A Spatial Assessment of the Interplay Between Green Space, Climate, and Socioeconomic Dimensions in Amsterdam

Anika M. Wittenberg, S4798074

Campus Fryslân, University of Groningen

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Dr. Carol Garzón López

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Abstract

It is well known that green spaces play a crucial role in urban areas, offering many benefits to residents and the environment alike. This study explores the dynamics between green space characteristics, climate change, and socioeconomic aspects in the boroughs of Amsterdam. A GIS-based approach was used to investigate the distribution of green spaces and predicted temperature anomalies according to climate change scenarios. Then, a Pearson correlation and principal component analysis were employed to explore the interplay between green spaces, predicted temperature anomalies, and the socioeconomic backgrounds of residents. The findings demonstrated that the west of Amsterdam is predicted to warm the most. Strong positive correlations were identified between population and temperature changes as well as traffic and temperature changes. Little to no correlation was found between income and health in relation to the predicted temperature increases. Income and health also showed mostly negative correlations with green space characteristics. Green space size indicated a strong negative correlation with temperature increases, followed by quality, while the correlation with the number of green spaces was weakly positive. This research reveals that the current green space characteristics across Amsterdam's boroughs do not align with the anticipated changes in temperature. These temperature changes are expected to reinforce existing inequalities in some boroughs and create new challenges in others that currently have few social inequalities.

Keywords: green spaces, climate change, temperature increase, socioeconomic, inequalities, cities, interdisciplinary.

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The global urban population has risen significantly over the last century. Currently, more than half of the Earth's population lives in cities (UN-Habitat, 2022). This trend is predicted to continue, with 68% of the population expected to live in urban areas by 2050 (United Nations, 2019). However, urbanisation is becoming a critical issue as it poses various environmental, social, and economic challenges. Urban growth often leads to increased pollution and temperatures in cities which negatively impact the environment and the residents' quality of life (Chapman et al., 2017). Cities also have high demands for water, energy, and other resources, which can lead to the overexploitation and depletion of these resources. Furthermore, overcrowding and inadequate infrastructure strain cities' capacities to provide essential services, resulting in social inequality, health issues, and higher crime rates (X. Q. Zhang, 2016). This is often compounded by insufficient urban planning and governance, which not only makes it difficult to manage these impacts effectively but also further reinforces these issues (UN-Habitat, 2022).

The climate crisis and its impacts are already being felt in urban areas globally with effects and risks spreading across different sectors and also affecting the well-being of residents. However, at the same time, cities are not just at risk but also drivers of these climatic and ecological changes (Maxwell et al., 2018). While urbanisation itself does not contribute much to global temperature changes, it intensifies local land surface warming (Zhou et al., 2022). For example, urban heat islands (UHIs) are a phenomenon in which cities are warmer than adjacent rural areas. Several factors contribute to this, some of these being the high thermal mass emitted by concrete and asphalt surfaces, the restricted ventilation capacity created by tall buildings, and the compounding impact of heat emissions from vehicles and air conditioning (Akbari et al., 2015). Studies have predicted that the UHI effect will likely increase by 50% to 200% by the year 2100 (Zhou et al., 2022). However, these increasing temperatures are not evenly distributed within cities. The UHI is usually stronger in urban centres than peripheral areas (Chen et al., 2022; X. Li et al., 2019). This intra-urban variation may also lead to different effects of heat stress on different demographic and socioeconomic groups. Extreme heat has the greatest impact on the urban poor and underprivileged communities (Chakraborty et al., 2019). These local consequences are expected to worsen with future warming trends and further exacerbate socioeconomic vulnerabilities (Naheed & Eslamian, 2022), creating feedback loops.

Amidst these challenges, urban green spaces play an important role as a nature-based solution. They enhance the overall well-being of urban residents while simultaneously improving urban resilience to the climate crisis through their ecosystem services. Ecosystem services are defined as the advantages that humans derive from ecosystems, including resources, environmental regulation, cultural enrichment, and the intrinsic value of ecosystems themselves (Secretariat of the Convention on Biological Diversity, 2004). For example, green space benefits also include improving air quality and absorbing pollutants, contributing to UHI mitigation and microclimate regulation, providing habitats, and promoting biodiversity (Aram et al., 2019; Cheung et al., 2022; Hobbie & Grimm, 2020; Naeem et al., 2018; Zölch et al., 2016). Additionally, they also serve as communal gathering spaces, foster social cohesion, provide opportunities for recreational activities, reduce stress levels, and improve mental health and the overall quality of life for urban residents (Cheng et al., 2019; Dickinson & Hobbs, 2017; Jennings & Bamkole, 2019; Kondo et al., 2018; Kosanic & Petzold, 2020).

But these very green spaces face threats due to urbanisation, land use changes, invasive species, and inadequate maintenance along with the increasing effects of climate change such as heatwaves, droughts, and floods (Kruize et al., 2019; Whitmee et al., 2015). They pose significant challenges to the sustainability and resilience of these spaces. While there is an encompassing body of literature that recognises the critical role that green spaces play in urban environments and covers how they can help with climate change adaptation and mitigation, this mostly focuses on temporal rather than spatial scales (Graça et al., 2022). While there have been some studies into the triangular connection between socioeconomic, climate, and green space or vegetation factors (Chang et al., 2024; Dobbs et al., 2017; W. Zhang et al., 2021), these did not consider intra-urban differences. That is why this research aims to provide a case study that examines variations in green space distribution and their associations with climate change and socioeconomic backgrounds on a borough level in Amsterdam. This will be examined by answering the following research question:

How do green space characteristics, scenarios of climate change, and urban residents' socioeconomic backgrounds interact spatially to shape the future of Amsterdam?

Climate change in this case does not refer to the overall extent and magnitude of climate change impacts in Amsterdam. Instead, it only refers to rising temperatures to address a specific and measurable variable of climate change that directly impacts urban residents' daily lives. This is also because there has not been a lot of research on temperature changes in Amsterdam yet (Golroudbary et al., 2018). Ultimately, the goal of this research is twofold: to provide insights that help understand the complex relationships of the compounded vulnerabilities and interconnected challenges of climate change and socioeconomic disparities in Amsterdam, and to inform urban planning and policy decisions to make Amsterdam a more sustainable, resilient, and equitable city.

After providing contextual information that explains the reasons why Amsterdam was chosen as a case study and defines terms such as borough and green space, the methodology is outlined. It describes and justifies the approaches that were taken for the analyses of green spaces, temperature anomalies, socioeconomic indicators, and their correlations. The results section presents findings from each of these analyses, shedding light on the state of green spaces, climate patterns, and socioeconomic conditions in Amsterdam separately, and then reveals how they are correlated. After that, the spatial variation in temperature increases, the role of green space characteristics on temperature mitigation and socioeconomic backgrounds, and the relationship between socioeconomic vulnerabilities and rising temperatures are discussed. Possible explanations for these correlations are given. Finally, recommendations for Amsterdam and urban areas worldwide as well as recommendations for further research are made and limitations are explained.

Contextual Background

Case Study – Amsterdam

Figure 1. *Map of Central Amsterdam. Green represents green spaces, blue represents water, and grey represents grey infrastructure (modified from European Environment Agency (2021)).*

With a population of 918,117 in 2023 (Statista, 2023b), Amsterdam is a medium-sized city in Western Europe and serves as the capital of the Netherlands. It is also a city that is situated on low-lying land, with much of the city even built below sea level. This makes it particularly vulnerable to flooding and other climate-related risks such as storm surges and heavy rainfall events (Van der Hoeven & Wandl, 2014). The city's green spaces thus play a crucial role in mitigating these risks by absorbing water and reducing runoff, thereby helping to prevent flooding. Overall, the city's parks are distributed evenly throughout its urban fabric. Amsterdam features several large parks that are located centrally within the city, such as Vondelpark or Oosterpark (Figure 1).

Amsterdam's population density has been steadily increasing in recent years. It is the most densely populated city in the Netherlands, rising to 5,333 inhabitants per km² of land in

2023 (Statista, 2023a). High population density typically corresponds to increased urbanisation and development, leading to more impervious surfaces such as roads, buildings, and footpaths (Ramezani et al., 2021). These surfaces absorb and retain heat which exacerbates the UHI effect. Due to limited space available for development, densely populated cities like Amsterdam face challenges in preserving and expanding green areas.

Amsterdam is also part of the C40 Cities, a network of mayors around the world that are united in the attempt to combat the climate crisis (C40 Cities, 2024). This is relevant because as a member, Amsterdam has access to a wealth of resources, expertise, and best practices from other cities around the world. By actively engaging with the C40 network and participating in collaborative initiatives, Amsterdam demonstrates its leadership and commitment to addressing climate change and promoting sustainability. As a major international city, its experiences and lessons learned have global relevance.

Definitions

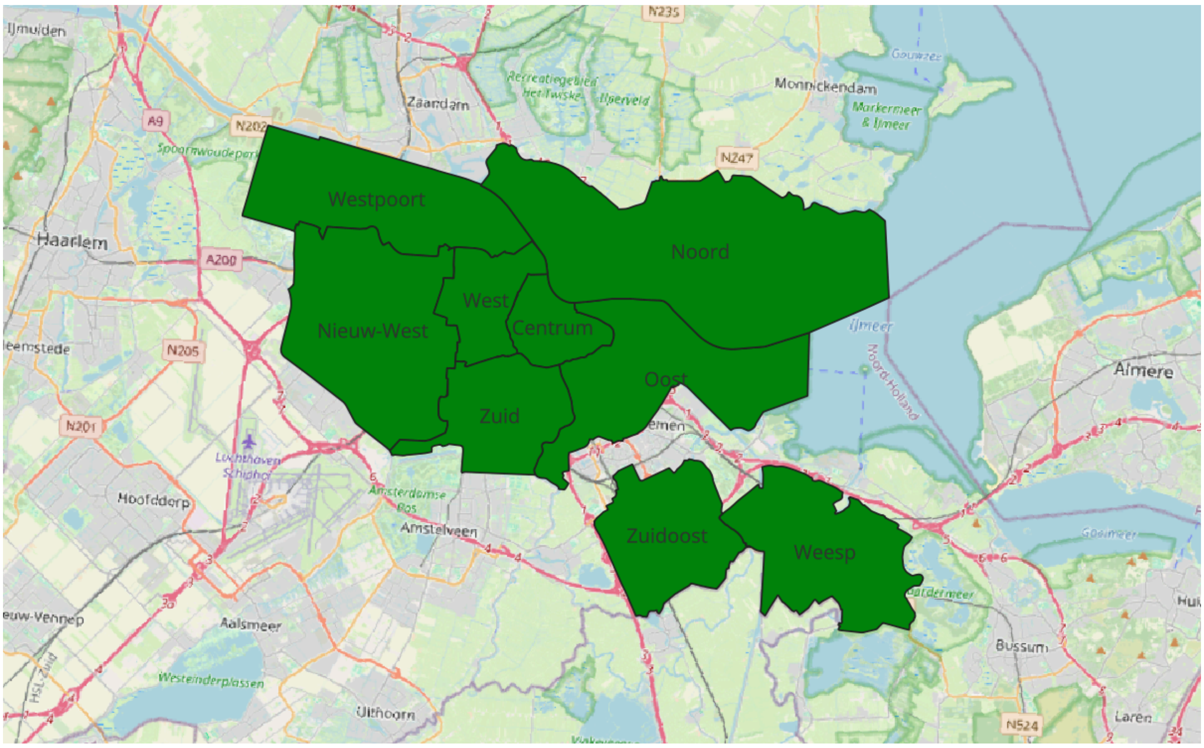

Figure 2. *The boroughs of Amsterdam (modified from Gemeente Amsterdam (2022a)).*

The analysis compares the nine boroughs of Amsterdam (Figure 2). These are the principal subdivisions of the municipality, known as *stadsdeel* (borough) and *stadsgebied* (city area). To ensure clarity and consistency, all subdivisions will be referred to as boroughs in this study. Apart from Westpoort and Weesp, they all have their own district committee that they are governed by (Gemeente Amsterdam, n.d.-b). Westpoort is sometimes not considered a *stadsdeel* or *stadsgebied* as it is an industrial area with just few inhabitants, meaning that it is governed directly by the municipality (Overheid.nl, 2024). Weesp is the only borough that is *stadsgebied* rather than a *stadsdeel* as it only joined the municipality of Amsterdam in 2022 (Gemeente Amsterdam, 2022b).

