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Heat adaptation through urban greening: Geospatial evidence on socioeconomic needs, political goals, and financial constraints

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Heat Adaptation through Urban Greening: Geospatial Evidence on Socioeconomic Needs, Political Goals, and Financial Constraints

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Heat Adaptation through Urban Greening: Geospatial Evidence on Socioeconomic Needs, Political Goals, and Financial Constraints

Paulin Zahn and Miriam Rehm

September 2026

Abstract:

This paper investigates whether land use changes of greening are linked to socioeconomic needs, political goals, and financial constraints. It uses data for 153 German cities at the 1km grid level and at the city level from the CORINE Land Cover Plus Backbone dataset, and combines them with spatial indicators of heat exposure, socioeconomic disadvantage, demographic structure, population size, local political characteristics, and fiscal capacity. We find that German cities experienced more sealing than greening between 2018 and 2023, with only seven cities showing a net increase in green space. There is no discernible link between greening and needs as measured by higher heat exposure, greater socioeconomic disadvantage, or population growth at the spatial grid level. We also do not find evidence that a city adopting a heat plan or the political orientation of municipal governments are linked to increased greening. However, our data show that fiscal capacities matter, as fiscally constrained municipalities undertake lower greening.

1. Introduction

Climate-related challenges disproportionately fall on cities, even in temperate countries like Germany (Schwingshackl et al. 2024). Higher temperatures cause environmental, health, and productivity risks, particularly in densely populated urban areas (Karwat and Franzke 2021, He 2022). Vegetation is one of the most important measures for low-emissions heat adaptation, since it can both absorb water and protect urban areas from flooding while also reducing temperatures in cities (Zölch et al. 2017). In German cities, however, both access to green spaces (König 2024) and the capacity to adapt to increasing heat vary across socioeconomic groups (Osberghaus and Abeling 2024).

Understanding the factors that drive heat adaptation is thus highly relevant (Adger 2003). Urban greening is particularly urgent in urban areas exposed to high heat stress (Gill et al. 2007) and in neighborhoods with populations that are especially vulnerable to extreme temperatures (Malloy and Ashcraft, 2020), including low-income households (Osberghaus and Abeling 2021; Grislain-Letrémy, Sixou and Sotura 2025), migrant communities (Klopfer and Pfeiffer 2023; König 2024), and elderly residents (Ebi et al. 2021). The need for adaptation is recognized politically: nearly two thirds of German cities have adopted climate adaptation and heat action plans (subsumed hereafter under "heat plans" for simplicity). These plans identify high-need urban areas (Otto et al. 2021) and aim to adapt these areas to heat-stress (Hannemann et al. 2023), but it is not yet well understood whether they succeed in doing so. In fact, research shows that the party affiliation of municipal governments may shape the implementation of heat adaptation policies (Bayes, Molden and Druckmann 2026). At the same time, cities are faced with constraints that may affect their greening efforts: housing and land shortages intensify competition over limited urban space (United Nations 2018). Finally, cities suffer from long-standing and well-documented financial constraints (Truger 2018; Beznoska and Kauder 2019) which may reduce their capacity to implement and maintain urban greening measures. This paper thus investigates whether urban greening is linked to sociodemographic needs, political goals, or financial constraints at the municipal level. Concretely, we use a novel geocoded dataset to analyse how public climate adaptation measures and lack thereof (that is, greening and sealing) were allocated in German cities between 2018 and 2023. To understand whether and how green spaces are targeted, we link these data to a distributional analysis covering the population's needs (socioeconomic disadvantages, demographic structure), local political characteristics, and cities' fiscal capacities.

Urban greening is particularly relevant in areas strongly affected by urban heat, as greening can mitigate local temperatures (Gill et al. 2007). Urban areas experiencing the highest heat exposure are also those characterized by the greatest degree of surface sealing (Klopfer and Pfeiffer 2023). The literature is unequivocal that the distribution of green spaces across diverse social groups matters (Eyni et al. 2025), and it has shown that low-income groups (Osberghaus and Abeling 2021; Grislain-Letrémy, Sixou and Sotura 2025), non-natives (Klopfer and Pfeiffer 2023), and the elderly (Ebi et al. 2021) are particularly vulnerable to heat. A sizeable strand of the literature studies the current distribution of greening, and in particular its availability for groups with a low socioeconomic status in individual municipalities (Lakes, Brückner and Krämer 2013; Schüle, Gabriel and Bolte 2017; Xu et al. 2018; Klopfer and Pfeiffer 2023). Lakes, Brückner and Krämer (2013) show a positive correlation between vegetation and socioeconomic status in Berlin, suggesting that groups with a low socioeconomic status tend to live in areas with less vegetation and a lower quality of the environmental index. Klopfer and Pfeiffer (2023) similarly find strong negative correlations between high land surface temperatures and the provision of green spaces as well as positive correlations between green spaces and social status for the metropolitan Ruhr area in Western Germany. Evidence for Munich similarly indicates a negative association between socioeconomic status and green spaces at the neighborhood level (Schüle, Gabriel, and Bolte 2017), although the strength and significance of this relationship varies spatially and depends on local urban structures (Xu et al. 2018). Most relevant for this paper, König (2024) investigates patterns of environmental inequality with remote sensing data on urban green spaces and data on socioeconomic and demographic factors in 243.607 urban neighborhoods in Germany. The study finds no effect for individuals with a low socioeconomic status, but shows that non-Germans are less likely to live close to green spaces.

