Sterre Blok

Amsterdam University College

Social Sciences Capstone

Monitoring the Consequences of Conflicting Land Use Policies: An Enhanced NDVI Analysis of Amsterdam

Email author: **sterre.blok@student.auc.nl**

Supervisor: **Dr. Eric Koomen (VU) e.koomen@vu.nl**

Reader: **Dr. Eduardo Simao Da Graca Dias (VU) e.simaodagracadias@vu.nl**

Tutor: **Dr. Thijs Etty (AUC)**

Date: **31/05/2023**

Word count: **10,212**

Abstract

Urban green spaces are important for the well-being of citizens and the environment but are threatened by the densification of cities. In this study, the development of new urban built-up at the expense of urban vegetation is monitored between 2017 and 2022 within the city ring (A10) of Amsterdam. Based on satellite data, an NDVI analysis was performed for both years. To gain additional insight into the land use change, this data was enhanced by topographical data from the BGT. This revealed that 8.24% of urban green spaces within the study area were primarily lost to infrastructures and secondarily to residences. Most lost greens spaces were public green. This implies that the current goal of the municipality of Amsterdam to balance the contradicting planning of rigorous greening and growth within the city borders, has not been met in the past years. This research, therefore, shows that additional policy measures are necessary to support the city's livability, sustainability and climate adaptability with urban green spaces.

Keywords: Amsterdam; land change monitoring; urban green spaces; densification; urban planning; climate adaptation

List of abbreviations

BGT: Basisregistratie Grootschalige Topografie (basis registration large-scale topography)

EVI: Enhanced Vegetation Index

Ha: Hectare

NDVI: Normalized Difference Vegetation Index

LUC: Land Use Change

UGS: Urban Green Spaces

UHI: Urban Heat Island

Acknowledgments

As this is the last deadline I will hand in as part of my bachelor's at AUC, I would like to thank all AUC lecturers and students that have helped me to come to this point of graduating. In particular, my tutor Thijs Etty, who helped me discover my interests in the field of social environmental sciences. Thanks to him I was able to pursue a study program that perfectly fits my curiosity, which ultimately led to this capstone.

A big thank you to my reader Dr. Eduardo Simao Da Graca Dias for helping me find satellite data, for answering my questions, and, of course, for being my reader. Thank you to Lynn and Renato, who I could always consult whenever I got stuck. Thank you to my mother, who proofread my capstone for me. And, of course, many many thanks to my supervisor Dr. Eric Koomen. I very much appreciate all the time and attention he put into helping me with this research. His ideas, enthusiasm, and support have allowed me to write a capstone that I am proud of.

Table of contents

1. Introduction

While urban areas already house 55% of the world population, they are rapidly expanding (Grêt-Regamey et al., 2013; United Nations, 2019, p.19). Furthermore, cities worldwide are responsible for between 71% and 76% of global greenhouse gas emissions (Hoornweg et al., 2011). Therefore, cities have great leverage in combating climate change but also carry great responsibility for protecting their growing densely populated regions against environmental hazards (Lin et al., 2021). A readily available planning approach to protect urban areas from environmental problems, like heat and drought, is adding vegetation to the city with so-called Urban Green Spaces (UGS; Grêt-Regamey et al., 2013; Mathey et al., 2011). UGS are vegetated areas in cities like gardens, railway corridors, and (post-stamp) parks (Gupta et al., 2012). UGS cool down the city through shade provision and evapotranspiration, and mitigate air pollution (Bolund & Hunhammar, 1999; Bowler et al., 2010). Besides that, they combine the advantages of infiltrating rainwater which prevents floods, they absorb harmful greenhouse gasses, and they provide space for biodiversity in cities (Aronson et al., 2017; Haaland & van den Bosch, 2015; Strohbach et al., 2012).

The municipality of Amsterdam takes these ecosystem services of UGS into account in its future urban planning as proposed in the Amsterdam Environmental Vision (AEV) 2050 (Gemeente Amsterdam, 2021). Next to the highlighted importance of UGS, the AEV also describes Amsterdam's aim of densification for both economic and sustainability purposes. Denser cities allow commuting by bike, public transport, or as pedestrians, which reduces the demand for cars and therefore the use of fossil fuels (Coolen & Meesters, 2011; Haaland & van den Bosch, 2015). Other sustainability advantages of compact cities are that high urban density reduces energy consumption, and building and infrastructure materials (Bibri, 2020).

Although it is proposed in the AEV that densification and greening should ideally be combined, Giezen et al. (2018) showed in their research that 11% of UGS in Amsterdam have been replaced by built-up between 2003 and 2016. They demonstrated that ideas to green and densify the city of Amsterdam simultaneously have opposed one another in the past. In order to gain insight and prevent this conflict, precise monitoring of land-use change in the city is essential. In their research paper, Giezen et al. (2018) propose satellite image remote sensing to analyze the effects of land use policies.

There are important shortcomings to their study approach of solely using satellite imagery. When using remote sensing, all land use that cannot be classified under built-up or water can be labeled as green space. However, losing a public recreational park is a far greater loss to the city than the loss of for example construction sites with few plants between the sand (Lepczyk et al., 2017; Morya & Punia, 2021). Moreover, the municipality of Amsterdam describes in its AEV that it would like to become a car-free city, which would result in a growing demand for public transport and cycling infrastructure (2021, p. 55). Therefore a distinction between a change of different types of green and different forms of new urban built-up provides a lot of additional insight to the land use change. This capstone research will build on the study by Giezen et al. (2018). The shortcomings of their study will be addressed by combining satellite remote sensing data with topographic data from the Basisregistratie Grootschalige Topografie (BGT). This enhanced dataset will allow benefiting from the advantages of both data types and is, therefore, most suitable for comprehensive land use change analysis (Harris & Ventura, 1995). The dataset will then be used to carry out an extensive pixel-by-pixel land-use change analysis. With this, I will demonstrate the different types of urban transitions that have taken place in Amsterdam between 2017 and 2022. Since the research by Giezen et al. monitored the land use change in Amsterdam until 2016, my study will be a follow-up. Since 2016 higher-resolution data have become available, which will improve the precision of the monitored change.

I will start my capstone research with a theoretical framework in which I will outline the benefits of UGS and densification and their interaction. I will also synthesize the policies laid out by the municipality of Amsterdam, and research how land use policies have affected land use change in other cities. This framework is important to understand the essence of UGS and what threatens them. It will provide additional insight into the implications of the detected land use changes in the practical part of this research and therefore contextualize the research in the wider academic discourse of densification versus greening. This is followed by the methodology and the results of the spatial analysis which will be presented in a map and later discussed on the basis of land use change statistics. Ultimately, my literature review and GIS analysis will answer the overarching research question: to what extent have different forms of urban development in Amsterdam resulted in a loss of different categories of UGS between 2017 and 2022?

2. Urban Green Spaces

2.1 Defining UGS

UGS are vegetated areas in cities (Kabisch & Haase, 2013). Examples of UGS are (post-stamp) parks, gardens, sports fields, lanes of street green, and railway corridors (Gupta et al., 2012). UGS can be divided into two categories: public and non-public (Feltynowski et al., 2018). Public UGS would, according to Feltynowski et al. (2018), include parks, forests, street green, cemeteries, green facades, railway corridors, and grass fields. Private urban green spaces are by Coolen & Meesters (2011) defined as an outdoor extension of dwellings. This includes (allotment) gardens and green roofs.

Another type of green space that cannot be classified under either category, is informal green space. Rupprecht and Byrne (2014) defined these UGS as ‘neglected’ vegetated areas that are unrecognized by owners or governing institutions as spaces for inhabitants. If land use in a city is divided into three categories: UGS, built-up, and water, any land use in the city that is not built-up, or water could be perceived as a UGS. But, informal UGS, like sporadically vegetated areas on construction sites, provide fewer social and environmental advantages than other types of ‘formal’ UGS (Morya & Punia, 2021). In the following literature sections of the paper, the term UGS will refer to any type of urban green space, excluding informal UGS. In the spatial analysis part of this paper, however, both formal and informal as well as public and non-public UGS will be monitored and discussed.

As this research on land use change aims at distinguishing between these types of UGS to demonstrate the gravity of their loss, it is primarily important to understand the advantages of UGS, and the differences between public and private UGS. All types of formal UGS provide a multitude of social and environmental benefits that are essential for the well-being of the city. In the following section, these advantages will be explored.

2.2 Social advantages of UGS

One of the most important social advantages of UGS is that they provide space for recreation and leisure (Bolund & Hunhammar, 1999). Because of that, UGS can improve mental and physical health as they provide aesthetically pleasing space for physical activities (Richardson et al., 2013). Physical activities provoked by UGS reduce the likelihood of physical illnesses like cardiovascular diseases, diabetes, and cancer (Folsom et al., 2000; Manson et al., 2003). Added to that, the provision of green spaces in neighborhoods is positively correlated with lowered blood pressure, as well as longer longevity of the elderly, and sooner recovery of hospital patients (Hartig et al., 2003; Tanaka et al., 1996; Ulrich, 1984).

This is induced by the aesthetic enjoyment associated with UGS, which is derived from the visual contact with nature, as well as the scent and sound of vegetation that provide a sense of peacefulness (Jim & Chen, 2006; Smardon, 1988). UGS naturally reduces noise pollution, and UGS enact 'natural sounds', that are commonly perceived as pleasant, relaxing, and stress-reducing (Alvarsson et al., 2010; Dzhambov & Dimitrova, 2014; Sakieh et al., 2017; Uebel et al., 2021). This is strengthened by the fact that UGS provide opportunities to meet neighbors, contributing to improved social cohesion (Kemperman & Timmermans, 2014). For example, a study by Kweon et al. in 1998 found that elderly people that live in a city with better accessibility to common UGS have more social contact than those with fewer green spaces, which reduces loneliness in this cohort. Multiple factors determine the quality of UGS and their attractiveness to urban citizens (Zhou & Parves Rana, 2012). For instance, naturalness, maintenance, diversity, and safety play a role in how UGS are perceived and used (Jorgensen et al., 2002; Kuo et al., 1998). In these aspects, formal UGS that are generally better maintained, differ from informal UGS, that are less safe, but one could say also more natural (Feltynowski et al., 2018).

It is however important to note that not all UGS are equally accessible (Fan et al., 2017; Jennings et al., 2012). Whereas street trees and parks are openly accessible for everyone to enjoy, private UGS, like gardens, are not. The social benefits of UGS mentioned, like illness reduction, and increased relaxation are provided by both public and private UGS (Haaland & van den Bosch, 2015). The benefits of meeting neighbors, and reducing loneliness can however only be ascribed to public UGS (Zhu et al., 2019). Coolen and Meesters (2011) studied the difference between these types of UGS in the Netherlands. They state that there is a gap between government policy of providing denser cities with more UGS and consumer housing preference that includes a private garden. Research by Bernardini and Irvine (2007), however, found that public UGS are mainly enjoyed by people who do not have a garden. This indicates that both garden and non-garden owners value UGS in their nearby environment. However, as houses with gardens are more expensive, public UGS are a good substitute for people with lower incomes (Lehberger et al., 2021; Limsombunc et al., 2004).

2.3 Environmental advantages of UGS

On top of the social effects, UGS provide multiple environmental ecosystem services (Breuste et al., 2013; Niemelä et al., 2010). Ecosystem services are defined by Costanza (1998) as “the benefits humans derived from the functions of ecosystems”. An instance of an ecosystem service provided by UGS is that they cool down cities in times of heat stress through evapotranspiration and shade provision, mitigating the urban heat island (UHI) effect (Bowler et al., 2010). Research by Blok et al. (2022) showed that in Amsterdam, the UHI effect was effectively reduced by UGS by 0.22 to 1 degree. As illustrated in Figure 1, the UHI effect is significantly lower in areas with close proximity to UGS, or green spaces in general.