Green spaces are defined based on Taylor & Hochuli (2017). A green space is considered urban vegetation, usually relating to a vegetated variant of open space. This reflects a human influence and reliance on green spaces. Specifically, the following classifications are included in the definition: forests, green urban areas, herbaceous vegetation associations like natural grassland and moors, pastures, and wetlands. These were predefined by the European Environment Agency in the Urban Atlas Land Cover/Land Use data set (European Environment Agency, 2021). Pastures were added to include another type of diversity, as they are rich in biodiversity (Craft et al., 2022).

Methodology

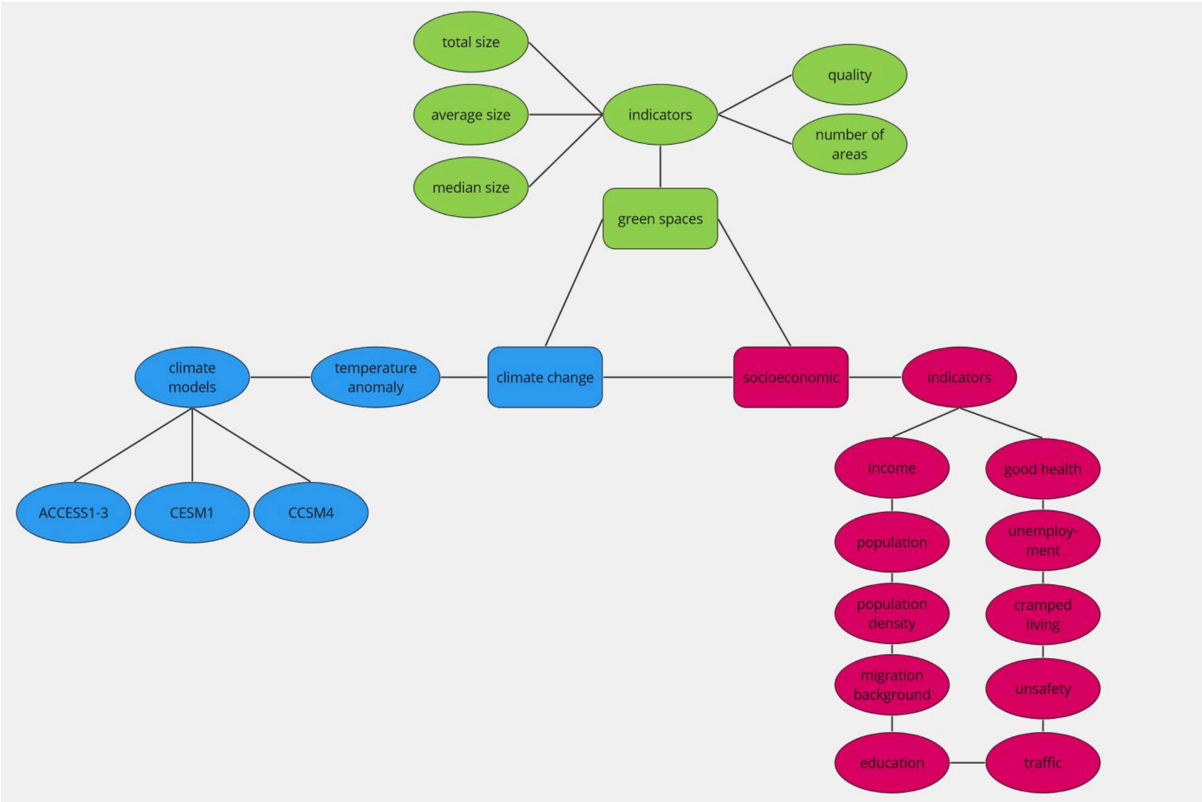

Figure 3. *Overview of indicators: Green space, climate change, and socioeconomic factors will be analysed for each borough of Amsterdam and cross-examined for correlations.*

Three separate analyses were carried out to gain an overview of green space, climate, and socioeconomic dimensions in Amsterdam. First, the green space characteristics of each borough were calculated, then temperature changes and their spatial distribution were computed, and finally, the socioeconomic profiles of each neighbourhood were analysed. Figure 3 visualises the three dimensions that were examined. The findings of these three analyses were then correlated with one another to examine the interplay between the dimensions.

Green Space Analysis

Green spaces in each borough were examined based on five indicators: number of green spaces, total green space area, average green space area, median green space area, and green space quality. The goal of using these indicators was to provide a comprehensive understanding of the green space landscape in each borough. All green space data were sourced from the Urban Atlas Land Cover/Land Use data set through Copernicus (European Environment Agency, 2021). The Urban Atlas data provide detailed information with high spatial resolution and follow standardised protocols and classification themes established by the European Environment Agency for land cover and land use mapping. The data were calculated based on the *INDELING_STADSDEEL* (borough division) data set by the *Onderzoek en Statistiek* (Research and Statistics) department of the municipality of Amsterdam (Gemeente Amsterdam, 2022a). To do this, the *Zonal Statistics* tool in *QGIS* 3.34 (QGIS.org, 2024) was used. The data on areas and numbers were calculated using pivot tables in Excel.

Green space quality was assessed through an index which was calculated by multiplying the total green space area of the borough and the diversity of types of areas. The diversity was calculated as a value between 0 and 1 according to a modified Simpson's Diversity Index, a metric commonly used to measure the diversity of species within a community. This approach allowed for the inclusion of the relevance of area size and diversity as a proxy of green space quality (Wu et al., 2022). In the following equation, *a* represents the total green space area, *A* the total borough area, *n* the number of green spaces per type *i*, and *N* the total number of green spaces per borough:

$$\text{green space quality index} = \left(\frac{a}{A}\right) \times \left(1 - \frac{\sum n_i(n_i - 1)}{N(N-1)}\right)$$

Climate Analysis

When analysing climate change in Amsterdam, temperature emerges as the most critical Essential Climate Variable (ECV) for several reasons. Surface Air Temperature plays a foundational role in shaping the climate system, influencing and being influenced by a wide range of hydrological and atmospheric processes (Global Climate Observing System, n.d.; IPCC, 2018). Temperature scenario data are also more readily available than data on other

other ECVs. Furthermore, Amsterdam is known for its innovative and sophisticated water management systems and there is already a lot of research on the ECVs sea level and precipitation in Amsterdam, especially their impact on flood risk (Dai et al., 2018; Hasselaar & IJmker, 2021; Kim & Newman, 2019; Sharma, 2022; Van der Hoek et al., 2014).

Thus, climate change vulnerability was assessed by analysing the surface air temperature in various Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models of free online data from the Climatologies at high resolution for the earth's land surface areas (CHELSA) data set (Karger et al., 2017; Karger et al., 2018a; Karger et al., 2018b). All CHELSA data sets have a spatial resolution of 30 arc seconds which is equivalent to approximately 1 km at the equator.

Three models were selected based on a relative error measurement of CMIP5 model performance and the ones with the lowest error for surface air temperature (2 m) were chosen: ACCESS1-3, CESM1, and CCSM4 (IPCC, 2013). The decision to use three different models was taken to account for differences in projection and allow for comparisons. By integrating data from multiple climate models, the analysis aims to generate robust and spatially explicit information. The models are scenarios for the period of 2041 until 2060 and show the daily maximum air temperatures at 2 m averaged over one month ("tasmax") of the Representative Concentration Pathway (RCP) 4.5. This RCP was chosen because it strikes a balance between high-emission and low-emission scenarios. It represents a future trajectory where some efforts are made to mitigate greenhouse gas emissions, leading to a stabilisation of radiative forcing at 4.5 W/m² by the end of the 21st century without ever exceeding that value (Van Vuuren et al., 2011).

Twelve data sets were downloaded per model, each containing data for one month of the year (Karger et al., 2018a). They were then merged into one data set by computing a value for each cell of the output raster using the *Cell Statistics* tool in *QGIS*. This was done twice for each data set, once according to the mean values and once according to the maximum values, producing a total of six new data sets. Both mean and maximum were used to allow for comparisons. Each data set was then cropped to show the boroughs of

Amsterdam based on the *INDELING_STADSDEEL* data set that was also used for the calculation of green spaces.

Finally, the same was done for the maximum temperatures in a reference period of 1981 until 2010 to get an insight into reference values and compute the temperature anomalies. These data were also taken from CHELSA (Karger et al., 2018b). The reference period was chosen based on data availability and because 1981-2010 is commonly used as a standard reference period for climate assessments and projections by international organisations such as the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO). The data for the reference period were then subtracted from the scenario results to calculate the temperature anomalies. In doing so, the analysis can identify areas experiencing significant temperature increases and compare differences between boroughs.

Socioeconomic Analysis

The socioeconomic analysis looks at various relevant indicators that give an overview of the sociodemographic and socioeconomic backgrounds of the people in each borough. The specific indicators include income, population, population density, migration background, education, health, unemployment, cramped living, unsafety, and traffic (see Appendix B). Although traffic is traditionally not considered a socioeconomic indicator, it was included because traffic patterns and congestion can affect individuals' ability to access employment, education, or healthcare facilities. All data come from the *Dashboard Kerncijfers* (Key Figures Dashboard) of the *Onderzoek en Statistiek* department of the municipality of Amsterdam (Onderzoek en Statistiek, 2024). For each indicator, the data for the most recent year available were downloaded and put into one table. Many indicators were unavailable for the borough of Westpoort. As the data were not sufficiently comprehensive to ensure the integrity and reliability of the findings, Westpoort had to be excluded from the analysis.

Through this examination, boroughs that are more vulnerable to the effects of rising temperatures can be identified. This holistic approach allows not only for a more comprehensive analysis but also contextualisation. The additional socioeconomic perspectives help understand the associations between environmental and social factors and provide a more detailed and complete picture of urban challenges. For example, understanding the distribution of income levels across boroughs can shed light on potential disparities in the utilisation of green spaces as well as temperature changes in boroughs. This identification is crucial for prioritising interventions and allocating resources efficiently.

