urban green is the main source of contact with nature for urban citizens. In various ways, urban green has been proven to provide multiple benefits to people (De Ridder, Adamec et al. 2004, Elmqvist, Fragkias et al. 2013) that contribute to essentials such as health and psychological wellbeing, which makes contact with urban green a significant component of quality of life. This is not only the case for public green spaces, but also for urban green as land cover, as it can deliver different, though equally relevant benefits (Connop, Vandergert et al. 2016, Francis and Jensen 2017). However, the role of urban green in the urban ecosystem is often undervalued (Young 2011). Especially in compact cities the provision of urban green space is a major challenge (Haaland and van den Bosch 2015). For example, public green spaces are often easier to access for more affluent communities, as revealed in several studies (Van Herzele, De Clercq et al. 2004, Kabisch and Haase 2014, Ferguson, Roberts et al. 2018, Nesbitt, Meitner et al. 2019). Since density and human access to nature are considered as core values of sustainable urbanism (Roggema 2016), equal spatial distribution of urban green is an important component for sustainable urban planning (Farr 2011).

Two particular pressures on the urban environment generate negative impacts, which are a challenge for sustainable urban planning to tackle. Demographic pressure, through influx of residents or internal growth results in expansion and densification of the urban tissue. In general, urban growth goes hand in hand with increased imperviousness (Phinn, Stanford et al. 2002, Van de Voorde, Jacquet et al. 2011), leading to less urban green (public and non-public), increased runoff of rainfall which can cause flood events, and decreased biodiversity (Arnold and Gibbons 1996, De Bondt and Claeys 2010, Strohbach, Döring et al. 2019). Moreover, the presence of impervious materials increases the heat storage capacity of the urban fabric. This, in combination with the absence of natural cooling through shading and evapotranspiration by vegetation, intensifies the urban heat island effect (Reder, Rianna et al. 2018). The second pressure, climate change, which generates more intense rainfall and more frequent heat wave events, aggravates the negative impacts of demographic pressure (Wilby and Perry 2006, Gill, Handley et al. 2007, Kabisch and van den Bosch 2017, Reder, Rianna et al. 2018). These are just a few consequences that may have a direct impact on the health of urban citizens (Heaviside, Macintyre et al. 2017, Kondo, Fluehr et al. 2018). The costs of health impacts induce a societal and financial burden on communities. Optimizing the provision and performance of vegetated areas in dense cities can mitigate the negative consequences of demographic pressure and climate change and lead to a higher quality urban environment. Urban green can reduce rainwater runoff and reduce flooding risk while improving the water quality of natural streams and simultaneously reduce the cost of technical/grey infrastructure; it can improve air quality; provide natural cooling and reduce the urban heat island effect. Green spaces can also provide health benefits through recreation and relaxation, and offer place for social interaction and learning (Bolund and Hunhammar 1999, De Ridder, Adamec et al. 2004, Lafortezza, Carrus et al. 2009, van den Berg, Wendel-Vos et al. 2015, Connop, Vandergert et al. 2016, Douglas, Lennon et al. 2017)

The nature of the challenges, their complexity and their societal implications call for a framework that is a triad of: i) interdisciplinary approaches; ii) evidence-based decision making, and; iii) public participation and inclusion. Strategic plans and policy guidelines have the tendency to be thematic and sectorial, and lack an interdisciplinary approach. Due to the complexity of the urban system, and the challenges being related to multiple disciplines, the problems of the sustainable city transcend conventional disciplinary boundaries, and require an interdisciplinary approach (Evans and Marvin 2006). This complexity also requires a clear overview, which can be achieved when problems and solutions can be analyzed and interpreted based on evidence. This not only holds for the current situation, but also for projections towards the future. Too often, planning and design strategies or rules ignore present challenges and are not sufficiently future-oriented either (Malekpour, Brown et al. 2015). The pressures that were sketched earlier generate challenges that are related to growth and change. Therefore, solutions must be more than ever future-oriented, which can only be evaluated properly when future implications are clear, and therefore evidence-based. Planners and policy makers today tend to use established norms and methods that do not sufficiently grasp the complexity of human-nature interaction. Current standards, as used in practice (e.g. planning regulations, green space provision standards, building codes) are often intuitive and normative, and policy makers are often confronted with institutional barriers to uptake green infrastructure adaptation, lack resources or information, or apply guidelines that do not sufficiently respond to the needs of local inhabitants (Measham, Preston et al. 2011, Matthews, Lo et al. 2015, perspective.brussels 2018). Actions, whether in planning or in policy, require well-informed decision-making, and fair and informed decision-making requires a set of evidence-based guiding principles and tools. The subject of sustainable urban planning is the urban environment, and therefore the people that live in it. As such, there is an opportunity to embrace cultural and social diversity that characterizes the population of the cities of today. Good governance and decision-making processes aim to be sustainable and supported by the people that are affected by it. Therefore, they encourage citizen representation and involvement, which makes the third pillar of the framework public participation and inclusion. These three key characteristics (being evidence based, inclusive, and interdisciplinary) are important handles in order to engage in efficient and effective sustainable urban planning (Farr 2011, Roggema 2016). Areas for decision making include policy, planning, and design. These fields are not strictly separated, especially when design is involved in scenario development for policy making and planning (Bason 2014). To summarize, there is a need for an evidence-based framework for urban green in sustainable planning and design that incorporates citizens' needs and that is built on an interdisciplinary foundation. Such a framework should incorporate three capabilities: serve as a diagnostic tool, provide analytical capacities and insights, and offer projective capabilities.

1.3 Brussels as a case study

The area of Brussels and its surroundings has been chosen as the subject for this work. The case of Brussels is emblematic and fits all aspects of the earlier described problematic. The Brussels-Capital Region (BCR) is expected to face a strong demographic rise of 28% in the period 2016-2060 (Federaal Planbureau 2017). The area has a strong diversity in terms of spatial distribution of the population, socio-economic characteristics, built-up typologies, and open space features. While simulations for Brussels show a slight decrease of the urban heat island effect under a IPCC SRES A1B climate change scenario towards the end of the century (2071-2100, with unchanged land use), a doubling of heat wave events is expected (Hamdi, Van de Vyver et al. (2013). Precipitation histograms of the IRC/KMI since 1880 show no significant increase in precipitation extremes, but higher imperviousness due to the urban development process has increased flooding occurrences and intensities (De Bondt and Claeys 2010). This is reflected in the increasing juridical focus on urban aspects of damage claims (MER Regenplan 2008-2011) and the creation of the Regional Flood Control Plans.

Separate plans have been developed for the Brussels-Capital Region concerning water management, green space management and land use, and regional sustainable development, yet their interconnections remain under-investigated. The 'Regional Urban Regulation' (GSV/RRU) includes standards regarding improvement of the living environment, residential functions and beautification of the city. Except for limited regulations regarding rainwater treatment, very little is mentioned regarding sustainable urban design and planning. The 'Plan Nature 2016-2020' (IBGE/BIM 2013) as a strategic planning document emphasizes the role of urban green, however, it has a strong focus on biodiversity. Strategies related to the spatial distribution of urban green are based on simple indicators and do not include citizen consultation, as the main goal of the plan is the preservation of the urban green. While several measures are declared, the document does not take on a proactive position in the development of strategies for the improvement of urban green.

1.4 State of the art

In scientific terms, the study focuses on making advance in three specific areas: i) public green space quality and; ii) public green space accessibility and proximity; and iii) supporting policy and practice with interdisciplinary, participatory and evidence-based frameworks. The following sub-sections, therefore, provide a brief state of the art in these three areas of scientific research.

1.4.1 *Green space quality and its relation to benefits offered by green spaces*

Urban green spaces (UGS) have been the subject of a wide range of studies, yet correlations with assumed benefits have been often based on their presence or abundance, and less based on their qualities (Kabisch and Haase 2013, Haaland and van den Bosch 2015). Several recent studies, however, point to the importance of assessing urban green space quality (Velarde, Fry et al. 2007, Bertram and Rehdanz 2015, de la Barrera, Reyes-Paecke et al. 2016, Ode Sang, Knez et al. 2016, Hedblom, Knez et al. 2017, Zhang, Van den Berg et al. 2017, Madureira, Nunes et al. 2018). Regarding non-material benefits of urban green, many studies are health-related (Hillsdon, Panter et al. 2006, Annear, Cushman et al. 2009, Schipperijn, Bentsen et al. 2013). Regardless of their availability to residents, lower quality areas of green space may be less conducive to facilitating physical activity or a restorative experience (Annear, Cushman et al. 2009). Van Dillen, de Vries et al. (2012) concluded that for neighborhood green space, quality indicators tend to have added predictive value for health. As such, green space quality may be a better predictor of health than quantity alone (Richardson, Pearce et al. 2010). Few studies provide insights in the different aspects of green space quality and relations between green space characteristics and perceived quality. Most studies are geared towards monetary or benefit valuation of green space (Morancho 2003, De Ridder, Adamec et al. 2004, Kong, Yin et al. 2007), or discuss a specific aspect of green space quality (e.g. visual or acoustic). Currently, there is a lack of robust and scientific methodologies for the assessment of green space quality, especially from the user's perspective. Scholars have developed instruments (Table 1) to measure park quality (Van Herzele and Wiedemann 2003), however, these tools often require costly and time-consuming field surveys (Rigolon and Németh 2016). Some tools make use of remote sensing data (Edwards, Hooper et al. 2013) or have been developed to run fully or partly on publicly available geospatial data (Van Herzele and Wiedemann 2003, Rigolon and Németh 2016). The data driven tools that are reported however, are parameterized based on literature instead of user experience or user feedback. A tool to measure green space quality that relies on available geospatial data but also incorporates user feedback on green space qualities might be valuable for a wide range of researchers and stakeholders. If such a tool would be able to link physical features of green spaces with perceived quality, it may also be useful for designers and planners to determine how to improve green space quality by design and management, and thereby, useful for sustainable planning and design. Integrative approaches combining GIS-derived quality indicators with users' experience of green spaces might indeed offer interesting prospects for the planning, design and management of green spaces in urban areas (Khan, Moulaert et al. 2014, Kothencz and Blaschke 2017). Investigating the relationship between green space characteristics and green space qualities as perceived by users of these spaces, and how quality can be inferred from GIS-based indicators describing different features of green spaces, will be one of the main goals of this research.

Author (year)	Abbrev.	Name	Type
Rigolon and Németh (2016)	QUINPY	QUality INdex of Parks for Youth	Driven by available geospatial data
Bird, Datta et al. (2015)	PARK	Parks, activity and recreation among kids tool	Site audit
Edwards, Hooper et al. (2013)	POSDAT	Public Open Space Desktop Auditing Tool	Remote sensing and web data
van Dillen, de Vries et al. (2012)	-	Green Space in Urban Neighborhoods	Site audit
Gidlow, Ellis et al. (2012)	NGST	Neighborhood Green Space Tool	Site audit
Kaczynski, Wilhelm Stanis et al. (2012)	CPAT	Community Park Audit Tool	Site audit
Green Flag Award Scheme (2008)	-	Green Flag Field Research Tool	Site audit
Bedimo-Rung, Gustat et al. (2006)	BRAT-DO	Bedimo-Rung Assessment Tools - Direct Observation	Site audit
Saelens, Frank et al. (2006)	EAPRS	Environmental Assessment of Public Recreation Spaces	Site audit
Lee, Booth et al. (2005)	PARA	Physical Activity Resource Assessment	Site audit
Cavnar, Kirtland et al. (2004)	-	Recreation Facility Evaluation Tool	Site audit
Van Herzele and Wiedemann (2003)	-	A monitoring tool for the provision of accessible and attractive urban green spaces	Map interpretation, geospatial data, and site audit

Table 1: Overview of green space quality assessment tools, based on listing by Rigolon and Németh (2016) and Gidlow, Ellis et al. (2012).

1.4.2 *Green space accessibility and proximity*

The World Health Organization and the United Nations emphasize the importance of an increased provision of urban green space for population health (Douglas, Lennon et al. 2017) and the Habitat III Agenda places human health as key urban goal for the 21st Century (UN General Assembly 2016). Studies have provided evidence of a positive relationship between life expectancy or perceived health and access to green space (Takano, Nakamura et al. 2002, Maas, Verheij et al. 2006). A multitude of benefits of urban green spaces contributing to people's quality of life has led to a broad consensus of the value of urban green spaces in cities in moving towards a more sustainable urban planning (Haq 2011). The European Commission has promoted the development of green spaces by means of e.g. the Green Infrastructure Strategy, Biodiversity Strategy, Habitats Directive (Haase, Kabisch et al. 2017) and the research programme Horizon 2020 (EC 2016), which emphasizes the "provision of universal access to safe, inclusive and accessible, green and public spaces" in order to address the Sustainable Development Goal 11: "Make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations 2017). Spatial distribution of urban green spaces, and more precisely, distance to green spaces has been found to be the most important precondition for use of green (e.g. Grahn 1994), as cited in Van Herzele and Wiedemann (2003), and accessibility to public green spaces has been associated with use and physical activity (Kaczynski, Potwarka et al. 2009, McCormack, Rock et al. 2010). Therefore, an important aspect in the study of urban green spaces is proximity of citizens to green spaces, and how true planning standards for green space proximity compare to human experience. Several scientific studies have addressed this question (Van Herzele and Wiedemann 2003, De Clercq, De Wulf et al. 2007, Ståhle 2010). Even though planning standards for green space accessibility are being applied in practice (planning and policy), no studies have been found that question the consistency of green space proximity standards and how true these standards are to the citizens' preferences. Studies that use green space proximity for analysis of other aspects use arbitrarily chosen standards. Monitoring tools on green space proximity include models based on remote sensing (e.g. Gupta, Kumar et al. 2012, Li, Meng et al. 2014), geospatial data (La Rosa 2014) or a mix of data sources (Van Herzele and Wiedemann 2003), including web-based open source data (e.g. Le Texier, Schiel et al. 2018); see: Appendix 8.2 'Model comparison'. Cities that have decided to monitor their public green space provision mostly employ their own standards and the use of multi-level indicators relating maximum travel distance to the size of green spaces (Lancaster 1983, Harrison, Burgess et al. 1995, Boverket 1999, Ståhle 2002, Van Herzele 2005, Mayor of London 2008) is limited compared to the use of rudimentary indicators (e.g. perspective.brussels 2018). In this research, we will compare multi-level accessibility standards that are used internationally to local preferences inquired through a survey. Based on the data gathered through the survey and the work done on green space quality assessment, we will develop a tool in this study for linking proximity with quality of green spaces and apply the tool to the Brussels case. The linking of proximity and quality in this study is inspired by earlier work by Van Herzele and Wiedemann (2003), who explored this concept in several applied studies (e.g. Van Herzele, Wiedemann et al. 2000).

1.4.3 *Supporting policy and practice with participatory and evidence-based frameworks*

The complexity of the current and future challenges urban areas are facing has led to the development of a diversity of spatial planning tools and design criteria, especially at the local scale (Beatley 2000). To arrive at – and support – apt policies and interventions for urban design and planning, reliable methods and means of analysis, scenario development, and scenario assessment are needed. So far, in research, limited attention has been given to the principles of sustainable urban design and planning and how an evidence-based framework might be translated into policy and practice. While often difficult to realize, participation is considered an important aspect of sustainable urban planning (Nisha and Nelson 2012) and this for three reasons: it is considered as good governance; it represents a shift away from traditional decision making to cooperative planning and decision making, and; it is considered relevant for achieving social sustainability (Joss 2014). Therefore, public participation can improve urban sustainability both practically and procedurally. Public participation has been studied widely, and it is suggested that all modes of participation can potentially benefit society (Pluchinotta, Kazakçi et al. 2019). Literature considers participation as a necessity, though most cases focus on letting stakeholders choose between alternative options (Ferretti, Pluchinotta et al. 2019), which leaves design out of the process. Policymaking tends to incorporate stakeholders late in the process, but meaningful participation requires engagement into all the phases (Pluchinotta, Kazakçi et al. 2019). Collaborative design is especially relevant for tackling multi-disciplinary challenges due to its integrative process (Carmona 2014). Whereas establishing broad consensus on the merits of urban sustainability is relatively straightforward, finding agreement on priorities and specific interventions within the context of often overlapping interests is way more difficult (Joss 2014). While the advantages of co-design are manifold, design based participation also has been criticized for its subjective approach and focus on the requirements of the designer can lead to failing to meet the needs of the end users (Nisha and Nelson 2012). Therefore, an evidence base for design-based participatory processes is highly recommended, as it promises to meet the needs of the end users in an integrative way as well as promoting social and applied sustainability.

Relying on an inquiry in which design is a substantial part of the research process, creates the possibility to address the spatial and interdisciplinary character of the problematic. Ideally, research by design opens up a pathway to new insights through the inclusion of contextualized possible alternatives (Hauberg 2012). Academically sound knowledge on landscape and urban design often requires inclusion of design in the research process (Lenzholzer and Brown 2016), thus landscape design and urban design need to develop research methods that are discipline specific and academically accepted. These methods will include combinations of research and of design (Creswell and Clark 2017). A synthesis of ecological knowledge, and social and cultural understanding of resident's perceptions and values should inform innovative design and planning approaches (Nassauer and Raskin 2014).

In this study we will use the green space quality and proximity assessment tool, developed in the first phase of our research, for co-developing interventions and strategies for improving green space provision in the Brussels study area and assessing their impact.

1.5 Objectives and research questions

This research intends to contribute to the development of a more ecological framework for sustainable urban design and planning aimed at integrating nature in the city more effectively and in an evidence-based way. This overarching goal implies contribution to the state of the art on the perception of urban green, development of indicators and tools for decision and policy making, and exploring the potential of solutions and recommendations through co-developed scenarios. The ambition of the framework also comprises three key characteristics, as defined in the problem statement: fair and informed decision-making requires a set of evidence-based guides and tools; policy guidelines and strategic projects require public support and therefore inclusiveness through participation in order to include citizen's needs in efforts to improve the urban environment, and; complex challenges require interdisciplinary approaches. Tools that will be developed in the research must have diagnostic capabilities in order to indicate problematic areas and situations, provide analytical insights to show how solutions can be formulated, and include projective capabilities to create and evaluate development scenarios. In order to achieve the main goal and objectives, the research will respond to a series of specific objectives and research questions that are organized in the following two main focus areas of the study.

1.5.1 *Focus area: public green space, quality and proximity*

Public green space quality and accessibility are the **first focus** of the work. The aim is to develop a scientific base and a spatially explicit tool for green space quality and green space proximity assessment informed by users' preferences. The assessments require an understanding of what constitutes perceived quality of public green spaces and what constitutes perceived access to public green spaces. These understandings will be informed through a citizen survey. Models will be developed for both quality and proximity assessment and integrated into one public green space assessment tool.

In terms of diagnostics, the tool should help planners and policy makers to identify problem areas with poor public green space provision, identify opportunities for the improvement of urban green quality, and allow for comparison with spatially explicit socio-economic indicators. The analytical power of the tool should allow for determining how the physical characteristics of green spaces are linked to perceived quality, and how the attraction range and the distribution of green spaces determines a sense of accessibility. Projective capabilities will be added to the framework by proposing a method for scenario development and analysis. Exploring different scenario pathways and analyzing the outcome can lead to an assessment of policy and planning choices. Stakeholders will be involved for testing the developed proximity and quality frameworks and for co-developing interventions and strategies for improving the green space provision in the study area. By developing a taxonomy of green space development possibilities, several scenarios will be defined, and their impact will be measured with the earlier developed models. One of the aims will be to assess the impact of the scenarios on different (socio-economic) population groups and draw policy recommendations from this analysis.

The aims of the first part of the research are thus summarized into the following research questions that this work will address the questions:

- how can GIS data be linked to user's perception of the quality of public urban green spaces and how may this inform policy makers, planners and designers in proposing planning solutions within the concept of sustainable urbanism?
- what can be learned from collaborative scenario development in terms of urban green space quality and provision, and how do scenario outcomes relate to the socio-economic distribution in the Brussels case?

1.5.2 *Focus area: densification and land cover scenarios*

A **second focus** of the work addresses the influence of anticipated or expected changes in urban form on land cover. The objective of this part of the research is to explore the influence of the choice of building typologies and street typologies, as well as population density, on the presence of different types of urban green in the city. This will be achieved by firstly mapping existing land cover and assess the impact of alternative development scenarios on land cover change, based on different densification strategies and typologies of urban fabric. Land cover is one of the main inputs required in hydrological models and climate models used for assessing impacts of urban development on regulatory ecosystem functions (water and climate regulation). The output of this work may thus serve as input for assessing the impact of alternative urban development scenarios on regulating ecosystem services, as well as for specifying policy recommendations for building codes and sustainable urban development.

The aims of this part of the research are summarized into the following research questions related to the definition of densification scenarios for the study area:

- How do urban sustainable and unsustainable typologies (street and built-up) translate into corresponding land cover?
- What impact do different densification scenarios have on urban land cover distribution in the Brussels study case?

Concerning the diagnostic and analytical potential of the work, it should allow planners and decision makers to assess where densification and subsequent land cover change is possible and desirable. It should inform end-users (e.g. regional planning department, city planning office, urban designers) whether a street or built-up typology – given its density – is leaning more to the sustainable side, involving sufficient infiltration, retention, and vegetated surfaces; or whether it is closer to the unsustainable kind. This can be done by means of an inventory of existing typologies and newly developed (considered as more sustainable) typologies that serve as benchmark for different densities. Projective capabilities should inform planners and policy makers about the consequences of regulation and building codes. The main indicators are in this case the densification potential and the modelled land cover change. A central question to be answered is whether principles of sustainable urbanism can at the same time increase population density at strategic locations and improve the land cover composition of these areas.

1.6 Methodology

To produce evidence-based recommendations for sustainable urban design and planning, the study will be embedded in scientific literature, draw data from local questionnaires, and rely on data driven spatial modeling and participatory research-by-design. The following research tools will be applied:

Reviewing international literature - The methodologies, as well as data that is not derived from local surveys and questionnaires, will be grounded in literature comprising peer reviewed articles and books. Results and conclusions will be confronted with international literature whenever possible.

Surveys and questionnaires - Part of the data collection in this study will be based on-site surveys through observation (non-participatory) and on-site and online questionnaires (participatory). For these activities, a surveying and questionnaire tool will be developed which guides and supports the collection of data by smartphone and PC. The main purpose will be to provide data for statistical analysis of the use and perception of public green spaces. The tool developed will support automatic geo-tagging of entries and retrieving coordinates from indications made by respondents on maps. As such, survey and questionnaire data can be introduced into a GIS environment for spatial analysis.

GIS modeling - GIS models will be coded using ArcGIS software with support of a graphical user interface, named ModelBuilder. The intuitive model building tool supports iterations of sub-models, which is highly useful for the spatial analysis conducted in this work. The models to be developed are computation-intensive and will require repeated reading and writing of many large datasets. This process will be made more efficient through the use of a virtual RAM disk.

Research by design - To address urban challenges, there is a strong interest in the formulation of design options, as well as in assessing the impact of alternative scenarios for urban green space development. The preferred method for the formulation of design options/opportunities is collaborative design, supported by indicators of the current state. The co-production of scenarios through design and the impact assessment of alternative design options, along with the scientific and practical output it delivers, can be considered as research by design, i.e. an inquiry in which design is a substantial part of the research process, forming a pathway to new insights through the inclusion of contextualized possible alternatives, validated through an interdisciplinary peer review of experts (Hauberg 2012). For these exercises, workshops will be organized with stakeholders, researchers focusing on several related disciplines, designers and master students of architecture and urban studies. Thus design will be used not only as an integrative or interdisciplinary component of the research, but also as a trans-disciplinary mode of research involving stakeholder participation and co-production.

1.7 Structure of the manuscript

The manuscript follows the objectives outlined earlier in this introduction. The different parts of the research are presented as chapters and written as separate journal articles, which have been published, are in peer review or will be submitted shortly.

In the second chapter, the impact of different features of urban green spaces is assessed in relation to perceived quality, and how GIS data can be enabled for green space valuation and design. Through the identification of the various aspects of quality from international literature and questionnaire work with green space visitors, a model is developed that couples GIS-based metrics with perceived green space quality. With this model, green space quality can be assessed for a large territory in a consistent manner.

In the third chapter, residents' access to public green spaces is examined. The chapter presents a GIS-based tool to evaluate accessibility to – and the earlier modelled quality of – urban green spaces. The tool builds on earlier research on green space accessibility (as listed in Appendix 8.2). Drawing on earlier research, planning standards and analysis of local preferences acquired through questionnaires, a series of indicators is presented. These indicators shed light on the proximity to and quality of green spaces, with the aim of supporting decision making and design and planning at the urban scale.

In the fourth chapter, the developed models are used for scenario analysis of public urban green spaces. By means of research by design in a collaborative workshop, earlier developed indicators are used to indicate and tackle problem areas. All presented solutions are analyzed and classified, allowing for the formulation of scenarios for public green space development. Model output is overlaid with socio-economic data in order to gain insights in the social justice aspect of green space scenarios and potential investments.

In the fifth chapter, a GIS- and design-based simulation model of potential future land cover change is developed for the Brussels-Capital Region. In order to assess potential land cover change, two densification strategies are formulated, a business-as-usual and a sustainable scenario. For both, the development parameters and constraints are listed, along with potential typologies and related land cover fractions. By combining spatially explicit scenarios for densification with expected land cover fractions of scenario-related typologies of private and public space, land cover changes can be made spatially explicit for both scenarios. These outcomes may serve as input for future modelling of heat and water related impacts of development on regulating ecosystem services. Whereas the analysis is highly contextual due to the specificity of the study area, the method may support high-resolution ecosystem service assessment of future scenarios in other locations.

The conclusion of the manuscript includes a reflection on how the objectives have been met, what has been achieved, how the study contributes to the state of the art, and which limitations have been met regarding data, modelling, scenario development and analysis. Finally, new questions that have arisen during the research are discussed and suggestions for future research are presented.

1.8 Description of the study area

The case study area contains the Brussels-Capital Region and its immediate surroundings. The area has a dimension of 26 by 26 km (Figure 1, continuous line and Figure 2). It includes the dense city centre, as well as lower density areas surrounding the centre. It also includes major natural entities in the landscape (e.g. vast forest areas). Two regions are included: the BCR (161 km^2), with an average population density of 7025 inhabitants per km^2 and a continuous built-up area spread over 19 communes; and part of the surrounding area of Flanders characterised by urban sprawl, with an average population density of 477 inhabitants per km^2 (calculated from spatial CENSUS data (FOD Economie 2011)). To allow correct calculation of green space indicators on the edge of the study area, a buffer of 5 km was added in each direction (Figure 1, dashed line). The topography of the area is dominated by the valley of the Zenne river flowing from the undulating south – referred to as Middle Belgium – to the flat north – referred to as Low Belgium. Several small tributary valleys connect transversally, and form the natural basis of a green space structure in less dense areas. There are several concentrations of very large green spaces, such as the medieval Forêt de Soignes, which is situated on the divide of the Zenne valley and the Dijle valley, the royal domain (or gardens), which are not open to the public, and continuous stretches of agricultural and privately-owned land in the periphery.

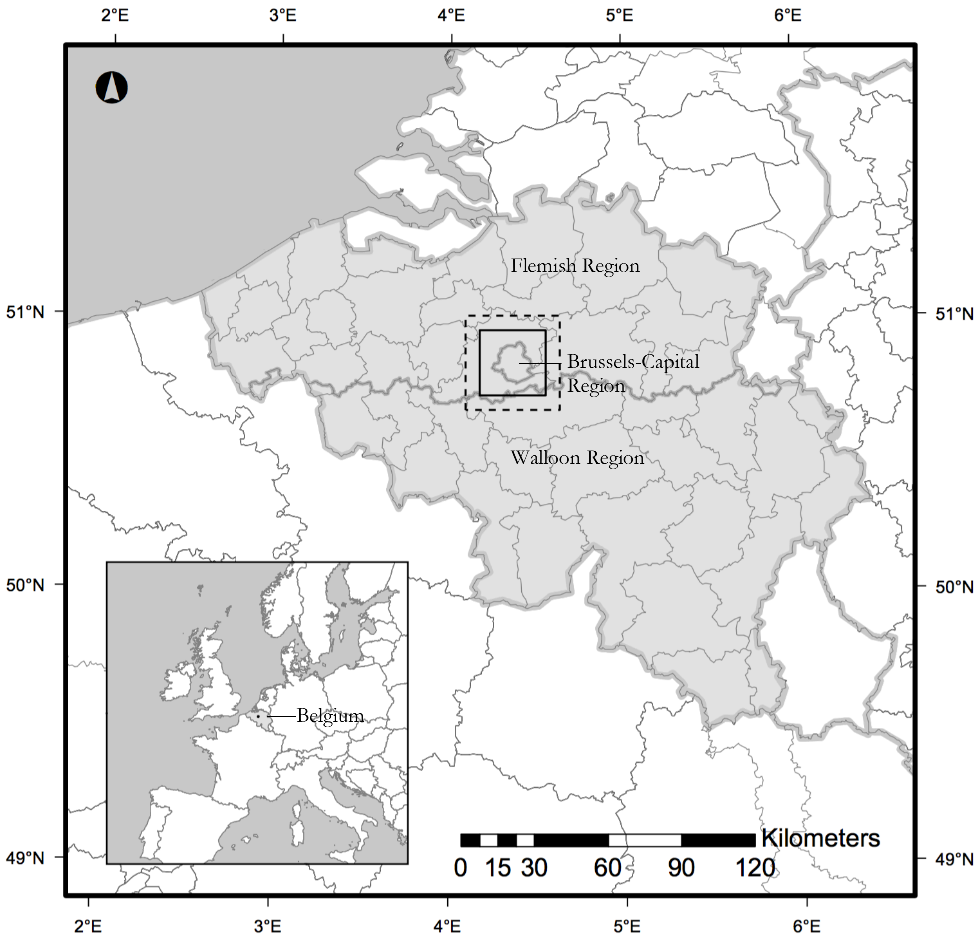

Figure 1: Study area (continuous line) and calculation area of the models (dashed line). Belgium is marked in grey.

Figure 2: Satellite image of the study area.

2

2 Urban green space qualities — An integrated approach towards GIS-based assessment reflecting user perception

Abstract

For city dwellers urban green space is the primary source of contact with nature. Qualitative green space is increasingly perceived as an important factor for quality of life in urban areas and a key component of sustainable urban design and planning. In this study, the relation between different features of urban green spaces and perception of green space qualities was analyzed by combining the outcome of a survey on green space perception with GIS-based spatial metrics. A survey has been conducted among residents of the Brussels Capital Region and surroundings to assess the relative importance residents assign to different qualities of urban green spaces and how they value these qualities within visited spaces. Quietness, spaciousness, cleanliness and maintenance, facilities and feeling of safety are identified as important qualities of public green spaces, while naturalness, historical and cultural value are perceived as less important qualities. A GIS-based model was developed to infer naturalness, quietness and spaciousness as perceived by users of public green spaces from green space properties. Using variables describing biological value, land-cover composition, green space area and shape, good correlations were obtained between GIS-based assessment of naturalness and spaciousness and how green space users perceive these qualities. The model proposed may be useful for simulating green space development and improvement scenarios and assess their impact on perceived quality. Thus it may serve as a spatial decision support tool for improving the quality of urban green spaces.

Research Highlights

- An approach for assessing green space quality including seven quality components is put forward.
- A multi-criteria model for assessing green space quality is proposed.
- GIS-based modelling is coupled with how green space quality is perceived.
- The indicator maps obtained may support green space management and design.

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2.1 Introduction

Positive perceptions of green and open space are only surpassed by dwelling characteristics as important predictors of high levels of neighborhood satisfaction (Douglas, Russell et al. 2018). A proper assessment of the role and benefits of green spaces (GS) for urban residents is an important concern in the emerging area of urban ecosystem services (ES). Since the last decennium of the 20th century, the concept of ES has gained an important role in the debate on sustainability and quality of life (Lappé 2009, Burkhard, Petrosillo et al. 2010). Neßhöver, Beck et al. (2007) consider ES as the missing link between ecosystems and human wellbeing. Also on the policy level more attention and action is directed to the dependence of man on nature and its ecosystems. In urban areas, the aspect of non-material benefits or cultural ES is highly relevant (Chang, Qu et al. 2017) and GS quality is a major factor for how people receive cultural ES. In order to reinforce this link in urban areas, an understanding of the quality and management of urban ecosystem services is required to ensure sustainable urban planning (Luederitz, Brink et al. 2015) and general wellbeing.

Urban green spaces (UGS) have been the subject of a wide range of studies, yet correlations with assumed benefits have been often based on their presence or abundance, and less based on their qualities (Kabisch and Haase 2013, Haaland and van den Bosch 2015). Several recent studies, however, point to the importance of assessing urban green space quality (Velarde, Fry et al. 2007, Bertram and Rehdanz 2015, de la Barrera, Reyes-Paecke et al. 2016, Ode Sang, Knez et al. 2016, Hedblom, Knez et al. 2017, Zhang, Van den Berg et al. 2017, Madureira, Nunes et al. 2018). Rather than a biased preoccupation with green-space acreage and tree counts, planners should also consider the geometry of the green network and the quality of the greenery (Jim 2004) and the various aspects of GS quality (Bertram and Rehdanz 2015). Many studies on urban green quality are health-related and yield mixed results. For example, Hillsdon, Panter et al. (2006) and Schipperijn, Bentsen et al. (2013) found no associations between access to urban GS on the one hand, and recreational physical activity on the other hand. However, the latter determined associations between the presence of features and physical activity. Annear, Cushman et al. (2009) found that residents of an area with a poor quality physical and social environment appear to engage in leisure time physical activity less frequently than those living in a higher quality area of the same city. Regardless of their availability to residents, lower quality areas of green space may be less conducive to facilitating physical activity or a restorative experience (Annear, Cushman et al. 2009). Van Dillen, de Vries et al. (2012) concluded that for neighborhood green space, quality indicators tend to have added predictive value for health indicators and naturalness of a place has been linked to higher general wellbeing (Knez, Ode Sang et al. 2018). As such, green space quality may be a better predictor of health than quantity alone (Richardson, Pearce et al. 2010).

The concept of 'quality' of GS is complex and multi-dimensional (Khan, Moulaert et al. 2014). Moreover, there is a lack of robust and scientific methodologies for the assessment of green space quality, especially from the user's perspective. Most studies are geared towards the monetary or benefit valuation of green space (Morancho 2003, De Ridder, Adamec et al. 2004, Kong, Yin et al. 2007), or discuss a specific aspect of green space quality (e.g. visual or acoustic). Cohen, Potchter et al. (2014) state that the small number of studies on quality assessment of UGS does not base their assessment on the analysis of in-situ objective measurements and their cumulative impact in a specific location. For a large study area (metropolitan), a full in-situ analysis may not be feasible though and GIS data may be a useful substitute for in-situ measurements. Until now, little work has been done coupling GIS-based assessment of green space quality to how GS are perceived by users. Integrative approaches combining GIS-derived quality indicators with users' experience of GS might offer interesting prospects for the planning, design and management of GS in urban areas (Khan, Moulaert et al. 2014, Kothencz and Blaschke 2017).

Urban growth and transformation presents numerous challenges for the maintenance of UGS, and consequently also for human health and well-being (Tzoulas, Korpela et al. 2007). In the context of the Brussels Capital Region (BCR), an expected population growth of 14,000 per year on a population of 1,167,951 in 2015 (FOD Economie 2013), makes well-informed densification strategies a pressing issue. Maintenance and improvement of accessibility and quality of GS is a crucial part of developing such strategies. With the aim of developing an integrated approach for the assessment of UGS qualities, this study is based on a survey that is conducted among residents of the BCR to assess perceived importance of GS qualities contributing to the provision of cultural ES. Cultural ES are usually defined as the intangible and nonmaterial benefits provided by nature (Hirons, Comberti et al. 2016). A GIS-based model is then developed to infer quality indicators, such as, naturalness, quietness and spaciousness from spatial properties of GS. The model relates GIS-based metrics describing GS properties to the survey outcomes on the perception of GS quality. Integrating different components of green space quality, the model may be useful as a decision support tool for planners, designers and policy makers and may provide valuable insights for the design of public GS and qualitative urban development.

2.2 Materials and methods

2.2.1 *Materials*

The data on which this study is based is threefold. Firstly, definitions of GS quality were collected from 20 peer-reviewed essays, revealing 168 quality attributes (Table 2). The papers were selected based on a search for the term 'green space quality', and further selected based on studies that describe or include multiple characteristics contributing to quality. The focus was on generic aspects of green space quality and less on detailed or highly specific characteristics up- or downgrading people's perception of green spaces, e.g. presence of flowerbeds, or exercise trails. Grouping of these variables served as a basis for defining seven GS sub-qualities that are assumed in this study (see section 2.2.3). Secondly, an online and on-site questionnaire in three languages (English, French, Dutch; see section 2.2.4) was conducted to assess users' opinions on public green space quality, with 371 valid responses. Thirdly, several GIS data layers were prepared: the delineation of publicly accessible GS and the data that served for the assessment of sub-qualities of these spaces by combining questionnaire output with GIS modelling. The latter set of layers was probed on all locations that were geo-tagged during the entry of a questionnaire and the retrieved data was added to the questionnaire responses. All types of GS were included in the analysis, the sole criterion for selection being their public character. The types range from 19th century formal GS, public areas of housing projects, to GS developed in cooperation with locals, including allotment gardens and spaces for community activities.

Source	Country	Site categorization	Research type	# quality attributes or character-istics	# vari-ables
Bertram and Rehdanz (2015)	EU	Urban green space	Empirical	4	21
Grahn and Stigsdotter (2010)	SE	Urban green space	Empirical	8	65
Sugiyama, Thompson et al. (2009)	UK	Neighborhood open space	Empirical	14	-
Doick, Sellers et al. (2009)	UK	Urban green space	Case study	14	-
Chen, Adimo et al. (2009)	CN	Urban green space	Empirical	8	-
Sanesi and Chiarello (2006)	IT	Urban green space	Empirical	11	-
Hillsdon, Panter et al. (2006)	UK	Public parks	Empirical	8	-
Caspersen, Konijnendijk et al. (2006)	DK	Green spaces	Theory	7	38
Eng and Niininen (2005)	UK	Public parks	Empirical	25	-
CABE (2005)	UK	Green spaces	Theory	8	-
Van Herzele and Wiedemann (2003)	BE	Urban green space	Theory	5	30
Mens en Ruimte (1999)	BE	Green spaces	Theory	1	-
Gobster (1998)	US	Public park / neighborhood boundary parks	Empirical	7	-
Smith, Nelischer et al. (1997)	CA	Urban Community	Theory	6	28
Coeterier (1996)	BE	Landscapes	Empirical	8	-
Grahn (1991)	SE	Green spaces	Empirical	8	-
Burgess, Harrison et al. (1988)	UK	Local public parks / Neighborhood parks	Theory and empirical	13	-
Bradley and Millward (1986)	UK	Parks / Green open space	Empirical	6	-
Kaplan (1984)	US	Urban nature	Theory	7	-

Table 2: Studies exploring quality attributes used for assessing qualitative or successful green space 1984-2015, (with permission, based on Abdul Malek, Mariapan et al. 2010)

Type	Source	Date	Coverage	Purpose
Natural reserves	IV	2002	Flanders	i ii
Natural reserves	BE	9999	Brussels	i ii
Forests	IV	2000	Flanders	i
Forests	URBIS	2013	Brussels	i
Natura 2000 habitat zones (a)	IV	2008	Flanders	i ii
Natura 2000 habitat zones (a)	BE	9999	Brussels	i ii
Parks	IV	2014	Flanders	i
Parks	URBIS	2013	Brussels	i
Water bodies (d)	IV	2015	Flanders	i
Water bodies (d)	URBIS	2013	Brussels	i
Biological value	IV	2010	Flanders/ Brussels	i ii
Protected landscapes	IV	2001	Flanders/ Brussels	i ii
Roadside green	URBIS	2013	Brussels	i
Noise map railways day/evening/night (e)	LNE	2011	Flanders	ii
Noise map roads day/evening/night (e)	LNE	2011	Flanders	ii
Noise map (combined)_5m (e)	BE	9999	Brussels	ii
Vegetation map * (water, bare, low veg., dense vegetation) (b,c)	Van de Voorde, Canters et al. (2010)	2010	Flanders/ Brussels	ii
Composed green space delineation (a,b,c,d,e,f)	comp.	-	Flanders/ Brussels	ii
IV (Informatie Vlaanderen)	https://download.agiv.be			
URBIS (Brussels Urban Information System)	http://cibg.brussels/nl/onze-oplossingen/urbis-solutions/download			
BE (Brussels Environment)	http://wfs.ibgebim.be/			
LNE (Environmental department of the Flemish Region)	https://www.mercator.vlaanderen.be/zoekdienstenmercatorpubliek/			
Purpose:	i) green space delineation; ii) quality assessment			

Table 3: GIS input maps (all are in vector format, except for (*), which is in raster format). Labels (a) – (f) appear in Table 11 in order to clarify how these layers were used in the quality modelling/calculation.

Both the Flemish Region and the BCR apply their own standards for the registration of GIS data, with the exception of European data (e.g. EU Habitat Directives). Therefore, thematic maps were produced by merging data derived from various sources (Table 3, purpose ii). Next to administrative and environmental data in vector format (Table 3), a vegetation map distinguishing between dense/woody and herbaceous vegetation was obtained from a Quickbird remotely sensed image through NDVI thresholding (Van de Voorde, Canters et al. 2010). Contours of public GS were derived from the shapes present in the available GIS layers (e.g. forests, habitat directive areas, natural reserves, biologically valuable areas) (Table 3, purpose i).

2.2.2 *General approach*

The proposed method for GS quality assessment is based on the premise that perceived green space quality can be conceived as being the outcome of an appreciation of various sub-qualities of GS, which may have different importance to the user. Various scholars claim that people experience a landscape as a system, in which things are structurally and functionally related to each other, in accordance to holistic landscape views. Therefore, the appreciation of a landscape is context dependent (Coeterier 1987, Antrop 1989, Coeterier 2000) as cited in (Van Herzele and Wiedemann 2003). In this study though, we will assume that for GIS-based analysis the benefits of decomposing GS quality into measurable sub-qualities - resulting in a simple and easily reproducible overall quality indicator - outweigh the disadvantage of not taking full account of a more holistic view on the landscape.

Based on a literature review to indicate quality attributes of GS, a classification of main aspects of green space quality (so-called sub-qualities) is proposed. Sub-qualities, which may be inferred from GIS data, were used as variables in a multi-criteria assessment of overall quality using a weighted linear modelling approach. Overall quality and sub-quality appreciation of GS, as well as perceived importance of sub-qualities were obtained through questionnaire input from users (see: 2.3.3). The questionnaire was developed as a web application, in order to serve as an online questionnaire and as a smartphone interview tool. The majority of responses were collected on-site. The relation between overall quality and sub-qualities on the one hand, and between perception of sub-qualities and GIS-based indicators describing each of these sub-qualities on the other hand, is modelled and validated based on the questionnaire responses. This will provide an insight on the extent to which features of GS have an influence on people's opinions about the quality of GS, and whether a simple additive model is suited for assessing overall quality as perceived by GS users. In landscape preferences, variations exist in terms of cultural background (Kaplan and Herbert 1987, Fraser and Kenney 2000, Özgüner 2011), as well as in terms of gender (Wang and Zhao 2017). Therefore, depending on the number of questionnaire responses, the data will be split into two or more groups to investigate the significance of differences in preferences regarding sub-qualities. Results can either provide a (dis)confirmation of a trend or contribute to a culturally sensitive model.

2.2.3 *Determining relevant aspects of green space quality*

Human-environment studies in various western countries have shown with remarkable consistency cross-cultural universal patterns in people's preferred environments (Van Herzele 2005). In recent years many studies have focused on residents' preferences of GS characteristics (Madureira, Nunes et al. 2018). In order to determine GS qualities that are relevant, and how these qualities contribute to overall quality of UGS as perceived by GS users, 20 essays and case studies from the last three decades were reviewed for their proposed quality attributes or characteristics (Table 2). The literature survey was done with the following goals: a) come up with a comprehensive, yet manageable set of clearly distinct quality aspects; b) cluster quality aspects into larger themes; c) unravel the meaning of complex definitions of qualities such as e.g. 'wilderness' (Caspersen, Konijnendijk et al. 2006), 'contextual integrity' (Van Herzele and Wiedemann 2003) or 'legibility' (CABE 2005); d) define underlying qualities such as 'cleanliness', which is for example present in the descriptions of the dimensions 'nature', 'prospect' and 'refuge' in the classification by Grahn and Stigsdotter (2010); e) define useful variables to measure the proposed qualities and check for compatibility with available GIS data layers. The 165 quality aspects obtained from the literature survey could be classified into eight larger themes (Table 4) or were considered as 'user characteristics and interaction', 'resulting sub-qualities', or 'omnipresent or under-represented'. Although great similarities are found in terms of qualities considered in different studies, not all studies cover all the themes identified.

Seven major themes have been distinguished for this study, which from now are referred to as sub-qualities of UGS. These seven sub-qualities are split into two main groups: a) 'inherent sub-qualities' (INH) comprising nature and biodiversity (NAT), quietness (QUI), historical and cultural value (HIS), spaciousness (SPA); and b) 'use-related sub-qualities' (USE) comprising cleanliness and maintenance (MNT), facilities (FAC), and feeling of safety (SAF). Indicators that are derived from thematic GIS layers can describe inherent qualities. Use-related qualities can only be valued through on-site or online surveys.