The existing literature also documents that although individual adaptation measures such as green roofs and facades, awnings, or air conditioning can reduce heat exposure even where urban planning and public policy fails to do so, these measures require costly investments which are particularly burdensome for low-income groups (Chakraborty et al. 2019): Not only are lower income and higher age groups more affected by urban heat islands, but they also have fewer capabilities to adapt to high temperatures (Doremus, Jacqz and Johnston 2022; Osberghaus and Abeling 2021; Grislain-Letrémy, Sixou and Sotura 2025; Slesinski et al. 2025).

These distributional patterns are unlikely to arise independently of other urban dynamics, historical and institutional factors in urban development notwithstanding (Fritsch and Wyrwich 2021). Besides heat adaptation and urban greening, cities are faced with population growth and

rising needs for housing and land shortages (United Nations 2018; Danne, Gorning and Pagenhardt 2025), which previous research has linked to sealing (Behnisch, Poglitsch and Krüger 2016). City governments thus face a trade-off between the need for climate adaptation that results from rising temperatures on the one hand and rising housing and business construction resulting from population growth on the other hand (Erlwein et al. 2023).

However, whether vulnerable groups benefit from heat adaptation measures under these conditions remains an open question. The research on whether social adaptation measures are targeted at vulnerable groups is in its infancy. Syrbe et al. (2025) develop a monitoring approach for the location, size, and effectiveness of urban green spaces and analyse changes between 2019 and 2021 but without linking these patterns to socioeconomic indicators. To the best of our knowledge, two recent studies examine social indicators and heat adaptation in individual locations in the U.S.: Li et al. (2023) find that while heat exposure declined over a period of 20 years, vulnerable groups benefitted underproportionally from heat adaptation in Charlotte. Eyni et al. (2025) analyse the distributional outcomes of heat adaptation measures in Baltimore. For Germany, Wendnagel-Beck et al. (2021) examine the text of climate adaptation plans, project plans and cartographic information and conduct interviews in two German cities and find that social indicators receive less attention than physical indicators of cities. This dearth of evidence on how public heat measures are distributed (Lager et al. 2023) is one gap that this paper aims to improve.

Nearly two thirds of German cities implemented heat plans to address rising urban temperatures and specify local heat adaptation measures (Otto et al. 2021). These municipal strategies are embedded in broader national and international climate adaptation goals that emphasize urban greening to improve living conditions and mitigate heat stress (Matthies et al. 2008; BMUKN 2024). The objective of these plans is to identify urban areas requiring priority action due to their building layout, construction materials, and social structure. In particular, they aim to improve access to green spaces in highly sealed urban heat islands and for socially disadvantaged groups (BMUKN 2024). To the best of our knowledge, this is the first evaluation investigating the effects of heat plans on land use changes across municipalities. However, the degree to which cities implement such plans varies considerably. An investigation by Otto et al. (2021) shows that adaptation politics vary across German cities for several reasons: cities that started early, that are larger, and that have more opportunities to obtain funding tend to do show more commitment to adaptation policies (Otto et al. 2021). Recently, Otto et al. (2025) analyse municipal adaptation activity in 104 German cities and show that socioeconomic factors

of cities are only weakly linked to adaptation activities, while larger, more compact, and more exposed cities show higher adaptation activities.

Erlwein et al. (2023) also find that larger cities employ climate adaptation managers more often, whereas smaller cities lack the necessary resources. Their results also show that the change of political majorities can influence the adaptation behavior of cities (Erlwein et al. 2023). Research on the U.S. finds that party politics and adaptation behavior matter (Bayes, Molden and Druckmann 2026) and that climate and environment politics vary across different political governments (Matuszczak et al. 2020).

These adaptation goals are hemmed in by a constraint: Municipalities have been under financial pressure for several decades (Beznoska and Kauder 2019). Current research identifies the expenditure side as the main driver of these fiscal constraints, as municipal spending consistently exceeds available revenues. Legally mandated tasks including rising social expenditures and personnel costs contributed to a strong growth in municipal expenditures that is difficult to offset through own-source revenues (Döring and Wohltmann 2025). As a consequence, municipalities carefully prioritize their spending and often treat investments as an adjustment variable, contributing to a growing investment backlog that further restricts their long-term fiscal and economic capacity (Döring and Wohltmann 2025). Two indicators capture this fiscal stress: First, liquidity credits indicate structural underfunding despite their original design to cover short-term liquidity shortages, as they are now often used to finance ongoing deficits on a permanent basis (Beznoska and Kauder 2019; Döring and Wohltmann 2025). Therefore, high levels of liquidity credits can be seen as a sign of fiscal stress and increased financial risk (Bertelsmann Stiftung no date). Second, revenues are captured through trade tax revenues on profits of local businesses, which are one of the most important sources of municipal revenue in Germany (Neimanns and Bremer 2025).