Correlation Analysis

Finally, the three categories of data were compared using correlation analysis. This was performed to identify relationships between different variables. To gain a more qualitative understanding of the residents' attitudes towards and opinions on green spaces, residents' views were also analysed in the correlation analysis. Three indicators that look at how the residents of each borough perceive green spaces were evaluated: perceived availability of green spaces, perceived appearance of green spaces, and perceived maintenance of green spaces. Additionally, to understand the significance of the results in the context of residents' well-being, three more indicators were evaluated to be used in the correlation analysis: self-reported happiness, neighbourhood satisfaction, and future confidence. The data on green space perception and residential well-being were also downloaded from the *Dashboard Kerncijfers* (Onderzoek en Statistiek, 2024).

By incorporating these perspectives alongside quantitative data, the goal was to gain more comprehensive and holistic insights into the relationship between green spaces, borough characteristics, and community well-being. This also helps shift the focus from purely quantitative or physical aspects of boroughs to a more human-centric perspective. Correlating these variables helps assess the extent to which green spaces, for example, contribute to residents' well-being. However, it is important to note that even though the data represent qualitative aspects, they were measured quantitatively. An overview with measurement explanations given for each socioeconomic, green space perception, and residential well-being indicator can be found in Appendix B.

The correlation analysis itself was made up of two parts. In the first step, a colour-coded correlation heatmap including the Pearson correlation coefficient (PCC) was generated to quantify the strength and direction of relationships between variables. These analyses were performed in *RStudio* (2024.04.0+735; RStudio Team, 2024) using *R Statistical Software* (v4.4.0; R Core Team, 2024). The packages *ggplot2* (v3.5.1; Wickham, 2016) and *reshape2* (v1.4.4; Wickham, 2007) were used to calculate these correlations and visualise them. The heatmap provides a colour-coded visual representation of the correlation matrix, making it easier to highlight and identify patterns and possible trends between multiple variables simultaneously. Including the PCC facilitated the identification of strong positive or negative correlations and weak or no correlations.

Then, significant results were put together in a principal component analysis (PCA). As a correlation heatmap only measures linear relationships, the PCA was performed to gain a multidimensional insight into specific interactions. A PCA also captures the maximum variance in the data, allowing for a compact representation of the data set that retains most of the important information. The *factoextra* (v1.0.7; Kassambra, 2020) as well as *ggplot2* packages were used in *RStudio* to visualise the results in the form of biplots. As the findings of temperature increases showed the same spatial distribution and the correlation heatmaps showed strong positive correlations among temperature anomalies, the temperature anomalies were averaged into one variable for the visualisation of the results. An overview of all correlation results can be found in Appendix A.

Results

Green Space Characteristics

Borough	Total green space area	Green urban area	Forest area	Herbaceous vegetation area	Pasture area	Wetlands area
Centrum	221,563	221,563	0	0	0	0
Nieuw-West	10,327,553	4,079,802	855,827	69,048	4,916,130	406,746
Noord	26,411,661	2,146,819	180,036	68,738	24,016,068	0
Oost	5,429,740	2,080,843	24,496	0	3,324,401	0
Weesp	30,949,305	1,692,442	3,545,702	0	25,711,161	0
West	1,576,587	1,576,587	0	0	0	0
Zuid	3,456,581	2,508,925	719,960	0	227,696	0
Zuidoost	8,009,942	4,407,171	323,202	0	3,279,569	0
Borough	**Total number of green spaces**	**Number of green urban areas**	**Number of forests**	**Number of herbaceous vegetations**	**Number of pastures**	**Number of wetlands**
Centrum	20	20	0	0	0	0
Nieuw-West	175	104	15	4	48	4
Noord	146	77	4	1	64	0
Oost	88	67	1	0	20	0
Weesp	77	26	8	0	43	0
West	30	30	0	0	0	0
Zuid	90	74	14	0	2	0
Zuidoost	97	87	9	0	1	0
Borough	**Average green space area**	**Average green urban area**	**Average forest area**	**Average herbaceous vegetation area**	**Average pasture area**	**Average wetlands area**
Centrum	11,078	11,078	0	0	0	0
Nieuw-West	59,015	39,229	57,055	17,262	102,419	101,687
Noord	180,902	27,881	45,009	68,738	375,251	0
Oost	61,702	31,057	24,496	0	166,220	0
Weesp	401,939	65,094	443,213	0	597,934	0
West	52,553	52,553	0	0	0	0
Zuid	38,406	33,904	51,426	0	113,848	0
Zuidoost	82,577	50,657	35,911	0	3,279,569	0
Borough	**Median green space area**	**Median green urban area**	**Median forest area**	**Median herbaceous vegetation area**	**Median pasture area**	**Median wetlands area**
Centrum	5,071	5,071	0	0	0	0
Nieuw-West	19,220	14,478	34,821	15,705	51,367	99,259
Noord	27,691	15,071	46,089	68,737	59,875	0
Oost	15,852	13,190	24,496	0	31,466	0
Weesp	23,314	9,094	126,352	0	29,240	0
West	26,479	26,479	0	0	0	0
Zuid	11,916	11,024	21,130	0	113,848	0
Zuidoost	20,913	17,474	22,316	0	3,279,569	0

Borough	Green space quality index	Total borough area
Centrum	0.000	8,044,519
Nieuw-West	0.154	38,020,252
Noord	0.220	63,836,776
Oost	0.066	30,599,380
Weesp	0.669	26,393,606
West	0.000	10,631,331
Zuid	0.061	17,276,614
Zuidoost	0.076	19,887,443

Table 1. *Green space data (m², except for the green space quality index), rounded to the nearest whole number.*

There are significant disparities in the total area of green spaces across boroughs. Weesp and Noord have notably larger areas of green space compared to other boroughs (Table 1). The sizes range from 221,563 m² in Centrum to 30,949,305 m² in Weesp, the borough with the largest total green space. Nieuw-West and Noord have the highest green space quantity with 175 and 146 areas respectively, whilst Centrum has the smallest number with only 20. Weesp has the highest average green space area by far with 401,939 m², followed by Noord with 180,902 m², whilst Centrum only has an average of 11,078 m². Noord has the highest median green space area (27,691 m²), Centrum the lowest with 5,071 m².

Urban green areas contribute substantially to the total green space area in most boroughs (Table 1). Zuidoost has the highest area of urban green spaces with 4,407,171 m², closely followed by Nieuw-West with 4,079,802 m². Nieuw-West also has the highest number of green urban areas. Centrum has the smallest area, only 221,563 m², even though this is the only type of green space in that borough. The borough with the highest average green urban area size is Weesp but it also has the second lowest median (Table 1). West has the highest median green urban area size.

While some boroughs have significant forested areas contributing to their total green space sizes, others, like Centrum and West, lack forested areas entirely (Table 1). Nieuw-West and Zuid have the highest number of forest-covered areas, 15 and 14 respectively, but Oost only has one. This highlights the diverse landscape compositions and environmental characteristics across boroughs. Weesp also has the largest area covered by forests, namely 3,545,702 m², and the highest average and median too.

There are only two boroughs that include herbaceous vegetation: Nieuw-West and Noord. Nieuw-West has four areas but Noord only one, although they are very similar in total size (69,048 m² and 68,738 m² respectively). Noord and Weesp are the boroughs with the biggest total pasture size (24,016,068 m² and 25,711,161 m² respectively), while Centrum and West do not have any. Noord also has the highest number of pasture areas (64). Zuidoost has the highest average and median, but at the same time, it only has one pasture area in its borough (Table 1). Wetlands by far make up the smallest proportion of total green space area, with Nieuw-West standing out as it is the only borough that has wetlands. Whilst the borough only has four wetland areas, their average size is just slightly smaller than the borough's average pasture size, although there are 48 of those (Table 1).

Centrum and West have a green space quality index of zero, making them the lowest green space quality boroughs overall. Weesp has the highest with 0.669 followed by Noord with 0.22. Noord is the biggest borough by far in area size and Centrum and West are the smallest (Table 1).

Climate Change

Recent Temperatures

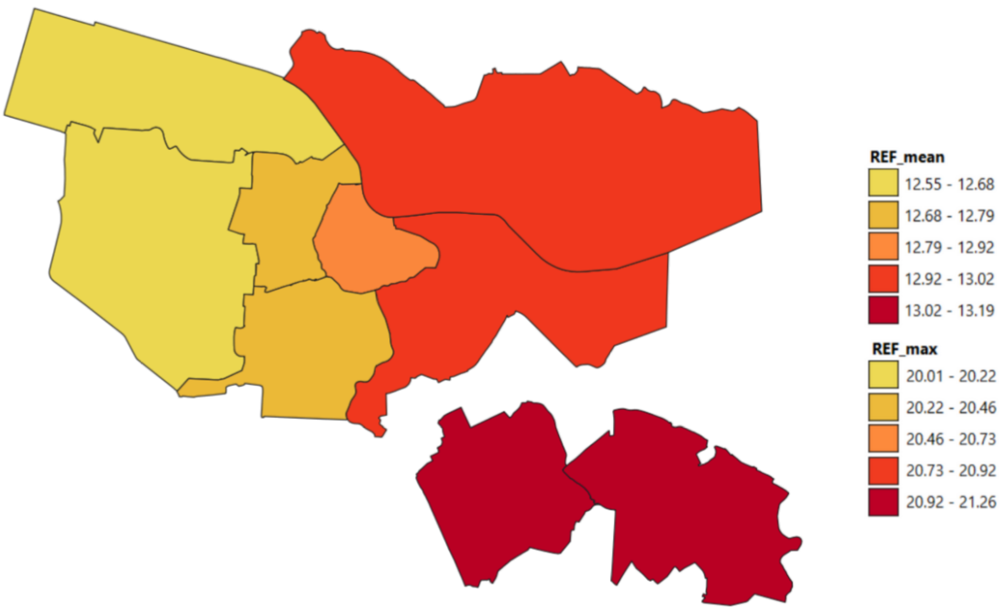

Figure 4. *Maximum annual temperature (°C) in Amsterdam 1981-2010. Both calculations showed the same spatial distribution.*

The recent temperature variation is based on a reference period from 1981 until 2010. Figure 4 shows the maximum temperature based on monthly data that was merged based on mean and maximum separately. However, while the scales are different, the spatial distribution was the same. The boroughs in the west are the coldest boroughs of Amsterdam (mean: 12.55°C-12.68°C, maximum: 20.01°C-20.22°C). The boroughs that are separated from the rest of Amsterdam in the southeast are the warmest (mean: 13.02°C-13.19°C, maximum: 20.92°C-21.26°C). Westpoort is the coldest borough and Weesp is the warmest which indicates a southeast-to-northwest temperature gradient. The more southeast you are in Amsterdam, the higher temperatures you have and the more northwest, the lower the temperatures.