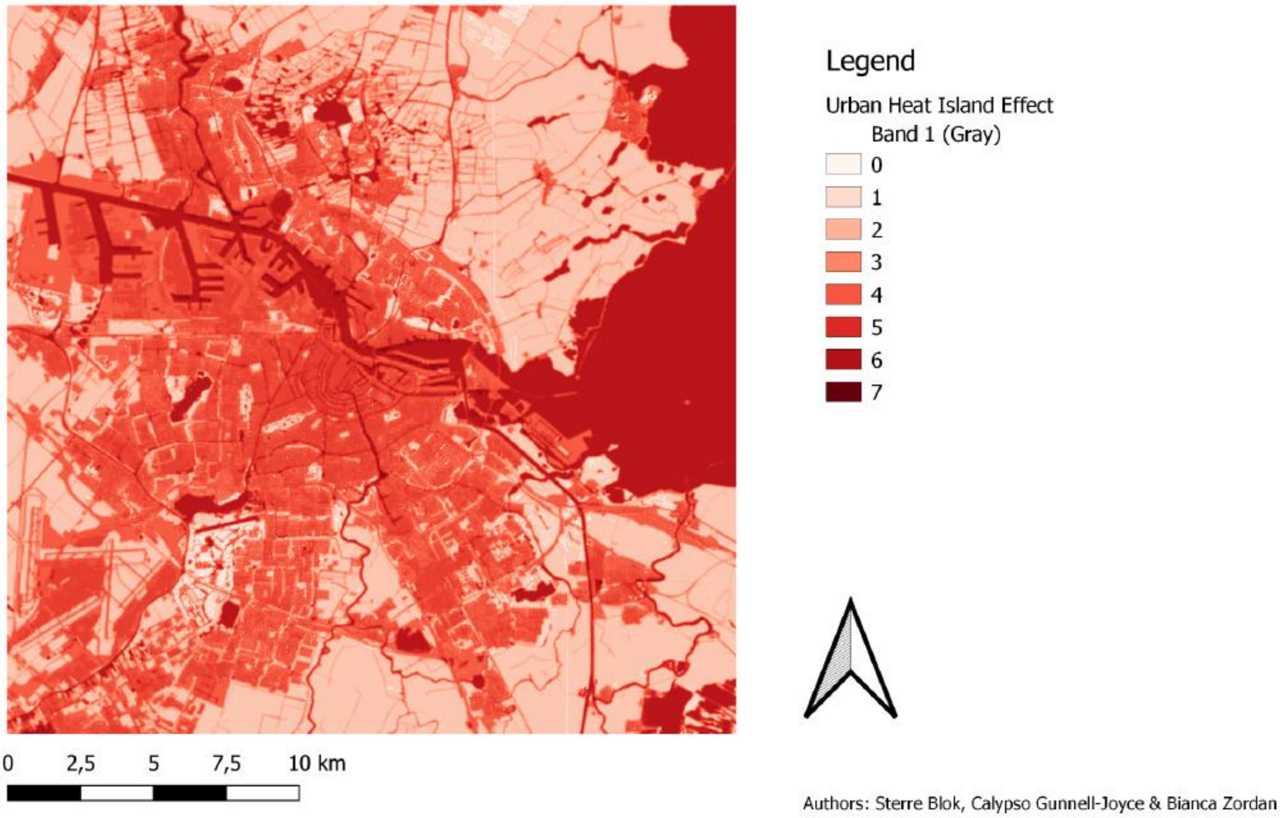

Figure 1: Urban heat island effect in June 2019, Amsterdam, The Netherlands. (Blok et al., 2022).

Trees specifically absorb solar radiation by up to 20% (Gold et al., 1996; Davies et al., 2008). This reduces residential energy consumption in summer since it eliminates the need for air conditioning (Simpson, 2002).

Apart from the reduction of the need for energy-consuming cooling methods, UGS can also directly mitigate air pollution, by filtering particulates from the air (Bolund & Hunhammar, 1999; Givoni, 199). Vegetation also naturally absorbs CO_2 emissions, reducing their adverse effect on global warming (Bell et al., 2011; Tallis et al., 2011). In the process of photosynthesis, plants absorb CO_2 from the atmosphere, after which the carbon is stored in the plants organic matter as biomass (Leung et al., 2011). On average, one medium-large tree of 50 m^2 can sequestrate 11 kg of carbon yearly (Akbari, 2002).

Moreover, an important benefit of UGS, which makes them indispensable in urban areas. is their ability to facilitate rainwater infiltration and storage in cities (Strohbach & Haase, 2012; Bolund & Hunhammar, 1999). UGS reduce peak flows in times of excessive rainwater fall and reduces the speed of runoff, which then reduces the scour of soil by runoff (Keke et al., 2018). The capacity of rainwater accommodation is influenced by the total surface area of vegetation (Gill et al., 2007). Effective rainwater management is essential in cities and will become more important in the near future due to climate change (Loibl et al., 2021; Zhang et al., 2012).

Lastly, another reason to be in favor of urban green spaces in terms of environmental benefits is that urban areas house numerous native and non-native species that can support endemic species in need of conservation (Aronson et al., 2014; Ives et al., 2015). The value of biodiversity varies over different types of urban green spaces, say Beninde et al., (2015). According to them, among other things, the size, quantity, and quality of UGS positively differentiate the types and quantity of species living in UGS. Knowledge about the ecological role of different types of UGS should be used when decisions have to be made between which UGS are most important to preserve, and which ones are less harmful to replace (Lepczyk et al., 2017).

In terms of environmental benefits, public and private UGS provide the same ecosystem services (Bernardini & Irvine, 2007; Haaland & van den Bosch, 2015; Hanson et al., 2021). However, generally, UGS are less accessible to marginalized societal groups, resulting in environmental inequity (Jennings et al., 2012; Pham et al., 2012). For this reason, ecosystem services of UGS that are only obtained by UGS close to the living environment, like cooling, and air pollution mitigation, are unequally distributed (Blok et al., 2022; Matos et al., 2019; Wolch et al., 2014). This leads to, among other things, worse mental and physical health, as well as higher energy costs for cooling methods by marginalized groups (Jensen &

Gatrell, 2009; Yang et al., 2021). For this reason, the accessibility of UGS plays a role in the distribution of environmental benefits derived from them.

2.4 Threat to UGS: densification

Despite the many benefits of UGS, they are threatened in most cities (Bolund & Hunhammar, 1999; Berghauser Pont et al., 2020). Cities aim to expand economically by developing built-up space for new residents and businesses, which requires scarce unbuilt space (Haaland & van den Bosch, 2015). UGS, primarily informal, can be perceived as unbuilt and therefore suitable for densifying built-up in urban areas. This densification will enhance what is called a 'compact city' (Coolen & Meesters, 2011).

Much like urban green spaces, compact cities are noted to have several social and environmental advantages (Tappert et al., 2018). In a compact city, the densification of residences is combined with mixed land use, intergrading among other land uses; recreation, education, businesses, and other forms of industry (Dehghani et al., 2022; Zhang et al., 2021). This allows citizens to commute to their day-to-day activities using only bikes, public transport, or as pedestrians (Coolen & Meesters, 2011; Haaland & van den Bosch, 2015). This limits greenhouse gas emissions and air pollution (Basagaña et al., 2018; Massink et al., 2011).

In a dense city, more people make use of public transport networks because their distance to public transport stops is on average reduced (le Clercq & de Vries, 2000). This would make public transport economically more efficient (Hall et al., 2018). The more sustainable public transit infrastructure would reduce the demand for fossil fuels, and it would free up large areas of space as car roads and parking spots become unnecessary (Gössling, 2020; Woodcock et al., 2007).

Another greenhouse gas reducing advantage of compact cities is that if residences are built closer to, or on top of one another, energy use for heating, cooling, and lighting is reduced, because these can be shared by the citizens (Jenks et al., 2000; Loibl et al., 2021; Mohammadi et al., 2021). In terms of heating, Rafiee et al. (2019) studied the effect of denser urban planning on heat consumption in Amsterdam and concluded that housing units with less exposed circumference have lower heating demand.

While UGS generally improve the microclimates in cities, densification can have the opposite effect (Loibl et al., 2021). Because of a reduction in wind speed caused by buildings, ventilation is weakened. Therewith, the urban heat island effect is accelerated by the sealed cover of built-up (Blok et al., 2022). Projections on climate change indicate that in Europe, the frequency and gravity of heat waves will increase over the coming years (van Hove et al., 2015). During these heat waves, solar radiation is absorbed by gray built-up, like buildings and roads (Buyantuyev & Wu, 2009). At night, this captured heat is slowly released, increasing the urban temperature (Koomen & Diogo, 2015; Kuang et al., 2014). Compared to rural areas with less built-up, the cooling in the evening in cities is therefore slower (Rafiee et al., 2016). On the contrary, during the daytime, the shading provided by high buildings can have a cooling effect on the city (Loibl et al., 2021).

3. Research context

3.1 Study Area: Amsterdam city ring

The study area that was chosen for this research was the area within the A10 highway inner city ring of Amsterdam (see Figure 2). Amsterdam, situated in the province of North Holland is the capital city of The Netherlands, and with that also the biggest city of The Netherlands. On January 1st, 2022 (before the annexation of Weesp), the municipality of Amsterdam had 882.633 inhabitants (Centraal Bureau voor de Statistiek, 2022). Approximately 500,000 citizens live within the city ring (Giezen et al., 2018). The inner city ring surface is 71 km², while the entire municipality is 219 km². This means that the area within the city ring is the most densely built area of the municipality. Therefore greening and densification policies are most likely to conflict in this area, making it most relevant for this research. This study area will allow me to compare my results to those of Giezen et al. (2018), who chose the same study area, for the same reasons.

Figure 2: Study area by Giezen et al. (2018) which is also the study area for this research

3.2 Previous policies in Amsterdam

In section two of the annex of the Greenvision, the history of green management by the municipality is described (2020). Amsterdam is both historically and currently a very green city. Almost all green in the city was once created as part of the city's development. The Housing and Health Act of 1901 prescribes the necessity of green space for everyone and motivates the municipality to provide more green spaces.

Amsterdam's aim of expanding its UGS is reinforced by the Algemeen Uitbreidingsplan: General Expansion Plan (AUP), by Cornelis van Eesteren in 1935 (Amsterdams Stadsarchief, 2019). In this plan, he determined that 'light, air, and space' should be centralized in future urban planning. For each citizen, the minimum amount of green space was statistically calculated. As was the minimum distance of green space to their homes. This increase in green could, according to van Eesteren, be achieved through densification. Urban planners therefore tried to make the city as compact as possible, limiting the travel time of citizens (Gemeente Amsterdam, 2020).

3.3 Current policy context

This view is still prevalent in the current plan laid out by the municipality, the Amsterdam Environmental Vision (AEV) 2050 (Gemeente Amsterdam, 2021). In the AEV it is predicted that the population of Amsterdam will approximately increase to 1.1 million citizens by 2050 (p. 24). To accommodate these citizens, the municipality has proposed to build 150.000 new residences in the coming years. Chapter 4.4 of the AEV (p. 52) is called 'Growth within the Borders' and expresses that the city will only be extended inwards, leaving the polder surrounding Amsterdam untouched. This will further densify the city. These plans are in line with the prescription of the UN-Habitat of over 150 citizens per hectare (Berghauser Pont et al., 2020). High urban density reduces the demand for building and infrastructure materials (Bibri, 2020). Densification therefore also contributes to the municipality's aim to become a circular city (2020, p. 178). In circular cities, resources are reduced and reused as much as possible (Williams, 2019).

As described in the AEV, the city of Amsterdam aims to combine both densification and greening to benefit from the social and environmental benefits of both (Gemeente Amsterdam, 2021; Giezen et al. 2018). Another important reason to combine the two is that UGS mitigate the negative effects of densification (Bernstein et al., 2004; Loibl et al., 2021; Okkels et al., 2018). However, providing both new residences and UGS requires unbuilt space, which is often scarce in cities, especially in Amsterdam (Haaland & van den Bosch, 2015; Giezen et al., 2018).

The municipality of Amsterdam has multiple ideas on how and where to implement more UGS. Chapter 4.4 (p. 56) is called ‘Rigorous Greening’. It describes how Amsterdam would like to become more climate adaptable, livable for humans, animals, and plants, and improve its urban quality by greening the city. The AEV mentions how Amsterdam has become a much greener city over the past sixty years, and how it aims to continue this trend. In this chapter, the municipality promises to apply a target goal for each newly developed neighborhood to reserve space for flower beds and parks. Amsterdam will provide new green in larger areas as well as ‘snippet green’, so that every house has some green area close to home. ‘More street trees and green and fewer tiles’, is stated as one of the aims of the municipality in the Greenvision (2020, p. 18). In both the Greenvision, and AEV, it is continuously repeated that in places where a quantitative increase of UGS is impossible due to densification constraints, the municipality aims at improving the quality of UGS (Gemeente Amsterdam, 2020, p. 5; Gemeente Amsterdam, 2021, p. 56).