This paper investigates how municipalities have navigated these challenges by asking how urban greening dynamics have developed in recent years, whether they are targeted at vulnerable groups, and whether they are related to the politics and finances within cities. Concretely, we examine how urban greening evolved in 153 German cities between 2018 and 2023 using novel CORINE Land Cover plus Backbone data. We investigate whether greening efforts are spatially aligned with areas of higher heat exposure, socioeconomic vulnerability and population size, and we explore how adaptation planning, political contexts, and local fiscal capacity shape the dynamics of urban greening.

In doing so, the paper contributes to research in economic geography on urban environmental change, climate adaptation, and sociospatial inequality in several ways. First, to the best of our knowledge, this is the first study to analyse changes in land use or adaptation on a large scale and examine their distributional effects across Germany. It provides a systematic overview of recent changes in urban greening and sealing across a large sample of German cities and relates these dynamics to key urban and socioeconomic characteristics. By relying on a harmonized dataset, the study secondly enables systematic comparison across a large number of cities, with the option to investigate cities individually at a more detailed level. Finally, the paper advances urban greening monitoring approaches by integrating socioeconomic factors alongside climate adaptation considerations, thereby addressing the sociospatial dimensions of urban heat in marginalized and low-income communities.

The results show that German cities sealed more of their surfaces than they greened during the time period under observation. Where greening did take place, the development of new green spaces is not linked to areas affected by heat or to higher need indicated by higher age or a low socioeconomic status in terms of poverty or migration background, and population growth does not lead to a decrease in urban greening. What is more, our results show that neither heat plans nor party politics appear to be linked to more greening. We do find, however, that the amount of sealing correlates with cities' financial constraints.

The rest of the paper is structured as follows. The next section describes the data, introduces the indicators and describes the methodology. Section 3 contains the results on urban greening dynamics and socioeconomic needs, political goals and financial constraints, respectively. Section 4 concludes.

2. Data

We make use of the novel, harmonized geo-coded CORINE Land Cover plus Backbone data set to capture both the level and change of greening and sealing in the years 2018 and 2023. We match these with administrative data at 1km x 1km grid resolutions for urban heat from the German Weather Service, the prevalence of low socioeconomic status and population data from the Federal Employment Agency (Helbig 2023), the share of elderly residents and migration background from the German Census 2022. For our political variables, we use data at the city level covering political orientations of municipal governments, the existence of formal heat plans, and the financial situation of cities. All datasets are projected into a common coordinate reference system, ETRS89 / LAEA Europe (EPSG: 3035), to ensure spatial consistency across

layers. This yields 20.765 observations for 153 medium-sized to large German cities covering nearly 40% of the German population, in the years 2018 and 2023.

The dependent variable is changes in urban green spaces as an indicator of public heat adaptation efforts based on the CORINE Land Cover plus Backbone dataset for 2018 and 2023, following the approach applied by Metsoja et al. (2025), as it provides the highest accuracy among land-use datasets (Ursu et al., 2025) with a spatial resolution of 10m × 10m which we aggregate to 1km x 1km and to the city level to ensure consistency with the other data sources. Green surfaces include woody needle-leaved trees, woody broadleaved deciduous trees, woody broadleaved evergreen trees, low-growing woody plants, permanent herbaceous vegetation, periodically herbaceous vegetation, as well as lichens and mosses; they exclude areas with less than 30% vegetation cover that are typically associated with stone or gravel surfaces (non- and sparsely vegetated areas). We do not consider water, snow and ice, coastal seawater buffer, outside area, or areas lacking data in this analysis. Our dependent variable is the change in green spaces in percentage points and square meters by subtracting the share of green space per grid in 2018 from that in 2023. Baseline greening per capita, which shows square meters of green space per person and only includes grids that were inhabited on average between 2013 and 2017, is used as a control variable for partial correlations.

The first set of explanatory variables intends to capture socioeconomic needs surrounding greening. First, urban heat islands capture the requirement for adaptation measures. Data for annual mean daytime maximum urban heat island intensity at a 1km x 1km resolution in 2017 are provided by the German Weather Service (German Weather Service 2024). Values range from 0 to 80, with higher values indicating stronger heat island effects.

Next, we use three variables covering socioeconomic disadvantage and distributional questions: the share of social assistance recipients as an indicator of low-income populations, migration background and age. Social assistance recipient data are provided by the German Federal Employment Agency (Helbig 2023), measuring the average share of individuals receiving long-term benefits under the German Social Code II[1] relative to the population under 65 years of age for 2013 to 2017. Migration background is the share of individuals with non-German citizenship in the total population, based on the German Census (2022) data. Individuals are classified as foreigners if they hold a non-German citizenship; persons with German citizenship are classified as German regardless of additional nationalities. Age, also from the Census (2022),

[1] In Germany, unemployed individuals receive means-tested social assistance under the German Social Code II when unemployment assistance is terminated after 12 months.

is measured as the share of the population aged 65 years or older within each 1km grid cell. Some values are flagged as statistically uncertain according to census documentation. A total of 780 grid cells contain missing values due to spatial joins between migration and age datasets. For the socioeconomic status and the age analysis, only inhabited grid cells are included.

The last variable for this set of explanatory variables is population growth from the German Federal Employment Agency (Helbig 2023), which captures the need for additional sealing due to additional housing and business space. It is calculated for each city by dividing the absolute population change between 2018 and 2022 by the population size in 2018. Furthermore, the population size in 2022 is used for distinguishing large from small cities in investigating other explanatory variables.