NAT - The level of naturalness is a factor that has positive effects on both human well-being (Stigsdotter and Grahn 2011, Ode Sang, Knez et al. 2016, Knez, Ode Sang et al. 2018) and biodiversity (e.g. Sandström, Angelstam et al. 2006), and high perceived naturalness leads to more activities and attributed aesthetic values (Ode Sang, Knez et al. 2016). It is an expression of the similarity to ecosystems with small human impact (Peterken 1996) and thus refers to a sense of wilderness and freedom (Grahn and Stigsdotter 2010). Many preference studies of outdoor recreation environments, by e.g. Kaplan and Kaplan (1989), have found that a strong manifestation of nature is perhaps the most essential experience dimension of UGS. Presence of wooded area has a significant effect on physical activity (Kaczynski, Potwarka et al. 2009, Schipperijn, Bentsen et al. 2013). Wilderness-like areas can generate a strong preference among users, but also a fear or feeling of vulnerability (Jorgensen, Hitchmough et al. 2007, Jansson, Fors et al. 2013).

QUI - The choice for a green environment is also influenced by its degree of peacefulness (Grahn 1991), quietness (Van Herzele and Wiedemann 2003) and relaxation (Sanesi and Chiarello 2006). For both inhabitants that have access to a quiet garden and those without, availability of nearby green areas reduces long-term noise annoyances and prevalence of stress-related psychosocial symptoms (Gidlöf-Gunnarsson and Öhrström 2007). According to Van Herzele and Wiedemann (2003), "the degree of congruence between sound and the spatial, cultural or social context in which it is produced, plays an important part in defining this subjective response (López Barrio and Carles, 1995)."

HIS - The historical and cultural value of GS has a landscape dimension and an artifact dimension which deliver satisfaction through understanding the surrounding environment in terms of nature or culture. An area with tangible heritage (physical historical evidence) promotes feelings of time depth and belonging (Caspersen, Konijnendijk et al. 2006). According to several authors, green space quality is influenced by landscapes being protected, having contextual integrity, being considered as heritage, or by parks with a significant age containing artifacts referring to a past time (Van Herzele and Wiedemann 2003, Caspersen, Konijnendijk et al. 2006, Grahn and Stigsdotter 2010).

SPA - People's preference for spacious and un-fragmented areas (Grahn and Stigsdotter 2010) can be explained by the quality of the feeling of being away from all rules of the town and forgetting about limits, time and space (Kaplan 1990). Criteria involve free movement and unawareness of limited dimensions of the green space (Grahn 1991). Therefore, both the size (area), as well as the degree of irregularity - or inversely, compactness - relate to spaciousness. Other variables mentioned in literature related to spaciousness are legibility (CABE 2005), unity and spatiality, or the degree of coherence (Coeterier 1996).

FAC - The sub-quality 'facilities' indicates the balanced provision, decent state and qualitative design of outdoor amenities such as qualitative and sufficient paths contributing to walkability (Doick, Sellers et al. 2009), sufficient seating (Smith, Nelischer et al. 1997), recreational facilities such as a challenging play space (CABE 2004), sport facilities (Sanesi and Chiarello 2006) or exercise supporting facilities (Doick, Sellers et al. 2009). Amenities also include signage and lighting (Eng and Niininen 2005), restrooms (Grahn and Stigsdotter 2010) and enclosure (CABE 2005).

MNT - Also contributing to perceived green space quality are cleanliness (CABE 2004, Jim and Chen 2010) and good maintenance (Burgess, Harrison et al. 1988, Eng and Niininen 2005). They result from decent park management (Coeterier 1996, Gobster 1998, Sanesi and Chiarello 2006, Doick, Sellers et al. 2009) and sufficient funding, as well as user behavior. Cleanliness involves shared responsibility by users and managing institutions.

SAF - CABE Space (2005) found that what bothers the public most about GS is when they are not kept clean or safe. A low personal safety level influences the appreciation by frequent users as well as occasional users, and is particularly important for older people's quality of life (Sugiyama, Thompson et al. 2009). Certain fears have a particular importance for specific population groups (Madge 1997). The feeling of safety is influenced by individual and social factors, as well as factors in the environment, including the type of vegetation (Jorgensen and Anthopoulou 2007, Jansson, Fors et al. 2013), although the individual factors are the most influential (Sreetheran and van den Bosch 2014).

Accessibility (ACC), defined here as the proximity of public GS to the place of residence is not considered as a sub-quality of GS, but rather as a precondition for use (Van Herzele and Wiedemann, 2003) and is therefore not included in this study. Quality and proximity can be combined in a green space provision model though (Stessens, Khan et al. 2017).

2.2.4 *Perceived green space quality*

During the months of August, September and October of 2015 and 2016, a survey in the form of an online and on-site questionnaire was carried out in three languages (English, French, and Dutch) to gather data on GS visitors' perception of overall quality, as well as perceived importance and rating of sub-qualities of GS. GS for on-site data gathering were selected in such as way as to ensure a proper balance between central vs. peripheral locations, different levels of neighbourhood prosperity and representativeness of size. Participants of the on-site survey were approached randomly during daytime visits (9:00-21:00). Green space visitors willing to answer questions were asked to complete the questionnaire. Each GS was surveyed for a total of 4-6 hours, at different moments of the day (morning, afternoon, evening), during weekdays and weekends. The same online form supported both the on-site and online questionnaire, which included rating scales, multiple-choice questions, and map input (GS location). On-site, the interviewer read out the questions to the interviewee, while online, the interviewees completed the process by themselves. To stimulate online participation, an announcement of the survey was distributed via different mailing lists (contacts of Brussels Environment, citizen action groups, neighbourhood committees). The online questionnaire was open during the period of on-site data collection.

The reason for choosing for a questionnaire survey relates to two of the key characteristics of the research, being evidence-based indicators and a participatory process. Only by interviewing the inhabitants of the study area, the developed models can be as close as possible to the perception of the people. While the participation is indirect in this case, there is strength in drawing data from the study area. It allows comparing the data with international literature, which can confirm the trends in literature and at the same time calibrate the model to the local context. Moreover, personal communication with the respondents gives insights through anecdotes and conversations. Therefore it is a good way for proofing the conceptual setup (e.g. important missing questions). The personal interaction did not indicate a missing question in the case of this survey, but did give indications on how to reorder the questions in order to keep the focus of the respondent. Questions on a 7-point semantic scale are a big part of the questionnaire. The risk of ambiguity was kept as low as possible by giving an explanation in words (labels) for every point on the scale.

Table 5 gives an overview of the topics addressed in the questionnaire. The main questions and responses used in this study pertain to the earlier described GS sub-qualities. Regarding each sub-quality, two questions were asked: "How do you feel about the [e.g. quietness] in this green space?" (7-step score from 'very unsatisfied' over 'neutral' to 'very satisfied') and "How important is [e.g. quietness] for you in a green space?" (4-step score from 'not important' to 'decisive'). Apart from information on perception of GS quality, participants were also asked about their GS proximity preferences, frequency of GS visits, the presence of green and the access to green in their neighbourhood of residence, yet this information was not used for the present study. As the respondents had to indicate their age and gender, the sample of respondents could be verified for representativeness in relation to the demographic structure of the BCR.

2.2.5 *Delineating public green spaces*

In order to define which areas can be considered as public GS, a stepwise selection process was conducted. Land use plans that delineate park areas do not include all GS with public use. Data layers that are specifically public (parks, forests [URBIS], roadside green) were combined with a selection of complementary green spaces that have shown to have public access. These spaces include natural reserves, forests [IV], Natura 2000 areas, water bodies, areas with high biological value, and protected landscapes. Of these layers, some features are accessible, while others are not. For determining their public access, they were overlaid with a publicly available layer of paths generated by GPS tracking. A threshold density of path length per GS area was set in order to consider the GS as public. This method was considered to be sufficiently reliable by manually verifying a selection of samples. Ownership data was not available for all parcels, and public ownership does not guarantee public access and vice versa. Therefore, this information was not used. Since not all layers are delineated in the same way, and since perimeter length is important for the analysis, the perimeters were smoothened out by outward and inward buffering. Afterwards, the selected GS were sliced up by a selection of roads that act as barriers.

Sub-qualities [CODE]	Characteristics from the essays mentioned in Table 2 (duplicates and synonyms were left out)	Data origin
1. Preconditions for use (not included in this study)*		
Accessibility (ACC)	proximity to the residence, accessibility, and connection, barrier-free, amount of green spaces	n.a.
2. Sub-qualities (subject to this study)		
2.A. Inherent sub-qualities (INH) (informed by GIS data and by questionnaires)		
Nature and biodiversity (NAT)	naturalness, wilderness, biodiversity, forest, natural setting, non-materialistic, air quality, nature conservation, scenic beauty, environmental functions, possibility for involvement with nature, varied topography	GIS (Quest.)
Quietness (QUI)	quietness, auditory factors, relaxation, peacefulness	GIS (Quest.)
Historical and cultural value (HIS)	continuity of culture reflected in the landscape, dense pattern of characteristic elements, contextual integrity, relics of traditional landscapes, cultivated, old	GIS (Quest.)
Spaciousness (SPA)	space, unity, spatiality, legibility, landscape, vista	GIS (Quest.)
2.B. Use-related sub-qualities (USE) (informed by questionnaires)		
Facilities (FAC)	lots of seating, quality of paths and walkability, challenging play space, outdoor amenities, recreational facilities, sport facilities, enclosure, signage and lighting, supporting exercise, square-like, quality in design	Quest.
Cleanliness and maintenance (MNT)	cleanliness, good maintenance, park management, funding	Quest.
Feeling of safety (SAF)	safety and security, supervisions of users, well established advisory council, enclosure, human scale	Quest.

Table 4: Thematic clustering of quality aspects relevant to the assessment of quality of green open spaces (*) see: (Stessens, Khan et al. 2017).

Personal information about the respondent	
Gender	multiple choice
Age	integer [years]
Cultural background*	multiple choice
Secondary cultural background*	multiple choice

* The question of cultural background is aimed at identifying articulations across social groups that live in Brussels and that identify with a certain culture, and was described as the country the respondent felt culturally most connected to. Therefore 'Belgian' could be answered by a range of individuals from 'having Belgian roots', up to 'immigrated a few years ago'

Table 5: Questionnaire content (continues on next page).

Personal impression of a single visited green space (or chosen green space when answered online)

Inquired aspect	Appreciation (visited/chosen green space)	Importance (green spaces in general)
Overall quality	x	
Cleanliness and maintenance	x	x
Naturalness and biodiversity	x	x
Quietness	x	x
Historical and cultural value	x	x
Spaciousness	x	x
Facilities	x	x
Feeling of safety during the day	x	
Feeling of safety during the evening	x	
Feeling of safety		x
Rating scales	1) very unsatisfied; 2) unsatisfied; 3) slightly unsatisfied; 4) neutral; 5) slightly satisfied; 6) satisfied; 7) very satisfied	0) not important; 1) somewhat important; 2) important; 3) decisive

Residence of the respondent and personal preferences

Maximum preferred traveling time towards green space on the scale of the:	
- neighborhood	integer [minutes]
- city	integer [minutes]
- metropolitan area	integer [minutes]

Questionnaire information

Location of submission	WGS84 coordinates
Time of submission	date and time [YYYY/MM/DD hh:mm]

Table 5: Questionnaire content

2.2.6 *Modelling reported green space quality*

The purpose of the modelling work in this study was two-fold. First, we wanted to establish a relation between the overall quality of GS as perceived by users and the way these users rate different sub-qualities using a weighted linear modelling approach:

$$q = \sum_{i=1}^{I+K} w_i q_i$$

(Eq. 1)

where *q* refers to overall quality, w_i are the sub-quality weights, and q_i are the sub-quality ratings. *I* is the number of inherent sub-qualities, *K* the number of use-related sub-qualities included in the analysis. The weights were obtained through multiple linear regression (MLR) without an intercept (MLR in Figure 3). The analysis was restricted to GS with a minimum of ten responses, resulting in a training set of 256 questionnaire responses (25 GS) and a holdout validation set of 93 responses (9 GS). Seven-point ratings of overall quality and sub-quality appreciation (see Table 5) were stretched on a range from 0 to 100. The sub-quality weights (coefficients) obtained through MLR were compared to the reported importance of the sub-qualities, as inquired through the questionnaires, in order to validate the outcome of the modelling. Next, for all inherent sub-qualities, the relation was modelled between GIS-based metrics derived from relevant data layers, describing different GS properties, and sub-quality user ratings. To do so, the detail of analysis was altered from the visitor level to the level of GS, again focusing on GS with minimum ten responses and using the same training and validation data as above. Average reported sub-quality ratings for each GS, obtained through the questionnaires were used as the dependent variable, GIS-based metrics as independent variables:

$$q_i = u_i + \sum_{j=1}^{J} v_{ij} x_{ij}$$

(Eq. 2)

where q_i is the average rating for sub-quality i, obtained from the questionnaire, x_{ij} are the values of the GIS-based GS metrics j describing sub-quality i, v_{ij} are the model coefficients and u_i is the intercept (MLR* in Figure 3). Different metrics potentially explaining the variance of the sub-quality ratings were first selected. Products of metrics were included to deal with possible metrics interaction. A stepwise regression approach was applied to remove non-significant variables from the regression equation (p-level verification with $\alpha = 0.05$).

Both steps in the modelling were then coupled, translating GIS-based metrics into an assessment of inherent quality of each green space in the study area (MODEL INH in Figure 3):

$$q_{INH} = \sum_{i=1}^{I} w_i \left(u_i + \sum_{j=1}^{J} v_{ij} x_{ij} \right)$$

(Eq. 3)

The GIS-based assessment of GS quality is limited to the level of inherent quality instead of overall quality because use-related sub-qualities are not informed by GIS data. However, the ratings of use-related sub-qualities q_k can be included in the assessment of overall quality for the GS where they are known:

$$q = q_{INH} + q_{USE} = \sum_{i=1}^{I} w_i \left(u_i + \sum_{j=1}^{J} v_{ij} x_{ij} \right) + \sum_{k=1}^{K} w_k q_k$$

(Eq. 4)

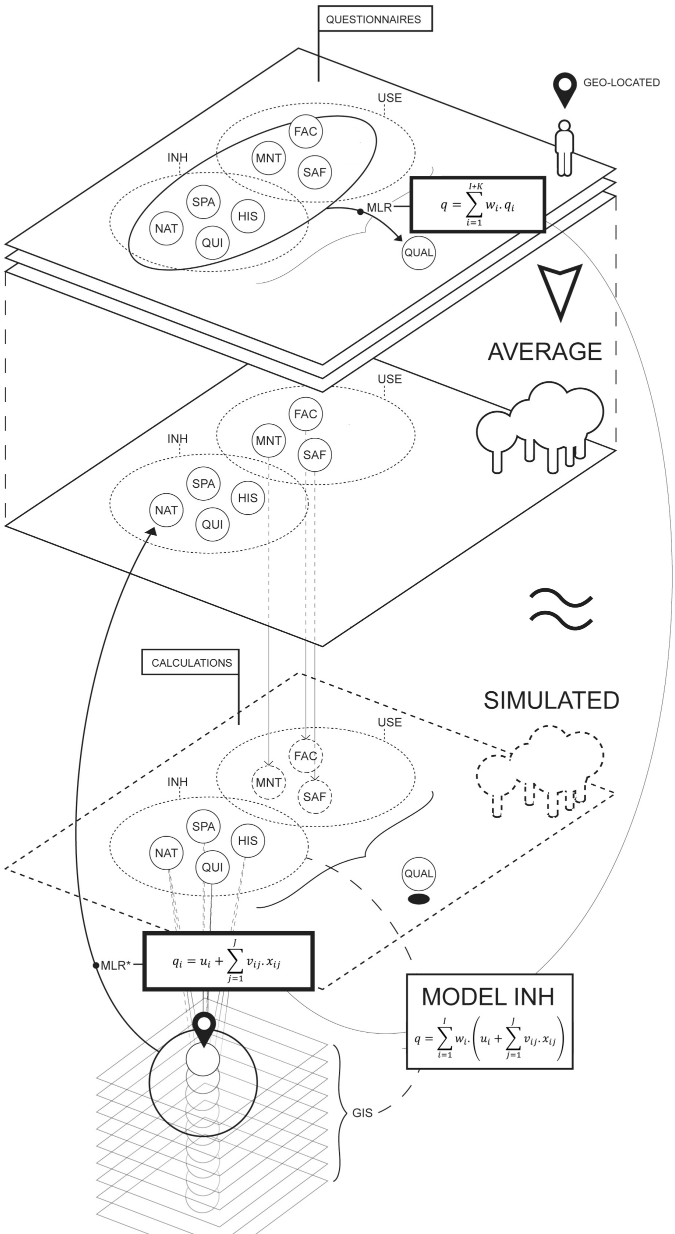


Figure 3: Conceptual scheme of the proposed approach for assessment of green space quality. The top layers represent questionnaire responses, from which the sub-quality weights are derived through MLR. The average sub-quality ratings per GS (middle layer) constitute the dependent variables for the second MLR(*) with GIS-based metrics as independent variables. The model for inherent GS quality is obtained by integration of both regression models (GIS-based) and approximates the average inherent quality from the user's perspective (questionnaire-based).

2.3 Results

2.3.1 *Questionnaire results*

The survey resulted in 371 responses of which 349 entries were considered complete and valid, and being part of a group of 10 or more responses per GS. The campaigns of 2015 and 2016 resulted in 51% and 49% of the total number of responses respectively. The majority of the responses were gathered on site (87%). Since exactly the same interface and questions were used for the online and on-site questionnaires, the matching of samples from both surveys was deemed justifiable. Per GS, 3-5 respondents on 10 indicated to identify most with a non-Belgian country. In each GS maximum two of these identified with the same country. While the question of cultural affinity is not the same as inquiring about nationality, the percentage of non-Belgian nationalities throughout the different communes in the Brussels-Capital Region (18% - 49%) corresponds to these values in a broad sense (Statistiek Vlaanderen 2018). The overall rate of male to female in the sample is 49:51 and maximally varies between 1:2 and 2:1 per GS.

2.3.2 *Perceived importance of sub-qualities and relation to cultural differences and gender*

Table 6 shows each sub-quality's importance, as rated by the questionnaire participants. In this table, the ratings were scaled from the questionnaire format (0-3) to the scale 0-1. It appears that the average respondent rates naturalness and biodiversity, and historical and cultural value as substantially less important than the other sub-qualities. For people not culturally identifying with Belgium or with Catholic-European culture, ratings for naturalness and biodiversity and for historical and cultural value are even lower. It should be mentioned though that the sample size of people identifying with countries other than Belgium is too low to draw firm conclusions about cultural variations in the reported importance of different sub-qualities, even when clustered in groups from the Inglehart-Welzel classification, i.e. nine clusters worldwide (Inglehart and Welzel 2010). The reason is that 165 respondents chose not to disclose the optional information about cultural background. Large clusters are Catholic-European $(n = 160)$ versus people not from this group $(n = 46)$, as well as Belgian $(n = 125)$ versus non-Belgian respondents $(n = 81)$. The strongest differences in reported importance for Belgian versus other than Belgian respondents pertain to naturalness and biodiversity ($\Delta_{avg} = 0.28$), historical and cultural value ($\Delta_{avg} = 0.13$), and cleanliness and maintenance ($\Delta_{avg} = 0.09$). These differences are all significant when subjected to a T-test with $\alpha = 0.05$ (Table 7), while the differences reported for other sub-qualities are not significant. The former two qualities are more important to Belgian respondents than to 'other than Belgian' respondents, while the latter, cleanliness and maintenance, is more important to 'other than Belgian' respondents. All sub-qualities are rated slightly more important by women than by men, with the difference in rating for feeling of safety and quietness being most pronounced. However, only the difference in importance of the quality 'feeling of safety' seems to be indicative of a possible gender effect, although not significant at the 0.05 level.

2.3.3 *Modelling of sub-quality weights*

MLR analysis without intercept was conducted to predict the overall quality of GS as perceived by the user from the questionnaire ratings of the different sub-qualities. First, a collinearity test was performed between all pairs of variables, which indicated little ($r \leq 0.30$) to low ($0.30 < r \leq 0.50$) correlation (Hinkle, Wiersma et al. 2003) for all combinations (Table 7), with the highest correlation for SPA vs. QUI, and SAF vs. MNT and FAC. This relates to verbal feedback from questionnaire participants stating that spaciousness generates quietness while cleanliness and maintenance or decent facilities generate a feeling of safety. NAT and HIS have the lowest correlation with the other variables. In the MLR, HIS appeared to be not significant, so the variable was removed. Without HIS, a correlation of $r = 0.74$ between predicted and perceived overall quality was obtained. This relatively low correlation can be attributed to differences in judgment between individuals on the relative importance of the various GS sub-qualities. When the coefficients obtained are applied to the average response per GS, the correlation reaches $r = 0.92$ (Figure 4) and $r = 0.82$ for the validation set. Hence, the valuation of sub-qualities provides a good explanation of overall quality as reported by the respondents. This implies that overall quality can be conceptualized as a weighted combination of sub-quality ratings with weights obtained through MLR.

Importance according to respondent	*NAT*	*QUI*	*HIS*	*SPA*	*MNT*	*FAC*	*SAF*
Average	**0.46**	**0.69**	**0.30**	**0.62**	**0.75**	**0.64**	**0.67**
Women	*0.47*	*0.71*	*0.31*	*0.62*	*0.75*	*0.64*	*0.68*
Men	*0.46*	*0.67*	*0.29*	*0.61*	*0.73*	*0.64*	*0.64*
Belgian*	0.62	0.69	0.37	0.63	0.71	0.62	0.65
Catholic European**	0.57	0.68	0.34	0.61	0.72	0.63	0.65
Other than Belgian*	0.34	0.71	0.24	0.63	0.80	0.67	0.68
Other than Catholic European**	0.31	0.71	0.22	0.66	0.80	0.65	0.67
T-test p-value women-men	*0.27*	*0.20*	*0.18*	*0.10*	*0.28*	*0.56*	*0.09*
T-test p-value Belgian-other than Belgian	<0.01	0.25	0.03	0.18	0.05	0.26	0.46

Table 6: Average rating of a sub-quality by respondents of the survey from 'not important' (0), over 'somewhat important' and 'important' to 'decisive' (1). (*, **) indicates regions to which respondents feel culturally most connected and does not depict nationalities. (**) is a clustering of nations according to the Inglehart-Welzel classification. Significance of differences is indicated by the p-value of an unpaired T-test comparing average ratings for different subgroups of the population.

[*r*]	*MNT*	*NAT*	*QUI*	*HIS*	*SPA*	*FAC*	*SAF*
MNT	1	-	-	-	-	-	-
NAT	0.19	1	-	-	-	-	-
QUI	0.27	0.18	1	-	-	-	-
HIS	0.17	0.29	0.01	1	-	-	-
SPA	0.28	0.11	0.49	-0.01	1	-	-
FAC	0.34	0.17	0.31	0.03	0.36	1	-
SAF	0.42	0.10	0.34	0.05	0.23	0.38	1

Table 7: Collinearity of variables (Pearson correlation).

	MLR coefficients, no intercept	Normalized MLR coefficients (weights)
NAT	0.11	0.10
QUI	0.15	0.14
HIS	n.a.	n.a.
SPA	0.18	0.16
Share INH	**40%**	**40%**
MNT	0.33	0.31
FAC	0.22	0.20
SAF	0.09	0.09
Share USE	**60%**	**60%**

Table 8: MLR coefficients and relative weight of sub-qualities.

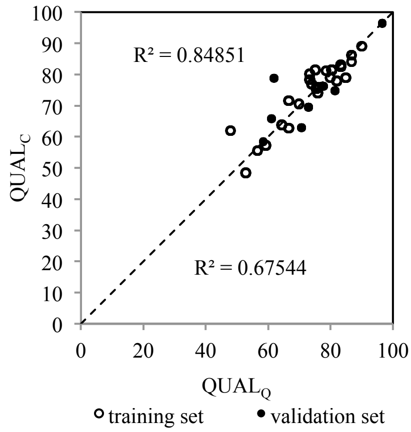


Figure 4: Correlation between reported overall quality ($QUAL_Q$) and GS quality calculated from reported sub-quality ratings ($QUAL_C$), based on MLR of overall quality. Coefficients of determination indicated above the 45° line refer to the training set (model fit), below refer to the validation set (model validation).

Variable	NAT	SPA	QUI
Intercept	x	x	x
f_{BIO}	x		
f_{GRE}	x		o
f_{TRE}	x	x	o
f_{WAT}	x		o
$f_{BIO} \cdot f_{TRE}$	x		
$f_{BIO} \cdot f_{GRE}$	o		
$f_{BIO} \cdot f_{WAT}$	x		
R_{inscr}	x	o	x
A	x	x	x
$\sqrt{A}$		o	
P		o	
$\sqrt{P}$		o	
$A.f_{TRE}$	o	x	
$P.f_{TRE}$		o	
$R_{inscr} \cdot f_{TRE}$		x	
NOI_{avg}			x
NOI_{min}			o

Table 9: Variables included in the modelling. The variable selection method is backward elimination, starting with variables indicated by 'x' and 'o', to arrive at variables indicated by 'x'.

When we assign responsibilities to the different sub-qualities, one can say that city maintenance services have a strong responsibility for the sub-quality facilities (20% of total weight) and an influence on - or shared responsibility for – naturalness, maintenance and cleanliness, and the feeling of safety (50%) (Table 8). Users have a shared responsibility for cleanliness and maintenance, and the feeling of safety (40%). Designers and developers of public space construction codes have a unique responsibility for the sub-qualities spaciousness and quietness (30%), and an influence on all sub-qualities (100%).

2.3.4 *Inherent quality assessment using GIS-based indicators*

To predict questionnaire-based sub-quality ratings from GIS data, first a selection was made of indicators potentially contributing to the assessment of *NAT*, *SPA* and *QUI* (Table 9). The selection of variables includes cross-product terms to deal with possible interaction effects between some of the indicators. Using backward elimination, the variables with the highest p-level were removed until for each remaining variable the null hypotheses could be rejected ($\alpha < 0.05$). As explained in the method section, to calibrate and validate the models for *NAT*, *SPA* and *QUI*, an independent training set of 256 questionnaire responses (25 GS) and a holdout validation set of 93 responses (9 GS) were used. Table 10 shows the model definition for each of the inherent sub-qualities. For use-related sub-qualities, which cannot be assessed from the available GIS-data, the average sub-quality ratings of minimum 10 questionnaires per park were used to define use-related quality (*USE)* for each GS.

$$QUI_{C,ALT} = -2{,}857. NOI_{AVG} + 208$$

(Eq. 5)

With NOI_{AVG} being the average sound pressure level over the green space considered. Using MLR-deduced weights, the GIS-based inherent quality of a green space is finally calculated as:

$$INH_C = 0.10 \,. NAT_C + 0.16 \,. SPA_C + 0.14 \,. QUI_C.$$

(Eq. 6)

The models enable us to extrapolate the relationships established between GIS-based metrics and perceived green space qualities for *NAT* and *SPA* to all GS in the study area and, as such, to assess both sub-qualities of these spaces taking user perception into account. The standard model used for *QUI* also enables us to assess perceived noise levels throughout the whole study area. When the three models are applied to all public GS in the BCR, the maps in Figure 6 are obtained. The maps give an idea of how different urban parks score on each of the three quality aspects considered (*NAT, QUI, SPA*). Figure 6-D shows an assessment of inherent quality for all public GS, as obtained by applying Eq. 6 and rescaling values to the 0-100 interval. By summing inherent quality (INH_C) and use-related quality (*USE*) indicators, as in Eq. 4, overall quality can be calculated for all GS when questionnaire data are available ($QUAL_C$). A comparison with the average overall quality per GS, as obtained from the questionnaire ($QUAL_Q$) shows a strong relationship between modelled and observed quality assessment (Figure 5, bottom right), with R^2 values of 0.76 and 0.66 for the model calibration and model validation dataset respectively.

Code	Sub-quality equations
$QUAL$	$= INH + USE$
where:	
INH	$= 0.10.NAT_C + 0.16.SPA_C + 0.14.QUI_C$
USE	$= 0.31.MNT_Q + 0.20.FAC_Q + 0.09.SAF_Q$
where:	
NAT_C	$= a + b.f_{BIO} + c.f_{TRE} + d.f_{GRE} + e.f_{WAT} + f.f_{BIO}.f_{TRE} + g.f_{BIO}.f_{WAT} + h.A + i.R_{inscr}$
SPA_C	$= j + k.A + l.f_{TRE} + m.A.f_{TRE} + n.R_{inscr}.f_{TRE}$
QUI_C	$= o + p.NOI_{avg} + q.A + r.R_{inscr}$ (later replaced by $QUI_C = -2{,}857.NOI_{avg} + 208$)
MNT_Q	Average rating of min. 10 questionnaires/park on a scale of 0-100
FAC_Q	Average rating of min. 10 questionnaires/park on a scale of 0-100
SAF_Q	Average rating of min. 10 questionnaires/park on a scale of 0-100
where:	
f_{BIO}	Fraction of biologically valuable zones and/or composed zones with presence of biologically valuable elements (a)
f_{GRE}	Fraction of land covered by vegetation (b)
f_{TRE}	Fraction of land covered by dense vegetation or tree canopies (c)
f_{WAT}	Fraction of land occupied by water (d)
NOI_{avg}	GS average of the combined simulated sound pressure level of air, rail and road traffic (Lden) [dB]
A	GS area [m^2] (e)
R_{inscr}	Radius of the largest possible inscribed circle in the GS [m] (f)

Table 10: Relation between overall quality (QUAL), inherent (INH) and use-related (USE) quality and sub-quality ratings as perceived by users of GS, as well as relations between GIS-based metrics describing properties of GS and inherent green space sub-quality ratings (ratings vary between 0-100). Labels (a) – (f) appear in Table 3 in order to clarify which source was used to calculate the variables.

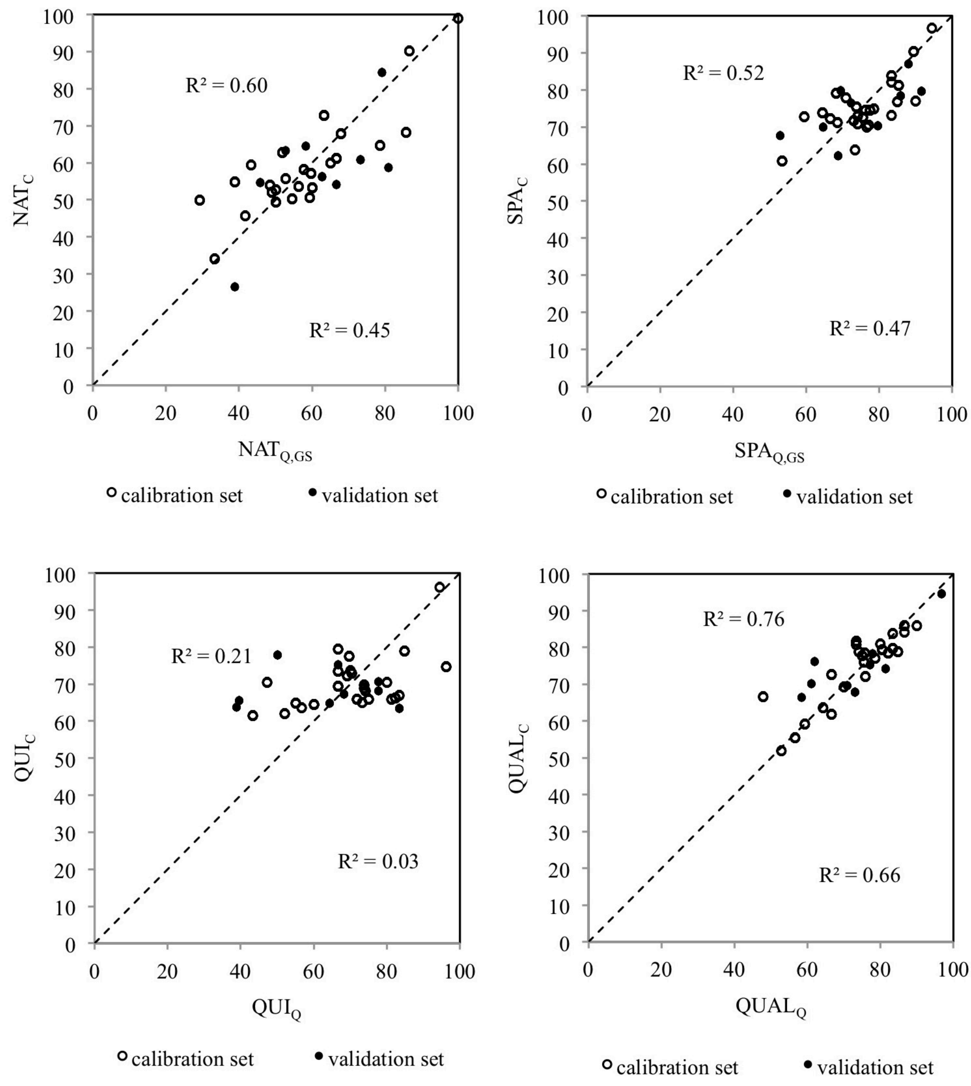


Figure 5: Scatter plots of questionnaire-reported (Q) against calculated (C) (sub-) quality ratings for naturalness and biodiversity (*NAT*), spaciousness (*SPA*), quietness (*QUI*) and overall quality (*QUAL*). Coefficients of determination indicated above the 45° line refer to the calibration set (model fit), the ones below the line refer to the validation set (model validation).

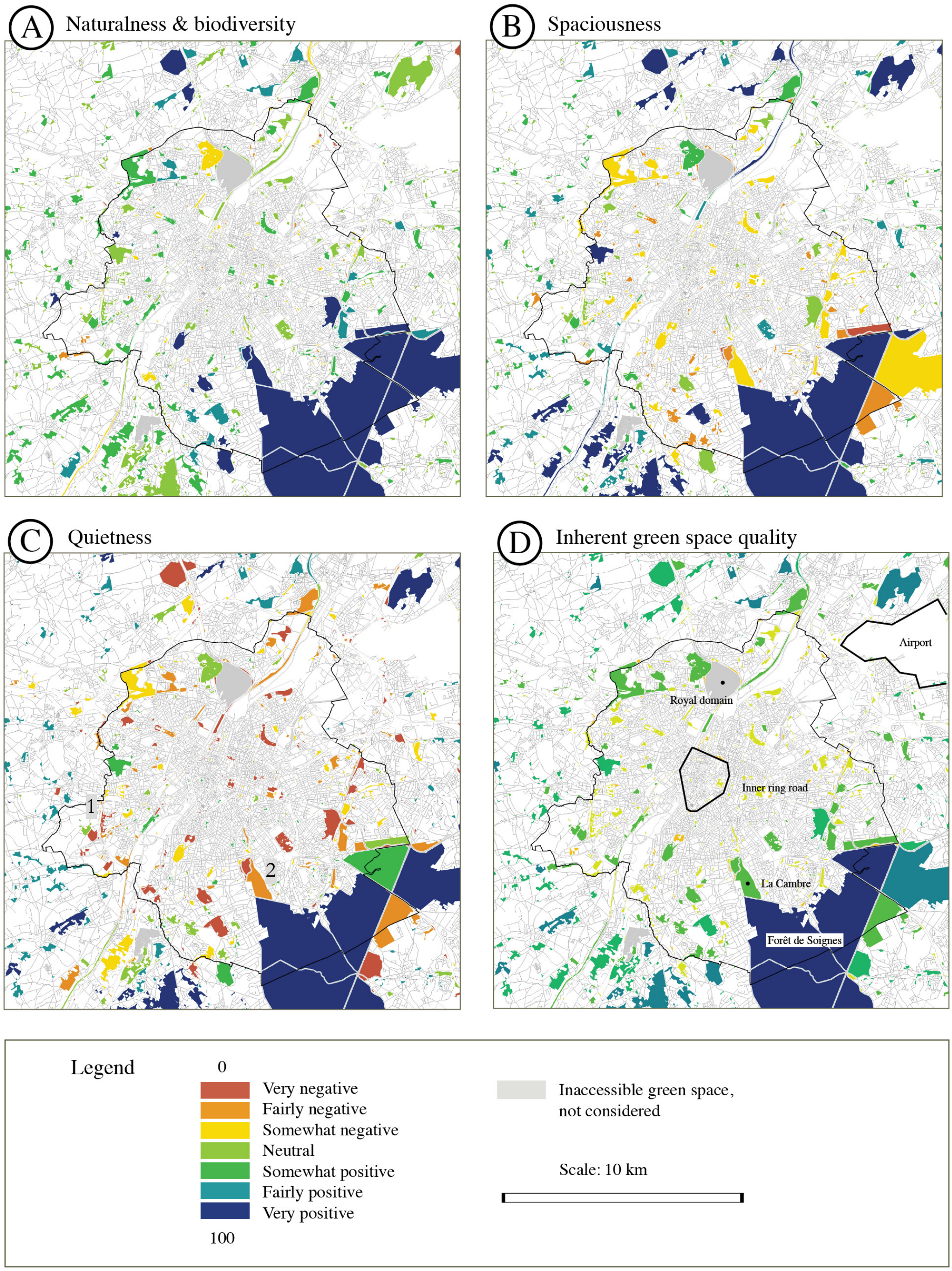


Figure 6: Naturalness and biodiversity, spaciousness, quietness and inherent quality of green spaces in Brussels. The outline shown represents the Brussels-Capital Region, surrounded by the Flemish Region.

2.4 Discussion

Improving our understanding of how people experience UGS and how they value UGS qualities is important for policy makers and planners, as it may inform them how to design and manage UGS that meet user needs (Wan and Shen 2015, Lindholst, Konijnendijk van den Bosch et al. 2016, Chang, Qu et al. 2017). Our survey results demonstrate that cleanliness and maintenance, quietness and safety are perceived as the most important qualities of UGS in the BCR, followed by the presence of adequate facilities and spaciousness. The important role of what we have referred to in this study as use-related qualities (cleanliness and maintenance, safety, facilities) in green space perception is confirmed by many other studies. In a comparative analysis on four European cities, Bertram and Rehdanz (2015) identified cleanliness and low crime as the most important characteristics determining park visitors' perception of UGS. A recent study on preferences for UGS characteristics in three Portuguese cities highlights cleanliness and maintenance as the most important attribute of UGS (Madureira, Nunes et al. 2018). Earlier studies by Jim and Chen (2006) and Qureshi, Breuste et al. (2013) also point at the importance of cleanliness and maintenance in the use and valuation of UGS. Gender differences in perceived importance of use-related qualities prove to be weak, which is also found in other studies (Jim and Shan 2013). Only with respect to safety a slight gender effect is observed. This corroborates the findings of other work indicating that women are more concerned about security in UGS than men (Burgess, Harrison et al. 1988, Sanesi and Chiarello 2006, Sreetheran and van den Bosch 2014), unless the spaces have a cultural understanding as 'safe' in specific countries (Jansson, Fors et al. 2013).

Of the inherent GS qualities identified in our study quietness and spaciousness are perceived as most important, while naturalness and biodiversity as well as historical and cultural value receive lower importance ratings. The relatively low importance attached to naturalness contrasts with the results of other studies on perception of GS characteristics (Bertram and Rehdanz 2015, Kothencz, Kolcsár et al. 2017, Madureira, Nunes et al. 2018). It draws attention to the fact that, while some GS characteristics may be valued similarly in different cities, beliefs about the importance of GS features may also differ depending on local context. Indeed, while observed differences in importance of sub-qualities between studies and cases can be partly attributed to the chosen methodology and questionnaire setup, several studies have also emphasized that preferences for GS may be strongly influenced by complex interactions between GS supply and demand, and benefits which residents obtain from GS (Voigt, Kabisch et al. 2014, Zhang, van Dijk et al. 2015, Kremer, Hamstead et al. 2016). Such interactions may depend on multiple factors, including the physical characteristics and accessibility of GS (Bertram and Rehdanz 2015) and the size, density and morphology of the surrounding urban area (Kothencz and Blaschke 2017). Madureira, Nunes et al. (2018) hypothesize that city size may be a factor in explaining the preference for some sub-qualities of GS, indicating that quietness - which came out as the most important inherent quality of GS in our study - seems to be rated as more important in larger, densely populated cities. The fact that naturalness is perceived as less important by GS visitors in our study may have to do with the inclusion of both small and larger GS. Naturalness seems to be considered as more important in larger GS (Bullock 2008). Verifying this hypothesis would require a more detailed study, focusing on use and valuation of GS of different size, offering different facilities. Also socio-demographic characteristics of park visitors, social practices and cultural context affect the way in which people use GS and experience and value their contacts with nature (Plieninger, Dijks et al. 2013, Voigt and Wurster 2015, Camps-Calvet, Langemeyer et al. 2016). This may also play a role in the perceived importance of naturalness. As our results show, GS users that culturally identify as non-Belgian – which represent a large group – perceive naturalness as less important, while "Belgian" GS users rate naturalness equally high as spaciousness and presence of adequate facilities. As indicated in other recent studies, generic assumptions about GS preferences should be avoided (Madureira, Nunes et al. 2018). Given the diversity of preferences, a one size fits all approach for the design and management of UGS will not meet the general publics' needs and desires (Howley 2011). Ultimately, public GS design should be tailored to various cohorts of citizens, as it relates directly to the citizen's quality of life. Cities often show a cultural stratification in neighborhoods. Due to the small attraction radius, smaller green spaces can take into account the preferences of the cultural groups that are most represented in the area, when the cultural variation in preferences is known. Larger green spaces, which have large attraction radii and have a stronger cultural mix of visitors, can be diversified in their layout and amenities.

In our study we also demonstrated that the overall appreciation of GS, as indicated by their users, can be related to user's ratings on a set of inherent and use-related sub-qualities by conceptualizing overall quality as a weighted sum of important sub-quality components. Use of a simple, additive sub-quality-based approach for valuing GS provides useful insights for the improvement of GS through design, planning and policy interventions, as it allows identifying underperforming sub-qualities per green space, per area legislative or management unit, or for the study area in general. It should be kept in mind though that while GS can be improved with a focus on specific sub-qualities, solutions should always be approached in an integrated way, taking in account context and situation, which is one of the main qualities of design as a discipline.

Following the concept of the ES cascade model, biophysical properties of GS may provide ES that potentially offer benefits to GS users (Haines-Young and Potschin 2010). Results of our study show that the inherent sub-qualities naturalness and biodiversity as well as spaciousness of GS can be informed by GIS data and that relationships between measured and reported quality, obtained from a representative sample of public GS, can be extrapolated over a larger area, using GIS-based descriptions of GS properties. The appreciation of naturalness proves to be well correlated with biological value, land-cover composition, and area-shape characteristics of parks. Naturalness and biodiversity might be improved in smaller urban parks, as well as for surroundings of (social) housing complexes or in formal parks, by introducing more local species of plants, which in turn attract more living species (Bastian 2013). Spaciousness, on the other hand, seems not only dependent on surface area, but also on shape of the area and tree cover fraction. The influence of tree cover corresponds to the statement of Grahn (1991) that the feeling of space depends on the unawareness of limited dimensions of GS (Van Herzele and Wiedemann 2003). Knowledge on how the physical and spatial structure of the landscape affects user valuation is instrumental for urban planners and green space managers and may help in guiding improvements to parks that either exist already or are envisioned for the future.

Perceived quietness proved harder to model based on GIS data. The low correlation observed between modelled and reported quietness may be due to various reasons: a) the inquired ratings of quietness (QUI_Q) were obtained at varying points in time, thus with significantly differing noise levels depending on the hour, day of the week and various contingencies, unlike the GIS-based maps which describe sound pressure level averages based on estimated traffic volumes for 24h weekdays; b) the rating of quietness may be more dependent on specific locations in the park than the rating of naturalness and spaciousness; c) the masking effect by pleasant sounds leading to a decreased perceived loudness (Coensel, Vanwetswinkel et al. 2011) could not be taken into account; d) aircraft noise has been found to be more annoying and railway noise less annoying than noise caused by car traffic (Miedema and Vos 1998), however, the conversions proposed in the "Genlyd" Noise Annoyance Model (Pedersen 2007) could not be applied here since the noise map for the BCR does not include separate values for road, rail and air traffic. Simulated sound pressure maps for different source types based on models calibrated for different moments of the day might increase the correlation between GIS-based noise analysis and the quietness sub-quality as perceived by GS users.

In terms of naturalness and biodiversity, ratings obtained for the BCR are especially high for larger areas or stream-bound GS (Figure 6-A). Spaciousness for areas of the same size is higher in (semi-)rural areas. In urban areas, small to medium sized parks in the center and the 19th century belt tend to score low on spaciousness (Figure 6-B). Although the larger share of parks in the Brussels area is not influenced by highway noise (Figure 6-C), special attention should be given to peripheral GS crossing the Brussels Ring (Figure 6-C-1), since they connect the city to the hinterland, in the case of Brussels often as part of a tributary valley. Currently, noise shielding is rarely present for GS. This technique is mostly used for lowering the impact of traffic noise on residential areas, but could also be used to improve quietness in GS. Scenic roads through forested areas, e.g. the La Cambre park (Figure 6-C-2), take their toll on the parks' quietness, but equally on their spaciousness, as they split up the parks in smaller segments (Figure 6-C-1).

In general, inherent quality appears to be high in either large GS or peri-urban GS. Therefore, the proposed model is especially useful for improving small to medium scale urban GS. For peripheral GS, a more specific green space valuation process is needed that would evaluate the role of agricultural land use in green space perception.

The valuation of GS in this study does not reflect the recreational use of agricultural areas, where perceived GS constitutes a combination of publicly accessible roads or paths and privately owned farmland. Defining a green space valuation method that includes the way farmland contributes to the experience of GS could alter the modelling of spaciousness for peripheral GS, as well as other green space qualities.