Temperature Anomalies

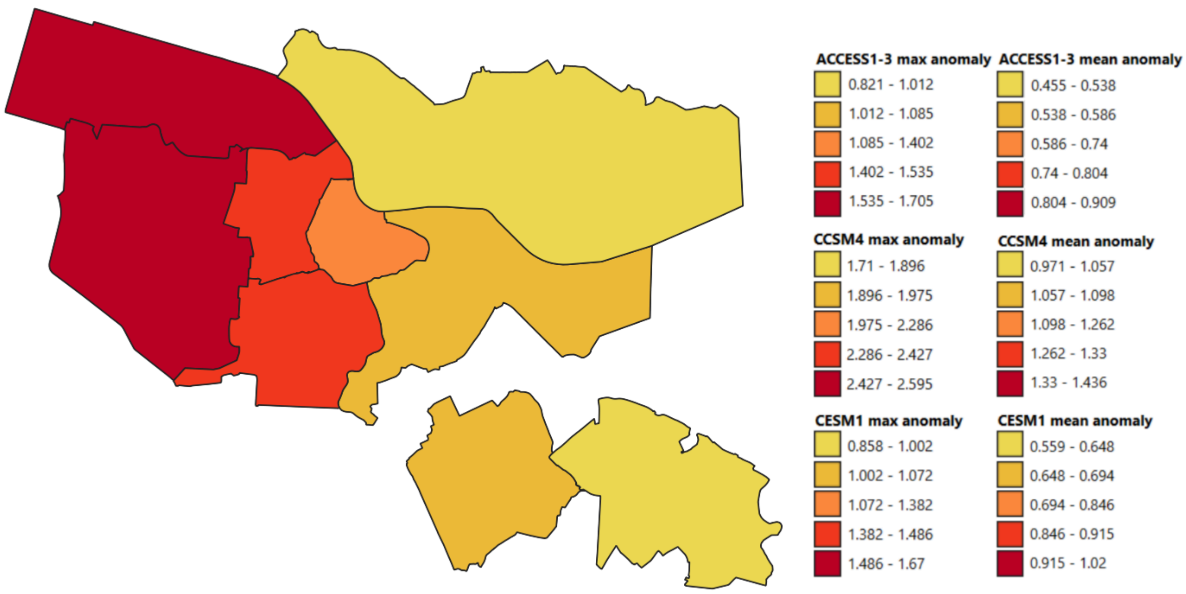

Figure 5. *Projected temperature anomaly (°C) in Amsterdam based on expected heat stress 2041-2060 with reference period 1981-2010 (CMIP5 4.5 RCP; ACCESS1-3, CCSM4, CESM1). Each calculation showed the same spatial distribution.*

All six temperature anomaly calculations also showed the same results regarding the highest and lowest anomalies, although at different scales (Figure 5). The CCSM4 model was the most pessimistic as it predicted the maximum anomaly to be between 1.71°C and 2.595°C and 0.971°C to 1.436°C for the mean temperature anomaly. On the other hand, the ACCESS1-3 model only predicted a range of 0.821°C to 1.705°C for the maximum anomaly and 0.455°C to 0.909°C for the mean. The CESM1 model was similar, with a maximum temperature anomaly range of 0.858°C to 1.67°C and a mean anomaly range of 0.559°C to 1.02°C.

The west of Amsterdam seems to be the most affected and the east is the most resistant to rising temperatures. This creates a west-to-east warming gradient. Nieuw-West is the borough with the highest expected warming (range of 0.909°C to 2.595°C) and Weesp the one with the lowest (range of 0.455°C to 1.71°C). Overall, Nieuw-West's average temperature is expected to increase by approximately 0.45°C more than Weesp considering the mean calculation and even approximately 0.8°C considering the maximum.

Socioeconomic Profiles

Name	Income (€ per year)	Population (total)	Population density (per m²)	Migration background (%)	Education (%)	Good health (%)	Unemploy-ment (%)	Cramped living (%)	Unsafety (%)	Traffic (1-10)
Centrum	55,300	91,733	14,675	50.6	62	74	4	7	22	3.3
Nieuw-West	42,300	164,789	5,037	72.1	32	63	5	14.4	32	3.6
Noord	42,100	108,792	2,718	55.9	37	67	5	12.2	26	3.1
Oost	51,200	147,712	7,738	55.6	55	68	4	7.9	21	3
Weesp	53,600	25,409	1,094	32.9	28	72	6	4.4	11	2.8
West	46,300	150,374	16,097	57.3	55	70	5	10.6	22	3.4
Zuid	61,300	149,000	9,730	52.6	60	75	5	7.1	15	3.2
Zuidoost	35,800	92,378	5,207	78.8	30	56	7	12	29	2.6

Table 2. *Overview of socioeconomic indicators (modified from Onderzoek en Statistiek (2024)).*

Zuidoost is the most socioeconomically disadvantaged borough across multiple metrics (Table 2). It has the lowest average income (35,800 € per year), second lowest education level (30%), lowest reported good health (56%), highest unemployment (7%), and high cramped living conditions (12%) and unsafety (29%), although it has the lowest reported traffic nuisance (2.6). Nieuw-West also shows significant socioeconomic challenges that become obvious in the borough's low income (42,300 € per year), low education level (32%), highest share of cramped living conditions (14.4%), unsafety (32%), and also the highest reported traffic nuisance (3.6). The two boroughs also have the highest shares of people with migration backgrounds (78.8% in Zuidoost, 72.1% in Nieuw-West).

On the other hand, Zuid stands out as the most socioeconomically advantaged borough with the highest income (61,300 € per year), highest share of good health (75%), second highest education level (60%), low share of cramped living conditions (7.1%) and unsafety (15%), and low unemployment (5%). Weesp is also in a relatively favourable position due to its low population density (1,094 inhabitants per km²), low perceived unsafety (11%), low cramped living conditions (4.4%), and high share in reported good health (72%). Weesp also has the lowest share of residents with migration backgrounds, as only one in three people or their parents were not born in the Netherlands (32.9%).

Central boroughs like Centrum and West generally show moderate to high socioeconomic status with higher incomes (55,300 € per year in Centrum, 46,300 € per year in West), high share of good health (74% in Centrum, 70% in West), and high education levels (62% in Centrum, 55% in West). However, they also experience the highest population densities (14,675 inhabitants per km² in Centrum, 16,097 inhabitants per km²) and moderate levels of unsafety (22% in both Centrum and West).

Zuidoost and Weesp are the two boroughs that are outlying to the southeast. Despite that, they show significant contrasts. Zuidoost is the lowest across the socioeconomic metrics and Weesp is on the more advantaged side. The peripheral boroughs in the west and north, namely Noord and Nieuw-West, have lower incomes (42,100 € per year in Noord), higher migration backgrounds, lower education levels, and higher levels of cramped living conditions and unsafety, indicating lower socioeconomic status (Table 2).

Correlations

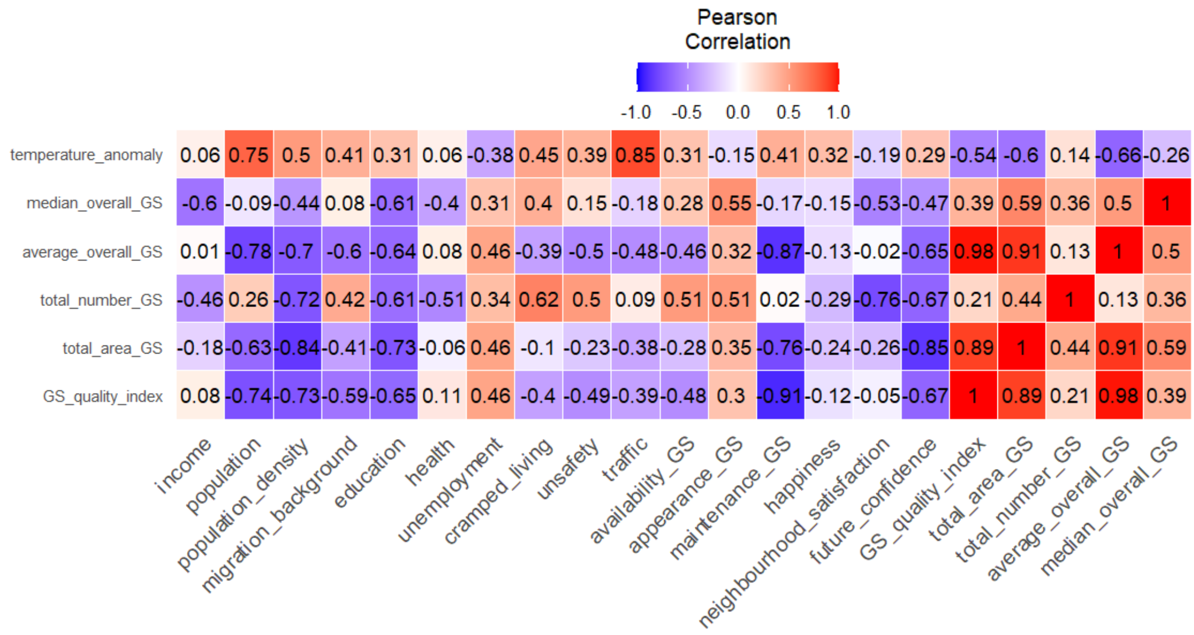

Figure 6. Correlation heatmap of socioeconomic factors and green space characteristics with green space data and climate data, showing Pearson correlation coefficient.

As population increases, so do expected temperatures (PCC: 0.75) but most green space indicators decrease. The same goes for the population density, which shows a slightly weaker but still positive correlation with the temperature anomaly (PCC: 0.5) but overall similar or stronger negative correlations with green space characteristics (Figure 6). This trend suggests that more populated and more densely populated boroughs tend to have fewer, smaller, and lower-quality green spaces but expect higher temperature changes. Furthermore, boroughs with high traffic nuisance are also associated with high anticipated temperature increases (PCC: 0.85).

However, some correlations are also notable because they seem counterintuitive. As the numbers of green space characteristics increase, so does unemployment but the level of education decreases (Figure 6). As the future confidence of residents and their neighbourhood satisfaction increase, the correlations with green space characteristics decrease (Figure 6). Future confidence and the total green space area especially are strongly negatively correlated (PCC: -0.85). While the perceived appearance of green spaces is negatively associated with the temperature anomaly (PCC: -0.15), availability and maintenance have a positive correlation with the temperature anomaly (PCC: 0.31 and 0.41 respectively).

It is also worth mentioning that there is little or no correlation between income and health in relation to climate (PCC: 0.06 for both indicators). However, they both show a negative correlation with a lot of green space indicators (Figure 6). The PCC is positive just for the average green space size and green space quality, which shows that the average size and quality seem to go up with income and health, although the correlation is very weak. The PCC of the average size is 0.01 with income and 0.08 with health and the green space quality with income is 0.08 and 0.11 with health. These similarities also indicate a strong correlation between income and health. Along with unemployment (PCC: 0.39), income and health are the only socioeconomic indicators that correlate positively with green space quality.