Our second set of variables covers (political) goals linked to heat reduction: a novel data set covering heat plans; and local party politics. Municipal heat adaptation policies are captured using information from officially published heat plans as of September 2025. We generate the binary variable indicating the existence of a heat plan from a systematic web search, which we complemented with 153 direct inquiries to city administrations. These yield 98 cities with a heat plan and 55 cities without one.[2]

To analyse the political context at the city level, we use data from the German Election Database (Heddesheimer et al. 2025). Following Neimanns and Bremer (2025), we classify Die Linke, Bündnis 90/Die Grünen, and the Social Democratic Party (SPD) as left-leaning, and Christian Democratic Union/Christian Social Union (CDU/CSU), the Free Democratic Party (FDP), and the Alternative for Germany (AfD) as right-leaning. The party receiving the largest vote share in municipal elections before 2018 (2013 to 2017) is used to define local party politics.

Finally, municipal fiscal capacity is measured following Neimanns and Bremer (2025) using data from Bertelsmann Stiftung (no date) for the period 2013–2017 to capture financial conditions prior to 2018 using the statistical offices of the German federal states and FORA mbH. Two indicators are used: First, liquidity credits (cash or overdraft credits) per capita are calculated as the total volume of municipal liquidity credits divided by the number of residents. Second, net trade tax revenue per capita is used as an indicator of local economic strength. Values are calculated per resident and expressed in Euro.

[2] See the list of cities and coding information in Appendix Table A1.

Table 1. Variables.

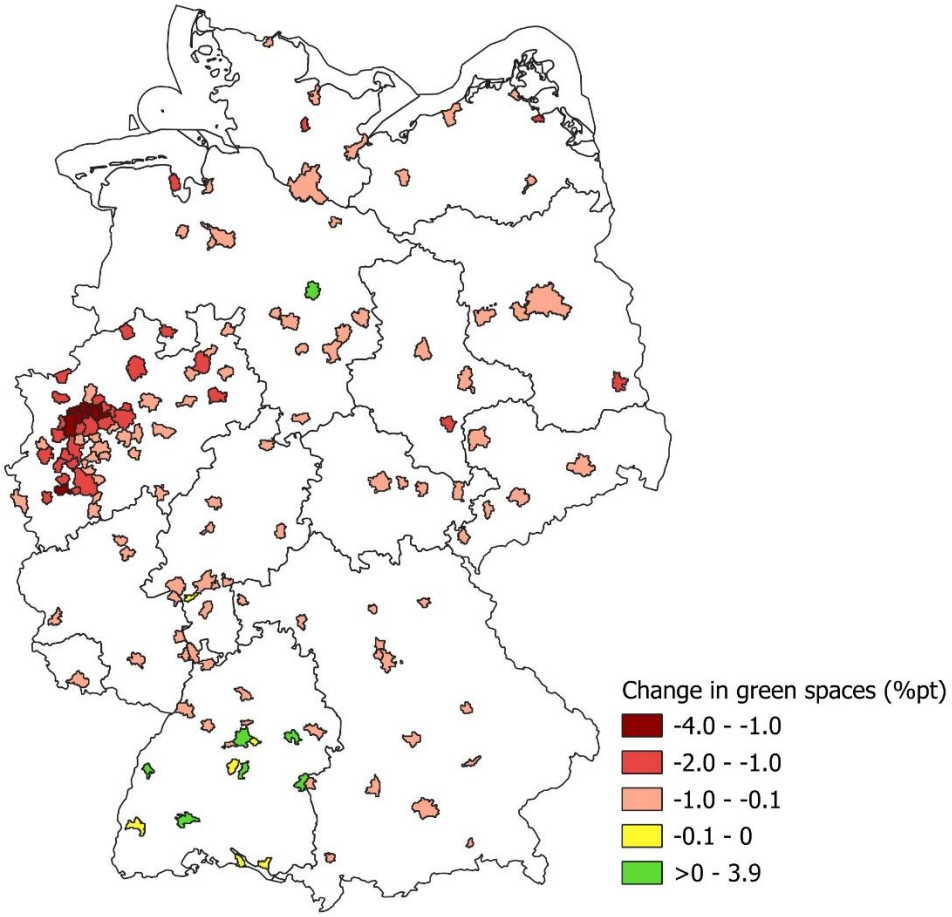
Variable	Definition
Change in green space	Change in green space share between 2018 and 2023, unit: percentage points
Baseline greening (per capita)	Share of urban area covered by green space (per capita) in 2018, unit: % (per capita in m^2)
Urban heat island effect	Index of daily maximum urban heat island intensity in 2017, unit: scale 0–80
Low socio-economic status	Share of people receiving benefits under SGB II among all residents under the age of 65 (mean annual value, 2013–2017), unit: %.
Migration background	Share of residents without German citizenship in 2022, unit: %
Age	Share of residents aged 65 and above in 2022, unit: %
Relative population growth	Percentage change in total population between 2018 and 2022, unit: %
Heat plan	Dummy variable indicating the existence of a heat action or climate adaptation plan by 2025, unit: 1 = yes, 0 = no.
Political majority orientation	Political orientation of the strongest party in municipal elections before 2018, categorized as left-wing or right-wing, unit: left and right
Liquidity loans per capita	Average liquidity loans allocated to finance current expenditures per resident in the core budget (mean annual value, 2013–2017), unit: euros
Net trade tax revenue per capita	Net business tax revenue per resident after deducting the business tax allocation (mean annual value, 2013–2017), unit: euros

Note: This table shows the dependent variable change in green spaces in the first row, the control variable baseline greening (per capita) in the second row, and the independent variables.