Even in places where it might appear as if there is no place for new UGS, the municipality is looking into ways to green. For example on infrastructure by providing green tram infrastructure networks, or by establishing parks on car tunnels (p. 39). Moreover, the municipality wants to make Amsterdam car-free, which will free up a lot of space (p. 18). It also wants to make efficient use of existing free space by installing more green facades and green roofs (p. 3; p. 56).

Although planning approaches are given extensive attention in the AEV and plans on how to combine the two are discussed, no attention is paid to explicit policy regulations. This could be absent because previous counteracting trends in Amsterdam are unknown. This research will provide the municipality of Amsterdam and its appointed city planners with information on the effectiveness of their plans in the most recent years. This could make them aware of this issue and reinforce them to pay additional attention to the synergy of greening and densification in the execution of the plans of the AEV.

3.4 Academic context

According to Giezen et al. (2018), a lack of UGS preserving policies and oversight during the implications of some planning projects can lead to an under-prioritization of sustainability. Long-term policies aimed at combining UGS and densification, should according to Giezen et al. (2018) be specific to incentivize developers to follow them. These policies are currently lacking in multiple cities worldwide. (Brunner & Cozens, 2013; Byomkesh et al., 2011; Zhou & Wang, 2011). In a study on 100 local governments in Australia, it was shown that councils that offered more policy instruments had more UGS like green roofs and green facades than councils where policies like that were limited (Irga et al., 2017). Another method to make sure green space is protected from densification policies is, according to Balikçi et al. (2021), to manage UGS and urban development within the same department of the municipality. This is currently the case in Amsterdam, say Balikçi et al. (2021).

Giezen et al. (2018) have researched the consequences of the lack of provision on contradicting urban planning policies in the inner city ring of Amsterdam and found that in 13 years time, 11% of UGS had been lost for the benefits of densification. They propose that a GIS-based analysis using remote sensing offers the opportunity to most accurately assess land use change over time. Using high-resolution satellite images (1.84 m by 2.41 m), they classified the land use of Amsterdam in both 2003 and 2016 into three land-use types within the urban area; vegetation (green), built-up (red), and water (blue), and compared the two years. Their motivation for using this method is that standard statistical or topographical data do not cover all actual changes in green space, as topographical datasets do not exist for each year and land-change research requires up-to-date data. Satellite remote sensing does, however, capture every little change in land use, thus say Giezen et al. (2018). They exemplified their results in two maps as presented in Figure 3.

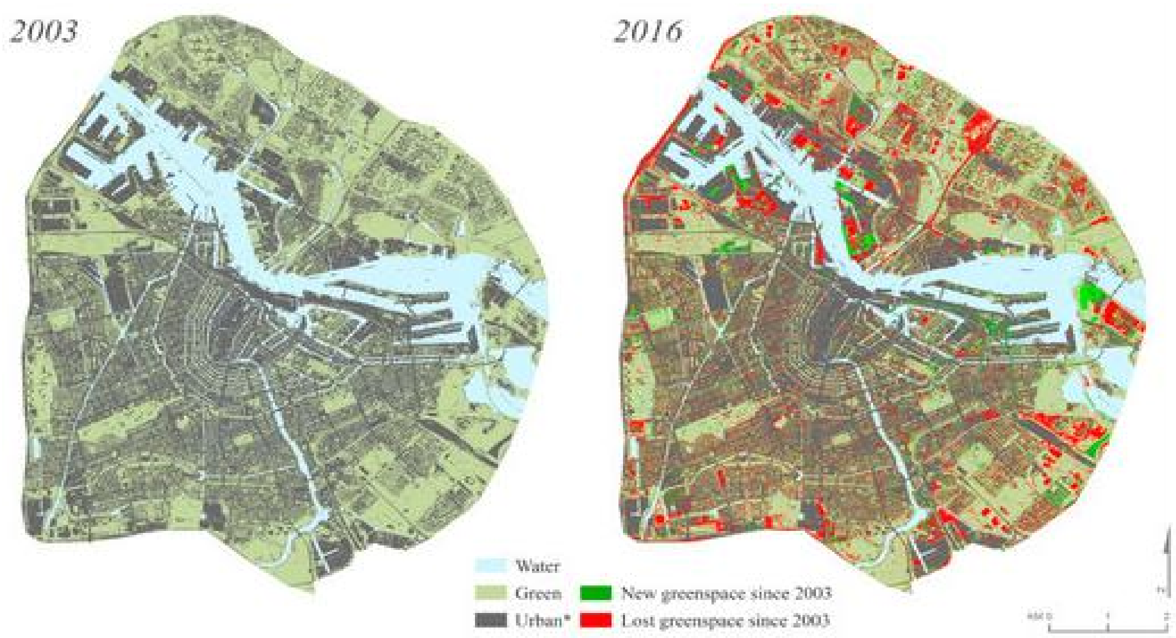

Figure 3: Land use change within Amsterdam city ring between 2003-2016 (Giezen et al., 2018).

While their research offers an interesting insight into the loss of green spaces in Amsterdam, multiple improvements to their study are possible. The first one is that since their most recent satellite image is from 2016, it shows no insight into the present course of policy outcomes in Amsterdam. The study by Giezen et al. (2018) also lacks a distinction between different types of urban green that are lost, and different types of built-up that green was replaced with. This additional analysis is necessary since loss of, for example, recreational parks is far more influential to the urban environment than the loss of construction sites that can in an NDVI analysis also be classified as green. Almost all new built-up will therefore be at the expense of green. What would provide additional and more comprehensive information on the loss of green space, is to know if the lost UGS are public or private. The accessibility of UGS affects who can benefit from the environmental and social advantages and therefore has added value to include.

Similar research on urban land use change from vegetation to built-up was performed in the UK by Dallimer et al. (2011). In their research, they first used Landsat Thematic Mapper data with a resolution of 30 by 30 meters to assess large temporal changes in land use, such as the expansion of housing estates. Thereafter, they used moderate-resolution (the exact resolution is not specified) imaging spectroradiometer Enhanced Vegetation Index (EVI) data between 2000 and 2008 to allow for more precise monitoring of small-scale land use change, such as the removal of street trees. They used both monitoring methods to be able to distinguish between large surface land use change and loss of street green. Combining these two analyses, they monitored land use change in 13 British cities. Although it is difficult to prove a causal correlation between land use change and densification, their results were similar to those of Giezen et al. (2018), in stating that UGS decreased because the cities densified due to population increase.

The research of Byomkesh et al. (2011) documented the spatial-temporal dynamics of UGS in Dhaka, Bangladesh with the help of satellite images. They enhanced their research by trying to determine the drivers of land use change in additional fieldwork with interviews, expert discussions, and observational techniques. Their results were that green space in Dhaka decreased by 20.4% in just 13 years, due to a significant increase in population and lack of policy due to poor political motivation and management.

A study that does not research land use change, but does research the division between public and private UGS is by Pristeri et al. (2021). In their paper, they propose that an additional focus on private green on top of public green would be beneficial in terms of adding ecosystem services through the provision of UGS. For that reason, they did an NDVI analysis and in addition to that classified the property status of the monitored UGS in the Italian city Padua. In their case, private green spaces represented 80% of UGS within the municipality.

3.5 Value of the research

Apart from Giezen et al. (2018) who researched land use change within the city ring, and a consecutive paper researching land use change in the whole municipality by Baliçi et al. (2022), similar studies on the metropolitan area of Amsterdam are thus far non-existing. As expressed before, there are opportunities for improvement in their research by enhancing satellite data with topographical data to make a distinction between different types of greenspace that is lost, and different types of built-up that it is replaced by. Similar data fusions are common in research concerning land classification (Iacobucci et al., 2020; Luoto et al., 2002; Saadat et al., 2008), and have also been used for land-use change detection in urban areas (Mallupattu & Sreenivasula Reddy, 2013). Harris and Ventura recommend in their paper from 1995 the data fusion of satellite data with other data types to improve both the specificity and accuracy of land-use classification. Since a land use change analysis of this kind has not been performed in Amsterdam, it is important to step in on this research gap by adding to previous land use change monitoring methods.

Further developing this research field is important to evaluate the effectiveness of sustainable and climate adaptation improving land use policies. When urban planners want to implement either or both greening and densification, they need to be aware of the consequences of such ideas in the past. This would stimulate them to pay extra attention to the negative trade-offs, which avoids reaching policy goals. On top of that, the results of land use changes, as mapped in my thesis research, could be extrapolated and simulated to show what the result would be if the current course of policy making resulting in the loss of UGS would be continued. All of which is necessary to achieve the desired outcomes of the policies that are aimed at decreasing the climate vulnerability of a growing number of urban citizens worldwide, making this research of both academic and social importance.

4. Methodology

4.1 Data

The first part of the research is aimed at developing an enhanced dataset of the division of urban green and built-up in the inner city ring (A10 ring road) of Amsterdam. For this dataset, remotely sensed imagery data, classified based on NDVI values, is combined with the official topographic map of the Netherlands of 2022; the BGT (Kadaster, 2022.). The BGT will distinguish what types of land use have been lost over the years and what new land use lost UGS have turned into.

The satellite images are obtained from the Netherlands Space Office (2022). Table 1 summarizes all information on the used satellite data. This satellite imagery is cut to the inner city ring of Amsterdam.

Table 1: Satellite images information

Acquisition date	**Satellite**	**Bands used**	**Resolution**	**Image**
06/07/2017	TripleSat	NIR Red Green Blue	0.8 m	
23/06/2022 11/08/2022	SuperView-1	NIR Red Green Blue	0.5 m	

For the land use change detection, the resolution of the 2022 satellite data, which currently is 0.5 meters, is converted to that of the 2017 data, of 0.8 meters. Both satellite images must have the same pixel size so the comparison will lead to a more accurate detection of temporal change in land use (Balikçi et al., 2021; Du et al., 2002).

4.2 Detecting land use change

First, since the satellite images from 2022 are taken on two separate dates, the values of the different layers are normalized. Then the Normalized Difference Vegetation Index (NDVI) of each satellite layer is calculated. This remote sensing method is different from what is done in the study by Giezen et al. (2018). However, calculating the NDVI is a more common method of vegetation classification and is more often used in other studies to classify vegetation from satellite images to detect changes (Usman et al., 2015; Yasin et al., 2022). By trial and error and carefully cross-checking the vegetation on the satellite image, the threshold value that corresponds with the detected vegetation is determined. This value is for the 2017 image -0.05 and for the 2022 image 0.6. After this, the UGS from both years are combined in one layer. This layer shows what parts remained UGS, where UGS were lost, and where UGS were added.

There are multiple pixels that were isolated from pixels in the same category. This hinted at misclassification. These isolated pixels were discarded, just like what was done in the research by Giezen et al. (2018). Areas with less than a diameter of 1.6 meters of the categories non-green, green, new green, or lost green were filtered out. This could have led to a loss of valuable information on, for example, the loss of single street trees, which still provide environmental value to neighborhoods. However, the risk of misclassification of these areas was more likely.

Following the satellite NDVI review, the 44 land use categories that are in the initial BGT dataset are classified into 9 more comprehensive categories (see Figure 4 and see Table 2. A table with the classification per initial BGT category can be found in Annex 1).

Table 2: Reclassified land-use categories from the BGT.

Number	**Reclassified category**	**Includes BGT categories**	**Land use function**
1	Informal UGS	Sand, bare terrain	UGS
2	Private UGS	Agriculture, gardens, allotment gardens	UGS
3	Public UGS	Bushes, green verges, grass, forests	UGS
4	Residences	Houses, balconies, canopies	Built-up
5	Industry	Bassins, warehouse, storage tanks	Built-up
6	Public transport infrastructure	Train rails, public transport roads	Built-up
7	Walking/cycling infrastructure	Bicycle lanes, pedestrian areas, sidewalks	Built-up
8	Car infrastructure	Car roads, highway, parking space	Built-up
9	Water	Watercourse, water surface	Water

Figure 4: BGT reclassification

The vegetation categories were chosen to distinguish between informal, and formal UGS. Moreover, the analysis of whether the lost green is publicly or privately accessible is important to assess because the type of green space has an effect on the extent that citizens can benefit from them (Jennings et al., 2012). Both land use types provide environmental benefits, but the social and health implications are different depending on proximity to accessible UGS (Bolund & Hunhammar, 1999).