Furthermore, green space quality is positively correlated with the total green space size (PCC: 0.89), average size (PCC: 0.98), median size (PCC: 0.39), and total number (PCC: 0.21), indicating that higher quality green spaces are also associated with larger total areas and higher numbers of green spaces. Additionally, as green space expands, it is often distributed among multiple locations rather than concentrated in fewer large areas (PCC: 0.91 for average area and total number). Larger areas of green spaces also significantly increase the median green space size (PCC: 0.59). The green space quality index and green space appearance are positively correlated (PCC: 0.3). With a PCC of -0.91, green space quality and the perceived maintenance of green spaces are highly negatively correlated.

When it comes to the correlation between green spaces and the climate, it is evident that the correlations overall are mostly negative, even if the correlation is not always strong (Figure 6). The strongest correlation is between the average green space area and temperature anomaly (PCC: -0.66). Slightly less strong are the correlations between total green space size and temperature anomaly (PCC: -0.6) as well as green space quality and temperature anomaly (PCC: -0.54). Only the correlation between the expected warming and the total number is positive (PCC: 0.14). These associations suggest that green space size and quality seem to have an influence on warming, preventing or at least slowing it down, while the quantity seems irrelevant.

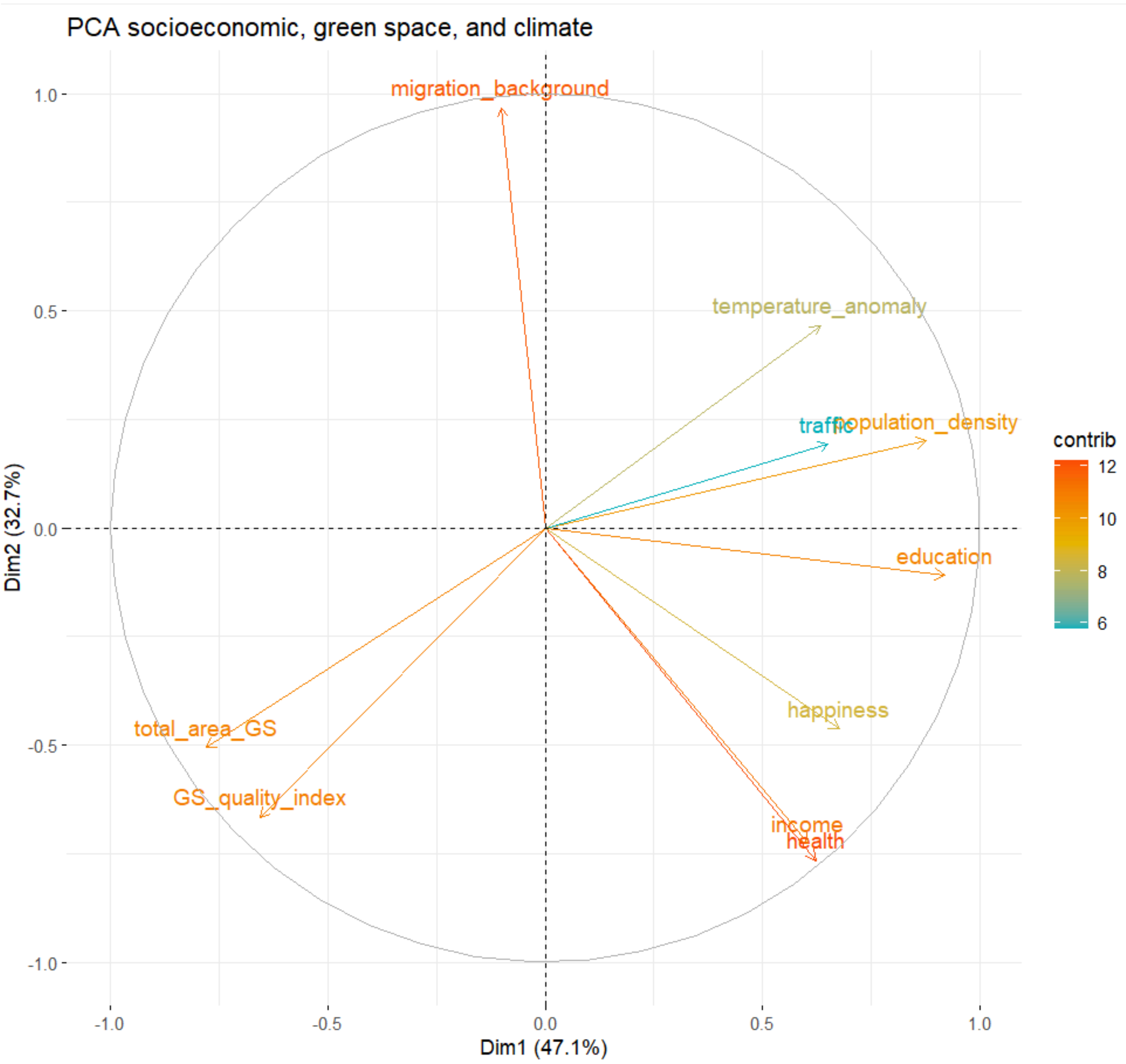

Figure 7. *Principal Component Analysis for selected socioeconomic and green space indicators, and temperature anomaly.*

In this principal component analysis, the first dimension explains 47.1% and the second explains 32.7% of the variance, accounting for almost four-fifths of variance overall.

The socioeconomic indicators seem to have the highest contribution, while traffic has the lowest. Income and health are very closely correlated, with happiness being similar, and are displayed almost directly opposite of the migration background (Figure 7). The negative correlation with the residents' migration background reveals that people with a migration background are likely to have worse health, lower income, and be unhappy. Population density does not seem to correlate with this, whilst education correlates slightly with income and health. Being located on opposite sides of one another, it is also evident that green space size and green space quality seem to have a negative correlation with the temperature anomaly, traffic, and population density (Figure 7), as was seen before in the heatmap (see Figure 6).

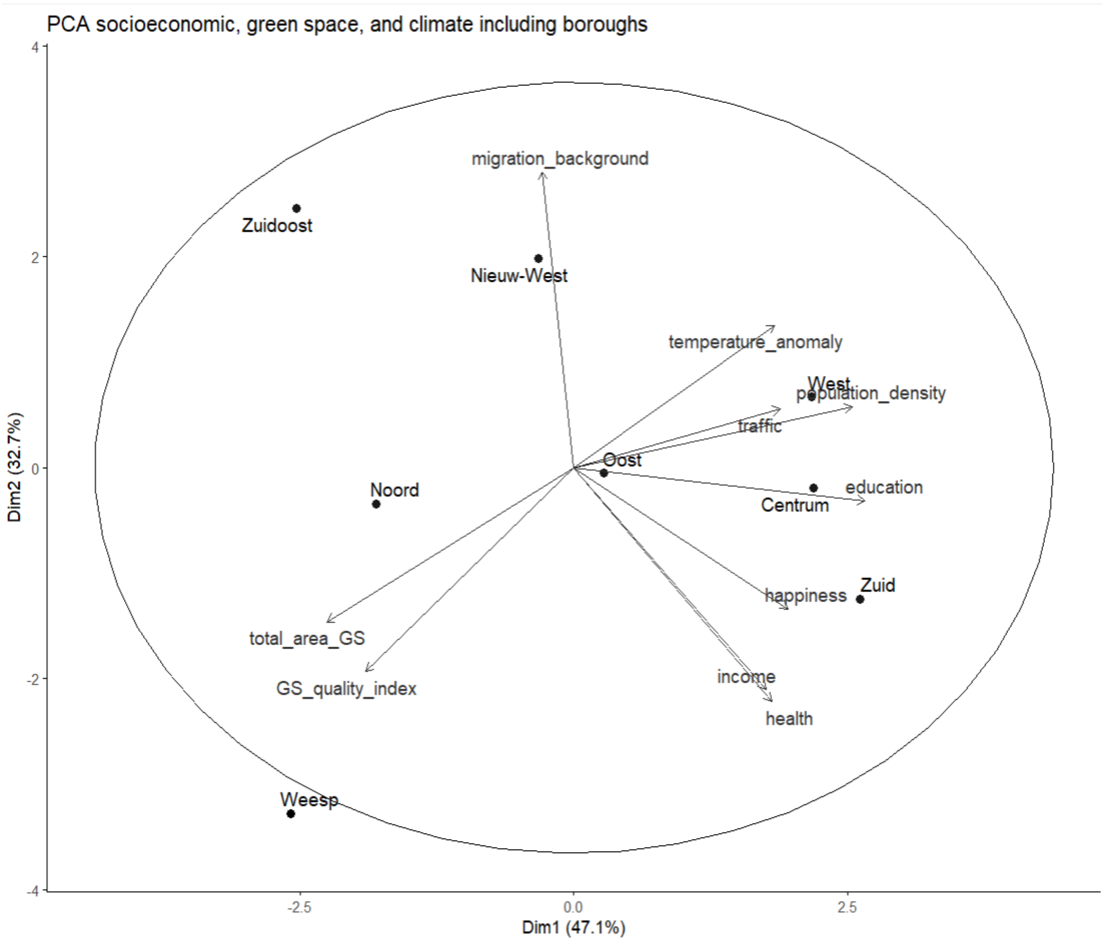

Figure 8. *Principal Component Analysis for selected socioeconomic and green space indicators, and temperature anomaly, showing the boroughs.*

Regarding the boroughs, Weesp seems to have the best living conditions (Figure 8). It enjoys high green space quality and big green spaces, whilst expecting only low temperature increases. Additionally, income and health also seem to be relatively high in Weesp in comparison to some of the other boroughs. Oost and Noord are located towards the middle, with Oost being the most central, which indicates fewer extremes but these boroughs still enjoy similar benefits to Weesp, albeit to a lesser extent (Figure 8). Zuidoost stands out as an outlier due to its low income and bad health. Zuid is the happiest borough and has a relatively high income, good health, and good education while expecting a moderate temperature increase. However, it also does not enjoy the best or biggest green spaces. The boroughs that seem to be the most disadvantaged are West and Nieuw-West due to a high temperature anomaly, low income and bad health, and small and low-quality green spaces, and Zuidoost due to its poor socioeconomic situation (Figure 8).

Discussion

Building upon the results presented above, the discussion delves into the multifaceted implications of spatial variation in climate impact, green spaces, and socioeconomic inequalities in Amsterdam. Possible reasons for the spatial distribution of anticipated temperature increases are provided and the role of green space characteristics for temperature mitigation is examined. Additionally, the intersection of disparities in green space access with residents' socioeconomic backgrounds, and how socioeconomic factors interact with susceptibility to urban heat exposure are explored. Suggestions for policy interventions in Amsterdam and broader consequences for urban development globally are presented. Finally, limitations of the study and recommendations for future research are given.