Source: own elaboration.

For an overview of our data, Table 1 contains an overview of the dependent and explanatory variables and their definitions and Figure 1 shows a map of our dependent variable, the change in the share of urban green spaces between 2018 and 2023 across our sample of 153 German cities. The vast majority of cities show negative changes for greening (colored in shades of red in Figure 1). Several cities exhibit no change in greening in yellow, while only seven out of the 153 cities gained green spaces over the period under observation, colored green. Six of these seven cities are located in the wealthy South-Western federal state of Baden-Wuerttemberg. Changes in greening range from 400 m² to 3,200 m², which amounts up to 0,4 percentage points of urban surface. For further information on our dependent variable, see Figure A1 in the Appendix for a map of the baseline share of green space in 2018, and Figure A2 in the Appendix for sealing.

Figure 1. Change in the share of green space in German cities between 2018 and 2023.



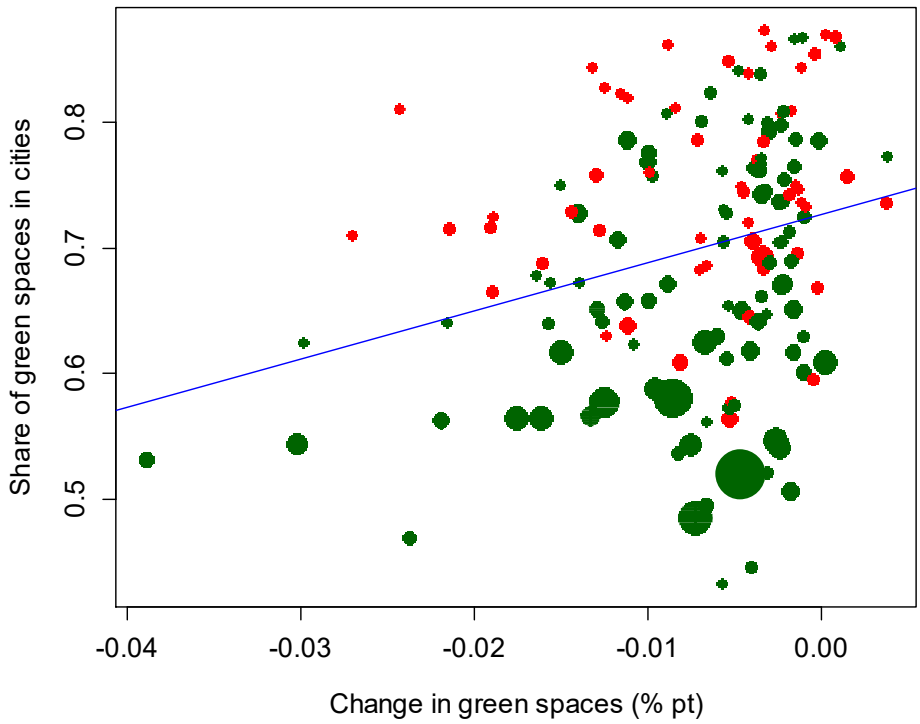
Note: This figure shows the proportion of urban space that changed either to or from green surfaces for our sample of 153 cities.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023.

Finally, since the change in greening may depend on the baseline level of green spaces already present in urban spaces, we show the correlation between these two indicators in Figure 2, while also providing a first glimpse at the relation with city size and heat plans. First, there is a positive correlation between the level and the change of the share of green spaces in our 153 cities. That is, cities that already have a larger share of urban green spaces also tend to gain more green spaces. Although this correlation largely disappears at the grid level, we control for the baseline greening in the rest of the paper (see Figure A3 in the Appendix). Second, baseline greening appears to be negatively correlated with city size as the size of the dots demonstrates: larger cities have a lower baseline greening in 2018 ($r = -0.38$; $p < 0.01$); within large cities, the largest also seem to lose a smaller share of green spaces. Third, the coloring of the dots shows that smaller cities are less likely to have a heat plan, and that the level of greening appears to be

negatively correlated with the existence of a plan, while there is little detectable correlation with the change in greening at the city level.

Figure 2. Level and change in the share of urban green spaces, city size, and heat plans.



Note: This figure shows a linear regression line correlating the unweighted level (baseline greening in 2018) and the change in the share of urban green space from 2018 to 2023 for all 153 cities ($r = 0.27$; $p < 0.01$). The size of the dot indicates city size and the color the existence of a heat adaptation plan (green = yes, red = no).

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster), Census 2022, own work based on a survey and research on heat plans.

Regarding methods, this paper applies scatterplots and Pearson correlation coefficients to describe the relationship between land cover data and the other indicators. As discussed, we control for baseline greening per capita using partial correlations. To test spatial autocorrelation, we calculate global Moran's I for each variable based on a queen-contiguity spatial weights matrix with row-standardized weights.