The built-up categories were chosen because the total infrastructure category makes up 27.7% of all land use in 2022. Therefore it is interesting to provide supplementary insight into what types of infrastructure took over the lost green spaces. This has implications for the goals of the AEV, in which it is described that Amsterdam wants to become a car-free city and that green has to replace space that is currently designated for cars. Water cannot be classified under vegetation or built-up, and it is not important for this research to distinguish between different types of water.

The BGT dataset used in this analysis shows the land use division in the year 2022. This is the same year as the last year of the satellite data used for the remote sensing land use change analysis in this study. This means that the BGT allows to distinguish which land use class has replaced the monitored UGS loss. When for example the land use change analysis shows that a specific area of UGS is lost between 2017 and 2022, and according to the BGT this area is in 2022 residential, it can be concluded that UGS is lost to build new residences. If a small patch of UGS within a larger area of one type of UGS is lost, it can be assumed that the lost green was in 2017 the same type as its surrounding area in 2022. This allows assumptions about what type of green space has been lost. Fragmented loss of green can be distinguished on the map, but can however not be separately assessed from the statistics derived from this study. Therefore, the statistics cannot provide accurate insight into the type of land use that is lost in 2015.

To demonstrate the change in land use, a pixel-by-pixel comparison of land use is performed. All steps that are taken to conduct my research can be reviewed in the flowchart as seen in Figure 5.

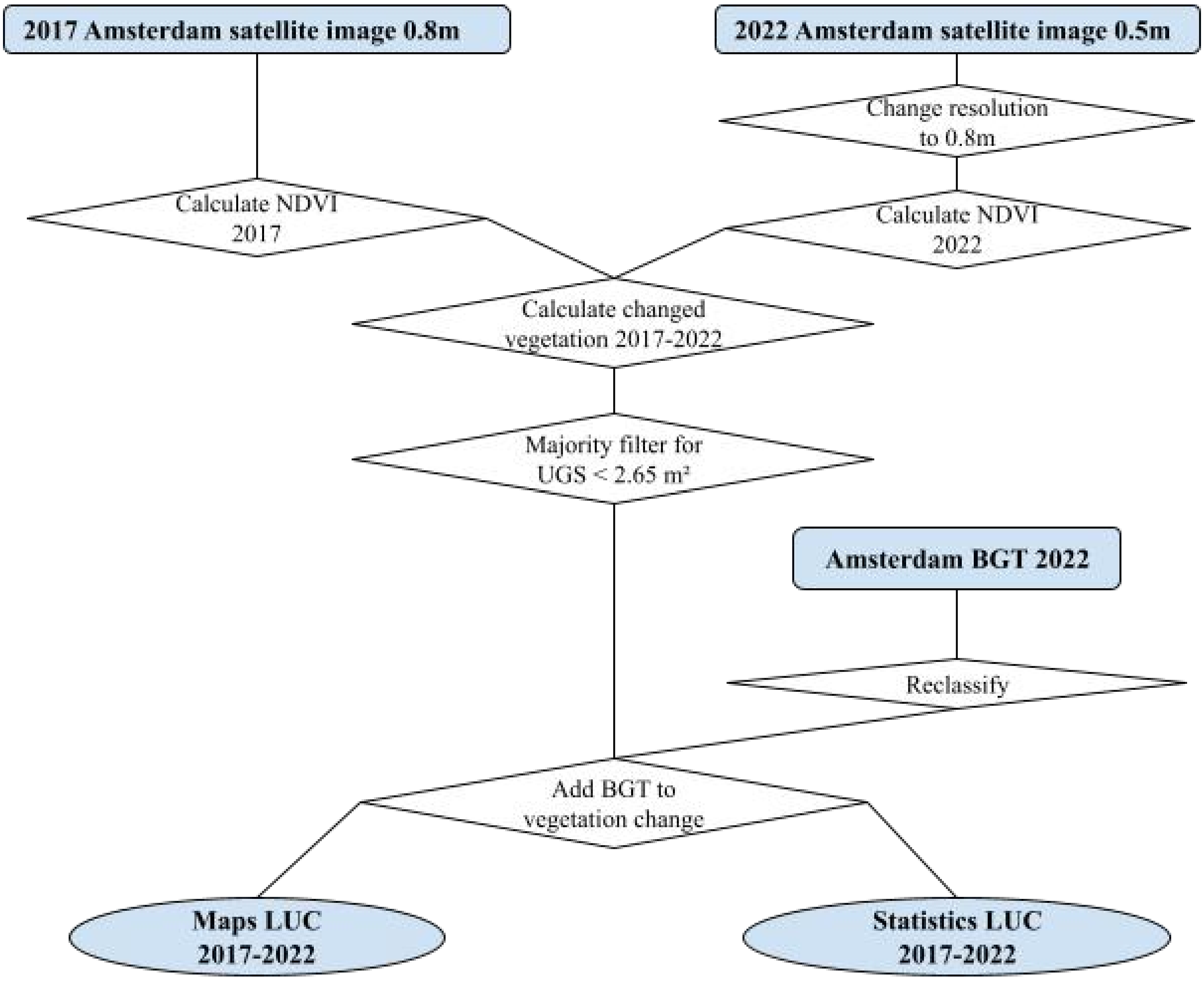

Figure 5: Flowchart with the data and steps of the spatial analysis of this research

5. Results

5.1 Results in maps

Figure 6 represents the monitored land use change within the inner city ring of Amsterdam. This map presents the three UGS categories (Public, Private and Informal), and the land uses water in blue, and built-up in gray. Red presents in this map the loss of green space and orange is new green space.

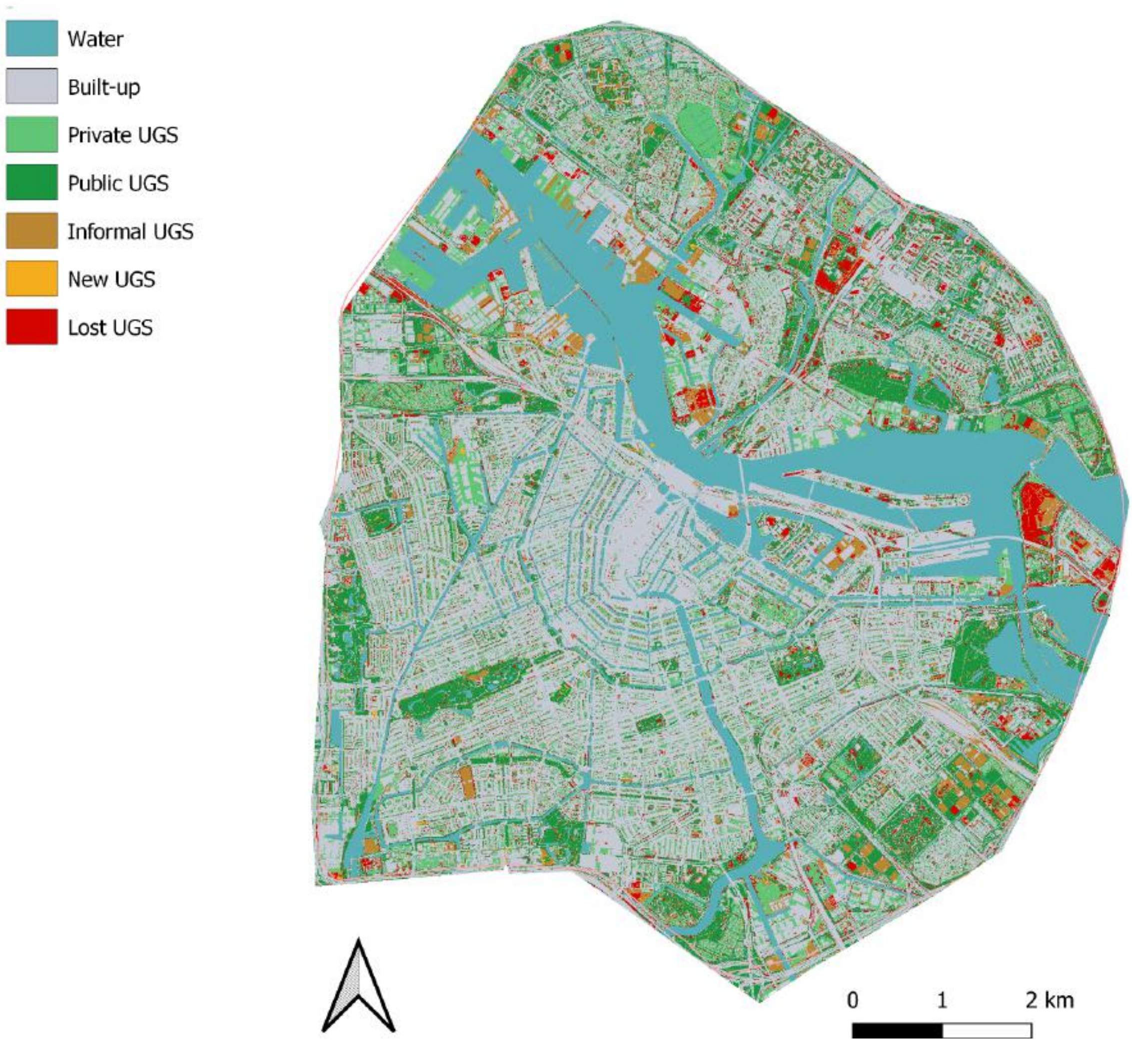

Figure 6: Change in urban green spaces within the Amsterdam city ring.

Data was obtained from satellietdataportaal.nl (Netherlands Space Office, 2022) and the Basisregistratie Grootschalige Topografie (Kadaster, n.d.). All calculations were made by the author.

The land use change is scattered across the map. There are multiple small patches of lost vegetation as well as new green spaces. Some of these scattered pieces could possibly be attributed to inaccurate classification due to inexact NDVI values. Another explanation for this fragmented change is that densification is often achieved by establishing new buildings in previous open spots, or by expanding existing buildings (Haaland & van den Bosch, 2015). When zooming in on the map, it becomes visible that equally as much of the fragmented change can be attributed to public UGS as to private UGS. Change in informal UGS is however not fragmented. Informal UGS sites are either completely lost, or have not changed.

There is also a shift in multiple larger green areas. It is notable that this is mainly present in Amsterdam Noord above the IJ and in the harbor neighborhood in Amsterdam West. This change was expected as these are the areas within the city ring that are rapidly changing and developing (Gemeente Amsterdam, n.d.-a; Gemeente Amsterdam, n.d.-c).

Also, Zeeburgereiland shows many changes in vegetation. It is only since 2010 that this island part of the city is being developed as a residential area (Gemeente Amsterdam - Stadsdeel Oost, 2014). For that reason, the island has been under construction between 2017 and 2022, explaining the large changes in land use. According to the website of the municipality (n.d.-d), there are plans to double the number of inhabitants on the island in the coming years. This will likely result in more change in vegetation.

Also the parks in Amsterdam exhibit a change in vegetation. This is mainly the case for Sportpark Middenmeer and Sportpark Drieburg in Amsterdam East, where many sports fields are located. The shape of the changed land use indicates that sports fields are both being added and removed. Some of the sports fields close to the train rail in Amsterdam East are from soccer club Zeeburgia, which stated on its website that some of their grass soccer fields would be replaced with artificial grass, which explains part of some of the lost vegetation in that area (Zeeburgia, 2016).

In the city center along the canal belt, there is very little change in vegetation. The reason for this could be that this part of Amsterdam has a protected Unesco world heritage status (Gemeente Amsterdam, n.d.-b). Changes in Unesco areas that do not comply with the core values of Unesco could lead to a loss of Unesco status (Simons, 2021). This leads to a situation in which each new urban development plan should be carefully considered before it is executed, limiting changes in these areas. Moreover, the city center area had by default little urban vegetation.

5.2 Results in statistics

In 2017, 38.59% of the area within the city ring of Amsterdam was vegetation. In 2022 this was 33.20%. Between 2017 and 2022, 6.24% of the area within the city ring lost green spaces. On 0.86% of the surface within the city ring UGS were added. This comes down to a total loss of 351.17 hectares. It means that 8.24% of the green spaces that existed in 2017 were lost in 5 years.