Spatial Variation in Climate Impact

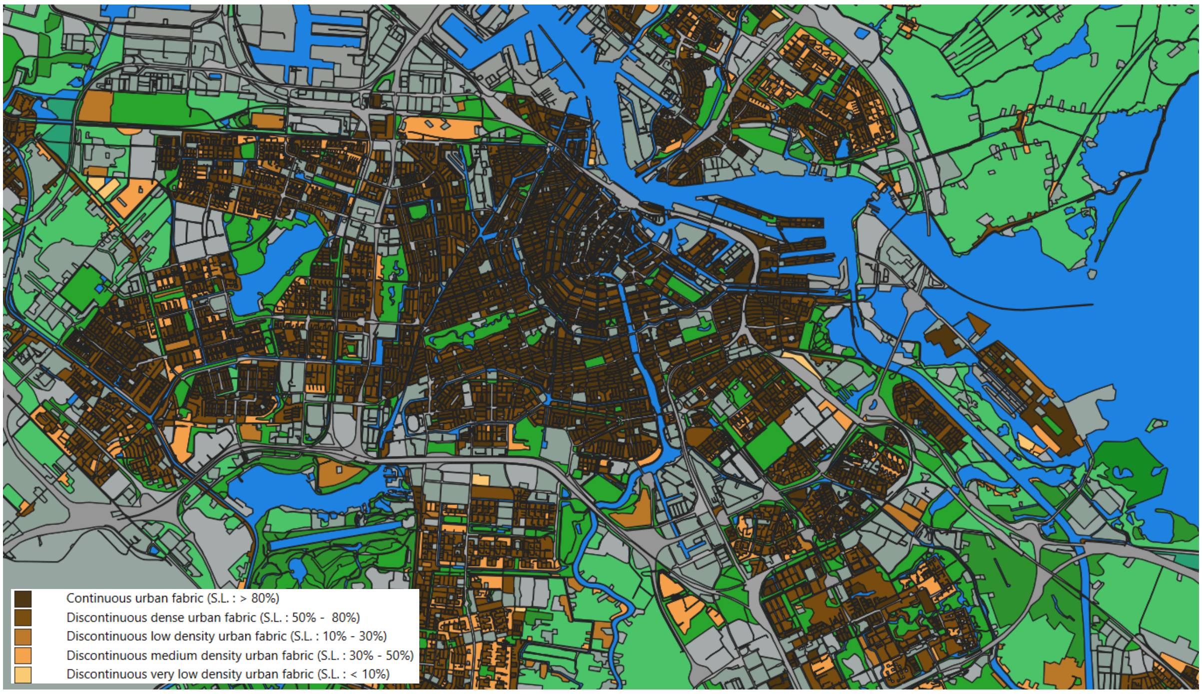

***Figure 9**. Density of urban fabric in Amsterdam in 2018 (modified from European Environment Agency (2021)). Green represents green spaces, blue represents water, brown represents residential areas, and grey represents other grey infrastructure.*

Surface temperature differences in cities are associated with patterns of land use and buildings. These differences in urban morphology create variations in heat absorption and retention, leading to localised microclimates and exacerbation of the UHI effect (Allegrini et al., 2015; Kouklis & Yiannakou, 2021). The west of Amsterdam is more dense in urban fabric than the east which features a less densely built environment and less built environment overall (Figure 9). The east of the city is also less densely populated. Boroughs like Weesp and others in the southeast feature more residential and rural characteristics. These boroughs also allow for better wind circulation due to their more open built environment (Allegrini et al., 2015).

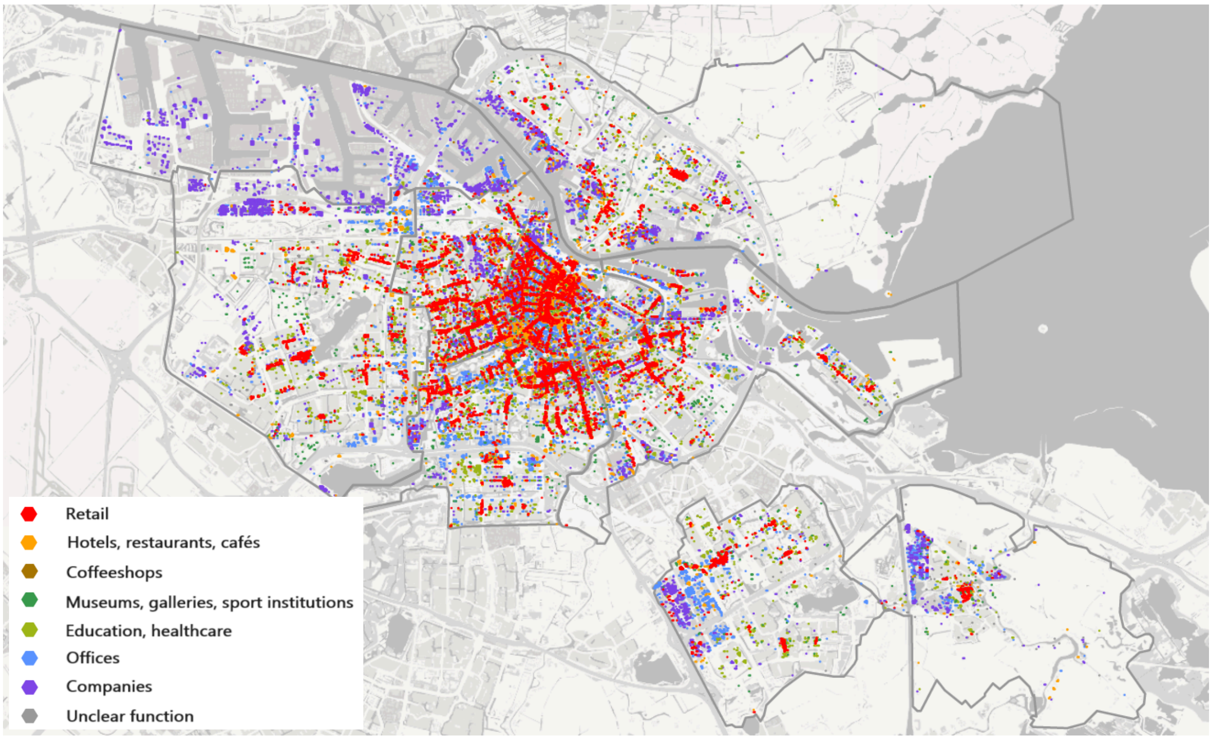

Figure 10. *Non-residential uses of Amsterdam (Gemeente Amsterdam, n.d.-a).*

When considering non-residential uses, the west, especially the borough of Westpoort, stands out as the industrial area of Amsterdam (Figure 10). These areas often generate more heat due to machinery, traffic, and energy use (Liu et al., 2021; Rao et al., 2018). Whilst Nieuw-West was the borough with the second highest temperature anomaly after Westpoort, it is likely to experience many of the same effects due to its proximity to Westpoort, even if there are not as many companies present. There is less industry present in the eastern boroughs (Figure 10), possibly adding to the explanation for why these are expected to experience lower temperature increases than the western boroughs.

The differences in expected temperature anomalies for the future are also associated with green space distribution. There is a negative correlation between the temperature anomalies and both the total and average area of green spaces. This shows that boroughs in the east tend to have larger areas of green space, while also being predicted to experience a lower temperature change. The negative association between green space characteristics and temperature anomalies thus underscores the importance of green infrastructure in mitigating the UHI effect and improving climate resilience. Even though Nieuw-West is the borough with the most green spaces and a relatively high quality, the correlation analysis showed that population density is negatively associated with green space characteristics. Weesp, a borough with low population density and larger and higher-quality green spaces, is an example of this as it is the borough with the lowest expected temperature warming.

This temperature variation, however, cannot solely be explained by urban factors. As global climate models were used, this impacted the results. The spatial variation of temperature anomalies in and beyond Amsterdam can also be explained by changes in ocean temperatures that will impact coastal areas on the North Sea (Dieterich et al., 2019; Tinker & Howes, 2020), changes in circulation of the North Sea due to climate change-driven change in the North Atlantic and Arctic Oceans (Holt et al., 2018), changes in atmospheric circulation patterns (Faranda et al., 2023), and changes in precipitation patterns (Jacob et al., 2018; Van Der Wiel et al., 2024; Van Dorland et al., 2024). Additionally, these patterns influence each other and create feedback loops, in some cases even leading to extreme weather events (Ibebuchi, 2022; Van Dorland et al., 2024).

Whilst green spaces are unavoidable for mitigating climate change and enhancing air quality in cities, climate change itself also has an impact on these spaces. Areas that are more vulnerable to climate change tend to have poorer green space quality and distribution, exacerbating their vulnerability. This indicates that as adverse impacts of the climate crisis intensify, the role of green spaces in urban environments will become more pronounced. While happiness did not show a strong correlation with green space characteristics, it is likely that green spaces will also play a bigger role in influencing happiness in the future, as they provide essential respite from rising temperatures and contribute to well-being.

Effectiveness of Green Space Characteristics in Urban Temperature Regulation

This research showed that green space quantity does not seem to be associated with rising temperatures, but rather it is only quality and size that matter, although size is slightly more important. The correlation between the temperature anomaly and the number of green spaces is positive, indicating that smaller, fragmented green spaces are less effective at cooling compared to larger, contiguous areas and higher-quality areas.

High-quality spaces are effective because they provide ecosystem services, such as carbon sequestration, air purification, and temperature regulation (Baró et al., 2014; De Carvalho & Szlafsztein, 2019). Additionally, well-managed green spaces can also mitigate the UHI effect by reducing surface temperatures and energy consumption (Cao et al., 2010).

However, overall, large green spaces were shown to be the most effective at mitigating temperature increases. These findings were also observed by Jaganmohan et al. (2016) who measured the cooling effect of urban forests and parks and found that bigger spaces (i.e., urban forests) are better at cooling. These spaces typically have a greater capacity to sequester carbon dioxide through photosynthesis and provide more significant cooling effects through transpiration and shading. They can also support more diverse ecosystems which can enhance resilience to climate change impacts (Gioia et al., 2014; Sarı & Bayraktar, 2023).

Interestingly, while larger and higher-quality green spaces have a significant positive impact on temperature mitigation, the perceived appearance of green spaces is negatively associated with the expected rise in temperatures. Perceived availability and maintenance, on the other hand, are relatively positive in correlation with the temperature anomaly. This shows that the perception of green spaces does not always mirror their actual environmental benefits.

Green Space Distribution and Socioeconomic Inequalities

The results showed that green space size and number decrease, as income, health, and happiness increase. Green space quality had a weak positive correlation with these indicators, suggesting a very small increase in quality in more affluent boroughs of Amsterdam. These findings seem counterintuitive as most bodies of research show that green spaces are more numerous and bigger in affluent areas of cities (Schüle et al., 2019;

Wolch et al., 2014; H. Zhang et al., 2022), areas with better residential health (Akpinar et al., 2016; De Haas et al., 2021; Kondo et al., 2018), and areas with happier residents (Kwon et al., 2021). However, some sources also suggest that there are no or even negative correlations between green spaces and either income or health or both (Andrusaityte et al., 2016; Astell-Burt et al., 2013; Gan et al., 2017; Hajna et al., 2023; Lai et al., 2019). For example, a review on the impact of green space and biodiversity on health by Lai et al. (2019) showed that while the reported effects between green space and health were generally positive, almost one-quarter of all papers identified either no or even negative effects. Gan et al. (2017) studied green environmental justice in two socioeconomically disadvantaged neighbourhoods of Amsterdam and had similar findings. Both neighbourhoods had more green spaces than the overall average of Amsterdam. Quality, however, was judged as poor when residents were asked.