Within the proposed methodology, more detailed surveys can improve the models proposed. Striving for a full inventory on use-related qualities will allow the modelling approach to be extended to an assessment of the overall quality of GS. The research would also benefit from including community and social diversity related aspects, regularly cited in other studies on the valuation of GS (e.g. Germann-Chiari and Seeland 2004, Kingsley and Townsend 2006, Arnberger and Eder 2012, Bertram and Rehdanz 2015). Currently, model parameters are based on the average questionnaire respondent, yet a more extended survey dataset would allow for including parameters pertaining to spatially explicit cultural differences among green space users. This is especially relevant for Brussels, due to the strong cultural differences between and within neighborhoods. With culturally articulated weightings, policy and design proposals can better serve the local population.

Future research should also involve proximity between residents and the GS they visit as a precondition for use, as well as explore the potential of the generated indicators for urban design, planning and policy making through design research or design charettes and scenario-based simulation workshops.

2.5 Conclusions

A new approach for green space analysis in an urbanized environment has been presented in the form of a tool for mapping perceived quality of GS. Conceptually, the tool is inspired by research where quality has been studied as a combination of quality characteristics, or sub-qualities (Van Herzele and Wiedemann 2003, Eng and Niininen 2005). Through a literature study, seven sub-qualities were defined: three use-related (MNT, FAC, SAF) and four inherent sub-qualities (NAT, SPA, QUI, HIS). All sub-qualities as well as their relative importance can be informed by means of questionnaires. Based on questionnaire output, a model was proposed describing the perceived quality of GS as a weighted linear combination of the sub-qualities identified. Scholars as Van Herzele and Wiedemann (2003) have studied the formulation of sub-quality indicators through the use of standards informed by GIS data and expert surveying and thus made important steps in the spatial analysis of green space quality. However, this study tries to avoid the use of standards and expert surveying, in order to directly link GIS data with a user perception of quality. The statistical analysis of questionnaire data allowed to: determine the relative importance of sub-qualities (i.e. weighing factors), and; predict the perceived quality of certain sub-qualities directly from GIS data.

The objective of this study was to assess the impact of different features of UGS on how GS are perceived and to enable GIS data for green space valuation and design, matching the user's perspective. The proposed methodology conceptualizes the perceived quality of UGS as being the result of an appreciation of several sub-qualities. Through a literature study, seven sub-qualities were defined: three use-related (MNT, FAC, SAF) and four inherent sub-qualities (NAT, SPA, QUI, HIS). All sub-qualities as well as their relative importance can be informed by means of questionnaires. Based on questionnaire output, a model was proposed describing the perceived quality of GS as a weighted linear combination of the sub-qualities identified.

Results of the research demonstrate that the user's perception of inherent qualities such as 'naturalness and biodiversity' (NAT) and 'spaciousness' (SPA) can be modelled by available GIS-based data, with model results showing a clear correspondence with quality rankings as perceived by citizens. The GIS-based models allow for an extrapolation of questionnaire-based quality assessments of a selection of parks to all public GS in the area studied. The developed model and the proposed green space quality indicators can support planners, designers and policy makers to imagine scenarios for improving GS and test these scenarios spatially for their predicted impact on perceived quality. This is a valuable asset, since development strategies which fail to provide for properly planned GS may be detrimental to neighborhood quality of life (Douglas, Russell et al. 2018). Scenarios may encompass the spaces themselves, as well as external features such as traffic regulation, management strategies and user involvement. Hopefully the actors will adopt a more integrated approach for the development of recreational UGS and enhancing their cultural ecosystem services in general based on the provided quantitative decision support.

The model is still limited as to its ability to describe use-related sub-qualities. It also does not incorporate community and social diversity related aspects. However, through a more extensive survey targeting specific population groups, and with the emergence of more citizen involvement in local GS, this hiatus can be addressed. GS quality assessment can also be coupled to a proximity and accessibility model (precondition for use) to assess how local residents are served in terms of public urban green, as reported in (Stessens, Khan et al. 2017).

3

3 Analysing urban green space accessibility and quality — A GIS-based model as spatial decision support for urban ecosystem services in Brussels

Abstract

With the majority of people living in cities, urban green spaces are the primary source of contact with nature. Access to ecosystem services provided by urban green spaces is increasingly perceived as an important factor for quality of life, and it is a key component of sustainable urban design and planning. This chapter presents a novel GIS-based tool to evaluate accessibility to – and quality of – urban green spaces. To demonstrate the tool's applicability, it was implemented in Brussels. A series of indicators to evaluate the proximity to and quality of green spaces is proposed in the light of the analysis with the aim of supporting decision making and planning at the urban scale. The proximity and quality sub-models were parameterised through a comparative study of planning standards and through analysis of local preferences, acquired by means of a questionnaire. Applying the model to Brussels showed that approximately equally sized population groups have low, medium, and high access to green spaces. Concerning the proposed method for measuring green space quality, 62% of the population resides in urban blocks with access to green spaces with a lower than average quality score, which reveals a significant margin for improvement.

Research Highlights

- A GIS model is proposed for mapping green space proximity at the level of urban blocks.
- Proximity and green space quality are combined into a single indicator.
- An analysis is conducted for the Brussels Capital Region and its surroundings.
- Areas with high and low scores in terms of green space provision are mapped.
- Design and policy options can be simulated for green spaces' quality and proximity.

Based on: Stessens, P., A. Z. Khan, M. Huysmans and F. Canters (2017). "Analysing urban green space accessibility and quality: A GIS-based model as spatial decision support for urban ecosystem services in Brussels." Ecosystem Services 28: 328-340.

3.1 Introduction

3.1.1 *Premise*

Green infrastructures have gained importance in planning and policymaking (Pulighe, Fava et al. 2016), thanks to the ecosystem services (ES) they provide for city dwellers (Tzoulas, Korpela et al. 2007) and their potential for climate change mitigation and adaptation (Demuzere, Orru et al. 2014). Since the last decade of the 20th century, the ES concept has become increasingly important in the debate on sustainability and quality of life (Lappé 2009, Burkhard, Petrosillo et al. 2010). It is considered the missing link between ecosystems and human well-being (Neßhöver, Beck et al. 2007). In accordance with the Millennium Ecosystem Assessment (MEA) (2005) report, in this study urban green spaces (GSs) are considered providers of regulating and cultural ES, contributing to the quality of life of urban citizens. The presence of GS has a positive impact on air quality, climate, and the hydrological cycle in urban areas. GSs also provide recreational facilities for residents, offer a place of refuge from the busyness of daily life, and bring residents into contact with nature (Reid 2005, Sandifer, Sutton-Grier et al. 2015, Bennett, Cassin et al. 2016).

In cities around the world, urban growth presents numerous challenges for the provision and maintenance of urban GSs and, consequently, also for human health and well-being (Tzoulas, Korpela et al. 2007). Effects of current and predicted climate change exert additional stress on urban environments through the increased occurrence of heat waves, droughts, flooding, and water supply problems (IPCC 2007). These prospects challenge urban planners and policymakers to move beyond solely managing the urban landscape (Pulighe, Fava et al. 2016) – and to take up and incorporate the concepts of ecosystems functions, resilience, sustainability, biodiversity, and human well-being into the urban governance agenda and policies (FAO 2011, Hansen, Frantzeskaki et al. 2015).

At the policy level, more attention is given to and action directed at the dependence of humans on nature and its ecosystems. However, knowledge about the link between green infrastructure and ES delivery, as well as its potential for urban planning and management, is still limited (Baró, Haase et al. 2015). Currently, nature development institutions, planning agencies, urban development agencies, infrastructure departments, and researchers, both internationally (Beatley 2014) and in the context of Brussels (Loeckx, Corijn et al. 2016), are calling for combining ES and ecology-driven approaches to achieve sustainable urban development. The Brussels Capital Region (BCR) had an expected population growth of 14,000 per annum over a population of 1,167,951 in 2015 (FOD Economie 2013). This makes well-informed densification strategies a pressing issue, of which maintaining and improving accessibility and quality of public GSs is a crucial part. Furthermore, to successfully tackle major challenges (sustainability, climate change, social exclusion, economic deprivation, and uneven development) in the field of urban design and planning (Madanipour 2006, Khan 2010), an integrated ecosystems approach will be necessary (Khan, Moulaert et al. 2013).

The complexity of the current and future challenges urban areas are facing has led to the development of a diversity of tools and design criteria, especially at the local scale (Beatley 2000). To arrive at – and support – apt policies and interventions for urban design and planning, reliable methods and means of analysis, scenario development, and assessment are needed. Through this research, we seek to contribute to the development of a robust methodological framework for assessing public GS provision and its ES, focusing on proximity to GSs as well as their perceived quality. This challenge is approached by means of data-driven geographical information system (GIS) modelling, resulting in a GIS-based spatial decision support tool for designers, planners, and policymakers. From existing spatial datasets or user-created scenarios, the tool generates both spatially explicit and general indicators for the availability and quality of GSs for urban residents. The underlying motivation for our research is (1) to arrive at a better understanding of the nature–human interaction for urban design and planning, and (2) to provide an objective basis for interdisciplinary discussion and collaboration on the topic of ES provided by urban GSs.

3.1.2 *Functional levels*

Since early modern urban planning, multiple standards and indicators have been developed to quantify access to and attractiveness of urban GSs. These include simple area-based indicators, e.g. open space area per person, as described by Richard

Baumeister in 1876, or the open space area ratio (OSR), which is calculated by dividing open space area by the total floor area instead of by the number of people. In 1952, the Stockholm General Plan, inspired by the Regional Planning Association of America (RPAA) and much of Abercrombie's work (e.g. the 1944 Greater London Plan (Abercrombie 1944)), prescribed a standard of 300 m as the maximum distance to playgrounds, following a questionnaire at Stockholm's kindergartens (Stockholms stadsplanekontor 1952). This, together with RPAA's neighbourhood unit paradigm, is one of the early examples of mainstreaming the use of an 'accessibility-' or 'location'-based measure for public GS provision in urban planning.

During the 1960s and 1970s different kinds of GS descriptive measures were proposed to define open space standards. The National Recreation and Playground Association in the USA (Lancaster 1983), the European Common Indicators in the EU (Tarzia 2003, Cassatella and Peano 2011), English Nature in the UK (Harrison, Burgess et al. 1995), and the National Board of Housing Building and Planning in Sweden (Boverket 1999) published guidelines on GS accessibility. Common among them has been the idea of relating distance to GS (e.g. 300 m) to the size of open space. This concept has been applied in several GS studies (Van Herzele and Wiedemann 2003, Giles-Corti, Broomhall et al. 2005, Choy and Prineas 2006, Kong, Yin et al. 2007). The rationale behind this approach is that the size of a GS determines the range of functions or activities the GS is able to support. This is referred to as the GS's functional level, and residents will be prepared to cover longer distances to reach a larger GS, because of its improved offer in terms of amenities, potential uses, and benefits. Each functional level is thus linked to a particular size range and to the maximum distance people are willing to cover to get to a GS of that size. Functional level thus reflects attractiveness in terms of size and accessibility in terms of distance. This idea is supported by various empirical studies (Crouch 1994, Berggren-Bärring and Grahn 1995) as cited in (Van Herzele and Wiedemann 2003).

GIS has made it relatively easy to work with standards in the literature related to the functional level concept. The question remains, however, whether these distance-versus-size standards are true to human experience. Few scientific studies have addressed this question (Van Herzele and Wiedemann 2003, De Clercq, De Wulf et al. 2007, Ståhle 2010). The findings in these studies indicate that a more thorough consideration of the concepts of attraction and accessibility is needed (Ståhle 2010). Fundamental to the concept of functional levels is that their classification constitutes a nested hierarchy. The latter allows higher functional levels (related to larger spaces) to embed lower levels (related to smaller spaces). Size can provide only an indication of the functions a particular GS may potentially provide, and it does not necessarily correspond to the actual uses or benefits the GS supports. Therefore, in this chapter we will refer to the concept of size-related functionality as theoretical functional level (TFL). Each TFL will be assumed to have a specific attraction radius (i.e. consensus of maximum travel distance). As indicated above, the naming of different TFLs thus usually corresponds to the typical scale of the area the GS is assumed to serve (e.g. neighbourhood scale).

3.1.3 *Combining proximity and quality*

Van Herzele and Wiedemann (2003) describe how Coeterier (2000) used Herzberg's two-factor theory (Herzberg, Mausner et al. 1959) to explain how urban environments are perceived and used. Restrictions determine whether people will actually visit a particular urban environment. These are referred to as 'preconditions' for use. Distance has been found to be the most important precondition for use of GSs (e.g. Grahn 1994). Once the preconditions are fulfilled, 'satisfiers' (in the case of GSs, qualities such as unity – forming a complete and harmonious whole – naturalness, and facilities) will determine how long users will be inclined to stay. Human–environment studies in different western countries have shown remarkably consistent cross-cultural universal patterns in people's preferred environments (Van Herzele 2005). Visitors prefer parks combining many features (a diversity of natural and social features), which in turn encourage many activities. Moreover, there is a relation between the availability of different features and the frequency of visits. This makes the variety of features a goal in itself, either within one GS or within the different functional levels within reach of the residents (Van Herzele and Wiedemann 2003). Apart from investigating preconditions, namely GS proximity, the quality of GSs in relation to the inhabitants' needs (satisfiers) will be modelled and assessed in this research.

3.1.4 *Approach*

This chapter presents a model to analyse and assess urban residents' access to public GSs. A proximity sub-model, based on the concept of TFL, is coupled with an existing GS quality model developed in earlier research (Stessens, Khan et al. submitted). This will make it possible to assess which TFL and which level of GS quality is within reach of each urban block and thus available to the residents. The proposed approach was applied to the BCR and may be used for scenario evaluation. Survey and questionnaire data were collected to parameterise the model and to compare TFL standards found in the literature with local preferences. The model output has been transformed into a set of spatial and non-spatial indicators that will be potentially useful for the assessment of scenarios addressing the most pressing issues related to the provision, accessibility, and quality of GS in the urban area.

3.2 Material and methods

3.2.1 *Overall model structure and input data*

The model for calculating proximity has been developed in the ModelBuilder environment of ArcGIS for Desktop, which provides a visual programming language for geoprocessing workflows. The meta-structure of the model is shown in Figure 7. The actual proximity calculation module processes three input maps: a map of urban blocks on which the final output (proximity and quality indicators) is also shown; a path raster image on which distances to GSs are calculated; and the GS layer, enriched with GS quality and sub-quality information. The last is produced for all GSs in the study area by a module for quality assessment that was developed in earlier research (Figure 7). This module is described in more detail in Chapter 2 (Stessens, Khan et al. submitted) and is summarised here in Table 11 and Table 12. GS quality is described as a weighted linear combination of inherent (e.g. naturalness) and use-related sub-qualities (e.g. feeling of safety). The former can be inferred from publicly available GIS data; the latter need to be questioned on site. Therefore, in this study only the inherent qualities were taken into account, making up 40% of the overall quality, which explains why the maximum score for inherent quality is measured on a scale of 0–40. Weights for each sub-quality were obtained through multiple linear regression

(MLR) modelling by fitting ratings that GS visitors gave to overall quality (dependent variable) for a sample of GSs, to ratings given to sub-qualities of these GSs (independent variable) (Table 11). The variables used to calculate sub-quality scores for each GS are documented in Table 12. To obtain sub-quality scores for naturalness, spaciousness, and quietness, a multi-criteria approach was used, involving multiple variables. For this study, the inherent quality of all GSs in the study area was calculated with this model, based on GIS data.

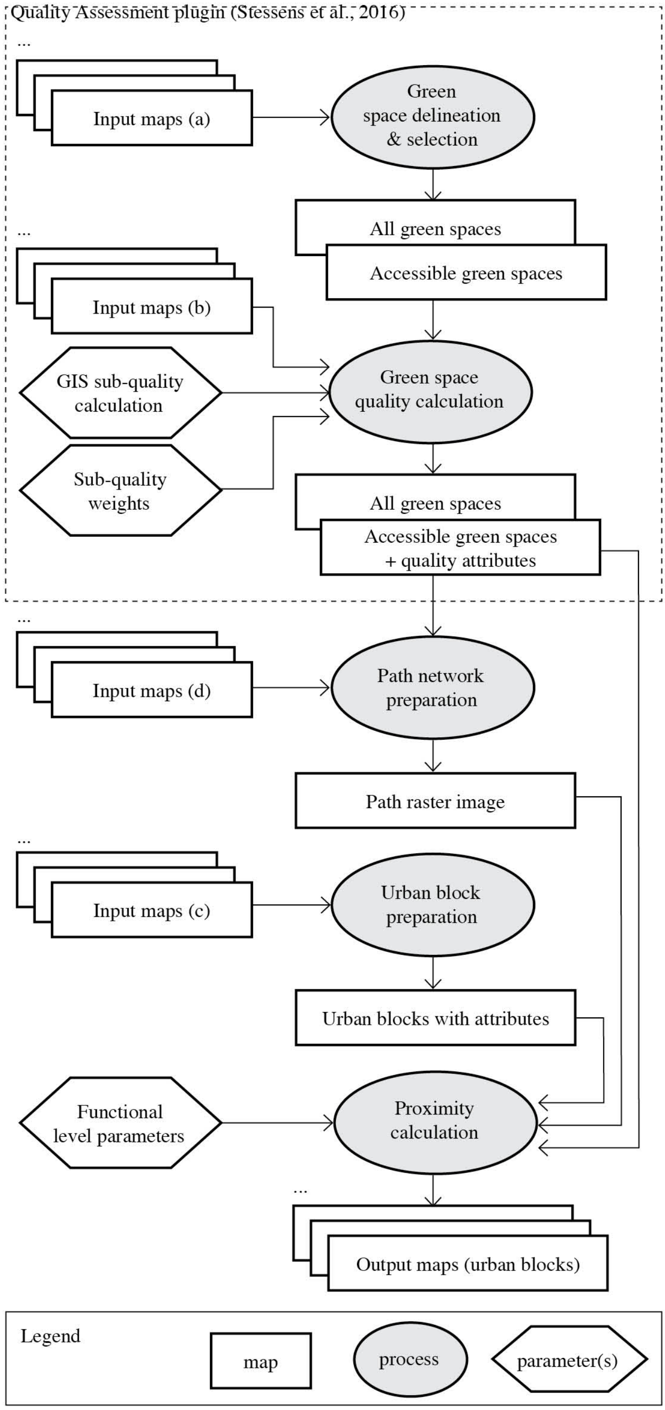


Figure 7: Model structure, proximity model with quality assessment model embedded

Code	Sub-quality weights (Stessens, Khan et al. submitted)	
Inherent qualities (INH, data based)		
NAT_C	Naturalness and biodiversity	0.10
SPA_C	Spaciousness	0.16
QUI_C	Quietness	0.14
	Share of inherent qualities	*40%*
Use-related qualities (USE, questionnaire based, average of minimum 10 questionnaires per park)		
MNT_Q	Cleanliness and maintenance	0.31
FAC_Q	Facilities	0.20
SAF_Q	Feeling of safety	0.09
	Share of use-related qualities	*60%*

Table 11: Weighting of sub-qualities in the calculation of overall quality

Code	Sub-quality equations (Stessens, Khan et al. submitted)
Inherent qualities (scale = 100)	
QUAL	= INH + USE
where:	
INH	$= 0.10.NAT_C + 0.16.SPA_C + 0.14.QUI_C$
USE	$= 0.31.MNT_Q + 0.20.FAC_Q + 0.09.SAF_Q$
where:	
NAT_C	$= a + b.f_{BIO} + c.f_{TRE} + d.f_{GRE} + e.f_{WAT} + f.f_{BIO}.f_{TRE} + g.f_{BIO}.f_{WAT} + h.A + i.R_{inscr}$
SPA_C	$= j + k.A + l.f_{TRE} + m.A.f_{TRE} + n.R_{inscr}.f_{TRE}$
QUI_C	$= o + p.NOI_{avg} + q.A + r.R_{inscr}$
MNT_Q	Average of min. 10 questionnaires/park
FAC_Q	Average of min. 10 questionnaires/park
SAF_Q	Average of min. 10 questionnaires/park
where:	
f_{BIO}	Fraction of biologically valuable zones and/or composed zones with presence of biologically valuable elements
f_{GRE}	Fraction of land covered by vegetation
f_{TRE}	Fraction of land covered by dense vegetation or tree canopies
f_{WAT}	Fraction of land occupied by water
NOI_{avg}	GS average of the combined simulated sound pressure level of air, rail and road traffic

Table 12: Parameterisation of GIS- and survey-informed sub-qualities

Path calculations in the proximity sub-model are based on road axis data (*UrbAdm_Sa* for Brussels and *GRBgis_Wbn* for Flanders). Since the road axis data have an attribute indicating the type (highway, double lane, street, path, etc.) and level (tunnel, street, viaduct) of each road, paths suited to walking and cycling could be easily selected from the dataset. Most trails through forests and fields are not part of these GIS layers. Therefore, in addition, a map of jogging tracks (generated from geo-location points uploaded by running apps for smartphones) was added to the path network. The selected GSs were integrated in the path network. Two additional scenario-specific input files can be specified when producing the final paths map: the paths to be removed in a certain scenario and the paths to be added.

GSs were delineated through selection and spatial overlay of existing GIS data (Stessens, Khan et al. submitted), listed in Appendix 8.1. Roads considered a barrier (of non-local character) were set to automatically divide GSs into parts. Urban blocks were used as the smallest spatial unit for calculating indicators. The benefit of using urban blocks are as follows: (1) indicators at the level of urban blocks can point to problems at scale levels smaller than the neighbourhood or statistical sector (i.e. the smallest unit for socio-economic statistics in Belgium); (2) the block level of detail allows for more effective design interventions; and (3) based on cadastral information, demographic data can be disaggregated from the resolution of statistical sectors to urban blocks, which in turn may be beneficial for defining interventions. In the BCR datasets urban blocks are clearly defined (*UrbMap_Bl*). For Flanders, urban blocks were defined by dissolving neighbouring parcels from the *Grootschalig Referentiebestand* (GRB) into urban block units.

3.2.2 *Defining theoretical functional levels of urban green spaces*

Apart from input maps, the model requires parameters describing the relation between GS size and attraction radius. This relation is directly linked to the concept of functional levels of GS (Van Herzele and Wiedemann 2003). As explained in section 1.2, the definition of TFLs is based on the idea that different sizes of GS provide different functions. A set of TFLs can be defined in the form of consecutive ranges of GS size, which are usually named in terms of the scale of the area that the GS serves, e.g. residential, neighbourhood, quarter, district, city, urban and metropolitan GS. In most standards, three to seven TFLs are distinguished (Lancaster 1983, Harrison, Burgess et al. 1995, Boverket 1999, Dienst Stedelijke Ontwikkeling en Beheer 2001, Ståhle 2002, Mayor of London 2008). A maximum attraction distance characterises each TFL. The criteria used in this study for defining different TFLs are based on an analysis of international standards found in the literature and used in practice (Table 13).

At first sight, the international literature on threshold values for area and distance used (in Table 13: (a) (Harrison, Burgess et al. 1995); (b) (Mayor of London 2008); (c) (Lancaster 1983); (d) Dienst Stedelijke Ontwikkeling en Beheer, 2001; (e) (Boverket 1999); (f) (Ståhle 2002); (g) Van Herzele (2005)) does not seem to show a clear consensus. Based on the definition of the various standards (Table 13), the correlation between GS area (*A*) and maximum distance (*d*) was analysed for each standard over n functional levels $(r^2(A_i, d_i) \text{ for } i = 1 \rightarrow n)$, and for the base 10 logarithm of the standards' values $(r^2(log_{10}(A_i), log_{10}(d_i)) \text{ for } i = 1 \rightarrow n)$. Correlations were found to be higher on the logarithmic than on the linear scale (Table 14). Therefore, to find out if the TFL definitions used in different standards are comparable, the relation between the minimum size and the maximum distance for different standards was described as a log-transformed linear model: $log_{10}d = a.log_{10}A + b$, or:$d = 10^{(a.\, log_{10}(A)+b)}$, subsequently referred to as $d(A)$. Eight sets of distance–size (d_i, A_i) tuples representing 36 data points were taken from the different standards (Table 13). The size–distance relationship obtained from the literature was used to calculate maximum distance (d_i) for the different TFL sizes (A_i) applied in this study.

Standard's name Functional level name	Standard's minimum size, *A (ha)* for different TFLs: Resi-dential	Play	Neighbour-hood	Quarter	District	City	Metro-politan	Standard max. dist. *d (m)*
English Nature – ANGST[(a)]								
Natural green space			2					300
Natural green space					20			2000
Natural green space						100		5000
Natural green space							500	5000
Greater London Authority[(b)]								
Small open spaces		0.4						400
Local parks and open spaces			2					400
District parks					20			1200
Metropolitan parks						60		3200
Regional parks							400	3200
US National Recreation Association[(c)]								
Neighbourhood park		0.2						800
Playfield				8				1600
Community park					10			3200
Major park						40		2350
Reservation							400	–
US Local Planning Administration								
Playground		1.2						400
Neighbourhood park			2					800
Playfield				7				800
Community park					8			2400
Major park						40		3525
Reservation							200	4700
Eindhoven GS Proximity Standard[(d)]								
Local parks			2					400
Neighbourhood park				4.25				800
District park					14			1600
City park						135		3200
National open space guidelines[(e)]								
Pocket parks	0							50
Local parks		0.3						200
District parks					10			800
Nature areas							1000	–
Stockholm open space guidelines[(f)]								
Local parks			0.5					200
District parks				5				500
Nature areas						50		1000
Van Herzele[(g)]								
Residential green	0							150
Neighbourhood green			1					400
Quarter green				5				800
District green					10			1600
City green						60		3200
Urban or metropolitan forest							200	5000

Table 13: Functional levels of internationally used green space standards. For each standard, minimum size *(ha)* and maximum attraction distance *(m)* are indicated, corresponding with the respective functional levels

Distance-area tuples belonging to:	Linear correlation r^2	Log correlation r^2
English Nature – ANGST[a]	0.53	0.89
Greater London Authority[b]	0.49	0.89
US National Recreation Association[c]	0.19	0.75
US Local Planning Administration	0.69	0.84
Eindhoven GS Proximity Standard[d]	0.89	0.94
National open space guidelines[e]	0.97	1.00
Stockholm municipal open space guidelines[f]	0.91	0.99
Van Herzele[g]	0.84	0.99
All standards combined	**0.48**	**0.80**

Table 14: Correlation of distance-area values in international green space proximity standards

Max. distance / *Min.green space size*	Function $d(A_i)$ from literature (iii)	Function $d(A_i)$ from questionnaire average (iv)
Van Herzele and Wiedemann (2003) (i)	(a)	(b)
Literature average (ii)	(c)	(d)

Table 15: Four calibration options for defining and/or validating distance–size relationships for different functional levels

To compare internationally applied standards with local references in the BCR, personal preferences for maximum travel time to neighbourhood GS, city GS and metropolitan GS were acquired through a questionnaire. During the summer of 2015 and 2016, a survey in the form of online and on-site questionnaires on GS features, quality preferences, proximity preferences, and perceived quality of GSs were carried out in three languages (English, French, and Dutch). In total, 122 visitors across 56 public GSs in the study area gave their opinion on maximum travel time. The majority of this feedback was received on site, and online participation was limited. As the respondents had to indicate their age, the sample could be verified for representativeness in relation to the actual demography of the BCR. Reported maximum travel times were converted into distance, based on average travel speed using the most suitable mode of transport: walking for neighbourhood GS, and bicycle for city and metropolitan GS. The log-transformed relationship between distance and size in the results of the survey was also investigated.

After deducing the relation $d(A)$ between minimum size and maximum distance (either standard based or survey based), thresholds could be determined for A_i to define the TFLs $((A_1, d_1), \dots, (A_n, d_n))$. Two options were considered for defining the minimum GS size (Table 15): (i) use of locally defined GS sizes as proposed by Van Herzele and Wiedemann (2003) and promoted in several Belgian studies; and (ii) use of average GS sizes based on the selection of international standards. Similarly, two options were considered for defining the maximum distance: (iii) $d(A_i)$, based on the size–distance relation derived from literature; or (iv) $d(A_i)$, based on the relation derived from the questionnaires. Ultimately two ways of defining TFLs were deemed relevant: $A_1, A_2, \dots, A_n$, as determined by Van Herzele and Wiedemann (2003), with $d(A_i)$ based on the questionnaire averages; and $A_1, A_2, \dots, A_n$, as determined by literature averages, with $d(A_i)$ based on the literature. The former option is a local and pragmatic citizen-based approach, while the latter is a literature-based approach.

3.2.3 *Measuring proximity and proximity–quality coupling*

The GIS-based proximity calculation involves three data layers: urban blocks as destinations, path network data, and selected GSs as origins. GSs were chosen as origins to save computation time. The shortest distance from a defined point in space to any other point was calculated by means of the ArcGIS CostDist function on a raster image that defines all actual walking and cycling (soft mobility) trajectories. The proximity indicators that we chose to work with in this study indicate whether or not an urban block is within reach of a specific TFL of GSs, as well as the number of different TFLs of GSs within reach of each block. The proximity and quality modelling were then coupled to calculate the quality of GSs within reach of each urban block.

GSs with the same TFL and quality (rounded to the nearest integer value) were selected and the cost-distance tool was run for each TFL/quality combination. Then, for each urban block, distance values along the block's perimeter were collected and averaged to characterise the distance between the urban block and the relevant GSs. The urban blocks within acceptable distance of the selected GSs received the quality value for that run. This value was then compared with quality scores that had been obtained in previous TFL/quality iterations for that specific TFL, in order to keep the highest value, resulting in a list of quality values per TFL for each urban block. As most experts and users confirmed that residents will be inclined to visit the GS with the highest quality that is within an acceptable distance, it is assumed that, to depict GS quality (per TFL), as it will be perceived by a resident, it suffices to consider the highest quality GS that is within reach. It should be mentioned that, because of the hierarchical character of TFL definition, GSs of a certain TFL automatically form part of GSs of all lower levels, as they are assumed to provide lower level functions as well. For example, the Forêt de Soignes (metropolitan GS, over 4400 ha) is also part of the set of GSs providing GS at the neighbourhood level for residents living nearby. The model allows for selection of the quality attribute that will be assigned to the urban blocks. The default is 'inherent quality'; however, one may also select sub-qualities or characteristics such as 'presence of water in the GS' for the proximity–quality calculation. Each sub-quality is expressed on a scale from 0 to 100. The inherent quality, being a sum of a selection of sub-qualities, is expressed on a scale from 0 to 40. In the current implementation of the model, overall quality (inherent quality + use-related quality) cannot be documented, as so far not all public GSs have been surveyed to quantify their use-related quality. Once this has been accomplished, the tool will be able to incorporate both quality aspects in the calculation.

3.2.4 *Indicators*

To facilitate decision making, maps of landscape functions should (besides visualising the presence of a particular landscape function) also show the spatial heterogeneity in the quantity and quality of services provided (Troy and Wilson 2006, Meyer and Grabaum 2008). The multiple level proximity assessment allows the calculation of a range of potentially useful indicators (Table 16). The spatial outcome of the model indicates: (1) which urban blocks are within the catchment area of GSs of a certain TFL; (2) the number of different TFLs within reach of an urban block; (3) relative quality (Q_{rel}), which is the average quality obtained over all TFLs within reach of an urban block (taking into account the highest quality per TFL in case multiple GSs are within reach); (4) absolute quality (Q_{abs}), which is a similar average, in which TFLs that are not within reach are taken into account with a quality value of zero. The last two are different in the sense that (4) also takes account of a possible lack of variety of TFLs within reach and not merely a lack of quality. In addition, non-spatial indicators can be produced by overlaying maps of TFL proximity with demographic data (e.g. population share within reach of a particular TFL, population share with less than three TFLs within reach, etc.).

No.	Indicator	Type
1	Urban blocks within reach of residential green	Spatial
2	Population within reach of residential green	Non-spatial
3	Urban blocks within reach of play green	Spatial
4	Population within reach of play green	Non-spatial
5	Urban blocks within reach of neighbourhood green	Spatial
6	Population within reach of neighbourhood green	Non-spatial
7	Urban blocks within reach of quarter green	Spatial
8	Population within reach of quarter green	Non-spatial
9	Urban blocks within reach of district green	Spatial
10	Population within reach of district green	Non-spatial
11	Urban blocks within reach of city green	Spatial
12	Population within reach of city green	Non-spatial
13	Urban blocks within reach of metropolitan green	Spatial
14	Population within reach of metropolitan green	Non-spatial
15	Population within reach of less than three TFLs	Non-spatial
16	Number of TFLs within reach of an urban block	Spatial
17	Average of the highest green space quality within reach across TFLs	Spatial
18	Average of the highest GS quality within reach across TFLs, including TFLs not within reach as having zero quality	Spatial

Table 16: List of indicators

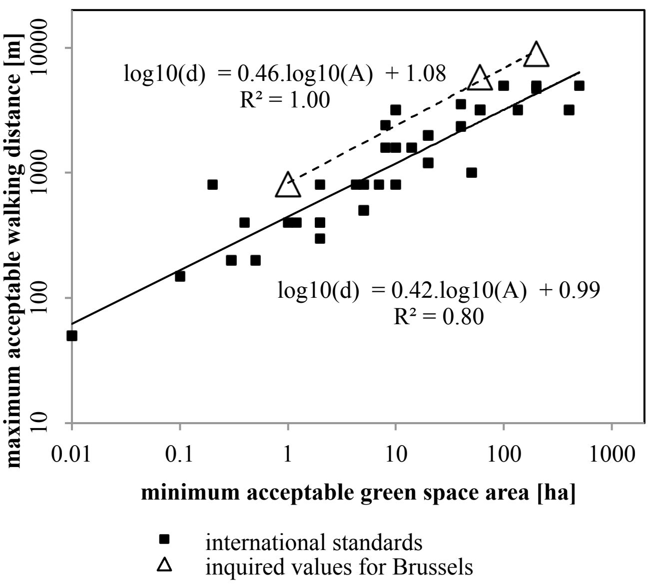


Figure 8: Log-transformed linear model of maximum distance versus green space area for international standards for green space proximity and questionnaire results.

3.3 Results

3.3.1 *Theoretical functional levels*

Minimum GS area (A) and maximum distance (d) for different TFLs, as defined in different standards, show a strong relation on a logarithmic scale. The size–distance correlation for each individual standard, based on the TFLs defined, has an r^2 value between 0.75 and 0.99 (Table 14), and the point cloud of size–distance pairs for all standards combined has an r^2 value of 0.80. The correlation between log A and log d can thus be considered very high. Therefore, a log-transformed linear model was used to describe $d(A)$, specified as $log_{10}d = a.log_{10}A + b$, or $d = 10^{(a.log_{10}(A)+b)}$, where, based on international standards, coefficient values $a = 0.419\ ; b = 0.985$ (r^2 = 0.80) were obtained (Figure 8). Table 17 illustrates average maximum travel distance thresholds for neighbourhood green, city green and metropolitan green obtained from the questionnaire by converting travel time by foot (neighbourhood green) or by bike (city green, metropolitan green) to corresponding distances. The distance residents are willing to cover versus GS size shows a strong log-linear relationship with coefficients $a = 0.459, b = 1.080$ (r^2 = 1.00) (Figure 8). As the plot shows, BCR residents tend to be somewhat less demanding with respect to GS proximity than the specifications of the international standards. For adults (18+), including elderly, the sample proved representative, as the maximum relative error, i.e. the difference between sample share and population share, divided by the population share for the BCR, for each age group, is 11.4%. However, children appear to be underrepresented in the sample. When comparing the responses of parents with children less than 12 years old with the responses of the rest of the population, young parents showed a preference for shorter (time) distances of up to –20% compared with the rest of the population. These observations may partly explain the differences between (time) distance preferences observed locally and distance threshold values used in internationally published standards, which are most often geared towards children and the elderly. For this study, it was ultimately decided to use the more demanding international standards-based size–distance relation as a basis for the modelling. Table 18 shows the average sizes of different TFLs obtained from international standards, as well as the corresponding distance thresholds derived through log-linear modelling that were used in this study.

TFL	Size (ha)	Max. travel time (min)	Speed (km/h)	Max. travel distance (m)
Neighbourhood green space	1	10	4.7	815
City green space	60	25	14	5820
Metropolitan green space	200	38	14	8951

Table 17: Maximum travel distance to different functional levels of green space, derived from inquired maximum travel time (on-site and online questionnaire)

TFL	Min. surface (ha) park or green space	Max. distance from home (m)
Residential green	0.06 (0.1)	136 (150)
Play green	0.52 (0.5)	348 (350)
Neighbourhood green	1.8 (2)	585 (600)
Quarter green	5.9 (6)	958 (1000)
District green	13 (15)	1345 (1400)
City green	69 (70)	2697 (2700)
Metropolitan green	450 (450)	5903 (5900)

Table 18: Literature-based theoretical functional levels (TFLs) with parameter values used for the proximity modelling. Rounded values in brackets. The TFL names correspond to the type of area they serve (see: section 2.3)

3.3.2 *Proximity analysis and proximity–quality coupling*

The proximity analysis for the study area, using the parameters based on international standards, shows that there is a lack of GS proximity for the lowest and highest TFLs: residential, play, city, and metropolitan GSs all reach less than 50% of the inhabitants of the BCR within an acceptable distance (Table 19). The number of different TFLs of GSs that are in reach of each inhabitant shows the diversity of the GSs provided. Four per cent of the inhabitants of the study area have no GS within reach and only 10% has access to all TFLs. The division is as follows: 21% has zero to two TFLs within reach, 29% has three to four TFLs within reach, and 50% has five to seven TFLs within reach (Table 20). The first group can be considered high priority for design and policy interventions. Concerning absolute inherent GS quality (Q_{abs}), the model output shows that 61% of the population is located in urban blocks with a score of less than 20 (50% of the maximum score) (Table 21), which reveals a significant margin for improvement. The actual share of GS for the BCR is 19% (accessible GS area divided by total study area). However, overall its population does not have optimal access to GS. The lack of GS proximity is not the result of a lack of urban GS, but it reveals a strong spatial inequality in the provision of GS.

TFL	Share of population served (%)
Residential green	48
Play green	47
Neighbourhood green	60
Quarter green	68
District green	70
City green	46
Metropolitan green	32

Table 19: Population shares with access to the different theoretical functional levels (TFLs)

Number of TFLs within reach	Population share (%)	Population share (%)
0	4	
1	7	21
2	10	
3	13	29
4	16	
5	23	
6	17	50
7	10	

Table 20: Population shares with respect to combined proximity of theoretical functional levels (TFLs)

Range of absolute inherent quality of green space (Q_{abs})	Population share (%)	Population share (%)
[0:4]	4	
]4:8]	7	
]8:12]	10	61
]12:16]	15	
]16:20]	20	
]20:24]	16	
]24:28]	10	
]28:32]	8	39
]32:36]	4	
]36:40]	1	

Table 21: Population shares with respect to absolute inherent quality

In terms of spatial distribution (Figure 9-A), there is a lack of residential GS in the de-industrialised and poor Canal Zone, while neighbourhood GS is almost non-existent along the southern and western part of the inner ring road (Figure 9-C). The same pattern is observed for quarter GS, with a clear lack of quarter GS in the Matongé area, the area north of the Central Business District (CBD) Manhattan and around the international airport and the city of Evere (Figure 9-D). District GS is well provided for along the regional border and the outer ring road (R0), but it is out of reach of inhabitants of the central parts of the city, including the CBD and the European district (Figure 9-E). While city GS is accessible from various, mainly peripheral, locations in the north and south-south-eastern part of the city (Figure 9-F), metropolitan GS serves the southern part of the BCR only through the Forêt de Soignes (right) and Hallerbos (left) (Figure 9-G). It should be noted that the vast Forêt de Soignes, which could be considered a single GS, is in our analysis fragmented into different smaller areas because the GS quality calculation module interprets a double lane throughway as a fragmenting element (Figure 10-A). To the north, the sole potential for metropolitan GS would be the opening of the royal domain to the public, an option that is currently under discussion. Other options would require active land acquisition and GS development. The combined proximity map, the total number of TFLs within reach (Figure 10-B), shows that the eastern part of Sint-Jans Molenbeek (a), as well as parts of the Kuregem Bara, Anneessens (b), and Dansaert (c) neighbourhoods and the area around Louiza and Matongé (d), lack public GSs within their reach. In the periphery, especially South-Grimbergen (e) and Diegem (f), there is a similar lack. High-proximity GS is found along tributary valleys of the Zenne canal valley, e.g. the Molenbeek valley (g-g') and the Woluwe valley (h-h'). In general, it can be concluded that the combined indicator for GS proximity increases away from the central canal area and towards the BCR–Flanders border. In the periphery, GS proximity varies depending on radial direction. The absolute inherent quality (Q_{abs}) of GS (Figure 10-C) roughly reflects the same pattern, but it enriches it with information on the naturalness, spaciousness, and quietness of GS within reach.

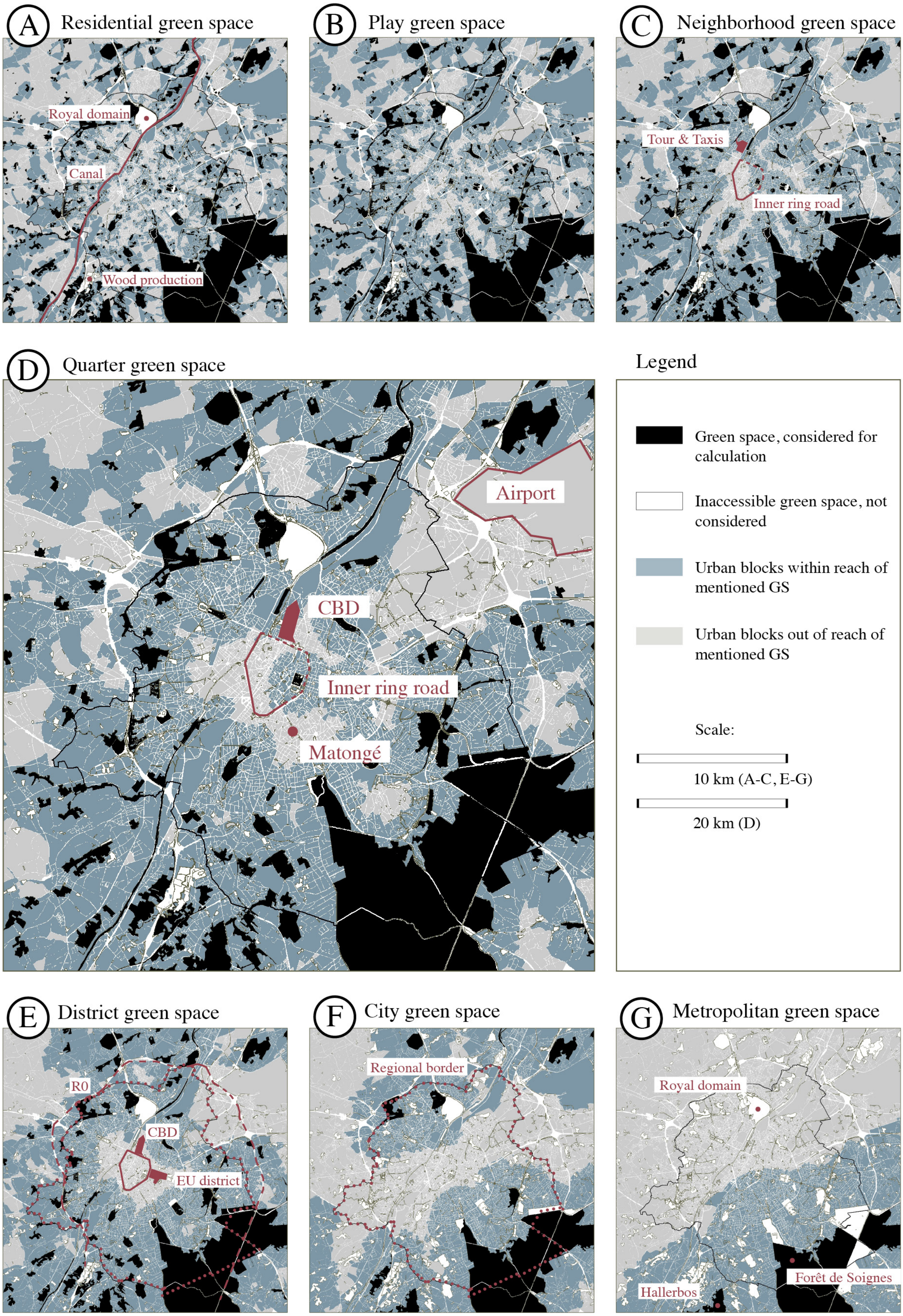


Figure 9: Green space area of influence per theoretical functional level. The white areas are not publicly accessible.