An important part of this research consisted of identifying not only where and if land use change within the city ring occurred, but also to more specifically define what type of UGS were lost and added. For this reason, topographical data from the BGT was added to the remotely sensed data. The BGT data used for this analysis is from 2022, which corresponds with the satellite data. This means that the categories describe what land use functions the lost UGS have turned into. The results can be read in Table 3.

Table 3: lost or added greenspace per category in hectares (ha) and percentages

	New green		Lost green		Change in green		Part of green spaces
	ha	%	ha	%	ha	%	%
Informal UGS	2.97	0.05	44.59	0.68	-41.61	-0.64	-0.98
Private UGS	10.35	0.16	88.23	1.35	-77.88	-1.19	-1.83
Public UGS	24.41	0.37	160.79	2.47	-136.38	-2.09	-3.20
Residences	2.79	0.04	18.67	0.29	-15.87	-0.24	-0.37
Industry	0.00	0.00	0.01	0.00	-0.01	0.00	0.00
Public transport infrastructure	0.18	0.00	2.94	0.05	-2.75	-0.04	-0.06
Walking/cycling infrastructure	4.89	0.07	45.35	0.70	-40.46	-0.62	-0.95
Car infrastructure	2.81	0.04	26.73	0.41	-23.92	-0.37	-0.56
Water	7.50	0.11	19.78	0.30	-12.28	-0.19	-0.29
Total	*55.91*	*0.86*	*407.08*	*6.24*	*-351.17*	*-5.39*	*-8.24*

As can be seen in Table 3, in all BGT categories green was lost. In sum, most green spaces are lost to what is in the BGT classified as infrastructure. This adds to a total of 1.63% of the area within the city ring, which is 67.14 hectares. 40.46 of these hectares were walking and cycling infrastructure and 23.92 hectares of greenspace turned into car infrastructure. The additional infrastructure is part of densification. In this case, we could state that UGS was lost because of a denser city. It is important to note that this loss of green space can also be caused by the removal of street trees, or because roadsides that used to be grown with informal vegetation are paved. This still would have been a loss of UGS for the benefit of infrastructure, but it could mean that not all UGS were directly replaced by new infrastructure.

15.87 hectares of green spaces were lost to build new residences, which is in line with the densification urban planning approach. 255.87 hectares of green space that were lost became, according to the BGT informal UGS, public UGS, or private UGS. This statistic hints at a misclassification of green areas within the BGT. The BGT is drawn in straight large blocks. Vegetation on the other hand is, as earlier mentioned, often fragmented. When cross-checking the larger vegetated areas that were ‘replaced’ by UGS on the satellite images, it became apparent that it was indeed the case that public vegetated areas were lost to construction sites that were not in the NDVI analysis of 2022 classified as UGS. Next to that, it became evident that the original BGT category ‘onbegroeidterreindeel: erf’ (bare terrain yard) consisted of both vegetated areas and non-vegetated areas. For that reason, vegetation that was lost in that category does in fact mean that valuable private UGS are lost.

The category that represents most of the new green space is public green. In total 24.4 hectares of new public green have appeared within the city ring. These changes to public UGS are very fragmented over parks and roadsides. This could mean that the trees in the parks have grown, or that the aim of the municipality to replace tiles with green has been pursued (2021, p. 56). However, also for the category public UGS, more vegetation was lost than added between 2017 and 2022.

6. Discussions

6.1 Implications of findings

The results of this study indicate that densification and greening policies did contradict in Amsterdam between 2017 and 2022. Densification aims by the municipality of Amsterdam were achieved at the expense of their greening aims. For all categories distinguished in this research, a loss of green was found.

Judging from the surrounding areas of the fragmented UGS change, and the land use change statistics, it can be concluded that this loss of green spaces consists of informal UGS and formal public and private green spaces. The formal categories mainly consist of actual vegetation like trees, (public or allotment) gardens, and parks and are therefore compared to informal UGS more valuable in terms of mental, and physical well-being and environmental advantages.

Whereas the loss of public and private green is mainly fragmented, the loss of informal UGS is not. This is probably because informal UGS consist mainly of construction sites that have been between 2017 and 2022 either constructed with new built-up, or have remained unbuilt. The aim of the municipality is to improve the quality of UGS, instead of the quantity in areas where UGS development is constrained by densification (Gemeente Amsterdam, 2020, p. 5; Gemeente Amsterdam, 2021, p. 56). Therefore the loss of informal green is a less important loss to the municipality. The fragmented loss of public and private UGS however is. The municipality has expressed aims to supply more fragmented 'post-stamp parks', so that all residences are supplied with some green in their near neighborhood (Gemeente Amsterdam, 2020, p. 45). Losing 'post-stamp sized' pieces of parks is therefore the opposite of what is intended

In the AEV it is described how the municipality would like to make the city car-free and to make use of the space this provides by adding additional green to the streets. This analysis however showed that in previous years 23.92 hectares of green space have been lost for new car infrastructure, hinting that the opposite has been achieved. Even more greenspace has been lost to walking or cycling infrastructure. This is in line with what is described in the Greenvision as the concept 'Green, unless' (2020, p. 33). The municipality states that it will try to replace tiles and asphalt with green in each project or initiative unless other functions make this impossible. The examples that are named for these 'unless' areas are pedestrian areas, bicycle roads, and public transport (p. 38). As these types of infrastructure are essential for making the city car-free. Green is less important than these types of land use according to the municipality, and therefore this land use change is in line with what they want.

There are also other effects of the land use change. The loss of informal and formal green spaces resulted in densification, which has its own environmental and social advantages. The added infrastructure of 76.66 hectares enables faster and more efficient transport. The 15.87 hectares of new residences accommodate many citizens in times of a housing crisis. Between 2017 and 2022, the population of Amsterdam increased from 844,947 to 882,633 citizens (AlleCijfers.nl, 2023). This is an increase of 4.5%. The residential space within the city ring grew by 1.59%. This means that some of the new residences were accommodated within the city ring of Amsterdam. Because this growth took place in an already densely populated area, these residences can enjoy all the positive effects of densification such as more efficient public transport, the possibility to travel by bike, and lower heating costs. All of these benefits of densification lead to a reduced environmental footprint. However, due to the UHI effect and the reduced wind speed that is more prevalent in densely built regions, air conditioning costs can increase in summer.

From the literature review, I can conclude that where densification only has greenhouse gas-reducing sustainability advantages, greening the city has on top of that also many social, health, and climate change adaptation advantages. Therefore the municipality of

Amsterdam wants to combine the two urban planning advantages as expressed in their Greenvision (2021). The Greenvision states that 'urban challenges' must not come at the expense of green space and its quality (p. 5). This research has proven that their attempts to do so between 2017 and 2022 have failed. Densification has replaced both private and public urban green spaces. The lost UGS are mainly formal (-214.26 ha of the total -255,87 ha), and more specifically public UGS (-136.36 ha). These are according to the literature review and the municipality the most valuable types of urban green spaces as they are accessible to all and therefore provide social and environmental benefits for everyone. For that reason, in order to achieve the goals the municipality has set for itself for 2050, it must rethink the current course of policy outcomes and use these findings in new urban planning projects. At least as much green as is taken should be given back to the city. But, since Amsterdam has expressed the goal to become a greener city than it is now, additional green is preferred.

6.2 Comparison to similar studies

The results of this study are very similar to those of Giezen et al. (2018). Their findings were that between 2003 and 2016, in 13 years time, within the Amsterdam city ring, 11% of UGS were lost. This was according to them a loss of 500 to 600 hectares of UGS. This study is a follow-up on that research and found that between 2017 and 2022, in 5 years time, 8.24% of UGS were lost. This is equivalent to a loss of 351 hectares.

What is worrying is that when these statistics are compared it can be concluded that the trend of reduction in UGS has not only continued, but that it is also happening more rapidly. An 11% decrease in 13 years implies an average loss of 0.85%, or 50 hectares per year. The findings of this study show a trend of 1.65%, or 70 hectares of lost green space per year. If the discovered rate of UGS-loss of Giezen et al. would have continued, all UGS in Amsterdam would be lost in 2102. If the rate discovered in this research would continue, this will be in 2077. Since the rate of UGS loss has increased, this can mean that this can even worsen in the future if insufficient action is taken.

If Figure 3, the results of Giezen et al. their research, and Figure 6, the results of this paper, are compared, there are some strong similarities. In both results, Zeeburgereiland is primarily colored red and orange, indicating it has been under development from 2003 until 2022. In the results from Giezen et al., there are also some changes in Sportpark Middenmeer and Sportpark Drieburg, indicating that grass fields are being replaced by artificial grass fields. They state about this in their discussion that the municipality sees artificial grass sports fields as 'recreational' green, whereas an NDVI analysis does not, providing additional insights into this loss of actual vegetated green. In this research, change in sports fields falls under the category of informal UGS, which is how the implications of the loss of sport field green can be separately assessed.

In both results, most developments took place in Amsterdam Noord and the harbor area in Amsterdam West. A difference between the results is that in this research the changes are more fragmented. This could be because there is less unbuilt space available for big land use change projects between 2017 and 2022 than there was between 2003 and 2016, and therefore expansion of built-up has primarily happened through infill development, which is common in western cities according to Haaland & van den Bosch (2015).

The results of this study can also be compared to similar land use change studies in different cities, like in British cities by Dallimer et al. (2011), and Dhaka, Bangladesh by Byomkesh et al. (2011). Compared to those cities, the results of this research are similar in that densification increased and urban green spaces were lost.

The part of the results of this study in which a distinction is made between the loss of different types of UGS that are replaced with different forms of urban built-up cannot be compared to the study by Giezen et al. (2018), or another study. This is due to the fact that similar studies where additional information through the enhancement of satellite data with topographical data thus far does not exist in other cities.

6.3 Limitations

Although the results of this study are in line with earlier and similar research, there are some limitations to the study that could have changed parts of the results. One is the use of NDVI for the remote sensing of satellite images. Although this is a method that is more often used for similar research projects (Usman et al., 2015; Yasin et al., 2022), classification based on the NDVI can result in some errors. Based on the NDVI scores ranging from -1 to 1, a choice has to be made between what the boundary value is between green and non-green. However, some green areas might have a score below this boundary and are therefore not included in the analysis. One example of this is urban green overshadowed by trees, because of the difference in the position of the sun in both images. This can be seen in the results in Figure 6 at the borders of larger UGS. The same applies to shadows of built-up. However, shifting the boundary value of the NDVI to include shadows could result in more misclassification because more built-up will then be classified as UGS. Although shadows on the satellite image of one year are outweighed by shadows on the image from the other year, and therefore will not have significantly influenced the statistics, this misclassification would preferably be avoided for more accurate results. A way to circumvent this problem is to use the semi-automated classification plugin tool and train it on training sites from different types of land use. This is also what Giezen et al (2018) did in their research.

Another limitation of the remote sensing analysis performed in this research is that the majority filter heavily influenced the results. For a sensitivity analysis, a second analysis was executed to see how the results would differ if no majority filter was applied. Without filtering out the land use change of less than 2.65 m^2, the results would have been that

21.81% of UGS would have been lost, which is a total of 631.95 hectares. As this number is implausibly high, it can be concluded that it was necessary to filter out small UGS. However, this also means that if a different minimum radius would have been chosen, this would have affected the results significantly. For this reason, another sensitivity analysis was done to see how the results would change if all areas of less than 16 m^2 would have been discarded. This would have resulted in 310.31 hectares of lost green space, which is 11.29%. These values are closer to the results of this study, indicating that discarding larger areas has less effect, then not filtering the results at all.

Although the BGT is one of the most accurate, up-to-date topographical datasets available on the Netherlands, the BGT land use classes are not as precise as land use classified by remote sensing. Combining both methods allows to reduce the limitations of using solely one of the two datasets, and allows benefitting from the advantages of both. Small misclassifications by the BGT became apparent when the results implied that green had been lost and replaced with UGS categories. To reclassify the initial BGT categories, it was difficult to make a decision whether some categories belonged to the class built-up or UGS. This was for example the case with category 9 'yard' (see Annex), which consisted of both a paved yard and a vegetated yard. It was decided to include this category in the private UGS class. This allowed the monitoring of the loss of private vegetated yards. However, it also resulted in a higher percentage of overall green within the city ring in both years, which could have slightly influenced the statistics derived from that.