3. Results

This section first examines spatial autocorrelation. We then explore the question of how the change in the share of green spaces is distributed within German cities at the 1km grid level with regard to socioeconomic vulnerabilities. These are captured by different indicators that may point to a higher need for the cooling effect of green spaces – such as heat islands, low-

income levels, age, migration –, while population growth captures a reduced ability to expand green spaces.

The results for the spatial autocorrelation using Moran's I show that urban green spaces (baseline greening in 2018) in our research area are clustered with a value of 0.65, whereas the changes in green surfaces show lower clustering with a value of 0.33. That is, the change in urban green spaces rarely occurs in neighboring 1km grids. The distribution of Moran's I values for our variables is shown in Figure A6 in the Appendix.

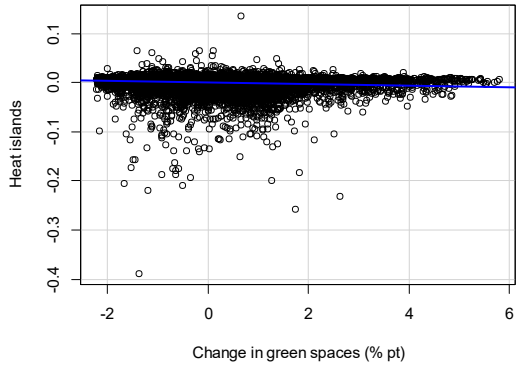
Figure 3 shows the correlations of the change in the share of urban green space with the first four indicators of need for greening – heat islands, the share of social assistance, of non-German residents, and of old-age residents –, controlling for baseline greening per capita in 2018 using partial correlations. The data show no evidence that cities preferentially undertook more greening in grid cells that are either affected by heat or have a high proportion of groups with higher needs for greening. As can be seen visually from the regression lines, the correlation is essentially flat in all cases. The Pearson correlation coefficient ranges from -0.05 for old age to -0.14 for low-income groups and is highly statistically significant. We therefore do not find support for the hypothesis that municipalities may undertake greening where there is the highest thermal need, despite the fact that our data support the well-established fact that greener areas are less likely to be overly hot in cities; urban heat islands are negatively correlated with the baseline level of green spaces (see Figure A4 in the Appendix).

In summary, we cannot see more than very low correlations on the grid level between increased or decreased greening in German cities and heat, high poverty, high migration, or high age. The distribution seems to depend on other factors.

Figure 3. Change in the share of green spaces and indicators of the need for greening.

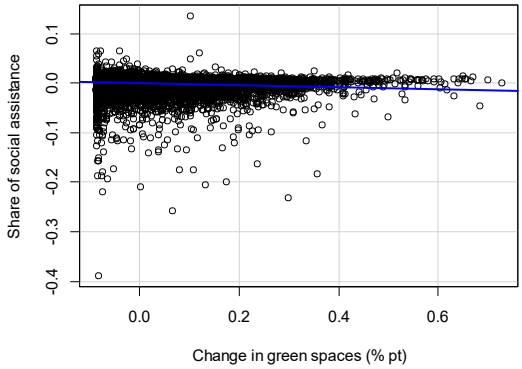
a) Heat islands

(r = -0.12; p < 0.01)



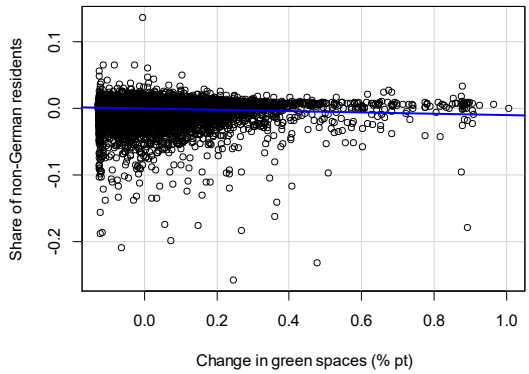
b) Share of social assistance

(r = -0.14; p < 0.01)



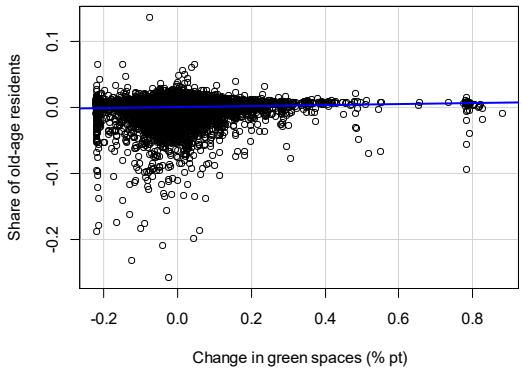
c) Share of non-German residents

(r = -0.09; p < 0.01)



d) Share of old-age residents

(r = -0.05; p < 0.01)



Note: The graphs show scatter plots of the residuals of partial correlations of the change in the share of urban green space between 2018 and 2023 on the x-axis with four indicators of need for greening on the y-axes: daily urban maximum heat (panel a, n=20.548), the share of social assistance recipients in the population (panel b, n=17.074), the share of non-German citizens (panel c, n=17.007), and the share of residents aged 65 and above (panel d, n=17.007) for 1km x 1km grids in 153 German cities. We control for the baseline greening per capita in 2018. Note that the axes of a partial-correlation plot do not correspond to the original measurement scales and show correlations of the regression residuals.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster), Federal Employment Agency (Helbig 2023), Census 2022 and German Weather Service 2024.