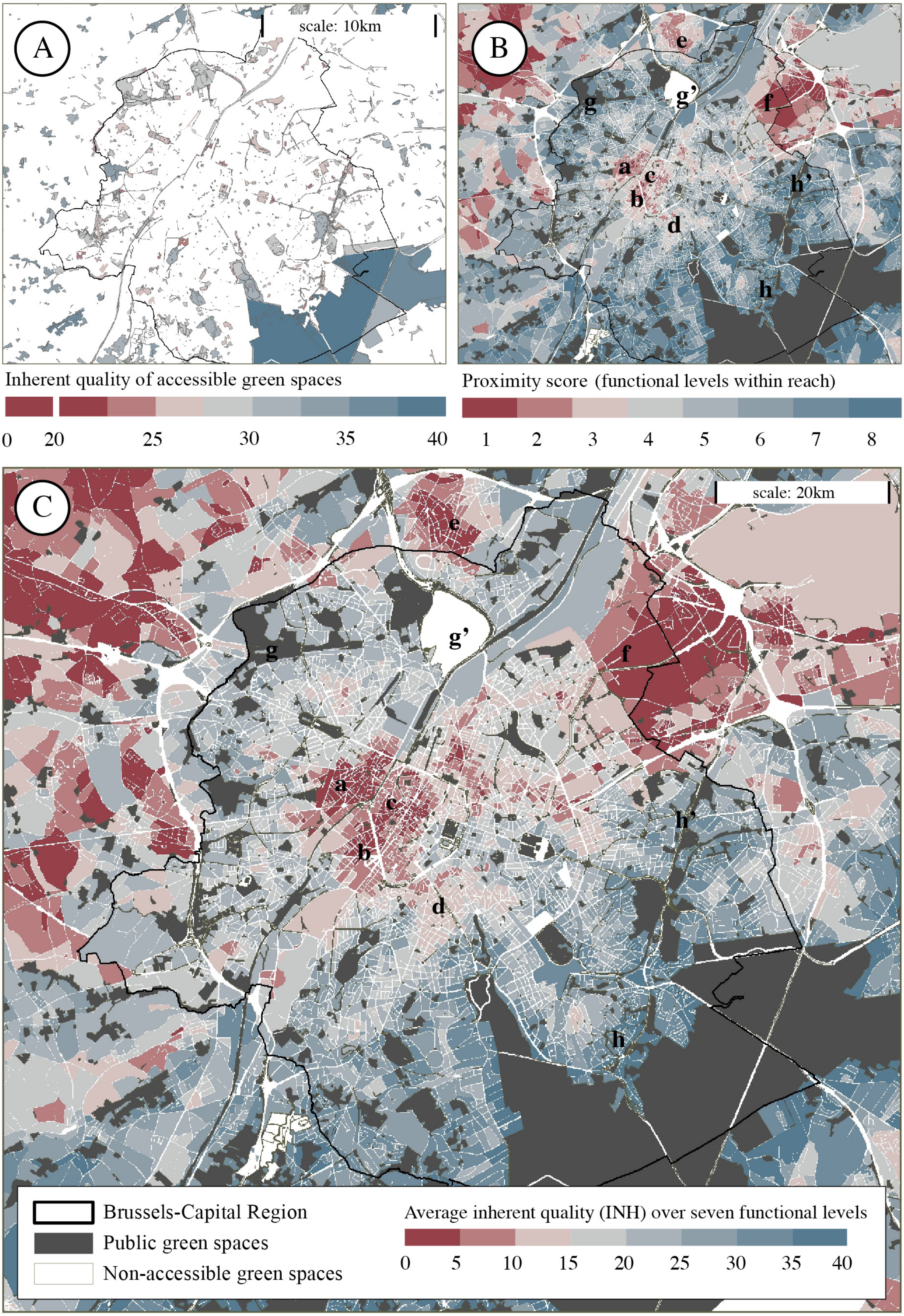


Figure 10: Three indicators as model output: inherent green space quality (naturalness and biodiversity, quietness, and spaciousness); total number of different theoretical functional levels within reach of each urban block; and average inherent quality of green spaces within reach of each urban block

3.4 Discussion

In this study, a GIS tool has been developed that translates the output of a previously developed GS quality assessment framework (Stessens, Khan et al. submitted) into useful, proximity-based indicators on GS provision for the inhabitants of the BCR. GS proximity in this study was modelled through GIS-based calculation of shortest path trajectories between urban blocks and GSs and the definition of thresholds for the maximum distance one is willing to cover to reach a GS in accordance with the well-known concept of functional levels (see: section 1.2). The proximity analysis builds further upon the methodology proposed by Van Herzele and Wiedemann (2003). The refinements are made by utilizing trajectory analysis instead of a mix of omnidirectional (virtual) paths and major barriers (railroad, canal), by refining the indicator scale (urban block instead of statistical sector), and by applying a mathematical size-distance relation, which is based on an analysis of known standards. Regarding the further development of quality assessment, the rating of inherent sub-qualities is GIS data driven. The quality model is derived from statistical analysis of local questionnaire data as proposed by Stessens, Khan et al. (submitted), which is a different approach than in the case of Van Herzele and Wiedemann (2003), where a mix of spatial data, expert interpretation of maps and additional site visits is employed. This allows the reporting of (1) the provision of public GSs, and (2) their quality and sub-qualities for each urban block. Further advancements have been made by proposing a method to calculate the green space quality that pertains to a place of residence.

By coupling a multi-level proximity assessment model with a quality assessment model, a clear overview of inequalities in the quality and accessibility of GS is obtained, both quantitatively (Table 19 - Table 21) and spatially (Figure 9, Figure 10). The maps produced thus facilitate well-informed design and policy interventions not only on GS, the path network connecting residents and GS, but also on densification and general planning strategies. The combined quality–proximity indicator (Q_{abs}) can be used to point out potential GS development areas. Moreover, when overlaid with the public transport network service area, it might also be used for indicating potential sites for densification that have excellent public GS provision. All GIS input in the model can be used to test different design and policy scenarios. The model developed might thus be used by consultants or city and regional officials of GS and planning departments to analyse the existing condition of GSs, to indicate the most pressing interventions, and to test the effect of scenarios for GS (quality) development. Being data driven and objective, the tool can encourage and support interdisciplinary collaboration (Matthies, Giupponi et al. 2007) between nature development institutions, planning agencies, urban development agencies, infrastructure departments, urban designers, and researchers.

In terms of proximity, the standards in the literature for the maximum distance people are willing to cover to reach GSs of a certain size were shown to be more demanding than inquired TFL threshold distances (Figure 8). Two factors may explain this difference. One is that children were underrepresented in the questionnaires (Stessens, Khan et al. submitted), whereas the literature standards take into account all ages and degrees of mobility. A second explanation could be the very diverse cultures in Europe's capital (Brussels) and its large socio-economic split in comparison with other western cities. This may have led to different results compared with standards that are based on a typical western public space culture. Certain groups have very different values and attitudes towards GSs (Swanwick 2009). The model could be further improved by collecting more detailed information on the actual use of public GSs in the BCR and by substituting literature-based time–distance thresholds for GS accessibility for user-based models of GS proximity. This would require more extensive surveys, as well as the incorporation of more detailed data on transport facilities in the BCR, including public transport such as the metro and the rail express network. The results would enable a more realistic estimate of travel time using different transport modes.

The proximity analysis applied to the study area also shows that lack of proximity to GS is most prevalent in the lowest and highest TFLs: residential, play, city, and metropolitan GS all reach less than 50% of inhabitants (Table 19). While studies are under way to address the question of inter-regional metropolitan landscapes (Loeckx, Corijn et al. 2016), the smallest fractions – residential and play GS – are a communal matter that needs to be addressed urgently. To this end, on-going efforts such as the 'Contrats de Quartier Durables' (Sustainable Neighbourhood Contracts) need to be continued. Due to its scale, residential GS development goes hand in hand with public space design, local street layout, and mobility strategies, and therefore it requires interdisciplinary collaboration.

Future research should involve exploring the potential of the indicators generated for urban design and policymaking through design research or design charettes and scenario-based simulation workshops. A similar spatial representation of regulating and provisioning ES could mobilise this design research to its fullest potential. Further research on the relation between socio-economic data and GS proximity and quality is also considered highly relevant for assessing the influence of inequality.

3.5 Conclusions

The objective of this study was to enable GIS data to be used as an urban green space evaluation and design tool that matches the user's perspective. It presents a new approach for green space analysis in an urbanised environment to map and allow design-based optimisation of the perceived quality and proximity of green spaces as cultural ecosystem services. The approach entails a GIS driven assessment of green space quality and proximity, and unifies these in a spatially explicit model. Green space proximity was modelled through GIS-based calculation of shortest path trajectories between urban blocks and green spaces. In the proximity calculation, use was made of the concept of functional levels, by defining thresholds for the maximum distance people are willing to travel to visit a green space of a certain size. Analysis of functional level definitions described in the international literature, as well as field work done in the Brussels study area showed that a log-transformed linear model is particularly effective for describing the relationship between green space size and maximum travel distance. Based on this relationship, a multi-level modelling approach was proposed for assessing green space proximity at the level of urban blocks.

Combining green space quality assessment with multi-level proximity modelling allowed the objective assessment of the current state of green space provision in the Brussels Capital Region. The research demonstrated that:

- Brussels shows a clear concentric pattern of low proximity and quality in the central parts of the region, and high proximity and quality in the periphery. This makes that nearly two third of the population has no access to high quality green spaces, leaving a great margin for improvement.

- The lack of green space proximity is the strongest for the lowest and highest functional levels (residential green and metropolitan green), with their respective proximity maps suggesting locations for possible future green space development. While residential green space development is a question of public space reorganization and housing (and city block) typologies, development of metropolitan green is a complex and multi-disciplinary challenge, for which the green space should be considered as a multifunctional green infrastructure.
- Currently, two tributary valleys (Molenbeek, Woluwe) of the Zenne valley cutting through Brussels offer both high proximity and quality of green spaces. A possible strategy could be to further develop the blue and green network structure in the remaining tributary valleys. However, problem areas call for more innovative strategies, as these are mostly situated relatively far from the current blue and green network crossing Brussels

By mapping the zones of influence of green spaces, their qualities, and travel trajectories to these spaces, and relating these to the urban fabric and its population, a tool has been developed for not only the monitoring of urban green ecosystem services. It can also be used for urban design, analysis of policy measures, and by extension, for design research and scenario development. The produced maps allow for well-informed design and policy interventions on green spaces, and on the path network connecting residents to these spaces. The modelling may also support densification and general planning strategies, as densification can be partially based on the indication of areas that provide their residents with sufficient provision of cultural ecosystem services. It is expected that the results of this research will contribute to the scientific basis for design research on urban green space provision and sustainable urban development planning and policymaking.

4

4 Exploring options for public green space development — Design research and GIS-based scenario modelling

Abstract

The use of public urban green spaces has a positive influence on human wellbeing. Therefore, insights in the provision of green spaces are crucial for planners and policy makers to propose optimal solutions for maintaining and improving urban environmental quality. A methodology is proposed for co-creating scenarios for green space development through green space proximity modelling and impact assessment of proposed changes. Through detailed assessment of green space development opportunities for the case of Brussels, interventions for green space development were classified based on relative investment scales. This resulted in three scenarios of increasing ambition. Results of scenario modelling are combined with socio-economic data in order to analyze the relation between average income and green space proximity. The analysis confirms the generally accepted hypothesis that non-affluent neighborhoods are on average underserved. The proposed scenarios reveal the possibility to reach a very high standard in green space proximity throughout the study area if authorities would be willing to allocate budgets for green space development that go beyond the regular construction costs of urban green spaces.

4.1 Introduction

4.1.1 *Access to public green spaces and quality of life*

With an expected increase in population of 28% by 2060 (Federaal Planbureau 2017), Brussels is facing the challenge of improving urban environmental quality while absorbing a strong demographic growth. A good understanding of access to Brussels' public green spaces (GS) is required, as these are essential for the wellbeing and quality of life of the region's inhabitants. This is not only important for the current state, but also for future development scenarios, as visiting urban green spaces has a general positive connection to reduced mortality (Coutts, Horner et al. 2010), health protection (Villeneuve, Jerrett et al. 2012), obesity in children and adults (Timperio, Salmon et al. 2005, Diez Roux, Evenson et al. 2007) and psychological well-being (Ernstson 2013). Next to mitigating impacts of air pollution and urban heat (Oliveira, Andrade et al. 2011), reducing risk of flooding (Scott and O'Neill 2014) and contributing to groundwater recharge (Batelaan and De Smedt 2007), urban GS offer opportunities to reconnect with nature and self (Fuller, Irvine et al. 2007), resulting in a feeling of rejuvenation, enhanced contemplation, and a sense of peace and tranquility (Kaplan and Kaplan 2003, Song, Gee et al. 2007, Lee, Jordan et al. 2015, Zhang, van Dijk et al. 2015). Access to urban GS has a positive effect on the development and well-being of children (Kahn and Kellert 2002) and may contribute in coping with a wide range of behavioral problems (Louv 2010).

4.1.2 *Unequal distribution of urban green space and accessibility benefits*

In an urban context, GS provision is often unequally distributed (Van Herzele and Wiedemann 2003, Kabisch and Haase 2014). Many studies reveal that GS accessibility benefits predominantly more affluent communities (Ferguson, Roberts et al. 2018, Nesbitt, Meitner et al. 2019). This is also the case for Brussels (Stessens, Khan et al. 2017). Disproportional access to green spaces is therefore increasingly recognized as an environmental justice issue (Wolch, Byrne et al. 2014). Planners and policy makers are nowadays challenged, not only with the need to enhance the provision of GS across the city, but also with questions of justice regarding GS access and multi-functionality of GS, and provision of a healthy urban environment for all citizens.

Recent studies have also highlighted the undesirable effects of urban greening, such as gentrification (Haase, Kabisch et al. 2017, Anguelovski, Connolly et al. 2018). The authors state that the benefits of bringing nature into neighborhoods, can be countered by destabilization of neighborhoods through property value pressure, unequal access and unequal benefits. In order for greening strategies to be inclusive, there has to be a deliberate acknowledgement of socio-spatial inequalities and they have to be planned in a way that they can serve as places of encounter for different groups of people (Haase, Kabisch et al. 2017). In this study, therefore, particular attention is paid to neighborhoods with low average income. The imperative to address environmental injustices and related health issues, as well as enhancing urban nature and biodiversity, has led planners to focus on traditional parkland acquisition programs, deployment of underutilized urban land, and defining innovative strategies for expanding green space resources (Barnett 2001). Such open space development, however, can create an urban green space paradox in poor areas (Wolch, Byrne et al. 2014), where improved attractiveness increases property value. The average income in the BCR is €13,535 in 2013, which is 21% under the average Belgian income (BISA 2016). The lowest median incomes are situated in the canal area, southwest to the center of Brussels. This is the historical industrial area, which is densely populated and which as a low public green space proximity score. The highest median income areas are situated in the 'second crown' of the region and mostly in the southeast quarter of the area. The numbers do not include foreign diplomats that have not been taken up in the national register.

4.1.3 *Alternative scenarios and innovative design strategies*

In all the challenges mentioned, the changing climate has agency. It not only forms but also alters the socio-political context in which GS and green infrastructure are developed (Nash 2005). To address these challenges, there is a strong interest in the formulation of design options, as well as in assessing the impact of alternative scenarios for urban GS development (Haaland and van den Bosch 2015). The preferred method for the formulation of design options/opportunities for GS development (OGSD) is collaborative design, supported by indicators of the current state of GS proximity. The co-production of scenarios through design and the impact assessment of alternative design options, along with the scientific and practical output it delivers, can be considered as research by design (RbD), i.e. an inquiry in which design is a substantial part of the research process, forming a pathway to new insights through the inclusion of contextualized possible alternatives, validated through an interdisciplinary peer review of experts (Hauberg 2012).

4.1.4 *Objectives*

The main objective of this chapter is to identify possible GS development scenarios for the Brussels' study area and to assess how these scenarios benefit the population of Brussels as a whole, as well as different socio-economic segments of the population. The research reported in this chapter makes use of the outcome of an earlier developed GIS model built for analyzing inherent quality of public GS (Stessens, Khan et al. submitted) and proximity (accessibility) of public GS (Stessens, Khan et al. 2017) from existing GIS data. The model is put to use in several ways: a) the indicators are used for designing scenarios and strategies for public GS development for Brussels in RbD workshops and in additional RbD by the authors; b) analysis of these scenarios (whether for single public GS or for the whole study area) is done through spatial and numerical comparison of the indicator scores; c) this allows the formulation of design strategies and approaches for public GS development, as well as policy recommendations. The research presented is novel in its combination of three aspects: a) high-resolution proximity indicators, calculated at urban block level, using path network distances; b) in-depth collaborative RbD exercises on opportunities for GS development (162 OGSD with estimated investment class) and; c) scenario based impact analysis in relation to socio-economic indicators.

4.2 Concepts and materials

4.2.1 *Concepts*

The methodology involves five concepts that are explained more in-depth first. The *proximity model* is the earlier GIS-based model that was developed for producing indicators for proximity of green spaces on different *Theoretical Functional Levels* (TFL).

The notion of TFL relates the distance to GS a resident is willing to cover to the size of the GS. The rationale behind this approach is that the size of a GS determines the range of functions or activities the GS may potentially support. It is assumed that residents will be prepared to cover longer distances to reach a larger GS, because of its improved offer in terms of amenities, potential uses, and benefits (Figure 8). This idea is supported by several empirical studies (Van Herzele and Wiedemann 2003, Giles-Corti, Broomhall et al. 2005). In the proximity model used in this study, seven theoretical functional levels (TFL) are defined, from the residential to the metropolitan scale, each corresponding with a minimum size and maximum distance, the latter obtained empirically (Table 22, Stessens, Kahn et al., 2017). *Design* is used in this study to test possibilities for creating GS and for testing these propositions against the multiple preconditions concerning development of GS. GS that are proposed on suited locations as a solution for the lack of GS on a specific TFL, are named *Opportunities for Green Space Development* (OGSD). When a specific set of OGSD is chosen for impact analysis, it is called a *scenario*.

4.2.2 *Materials*

GS proximity is modelled according to the procedure described in Stessens, Khan et al. (2017). Spatial indicators/maps produced by the model are calculated at the level of urban blocks and include identification of all urban blocks having a specific level of GS within reach (Table 23, Figure 11, top), as well as an overall proximity score ranging from 0-7, indicating for each urban block how many of the seven TFL are accessible (Figure 11, bottom). It is important to note that functional levels form a hierarchy where it is assumed that higher-level GS also offer the functions of lower level GS. For example, district GS are also taken in account in the calculation of access to neighborhood green, applying the maximum distance threshold for the latter. For the design exercises the proximity indicator maps (model output) were complemented with an aerial image of Brussels at 25cm resolution. Additional layers that were used for location finding of new GS are: a base map including buildings, parcel boundaries and existing GS, the public transport network (rail, metro, tram), surface water (streams and water bodies), protected landscapes and nature reserves, a noise map (road, rail and air traffic) and the biological valuation map (Table 23)

Figure 11: Urban blocks within reach of quarter green space (top) and proximity score of urban blocks (bottom)

TFL	Min. Surface[1] A (ha)	Max. distance from home[1] d (m)
Metropolitan green space	450	5900
City green space	70	2700
District green space	15	1400
Quarter green space	6	1000
Neighborhood green space	2	600
Play green space[3]	0.5	350
Residential green space[3]	0.1	150

Table 22: Theoretical functional levels (TFLs)
with parameter values used for the proximity modelling.

TYPE	Name	Source
Proximity indicator	Reach of residential GS	PM
Proximity indicator	Reach of play GS	PM
Proximity indicator	Reach of neighborhood GS	PM
Proximity indicator	Reach of quarter GS	PM
Proximity indicator	Reach of district GS	PM
Proximity indicator	Reach of city GS	PM
Proximity indicator	Reach of metropolitan GS	PM
Proximity indicator	Proximity score	PM
Aerial image	Orthophotos, medium-res 25cm, colour, Vlaams-Brabant, 2012*	IV
Forests	Bos	IV
	UrbMap_GB_F	URBIS
Habitat zones	Habrl	IV
	Natura2000_station	BE
Parks	LandUse_lam72 (NSN)	IV
	Urbmap_GB_B	URBIS
Water bodies	Wtz20001R500	IV
	UrbMap_WB_0	URBIS
Biologically valuable	BWK2	IV
Protected landscapes	Bslastdo	IV
Additional (roadside green)	UrbMap_GB_A	URBIS
Urban blocks	UrbMap_Bl	URBIS
Parcels	GRBgis Adp	IV
	UrbIS P&B	URBIS
Noise maps	geluidscontouren_ spoorwegen_Lden	LNE
	geluidscontouren_ wegen_alles_Lden	LNE
	Geluidskaart_5m*	IBGE
Mean income	Gemiddeld belastbaar incomen per inwoner (neihborhood scale)	WM
Population density	Bevolkingsdichtheid (neighbourhood scale)	WM

Sources

PM (proximity model)	Stessens, Khan et al. (2017)
IV (Informatie Vlaanderen)	https://download.agiv.be
URBIS (Brussels Urban Information System)	http://cibg.brussels/nl/onze-oplossingen/urbis-solutions/download
BE (Brussels Environment)	http://wfs.ibgebim.be/
LNE (Environmental department of the Flemish Region)	https://www.mercator.vlaanderen.be/zoekdienstenmercatorpubliek/
WM (wijkmonitoring)	https://wijkmonitoring.brussels

Table 23: Maps used for the design exercises and scenario development (all are in vector format, except for (*), which are in raster format)

4.3 Methodology

Table 24 provides an overview of the different steps in the methodology and the materials used in each step. The RbD was performed in two parts: i) during an interdisciplinary workshop with twelve participants, including researchers (e.g. architects and urban designers, planners, hydrologists, geographers), students in architecture and urban design, people from the regional office for environment, and regular citizens - here proximity maps per TFL were projected on whiteboard for drawing GS development scenarios; ii) during a smaller session (one researcher and one student) on GIS analysis, for processing the workshop outputs, and for additional scenario work. Complex solutions were further tested in AutoCAD. Based on the interventions needed for the realization of the green space, OGSD were classified according to investment scale, from regular investment to high additional costs. The spatial as well as demographic impact was then assessed for the whole study area as well as for two socio-economic groups in the BCR.

4.3.1 *Collaborative RbD workshop*

In the workshop, the study area was explored for public GS optimization possibilities with the help of the output of the proximity model. Maps depicting the accessibility of each separate TFL were used for identifying opportunities/options for green space development (OGSD). OGSD comprise all viable options to develop public GS or to expand an existing public GS. They are outlined by a perimeter and involve spatial interventions. All interventions necessary for the OGSD to be feasible were then determined and listed. In order to determine the relevant interventions, rudimentary design exercises were made such as drawing the perimeter on aerial imagery, overlay with other maps, or more detailed design exercises in case of complex potential public GS.

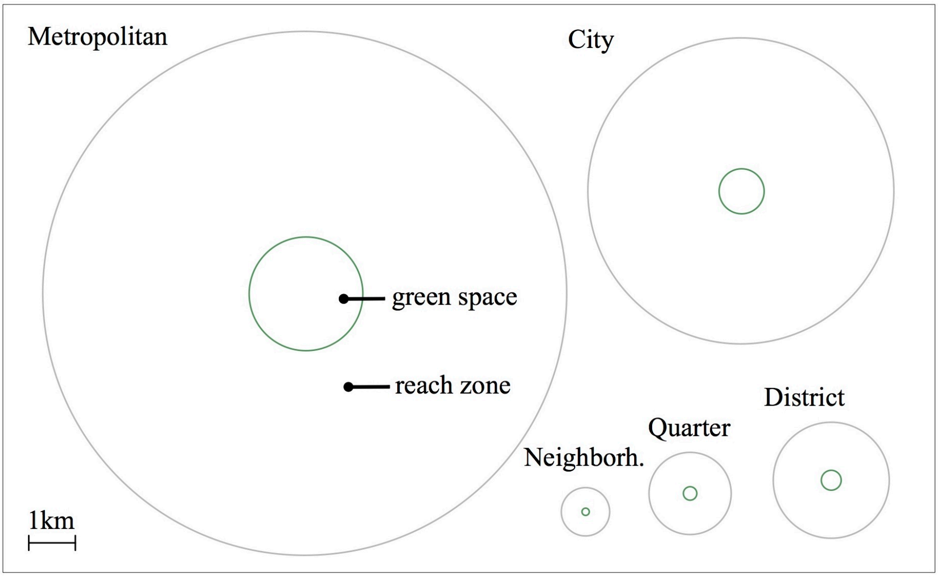
4.3.2 *Individual RbD*

Four questions are explored: i) whether the study area can be fully served at all TFL; whether typical 'standard' approaches exist for GS development and how these differ for each TFL; which scenarios can be formulated based on the design exploration, and; how do these scenarios relate to the earlier described correlation with socio-economic indicators?

<table>
<tr><th>Actions</th><th>Tools</th></tr>
<tr><td><u>Identifying problem and-or priority areas</u> (low number of TFL within reach)</td><td>Proximity score</td></tr>
<tr><td><u>Identifying opportunities</u> for green space enlargement and locations for new green spaces through <u>collaborative RbD</u>.
Methods:
• Projected maps on whiteboard, drawing and discussing potential interventions for each TFL
• Listing interventions and approaches per TFL</td><td>• Proximity indicator per TFL
• Proximity criteria: area; user distance threshold
• Base map: e.g. property boundaries; buildings; existing green spaces
• Aerial image</td></tr>
<tr><td><u>Identifying opportunities</u> for green space enlargement and locations for new green spaces through <u>individual RbD</u>.
Methods:
• Visual identification of possible locations through map overlay with a theoretical public GS (circle with radius $r_{PGS} = \sqrt{A_{TFL}/\pi}$ and a circle with its attraction radius $r_{ATT} = r_{PGS} + (\sqrt{2}/2).d_{TFL}$ (where the maximum distance d_{TFL} is adjusted to the road network)
• Testing of interventions through CAD or GIS-based design of green space configurations and adjustments to the surroundings (e.g.: road network, property limits)
• Listing in detail the types of interventions needed for expanding or creating the public GS</td><td>• Proximity indicator per TFL
• Proximity criteria: area; user distance threshold
• Base map: e.g. property boundaries; buildings; existing green spaces
• Aerial image
• Public transport network
• Surface water
• Protected landscapes
• Nature reserves
• Noise map
• Biological valuation map</td></tr>
<tr><td><u>Identifying types of GS development and developing scenarios</u>
• Sorting green spaces according to types/typologies of combined intervention types per TFL
• Determining investment class (simplified) of intervention types
• Classifying proposed public GS into investment class and scenarios (low/mid/high investment)</td><td>• List of proposed public GS</td></tr>
<tr><td><u>Impact analysis</u>
• Running the model with scenarios
• Analyzing the impact of scenarios on population (how many people have access to how many functional levels?; how does this improve with each scenario in relation to existing conditions?)</td><td>• Map of proposed public GS per scenario
• Proximity model
• Population map</td></tr>
</table>

Table 24: Methodological steps and materials used

TFL on scale



Existing green spaces and surface water in the study area

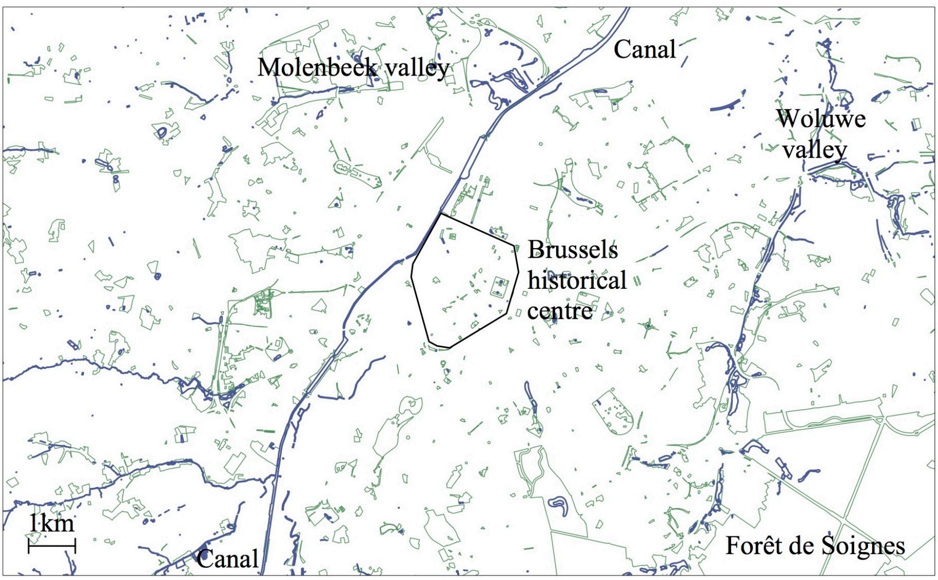


Figure 12: Minimum TFL areas plotted as circles and fragment of the study area on the same scale

4.4 Results

First, inequalities in the provision of GS in the BCR are briefly discussed, focusing on the proximity of GS of different functional levels. Next, the results of the RbD exercises for the improvement of GS proximity are discussed per TFL, and distinctive types and opportunities of GS creation are identified. In the last part, these OGSD are incorporated in three different scenarios, depending on how (financially) challenging different types of interventions are. In the scenario analysis, GS proximity for the 25% poorest neighborhoods is compared with scenario outcome for other neighborhoods.

4.4.1 *Inequalities in green space provision*

As Figure 13 shows, green proximity scores, expressing the diversity of TFL within reach of each urban block, are generally higher in the periphery of the BCR than in the central parts of the city. Weighting the lack of GS (reversed proximity score multiplied with the population density) highlights the lack of GS in the densely populated 19^{th} century belt around the center of the BCR (Figure 14). Figure 15 and Figure 16 show the urban blocks within reach of a certain TFL of GS and therefore also the gaps, where GS of the specific TFL should ideally be provided. Whereas the gaps in residential and play GS proximity are quite fragmented, in the higher TFL, clear zones start to appear, with a consistent lack in the historical center up to district GS and a north-south partitioning for city and metropolitan GS.

Figure 13: Proximity score at urban block level (dark 0 – 7 light).
Lines: Brussels-Capital Region (thick) and the 19 municipalities it is composed of (thin)

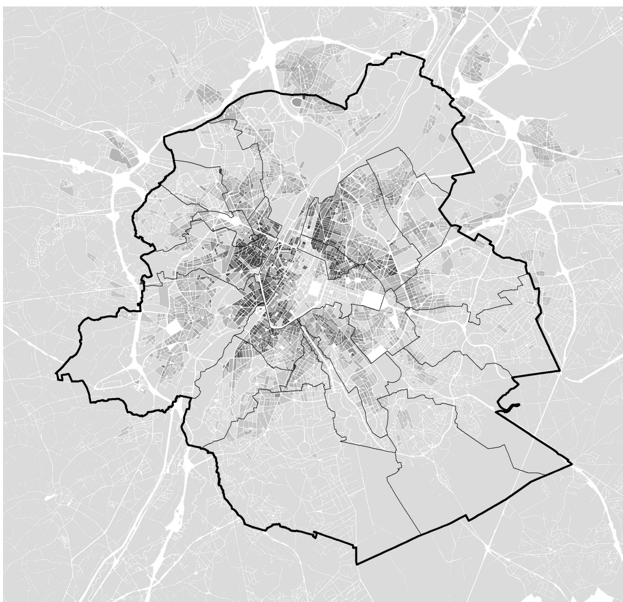


Figure 14: impact of lack of green space proximity
($impact = density.(7 - prox\ score$);
light: low impact, dark: high impact, i.e. low proximity scores in densely populated areas).
Lines: Brussels-Capital Region (thick) and the 19 municipalities it is composed of (thin)

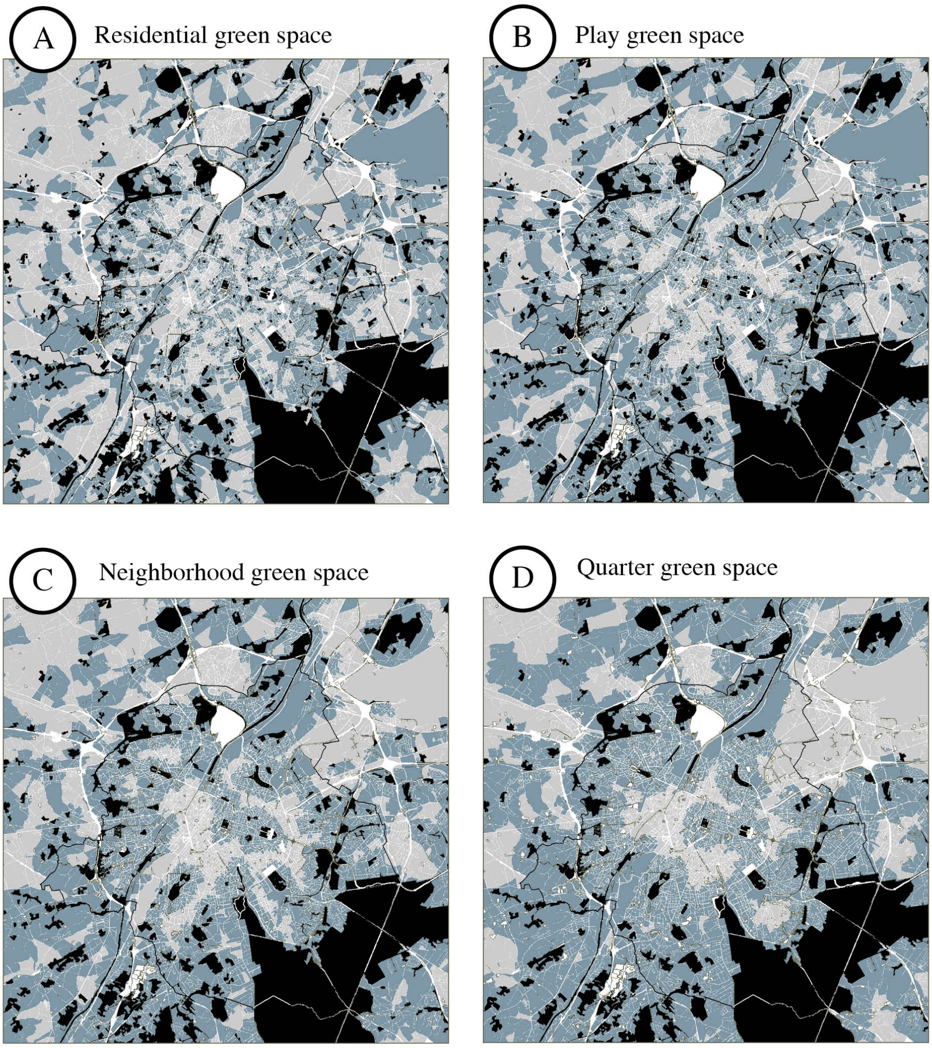


Figure 15: Urban blocks within reach of seven levels of public green space (continues on the next page).

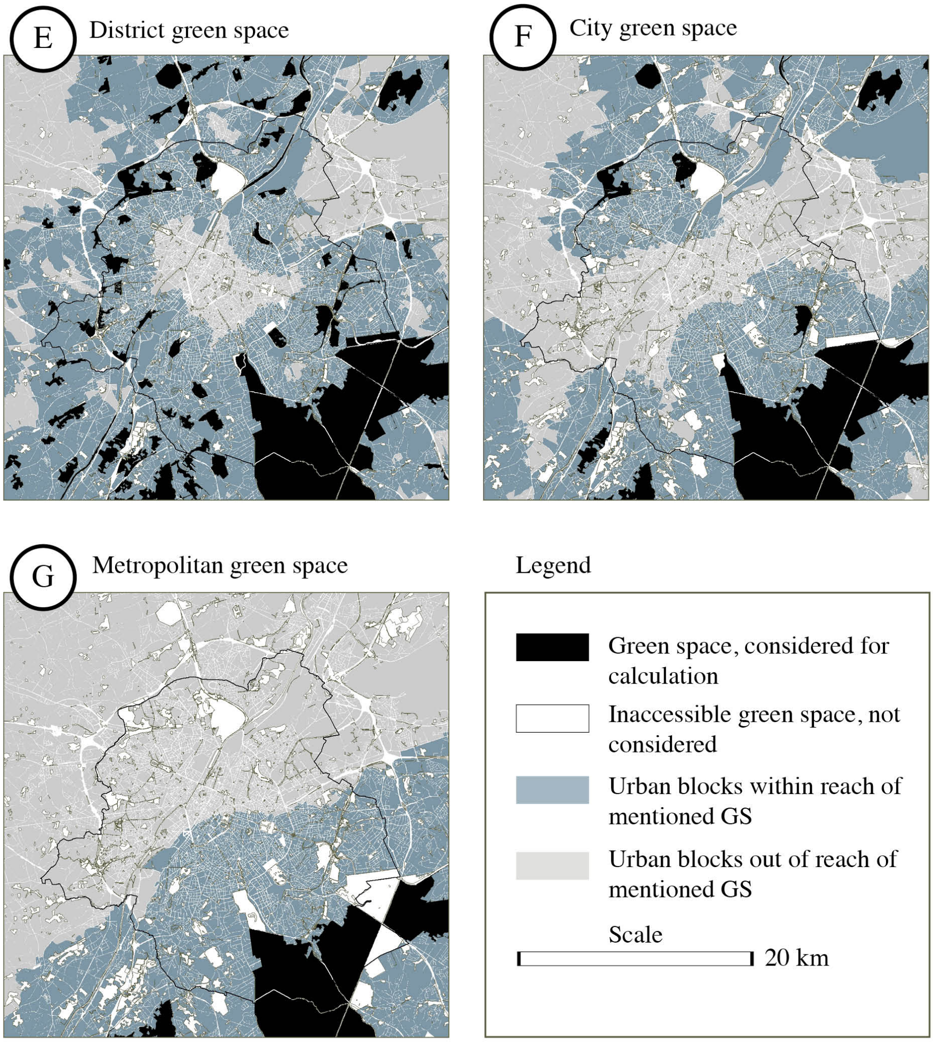


Figure 16: Urban blocks within reach of seven levels of public green space (continuation of the previous page).

4.4.2 *Research by design on improvement of public GS proximity*

In the design workshops, by means of the GS proximity indicators per functional level (Figure 15, Figure 16), 162 OGSD were identified for the whole study area (Table 25, Figure 17) relating to the TFLs neighborhood GS (level 3) to metropolitan GS (level 7). These OGSD were defined with the goal of increasing the amount of people within reach of a TFL with a minimum of interventions. By solving higher TFL first, starting with metropolitan GS, some OGSD could be considered redundant in lower levels, as they were already covered by the proposed GS on a higher level. For example, when introducing a metropolitan structure in the west of Brussels with a reach of 5900m, an outward buffer zone of 707m (theoretical displacement of 1000m distance reach of district GS, see: displacement, Table 22) was taken into account. Here, in this area, the introduced metropolitan GS already covered the district GS proximity. The proposed OGSD are visualized complementary to existing green spaces in Figure 17.

For the study area as whole, the levels residential GS (level 1) and play GS (level 2) would potentially result in a very high amount of OGSD and determining these is out of the scope of this work. Therefore, for these levels a focus area was selected (Figure 17, dashed line), in which 42 OGSD were defined. In total, 53 types of interventions needed for the realization of the proposed OGSD were identified (Table 26, Table 27). For quarter green (level 4) up till metropolitan green (level 7) OGSD can be grouped in types according to recurring interventions (Table 26). For residential (level 1) up to neighborhood green (level 3) interventions proposed are limited, so OGSD types are self-explanatory, referring to a particular type of intervention. Interventions proposed for all OGSD are listed in Appendix 8.3. The following sections provide a description of common and specific interventions related to the different types of OGSD.

TFL	Min. Surface[1] A (ha)	Max. distance from home[1] d (m)	Max. displacement[2] Δ (m)	Number of proposed green spaces
Metropolitan green space	450	5900	4172	10
City green space	70	2700	1909	12
District green space	15	1400	990	38
Quarter green space	6	1000	707	19
Neighborhood green space	2	600	424	62
Play green space[3]	0.5	350	247	8
Residential green space[3]	0.1	150	106	13

[1] Stessens, Khan et al. (2017)

[2] Considering the smallest displacement (71% of ground distance), taxicab geometry (Krause 1986)

[3] Restricted to focus area

Table 25: Number of and parameters related to proposed green spaces

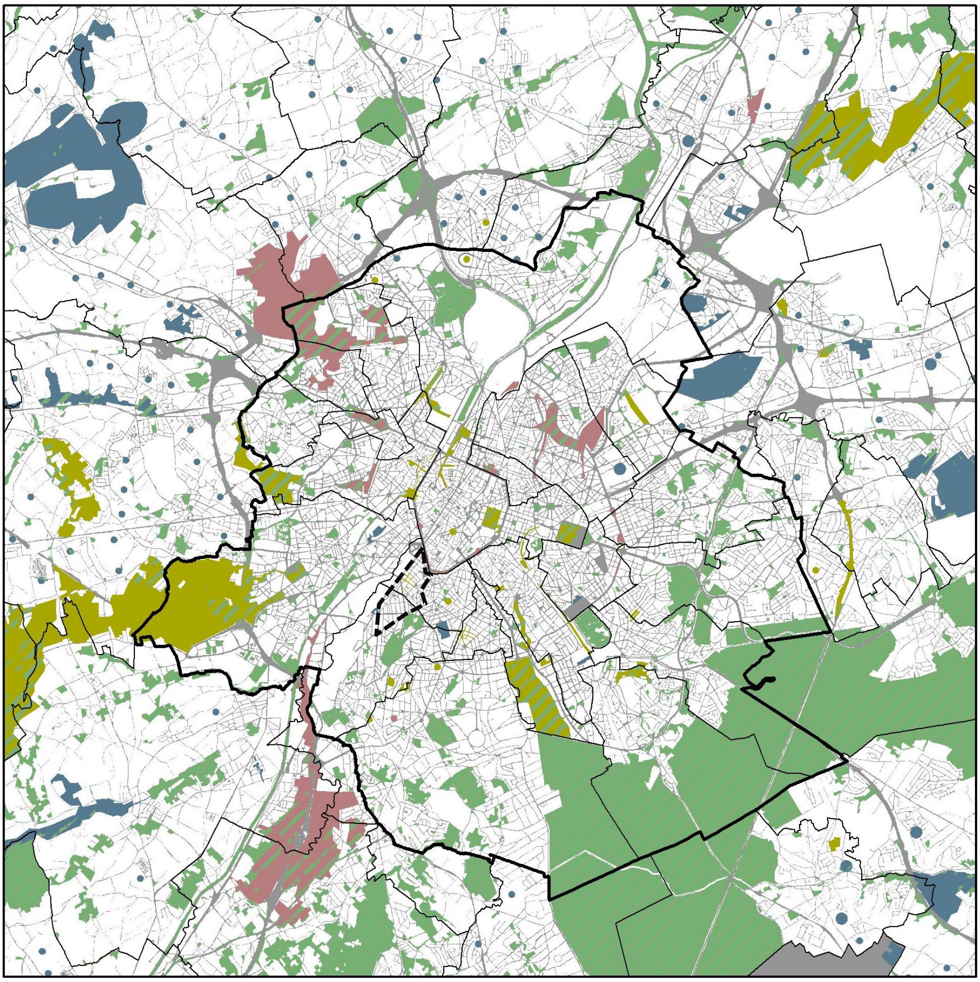


Figure 17: Existing public GS (green) and proposed public GS (blue: low investment; yellow: medium investment; red – high investment). Hatched GS are reconversions or expansions of existing GS. Dots are indications of green spaces without their actual shape. The size of the dot represents its actual TFL area, which has been verified visually to fit in the landscape. Thick line: Regional border Brussels-Flanders, thin line: city borders, dashed line: focal area for residential and play GS OGSD

Metropolitan GS (n=10)

The different approaches suggested for metropolitan GS development depend on the degree of urbanity of the surroundings. Common interventions that pertain to these types of OGSD are: i) for the implementation of measures for developing a green-blue network; ii) the need for deployment of walking and cycling trajectories; iii) the acquisition and integration of farmland in order for it to function (also) as park space and; iv) removing local roads or cutting traffic that divides the space into smaller segments. Other common strategies are the integration and connection of existing GS (including protected landscapes) into a metropolitan-size GS and noise shielding due to the proximity of traffic corridors. *Intra-urban* OGSD are specific in the sense that they most often require connections over a 2x2-lane road, require covering open railroad trenches due to the scarcity of open space, and can be made accessible by railway and tram for improved accessibility. *Peri-urban* OSGD often require land use change, including a halt for housing development in the delimited zone. Depending on their location, these public GS can play an active role in the relation between the city and hinterland, as natural water management zones (buffering upstream of the city or filtering and decontaminating downstream) (Stessens, Blin et al. 2016) or as local food production areas, functionally related to farmers' markets in the city (Allen 2003, Agence TER 2016). The spatial complexity is high in peri-urban areas, which requires creative approaches which do not only pertain to GS design, but also to system design of peri-urban activities such as waste management, logistics and production of energy, food and goods. Moreover, these spaces have a specific role in the development of housing and transportation, as it is often beneficial to create a highly accessible metropolitan density on its edges, given the spatial quality these metropolitan GS provide (Loeckx, Corijn et al. 2016). Whereas *intra-* and *peri-urban* OGSD often leave very little options for choosing their position, *rural* OGSD can be positioned in a way that they serve as an ecological bridge between valleys. Other than the necessity for land use change and halting housing development, they benefit from reversing the existing sprawl of single-family houses. In general, metropolitan GS can be considered as green infrastructure, which is the upgrade of urban green space systems as a coherent planning entity (Sandström 2002). If a green infrastructure is proactively planned, developed, and maintained it has the potential to guide urban development by providing a framework for economic growth and nature conservation (Van der Ryn and Cowan 1995, Walmsley 2006). Such a planned approach would offer many opportunities for integration between urban development, nature conservation and public health promotion (Tzoulas, Korpela et al. 2007).

City GS (n=12)

Rural OGSD on city level can be classified in three types, which are closely related and vary by their position in tributary valleys and the presence of existing private or public woodland. The scale of the public GS requires the deployment of walking and cycling trajectories. The three main types of city OGSD are: a) *agriculture reconversions*, which lie at the source of tributary streams and consist purely out of reconverted farmland (e.g. into a juxtaposition of small-scale farmland with high biological value and patches of meadows and woodland); b) *valley parks*, which contribute to the green-blue network of tributary streams and GS and are created by connecting existing woodland; c) *agriculture reconversions to valley parks*, which constitutes an overlap of the earlier mentioned types, and which due to the context most often require a re-routing of local roads. A fourth type is the *urban space optimization*. The lack of available land leads to interventions of high investment, such as covering of railroad trenches and connecting existing GS through creative use of available space. The high density of public transport allows these OGSD to be accessible from tram stops and most often also from railway stations. This type of OGSD requires cutting existing local roads due to high density of roads in the urban context.