Next to that, because only the BGT from 2022 had been used, no credible conclusions could be drawn on what type of UGS had been lost. It could be assumed that the lost green that is in the 2022 BGT classified as private green used to also be private in 2017. However, no reliable conclusions can be drawn from this. This study could be improved by enhancing the satellite data from both years with the consecutive year of BGT data, or CBS land statistics and then analyzing the transitions in land use.

Another limitation of this study is the generalizability to other cities, because of the historic city core of Amsterdam. This concern was also expressed by Giezen et al. (2018). Densification can happen in two ways, through infill, or high-rise development (Haaland & van den Bosch, 2015). Because the city center of Amsterdam is Unesco world heritage, high-rise development is off the table and most densification happens by infill. In areas outside of the city ring, this is not the case, leaving sufficient space for green development, as well as densification. This study can therefore not be generalized to the full city of Amsterdam. However, it could present useful insights for other cities with a historic core. This lack of generalizability also does not detract from the use of this study for the municipality of Amsterdam specifically, which has explicitly expressed its aim to prevent urban developments within the city ring at the expense of green, as is discovered by this spatial analysis.

In future research, limitations to this study can be avoided. Moreover, it would be interesting to perform this study on the full municipality of Amsterdam, to detect how densification and greening policies interact outside the city ring. It would also be enriching to look more specifically at the goals of the municipality of Amsterdam in terms of the quality of UGS development and monitor changes in that aspect.

This study could be compared to similar studies in other cities to see how differences in policy have resulted in different outcomes. Mendel Giezen, one of the authors of the initial paper this research is based on, also contributed to a study on a comparison of green space lost in Amsterdam and Brussels (Balikçi et al., 2021). With a similar land use change analysis of Brussels between 2015 and 2022, this research could provide a follow-up on that research too.

7. Conclusion

This research demonstrates that in the previous 5 years, densification policies of the municipality of Amsterdam have resulted in a loss of urban green spaces in the city ring of Amsterdam. Urban green spaces are an essential part of urban areas. They provide multiple social effects improving the well-being of urban citizens. They offer space for recreation, resulting in more social cohesion and promote positive health effects. The proximity to and availability of green spaces matter in the extent to which they provide benefits. Where public UGS provide benefits for all citizens, the positive effects of private UGS can only be enjoyed by a few.

Apart from social effects, there are also many environmental benefits to UGS. They reduce heat, which decreases energy consumption in summer, mitigate air pollution, take up CO_2, reduce rainwater runoff, and contribute to the biodiversity in the city. Despite the added values to cities, UGS are under the threat of densification. Densification also has many positive effects, such as more efficient transport which contributes to a reduction in car use and better health of citizens, and reduced energy consumption. To benefit from both planning methods, the municipality of Amsterdam wants to combine them. They therefore repeatedly state in their Environmental Vision that urban development must not come at the expense of UGS development.

This research aimed to monitor to what extent different forms of urban development in Amsterdam had resulted in a loss of different types of urban green spaces between 2017 and 2022. By monitoring the change in urban green spaces through calculating the NDVI of satellite images, this study demonstrates that the current aims of the municipality have not been met in previous years. Additional insights into the changing land use were added by including topographical data of the BGT in the land use change analysis. This allowed showing that urban green had been replaced by mainly walking and cycling infrastructure and new residences. In total, 8.24% of UGS within the city ring of Amsterdam were lost. This comes down to a total loss of 351.17 hectares. When the rate of loss of UGS is compared to the succeeded study by Giezen et al., it can be concluded that the rate of loss of UGS has increased over the last 5 years.

Studies in which land use policy outcomes are holistically monitored are essential for awareness within the municipality's urban planning departments, which leads to more effective green-protecting policies. This study can therefore contribute to more sustainable and climate-adaptable city planning, increasing the livability of the future city of Amsterdam.

8. References

Akbari, H. (2002). Shade trees reduce building energy use and CO2 emissions from power plants. *Environmental Pollution*, *116*, S119–S126. https://doi.org/10.1016/s0269-7491(01)00264-0

AlleCijfers.nl. (2023, April 6). *Statistieken gemeente Amsterdam*. AlleCijfers.nl. https://allecijfers.nl/gemeente/amsterdam/

Alvarsson, J. J., Wiens, S., & Nilsson, M. E. (2010). Stress Recovery during Exposure to Nature Sound and Environmental Noise. *International Journal of Environmental Research and Public Health*, *7*(3), 1036–1046. https://doi.org/10.3390/ijerph7031036

Amsterdams Stadsarchief. (2019, April 23). *AUP*. Amsterdam.nl/Stadsarchief. https://www.amsterdam.nl/stadsarchief/stukken/plannen/aup/

Aronson, M. F. J., La Sorte, F. A., Nilon, C. H., Katti, M., Goddard, M. A., Lepczyk, C. A., Warren, P. S., Williams, N. S. G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J. L., Kühn, I., MacGregor-Fors, I., McDonnell, M., Mörtberg, U., & Pyšek, P. (2014). A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1780), 20133330. https://doi.org/10.1098/rspb.2013.3330

Aronson, M. F., Lepczyk, C. A., Evans, K. L., Goddard, M. A., Lerman, S. B., MacIvor, J. S., Nilon, C. H., & Vargo, T. (2017). Biodiversity in the city: Key Challenges for Urban Green Space Management. *Frontiers in Ecology and the Environment*, *15*(4), 189–196. https://doi.org/10.1002/fee.1480

Balikçi, S., Giezen, M., & Arundel, R. (2021). The paradox of planning the compact and green city: analyzing land-use change in Amsterdam and Brussels. *Journal of*

Environmental Planning and Management, 1–25. https://doi.org/10.1080/09640568.2021.1971069

Basagaña, X., Triguero-Mas, M., Agis, D., Pérez, N., Reche, C., Alastuey, A., & Querol, X. (2018). Effect of public transport strikes on air pollution levels in Barcelona (Spain). *Science of the Total Environment*, *610-611*, 1076–1082. https://doi.org/10.1016/j.scitotenv.2017.07.263

Bell, M. L., Morgenstern, R. D., & Harrington, W. (2011). Quantifying the human health benefits of air pollution policies: Review of recent studies and new directions in accountability research. *Environmental Science & Policy*, *14*(4), 357–368. https://doi.org/10.1016/j.envsci.2011.02.006

Beninde, J., Veith, M., & Hochkirch, A. (2015). Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation. *Ecology Letters*, *18*(6), 581–592. https://doi.org/10.1111/ele.12427

Berghauser Pont, M. Y., Perg, P. G., Haupt, P. A., & Heyman, A. (2020). A systematic review of the scientifically demonstrated effects of densification. *IOP Conference Series: Earth and Environmental Science*, *588*, 052031. https://doi.org/10.1088/1755-1315/588/5/052031

Bernardini, C., & Irvine, K. N. (2007). The “nature” of urban sustainability: private or public greenspaces?. *Sustainable Development and Planning III*, *102*(3), 661–674. https://doi.org/10.2495/SDP070642

Bibri, S. E. (2020). Advances in Compact City Planning and Development: Emerging Practices and Strategies for Balancing the Goals of Sustainability. In M. Amer (Ed.), *Advances in Science, Technology & Innovation*. Cham Springer. https://doi.org/10.1007/978-3-030-41746-8_3

Blok, S., Gunnel-Joyce, C., & Zordan, B. (2022). *The Urban Heat Island Effect in Amsterdam The Netherlands*.

Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics*, *29*(2), 293–301. https://doi.org/10.1016/s0921-8009(99)00013-0

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, *97*(3), 147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006

Breuste, J., Schnellinger, J., Qureshi, S., & Faggi, A. (2013). Urban Ecosystem services on the local level: Urban green spaces as providers. *Ekologia*, *32*(3). https://doi.org/10.2478/eko-2013-0026

Brunner, J., & Cozens, P. (2013). “Where Have All the Trees Gone?” Urban Consolidation and the Demise of Urban Vegetation: A Case Study from Western Australia. *Planning Practice and Research*, *28*(2), 231–255. https://doi.org/10.1080/02697459.2012.733525

Buyantuyev, A., & Wu, J. (2009). Urban heat islands and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. *Landscape Ecology*, *25*(1), 17–33. https://doi.org/10.1007/s10980-009-9402-4

Byomkesh, T., Nakagoshi, N., & Dewan, A. M. (2011). Urbanization and green space dynamics in Greater Dhaka, Bangladesh. *Landscape and Ecological Engineering*, *8*(1), 45–58. https://doi.org/10.1007/s11355-010-0147-7

Centraal Bureau voor de Statistiek. (2022). *Inwoners per gemeente*. CBS.nl. https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/regionaal/inwoners

Coolen, H., & Meesters, J. (2011). Private and public green spaces: meaningful but different settings. *Journal of Housing and the Built Environment*, *27*(1), 49–67. https://doi.org/10.1007/s10901-011-9246-5

Costanza, R. (1998). The value of ecosystem services. *Ecological Economics*, *25*(1), 1–2. https://doi.org/10.1016/s0921-8009(98)00007-x

Dallimer, M., Tang, Z., Bibby, P. R., Brindley, P., Gaston, K. J., & Davies, Z. G. (2011). Temporal changes in greenspace in a highly urbanized region. *Biology Letters*, *7*(5), 763–766. https://doi.org/10.1098/rsbl.2011.0025

Davies, R. G., Barbosa, O., Fuller, R. A., Tratalos, J., Burke, N., Lewis, D., Warren, P. H., & Gaston, K. J. (2008). City-wide relationships between green spaces, urban land use and topography. *Urban Ecosystems*, *11*(3), 269–287. https://doi.org/10.1007/s11252-008-0062-y

Dehghani, A., Alidadi, M., & Sharifi, A. (2022). Compact Development Policy and Urban Resilience: A Critical Review. *Sustainability*, *14*(19), 11798. https://doi.org/10.3390/su141911798

Du, Y., Teillet, P. M., & Cihlar, J. (2002). Radiometric normalization of multitemporal high-resolution satellite images with quality control for land cover change detection. *Remote Sensing of Environment*, *82*(1), 123–134. https://doi.org/10.1016/s0034-4257(02)00029-9

Dzhambov, A. M., & Dimitrova, D. D. (2014). Urban green spaces′ effectiveness as a psychological buffer for the negative health impact of noise pollution: A systematic review. *Noise and Health*, *16*(70), 157. https://doi.org/10.4103/1463-1741.134916

Fan, P., Xu, L., Yue, W., & Chen, J. (2017). Accessibility of public urban green space in an urban periphery: The case of Shanghai. *Landscape and Urban Planning*, *165*, 177–192. https://doi.org/10.1016/j.landurbplan.2016.11.007

Feltynowski, M., Kronenberg, J., Bergier, T., Kabisch, N., Łaszkiewicz, E., & Strohbach, M. W. (2018). Challenges of urban green space management in the face of using inadequate data. *Urban Forestry & Urban Greening*, *31*(09), 56–66. https://doi.org/10.1016/j.ufug.2017.12.003

Folsom, A. R., Kushi, L. H., & Hong, C. P. (2000). Physical activity and incident diabetes mellitus in postmenopausal women. *American Journal of Public Health*, *90*(1), 134–138. https://doi.org/10.2105/ajph.90.1.134

Gemeente Amsterdam. (n.d.-a). *Centrumgebied Amsterdam Noord: nieuw stedelijk centrum*. Amsterdam.nl. https://www.amsterdam.nl/projecten/centrumgebied-amsterdam-noord/

Gemeente Amsterdam. (n.d.-b). *Grachtengordel Amsterdam Werelderfgoed*. Amsterdam.nl. Retrieved May 31, 2023, from https://www.amsterdam.nl/kunst-cultuur/grachtengordel-werelderfgoed/

Gemeente Amsterdam. (n.d.-c). *Haven-Stad: herontwikkeling gebied*. Amsterdam.nl. Retrieved November 6, 2020, from https://www.amsterdam.nl/projecten/haven-stad/

Gemeente Amsterdam. (n.d.-d). *Zeeburgereiland: nieuwe stadswijk aan het water*. Amsterdam.nl. https://www.amsterdam.nl/projecten/zeeburgereiland/

Gemeente Amsterdam. (2020). Groenvisie 2020-2050 - Een leefbare stad voor mens en dier. In Directie Ruimte en Duurzaamheid (Ed.), *amsterdam.nl*. https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/groen/