As discussed above, population growth may place pressure on cities to undertake less greening or to seal more surfaces. In our data, we do not find evidence that population growth correlates with sealing or the loss of green surfaces at the 1km grid level or at the city level (see Figure A5 in the Appendix).

Politically, heat plans are intended to guide the implementation of measures mitigating heat stress. We therefore turn to the question whether they help explain variation in adaptation behavior next. Employing our novel data set covering heat plans in 153 German cities, the left-

hand side panel of Figure 4 shows that cities with a heat plan not only have a lower median level of average greening (0.67) in 2018 than cities without heat plans (0.74). The density of their baseline greening is also notably lower than that of cities without heat plans. This can be interpreted as cities with a greater requirement for cooling through greening having a higher likelihood to develop heat plans.

However, our data do not contain evidence that the existence of heat plans led to larger increases in green urban spaces: The median change in the share of green spaces between 2018 and 2023 is around -0.5 percentage points, both for cities with and for cities without a heat plan. Similarly, the median change in green space in square kilometers for cities with heat plans is around -0.57 km² and without heat plans around -0.53 km². As the right-hand side panel of Figure 4 shows, the distribution of the change in green spaces in cities with and without heat plans is very similar not only at the median, but also at the upper and lower end.

Figure 4. Baseline greening and change in green spaces for cities with and without a heat plan.



Note: This figure shows the baseline share of green space in total urban space 2018 (left-hand side panel) and the change in the share of green space from 2018 to 2023 (right-hand side panel) for cities without and with a heat plan.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster) and own work based on a survey and research on heat plans.

As Table 2 shows, cities with a left-leaning municipal government before 2018 have a slightly lower median level of baseline greening at about 67% compared to cities with a right-leaning government at about 73%. Expectedly, heat plans in 2025 are more prevalent in cities that had a left-leaning government before 2018 (77%) than in cities with a right-leaning government (55%). We hypothesize that the party affiliation of municipal governments may correlate

systematically with the change in the share of green urban spaces. However, the median change in the share of green spaces in cities with a left-leaning government amounts to -0,57, compared to -0,43 percentage points for right-leaning governments.

Table 2. Differences in baseline greening, the change in green space, and heat plans by political orientation of municipal governments.

	Left-leaning municipal government (before 2018)	Right-leaning municipal government (before 2018)
Level of baseline greening 2018 (median)	67%	73%
Change in green space 2018-2023 (median)	-0,57% pt	-0,43% pt
Share of cities with a heat plan	77%	55%

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster), Heddesheimer et al. 2025 and own work based on a survey and research on heat plans.

The distribution of the citywide change in greening in the right-hand panel in Figure 5. Violin plots comparing the level and change in greening between municipalities with left- and right-leaning governments, however, suggests that the difference seems to be relatively small, with only slightly more cities with a left-leaning government and a higher loss of urban green space. This difference might be related to the observation that cities with a higher baseline level of urban greening tend to experience smaller losses of green space than cities with lower baseline greening.

Figure 5. Violin plots comparing the level and change in greening between municipalities with left- and right-leaning governments.



Note: This figure shows the baseline share of green space in total urban space 2018 (left-hand side panel) and the change in the share of green space from 2018 to 2023 (right-hand side panel) for cities a left- and a right- leaning municipal government.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster) and German Election Database.

The dataset provides a comprehensive view of greening practices across German cities, as well as insights into individual city behaviors. For instance, Duisburg, a city in North-Rhine Westphalia with less than 500.000 inhabitants, a reputation for an ailing local economy and a left-leaning municipal government. At about 54% of greening in 2018, it ranks in the medium to low range compared to other cities, and it lost a relatively high share of urban green spaces between 2018 and 2023 at about 3 percentage points. Although Duisburg adopted a heat plan, its negative change in greening worsened existing heat islands and the reduction in green spaces was correlated with areas in which a larger share of social assistance recipients reside.

In contrast, Bayreuth is a city in economically thriving Bavaria with over 70.000 inhabitants and a municipal government led by a coalition of conservative and right-wing parties. Bayreuth's level of greening is high; it amounted to about 75% in 2018 and it lost a relatively small share of it by 2023 at 0.4 percentage points. Although it did not adopt a heat plan, the loss was slightly lower in areas with urban heat islands and our data show no statistically significant correlation with socioeconomic characteristics.