District GS (n=38)

District level OGSD can be differentiated into six types. The first type, *functional level scaling*, involves the inclusion of existing GS, residual spaces and infrastructure interventions (e.g.: covering railroad trenches, removing park drives, re-routing traffic to un-fragment and to provide space for the public GS). The difficulty of finding space of this size, introduces options such as tunneling through traffic in order to couple existing GS. These OGSD have a high accessibility by public transport. A second type is the *Inner city district GS optimization*. It requires extensive redesign of circulation and rethinking of street layouts in order to expand existing GS to the district level. This type involves predominantly late 18th century parks. *Inner city continuous spaces* is a type where a chain of lower TFL spaces is re-designed as one continuous public GS. Interventions include the transformation of public GS bordering streets into pedestrian space, opening impervious surfaces, cutting local roads and re-routing local traffic in general. *Peri-urban district GS development* involves the use of agricultural land, mostly in the source area of tributary streams, with parts of the area delimited as protected landscape. Potential spaces are often near railways or highways, which requires noise shielding for their realization. *Rural district GS development* depends – as with other TFL – on the reconversion or integration of agricultural land. Other less frequently occurring OGSD types are: *publicly accessible estates* and *GS development in tributary valleys*. In areas with space scarcity, estates often have the right size for district level OGSD. Therefore, one of the strategies can be (partly) opening up the domains of these estates. GS development in tributary valleys is part of the large-scale public GS development possibilities in the range of city-district level that occur in less urbanized valleys.

Quarter GS (n=19)

The OGSD that were reoccurring for the quarter level are *expanding existing parks*, *conversion/reorganization, green roof on commercial buildings,* and *converting farmland to park space*. The first three types all include a form of expansion of existing GS. *Expanding existing parks* involves looking for greening potential in the public space around the existing park, whereby through traffic is put underground for the benefit of the public GS. Connectivity with the public transport network can be improved through the new layout. *Conversion/reorganization* involves the relocation of mono-functional sport facilities or reorganizing the area to attain a more publicly accessible and multifunctional area with a more natural character. In practical examples these conversions have potential real estate development and include adjustment of local roads. *Green roof on commercial buildings* activates spaces on top of commercial buildings near public GS. *Converting farmland to park space* is a peripheral form of quarter-level public GS creation through land use change.

Neighborhood GS (n=62)

Rather than combinations of interventions, OGSD types for the neighborhood level involve single type interventions of which the naming is self-explanatory. They have a high diversity and often include private terrains. In many cases, realization requires specific actions of a private partner or of administrative authorities, such as for *public space redevelopment of modern housing blocks,* the transformation of *private gardens to park space, publicly accessible estates, brownfield development, railroad optimization* (mostly covering tracks that are below street level) and *rural neighborhood GS development.* Despite the relatively small scale, in the first two approaches the amount of stakeholders can be very high and therefore the realization will require an elaborate participative process. Other than these, public spaces can be reorganized too. Strategies include enlarging existing public GS or creating public GS by *reorganizing sports fields* that are accessible for a limited public, and the creation of the *super-block.* The latter is a Spanish concept where a cluster of nine urban blocks is made accessible for motorized vehicles only by means of one-way loop streets and only for deliveries or drop-offs (Soret, Jimenez–Guerrero et al. 2013). This leaves room for the development of a green structure of neighborhood scale.

Play GS (n=8, focal area) and residential GS (n=13, focal area)

Given the small reach of play GS (350m) and residential GS (170m), solving the lack of availability for these types of GS for the whole study area is a task beyond the scope of this study. Therefore, a focus area of 1.5 km² was determined. The location of this area was based on low overall GS proximity score, high imperviousness and low average income, assuming that if GS provision in this area could be substantially improved by design, it will be possible in other areas too. Design exercises showed that the area selected can be provided with GS (8 play GS and 13 residential GS), and possible strategies for improving GS provision were deducted from these examples. Play GS - as the name indicates - are predominantly aimed at children. In the design workshops it was determined that in order to assure its use, equal attention should be given to the design of the space as to the design of children friendly routes towards it from the surrounding neighborhood. Five types of interventions were identified: *green roofs of public services, open schoolyards, boulevard segments* (in streets of 30m and wider)*, public space redevelopment of modern housing blocks* and*, large free parcels.* For residential GS, the same type of interventions reoccur consistently, with the additional type *reconversion of parking lots*. Residential GS can also be constructed by *combining parts of private gardens into a public green space*, a strategy that is supported by 51% of Brussels' inhabitants (n = 328, responses obtained in the questionnaire discussed in chapter 2). In this TFL, also *greening private parking lots* are an OGSD that is recurring frequently. In these lower TFL the potential of streets show the necessity of re-thinking the role of streets as mono-functional passing and parking spaces (Haaland and van den Bosch 2015) towards green multifunctional connecting spaces for neighborhoods, not only making homes accessible, but also connecting people. Multi-functionality also returns in the strategy of opening up school grounds for neighborhood recreation in off-hours, which is currently being investigated by the Flemish Community responsible for educational infrastructure in the study area (Vilain and Van Moerkerke 2016).

N°	*GS development option types*	Intra-urban metropolitan GS	Peri-urban metropolitan GS	Rural metropolitan GS	Valley parks	Agriculture reconversions to valley parks	Agriculture reconversions	Urban space optimization	Functional level scaling	Inner city district GS optimization	Inner city continuous spaces	Peri-urban district GS development	Publicly accessible estates	Rural district GS	District GS development in tributary valleys	Expanding park	Conversion/reorganization	Commercial green roof	Conversion/reorganization of park space
	TFL	Metr	Metr	Metr	City	City	City	City	Distr	Distr	Distr	Distr	Distr	Distr	Distr	Quart	Quart	Quart	Quart
	Interventions																		
1	Developing wetlands in valley bottom	x	x		x	x									x				
2	Developing a blue-green network	x	x	x	x	x									x				
3	Deploying walking and cycling trajectories	x	x	x	x	x	x												
4	Converting agricultural fields to park space with small scale agricultural character	x	x	x		x	x					x		x					x
5	Developing green areas around upstream tributaries			x			x					x							
6	Cutting local road	x	x	x		x		x			x	x					x		
7	Connecting existing public green spaces	x	x	x	x	x		x								x			
8	Halting housing development		x	x															
9	Reversing housing development			x															
10	Noise shielding	x	x	x								x							
11	Integrating protected landscapes	x	x	x								x	x						
12	Integrating estates												x						
13	Connecting separate parts over 4-lane road	x																	
14	Connecting to railway station	x						x											
15	Covering open railroad trenches							x											
16	Connecting to tram station	x						x			x					x			

(table continues on next page)

N°	*GS development option types*	Intra-urban metropolitan GS	Peri-urban metropolitan GS	Rural metropolitan GS	Valley parks	Agriculture reconversions to valley parks	Agriculture reconversions	Urban space optimization	Functional level scaling	Inner city district GS optimization	Inner city continuous spaces	Peri-urban district GS development	Publicly accessible estates	Rural district GS	District GS development in tributary valleys	Expanding park	Conversion/reorganization	Commercial green roof	Conversion/reorganization of park space
	TFL	Metr	Metr	Metr	City	City	City	City	Distr	Distr	Distr	Distr	Distr	Distr	Distr	Quart	Quart	Quart	Quart
	Interventions																		
17	Extending park over local road up to sidewalk										x								
18	Re-routing roads and traffic around or away from park										x								
19	Putting through traffic underground / covering open tunnels									x						x			
20	Transforming urban boulevard to park strip																		
21	Greening tram beds crossing the GS								x										
22	Cutting park drives for cars								x										
23	Connecting to metro station								x							x			
24	Re-integrating derelict / brownfield / unused land								x										
25	Developing real estate around GS																x		
26	Reorganizing open air sports facilities																x		
27	Opening up impervious surfaces										x							x	
28	Rooftop park extension on commercial buildings																	x	
29	Rooftop park extension on public buildings																	x	
…																			

Table 26: Types of GS development options (TFL residential – neighborhood excluded as these are self-explanatory, as they are related to one intervention).

N°	*Interventions*	Share in 162 OGSD
…		
30	Transforming local road into GS	8%
31	Moving logistic activities and light industry	6%
32	Transformation public space into park	5%
33	Activation of unused lawns	5%
34	Connecting over/under local road	4%
35	Part of private garden to park space	4%
36	Cutting parking spaces	4%
37	Rooftop park on top of industrial building	4%
38	Making fenced off grounds accessible integrating sports grounds	3%
39	Creating passages in-between buildings	3%
40	Connecting to highway	2%
41	Visual shielding	2%
42	Connecting nearby housing projects with park space	2%
43	GS in shared use with public services	2%
44	Converting parking space into GS	2%
45	Renegotiating industrial land for shared use	2%
46	Mega-roundabout	2%
47	Integrating nature reserves	1%
48	Connecting over causeway	1%
49	GS as part of strategic site redevelopment	1%
50	Connecting over water body	1%
51	Demolishing existing building for creation of GS	1%
52	Connecting separate parts over highway	1%
53	Reversing commercial building	1%

Table 27: Interventions not related to specific GS typologies

4.4.3 *Three scenarios of public GS development*

Most interventions identified require an additional investment apart from regular construction costs for public GS. These were assessed for their relative cost impact, with a subsequent classification of each type of OGSD into a basic, supplementary or full investment class (BASE, SUPP, FULL) (Table 28, detailed listing in Appendix, spatial representation in Figure 17). The classification is approximate due to the absence of detailed cost estimates, though sufficiently discriminating for its purposes, which is to define three public GS development scenarios based on approximate investment. The following cost increasing actions were considered for the scenario classification: tunnel construction or similar works; above ground infrastructure works; compulsory residential real estate acquisition; compulsory industrial/logistic real estate acquisition; altering public facilities; agricultural land acquisition and; installing noise barriers.

In the design exercises, the low cost OGSD (suited for the BASE scenario) were given priority when deciding on locations for public GS development in the scenarios. An optimal allocation was pursued in order to introduce a minimum of OGSD for a maximum improvement of GS accessibility for each functional level. With these preconditions, for the FULL scenario where a maximum coverage is attempted, at least 43% of the proposed public GS are not low cost.

The current state of GS proximity is described in detail in Stessens, Khan et al. (2017). To summarize, there is a strong lack of public GS in the area including East-Molenbeek and the west of central Brussels (area marked as A in Figure 18) and to a lesser extent in Sint-Joost-Ten-Node (Figure 18-B) and the Hallepoort-Louise-Matongé area (Figure 18-C). A few patterns are the cause of this: i) district GS is not present in the central parts of the BCR; ii) city GS only occurs along the northwest and southeast border of the BCR, resulting in a southwest-northeast oriented axis with reduced accessibility to higher-level green spaces; and iii) metropolitan GS is absent in the north, leaving the northern part of the BCR underserved (Stessens, Khan et al. 2017). Residential GS and play GS have more irregular patterns of

Scenario	BASE	SUPP	FULL
All	79	127	140
Metropolitan GS	2	(2)+6	(2+6)+2
City GS	5	(5)+5	(5+5)+1
District GS	26	(26)+7	(26+7)+5
Quarter GS	12	(12)+5	(12+5)+2
Neighborh. GS	39	(39)+20	(39+20)+3
Play GS*	0	0	0
Residential GS*	0	0	0

* Focus area OGSD not included

Table 28: Number of OGSD per scenario per functional level of the proposed GS.

coverage, yet are less well represented in dense urban areas, which in combination with the lack of other TFL reinforces the occurrence of problem areas. Results reveal that even though it is difficult to reach a good green space provision for poor neighborhoods, it is not impossible within the current urban tissue of Brussels.

The BASE scenario resolves mostly the lack of public GS in the periphery, though very little in the BCR itself (Figure 18). This is mainly due to the open space scarcity in the highly urbanized BCR implying more costly solutions. The SUPP scenario significantly improves the lack of public GS in East-Molenbeek as well as west of central Brussels, but does not fully solve the lack of GS in the Hallepoort area and Sint-Joost-Ten-Node and leaves Schaarbeek with a low proximity score (Figure 19). The FULL scenario solves the lack of GS proximity by bringing most urban blocks to a score 4-5 (Figure 20). Some of the peripheral agricultural areas keep low values, which is mainly due to the large units of land. This increases the average distance between the perimeter of the urban block and public GS. A reiteration of public GS placement or creating a finer path network could solve this issue. The average proximity score is 3.1 for CURR, 3.5 for BASE, 4.3 for SUPP and 4.7 for FULL.

Figure 21 depicts the population share per proximity score (the amount of different TFL within reach). Since proximity to residential GS and play GS are not considered in the scenarios, the proximity score can be maximum 5 instead of 7. Ideally the population share is 100% for proximity score 5 and 0% for 0-4. The existing state

CURR shows a large margin for improvement in the range 4-5. Around 1/5th of the population has a proximity score of only 1-2 and nearly 1/10th of the population has no neighborhood GS or larger within reach. Whereas the BASE scenario gives the impression of significant change when observing the maps, in terms of population impact there is a only a slight change of around 10% increase for proximity scores 4-5 and around 5% decrease in the proximity scores 0-3. The scenario halves the population with proximity score 0, but leaves about 5% of the population with no neighborhood GS or larger public GS within reach. The population with proximity scores 0-2 lowers from 30% to 19%, however, it requires the SUPP scenario to make this segment drop below 6%. In this scenario, changes become clear, as the population share with full access to higher-level GS (proximity score 5) reaches 53%, while the population with no access to public GS of neighborhood level or larger drops to 0%. In the FULL scenario, 78% of the population has a proximity score of 5 and 99% has a score of 3 or higher. The center-periphery contrast disappears and the BCR achieves a balanced, high quality provision of public GS.

As explained before, design interventions for residential GS and play GS have not been tested for the full study area due to the large amount of potential interventions. One of the most challenging test areas was selected for a design exercise, based on the lack of such public GS, low income and high imperviousness. Despite these preconditions, for the test area, the OGSD appeared to be sufficient to cover the lack of these small public GS. The higher-than-normal investment costs related to e.g. developing public intensive green roofs, parks in urban block interiors or car-free street and boulevard transformations make these OGSD not feasible within the BASE scenario. These spaces do not only require elaborate spatial design, but also innovation related to the stakeholder process, legislation and management. Examples are the management and insurance responsibilities for rooftop parks; the controversial aspect of making streets (partly) car free, the high number of landowners involved for implementing urban block interior parks and the access management; the high number of stakeholders for street transformation and; consultation with fire department and other emergency services and their willingness to change or co-create guidelines for unprecedented spatial configurations.

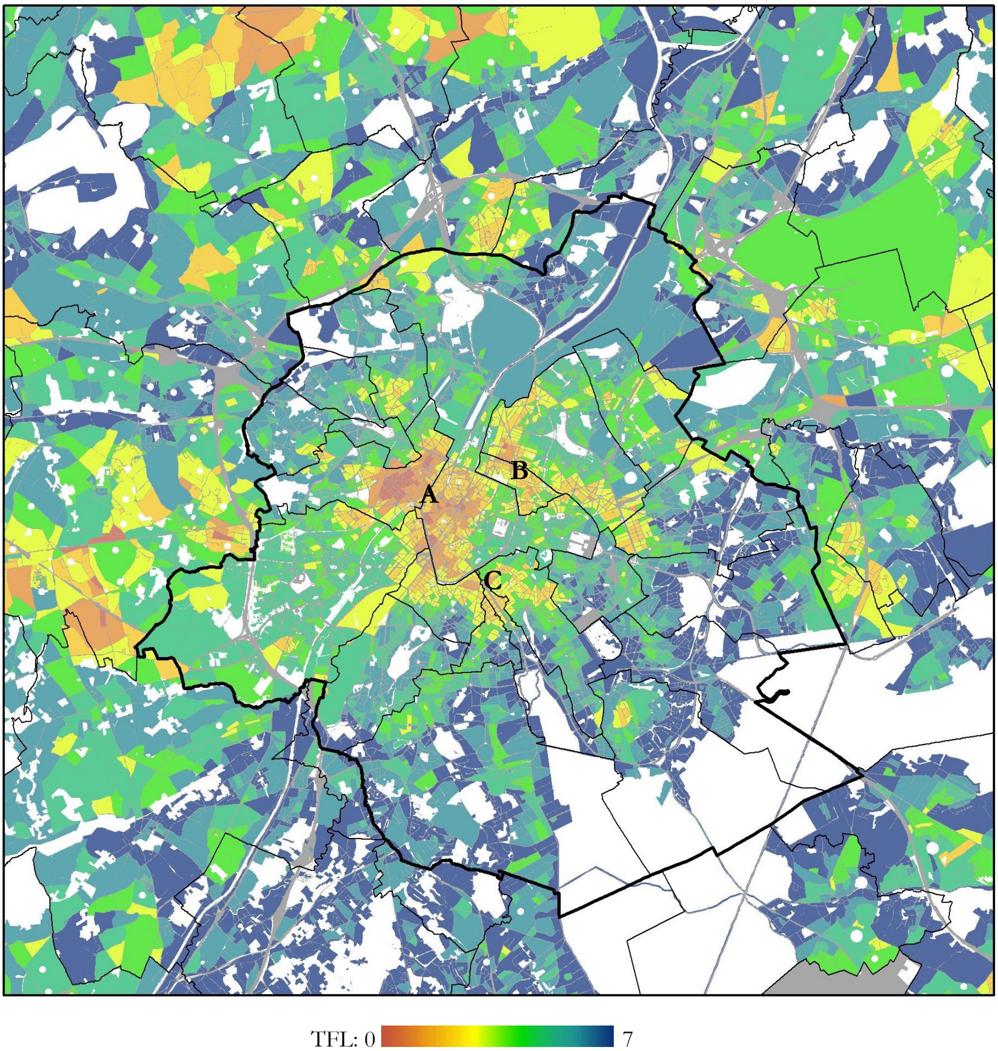


Figure 18: Number of TFL within range in scenario BASE

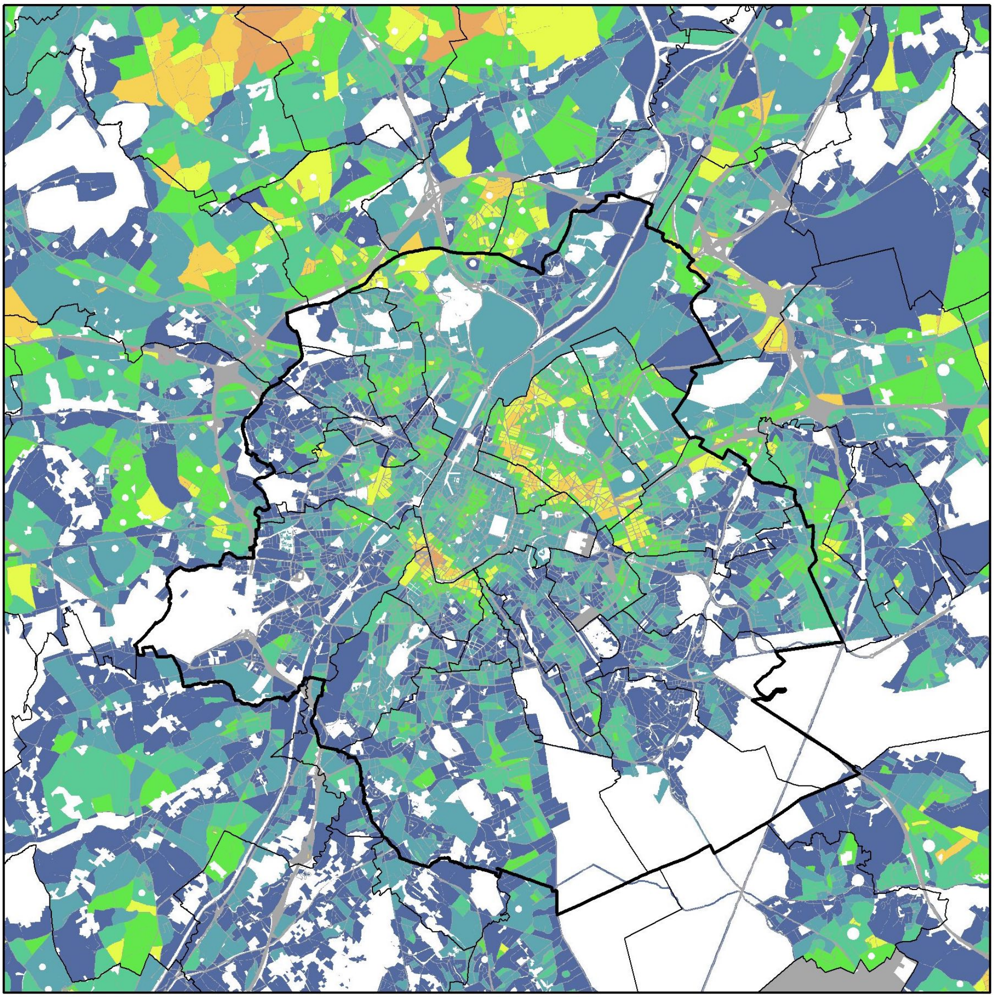


Figure 19: Number of TFL within range for scenario SUPP

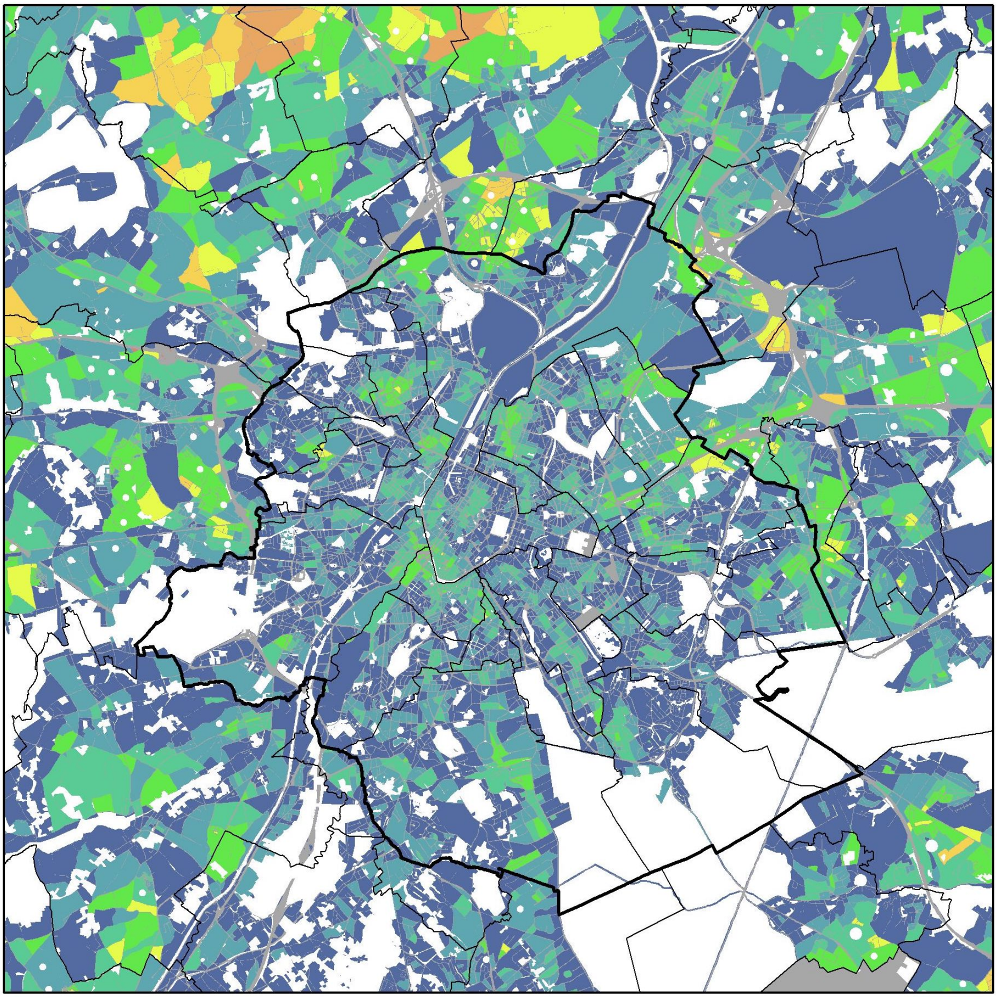


Figure 20: Number of TFL within range for scenario FULL

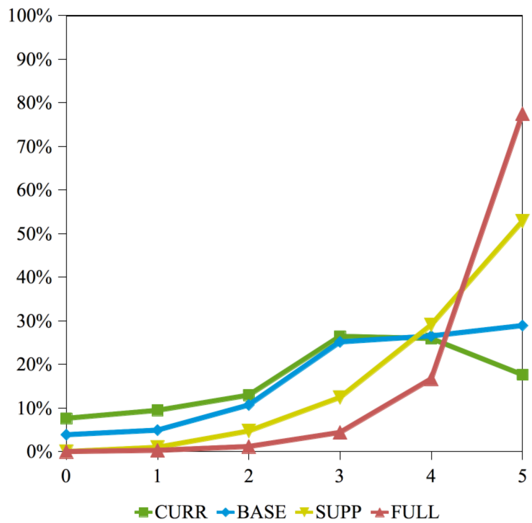


Figure 21: Share of population that has 1-5 TFL of public green space within range for CURR and scenarios BASE, SUPP, FULL

4.4.4 *Inequalities in green space proximity under different scenarios*

Figure 22 shows the spatial distribution of urban blocks located within low versus medium-to-high average incomes for the BCR. The focus is on the BCR only, given its high population density and public GS demand. The selected urban blocks form an almost contiguous area along the canal zone. Urban blocks are split into two categories: those located within the 25% statistical sectors with the lowest average reported income (BOT25) those located within statistical sector where the average reported income is higher (TOP75). In Figure 23, the influence of income on public GS accessibility is shown for the current situation, along with the potential of the three scenarios for improving access to public GS in low income vs. medium-to-high income neighborhoods. For each category, the population percentage with GS of different TFL within reach is shown for the current state (CURR) and for each of the three scenarios (BASE, SUPP, FULL). The lowest TFL residential GS and play GS, for which no interventions are proposed in the scenarios, show an increase in reached population due to the fact that higher TFL are considered as covering the functions of lower TFL if they are within reach (Van Herzele and Wiedemann 2003, Stessens, Khan et al. 2017). In the current state (CURR), metropolitan GS, city GS and residential GS are the lowest performing TFL region-wide with respectively 42%, 52% and 55% of the population reached. However, it is possible to elevate the reach of the five highest TFL to a very high level in the FULL scenario. In CURR, the average accessibility for all TFL for the BOT25 group in terms of fraction of the people reached is about 40% lower than for the TOP75 group (Figure 24), meaning that inhabitants living in the lowest income neigborhoods are strongly disadvantaged in in terms of public GS access. Access is especially low for the BOT25 group for city and metropolitan GS (Figure 23. The BASE scenario has nearly no impact (3%) in terms of improving people's access to GS overall. The SUPP scenario, on the other hand, leads to a substantial increase in accessibility for the five highest-level TFL, especially for BOT25 neighborhoods, where scenario impact is much higher than for the TOP75 group (Figure 25). Also for the FULL scenario the gain is higher for the disadvantaged BOT25 group than for the TOP75 group, restoring the balance for both groups in terms of access to GS for most TFL. Only for city green and residential green access to public GS remains lower for BOT25 than for TOP75 (Figure 25).

Figure 25 shows the population share per proximity score per scenario for the five highest-level TFL for both population groups. The disadvantage of the BOT25 group is clearly visible for CURR and for the BASE scenario. The results show a higher FULL scenario potential for the TOP75 group, as well as some similarity of potential between the TOP75-BASE scenario and the BOT25-SUPP scenario. Therefore, in case an equitable public GS development is the priority, public GS development goals and investment levels might be differentiated as such, in order to generate similar public GS provision for low-income neighborhoods and medium-to-high income neighborhoods.

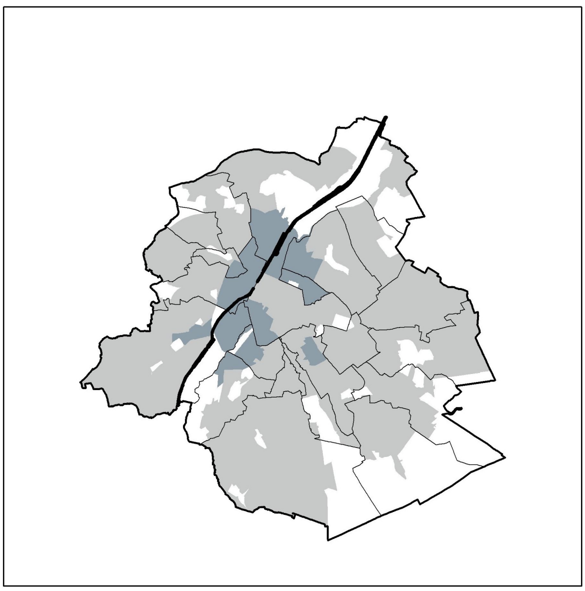


Figure 22: Urban blocks in neighborhoods with TOP75 (grey) and BOT25 (blue) average incomes; the Brussels Canal is shown in black. No data is shown in scarcely populated statistical sectors (white).

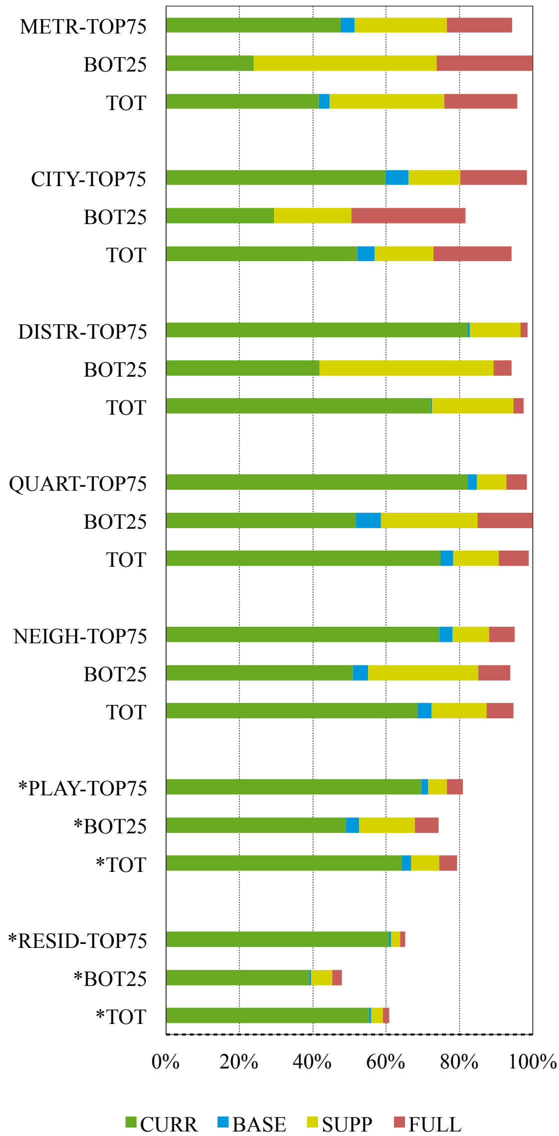


Figure 23: Percentage of population in low and in medium-to-high income neighborhoods (BOT25, TOP75) and in the entire BCR (TOT) having access to each TFL in each scenario

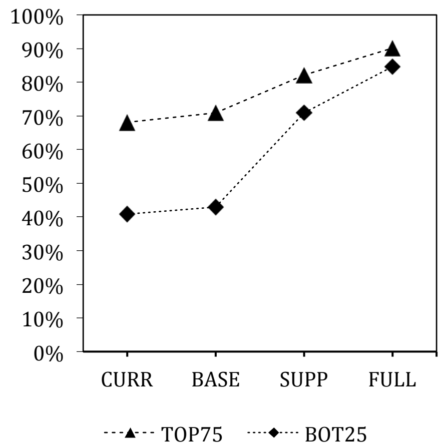


Figure 24: Average fraction of people reached for all TFL in each scenario for low income (BOT25) and for medium-to-high income groups (TOP75).

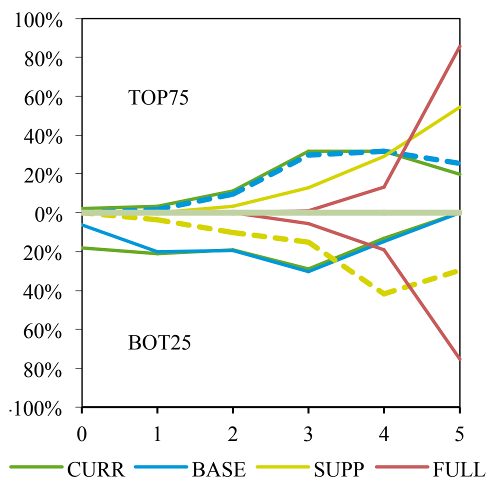


Figure 25: Population share per proximity score (0-5) for low income (BOT25) and for medium-to-high income groups (TOP75).

4.5 Discussion

The RbD experiment shows the potential of the TFL proximity model that was proposed earlier in chapter 3, and its indicators, as a design and decision-making tool. It allows for identifying problem areas. The output of the model helps in determining possible locations and interventions and allows measuring the impact of proposed solutions on citizens' access to public GS. The design exercises point to the necessity of infrastructure adaptations that reorganize or lessen traffic flow and of the acquisition of empty (parts of) residential plots in favor of the GS. In accordance with other studies, design exercises showed a range of possibilities in adaptive use of sub-optimal or vacant urban infrastructure, brownfields and gap sites (Wolch, Jerrett et al. 2011, Newell, Seymour et al. 2013, Haaland and van den Bosch 2015) or gap space on occupied sites, as well as in covering of rail corridors and development of intensive green roofs adjacent to public green spaces.

Different types of OGSD can be defined for each TFL, corresponding to a range of interventions, sometimes unique to the TFL, sometimes spanning over several TFL. Identifying these types can contribute to the streamlining of identifying suitable locations for their realization in the form of actual projects. Design exercises have shown the possibility for the BCR of moving away from a public GS status quo and reducing inequalities in public GS provision. The question whether solutions proposed are financially realistic is not addressed in this chapter, however, the relation between approximated level of investment and its effect has been explored by means of scenarios. Scenario definition in this study was limited to larger size green spaces, from metropolitan to neighborhood green. In further studies, the feasibility and typologies of OGSD at the level of residential and play green can be further elaborated, though exploration of RbD interventions in a focus area shows has shown the potential of a high level of GS provision for small public green spaces despite high built-up densities.

The need for strategic and holistic plans for the BCR that comprise the entire region (Jim 2013) is addressed by the sustainable regional development plan (BROH/AATL 2013, perspective.brussels 2018), of which the realization can be supported by the findings of this study. Effective green space planning is of crucial importance, especially in already compact cities (Haaland and van den Bosch 2015) due to the many constraints and particularly the scarcity of space (Pincetl and Gearin 2005, Schäffler and Swilling 2013, Tan, Wang et al. 2013).

One approach for defining suitable scenarios would be to address low proximity scores in a stepwise manner (remediating lowest proximity scores incrementally). Another approach, elaborated in this chapter, is to investigate the importance of different investment levels and the impact of simple vs. complex GS developments, by evaluating the remediation of low proximity scores in terms of cost and benefits. The latter can be expressed in terms of an increase in the share of inhabitants that benefit from implementing a specific scenario. In this study equitable GS improvement was prioritized by focusing the impact analysis on deprived, low income neighborhoods. Monitoring evolutions in the proximity score for different scenarios, thereby differentiating between various income groups (Figure 23), may be especially useful for setting policy priorities and for monitoring the balance between income groups in terms of access to a range of GS with different functionalities. However, there is a paradoxical aspect to the development of equity in access to GS. The inhabitants of neighborhoods that are made healthier and more attractive through new or improved GS development are often confronted with gentrification caused by increasing property value (Curran and Hamilton 2012, Wolch, Byrne et al. 2014), a process commonly referred to as environmental gentrification (Sieg, Smith et al. 2004). As such, policies and interventions can miss the intended receivers of benefits. Decision makers, planners and designers, should therefore make cities and neighborhoods 'just green enough' (Wolch, Byrne et al. 2014) and GS development is ideally paired with homeownership stimulation (Gura 2001), or GS development has to be planned in an orchestrated way throughout the city for minimal gentrification effects. A possible approach could be to improve proximity scores throughout the area without strongly affecting the relative ranking of the current situation. The gradual implementation of the BASE and SUPP scenarios in the BCR largely allow maintaining this relative ranking. In order to assess GS availability and the effect of future developments, scenario simulation is a key element in decision-making and design.

The three scenarios developed for the BCR show the negligible contribution of low-investment developments in the BASE scenario and the necessity of multidisciplinary, higher-investment GS development on challenging sites (SUPP/FULL scenarios). With regards to scenario implementation, mainly the interaction with traffic infrastructure poses a challenge, however, it can also act as a catalyst to move towards more sustainable mobility.

While this study focuses on GS proximity, recent work (Stessens, Khan et al. submitted) demonstrated that inherent aspects of GS quality, like naturalness and spaciousness, and how these qualities are valued by GS users, may be predicted from land-cover based variables such as the fraction of dense/woody vegetation, herbaceous vegetation, impervious area, and water within GS, as well as from variables indicating biological value. By including these types of variables in design exercises, the methodology proposed in this study may be extended by incorporating aspects of GS quality in the scenario modelling. Land-cover change related variables linked to GS development can also serve for a scenario analysis of water balance related impacts such as runoff, evapotranspiration and groundwater recharge (Batelaan and De Smedt 2001).

The location and structure of smaller OGSD (low TFL) in urban areas rely mostly on the available spatial opportunities. On the contrary, present landscape features such as streams and green patterns lead the allocation of larger OGSD (high TFL) and OGSD in peri-urban and rural areas. Concerning the design exercises and scenario development, the method of collaborative RbD clearly has its benefits by relying on the collective intelligence of the group. However, due to the need for static maps (prints or projections) and a limited combination of data layers to keep an overview, detailed design exercises have to be performed by a single person due to the nature of design. Therefore, the combination of RbD in groups and in solitude is considered most fruitful for and scenario development for urban GS.

4.6 Conclusions

Collaborative design was mobilized to explore the potential for GS development in Brussels and its surroundings. Analysis of the current state and of three GS development scenarios corresponding to different investment levels were conducted with the proximity model developed by Stessens, Khan et al. (2017), which enables spatially explicit analysis of citizen's access to green spaces of different size, fulfilling different needs. Impact analysis showed that inhabitants of low-income neighborhoods have limited access to larger green spaces. Actions to provide low-income neighborhoods with a good accessibility to public green spaces require creative solutions. These are spatial solutions, dealing with property, management and investments that go beyond the cost of regular GS development. Legal frameworks to designate urban GS are essential for reaching intended goals (Haaland and van den Bosch 2015).

The main objective of this chapter was to identify possible GS development scenarios for the Brussels' study area and to assess how these scenarios benefit the population of Brussels as a whole, as well as different socio-economic segments of the population. The proposed method generated an unprecedented view on the practical feasibility of providing high degree of GS proximity for the inhabitants of the Brussels-Capital Region and its surroundings. Whereas ordinary GS development would benefit both poor and rich neighborhoods to a very low degree, medium to high investments will mainly advance the poorer neighborhoods and bring them to a comparable level of GS proximity as the wealthier areas. The socio-economic bias of benefits by urban GS provision in the form of recreational nature, which is described in literature and proven for the case of Brussels, can be resolved. A caution towards negative effects of gentrification is advised, however.

The creation of scenarios involved collaborative workshops where: i) the GS proximity indicators developed in Chapter 3, along with the proposed supplementary maps were deemed very useful for identifying problem areas and locations and proposing solutions; ii) the process of collaborative RbD has proven to be an appropriate method for the same goal, especially for discussing the feasibility of solutions, and; iii) the necessity of the combination of various indicator maps and supplementary maps has confirmed the effectiveness of the graphic overlay method, commonly used in landscape design. The creation of scenarios can benefit from additional data regarding financial impact of proposed GS developments, however, the great relative investment scales allow for a rough classification from practical experience. A coarse classification of OGSD proved to be sufficient to formulate scenarios. The analysis of interventions needed for the realization for each OGSD resulted in a classification according to recurrent types per TFL. This is valuable information for further analysis, as they can streamline the process of finding OGSD in new cases.

The research is novel in its combination of three aspects: i) high-resolution proximity indicators, calculated at urban block level, using path network distances; ii) in-depth collaborative and individual RbD exercises (162 OGSD with estimated investment class), and; iii) scenario impact in relation to socio-economic indicators. Few academic studies have performed similar in-depth analyses of concrete situations with the support of GIS models and collaborative RbD. This is a method with significant potential for future studies and application potential for policy documents and spatial development plans.

Future research can be conducted on the mapping of aspects of inherent GS quality (quietness, naturalness, historical/cultural value), not for existing spaces, but for the remaining open space where OGSD can be located. This would be a valuable data layer to be involved in defining scenarios. The whole methodology can be streamlined by creating a user interface with real-time feedback on consequences of choosing certain locations of OGSD e.g. demographic impact, investment scale, water buffering potential, ecological network, or inherent quality aspects.

5

5 Typology-based land cover change simulation for future ecosystem service assessment

Abstract

One of the main challenges of the Brussels-Capital Region will be the improvement of urban environmental quality while dealing with a predicted demographic growth, increase of heat waves - aggravated by the urban heat island (UHI) effect - and increase of periodic drought and flood risk. This study presents a GIS-based and design-based assessment of potential land cover (LC) change for the Brussels-Capital Region (BCR). LC maps are key elements for modelling regulating ecosystem services (ES) and with the proposed methodology, they allow for spatially assessing the impact of future policies and subsequent developments. In order to assess potential LC change under predicted population growth, two densification strategies are formulated, a business-as-usual (BAU) and sustainable (SUS) scenario. For both, the development parameters and constraints are presented, along with LC fractions based on the existing fabric and on typological research respectively. By combining spatially explicit scenarios for densification with LC fractions of scenario-related typologies for private and public space, LC change can be made spatially explicit for both scenarios. The outcomes can then serve as input for further heat and water related modelling. These next steps, however, require a finer parameterization of LC classes in the existing modelling environments due to the heterogeneity of sustainable typologies. Whereas the analysis is highly contextual due to the specificity of one study area, the method may support high-resolution ecosystem service assessment of future scenarios in other locations.

5.1 Introduction

Brussels, like many other European cities, is currently facing numerous social, economic and environmental challenges. One of the main challenges of the Brussels-Capital Region will be the improvement of urban environmental quality while dealing with a predicted demographic growth of 28% or 336,421 inhabitants between 2016 (FOD Economie 2017), increase of heat waves - aggravated by the urban heat island (UHI) effect - and increase of periodic drought and flood risk. The European Climate Adaptation Platform summarizes Belgium's priority sectors as water management problems, heat waves and heat island effects (Climate-ADAPT 2013). Rising temperatures due to climate change are expected to slightly reduce the UHI contrast, but on the other hand will increase the amount of heat waves drastically (Hamdi, Van de Vyver et al. 2013). Reducing impervious surface cover, increasing the sky view factor (i.e. the percentage of sky visible from a horizontal surface, which allows for thermal radiation losses during the night), reduction of thermal capacity of construction materials, and a higher amount and healthy state of foliage have been indicated as factors that lower the capturing of heat and therefore reduce night temperatures, which is critical for the reduction of heat stress on inhabitants. Thermal behavior of urban areas mainly depends on land cover composition and urban structure (Verdonck, Okujeni et al. 2017). The same holds for the regulation of the water cycle (Pauleit and Duhme 2000). Currently, Brussels has a combined drainage system for rain/storm water and sewage. Most impervious surfaces, including streets and roofs, are directly connected to this system and cause annual flooding of collectors and sewers in the lower parts of tributaries (Figure 26). When the system is unable to cope with storm water peaks, the combined sewage overflows into the natural system, causing pollution and degradation. With the increasing intensity of rainfall due to climate change, a reduction of peak flow rate is key. Figure 26 depicts both heat and water related challenges for the study area.

This study proposes a GIS- and design-based assessment of potential land cover (LC) change for the Brussels-Capital Region (BCR). LC maps are a key input in the modelling of regulating ecosystem services (ES) and with the proposed methodology, they allow for spatially assessing the impact of future policies and subsequent developments on ES. Two scenarios are defined in this study for coping with expected demographic change, a business-as-usual (BAU) and sustainable (SUS) scenario, each corresponding to a different vision on urban development, and based on different built-up typologies and public space concepts. For both scenarios, development parameters and constraints will be discussed, along with potential typologies (for residential built-up and open space) and related LC fractions. Whereas BAU relies on existing land use/land cover relations, as observed in today's cityscape, for SUS, new built-up typologies are defined which take into account sustainable urban water management e.g. re-use of rainwater in buildings or rainwater buffering and infiltration. By combining spatially explicit scenarios for densification with LC fraction estimates for different typologies of private and public space, LC changes at parcel and street level can be made spatially explicit for both scenarios. These outcomes can then serve as input for ES assessment. Whereas the analysis is highly contextual due to the specificity of the study area, the conceptual framework proposed may support high-resolution ES assessment of future scenarios in other locations.

5.2 Materials

In order to enable spatially explicit mapping of LC change due to demographic growth, a GIS-based calculation process was developed that assesses densification potential at parcel level by number of additional households. The approach was conceived for application on the whole of Belgium including the regions Flanders, Wallonia and Brussels, but was limited to the BCR for the research presented in this study. The process relies on a variety of GIS data listed in Table 29, along with planning documents depicting a business as usual scenario (BROH/AATL 2006) and possible sustainable development actions for the BCR (perspective.brussels 2018). . Typological design of urban fabric relies on experience and expertise of the authors and has been inspired by examples from overview works (Ferguson 1998, Charlier, Eggermont et al. 2006, Fernandez Per, Arpa et al. 2007). A land cover map obtained by combining large-scale reference data on the built environment (UrbIS Brussels) with land cover data, derived from a Quickbird image (Van de Voorde, Canters et al. 2010), was used to extract current land cover fractions for parcels. Demographic data (FOD Economie 2013) on the level of statistical sectors was used for the calculation of population density, along with the Brussels land use map (Pras_Affectations_2017).