Gemeente Amsterdam . (2021, July 8). *Omgevingsvisie 2050 - een menselijke metropool* (F. van den Beuken, Ed.). Https://Amsterdam2050.Nl/; Gemeente Amsterdam. https://amsterdam2050.nl/wp-content/uploads/2021/09/Omgevingsvisie-Amsterdam-2050_Hoge-resolutie_20210906.pdf

Gemeente Amsterdam - Stadsdeel Oost. (2014, August 13). *Zeeburgereiland - Stadsdeel Oost*. Web.archive.org. https://web.archive.org/web/20140813053432/http://www.oost.amsterdam.nl/buurten-0/ijburg/zeeburgereiland/

Giezen, M., Balikci, S., & Arundel, R. (2018). Using Remote Sensing to Analyse Net Land-Use Change from Conflicting Sustainability Policies: The Case of Amsterdam. *ISPRS International Journal of Geo-Information*, *7*(9), 381. https://doi.org/10.3390/ijgi7090381

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environment*, *33*(1), 115–133. https://doi.org/10.2148/benv.33.1.115

Givoni, B. (1991). Impact of planted areas on urban environmental quality: A review. *Atmospheric Environment. Part B. Urban Atmosphere*, *25*(3), 289–299. https://doi.org/10.1016/0957-1272(91)90001-u

Gold, J. R., Haughton, G., & Hunter, C. (1996). Sustainable Cities. *Economic Geography*, *72*(1), 104. https://doi.org/10.2307/144514

Gössling, S. (2020). Why Cities Need to Take Road Space from Cars - and How This Could Be Done. *Journal of Urban Design*, *25*(4), 1–6. https://doi.org/10.1080/13574809.2020.1727318

Grêt-Regamey, A., Celio, E., Klein, T. M., & Wissen Hayek, U. (2013). Understanding ecosystem services trade-offs with interactive procedural modeling for sustainable urban planning. *Landscape and Urban Planning*, *109*(1), 107–116. https://doi.org/10.1016/j.landurbplan.2012.10.011

Gupta, K., Kumar, P., Pathan, S. K., & Sharma, K. P. (2012). Urban Neighborhood Green Index – A measure of green spaces in urban areas. *Landscape and Urban Planning*, *105*(3), 325–335. https://doi.org/10.1016/j.landurbplan.2012.01.003

Haaland, C., & van den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening*, *14*(4), 760–771. https://doi.org/10.1016/j.ufug.2015.07.009

Hall, P. (1999). Sustainable Cities or Town Cramming. *RSA Journal*, *148*, 72–81.

Hanson, H. I., Eckberg, E., Widenberg, M., & Alkan Olsson, J. (2021). Gardens' contribution to people and urban green space. *Urban Forestry & Urban Greening*, *63*, 127198. https://doi.org/10.1016/j.ufug.2021.127198

Harris, P., & Ventura, S. (1995). The integration of geographic data with remotely sensed imagery to improve classification in urban areas. *Photogrammetric Engineering and Remote Sensing*, *61*(8), 993–998.

Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., & Gärling, T. (2003). Tracking restoration in natural and urban field settings. *Journal of Environmental Psychology*, *23*(2), 109–123. https://doi.org/10.1016/s0272-4944(02)00109-3

Hoornweg, D., Sugar, L., & Trejos Gómez, C. L. (2011). Cities and greenhouse gas emissions: moving forward. *Environment and Urbanization*, *23*(1), 207–227. https://doi.org/10.1177/0956247810392270

Iacobucci, G., Troiani, F., Milli, S., Mazzanti, P., Piacentini, D., Zocchi, M., & Nadali, D. (2020). Combining Satellite Multispectral Imagery and Topographic Data for the Detection and Mapping of Fluvial Avulsion Processes in Lowland Areas. *Remote Sensing*, *12*(14), 2243. https://doi.org/10.3390/rs12142243

Irga, P. J., Braun, J. T., Douglas, A. N. J., Pettit, T., Fujiwara, S., Burchett, M. D., & Torpy, F. R. (2017). The distribution of green walls and green roofs throughout Australia: Do policy instruments influence the frequency of projects? *Urban Forestry & Urban Greening*, *24*, 164–174. https://doi.org/10.1016/j.ufug.2017.03.026

Ives, C. D., Lentini, P. E., Threlfall, C. G., Ikin, K., Shanahan, D. F., Garrard, G. E., Bekessy, S. A., Fuller, R. A., Mumaw, L., Rayner, L., Rowe, R., Valentine, L. E., & Kendal, D. (2015). Cities are hotspots for threatened species. *Global Ecology and Biogeography*, *25*(1), 117–126. https://doi.org/10.1111/geb.12404

Jenks, M., Williams, K., & Burton, E. (2000). *Achieving sustainable urban form* (p. 8). E & Fn Spon.

Jennings, V., Johnson Gaither, C., & Gragg, R. S. (2012). Promoting Environmental Justice Through Urban Green Space Access: A Synopsis. *Environmental Justice*, *5*(1), 1–7. https://doi.org/10.1089/env.2011.0007

Jensen, R. R., & Gatrell, J. D. (2009). Energy, Population and the Urban Canopy: An Integrated GIScience Approach Towards Modeling Human-Environmental Interactions. *Journal of Human Ecology*, *26*(3), 185–189. https://doi.org/10.1080/09709274.2009.11906180

Jim, C. Y., & Chen, W. Y. (2006). Perception and Attitude of Residents Toward Urban Green Spaces in Guangzhou (China). *Environmental Management*, *38*(3), 338–349. https://doi.org/10.1007/s00267-005-0166-6

Jorgensen, A., Hitchmough, J., & Calvert, T. (2002). Woodland spaces and edges: their impact on perception of safety and preference. *Landscape and Urban Planning*, *60*(3), 135–150. https://doi.org/10.1016/s0169-2046(02)00052-x

Kabisch, N., & Haase, D. (2013). Green spaces of European cities revisited for 1990–2006. *Landscape and Urban Planning*, *110*(110), 113. https://doi.org/10.1016/j.landurbplan.2012.10.017

Kadaster. (n.d.). *Basisregistratie Grootschalige Topografie (BGT)*. Www.kadaster.nl. Retrieved March 1, 2023, from https://www.kadaster.nl/zakelijk/registraties/basisregistraties/bgt

Keke, L., Zhengguang, W., Zhiping, L., Aihong, K., Chengsheng, Y., & Xueling, X. (2018). Improvement of Rainwater Infiltration Property and Its Effect on the Corresponding Storage Capacity of Soil in Urban Green Space. *E3S Web of Conferences*, *53*, 04044. https://doi.org/10.1051/e3sconf/20185304044

Kemperman, A., & Timmermans, H. (2014). Green spaces in the direct living environment and social contacts of the aging population. *Landscape and Urban Planning*, *129*, 44–54. https://doi.org/10.1016/j.landurbplan.2014.05.003

Koomen, E., & Diogo, V. (2015). Assessing potential future urban heat island patterns following climate scenarios, socio-economic developments and spatial planning strategies. *Mitigation and Adaptation Strategies for Global Change*, *22*(2), 287–306. https://doi.org/10.1007/s11027-015-9646-z

Kuang, W., Liu, Y., Dou, Y., Chi, W., Chen, G., Gao, C., Yang, T., Liu, J., & Zhang, R. (2014). What are hot and what are not in an urban landscape: quantifying and explaining the land surface temperature pattern in Beijing, China. *Landscape Ecology*, *30*(2), 357–373. https://doi.org/10.1007/s10980-014-0128-6

Kuo, F. E., Bacaicoa, M., & Sullivan, W. C. (1998). Transforming Inner-City Landscapes. *Environment and Behavior*, *30*(1), 28–59. https://doi.org/10.1177/0013916598301002

Kweon, B.-S., Sullivan, W. C., & Wiley, A. R. (1998). Green Common Spaces and the Social Integration of Inner-City Older Adults. *Environment and Behavior*, *30*(6), 832–858. https://doi.org/10.1177/001391659803000605 le Clercq, F., & de Vries, J. S. (2000). Public Transport and the Compact City. *Transportation Research Record: Journal of the Transportation Research Board*, *1735*(1), 3–9. https://doi.org/10.3141/1735-01

Lehberger, M., Kleih, A.-K., & Sparke, K. (2021). Self-reported well-being and the importance of green spaces – A comparison of garden owners and non-garden owners in times of COVID-19. *Landscape and Urban Planning*, *212*, 104108. https://doi.org/10.1016/j.landurbplan.2021.104108

Lepczyk, C. A., Aronson, M. F. J., Evans, K. L., Goddard, M. A., Lerman, S. B., & MacIvor, J. S. (2017a). Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. *BioScience*, *67*(9), 799–807. https://doi.org/10.1093/biosci/bix079

Lepczyk, C. A., Aronson, M. F. J., Evans, K. L., Goddard, M. A., Lerman, S. B., & MacIvor, J. S. (2017b). Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. *BioScience*, *67*(9), 799–807. https://doi.org/10.1093/biosci/bix079

Leung, D. Y. C., Tsui, J. K. Y., Chen, F., Yip, W.-K., Vrijmoed, L. L. P., & Liu, C.-H. (2011). Effects of Urban Vegetation on Urban Air Quality. *Landscape Research*, *36*(2), 173–188. https://doi.org/10.1080/01426397.2010.547570

Limsombunc, V., Gan, C., & Lee, M. (2004). House Price Prediction: Hedonic Price Model vs. Artificial Neural Network. *American Journal of Applied Sciences*, *1*(3), 193–201. https://doi.org/10.3844/ajassp.2004.193.201

Lin, B. B., Ossola, A., Alberti, M., Andersson, E., Bai, X., Dobbs, C., Elmqvist, T., Evans, K. L., Frantzeskaki, N., Fuller, R. A., Gaston, K. J., Haase, D., Jim, C. Y., Konijnendijk, C., Nagendra, H., Niemelä, J., McPhearson, T., Moomaw, W. R., Parnell, S., & Pataki,

D. (2021). Integrating solutions to adapt cities for climate change. *The Lancet Planetary Health*, *5*(7), e479–e486. https://doi.org/10.1016/S2542-5196(21)00135-2

Loibl, W., Vuckovic, M., Etminan, G., Ratheiser, M., Tschannett, S., & Österreicher, D. (2021). Effects of Densification on Urban Microclimate—A Case Study for the City of Vienna. *Atmosphere*, *12*(4), 511. https://doi.org/10.3390/atmos12040511

Luoto, M., Toivonen, T., & Heikkinen, R. K. (2002). Prediction of total and rare plant species richness in agricultural landscapes from satellite images and topographic data. *Landscape Ecology*, *17*(3), 195–217. https://doi.org/10.1023/a:1020288509837

Mallupattu, P. K., & Sreenivasula Reddy, J. R. (2013). Analysis of Land Use/Land Cover Changes Using Remote Sensing Data and GIS at an Urban Area, Tirupati, India. *The Scientific World Journal*, *2013*, 1–6. https://doi.org/10.1155/2013/268623

Manson, J. E., Greenland, P., & LaCroix, A. Z. (2003). Walking compared with vigorous exercise for the prevention of cardiovascular events in women. *ACC Current Journal Review*, *12*(1), 29. https://doi.org/10.1016/s1062-1458(02)01010-3

Massink, R., Zuidgeest, M., Rijnsburger, J., Sarmiento, O. L., & van Maarseveen, M. (2011). The Climate Value of Cycling. *Natural Resources Forum*, *35*(2), 100–111. https://doi.org/10.1111/j.1477-8947.2011.01345.x

Mathey, J., Rößler, S., Lehmann, I., & Bräuer, A. (2011). Urban Green Spaces: Potentials and Constraints for Urban Adaptation to Climate Change. *Resilient Cities*, 479–485. https://doi.org/10.1007/978-94-007-0785-6_47

Matos, P., Vieira, J., Rocha, B., Branquinho, C., & Pinho, P. (2019). Modeling the provision of air-quality regulation ecosystem service provided by urban green spaces using lichens as ecological indicators. *Science of the Total Environment*, *665*, 521–530. https://doi.org/10.1016/j.scitotenv.2019.02.023