There is also a green gentrification happening in Amsterdam (Anguelovski & Connolly, 2021; Planas-Carbonell et al., 2023). The attempt to introduce more green spaces to lower-income neighbourhoods and boroughs to improve attractiveness and public health makes these areas more desirable. This results in rising housing costs and gentrification, the displacement of the residents that the green space developments were supposed to benefit (Kim & Wu, 2021). These residents therefore face higher rents and end up in less desirable areas that have similar green space problems as where they lived before (Haase et al., 2017; Wolch et al., 2014). A study that compared green climate gentrification in different cities showed that in the borough of Noord in Amsterdam physical displacement and neighbourhood affordability are the most important social effects in the context of green spaces (Planas-Carbonell et al., 2023). This shows that while greening cities using green infrastructure and nature-based solutions has positive environmental effects, it can also have negative societal effects.

As Amsterdam has an overall high quality of life, good healthcare, and social services (European Commission, 2023), this might additionally reduce the measurable impact of green spaces on income and health in boroughs. For example, the Dutch cycling culture creates a lot of health benefits for people of all socioeconomic and demographic groups (Gao et al., 2017).

When it comes to community well-being, increased future confidence and neighbourhood satisfaction are associated negatively with green space characteristics. This shows that residents' positive outlooks and satisfaction are not strongly tied to green space distribution or quality. Instead, other factors like economic opportunities or social cohesion may be more influential in this regard. Pastures also make up a high share of green spaces in many boroughs, although they are not traditionally considered green space. This might be part of the explanation for why there are negative correlations between neighbourhood satisfaction as well as future confidence and green space characteristics. Overall, however, the correlations tend to be less negative or even positive when looking only at forest or green urban area associations with the two community well-being indicators. Pastures, on the other hand, have stronger negative correlations (see Appendix A). This is confirmed by Krekel et al. (2016) who showed that not all green areas are positively associated with life satisfaction.

Furthermore, the results showed that as population density increases, green space characteristics decrease. It indicates that less densely populated boroughs have more, bigger, and higher-quality green spaces. This is because there is land available for green space construction in peripheral areas but not in central areas that are usually more dense (Chang et al., 2017). Because of this imbalance, residents in different boroughs enjoy different amounts of ecosystem services (Chen et al., 2022; Wüstemann et al., 2017). Interestingly, however, McDonald et al. (2023) showed that high population density does not have to rule out a high presence of green spaces. Their analysis of urbanised areas in the United States showed that some neighbourhoods had more tree canopy than expected based on their population density.

But in the case of Amsterdam, the discrepancy between green spaces and population density creates and reinforces socioeconomic inequalities. Population growth, especially in central areas where buildings are more dense and space is valuable, leads to higher demand for residential and commercial development and more pressure to convert green spaces into built environments (Kabisch & Haase, 2014). This makes these areas more desirable to live in and drives up real estate prices, offering another explanation for why green spaces are less numerous and smaller in more affluent areas in Amsterdam. Properties that are located near green spaces, especially high-quality green spaces, also tend to have higher market values (Bockarjova et al., 2020). Green spaces are seen as desirable and enhance the attractiveness of a neighbourhood. The increased property values can in turn lead to higher tax revenues for local governments which can be reinvested in community infrastructure and services, such as better maintenance of green spaces.

Socioeconomic Vulnerability to Rising Temperatures

Whilst the correlation of both income and health with green space characteristics is mostly negative, the results for their correlation with rising temperature anomalies are weakly positive. This contradicts a lot of previous research on the relationship between rising temperatures and urban residents' socioeconomic backgrounds (Chakraborty et al., 2019; Landry et al., 2020; Mitchell & Chakraborty, 2014; Sarricolea et al., 2022; Sera et al., 2019; WHO, 2018). Wealthier residents have more money to retrofit their homes, live close to green spaces, and can afford air conditioning and other cooling technologies, among other things. While most studies tend to show that lower-income or more deprived neighbourhoods often face bigger climate change impacts, some studies also present counterintuitive findings, for instance, through higher temperatures in more affluent areas (Vargo et al., 2016) or higher air pollution (Feron et al., 2023).

While there is a positive correlation between cramped living conditions and rising temperatures, indicating that more densely built environments will warm more, income and cramped living conditions are strongly negatively correlated. Income and the temperature anomaly showed a positive but weak correlation. As discussed before, more affluent boroughs of Amsterdam often have fewer and smaller green spaces, although they are of higher quality. But the results showed that size is more important than quality which is a possible explanation for why the correlation of income, health, and happiness with the temperature anomaly is very weakly positive.

Instead, the more important indicators that play a role in predicting rising temperatures are population and traffic to a high extent (PCC: > 0.75), but also population density, migration background, and cramped living (PCC: > 0.41). Higher population and population density also mean more people, activities, and infrastructure that generate heat. Cramped living conditions often indicate higher population density too (Visagie & Turok, 2020). As the population grows in urban areas, so does the extent of impervious surfaces such as roads, buildings, and pavements. These surfaces absorb and retain heat from the sun leading to the UHI effect (Xiangli et al., 2019). Traffic contributes significantly to urban heat through greenhouse gas emissions and other pollutants from vehicles as they can enhance the UHI effect by trapping more heat (Al-Mohannadi, 2017; H. Li et al., 2018).

While the migration background itself is not a reason for higher temperatures, people with a migration background are more likely to have worse health, lower income, and be unhappy than people without a migration background. Those with a migration background are therefore also more likely to live in poorer housing conditions with less access to cooling technologies. This makes them more vulnerable to the impacts of heat stress and exacerbates their low socioeconomic status, adding to challenges that they are already experiencing such as struggles with language or cultural integration (Wang et al., 2018).

Implications for the Future of Amsterdam and Beyond

Based on the findings, the city of Amsterdam should prioritise integrated approaches that address climatic and socioeconomic challenges, for instance through equitable access to green spaces. Aligning green space development with broader socioeconomic goals and climate adaptation and mitigation strategies is crucial for urban resilience. These should be monitored and evaluated regularly to make adjustments if needed.

To effectively combat urban warming and pollution, it is recommended that Amsterdam should focus on enhancing the size and quality of green spaces to maximise their climate mitigation potential. Furthermore, the city should prioritise the development and enhancement of green spaces in low-income as well as densely populated areas. Investing in the maintenance of green spaces and prioritisation of biodiversity in management will improve their usability and ecological value, contributing to the well-being of all residents through recreational benefits but also cooling effects. Engaging local communities in the planning and development process is important to address their needs and preferences effectively. By incorporating community input, Amsterdam can create green spaces that are culturally relevant, socially inclusive, environmentally sustainable, and useful for temperature regulation. Finally, addressing socioeconomic inequities such as disparities related to migration background is essential for providing social cohesion and environmental justice. Targeted interventions should be developed to address the unique needs and vulnerabilities of these communities.

Globally, cities should also develop urban planning guidelines that incorporate green space infrastructure as a key component of their climate adaptation and mitigation plans, especially in underserved areas. In addition to the recommendations for Amsterdam, cities worldwide should develop policies to prevent green gentrification, for example, through affordable housing initiatives, if necessary. Cities should prioritise tracking and understanding correlations and causations within their own urban environments. By collecting and analysing data specific to the city's context, urban planners and policymakers can gain valuable insights into the relationships between factors such as green space distribution, socioeconomic indicators, and environmental outcomes. This localised data-driven approach enables cities to tailor their interventions and policies to effectively address the unique challenges and opportunities within their communities and ensure that their policies meet the intended goals.

Limitations

While this study provides valuable insights into the complex relationship between green spaces, socioeconomic factors, and climate change in socioeconomic environments, several limitations should be considered. One of the biggest limitations is that only correlations were examined. These only indicate associations and do not establish causality. This research cannot definitively determine whether changes in green space characteristics cause changes in socioeconomic or climate factors, or vice versa. The impact of urban morphology on microclimates is recognised but the details of how different types of built environments interact with the climate crisis may not fully be captured. This complexity can lead to the oversimplification of the findings. The study also does not account for all possible external factors influencing the observed relationships. Some economic opportunities, policy interventions, or certain infrastructural developments likely play significant roles too but could not be considered because that would have gone beyond the scope of the Capstone project.

Another limitation is that a global climate model was used to assess intra-urban temperature anomalies. This does not represent regional changes and introduces a level of uncertainty, as climate models are inherently complex. A smaller scale would be needed to assess the temperature anomalies and the UHI effect more accurately. The research also only focused on temperature changes as a representation of climate change and left out other potential impacts such as air pollution or precipitation, which can interact with green space characteristics and affect residents' health and well-being.

Furthermore, this study relies solely on secondary data and its availability. Due to that, not all data are from the same year. Instead, the most recent data available was chosen and used. The data also come from different sources which may have different levels of accuracy and reliability. This variability in data quality affects the robustness of the findings. Possible neighbourhood-level disparities are not captured as only aggregated data for the boroughs were used. One of the nine boroughs, Westpoort, had to be excluded entirely due to a lack of data availability. The use of secondary data also led to limited consideration of green space types. The differentiation is based on the categories defined in the Urban Atlas. However, this may not fully account for the diverse functions provided by different green space types.

The study also used many perception indicators instead of measurements for the socioeconomic indicators. This was also due to limited data availability and has likely influenced the results. The indicators based on perceived data are health, unsafety, traffic, availability, appearance, and maintenance of green spaces, happiness, neighbourhood satisfaction, and future confidence. This is important because, for example, subjective measures of happiness might not align with objective measures of green space characteristics. There can be a bias in self-reported data, influenced by factors such as social desirability or personal biases.

Furthermore, the indicator green space quality did not focus on quality on an ecological level but rather just on size and diversity. This was done due to a lack of data and time constraints. It might have influenced correlations as the green space quality indicator was calculated using green space size. Furthermore, the size of green spaces in a borough was sometimes greater than the size of the borough itself. This is because green spaces were not cropped to the spatial constraints of the borough in the GIS analysis but rather the full size of all green spaces was used, even if they extended beyond the borough. This was done to account for people who live on the outskirts of a borough, as their access does not end with the border of the borough but rather they will have access to bigger green spaces.

Recommendations for Future Research

To further advance the understanding of the interplay between green spaces, climate change, and socioeconomic factors in Amsterdam, several recommendations for further research can be made. A longitudinal study would help capture changes over time and provide insights into the long-term impacts of green space developments on climate resilience and socioeconomic factors and how climate change impacts green spaces. Extreme weather events such as heat waves could be investigated separately. An analysis of seasonal changes can reveal how green spaces and urban environments respond to different climate conditions throughout the year. To ensure a comprehensive examination of localised patterns and interactions it is important to not only expand the temporal scale but also focus on a finer spatial resolution, namely at the neighbourhood level. This would allow for the identification of intra-borough disparities. Through the integration of more detailed climate change projections, such as regional models, the accuracy of predictions related to temperature anomalies and their impacts could be improved.