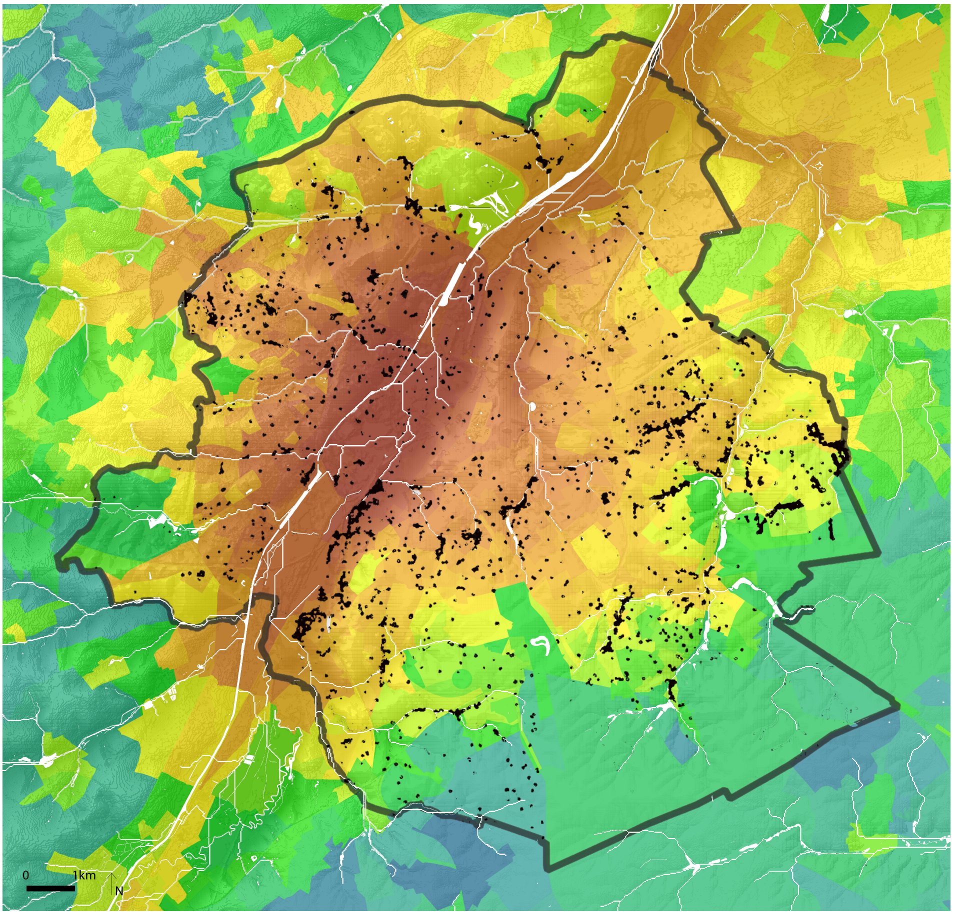


Figure 26: Reported flooding events 1999-2012 in the Brussels-Capital Region (marked by '•') and urban heat island represented by the mean nocturnal surface temperature during summer per statistical sector (blue-amber). Streams and waterways: white, Brussels-Capital Region boundary: grey.

Attribute	Description	Layer / source
shape	parcels	BRU_URBIS_P&B / CIRB
[hasmain]	The plot has a main building on it	BRU_URBIS_ADM_BU / CIRB
[resurb]	The plot has a land use class fit for residential use (which can be mixed) of an urban character	Pras_Affectations_2017 / Perspective.Brussels
[bioval]	The plot coincides (partly) with biologically valuable, or very valuable area	Bwk2 (biologische waarderingskaart) / Informatie Vlaanderen
[transp]	The plot lies within reach of public transport stations: train or metro (2250m, 600m)	NAVSTREETS (native) Vector / NAVTEQ
[protect]	The plot lies in a zone of protected landscapes (historical urban or natural)	Pras_Affectations_2017 / Perspective.Brussels
[area]	Projected surface of the plot (m2)	(shape)
[dens]	Population density of the surrounding plots within land use classes fit for residential use (inh/ha)	SCBEL01Z4 /

Table 29: Attributes added to cadastral map as parameters
for deciting the densification approach (Figure 29, Figure 30)

5.3 Methodology

5.3.1 *Process structure*

The goal of this research is to propose and apply a conceptual framework for assessing urban land-cover change at parcel/street level under different scenarios, using a typology-based approach. Such a framework may form the basis for ES impact assessment related to two scenarios that will be defined for the study area: a business as usual (BAU) and a sustainable scenario (SUS), which will both be compared to the existing situation (EXI). The focus in our work lies with private space and street segments, since public green spaces have been addressed in earlier work. As will be illustrated further on, for sustainable development, the functional integration of street and parcel are essential in design-based scenario definition.

Scenarios are in this exercise 'what if' questions for policy and planning. There is no timeframe defined, however, given the scope of the developed scenarios, the completion will at least span 3-5 decades. The construction of the scenario proceeds differtly for BAU and SUS. In the case of BAU, we ask ourselves 'what if we continue the current way of doing things across all disciplines (regulation, planning, mobility, design, construction)? For the SUS scenario, the question would be 'what if policy and planning made all (reasonable) efforts to minimize the impact of future development in terms of level of space consumption, low carbon footprint, use of nature-based systems for urban infrastructure, and future-oriented mobility concepts (e.g. shared vehicles)?' In this case, densification in urban cores and mobility hubs applies, along with space for water and nature (no construction in zones with flood risk). It involves the use of green roofs, vegetated streets, and the concepts of swales (open air buffering and infiltration) and domestic re-use of rainwater are taken into account. LC change is essentially based on two drivers: densification and renovation or renewal. Densification can be made spatially explicit based on the availability of new residential space in case of BAU and SUS. Renovation can be made spatially explicit by applying the yearly renovation rate randomly (Figure 27). The actual amount of approved renovation permits are known, but due to data lacking on the amount of rooftop renovation, the latter component is not included in this study.

A rule-based approach will be used to translate changes in built-up typologies into LC change for both scenarios. Existing GIS data at parcel level and planning documents (regional planning regulations, PRDD) allow for a parcel scale assessment of potential household (HH) increase (creation of allotments, infill or densification by addition/replacement) for both scenarios. To translate scenario-based densification patterns related to demographic growth into LC change, a relation between population density and LC fractions is established for BAU through density-LC analysis of the existing urban fabric and for SUS through typological research by design (RbD) (Figure 28). Both steps in the modelling approach are explained in Figure 28. The output of this exercise is LC fraction maps for each scenario, which can be used in models for ES assessment of e.g. water, heat, or air quality.

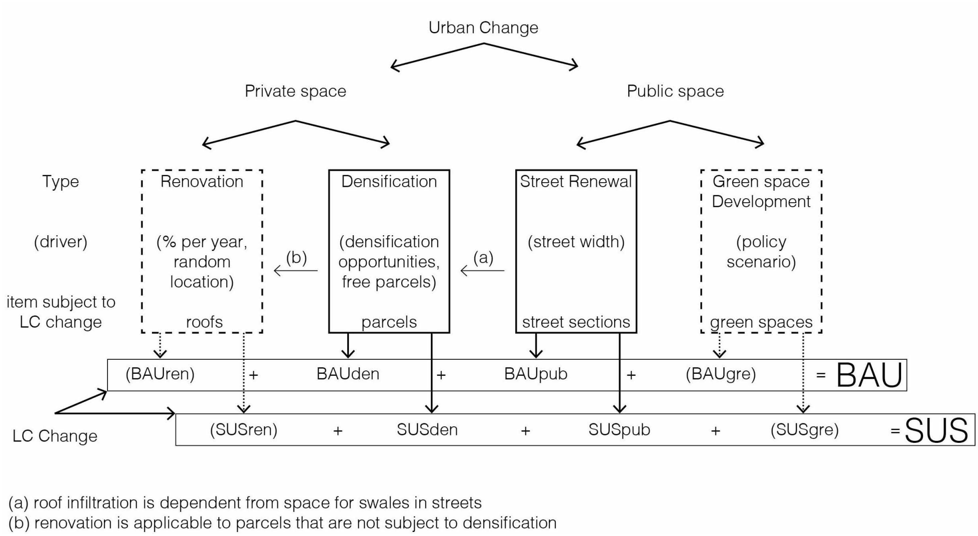


Figure 27: Conceptual scheme for land cover change simulation. In this study, only densification and street renewal is taken into account.

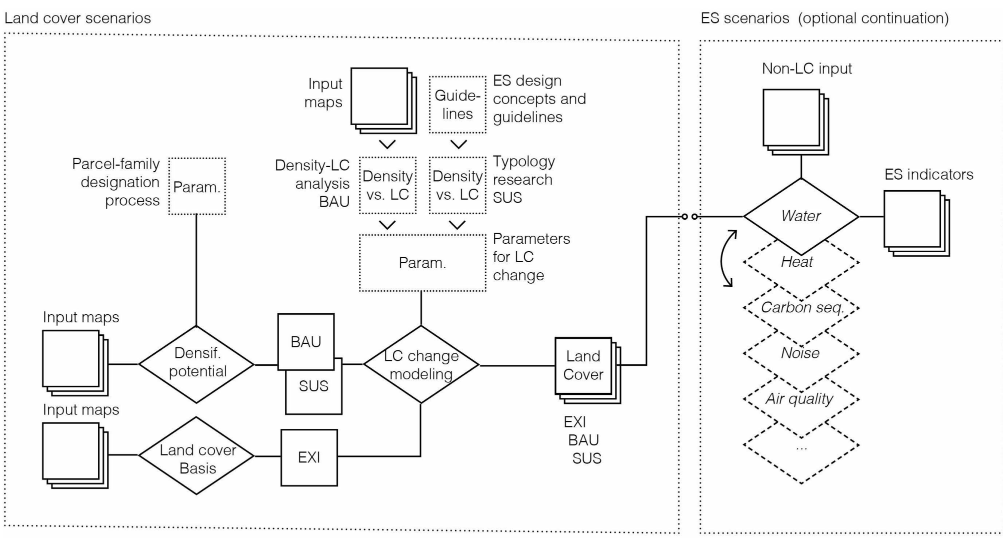


Figure 28: Process scheme for land cover change scenarios (current study), with optional continuation into ecosystem service assessment.

5.3.2 *Densification potential at parcel level*

To define the densification potential in each scenario at parcel level, parcels were overlaid with a series of base-maps in order to assign a set of attributes to each parcel (Table 29). These attributes were then used to calculate the maximum amount of additional HH that can be assigned to the parcel, using a rule-based approach (Figure 29, Figure 30). In the BAU scenario (Figure 29), only zoning (suited for residential use) is taken into account for selecting parcels for new residential development. Parcels including a main building remain unchanged. Parcels without a main building located in an urban core area are allocated the same density as the surrounding parcels. Urban core is defined in land use maps as centers of cities and villages as opposed to rural residential areas, which are if Flanders typically strips of housing along an arterial road. In order to calculate this density, the total population of the statistical sector is divided by the total area of built-up parcels. The average of 2.35 pers/HH or 0.425 HH/pers is used for transforming population density into household density. If a residential parcel is located outside of an urban core, it is either parceled out at 900m2 per household, which is the Flemish average, or filled in by one household if the parcel is smaller than 2500m2. Many parcels are larger than 900m2 but are not suited for densification due to their shape (deep but narrow on the street side). Therefore, an area of 2500m2 was chosen as a suitable threshold for parcellation by examining the geometric properties of a range of residential parcels outside urban core areas on the map.

In the SUS scenario (Figure 30), parcels suitable for development are selected based on zoning (suited for residential use), the absence of flood risk and the absence of high biological value. If a parcel is within 600m (short trip walking distance) of a train or metro station with 2000+ travellers on a weekday and the parcel is not located in a protected landscape, it is considered as a primary densification site, with a goal of 150 HH/ha. Practical examples show this as a density that is at the same time urban, dense and that leaves sufficient opportunities for green space and soil perviousness (Fernandez Per, Arpa et al. 2007). In other areas, parcels with a main building of which 1/20th of the area or less is built up are filled up based on surrounding density (same method as described earlier).

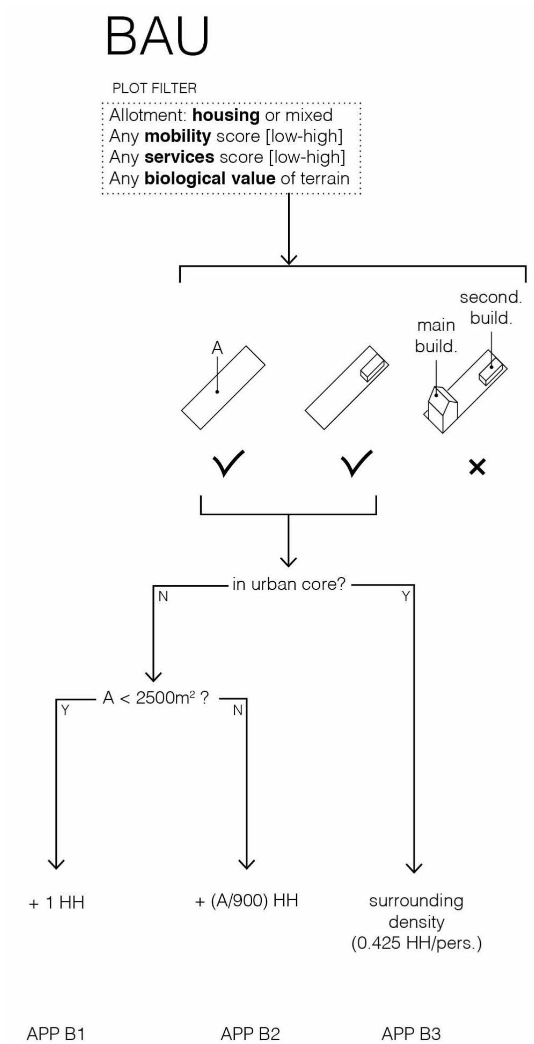


Figure 29: Decicion tree for BAU, for determining household densification potential and approach for densification

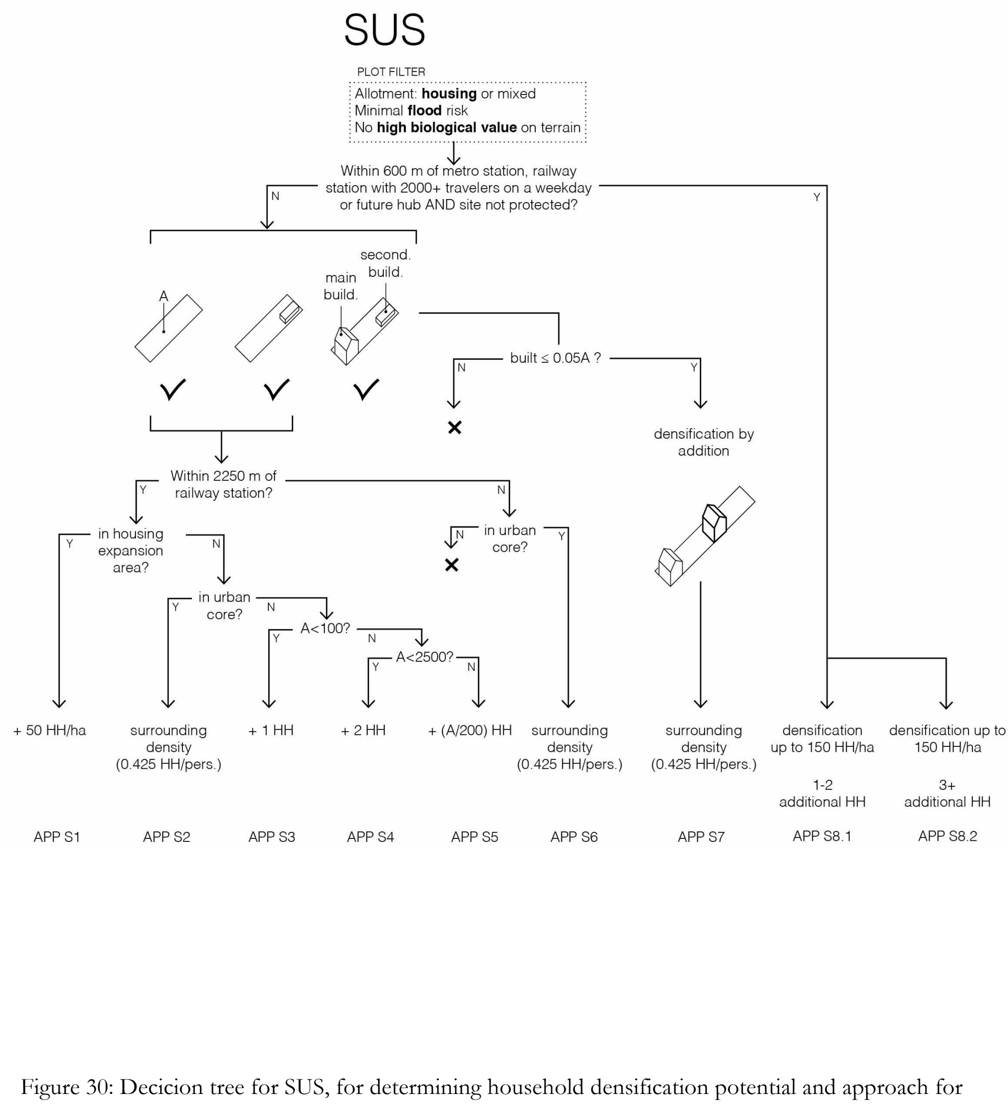


Figure 30: Decicion tree for SUS, for determining household densification potential and approach for densification.

Parcels without a main building within 2250m of a railway station, located in housing expansion area are considered for densification at 50HH/ha. For parcels outside housing expansion areas there are four options. If parcels are located within an urban core, the surrounding density is taken in account. In case they are not located in an urban core, if they are between 100m² and 2500m², 2 households are assigned per parcel, if they are smaller than 100m², 1 household is assigned. The threshold for 2 household units was determined by design tests, the 2500m² is the same threshold as considered in the BAU scenario for splitting up large parcels. Parcels larger than 2500m² are parceled out at 200m² per household, in contrast with the 900m² applied in the BAU scenario. Finally, if a parcel without a main building on it is not located within 2250m of a railway station, it will be allocated the surrounding density if located within an urban core, if not it will remain un-built. The latter rule ensures that open space outside urban core areas, and away from major transportation hubs, will be safeguarded from future development. Each leaf of the decision tree is labeled as an 'approach', corresponding to a specific way of filling up a parcel. This can be a building with a certain density from scratch or after demolishing the existing units, by adding, or by topping up existing buildings with extra floors. These approaches determine how corresponding LC fractions are assigned in the next stage of the modelling. Since the rule set was defined for application on the whole of Belgium, some cases do not apply to Brussels, and therefore some 'approaches' neither. These are respectively: housing expansion area, non-urban core, and APP S1, S3, S4, S5.

5.3.3 *Current land cover*

The scenarios were applied starting from the existing state of the study area (EXI). Current LC was based on 2D and 3D information on the built-up area (buildings, public spaces), along with information on land cover obtained from a Quickbird remotely sensed image covering the study area (Van de Voorde, Canters et al. 2010), and describing the distribution of impervious surfaces, dense/woody vegetation and low vegetation. For each parcel and for each street or street crossing the fraction of seven main surface types, corresponding to the first letter of the LC code documented in Table 30, was calculated. Roof characteristics were derived from 3D vector data (UrbAdm_Bu_Roof_3D) of the UrbIS dataset from the Brussels Regional Informatics

Centre. A threshold of 4% slope was taken into account to discriminate between sloping and flat roofs. The total area of existing green roofs is negligible in comparison to the total area of non-green roofs in the current state. LC fractions for private non-built spaces were derived from the interpreted Quickbird image. All street surfaces (UrbAdm_Ss) were classified as impervious with direct drainage (IDF, Table 30), with exception of roadside green (UrbMap_GB-A).

5.3.4 *BAU scenario*

Description BAU scenario

The LC change scenario for BAU is straightforward. Only parcels without a main building are filled up, and LC fractions are attributed to the parcels in function of the envisioned household density. This density is determined through the decision tree and the relation between household density and LC fractions is derived from the current state in existing residential zones in the study area. Regarding street renewal, no intentions are included for redesign or greening of the street layout. Existing LC fractions are kept.

Household density - LC relationship

Since different densities apply to specific locations in the scenarios, LC fractions defined in function of household density constraints allow for a flexible definition of LC scenarios. An analysis was conducted of the existing urban fabric to establish a relation between household densities and LC fractions for the BAU scenario. For this analysis, the area taken into account only covers private space (parcels) in residential land use classes, excluding public space and other land uses, such as industrial zones or park space. Per urban block, LC fractions were sampled from a rasterized LC map. Detailed information on population distribution was obtained by combining cadastral data (net residential area per parcel) and population density at statistical sector level. LC fractions proved to have a better correlation with household density d on a logarithmic or exponential scale than on a linear scale. Therefore, regression analysis for modelling the density-LC relationship was performed based on the natural logarithm ($\ln d$) and power ($d^{1/2}$) of density as independent variable.

5.3.5 *SUS scenario*

Description SUS scenario

Sustainable urban rain water systems go beyond the simple land cover classes determining runoff, (evapo)(transpi)ration and recharge. Rainwater can be used in buildings or may be buffered and infiltrated in swales (Figure 31). These options multiply the amount of building-related LC classes by four. An extension of the commonly used LC classes (bare soil, low/dense vegetation, impervious, water) is proposed in Table 30. Figure 31 and Figure 32 illustrate the difference between a BAU flow from impervious surfaces to the sewer and soil and an ideal SUS flow. Several combinations of buffer and swale use are represented in Figure 32. Practical examples show that even for high densities (150 HH/ha) and a soil with medium infiltration speed, swales can be dimensioned for an overflow with a return period of 250 years under current climate conditions (Stedenbeleid Vlaanderen 2018). This includes the hypothesis that the buffer for re-use is at full capacity, leading all evacuated rainwater from the roofs to swales.

In the SUS scenario, empty parcels are filled up and underused parcels are assigned a higher density (of the surrounding urban fabric) when they are in the vicinity (2250m) of mobility hubs, and areas within close proximity of these hubs (600m) are given a density of 150HH/ha when they are not in zones that are protected from urban transformation. All new buildings are to be built with green roofs. These surfaces are connected to re-use systems of which the re-used water is led to the sewer and overflow is infiltrated where possible. The possibility for infiltration depends on the street type, width and soil properties. In this scenario, a drastic transformation of street surfaces is envisioned, which goes hand in hand with a mobility shift towards walking, public transport and shared autonomous vehicles (SAV). Space that is freed up becomes pervious green space and swales. Their proportions are determined by the street width and soil properties.

LC code structure	Surface type	Rainwater evacuation	Rainwater flow
	Gable or sloping roof (R--) Flat roof (F--) Green roof (G--) Impervious (I--) Vegetation (V--) - dense (-HI) - low (-LO) - buffer area (-BU) Bare soil (BAR) Water (WAT)	Direct drainage (-D-) Infiltration (-I-)	Direct drainage of all flows (--F) Re-use buffer overflow drainage (--O)
LC classes			
VHI	Dense vegetation		
VLO	Low vegetation		
VBU	Vegetated buffer area		
WAT	Water		
BAR	Bare soil		
IDF(1)	Impervious surface…	…with direct drainage…	…of all flows
IIF(3)	Impervious surface…	…with infiltration…	…of all flows
RDF(1)	Gable roof…	…with direct drainage…	…of all flows
RDO(2)	Gable roof…	…with direct drainage…	…of overflow
RIF(3)	Gable roof…	…with infiltration…	…of all flows
RIO(4)	Gable roof…	…with infiltration…	…of overflow
FDF(1)	Flat roof…	…with direct drainage…	…of all flows
FDO(2)	Flat roof…	…with direct drainage…	…of overflow
FIF(3)	Flat roof…	…with infiltration…	…of all flows
FIO(4)	Flat roof…	…with infiltration…	…of overflow
GDF(1)	Green roof…	…with direct drainage…	…of all flows
GDO(2)	Green roof…	…with direct drainage…	…of overflow
GIF(3)	Green roof…	…with infiltration…	…of all flows
GIO(4)	Green roof…	…with infiltration…	…of overflow

Table 30: Overview of urban land cover classes including re-use and infiltration. Numbers (1)-(4) refer to Figure 32.

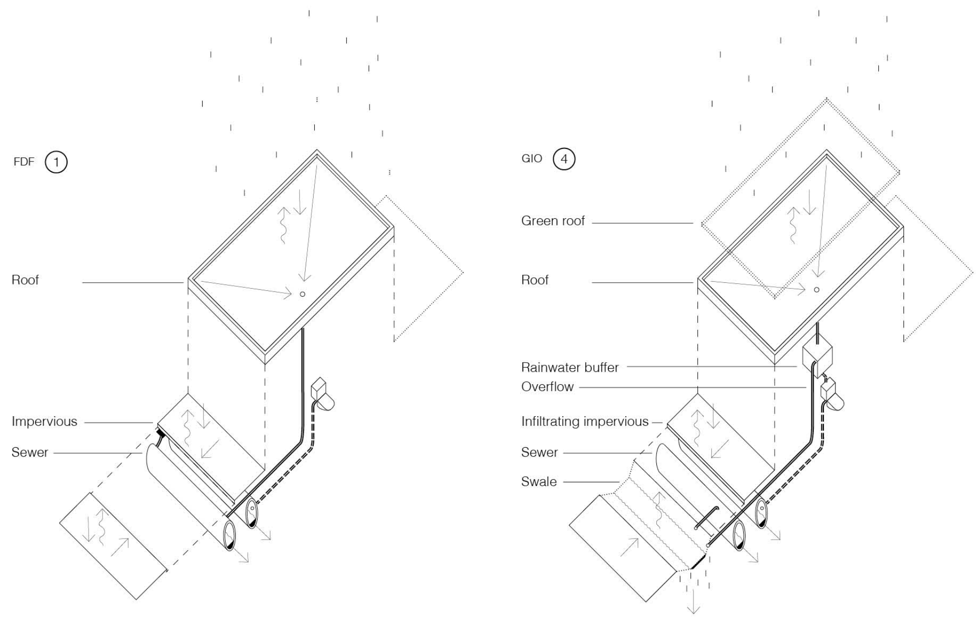


Figure 31: Two rainwater systems for buildings. Left, as considered in the BAU scenario, the roof is 'FDF', flat roof with direct drainage and no re-use; right, for the SUS scenario, the roof is 'GIO', green roof with infiltration and re-use.

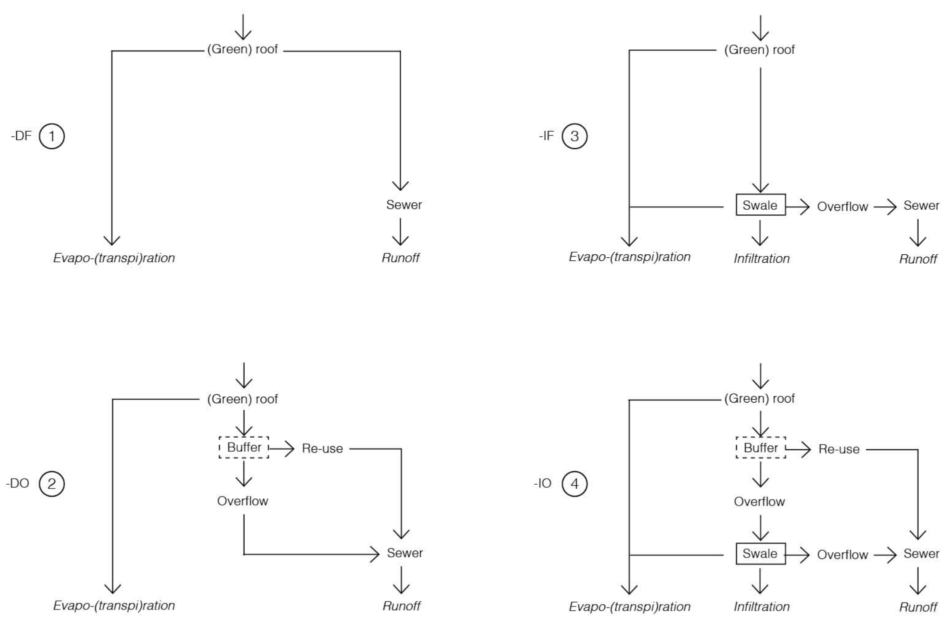


Figure 32: Four schematic representations of rain water flows with or without re-use and infiltration.

Definition of typologies

The SUS built-up typologies aim for ideal configurations with a maximum inclusion of ecosystem services. Their design follows a set of predefined objectives: low fraction of impervious surface; maximum water retention and infiltration through green roofs and runoff buffering and infiltration; compact buildings; high spatial quality; maximum access to gardens or private green space, and; provision of small- scale public green. For assessing the impact of the scenarios (building code policies being applied to the predicted household density changes), an attempt was made to develop typologies for residential or mixed land use for 5 different densities and from these typologies, a density-LC relation was established. In a next step, from this relation, approximate LC shares can be assigned to all densities. Types and corresponding characteristics are referred to as *gross* when public space is included and *net* when this is not the case. Densities are calculated as households per hectare (HH/ha) with an average of 2.35 people/HH and an average housing unit size of 74.93 m^2/HH net surface or 107 m^2/HH constructed surface. The typologies are listed in Table 31, with corresponding density, floor area over footprint area ratio (FAR) and the works that have inspired the design of these typologies. In typologies 2-5, commercial and/or office space is integrated in the design, since higher density typologies ideally have a mixed land use. The design exercises were based on realistic proposals of urban fabric and were further defined according to design principles of the SUS scenario regarding density-LC choices. The SUS typologies are depicted in Figure 34, together with a LC fraction summary in Figure 33. The average density of the Brussels-Capital Region in 2016 is 34 HH/ha and 79 HH/ha when considering only the net residential area (BRIC 2016). SUS typologies range from 46 to 174 HH/ha since lower densities are considered unsustainable. 50 HH/ha is defined as a minimum density for new development according to the Flemish Chief Architect (NAV 2016).

Type	Description	Density d (HH/ha) [Gross - *Net*]	FAR [Gross - *Net*]	Based upon
SUS01	Semi-detached with garden	46 *55*	0.41 *0.48*	Housing Heidebergstraat Leuven by BOB361 (Charlier, Eggermont et al. 2006)
SUS02	Semi-detached and park apartments	65 *68*	0.53 *0.56*	Previous type and and No. 22, Ankang Road, Kaohsiung City by Mecanoo
SUS03	Closed block	88 *106*	0.74 *0.89*	Coin Street by Haworth Tompkins*, Bodegraafsestraatweg by KCAP*
SUS04	Closed block	127 *170*	0.99 *1.32*	Coin Street by Haworth Tompkins*, Bodegraafsestraatweg by KCAP*
SUS05	Striga (mixed low/high rise)	174 *241*	1.75 *2.42*	Nieuw Zuid Antwerpen by Studio Associato Secchi-Viganó
				* (Fernandez Per, Arpa et al. 2007)

Table 31: Typology description, densities and design references

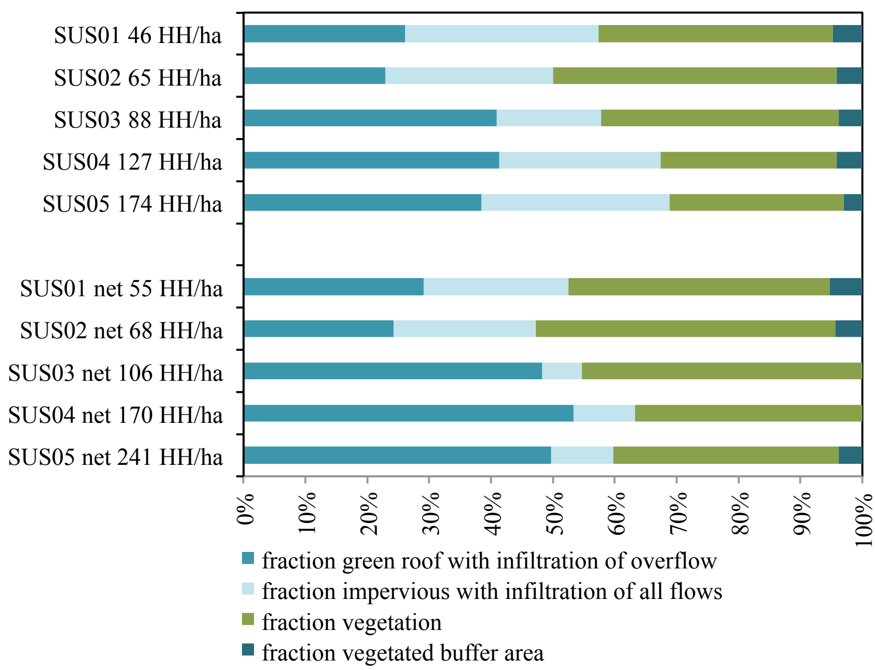
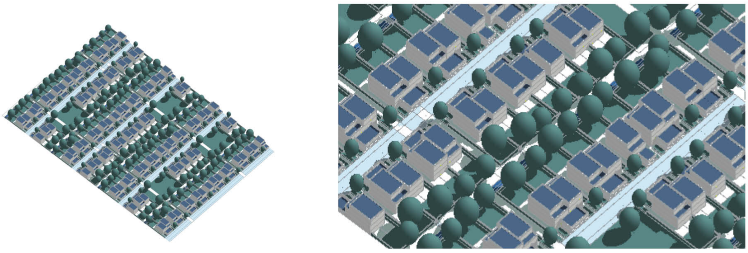
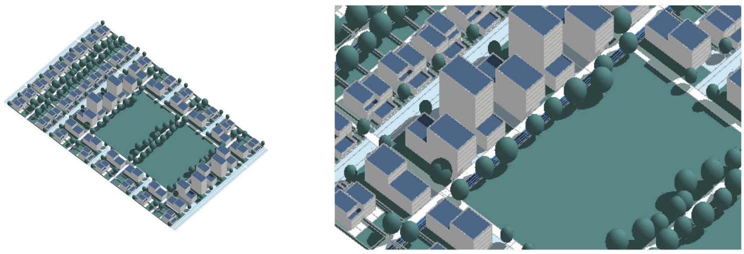


Figure 33: LC fractions of SUS typologies

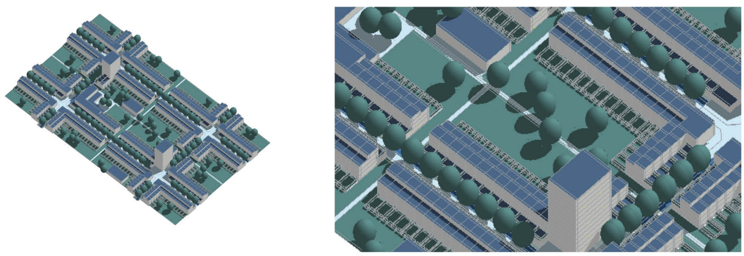
SUS1



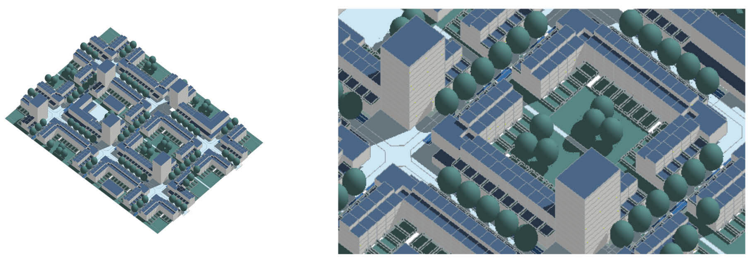
SUS2



SUS3



SUS4



SUS5

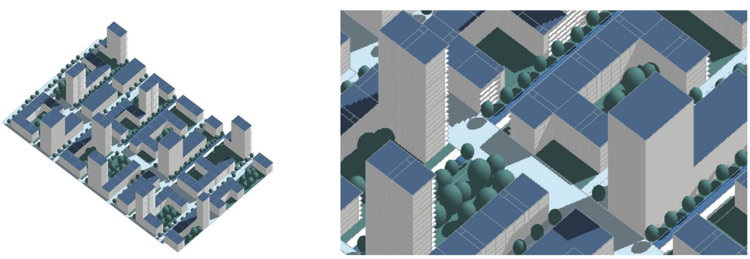


Figure 34: Sustainable typologies (blue surface: green roofs with infiltration of re-use overflow)

For street surfaces, similar typology driven LC fractions are derived. Maximum possibilities for greening and infiltration are explored. For street surfaces, the determining factors for change in the scenario definition are: i) street function or hierarchy; ii) street width; and iii) density of parking space. On residential or local streets, greening is considered possible by diminishing the amount of parking space taking the use of shared vehicles or shared autonomous vehicles into account. Because street sewers collect runoff from parcels and public pavement, buffer areas with an overflow (swales), are ideally placed in the street section instead of in gardens. A second reason for allocation of the swale on public grounds is the contribution it brings to combatting heat capture in street canyons. Vegetation has better thermal properties and the presence of the swale allows for trees to grow larger and more healthily, which in turn provides more shading for the paved parts of the street section.

In the SUS scenario, streets are being changed through: i) decreasing road parking space; ii) maximizing greening space; iii) providing space for infiltration of water from public and private impervious surfaces (e.g. roofs). Streets serving mostly for transit and commerce are henceforth called *circulation streets*. In the SUS scenario these streets maintain their current layout, as there is not much room for adjustment. For the same reason crossings receive the same treatment. Residential or local streets serve mostly for parking and access to dwellings and are named *living streets*. In the SUS scenario, they are considered as suitable for transformation. Each street width (1m increments) is tested – through design – for greening and swale potential in order to link scenario-based LC fractions to street width. Whether or not the street is able to provide infiltration services will depend on the street type, width and soil type (Figure 35). Widths of 14m and more can include a swale strip of 4m wide. For widths of 12-14m this is possible too, though in this case the regulation of 4m spacing between a fire truck path and a building is not adhered to (Figure 36). In case of narrow streets (<14m) without space for a swale strip, infiltration needs to take place on private space, which implies that runoff from public impervious space is not buffered. Decrease of impervious area in streets goes hand in hand with rethinking the purpose of the street. Drivers looking for parking spots generate most traffic in *living streets*. With the prospect of alternative options from shared vehicles to shared autonomous (electric) vehicles (SAV), the need for parking will drop to respectively 50% (SUS

P1/2) and less than 10%, with each shared autonomous vehicle freeing up more than 20 parking spaces (Zhang and Guhathakurta 2017) (SUS P1/6). With this shift, *living streets* can be designed primarily for soft mobility and occasional emergency services. Whereas SAV introduction would allow 90% of the existing parking in *living streets* to be transformed into pervious surface, in order to leave a margin space for drop-off, bike parking and waste collection systems, only 5/6th of the current parking space is transformed and considered to be pervious. Impervious surface is also reduced to a minimum for sidewalks and one-way streets where the remaining space is green and connection between paved surfaces (Figure 36).

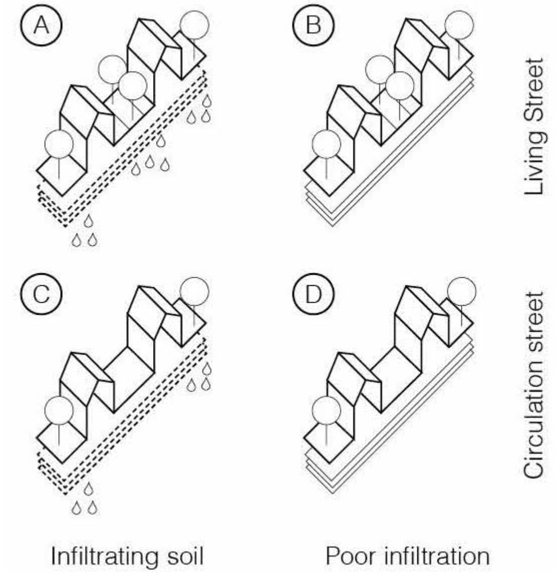


Figure 35: Greening and infiltration depending on street and soil type.

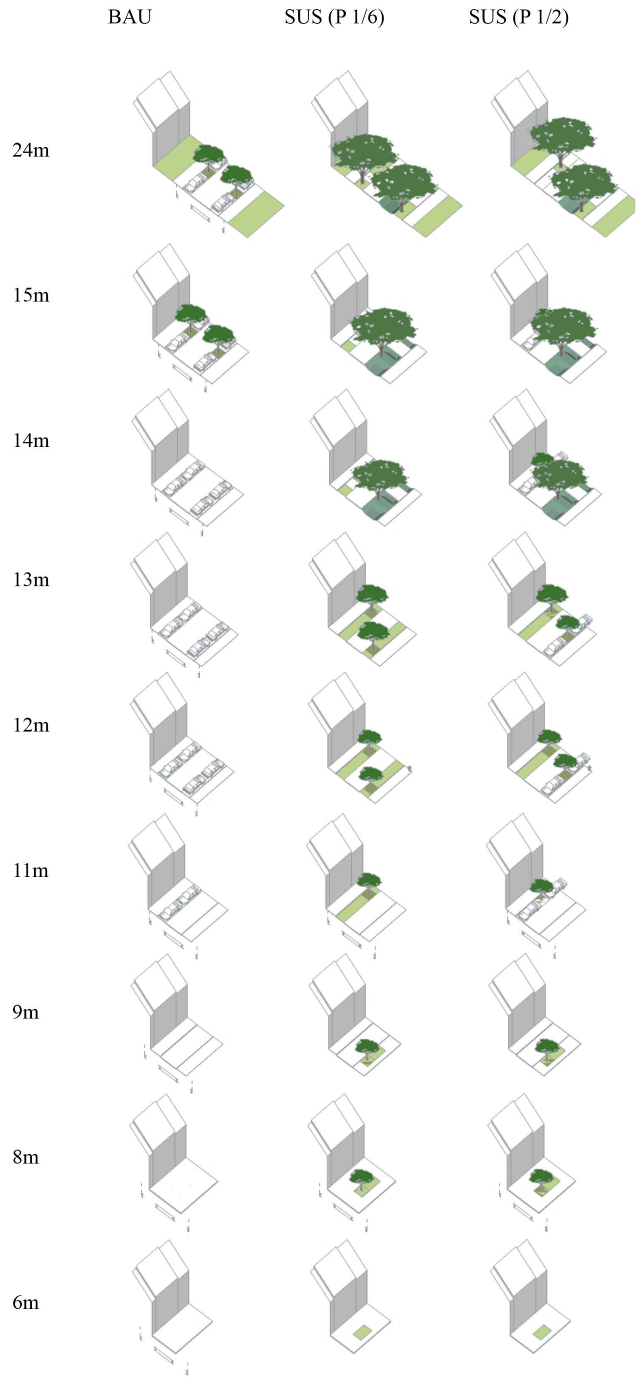


Figure 36: Street typologies (left to right: regular streets including fire truck markings, SUS with 1/6th space for drop-off, SUS with 1/2nd parking space)

Relation to land cover

For the SUS scenario, a similar density vs. LC analysis was made as for BAU, starting from the five urban fabric configurations (typologies) with varying density. In order to establish a LC-density relation, a non-linear interpolation function to infer LC fraction from household density was established for each of the LC types present (fGIO/fGDO, fIIF/fIDF, fVBU, fVEG), based on the LC fraction/density values for the five typologies. In a similar way, street LC fractions were measured for the designed street typologies, corresponding to different street widths, and an interpolation function was defined to infer the fraction of each of the LC types present in the typologies (fGIO/fGDO, fIIF/fIDF, fVBU, fVEG) from the street width.

5.3.6 *Typology-based land cover change*

In case a parcel is subject to change by densification, it is assigned an approach or "APP" code, depending on the outcome of the earlier described decision tree (Figure 29, Figure 30). LC fractions of the parcel will be altered accordingly. Most approaches involve a recalculation of LC fractions based on density, yet built-up characteristics can also be altered through policy implementation and building code without household densification. In the case of SUS, this is the alteration of flat roofs (FDF) to green roofs with re-use of rainwater (GIO, GDO). Depending on street segment characteristics (type – street or crossing, level – regional or local, width, existing LC fractions) and scenario definition, new LC fractions are assigned to individual street segments.

5.4 Results

5.4.1 *Densification potential at parcel level*

The application of the household allocation process results in the changes described in Table 32. Both scenarios aim for maximum development within the given constraints and typologies applied, i.e. all room for densification is appropriated. Whereas BAU only generates an additional 35,266 households, SUS generates 242,003 additional households. The majority of these can be attributed to densification at 150HH/ha within 600m of public transport hubs (APP S8.1 and S8.2, Figure 30). 3/4th of the parcels accommodate 1/4th of this share of additional households by adding levels to the existing buildings (APP 8.1) and 1/4th of the parcels accommodate 3/4th of this share of additional households through urban regeneration (rebuilding) at significantly higher density. The spatial distribution of these results is shown in Figure 38. The main driver for this difference is the urban reconversion of areas without protection with regard to heritage and within a 600m of transport hubs. In dense areas, this results in an addition of floors and a green roof (Figure 38, type S8.1) and in lower density areas, it results in a regeneration of the urban fabric with a net density of 150 HH/ha (Figure 38, type S8.2).