Mohammadi, S., de Vries, B., Rafiee, A., Esfandiari, M., & Dias, E. (2021). An exploratory study on the impact of physical and geospatial characteristics of the urban built environment on the buildings annual electricity usage. *Journal of Building Engineering*, *40*, 102359. https://doi.org/10.1016/j.jobe.2021.102359

Morya, C. P., & Punia, M. (2021). Impact of urbanization processes on availability of ecosystem services in National Capital Region of Delhi (1992–2010). *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-021-01748-8

Netherlands Space Office. (2022). *Sateliet data portaal*. Satelietdataportaal.nl; Netherlands Space Office. https://www.satellietdataportaal.nl/?loc=52.39627%2C4.900452%2C9z&marker=loc&acqdate=2014-09-04&acqid=20140904_102342_Sp6%2C20140904_102426_Sp6&sensor=Spot6_7&base=brtachtergrondkaart&res=0.5%2C0.8%2C1.5&datemin=20-06-2012&datemax=02-03-2023

Niemelä, J., Saarela, S.-R., Söderman, T., Kopperoinen, L., Yli-Pelkonen, V., Väre, S., & Kotze, D. J. (2010). Using the ecosystem services approach for better planning and conservation of urban green spaces: a Finland case study. *Biodiversity and Conservation*, *19*(11), 3225–3243. https://doi.org/10.1007/s10531-010-9888-8

Okkels, N., Kristiansen, C. B., Munk-Jørgensen, P., & Sartorius, N. (2018). Urban mental health. *Current Opinion in Psychiatry*, *31*(3), 258–264. https://doi.org/10.1097/yco.0000000000000413

Pham, T.-T.-H., Apparicio, P., Séguin, A.-M., Landry, S., & Gagnon, M. (2012). Spatial distribution of vegetation in Montreal: An uneven distribution or environmental inequity? *Landscape and Urban Planning*, *107*(3), 214–224. https://doi.org/10.1016/j.landurbplan.2012.06.002

Pristeri, G., Peroni, F., Pappalardo, S. E., Codato, D., Masi, A., & De Marchi, M. (2021). Whose Urban Green? Mapping and Classifying Public and Private Green Spaces in Padua for Spatial Planning Policies. *ISPRS International Journal of Geo-Information*, *10*(8), 538. https://doi.org/10.3390/ijgi10080538

Rafiee, A., Dias, E., & Koomen, E. (2016). Local impact of tree volume on nocturnal urban heat island: A case study in Amsterdam. *Urban Forestry & Urban Greening*, *16*, 50–61. https://doi.org/10.1016/j.ufug.2016.01.008

Rafiee, A., Dias, E., & Koomen, E. (2019). Analysing the impact of spatial context on the heat consumption of individual households. *Renewable and Sustainable Energy Reviews*, *112*, 461–470. https://doi.org/10.1016/j.rser.2019.05.033

Richardson, E. A., Pearce, J., Mitchell, R., & Kingham, S. (2013). Role of physical activity in the relationship between urban green space and health. *Public Health*, *127*(4), 318–324. https://doi.org/10.1016/j.puhe.2013.01.004

Rupprecht, C. D. D., & Byrne, J. A. (2014). Informal urban greenspace: A typology and trilingual systematic review of its role for urban residents and trends in the literature. *Urban Forestry & Urban Greening*, *13*(4), 597–611. https://doi.org/10.1016/j.ufug.2014.09.002

Saadat, H., Bonnell, R., Sharifi, F., Mehuys, G., Namdar, M., & Ale-Ebrahim, S. (2008). Landform classification from a digital elevation model and satellite imagery. *Geomorphology*, *100*(3-4), 453–464. https://doi.org/10.1016/j.geomorph.2008.01.011

Sakieh, Y., Jaafari, S., Ahmadi, M., & Danekar, A. (2017). Green and calm: Modeling the relationships between noise pollution propagation and spatial patterns of urban structures and green covers. *Urban Forestry & Urban Greening*, *24*, 195–211. https://doi.org/10.1016/j.ufug.2017.04.008

Simons, V. (2021, August). *Ruimtelijke ontwikkelingen binnen Unesco Werelderfgoed: wat is mogelijk?* Must. https://www.must.nl/blog/ruimtelijke-ontwikkelingen-binnen-unesco-werelderfgoed-wat-is-mogelijk/

Simpson, J. R. (2002). Improved estimates of tree-shade effects on residential energy use. *Energy and Buildings*, *34*(10), 1067–1076. https://doi.org/10.1016/s0378-7788(02)00028-2

Smardon, R. C. (1988). Perception and aesthetics of the urban environment: Review of the role of vegetation. *Landscape and Urban Planning*, *15*(1-2), 85–106. https://doi.org/10.1016/0169-2046(88)90018-7

Strohbach, M. W., Arnold, E., & Haase, D. (2012). The carbon footprint of urban green space—A life cycle approach. *Landscape and Urban Planning*, *104*(2), 220–229. https://doi.org/10.1016/j.landurbplan.2011.10.013

Strohbach, M. W., & Haase, D. (2012). Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. *Landscape and Urban Planning*, *104*(1), 95–104. https://doi.org/10.1016/j.landurbplan.2011.10.001

Tallis, M., Taylor, G., Sinnett, D., & Freer-Smith, P. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, *103*(2), 129–138. https://doi.org/10.1016/j.landurbplan.2011.07.003

Tanaka, A., Takano, T., Nakamura, K., & Takeuchi, S. (1996). Health Levels Influenced by Urban Residential Conditions in a Megacity—Tokyo. *Urban Studies*, *33*(6), 879–894. https://doi.org/10.1080/00420989650011645

Tappert, S., Klöti, T., & Drilling, M. (2018). Contested urban green spaces in the compact city: The (re-)negotiation of urban gardening in Swiss cities. *Landscape and Urban Planning*, *170*, 69–78. https://doi.org/10.1016/j.landurbplan.2017.08.016

Uebel, K., Marselle, M., Dean, A. J., Rhodes, J. R., & Bonn, A. (2021). Urban green space soundscapes and their perceived restorativeness. *People and Nature*, *3*(3), 756–769. https://doi.org/10.1002/pan3.10215

Ulrich, R. (1984). View through a window may influence recovery from surgery. *Science*, *224*(4647), 420–421.

United Nations, Department of Economic and Social Affairs, Population Division. (2019). *4 World Urbanization Prospects: The 2018 Revision* (ST/ESA/SER.A/420 ed., pp. 4, 19). United Nations.

Usman, M., Liedl, R., Shahid, M. A., & Abbas, A. (2015). Land use/land cover classification and its change detection using multi-temporal MODIS NDVI data. *Journal of Geographical Sciences*, *25*(12), 1479–1506. https://doi.org/10.1007/s11442-015-1247-y

van Hove, L. W. A., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., van Driel, B. L., & Holtslag, A. A. M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment*, *83*, 91–103. https://doi.org/10.1016/j.buildenv.2014.08.029

Williams, J. (2019). Circular cities. *Urban Studies*, *56*(13), 2746–2762. https://doi.org/10.1177/0042098018806133

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities "just green enough." *Landscape and Urban Planning*, *125*, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017

Woodcock, J., Banister, D., Edwards, P., Prentice, A. M., & Roberts, I. (2007). Energy and transport. *The Lancet*, *370*(9592), 1078–1088. https://doi.org/10.1016/s0140-6736(07)61254-9

Yang, Z., Song, Q., Li, J., Zhang, Y., Yuan, X.-C., Wang, W., & Yu, Q. (2021). Air pollution and mental health: the moderator effect of health behaviors. *Environmental Research Letters*, *16*(4), 044005. https://doi.org/10.1088/1748-9326/abe88f

Yasin, M. Y., Abdullah, J., Noor, N. M., Yusoff, M. M., & Noor, N. M. (2022). Landsat observation of urban growth and land use change using NDVI and NDBI analysis. *IOP Conference Series: Earth and Environmental Science*, *1067*(1), 012037. https://doi.org/10.1088/1755-1315/1067/1/012037

Zeeburgia. (2016, July 15). *Hoofdveld Zeeburgia wordt versneld kunstgras - AVV Zeeburgia*. Www.zeeburgia.nl. https://www.zeeburgia.nl/1/404/hoofdveld-zeeburgia-wordt-versneld-kunstgras/

Zhang, B., Xie, G., Zhang, C., & Zhang, J. (2012). The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China. *Journal of Environmental Management*, *100*, 65–71. https://doi.org/10.1016/j.jenvman.2012.01.015

Zhang, W., Lu, D., Chen, Y., & Liu, C. (2021). Land use densification revisited: Nonlinear mediation relationships with car ownership and use. *Transportation Research Part D: Transport and Environment*, *98*, 102985. https://doi.org/10.1016/j.trd.2021.102985

Zhou, X., & Parves Rana, M. (2012). Social benefits of urban green space. *Management of Environmental Quality: An International Journal*, *23*(2), 173–189. https://doi.org/10.1108/14777831211204921

Zhou, X., & Wang, Y.-C. (2011). Spatial–temporal dynamics of urban green space in response to rapid urbanization and greening policies. *Landscape and Urban Planning*, *100*(3), 268–277. https://doi.org/10.1016/j.landurbplan.2010.12.013

Zhu, Z., Lang, W., Tao, X., Feng, J., & Liu, K. (2019). Exploring the Quality of Urban Green Spaces Based on Urban Neighborhood Green Index—A Case Study of Guangzhou City. *Sustainability*, *11*(19), 5507. https://doi.org/10.3390/su11195507

9. Annex

9.1 Reclassified categories based on the BGT.

Innitial number	Attribute name	Reclassified category	Reclassified number
6	gebouwinstallatie: bordes	Residences	4
7	gebouwinstallatie: luifel	Residences	4
8	gebouwinstallatie: toegangstrap	Residences	4
9	onbegroeidterreindeel: erf	Private UGS	2
10	onbegroeidterreindeel: gesloten verharding	Informal UGS	1
11	onbegroeidterreindeel: half verhard	Informal UGS	1
12	onbegroeidterreindeel: onverhard	Informal UGS	1
13	onbegroeidterreindeel: open verharding	Informal UGS	1
15	onbegroeidterreindeel: zand	Informal UGS	1
17	begroeidterreindeel: bouwland	Informal UGS	1
20	begroeidterreindeel: grasland agrarisch	Private UGS	2
21	begroeidterreindeel: grasland overig	Public UGS	3
22	begroeidterreindeel: groenvoorziening	Public UGS	3
26	begroeidterreindeel: loofbos	Public UGS	3
27	begroeidterreindeel: moeras	Public UGS	3
29	begroeidterreindeel: rietland	Public UGS	3
30	begroeidterreindeel: struiken	Public UGS	3
33	ondersteunendwaterdeel: oever, slootkant	Public UGS	3

36	ondersteunendwegdeel: berm	Public UGS	3
37	ondersteunendwegdeel: verkeerseiland	Car infrastructure	8
45	bouwwerk_overig: bassin	Industry	5
46	bouwwerk_overig: lage trafo	Industry	5
48	bouwwerk_overig: overkapping	Public transport infrastructure	6
49	bouwwerk_overig: open loods	Industry	5
52	bouwwerk_overig: windturbine	Industry	5
53	bouwwerk_overig: opslagtank	Industry	5
55	bouwwerk_overig: niet-bgt	Industry	5
57	pand: woongebied	Residences	4
62	waterdeel: waterloop	Water	9
63	waterdeel: watervlakte	Water	9
67	wegdeel : OV-baan	Public transport infrastructure	6
68	wegdeel : fietspad	Walking/cycling infrastructure	7
69	wegdeel : inrit	Car infrastructure	8
70	wegdeel : parkeervlak	Car infrastructure	8
71	wegdeel : rijbaan lokale weg	Car infrastructure	8
72	wegdeel : rijbaan regionale weg	Car infrastructure	8
74	wegdeel : voetgangersgebied	Walking/cycling infrastructure	7

75	wegdeel : voetpad	Walking/cycling infrastructure	7
76	wegdeel : voetpad op trap	Walking/cycling infrastructure	7
77	wegdeel : woonerf	Residences	4
78	wegdeel : spoorbaan	Public transport infrastructure	6
79	wegdeel : rijbaan autoweg	Car infrastructure	8
80	wegdeel : overweg	Car infrastructure	8
81	wegdeel : rijbaan autosnelweg	Car infrastructure	8
82	wegdeel : baan voor vliegverkeer	Car infrastructure	8