Other factors that might play a role and could be investigated are the influence of proximity to water bodies and the type of buildings. Western Amsterdam is farther from major water bodies, whereas southeastern areas are closer and might benefit from proximity to the IJsselmeer and Amstel River. Western boroughs might also have older buildings and infrastructure that is less energy efficient and more prone to heat retention, which is something that could be looked into. Another possible aspect to investigate are the dimensions of health. An approach that differentiates between various physical and mental health factors, for example, could be useful to better understand impacts on health. Furthermore, signs that pointed to green gentrification were identified but no precise causality or conclusion could be drawn. Even though this was already confirmed for certain neighbourhoods, there have not been any in-depth investigations on a city level for Amsterdam. Therefore, to better understand connections and impacts, it is recommended to study the effect of green gentrification on the whole city.

Additionally, vegetation indices such as the normalised difference vegetation index (NDVI) or the leaf area index (LAI) could be used to further define and better understand green space quality. Through investigating functionalities and ecosystem services provided by different types of green spaces, their varied impacts on urban areas and resident well-being can be understood.

Lastly, a policy impact assessment would help evaluate the effectiveness of policy interventions aimed at enhancing green spaces, mitigating climate change, and reducing socioeconomic disparities. It would also identify best practices for urban planning and environmental management. All of these recommendations would also help investigate interdependencies and feedback loops more.

Conclusion

This study aimed to understand the complex dynamics between green spaces, the impact of climate change in the form of rising temperatures, and socioeconomic backgrounds in Amsterdam. In doing so, it revealed the complexity of urban ecosystems and the inequalities embedded within them.

Key findings included significant disparities among boroughs in all three aspects of the research. Urban green areas were the type with the highest share of total green space size and Weesp was the borough with the biggest green space area. There were substantial differences in types of green spaces, for instance, some boroughs did not include any forests or herbaceous vegetation. Furthermore, all temperature scenario calculations showed the same spatial distribution, even if at different temperature scales. A west-to-east warming gradient was observed, with the west being expected to warm the most, although the southeast is currently the warmest region of Amsterdam. However, the environmental risks are not equally distributed among poorer and more affluent boroughs. Zuidoost is the socioeconomically most disadvantaged borough, while Zuid is the socioeconomically most advantaged. Also taking into account green space distribution and anticipated temperature changes, Weesp was identified as the borough that is the most privileged overall, followed by Zuid. Nieuw-West, West, and Zuidoost stood out as the boroughs with the worst living conditions.

Out of the green space characteristics, green space size seemed to be the most important for mitigating temperature increases, whilst green space quality played a smaller role, and the green space number even showed a slightly positive correlation with rising temperatures. Surprisingly, affluent boroughs were found to have fewer and smaller green spaces. They also showed weak positive correlations with rising temperatures. Instead, indicators that correlated more strongly with rising temperatures were population, population density, traffic, migration background, and cramped living conditions.

The study recommended prioritising the creation of large, high-quality green spaces over quantity. Such policies must align with socioeconomic and climate adaptation and mitigation goals, recognising the interconnectedness of these factors. Introducing more green spaces requires careful planning and is not a straightforward plan. Data-driven approaches were emphasised for informed decision-making. Some of the recommendations for future research were to conduct more data analyses such as longitudinal studies, analyses of seasonal changes and extreme weather events, and an analysis at the neighbourhood level to understand correlations better. Limitations included the reliance on correlations without establishing causality, as well as the use of a global climate model at a small scale. Additionally, the dependence on secondary data from multiple sources might have impacted the reliability and accuracy of the results.

Overall, the study highlighted the pressing need for the equitable distribution of green spaces to enhance climate resilience and socioeconomic equity in urban areas. It underscores the importance of taking a comprehensive and inclusive approach to urban planning and environmental management. The case study also illustrated why environmental, climate, and social justice are truly interdisciplinary and intersectional. The unequal distribution of green spaces, coupled with socioeconomic disparities, is expected to grow in the future and exacerbate the vulnerability of impacts of climate change in Amsterdam, creating and reinforcing cycles of environmental and social inequalities. As urban populations continue to grow, the reliance on green spaces as critical components of urban resilience will also increase. However, by addressing the unequal distribution of green spaces, considering the needs of diverse communities, and integrating climate adaptation and mitigation strategies, Amsterdam and other cities around the world can work towards creating more sustainable, resilient, and equitable urban environments for all residents.

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Appendix A: Additional Data

Name	Availability GS (1-10)	Appearance GS (1-10)	Maintenance GS (1-10)	Happiness (%)	Neighbourhood satisfaction (1-10)	Future confidence (%)
Centrum	6.1	6.4	6.6	65	8.1	64
Nieuw-West	7.1	7.1	6.7	64	6.8	58
Noord	6.9	7.1	6.6	65	7.3	56
Oost	6.9	7	7	65	7.8	66
Weesp	6.1	7.2	5.8	66	7.8	57
West	6.9	7	6.9	69	7.7	66
Zuid	7.1	7.3	6.9	73	8.1	64
Zuidoost	7.4	7.4	7	62	7.1	60

Table A1. *Overview of green space perception and well-being indicators (modified from Onderzoek en Statistiek, 2024). This figure was not included in the text, as the indicators were only analysed as part of the correlation analysis and used for the discussion.*

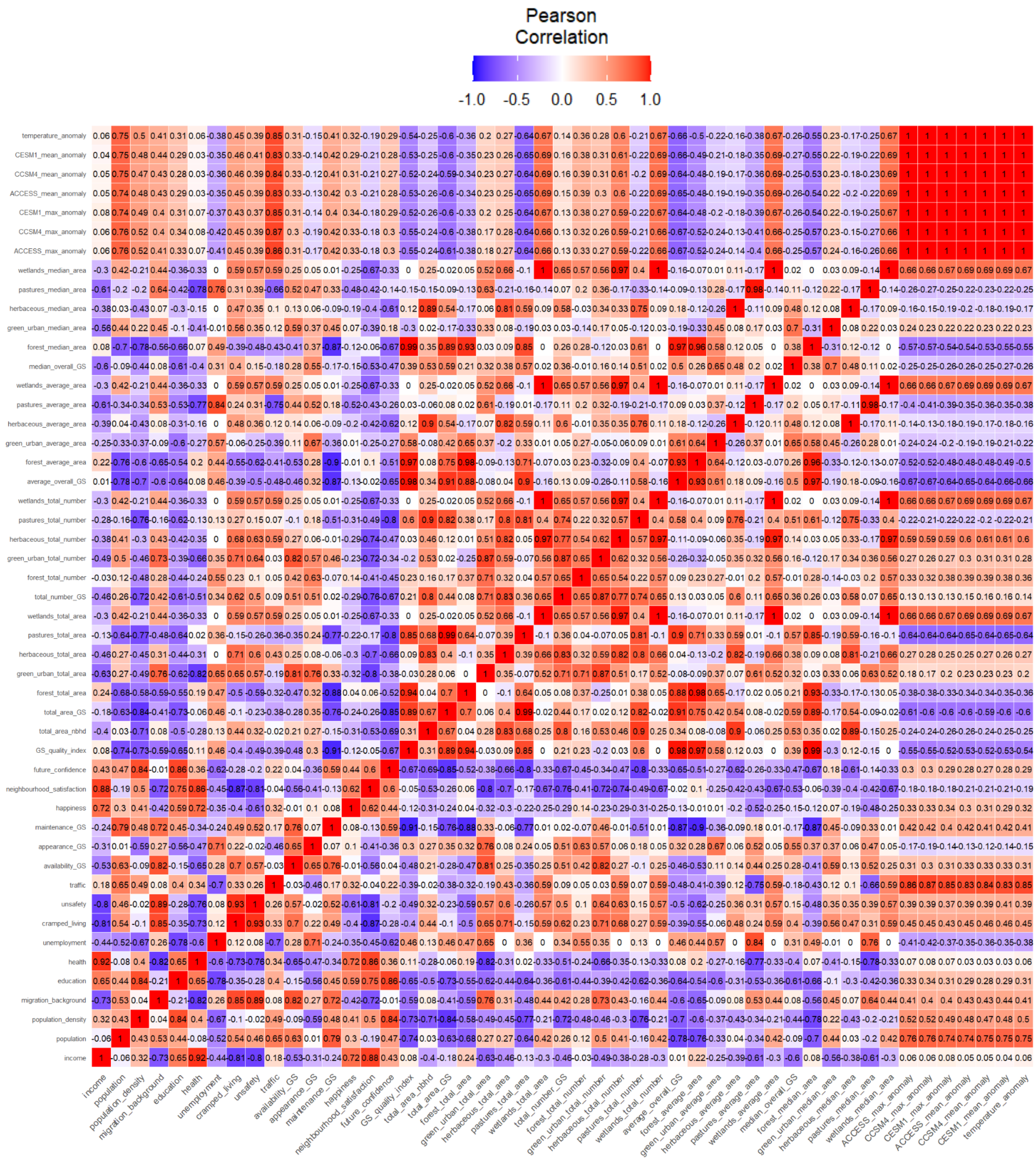

Figure A1. *Correlation heatmap of all indicators.*

Appendix B: Socioeconomic Indicator Explanations

Indicator	Definition	Year
Income	Mean disposable income per household. The disposable income is defined as the gross income minus current transfers paid (like alimony payments to an ex-partner)	2021
Population	Number of people registered in Amsterdam on January 1st	2024
Population density	Number of residents per km² of land	2024
Migration background	Percentage of people registered in Amsterdam not born in the Netherlands and/or with at least one parent not born in the Netherlands	2024
Education	Percentage of the population aged 15 to 74 with a HBO or WO degree (university degree)	2022
Health	Percentage of the population aged 19 and over that describe their own health in general as (very) good	2022
Unemployment	Percentage of the labour force aged 15 to 74 without employment. The labour force consists of all people with paid employment for at least 1 hour per week and all people without employment but	2022

	actively looking and immediately available for work	
Cramped living	Percentage of the housing stock with a living space of less than 20m² per resident	2023
Unsafety	Percentage of the population (aged 15 years and older) that occasionally (often, sometimes or rarely) feel unsafe in their own borough	2023
Traffic (nuisance)	Average score to the question: On a scale of 1 to 10, can you indicate the degree of inconvenience you are experiencing regarding the amount of traffic? Low score indicates little or no inconvenience, high score indicates high inconvenience	2021
Availability of green spaces	Average answer to the question: What is your opinion on the availability of green spaces in your neighbourhood? 1 = very insufficient and 10 = very sufficient	2021
Appearance of green spaces	Average answer to the question: How would you assess the green spaces in	2019

	your neighbourhood? 1 = very ugly and 10 = very beautiful	
Maintenance of green spaces	Average answer to the question: How would you assess the maintenance of green spaces in your neighbourhood? 1 = very insufficient and 10 = very sufficient.	2021
Happiness	Percentage of the population aged 18 and over that consider themselves a (very) happy person	2022
Neighbourhood satisfaction	Average answer to the question: How satisfied are you with your neighbourhood? Score on a scale from 1 to 10. A high score means a positive assessment, a low score is a negative assessment.	2021
Future confidence	Percentage of the population aged 18 and over that have confidence in the future	2022

Table B1. Socioeconomic indicator explanations (modified from Onderzoek en Statistiek (2024)).