5.4.2 *BAU density – land cover relationship*

Analysis of the relationship between existing land cover and HH density for residential land use at the level of urban blocks reveals that the fraction of impervious surfaces at block level ($fIDF_B$) is moderately to highly correlated with HH density d with $r^2 = 0.63$ (Figure 37) as:

$$fIDF_B = 0.063\sqrt{d} - 0.007. \qquad \text{(Eq. 1)}$$

Use of the logarithm of HH density results in a similar correlation, but the proposed relation (Eq. 1) shows a more realistic behavior at low densities (Figure 37). Fractions of low and dense vegetation (fVLO, fVHI) have no significant correlation with household density and are therefore described by their average share of vegetated surfaces for residential land use, which is 0.15 and 0.85 respectively. As such, based on impervious fraction, the fraction of low and dense vegetation can be characterized as:

$$fVLO_B = 0.15(1 - fIMP_B) \qquad \text{(Eq. 2)}$$

$$fVHI_B = 0.85(1 - fIMP_B) \qquad \text{(Eq. 3)}$$

Approach	# parcels	# households
Total BAU	*18,178*	*35,266*
APP B1	12	12
APP B2	0	0
APP B3	18,166	35,254
Total SUS	*78,915*	*242,003*
APP S1	0	0
APP S2	12,349	23,909
APP S3	10	10
APP S4	0	0
APP S5	0	0
APP S6	49	47
APP S7	1,546	7,539
APP S8.1	48,574	51,436
APP S8.2	16,387	159,062

Table 32: Outcome of household allocation process

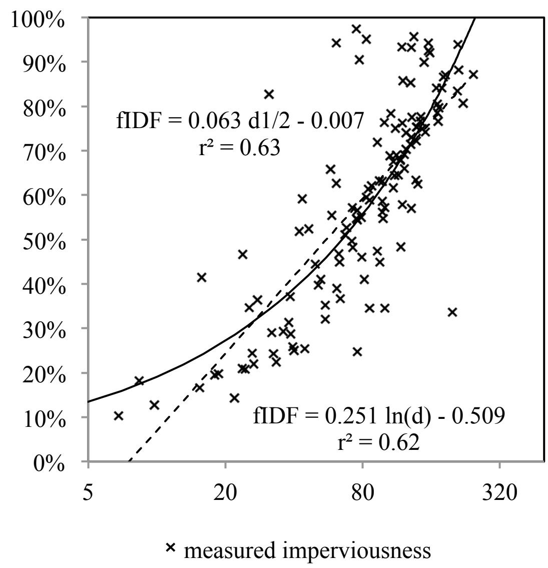


Figure 37: Scatter plot of household density in HH/ha (x-axis) and fraction of impervous surface cover (y-axis).

Figure 38: Types of change for each parcel in BAU and SUS (top and middle); parcels supported by street swales (bottom)

5.4.3 *SUS typology-based land cover fractions*

Figure 33 shows the LC fractions of the SUS typologies. As can be expected, roof surface increases with density. Impervious surface tends to decrease with density and green area drops with increasing density. For the SUS scenario, interpolation on the surfaces generated through SUS typologies between LC fractions and household density informs us on the fraction of green roof surface ($fGIO_S$), impervious surface ($fIIF_S$), infiltration space ($fVBU_S$) and green space ($fVEG_S$). The approximation is logarithmic (Eq. 4) and coefficients are listed in Table 33. Figure 39 shows the variation of LC fractions in function of density d for private space. Results for the same analysis for all space (private and public) are shown in Figure 40.

$$fFraction_S = \mathrm{a}\,(\mathrm{b}\ \ln d + \mathrm{c})$$

(Eq. 4)

Fraction	a*	b	c	r^2
net area				
$GIO_{S,net}$	0.96	0.186	-0.465	0.75
$IIF_{S,net}$	0.96	-0.104	0.656	0.95
$VBU_{S,net}$	0.96	-0.007	0.077	0.55
$VEG_{S,net}$	0.96	-0.067	0.734	0.55
gross area				
$GIO_{S,gross}$	0.96	0.128	-0.235	0.59
$IIF_{S,gross}$	0.96	-0.008	0.325	0.04
$VBU_{S,gross}$	0.96	-0.010	0.086	0.73
$VEG_{S,gross}$	0.96	-0.111	0.857	0.61

Table 33: Coefficients for LC fractions in function of household density for the net area (private) and gross area (private and public) (Eq. 4). (*) The parameter 'a' is a correction factor, applied after modelling the relationship between LC fraction and household density for different LC classes to ensure that the sum of fractions over all classes approximates 1.

When the soil is not suited for infiltration, $fGDO_S$ takes over the values of $fGIO_S$ and $fGIO_S = 0$. Similarly for $fIDF_S$ and $fIIF_S$.

The typological design exercises on *living streets* for SUS produce LC fractions for vegetated space as depicted in Figure 41. The option with reduction to $1/6^{th}$ of the current parking space is best approximated by separate functions for the width segments [4m,11m[and [11m,40m]:

$$\text{Where } w = [4{,}11[,\ fVEG = 0.14, \tag{Eq. 5}$$

$$\text{Where } w = [11{,}40],\ fVEG = 0.38\ \ln w - 0.79. \tag{Eq. 6}$$

In Figure 42 the LC fractions for BAU and SUS are shown. The potential for greening *living streets* is remarkable and reduces the impervious area of street segments from 95% to 61% (78% for the ½ parking scenario) or increases the vegetated street surface from 83 ha to 457 ha (130 ha for the ½ parking scenario).

5.4.4 *Change driven land cover scenarios*

When for BAU and SUS the density driven LC fractions are applied to the parcels subject to change, an estimate can be made of the future LC change under the two policies (Table 34, Figure 45). The results are represented spatially in Figure 45. Even with the strong densification of the SUS scenario, the amount of impervious surface is not different compared to the BAU scenario and only 1% higher compared to the existing state (Table 34). The decrease in regular (pervious) green space is compensated with an increase in swales. When green roofs are included as green space, the SUS scenario yields 8% more green surface. Note the remaining 4% of regular flat roofs (FDF). Flat roofs can become green roofs in scenarios that include compulsory roof greening during renovation and construction of a building, which increases the earlier mentioned surface to 12%. As such, the amount of green surface would rise from 50% (EXI) to 62% (SUS+).

These green space areas, as well as impervious space connected to swales, will have a reducing effect on runoff volume and runoff peaks. While in BAU the amount of directly drained surfaces (not buffered) goes up 1%, in SUS it goes down 10%. Therefore, there is a difference of 11% between SUS and BAU regarding the presence of surfaces that decrease runoff. Roofs and impervious surfaces have a 60-40 split of contribution in SUS. It can be concluded that by applying a sustainable typology, the study area can be given a significantly higher density while improving its hydraulic performance with regard to extreme rainfall events.

Compared to BAU, SUS leads to an increase of perviousness in the central part of the study area and a decrease in the periphery (Figure 46, top). The former is a positive trend, which may contribute to reducing the urban heat island (UHI), which is most prevalent in the central area. The higher perviousness in case of SUS will on average benefit the poorer areas more, which is positive in terms of climate change adaptation for vulnerable populations (Figure 43). Given the recent flooding events of combined sewage and storm water drains, the significantly lower amount of directly drained surface in SUS compared to BAU (Figure 46, bottom) can also be considered as a positive trait. In terms of LC fractions contributing to the reduction of runoff peaks, the decrease is located only on the periphery of the study area, in small quantities. In the remaining areas, these fractions are increasing, and are spatially correlated with most of the historical flooding events (Figure 47).

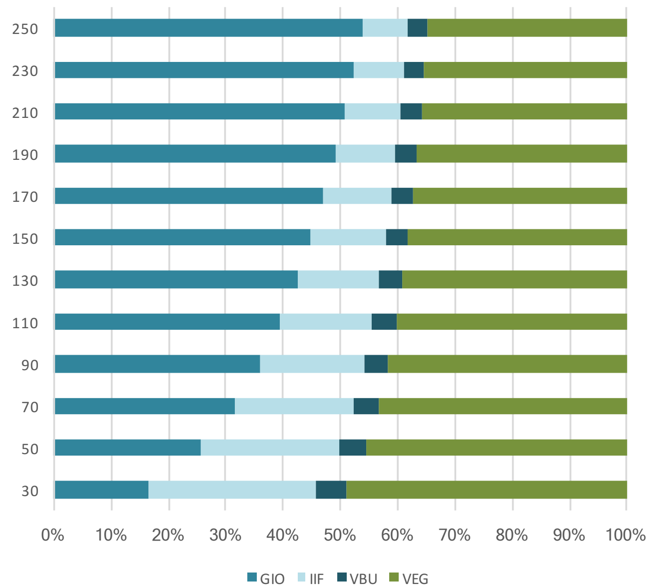


Figure 39: Net land cover fractions (private space) for sustainable typologies for different household densities.

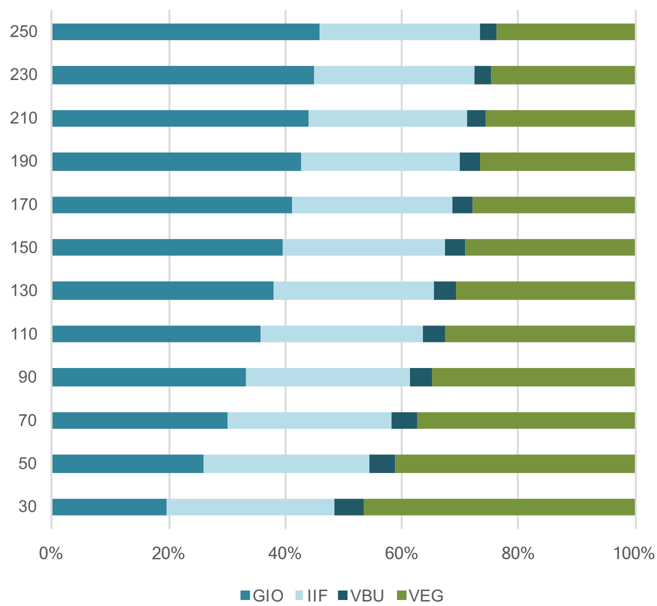


Figure 40: Gross land cover fractions for sustainablie typologies for different household densities.

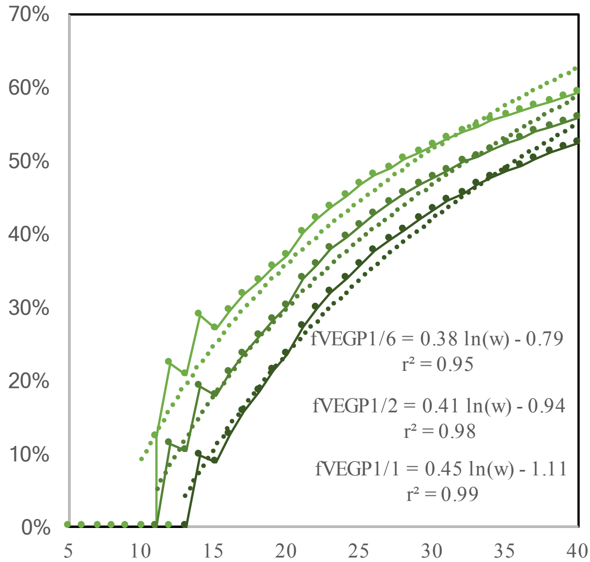


Figure 41: Maximum fraction of green space fVEG (y-axis) in *living streets*, in function of their width [m] (x-axis) and space assigned to parking.

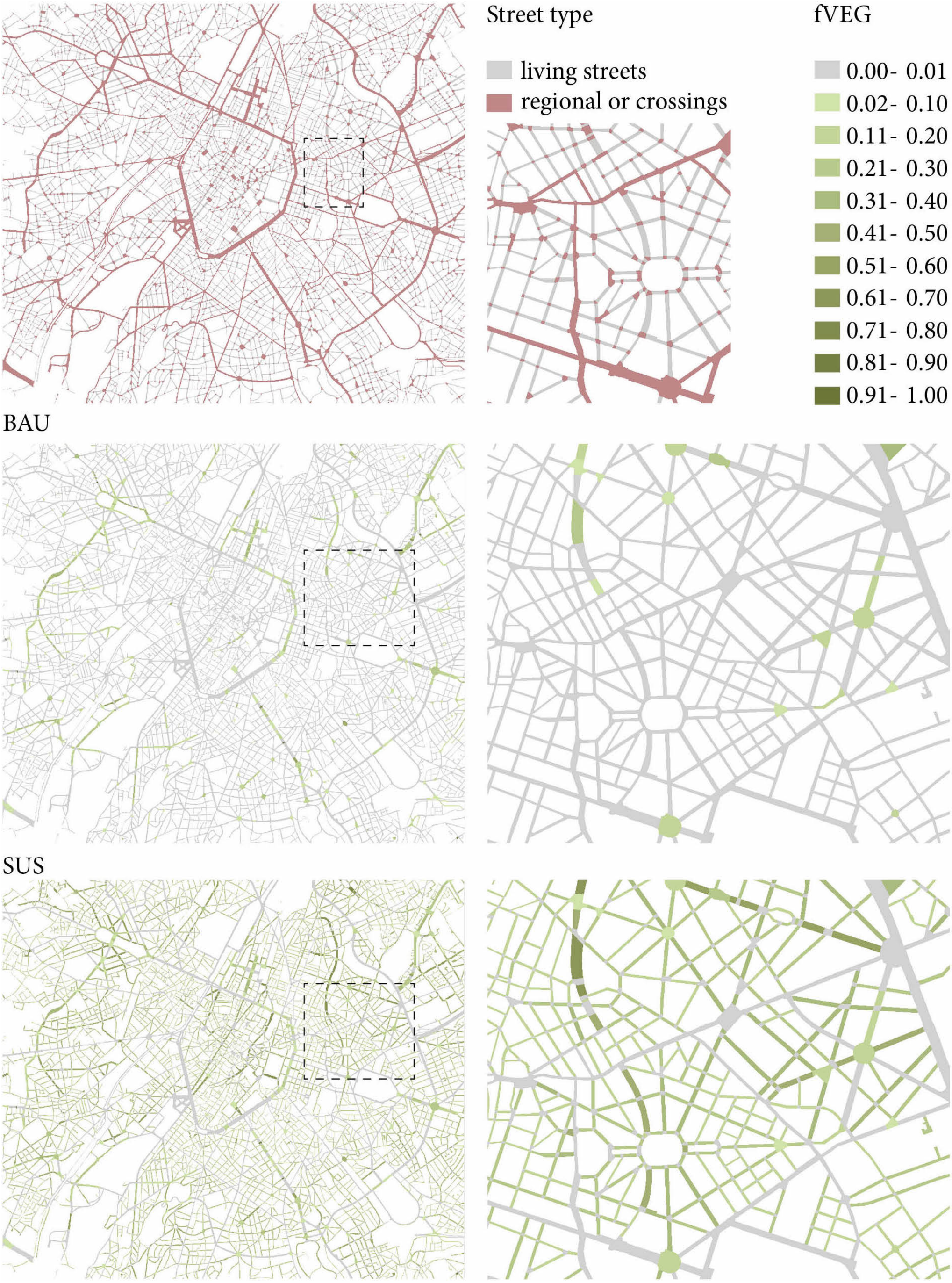


Figure 42: Street classification (upper left) and fractions of vegetation for streets in BAU and SUS.

	IDF	IIF	RDF	FDF	GIO	GDO	VHI	VLO	VBU	sum
EXI	0.33	0.00	0.10	0.07	0.00	0.00	0.41	0.09	0.00	1.00
BAU	0.34	0.00	0.10	0.07	0.00	0.00	0.40	0.09	0.00	1.00
SUS	0.29	0.03	0.07	0.04	0.02	0.06	0.40	0.08	0.01	1.00
Δ(SUS-BAU)	-0.05	0.03	-0.03	-0.03	0.02	0.06	0.00	-0.01	0.01	0.00
Pervious (EXI)	-	-	-	-	-	-	0.41	0.09	0.00	0.50
Pervious (BAU)	-	-	-	-	-	-	0.40	0.09	0.00	0.49
Pervious (SUS)	-	-	-	-	-	-	0.40	0.08	0.01	0.49
Δ(SUS-BAU)	-	-	-	-	-	-	0.00	-0.01	0.01	0.00
Green (EXI)	-	-	-	-	0.00	0.00	0.41	0.09	0.00	0.50
Green (BAU)	-	-	-	-	0.00	0.00	0.40	0.09	0.00	0.49
Green (SUS)	-	-	-	-	0.02	0.06	0.40	0.08	0.01	0.57
Δ (SUS-BAU)	-	-	-	-	0.02	0.06	0.00	-0.01	0.01	0.08
Directly Drained (EXI)	0.33	-	0.10	0.07	-	-	-	-	-	0.50
Directly Drained (BAU)	0.34	-	0.10	0.07	-	-	-	-	-	0.51
Directly Drained (SUS)	0.29	-	0.07	0.04	-	-	-	-	-	0.40
Δ (SUS-BAU)	-0.05	-	-0.03	-0.03	-	-	-	-	-	-0.11

Table 34: LC fractions for the study area per scenario and scenario comparison.

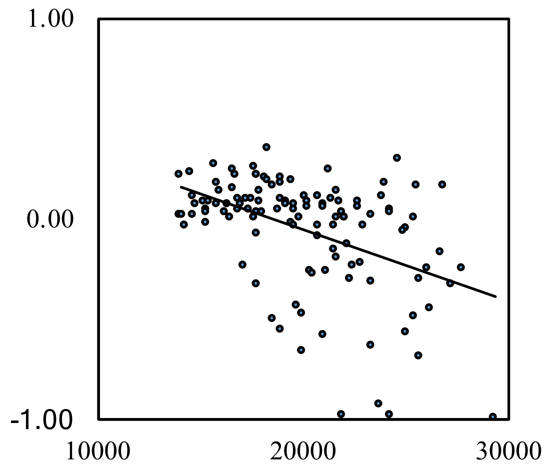


Figure 43: Normalized difference in pervious area in a SUS-BAU comparison (y-axis) against mean income per statistical sector (x-axis). Above zero represents more pervious in case of SUS, below zero represents more pervious for BAU.

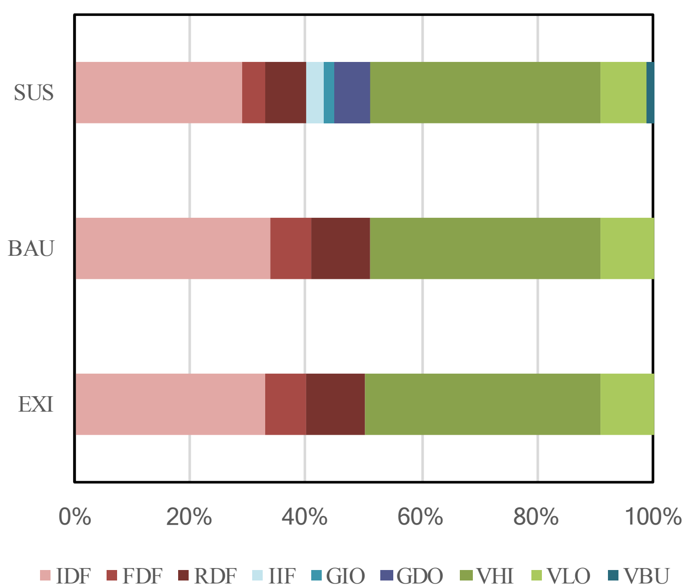


Figure 44: LC fractions per scenario for the entire study area

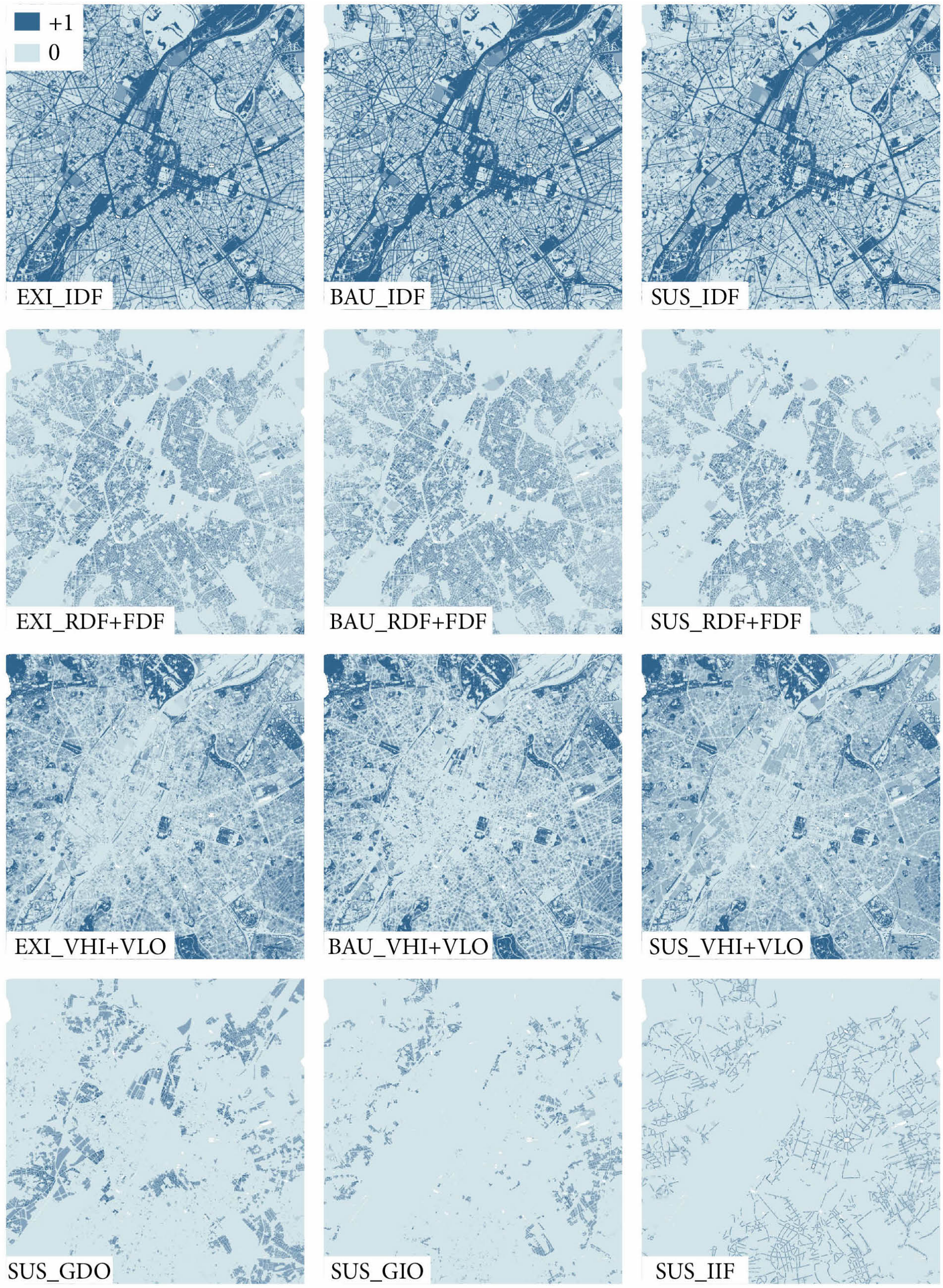


Figure 45: Land cover fractions at 20x20m resolution, sorted by scenario and land cover class as 'SCE_LCC'.

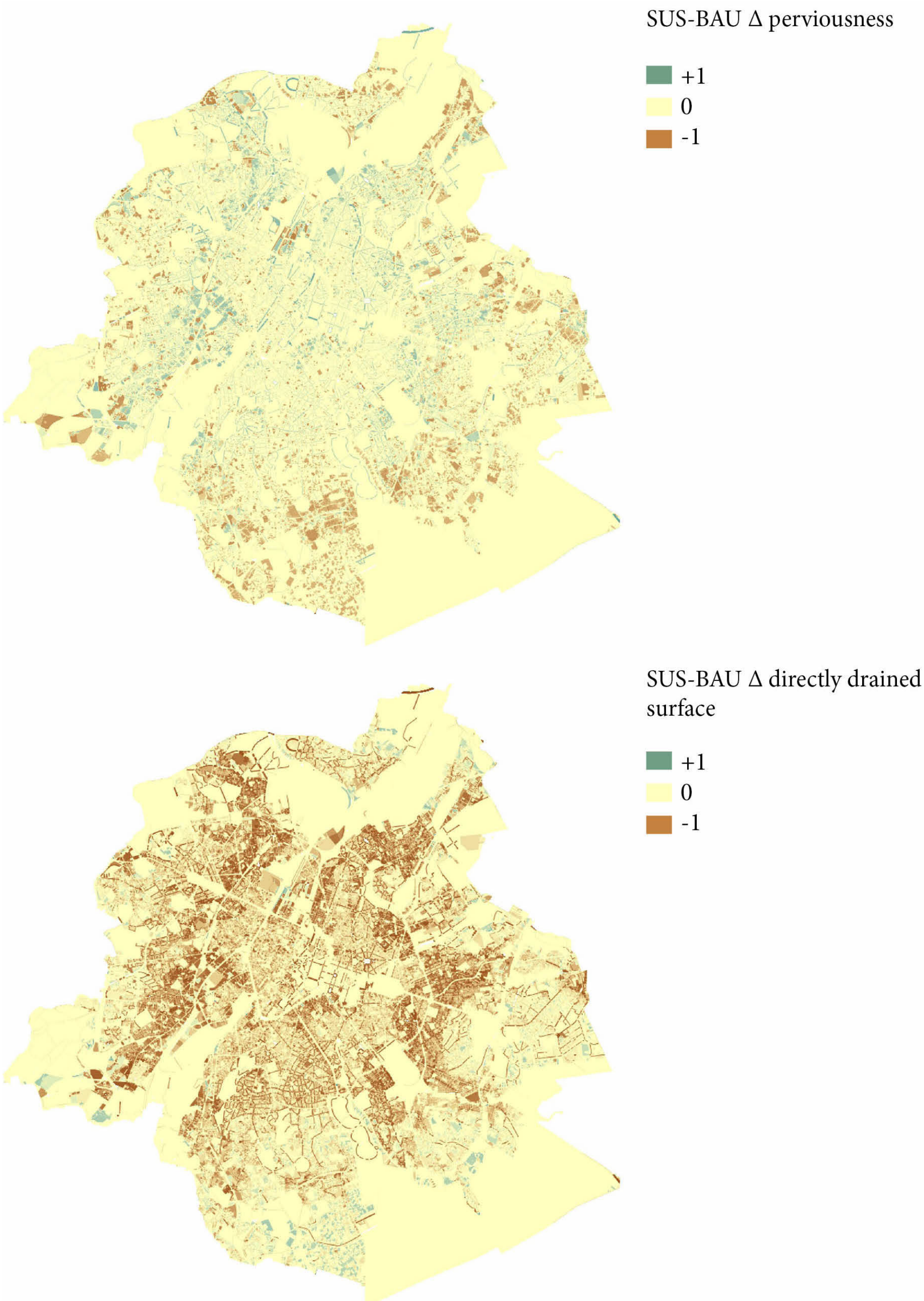


Figure 46: Differences in land cover fractions between SUS and BAU.

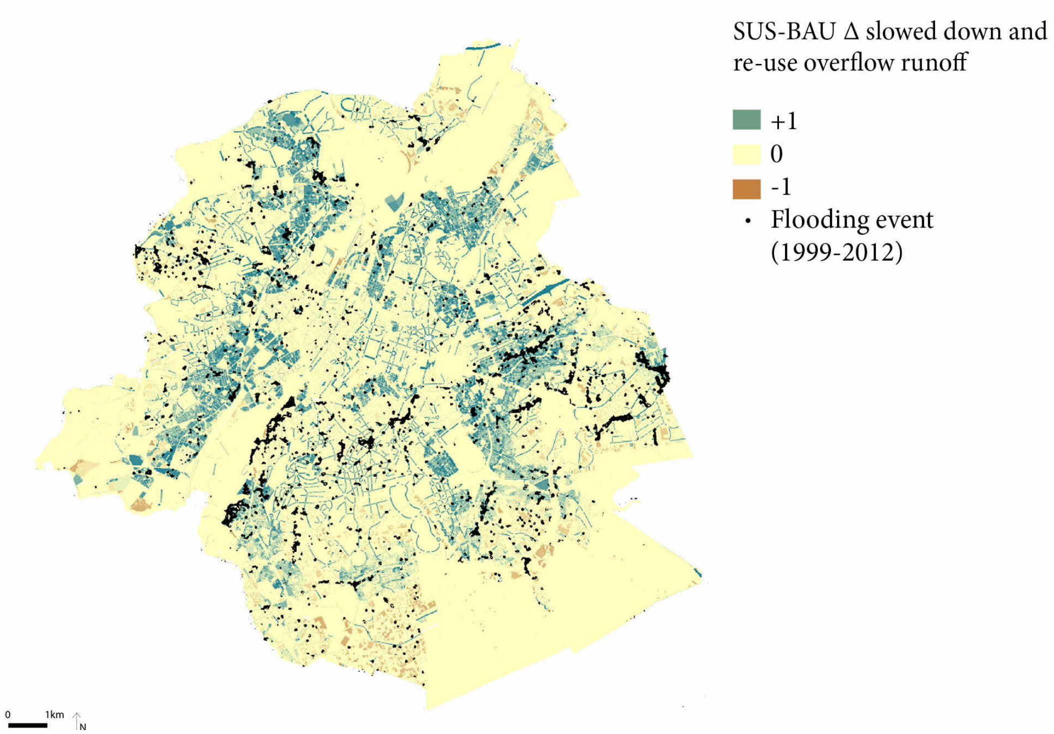


Figure 47: Differences between SUS and BAU regarding land cover fractions contributing to slowing down rainwater runoff.

5.5 Discussion

As part of the methodology, a relationship is established between household density and LC fractions, based on observation of the current state of land cover for BAU and typological design exercises for SUS. The limitation of this approach is that street patterns may influence the theoretical distribution of LC. On the other hand, the proposed LC fractions are neither optimistic nor pessimistic in their approximation, as they represent an average of existing configurations and typology configurations. These configurations have also proven to be consistent in the case of BAU (not verifiable for SUS). By developing more typologies, it would become possible to define a range between upper and lower LC fractions in function of density (instead of an average value), which makes it also possible to rank typologies based on in their performance.

The studied densification scenarios and the related LC change apply only to the areas currently assigned for residential or mixed land use. Special project zones (e.g. brownfield developments) are not included due to unclear formulation of development goals on the one hand, and the analytical clarity which comes with keeping focus on reconversion of existing urban fabric on the other hand. With space for 242,003 households, the SUS scenario is very ambitious and depicts a long-term frame. The predicted population growth towards 2060 is 59% available space for households in SUS, which reveals how much of the scenario can be realized in this time period. The hypothesis that densification is key for increasing urban resilience has been proven by the significant LC change, which is deemed more positive than the existing condition. Achieving such LC transformation without densification is highly unlikely due to the connected costs without return.

The likeliness of the SUS scenario to take shape as proposed in the nearby decades is very low. However, this exercise can spark the discussion on how to rethink the city in the light of pressing challenges regarding demographic change and urban resilience to climate change. Urban densification through regeneration of areas around hubs generates the most space for households. Yet this scenario is also the most complicated to put into practice, due to the large amount of stakeholders involved, especially landowners. Raising the permitted density or changing planning constraints alone will not suffice. Efforts are needed for stakeholder coordination, clustering development of parcels and quality control. The design exercises on urban block and street typologies reveal the need for a stronger integration of private and public space for water management and a different approach towards street layout where urban mobility and ecosystem services have to be considered together.

Concerning impact assessment of the scenarios in terms of regulating ES, the methodology proposed requires a more detailed parameterization of urban hydrological and energy balance models regarding urban LC characteristics to incorporate e.g. green roofs and impervious surfaces connected to infiltration areas, as well as surfaces where re-use of rainwater applies. Without these improvements, said models will not be able to show the actual effect of resilience increasing surfaces and strategies. When included it will allow for a proper assessment of co-benefits of sustainable strategies for urban development. From the LC fractions alone, it cannot be estimated by intuition whether overall recharge is influenced positively or negatively, as GIO (green roof with infiltration of re-use overflow) leads the re-used rainwater to the drain instead of the infiltration areas. Moreover, definition of land cover on the ground and roof level limits the assessment of dense vegetation in a hydrological or urban heat model. Urban streets often have impervious surfaces shaded by trees. From satellite images, this is recognized as dense vegetation (with pervious soil) and from urban planning data on street layout, this is seen as impervious surface, where the canopy interception and evapo-transpiration is overlooked. An additional LC class of 'tree canopy over impervious' could further increase the accuracy of hydrological and urban heat models.

Even with a very strong densification of the study area, it is shown that there is no need to increase imperviousness if public space is part of the equation. Moreover, in the SUS-scenario, greening and water-management related typologies mostly contribute to improving conditions in poorer areas of the city, where there is a strong need for improvement. While this may be considered a positive effect, one of the questions is to what extent sustainable densification strategies as proposed in this study would have an impact on gentrification.

5.6 Conclusions

This study proposes a GIS- and design-based approach to assess potential land cover (LC) change for the Brussels-Capital Region anticipating expected population growth. Two densification strategies are formulated, a business-as-usual (BAU) and a sustainable scenario (SUS). First, the potential for densification and urban regeneration is determined by establishing a set of rules, defining specific densification approaches based on local site conditions. By analyzing the existing urban fabric, a relationship between household density and land cover composition is defined, which is used as a basis for land cover change under the BAU scenario. For SUS, land cover fractions are based on the development of typologies for different densities. Streets are included in the scenarios with typologies depending on their function and width.

The methodology proposed can be used to assess the impact of spatial policies and the implementation of building codes and to evaluate whether a development proposal is leaning towards a business as usual or a sustainable configuration. The typology work for built-up and street configurations revealed conceptual inter-linkages between land cover change and mobility and between the design of private and public space. A drastic mobility shift away from the private car goes hand in hand with opportunities for sustainable street configurations, of which the water buffering capacity determines the layout and design of surrounding buildings and surfaces. The work can be considered as a call for a continued integrated approach towards densification strategies, mobility and urban resilience. The proposed scenarios include resilience-building configurations such as green roofs, rainwater buffering and infiltration, and re-use. One of the main conclusions of the case study on the Brussels-Capital Region is that densification can be deployed as a vehicle for positive land cover change and greening of the city.

Whereas more research on parametric design of typologies (e.g. CityEngine, which is a rule-based generator of urban form, in the way building codes would prescribe reality) could lead to more realistic simulations, the model constructed in this study has a fairly low computational load and allows for a comparative study of future policies addressing the challenges linked to demographic growth and climate change. Further research is needed on the refinement of water-management related land cover classes, as defined in this study, and on the integration of these land cover types in hydrological and urban climate modelling, enabling a reliable assessment of the contribution of proposed changes in terms of ecosystem services. The proposed LC types for sustainable configurations related to rainwater flows also need to be well parameterized for use in hydrological models, in order to properly capture the intricate processes underlying the urban hydrological cycle, and to assess their impact on runoff, groundwater recharge and other indicators.

6

6 Conclusion

The field of urban planning is evolving constantly and whereas in the past cities have moved away from their inherent entanglement with nature, current and future challenges urge planners to reconsider this reciprocal relationship. More than ever, policy makers, planners, designers, have to include future challenges in their decision-making and strategic thinking, while connecting their actions with the citizens they plan for. Ecologically oriented sustainable urban planning is a central concept in this paradigm shift. Acknowledging the importance of urban green is key in current debates on sustainable planning and urban resilience, and in striving for better environmental quality and livability in urban areas and in creating a healthy urban environment. Whereas scholars and practitioners have laid a solid foundation of conceptual frameworks and case studies on sustainability in urban planning, more efforts are needed to translate this growing body of knowledge into a framework that is: i) evidence-based; ii) participatory and inclusive, and; iii) interdisciplinary. The contribution of this work lies in the integrative effort of combining principles of sustainable urban design and planning with evidence-based research, through in-depth studies on the quality and accessibility of urban green and the use of that information in co-development strategies for improving green space provision. The work also includes the proposal of a framework for assessing the impact of alternative development scenarios on future urban land cover, which is important for assessing effects of urban planning decisions on regulatory ecosystem functions (water and climate regulation, air quality…). The work relies on knowledge, techniques and skills from multiple disciplines, including urban planning, urban design, landscape urbanism/architecture, geo-information science (GIS), geography, research-by-design, and co-creation.

A diagnostic and analytical apparatus has been developed for assessing public green space quality, public green space accessibility, scenario analysis for improving green spaces provision, and typology-based land cover change simulation. Through co-design of scenarios for public green space development, the research has demonstrated possibilities for moving towards a high standard of public green space provision throughout the Brussels Capital Region, substantially improving green space accessibility in non-affluent neighborhoods. Land-cover change scenario analysis also shows that densification strategies to cope with demographic growth – in combination with street design and building codes aligned with the principles of sustainable urban planning – can go hand in hand with greening of the city and improving urban resilience through urban regeneration. With the development of these, the framework offers diagnostic, analytical and projective capabilities.

6.1 Contribution of the research

The research contributes to the field of sustainable urban design and planning through developing an ecological framework – with diagnostic, analytical and projective capabilities – in three specific ways: by contributing to the state of the art on valuation of urban green; by providing indicators and tools for decision and policy making, and; by exploring the potential of solutions and recommendations from (partly) co-developed scenarios.

The first part of this work addresses the knowledge gap regarding our understanding of quality of urban green (Kabisch and Haase 2013, Haaland and van den Bosch 2015) and the lack of robust and scientific methodologies for the assessment of green space quality, especially from the user's perspective. It has furthered the insights in the relations between green space characteristics and green space quality, as urban citizens perceive it. Since green space quality plays a role in health of citizens (Annear, Cushman et al. 2009, Richardson, Pearce et al. 2010, van Dillen, de Vries et al. 2012), the delivered work may also indirectly contribute to the development of more healthy urban environments by offering more insight to planners and policy makers on the factors that contribute to urban green quality from the perspective of the user. The tools for green space quality and proximity assessment developed yield useful indicators, as confirmed during the research-by-design workshops. They may support decision making and policy making and are geared at making optimal use of available GIS data in order to avoid costly and time-consuming field surveys (Rigolon and Németh 2016). It is hoped that the models will encourage planners and policy makers to utilize the spatially explicit indicators proposed in this study in their processes. The objective of exploring the potential of proposing solutions and recommendations from co-developed scenarios has been achieved by applying the developed framework to the case of Brussels. The exploration of options for participation is an important aspect of sustainable urbanism (Nisha and Nelson 2012), which includes the shifting away from traditional decision making and opening up a pathway towards sustainability (Joss 2014). Workshops were organized for the evaluation of developed indicators and for the co-development of scenarios for improving green space proximity.

6.1.1 *Focus area: public green space, quality and proximity*

The first research questions regarding public green space use and valuation were:

- How can GIS data be linked to visitor's perception of the quality of public urban green spaces and how may this inform policy makers, planners and designers in proposing planning solutions within the concept of sustainable urbanism?
- What can be learned from collaborative scenario development in terms of urban green space quality and provision, and how do scenario outcomes relate to socio-economic distribution in the Brussels case?

In terms of diagnostics, the developed tools allow for planners and policy makers to identify problem areas with poor public green space provision, identify opportunities for the improvement of quality, and allow for comparison with spatially explicit socio-economic indicators. In terms of analytics, one of the objectives of this study was to gain more knowledge on what constitutes quality of public green spaces. A tool was developed for assessing different sub-qualities of green spaces from available GIS data. The tool relies on literature-based definitions of quality that are quantified and parameterized through questionnaire analysis. A linear model was defined to assess their relative importance and contribution to overall quality. Identifying the contribution of green space characteristics to perceived quality contributes to the body of knowledge in this field of green space valuation. Next to the work on green space quality, from the comparison of international standards and questionnaire data, an evidence base has been developed for the relation between size and proximity of GS as park users perceive it, which allows addressing inequalities of green space provision and formulating strategies within the context of sustainable urbanism.

Although not pursued in the scenario analysis in chapter 4, the developed model is capable of providing an assessment of scenarios for quality improvement, at the level of public green spaces, and at the level of urban blocks that are within reach of the studied green spaces. These capabilities were tested in separate workshops for the study of Metropolitan Landscapes (Stessens, Blin et al. 2016) where sub-qualities such as naturalness and biodiversity, quietness and spaciousness were compared for the existing situation and for design proposals. However, the projective capabilities of the model were tested for proximity analysis in this research. A spatial overlay of proximity indicators with income groups was carried out, similar to the analysis conducted in the environmental report MIRA-T 2004 by Van Herzele, De Clercq et al. (2004) for the existing conditions of several Flemish cities. In the present study, three scenarios were developed (apart from the existing condition), based on detailed descriptions of collaborative design proposals for the Brussels study area. Conclusions that could be drawn from the workshops, among others, are that not only inequalities in green space provision exist for low and medium-high income groups. Also the cost for improvement of green space proximity is higher in the low-income group areas. The collaborative scenario development process showed that the method proposed is accessible for all participants and that the design exercises automatically lead to interdisciplinary discussions. One of the conclusions of the workshop was also that the study area seems 'solvable'. The greening of underserved areas is a matter of priority, instead of a matter of spatial constraints. Observations as these are relevant to the process of sustainable urban design and planning, as described in the introduction.

6.1.2 *Focus area: densification and land cover scenarios*

Specific objectives related to land cover modelling in this study involved exploring and quantifying the influence of parcel typologies and street typologies for a business as usual, as well as a sustainable scenario. Describing land cover fractions of these typologies in function of density created a density-specific benchmark to compare development plans to. The outcome of this work allows for setting policy goals for sustainable urban design and planning in terms of land cover fractions and rainwater systems and provides a design-based and evidence-based framework for the specification of building codes. The typological exploration yielded a list of land cover classes that are specific to sustainable urban design and planning, which could be implemented in future hydrological models and climate models for urban areas.

The following research questions relate to the definition of densification scenarios for the study area:

- How do urban sustainable and unsustainable typologies (street and built-up) translate into corresponding land cover?
- What impact do different densification scenarios have on urban land cover distribution in the Brussels study case?

By studying the everyday processes for parcel infill and densification, and by defining a densification process based on the principles of sustainable urban design (e.g. walk-able and high-density urban areas near mobility hubs, compact building typologies, preserving valuable natural areas, space for water and floodscapes), two land use evolution scenarios were made spatially explicit. The densities in these land use plans in combination with the earlier described typological research allowed to project land cover fractions for the entire study area. A similar procedure was applied to street surfaces. In literature, future land use change has been modelled based on predicted changes in population and/or jobs through agent-based modelling or via cellular automata (e.g. Feng and Tong 2018). Reversely, population density has been predicted from land cover data (e.g. Wardrop, Jochem et al. 2018). However, detailed land cover projection (2m resolution, detailed urban land cover classes) from planning regulations at the metropolitan scale has not yet been undertaken. The developed scenario procedure allows for the spatial projection of policy choices (inform about the consequences of regulation and building codes) and to assess changes in urban green cover, impervious surfaces, and resilience-enhancing surfaces e.g. green roofs, swales, and buffered impervious surfaces. One of the main conclusions of this work is the confirmation that in the study area – through principles of sustainable urban design and planning –a strong increase of population density can go hand in hand with an increased amount of urban green and less surface cover with direct rainwater runoff.

Through the research and the questions posed, this work has contributed to the state of the art and the continuous development of new methods for evidence-based sustainable planning and design. Both focus areas of the research have shown the possibilities of increasing density and improving access to nature in urbanized areas, which are considered as the core values of sustainable urbanism (Roggema 2016).

6.2 Limitations of the research - data, modelling and other aspects

The public green space quality model as proposed in this study is still limited as to its ability to describe *use-related* sub-qualities (cleanliness and maintenance, facilities, community and social diversity, feeling of safety) from existing GIS data. These sub-qualities will always depend on user input. Next to traditional user surveys, use of interactive tools (e.g. mobile apps) could open up options for more extensive data collection, both for inherent quality aspects (e.g. noise assessment, as no satisfying link could be found in this study between model-based simulation of noise levels and reported quality of quietness) or for use related qualities. Another pathway would be to explore techniques to use data from social media (e.g. geo-tagged imagery) or mapping websites for complementing the quality modelling. Whereas the indicators produced in this research do not (entirely) classify as urban ES, they could potentially be further developed in order to give a quantified assessment of urban ES.

Regarding proximity analysis, maximum walking distance criteria used in our study are currently based on actual green space use. People that are less mobile, and that therefore did not make use of the green spaces sampled in our research, were not taken into account. A more inclusive and in-depth questionnaire also targeting people that do not make use of public green spaces could solve this. It is also recommended to focus more explicitly on demands of less mobile groups, such as children, elderly and people with disabilities in research on green space use and accessibility. Also, the definition of what is public green space is not straightforward, especially in the periphery of the city. If pedestrian paths in an agricultural environment would be considered as public green space as well, and these areas would be incorporated in the GIS analysis, the proximity modelling would become more nuanced and would lead to different results in the urban periphery.

In the scenario work regarding public green space development, cost classes for green space development are defined roughly, based on the interventions necessary for developing the proposed green space. A GIS based cost estimation including land prices and area-based construction costs can be useful for a further development of the scenarios. The simulations of land cover change in the final chapter did not include renovation of roofs throughout the city due to lacking data on the amount of rooftop renovations. Including this would have made the simulation more realistic, but on the other hand, it would have taken the focus away from the changes generated by the policy intentions as defined in the scenario. It would also have been interesting if the results of both public and private space scenarios could have been used as input for ecosystem service assessment modelling (e.g. for modelling impacts on runoff or water retention capacity). As indicated in the final chapter though, there is a need for a more detailed land cover parameterization in terms of hydrological characteristics to ensure that current hydrological modelling tools are able to fully grasp the complexity of hydrological processes in urban environments.

6.3 Questions for future research

In terms of green space quality perception, variations have been revealed in gender and cultural background. However, our analysis has been based on the average user and is not large enough to be split into more than two groups (e.g. female/male, Belgian/non-Belgian, Catholic-European/other). Even though the survey size was large enough to perform an analysis of the average user's assessment of green space qualities, it did not allow a detailed study of the role of social and cultural background as confounding factors in green space valuation. Given the strong socio-cultural diversity of the study area, a further exploration of this theme would provide a valuable addition to this research. Such insights might be used for the design of public green spaces that are aimed at specific population groups. The latter is highly relevant for smaller green spaces in cities such as Brussels, where a strong socio-cultural segregation is observed. To be inclusive and effective, cultural ecosystem service research needs to take into account how different values can be integrated. Green space interventions proposed for improving green space proximity might be ranked by priority if a weighing system would be developed which takes into account the population affected and population group needs in terms of urban green. It is most likely that central areas would be prioritized in such an approach. The design research has shown that these areas too, can be better served in terms of cultural ecosystem services, be it with high investments. Further research could help to identify the bottlenecks and system characteristics in policy and decision making that prevent these areas from being improved.

The model proposed in this study for simulating land cover change under different scenarios has a fairly low computational load and allows for a comparative study of future policies with regards to densification and land cover change. However, more research on parametric design of typologies and use of procedural city modelling software (e.g. CityEngine), as well as a further definition of building codes for sustainable urban planning and development could lead to more detailed and more reliable simulation results. In terms of modeling, further research is recommended on defining characteristics of land cover types related to sustainable urbanism (e.g. surfaces connected to a swale, green roofs, pervious paving). The outcome can then be implemented in ecosystem service assessment models (for indicators on e.g. water retention, cooling effects, carbon storage, air pollution…) and the contribution of the formulated scenarios in terms of impact on ecosystem services can be determined.

Further research can be conducted on the replicability of the framework, models and tools developed in this research for other contexts, e.g. European cities. The replicability will depend on the data availability in these contexts, and an investigation can be conducted on the effect of aspects such as city size or local preferences on the relevance of the framework.

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8 Appendices

8.1 Model input maps

TYPE	Name	Source	Date	Coverage	Purpose	Attribute based selection
Natural reserves	Natres	AGIV	2002	Flanders	a, b	CLASS = 400 OR 500 OR 800 (water, forest, parcelled forest)
	Natural_reserve	IBGE	9999	Brussels	a, b	-
Forests	Bos	AGIV	2000	Flanders	a	-
	UrbMap_GB_F	URBIS	2013	Brussels	a	-
Habitat zones	Habrl	AGIV	2008	Flanders	a, b	-
	Natura2000_station	IBGE	9999	Brussels	a, b	-
Parks	LandUse_lam72 (NSN)	AGIV	2014	Flanders	a	FEAT_TYPE = PARK (CITY/COUNTY) OR PARK (STATE)
	Urbmap_GB_B	URBIS	2013	Brussels	a	-
Water bodies	Wtz20001R500	AGIV	2015	Flanders	a	-
	UrbMap_WB_0	URBIS	2013	Brussels	a	-
Biologically valuable	BWK2	AGIV	2010	full	a, b	-
Protected landscapes	Bslastdo	AGIV	2001	full	a, b	OBJTYPE = LAND
Additional (roadside green)	UrbMap_GB_A	URBIS	2013	Brussels	a	-
Noise maps	geluidscontouren_ spoorwegen_Lden	LNE	2011	Flanders	b	-
	geluidscontouren_ wegen_alles_Lden	LNE	2011	Flanders	b	-
	Geluidskaart_5m*	IBGE	9999	Brussels	b	-
Land cover	vegmap * (water, bare, low veg., dense vegetation)	(Van de Voorde, Canters et al. 2010)	2010	full	b	-
Composed green space delineation	GreenSpace	comp.	-	full	b	-
Urban blocks	UrbMap_Bl	URBIS	2013	Brussels	c	-
Parcels	GRBgis Adp	AGIV	2015	Flanders	c	-
Road axes	UrbAdm_Sa	URBIS	2013	Brussels	d	-
	Wvb20001R500	AGIV	2015	Flanders	d	MORF ≠ 101, 107, 108, 111, 116
Inaccessible roads (axes)	UrbAdm_Sa_NoWalk	Authors	2016	Brussels	d	(manual selection)
Running tracks	running_tracks	Strava Labs	2015	full	a, d	-
planned paths	planned_path	Authors	2016	full	d	(manual input)

Purpose:	a) green space delineation; b) quality assessment; c) urban block; d) path network
AGIV	https://download.agiv.be
URBIS	http://cibg.brussels/nl/onze-oplossingen/urbis-solutions/download
IBGE	http://wfs.ibgebim.be/
LNE	through https://www.mercator.vlaanderen.be/zoekdienstenmercatorpubliek/

Table 35: GIS input maps (all are in vector format, except for (*), which are in raster format)

8.2 Model comparisons

Authors	La Rosa (2014)	Le Texier, Schiel et al. (2018)
Tools	Greenspace Monitoring Tool	The provision of urban green space and its accessibility: Spatial data effects in Brussels
Proximity analysis		
Green space selection	GIS data layer	Comparison of NDVI from Landsat, cadaster based map, OpenStreetMap
Scale	Census tracts	Neighborhood
Defining size-distance relation	Not applied	Not applied
Distance calculation	Euclidian and Network	Path-based
Path inclusion	Street network	Street network
Barrier inclusion	Automatic inclusion of barriers due to path passed distance calculation	Automatic inclusion of barriers due to path passed distance calculation
Urban form inclusion	Only road network and barriers	Only road network and barriers
Distance measured from-to	Green space contour to centroid of census tracts	Average distance of each cell in the neighborhood to the nearest public urban green space
Quality analysis		
Defining green space qualities	n.a.	n.a.
Rating qualities	n.a.	n.a.
Quality framework	n.a.	n.a.
Quality output	n.a.	n.a.
Proximity-quality coupling		
Method for translating green space quality to population	n.a.	n.a.
Output	Simple indicators (number of inhabitants with access to a particular GS) Proximity indicators (distance-weighed number of inhabitants with access to a particular GS)	Analysis of four dimensions: availability (ratio of green area per area), fragmentation (spatial dispersion), public-private ownership (ratio private area per green area, accessibility (distance), and data effects on these dimensions

Table 36: Comparison of methodologies for different green space models.

Authors Tools	Van Herzele and Wiedemann (2003) Greenspace Monitoring Tool	Stessens, Khan et al. (2017) Green Space Proximity and Quality Tool
<u>Proximity analysis</u>		
Green space selection	Manual	Procedural from several GIS data layers
Scale	Statistical sector	Urban block
Defining size-distance relation	From selected standard (Flemish Green Policy)	Linear regression of cluster of international standards (log scale), tested by comparison to average user preference in study area
Distance calculation	Omnidirectional/Euclidian (with barriers)	Network
Path inclusion	n.a.	All walking routes (sidewalks, squares, trajectories through nature and fields), combination of GIS data (maps) and GPS data (user input)
Barrier inclusion	Manual input of infrastructural barriers	Automatic inclusion of barriers due to path based cost-distance calculation
Urban form inclusion	Only through barriers	Street patterns, squares, barriers
Distance measured from-to	Green space contour (entrance?) to centroid of statistical sector	Average distance from green space contour to points on perimeter of urban block
<u>Quality analysis</u>		
Defining green space qualities	One-step selection: from literature	Two-step selection: from literature, with significance test by statistical analysis of visitor perception
Rating qualities	Mixed method: partly subjectively, map-based with additional site visits, site measurements (sound), calculated (degree of fragmentation)	Calculated from GIS data, model based on statistical analysis of visitor perception
Quality framework	Flexible according to type of green space via subjective interpretation	Rigid, not depending on kind of green space
Quality output	Threshold based (bad/neutral/good), from researcher's perspective	Score in accordance with user perception (1-100)
<u>Proximity-quality coupling</u>		
Method for translating green space quality to population	Percentage of inhabitants with at least one green area within reach (at different functional levels) and with a 'good' level of attractiveness	Average of best scores for each level within reach of the urban block, linked to demographic and other socio-economic indicators
<u>Output</u>	Indicators (spatial and non-spatial) that relate populations of statistical sectors to provision of green space accessibility and quality, based on parameters and criteria chosen by policy and mixed-method quality observations including subjective input.	Indicators (spatial and non-spatial) that relate populations of urban blocks to provision of green space accessibility and quality, based on parameters and variables available in GIS and informed by green space visitors

Table 37: Comparison of methodologies for different green space models.

8.3 Opportunities for green space development

No.	Type	Tunnel construction	Infrastructure works	Compulsory res. real estate acquisition	Compulsory industr. real estate acquisition	Changing public facilities	Agricultural land acquisition	Noise barriers	Constructing paths and routes	Number of strategies	Number of strategies for Metropolitan GS	Number of strategies for City GS	Number of strategies for District GS	Number of strategies for Quarter GS	Number of strategies for Neighborhood GS	Number of strategies for Play GS	Number of strategies for Residential GS
	TFL/N°									Tot	M	C	D	Q	N	P	R
	Name / count									59	9	8	13	9	21	5	8
1	Developing wetlands in valley bottom									#	4	5	2	1	0	0	0
2	Developing a blue-green network									#	9	6	2	2	0	0	0
3	Deploying walking and cycling trajectories								x	#	9	8	0	0	0	2	1
4	Converting agricultural fields to park space with small scale agricultural character						x			#	9	6	#	9	#	0	0
5	Developing green areas around upstream tributaries									11	5	3	3	0	0	0	0
6	Cutting local road									#	7	5	6	8	0	2	1
7	Connecting existing public green spaces									#	8	7	6	7	0	0	0
8	Halting housing development									9	5	3	0	0	0	0	0
9	Reversing housing development			x						7	5	2	0	0	0	0	0
10	Noise shielding							x		#	6	2	5	4	2	0	0
11	Integrating protected landscapes									11	5	1	4	0	0	0	0
12	Integrating estates									#	0	1	1	3	5	0	0
13	Connecting separate parts over 2x2-lane road	x								4	2	1	1	0	0	0	0
14	Connecting to railway station									11	4	2	1	2	0	1	1
15	Covering open railroad trenches	x								9	0	2	2	0	5	0	0
16	Connecting to tram station									#	2	3	5	5	0	0	0
17	Extending park over local road up to sidewalk									4	0	0	3	0	0	1	0
18	Re-routing roads and traffic around or away from park		x							8	0	0	4	1	2	1	0
19	Putting through traffic underground / covering open tunnels	x								9	0	0	5	3	1	0	0
20	Transforming urban boulevard to park strip		x							4	0	0	0	2	1	0	1
21	Greening tram beds crossing the GS									2	0	0	2	0	0	0	0
22	Cutting park drives for cars									2	0	1	1	0	0	0	0
23	Connecting to metro station									7	1	0	2	4	0	0	0
24	Re-integrating derelict / brownfield / unused land									7	1	0	2	1	2	0	1
25	Connecting to highway									4	3	1	0	0	0	0	0
26	Moving logistic activities and light industry				x					8	1	1	1	1	3	0	1
27	Integrating nature reserves									2	1	1	0	0	0	0	0
28	Connecting separate parts over highway	x								2	2	0	0	0	0	0	0
29	Connecting over causeway	x								3	2	0	0	1	0	0	0
30	Connecting over/under local road	x								7	1	1	2	2	1	0	0
31	Visual shielding									4	1	0	2	0	1	0	0
32	Making fenced off grounds accessible integrating sports grounds									5	0	1	2	1	1	0	0
33	Renegociating industrial land for shared use									3	1	0	0	0	0	2	0
34	Connecting nearby housing projects with parkspace									4	0	0	2	0	0	0	2
35	Re-designing ground floor and terrains of 60's housing blocks		x							8	0	0	1	0	6	0	1
36	Developing real estate around GS									5	0	0	0	5	0	0	0
37	Reorganizing open air sports facilities					x				#	0	0	0	3	4	2	1
38	Opening up impervious surfaces									#	0	0	2	5	0	5	8
39	Rooftop park extension on commercial buildings									1	0	0	0	1	0	0	0
40	Rooftop park extension on public buildings					x				3	0	0	0	2	0	0	1
41	Creating passages in-between buildings									5	0	0	0	2	0	0	3
42	Mega-roundabout		x							1	0	1	0	0	0	0	0
43	Mega-block		x							4	0	0	0	0	4	0	0
44	Part of private garden to parkspace			x						#	0	0	2	2	8	0	5
45	GS as part of strategic site redevelopment									2	0	0	0	1	0	0	1
46	Connecting over water body									2	1	0	0	0	0	0	0
47	GS in shared use with public services									3	0	0	0	0	2	0	0
48	Transforming local road into GS									#	0	0	0	1	8	2	2
49	Transformation public space into park									7	0	0	0	0	3	3	1
50	Rooftop park on top of industrial building									6	0	0	0	0	1	4	1
51	Reversing commercial building									1	0	0	0	0	0	1	0
52	Demolishing existing building for creation of GS									2	0	0	0	0	1	0	1
53	Converting parking space into GS									4	0	0	0	0	2	1	1
54	Cutting parking spaces									7	0	0	0	1	4	0	2
55	Activation of unused lawn									9	0	0	0	1	5	0	3

No.	Type	Intra-urban metropolitan GS	Peri-urban metropolitan GS	Rural metropolitan GS	Valley parks	Agriculture reconversions to valley parks	Agriculture reconversions	Urban space optimization	Functional level scaling	Inner city district GS optimization	Inner city continuous spaces	Peri-urban district GS development	De-privatizing domains	Rural district GS	District GS development in tributary valleys	Expanding existing parks	Conversion/reorganization	Green roof on commercial buildings	Converting farmland to park space	Railroad optimization	Private gardens to park space	Mega-block	De-privatizing estates	Public space redevelopment of housing blocl	Reorganizing sports fields	Brownfield development	Rural neighborhood GS development
	TFL/N°	M	M	M	C	C	C	C	D	D	D	D	D	D	D	Q	Q	Q	Q	N	N	N	N	N	N	N	N
	High investment class - FULL scenario	x						x		x						x											
	Middle investment class - SUPP scenario	x		x				x		x	x					x				x	x	x		x			
	Low investment class - BASE scenario		x		x	x	x		x			x	x	x	x		x	x	x				x		x	x	x
1	Developing wetlands in valley bottom	x	x		x	x									x												
2	Developing a blue-green network	x	x	x	x	x									x												
3	Deploying walking and cycling trajectories	x	x	x	x	x	x																				
4	Converting agricultural fields to park space with small scale agricultural character	x	x	x		x	x					x		x					x								x
5	Developing green areas around upstream tributaries			x			x					x															
6	Cutting local road	x	x	x		x		x			x	x					x										
7	Connecting existing public green spaces	x	x	x	x	x		x								x											
8	Halting housing development		x	x																							
9	Reversing housing development			x																							
10	Noise shielding	x	x	x								x															
11	Integrating protected landscapes	x	x	x								x	x														
12	Integrating estates												x										x				
13	Connecting separate parts over 2x2-lane road	x																									
14	Connecting to railway station	x						x																			
15	Covering open railroad trenches							x												x							
16	Connecting to tram station	x						x			x					x											
17	Extending park over local road up to sidewalk										x																
18	Re-routing roads and traffic around or away from park										x																
19	Putting through traffic underground / covering open tunnels									x						x											
20	Transforming urban boulevard to park strip																										
21	Greening tram beds crossing the GS								x																		
22	Cutting park drives for cars								x																		
23	Connecting to metro station								x							x											
24	Re-integrating derelict / brownfield / unused land								x																	x	
25	Connecting to highway																										
26	Moving logistic activities and light industry																										
27	Integrating nature reserves																										
28	Connecting separate parts over highway																										
29	Connecting over causeway																										
30	Connecting over/under local road																										
31	Visual shielding																										
32	Making fenced off grounds accessible integrating sports grounds																										
33	Renegociating industrial land for shared use																										
34	Connecting nearby housing projects with parkspace																										
35	Re-designing ground floor and terrains of 60's housing blocks																							x			
36	Developing real estate around GS																x										
37	Reorganizing open air sports facilities																x								x		
38	Opening up impervious surfaces										x							x									
39	Rooftop park extension on commercial buildings																	x									
40	Rooftop park extension on public buildings																	x									
41	Creating passages in-between buildings																										
42	Mega-roundabout																										
43	Mega-block																					x					
44	Part of private garden to parkspace																				x						
45	GS as part of strategic site redevelopment																										
46	Connecting over water body																										
47	GS in shared use with public services																										
48	Transforming local road into GS																										
49	Transformation public space into park																										
50	Rooftop park on top of industrial building																										
51	Reversing commercial building																										
52	Demolishing existing building for creation of GS																										
53	Converting parking space into GS																										
54	Cutting parking spaces																										
55	Activation of unused lawn																										

Table 38: Listing of identified opportunities for green space development and involved strategies 1/5

	TFL/N°	M1	M9	M4	M5	M2	M3	M6	M7	M8	M10	C1	C2	C4	C5	C6	C8	C9	C10	C11	C12	D1	D6
	High investment class	x	x																		x	x	
	Middle investment class			x		x	x	x	x	x					x				x	x			x
	Low investment class				x						x	x	x	x		x	x	x					
	Name / count	Koning Boudewijnpark,	Zuidelijke Zennevallei	Perk	Asse	Neerpede	Groenenberg	Kravaalbos (Liedekerke)	Hertigembos	Plutsingen	Kanaal	Bollebeek	Hagaard	Merchtem	Sint-Martens Bodegem Park	Sint-Pieters-Leeuw	NATO	Moorsel	Scheutbos	Terkamerenbos	Josaphat	Albertpark, Marie-Josépark, V	Tour&Taxis
	Type	Intra-urban MGS	Intra-urban MGS	Peri-urban MGS	Rural MGS	Rural MGS	Rural MGS	Rural MGS	Rural MGS	Rural MGS	Rural MGS	Valley parks	Valley parks	Agriculture reconversion to valley parks	Agriculture reconversion to valley parks	Agriculture reconversion to valley parks	Agriculture reconversions	Agriculture reconversions	Urban space optimization	Un-fragmented park space	Urban space optimization	functional level scaling	functional level scaling
1	Developing wetlands in valley bottom		x	x		x	x					x	x	x	x	x							
2	Developing a blue-green network	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x				
3	Deploying walking and cycling trajectories	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
4	Converting agricultural fields to park space with small scale agricultural character	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x				
5	Developing green areas around upstream tributaries				x	x	x		x	x							x	x	x				
6	Cutting local road	x	x	x			x	x	x	x	x			x	x	x				x	x		
7	Connecting existing public green spaces	x	x	x	x		x	x	x	x	x	x	x		x	x			x	x	x	x	x
8	Halting housing development			x		x	x	x	x		x				x	x			x				
9	Reversing housing development					x	x	x	x	x					x				x				
10	Noise shielding	x	x	x		x		x	x				x								x		
11	Integrating protected landscapes		x	x	x		x		x		x				x								
12	Integrating estates												x										
13	Connecting separate parts over 2x2-lane road	x	x																		x		
14	Connecting to railway station	x	x		x				x											x	x		x
15	Covering open railroad trenches																			x	x	x	x
16	Connecting to tram station	x	x																x	x	x	x	x
17	Extending park over local road up to sidewalk																						
18	Re-routing roads and traffic around or away from park																					x	
19	Putting through traffic underground / covering open tunnels																						
20	Transforming urban boulevard to park strip																						
21	Greening tram beds crossing the GS																					x	x
22	Cutting park drives for cars																			x		x	
23	Connecting to metro station					x																x	x
24	Re-integrating derelict / brownfield / unused land		x																			x	x
25	Connecting to highway		x	x					x				x										
26	Moving logistic activities and light industry		x																		x		
27	Integrating nature reserves						x									x							
28	Connecting separate parts over highway	x	x																				
29	Connecting over causeway		x	x																			
30	Connecting over/under local road		x																		x	x	
31	Visual shielding				x																		
32	Making fenced off grounds accessible integrating sports grounds																				x	x	
33	Renegociating industrial land for shared use		x																				
34	Connecting nearby housing projects with parkspace																					x	
35	Re-designing ground floor and terrains of 60's housing blocks																						
36	Developing real estate around GS																						
37	Reorganizing open air sports facilities																						
38	Opening up impervious surfaces																						
39	Rooftop park extension on commercial buildings																						
40	Rooftop park extension on public buildings																						
41	Creating passages in-between buildings																						
42	Mega-roundabout																				x		
43	Mega-block																						
44	Part of private garden to parkspace																						
45	GS as part of strategic site redevelopment																						
46	Connecting over water body	x									x												
47	GS in shared use with public services																						
48	Transforming local road into GS																						
49	Transformation public space into park																						
50	Rooftop park on top of industrial building																						
51	Reversing commercial building																						
52	Demolishing existing building for creation of GS																						
53	Converting parking space into GS																						
54	Cutting parking spaces																						
55	Activation of unused lawn																						

Table 39: Listing of identified opportunities for green space development and involved strategies 2/5

No.	TFL/N°	D2	D3	D5	D7	D18	D8	D10	D11	D12	D13	D14	D15	D16	D17	D9	D19	D20	D22	D23	D24	D28	D29
	High investment class		x							x							x						
	Middle investment class	x		x	x	x										x							
	Low investment class						x	x	x		x	x	x	x	x			x	x	x	x	x	x
	Name / count	Jubelpark	Koekelberg	Warandepark	Vijvers van Elsene, Abdij	Ste. Catherine	Zellik	Diegem	Machelen	Faubourg	Zaventem	Kasteeel ter Meeren	De Hoek	La hulpe	La hulpe Vallée	R0 afrit 1-2	Visserij						
	Type	Inner city district GS optimization	Inner city district GS optimization	Inner city district GS optimization	Continuous inner city spaces	Continuous inner city spaces	Peri-urban DGS development	Peri-urban DGS development	Peri-urban DGS development	Peri-urban DGS development	Peri-urban DGS development	De-privatizing domains	Rural DGS	Rural DGS	Valley bottom DGS	Highway rooftop park	Inner city DGS optimization	Rural DGS development	Rural DGS development	Rural DGS development	Rural DGS development	Rural DGS development	Rural DGS development
1	Developing wetlands in valley bottom														x		x						
2	Developing a blue-green network										x				x								
3	Deploying walking and cycling trajectories																						
4	Converting agricultural fields to park space with small scale agricultural character						x	x	x	x	x		x	x				x	x	x	x	x	x
5	Developing green areas around upstream tributaries						x	x	x														
6	Cutting local road				x	x	x		x	x							x						
7	Connecting existing public green spaces					x					x			x			x						
8	Halting housing development																						
9	Reversing housing development																						
10	Noise shielding						x	x	x	x	x												
11	Integrating protected landscapes						x	x	x			x											
12	Integrating estates											x											
13	Connecting separate parts over 2x2-lane road									x													
14	Connecting to railway station																						
15	Covering open railroad trenches																						
16	Connecting to tram station			x	x	x																	
17	Extending park over local road up to sidewalk			x	x	x																	
18	Re-routing roads and traffic around or away from park		x		x	x																	
19	Putting through traffic underground / covering open tunnels	x	x	x						x						x							
20	Transforming urban boulevard to park strip																						
21	Greening tram beds crossing the GS																						
22	Cutting park drives for cars																						
23	Connecting to metro station																						
24	Re-integrating derelict / brownfield / unused land																						
25	Connecting to highway																						
26	Moving logistic activities and light industry									x													
27	Integrating nature reserves																						
28	Connecting separate parts over highway																						
29	Connecting over causeway																						
30	Connecting over/under local road																x						
31	Visual shielding					x				x													
32	Making fenced off grounds accessible integrating sports grounds																x						
33	Renegociating industrial land for shared use																						
34	Connecting nearby housing projects with parkspace																x						
35	Re-designing ground floor and terrains of 60's housing blocks																x						
36	Developing real estate around GS																						
37	Reorganizing open air sports facilities																						
38	Opening up impervious surfaces				x	x																	
39	Rooftop park extension on commercial buildings																						
40	Rooftop park extension on public buildings																						
41	Creating passages in-between buildings																						
42	Mega-roundabout																						
43	Mega-block																						
44	Part of private garden to parkspace		x			x																	
45	GS as part of strategic site redevelopment																						
46	Connecting over water body																						
47	GS in shared use with public services																						
48	Transforming local road into GS																						
49	Transformation public space into park																						
50	Rooftop park on top of industrial building																						
51	Reversing commercial building																						
52	Demolishing existing building for creation of GS																						
53	Converting parking space into GS																						
54	Cutting parking spaces																						
55	Activation of unused lawn																						

No.	TFL/N°	Q1	Q2	Q20	Q5	Q7	Q3	Q6	Q10	Q11	Q9	Q13	Q4	Q8	Q12	Q14	Q15	Q16	Q18	Q17	Q19	
	High investment class		x	x	x																	3
	Middle investment class						x	x		x	x								x			#
	Low investment class	x				x			x			x	x	x	x	x	x	x		x	x	#
	Name / count	Abbattoir	Kruidtuin	Hallepoort	Montgomery	Haren	Ninoofsepoort	Schaarbeek kerkhof	Machelen	Zaventem	Witte Cité	Hanssenpark	Ducpétiaux	Diegem	Nossegem	Smeiberg	Hoge Heide	Terrestpark	Drogenberg	Hagaard	VRT	
	Type	opening up hardscape	expanding park	Inner city district GS optimization	boulevard to parkstrip	expanding park	complex node	conversion of sport and industrial land	reorganization of sports	sports facilities to green roof	commercial green roof	commercial green roof	prison to park	farmland to park	farmland to park	farmland to park	farmland to park	farmland to park	farmland to park	Opening up valley forest	GS as part of development	
1	Developing wetlands in valley bottom										x											
2	Developing a blue-green network										x									x		
3	Deploying walking and cycling trajectories																					
4	Converting agricultural fields to park space with small scale agricultural character					x			x	x				x	x	x	x	x	x			
5	Developing green areas around upstream tributaries																					
6	Cutting local road	x			x	x	x	x	x			x	x									
7	Connecting existing public green spaces	x	x	x	x	x	x		x													
8	Halting housing development																					
9	Reversing housing development																					
10	Noise shielding		x						x		x	x										
11	Integrating protected landscapes																					
12	Integrating estates				x											x				x		
13	Connecting separate parts over 2x2-lane road																					
14	Connecting to railway station			x								x										
15	Covering open railroad trenches																					
16	Connecting to tram station	x	x		x			x													x	
17	Extending park over local road up to sidewalk																					
18	Re-routing roads and traffic around or away from park				x																	
19	Putting through traffic underground / covering open tunnels		x	x	x																	
20	Transforming urban boulevard to park strip			x	x																	
21	Greening tram beds crossing the GS																					
22	Cutting park drives for cars																					
23	Connecting to metro station	x	x	x	x																	
24	Re-integrating derelict / brownfield / unused land												x									
25	Connecting to highway																					
26	Moving logistic activities and light industry							x														
27	Integrating nature reserves																					
28	Connecting separate parts over highway																					
29	Connecting over causeway				x																	
30	Connecting over/under local road		x								x											
31	Visual shielding																					
32	Making fenced off grounds accessible integrating sports grounds				x																	
33	Renegociating industrial land for shared use																					
34	Connecting nearby housing projects with parkspace																					
35	Re-designing ground floor and terrains of 60's housing blocks																					
36	Developing real estate around GS	x					x	x	x				x									
37	Reorganizing open air sports facilities							x	x	x												
38	Opening up impervious surfaces	x			x					x		x									x	
39	Rooftop park extension on commercial buildings										x											
40	Rooftop park extension on public buildings									x		x										
41	Creating passages in-between buildings														x				x			
42	Mega-roundabout																					
43	Mega-block																					
44	Part of private garden to parkspace						x												x			
45	GS as part of strategic site redevelopment																				x	
46	Connecting over water body																					
47	GS in shared use with public services																					
48	Transforming local road into GS													x								
49	Transformation public space into park																					
50	Rooftop park on top of industrial building																					
51	Reversing commercial building																					
52	Demolishing existing building for creation of GS																					
53	Converting parking space into GS																					
54	Cutting parking spaces													x								
55	Activation of unused lawn													x								

Table 40: Listing of identified opportunities for green space development and involved strategies 3/5

	TFL/N°	N2	N52	N53	N55	N56	N22	N44	N48	N50	N51	N14	N3	N5	N6	N57	N1	N7	N9	N11	N16	N4	N17	N36	N45	N46	N49	N21	N32	N38	N15	N23	N24	N47	N54	N8	N10	N12	N13	N18	N19	N20	N25	N27	N28	N29
	High investment class					x											x					x																								
	Middle investment class	x	x	x	x		x	x	x	x	x	x	x	x	x	x							x	x	x	x	x																			
	Low investment class																	x	x	x	x							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Name / count																																													
	Type	railroad optimization	railroad optimization	railroad optimization	railroad optimization	railroad optimization	private gardens to parkspace	private gardens to parkspace	private gardens to parkspace	private gardens to parkspace	private gardens to parkspace	private gardens to parkspace	mega-block	mega-block	mega-block	mega-block	boulevard to parkstrip	brownfield development	de-privatizing estates	de-privatizing estates		60's housing public space redevelopment	60's housing public space redevelopment	60's housing public space redevelopment	60's housing public space redevelopment	60's housing public space redevelopment	60's housing public space redevelopment	reorganizing sports fields	reorganizing sports fields	reorganizing sports fields	reorganizing sports fields			Industry/logistics redesign	brownfield development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development
1	Developing wetlands in valley bottom																																													
2	Developing a blue-green network																																													
3	Deploying walking and cycling trajectories																																													
4	Converting agricultural fields to park space with small scale agricultural character																																			x	x	x	x	x	x	x	x	x	x	x
5	Developing green areas around upstream tributaries																																													
6	Cutting local road																																													
7	Connecting existing public green spaces																																													
8	Halting housing development																																													
9	Reversing housing development																																													
10	Noise shielding																	x	x																											
11	Integrating protected landscapes																																													
12	Integrating estates		x						x										x	x												x														
13	Connecting separate parts over 2x2-lane road																																													
14	Connecting to railway station																																													
15	Covering open railroad trenches	x	x	x	x	x																																								
16	Connecting to tram station																																													
17	Extending park over local road up to sidewalk																																													
18	Re-routing roads and traffic around or away from park																x					x																								
19	Putting through traffic underground / covering open tunnels																x																													
20	Transforming urban boulevard to park strip																x																													
21	Greening tram beds crossing the GS																																													
22	Cutting park drives for cars																																													
23	Connecting to metro station																																													
24	Re-integrating derelict / brownfield / unused land																	x																	x											
25	Connecting to highway																																													
26	Moving logistic activities and light industry								x	x																								x												
27	Integrating nature reserves																																													
28	Connecting separate parts over highway																																													
29	Connecting over causeway																																													
30	Connecting over/under local road																					x																								
31	Visual shielding																	x																												
32	Making fenced off grounds accessible integrating sports grounds																	x																												
33	Renegociating industrial land for shared use																																													
34	Connecting nearby housing projects with parkspace																																													
35	Re-designing ground floor and terrains of 60's housing blocks																					x	x	x	x	x	x																			
36	Developing real estate around GS																																													
37	Reorganizing open air sports facilities																											x	x	x	x															
38	Opening up impervious surfaces																																													
39	Rooftop park extension on commercial buildings																																													
40	Rooftop park extension on public buildings																																													
41	Creating passages in-between buildings																																													
42	Mega-roundabout																																													
43	Mega-block												x	x	x	x																														
44	Part of private garden to parkspace					x	x	x	x	x	x	x																																		
45	GS as part of strategic site redevelopment																																													
46	Connecting over water body																																													
47	GS in shared use with public services																					x																								
48	Transforming local road into GS			x	x	x		x				x																																		
49	Transformation public space into park																																													
50	Rooftop park on top of industrial building																																													
51	Reversing commercial building																																													
52	Demolishing existing building for creation of GS																																													
53	Converting parking space into GS			x				x																																						
54	Cutting parking spaces			x		x		x						x																																
55	Activation of unused lawn									x				x									x						x						x											

Table 41: Listing of identified opportunities for green space development and involved strategies 4/5

	TFL/N°	N30	N31	N33	N34	N35	N37	N39	N40	N41	N42	N58	N59	N60	N61	N62		P1	P2	P3	P4	P5	P6	P8	R1	R2	R3	R5	R9	R10	R11	R12	R13	R14	R15	R16	R17
	High investment class																																				
	Middle investment class											x						x																			
	Low investment class	x	x	x	x	x	x	x	x	x	x		x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Name / count																																				
	Type	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	rural NGS development	private gardens to parkspace																									
1	Developing wetlands in valley bottom																																				
2	Developing a blue-green network																																				
3	Deploying walking and cycling trajectories																	x	x													x					
4	Converting agricultural fields to park space with small scale agricultural character	x	x	x	x	x	x	x	x	x	x																										
5	Developing green areas around upstream tributaries																																				
6	Cutting local road																	x	x													x					
7	Connecting existing public green spaces																																				
8	Halting housing development																																				
9	Reversing housing development																																				
10	Noise shielding																																				
11	Integrating protected landscapes																																				
12	Integrating estates																																				
13	Connecting separate parts over 2x2-lane road																																				
14	Connecting to railway station																	x														x					
15	Covering open railroad trenches																																				
16	Connecting to tram station																																				
17	Extending park over local road up to sidewalk																	x																			
18	Re-routing roads and traffic around or away from park																	x																			
19	Putting through traffic underground / covering open tunnels																																				
20	Transforming urban boulevard to park strip																																				x
21	Greening tram beds crossing the GS																																				
22	Cutting park drives for cars																																				
23	Connecting to metro station																																				
24	Re-integrating derelict / brownfield / unused land																																				x
25	Connecting to highway																																				
26	Moving logistic activities and light industry																																			x	
27	Integrating nature reserves																																				
28	Connecting separate parts over highway																																				
29	Connecting over causeway																																				
30	Connecting over/under local road																																				
31	Visual shielding																																				
32	Making fenced off grounds accessible integrating sports grounds																																				
33	Renegociating industrial land for shared use																					x		x													
34	Connecting nearby housing projects with parkspace																																x		x		
35	Re-designing ground floor and terrains of 60's housing blocks																													x							
36	Developing real estate around GS																																				
37	Reorganizing open air sports facilities																				x		x								x						
38	Opening up impervious surfaces																		x	x	x	x	x		x	x	x	x		x	x	x	x				
39	Rooftop park extension on commercial buildings																																				
40	Rooftop park extension on public buildings																											x									
41	Creating passages in-between buildings																											x			x				x		
42	Mega-roundabout																																				
43	Mega-block																																				
44	Part of private garden to parkspace											x													x			x	x				x		x		
45	GS as part of strategic site redevelopment																												x								
46	Connecting over water body																																				
47	GS in shared use with public services													x			x																				
48	Transforming local road into GS									x	x	x								x			x		x						x						
49	Transformation public space into park									x	x	x						x	x		x											x					
50	Rooftop park on top of industrial building														x			x	x	x	x												x				
51	Reversing commercial building																							x													
52	Demolishing existing building for creation of GS												x																							x	
53	Converting parking space into GS																					x														x	
54	Cutting parking spaces																									x	x										
55	Activation of unused lawn																									x	x										x

Table 42: Listing of identified opportunities for green space development and involved strategies 5/5

8.4 Land cover fractions per typology

LC code	LC description	BAU01	BAU02	BAU03	BAU04	BAU05	SUS01	SUS02	SUS03	SUS04	SUS05
fVEG	fraction vegetation	56	33	19	41	19	38	46	38	28	28
fVHI	— frac. dense vegetation	*47*	*28*	*16*	*34*	*16*	*27*	*32*	*27*	*20*	*20*
fVLO	— frac. low vegetation	*8*	*5*	*3*	*6*	*3*	*11*	*14*	*12*	*9*	*8*
fVBU	frac. vegetated buffer area	0	0	0	0	0	5	4	4	4	3
fIIF	frac. impervious with infiltration of all flows	0	0	0	0	0	31	27	17	26	30
fIDF	frac. impervious with drainage of all flows	25	36	27	17	25	0	0	0	0	0
fRDF	frac. roof (gable) with drainage of all flows	19	31	36	38	0	0	0	0	0	0
fFDF	frac. flat roof with drainage of all flows	0	0	9	5	0	0	0	0	0	0
fGIO	frac. green roof with infiltration of overflow	0	0	0	0	0	26	23	41	41	38
fGDF	frac. green roof with drainage of all flows	0	0	9	0	56	0	0	0	0	0

LC code	LC description	BAU01	BAU02	BAU03	BAU04	BAU05	SUS01	SUS02	SUS03	SUS04	SUS05
fVEG	fraction vegetation	60	40	29	49	21	42	48	45	37	36
fVHI	*— frac. dense vegetation*	*51*	*34*	*25*	*41*	*18*	*30*	*34*	*32*	*26*	*25*
fVLO	*— frac. low vegetation*	*9*	*6*	*4*	*7*	*3*	*13*	*15*	*14*	*11*	*11*
fVBU	frac. vegetated buffer area	0	0	0	0	0	5	4	0	0	4
fIIF	frac. impervious with infiltration of all flows	0	0	0	0	0	23	23	6	10	10
fIDF	frac. impervious with drainage of all flows	19	22	0	0	0	0	0	0	0	0
fRDF	frac. roof (gable) with drainage of all flows	21	38	43	46	0	0	0	0	0	0
fFDF	frac. flat roof with drainage of all flows	0	0	14	6	0	0	0	0	0	0
fGIO	frac. green roof with infiltration of overflow	0	0	0	0	0	29	24	48	53	50
fGDF	frac. green roof with drainage of all flows	0	0	14	0	79	0	0	0	0	0

Table 43: Land cover fractions per typology

List of figures

List of tables

Glossary

Business as usual

A scenario which assumes the current processes and regulations to continue into the future, often considered as a less sustainable option.

Ecological approach

Ecological means relating to or concerned with the relation of living organisms to one another and to their physical surroundings. An ecological approach to urban design and planning is a fundamental approach which is aimed at the efficient use of natural resources while adopting human activities in a less harmful way to the environment. Ecological urban planning was pioneered by people such as Frederick Law Olmsted (concerned with the preservation of the natural beauty and ecological function in the city, the development of several park systems), Ebenezer Howard (self-sustaining garden city model), Patrick Geddes (bioregionalism theory, integrating people, activities and land under an ecological balance), and Ian McHarg (ecological land use, suitability of human activities in relation to natural systems).

Ecosystem services

Ecosystem services (ES) can be defined as the benefits mankind receives from ecosystems. A common classification describes four general ecosystem service categories: supporting ES are the biochemical cycles (nitrate, phosphorous, carbon, etc...) that allow the other services to take place; provisioning ES encompass food production and biological production of raw materials; regulating ES act in climate regulation, flood control, air and water purification and disease-regulation, and; cultural ES provide the immaterial benefits e.g. recreation, aesthetic appreciation, inspiration and a general sense of well-being.

Decision-making

The act or process of deciding something especially with a group of people. It involves a thought process of selecting a logical choice from available options, weighing positives and negatives of each option. For effective decision making, the actor(s) must be able to forecast the outcome.

GIS-based model

A set of processing steps, predefined in a geographical information system (GIS) software, which transform geo-referenced input maps to an output (e.g. spatial indicator).

Green space

Urban green 'spaces' are in this work considered as spatial realms, which a person can enter, and which mostly have natural features. They can be close to wild nature, or have a cultivated, ornamental appearance. Public urban green spaces are the publicly accessible sub-category of these, whether they are subject to opening times or not.

Green space quality

It is difficult to summarize what exactly green space quality entails. A cross-cutting starting point in literature is that quality is something that is perceived by people, unless specifically stated otherwise. Qualitative green spaces have a spatial configuration of features (natural and artificial) positively influencing user satisfaction, as well as mental and physical wellbeing, and quality of life.

Indicator

The term has different meanings in different domains. Etymologically, it means 'which indicates something, which contributes information'. It is a parameter, or value derived from one or more parameters, that describes the state of a phenomenon, environment, or zone, with a significance which extends beyond that what is directly associated with the parameter's value. It is used for monitoring and evaluation, and useful for decision-making in the planning of spaces.

Inherent quality

A weighted sum of sub-qualities that are considered as inherent to a green space: 'naturalness', 'quietness', 'historical and cultural value', and 'spaciousness'. For the average Brussels inhabitant, 'historical and cultural value' is not significant in relation to overall quality; therefore it has not been incorporated in quality assessment in this study.

Land cover

Land cover refers to the material covering the earth, such as vegetation, paving, water, roofs, or bare land. In this study it is considered as the first material (class) encountered when the study area is approached vertically from above.

Options for green space development

In this work, options for green space development (OGSD) are locations that have been indicated during workshops as the best choice for potential implementation of a public green space, thereby addressing the lack of green spaces for inhabitants living in the close surroundings of these locations.

Research by design

Research by design is an inquiry in which design is a substantial part of the research process, and where the integrative function of design is harnessed. It forms a pathway to new insights through the inclusion of contextualized possible alternatives, most often validated through an interdisciplinary peer review of experts, however, in this study also non-experts partake in the design excercises.

Scenario

Scenarios describe possible futures. In planning they can consist out of a set of constraints or rules, or a specific spatial construct. Most often they are created in groups of two or more so they can be compared. In this research, scenarios are used as input for developed models so their effect on indicators can be measured. Scenarios are considered as a useful tool in analyzing situations involving complexity and uncertainty.

Sub-qualities

Sub-qualities are aspects of green space quality, which together describe overall quality. In this study, they are identified as 'naturalness', 'quietness', 'historical and cultural value', 'spaciousness', 'facilities', 'cleanliness and maintenance', and 'feeling of safety'.

Sustainable urban design and planning, or sustainable urbanism

This mode of urbanism is relates to the core idea of sustainability, which is to achieve a balance where both current and future (potential) human needs are being met. It is considered as a process of synergetic integration of economic, social, physical and environmental sub-systems of a city. Although this is a broad concept, in this study the focus lies with high-density urban form and access to nature with the perspective of urban environmental quality and resilience.

Theoretical functional level

The definition of theoretical functional levels (TFL) is based on the idea that different sizes of green space provide different functions. A set of TFLs can be defined in the form of consecutive ranges of GS size, which are usually named in terms of the scale of the area that the GS serves, e.g. residential, neighbourhood, quarter, district, city, and metropolitan GS. In this study, a maximum attraction distance characterizes each TFL. The term 'theoretical' refers to the idea that the size of the green space is considered to be able to provide certain functions, while this might not be the case in practice.

Typology

In urban planning and architecture, a typology is a classification according to characteristics. This set of characteristics can pertain to parameters (e.g. density, ground area) or spatial/physical aspects (e.g. form, materials). A specific characterized 'type' is often also referred to as a typology.

Urban green

Urban green comprises the vegetation elements in a city. In this study, urban green is defined in the broadest possible sense, from private backyard plants to small public and non-public green spaces, to larger parks and urban forests. The 'urban' part in the definition points to its proximity to humans and the idea that this green and these green spaces are part of the urban ecosystem.

Urban heat island effect

The thermal effect of an urban area having a higher average temperature than surrounding areas, primarily due to: materials absorbing more solar radiation and storing more heat than rural land cover; lack of evapotranspiration; geometric effects such as the street canyon, where infrared radiation is reabsorbed by materials in another plane. Anthropogenic heat flux (from infrastructure and building stock) has a small contribution.

Use-related quality

The sum of sub-qualities that pertain to the use of a green space: 'facilities', 'cleanliness and maintenance', and 'feeling of safety'.

List of abbreviations and acronyms

ACC	Accessibility
APP	Approach
BAR	Bare soil
BASE	Base (scenario)
BAU	Business As Usual (scenario)
BCR	Brussels-Capital Region
BE	Brussels Environment
BE	Belgium
BOT25	Bottom 25% of inhabitants sorted by income
BRIC	Brussels Regional Informatics Centre
BROH	Regional development office for the Brussels-Capital Region
CA	Canada
CAD	Computer Aided Design
CN	China
Δ	Difference (mathematical)
Eq.	Equation
ES	Ecosystem Service
EU	European Union
EXI	Existing situation
f(…)	Fraction of (…)
FAC	Facilities
FDF	Flat roof with Direct drainage of all Flows
FDO	Flat roof with Direct drainage of Overflow
FIF	Flat roof with Infiltration of all Flows
FIO	Flat roof with Infiltration of Overflow
FOD	Federal public service
FULL	Full option (scenario)
GDF	Green roof with Direct drainage of all Flows
GDO	Green roof with Direct drainage of Overflow
GIF	Green roof with Infiltration of all Flows
GIO	Green roof with Infiltration of Overflow
GIS	Geographic Information System
GS	Green Space
HH	Household
HIS	Historical and cultural value
HK	Hong Kong
IDF	Impervious surface with Direct drainage of all Flows
IIF	Impervious surface with Infiltration of all Flows
INH	Inherent green space qualities
IT	Italy
IV	Information Flanders
LC	Land Cover
LNE	Environmental department of the Flemish Region
LU	Land use
MNT	Cleanliness and maintenance
NAT	Naturalness
NAV	Network of Flemish architects
NDVI	Normalized Difference Vegetation Index
OGSD	Opportunity for Green Space Development
PGS	Public Green Space
PRDD	Plan Régional de Développement Durable
QUI	Quietness
RbD	Research by Design
RDF	Gable roof with Direct drainage of all Flows
RDO	Gable roof with Direct drainage of Overflow
RIF	Gable roof with Infiltration of all Flows

RIO	Gable roof with Infiltration of Overflow
SAF	Feeling of safety
SAV	Shared Autonomous Vehicle
SE	Sweden
SPA	Spaciousness
SUPP	Supplementary (scenario)
SUS	Sustainable (scenario)
TEEB	The Economics of Ecosystems and Biodiversity
TFL	Theoretical Functional Level
TOP75	Top 75% of inhabitants sorted by income
UGS	Urban green space
UK	United Kingdom
UN	United Nations
URBIS	Brussels urban information system
US	United States
USE	Use-related green space qualities
VBU	Vegetated buffer area
VEG	Vegetated area (green space that is not buffer area or green roof)
VHI	Dense (high) vegetation
VLO	Low vegetation
WAT	Water