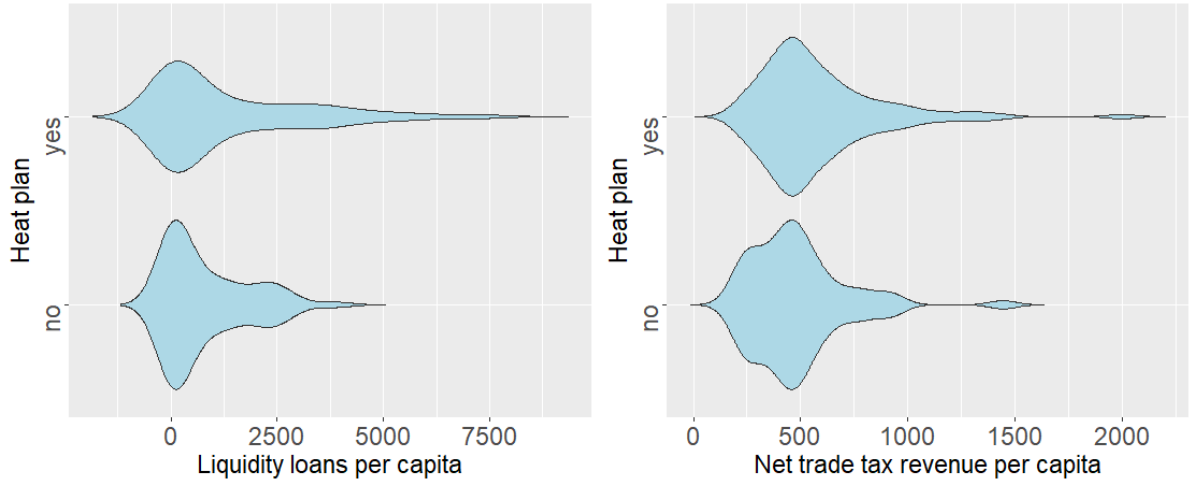
These examples illustrate the seemingly paradoxical nature of our results, while also pointing to a possible explanation: Duisburg, a city in Germany's "rust belt" struggling with deindustrialization and a declining population, is severely hampered by fiscal constraints with

liquidity loans amounting to about 3.400 € per capita and net trade tax revenue to about 360 € per capita. Compare this to thriving Bayreuth, which is not saddled with liquidity loans and receives net trade tax revenue of over 900 € per capita.

That is, Duisburg faces substantially greater fiscal constraints, and it is possible that limited financial capacity may hinder the implementation of greening measures despite a comparatively higher need for heat adaptation. We turn to this question next by investigating how urban greening dynamics are associated with liquidity loans, which are often used by cash-strapped cities to finance ongoing deficits, and net trade tax revenues, one of the most important sources of municipal revenue in Germany.

As Figure 6 shows, cities without a heat plan have very similar, if slightly lower, liquidity loans and net trade tax revenues as cities with a heat plan: The respective per capita median values are 317€ with versus 300€ without a plan for liquidity loans, and 501€ with versus 450€ without a plan for net trade tax revenues. That is, cash-strapped cities still appear to be similarly likely to draw up heat plans as their better-off peers.

Figure 6. Violin plots comparing the city level distributions of liquidity loans and net trade tax revenue per capita between municipalities with and without a heat plan.



Note: For Berlin, Bremen, Bremerhaven and Hamburg, no data on liquidity loans are available resulting in n = 149 and for net trade tax revenue n = 153.

Source: Bertelsmann Stiftung and own work based on a survey and research on adaptation plans.

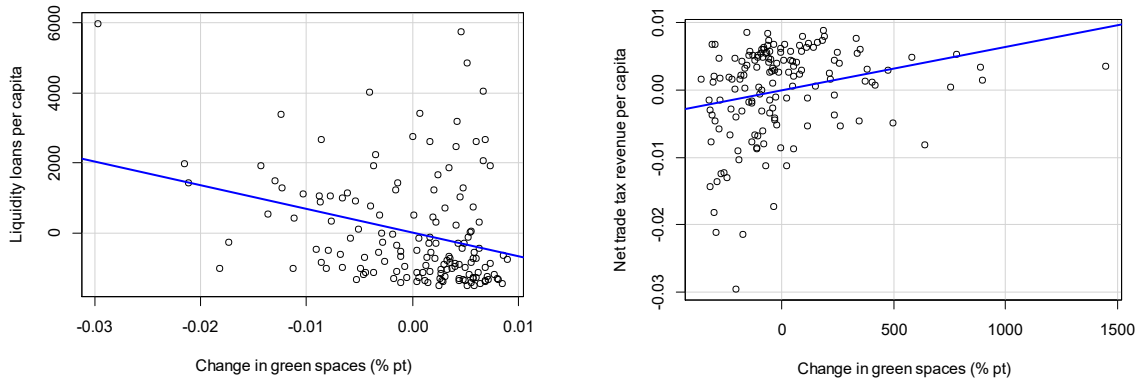
However, when it comes to implementation, the picture changes. Figure 7 depicts the change in the share of green space between 2018 and 2023 versus, first, liquidity loans per capita in the left-hand side panel, and, second, the trade tax in the right-hand side panel. The data show

statistically significant effects linking these fiscal constraints to the change in the share of green spaces: cities with higher liquidity loans per capita and those with lower net revenue per capita from the trade tax (i.e., in both cases a worse financial position) tend to have higher losses in green spaces after controlling for the level of greening. The Pearson correlation coefficients amount to –0.30 and 0.25, respectively, and are both statistically highly significant.

Figure 7. Change in the share of green spaces and indicators of financial constraints of municipalities.

a) Liquidity loans per capita
(r = -0.30; p < 0.01)

b) Net trade tax revenue per capita
(r = 0.25; p = 0.01)



Note: The graph shows scatter plots on the residuals of partial correlations of the change in the share of urban green space between 2018 and 2023 on the x-axis with two indicators of financial constraints of municipalities on the y-axes: liquidity loans per capita in EURO (panel a, n = 149) and net trade tax revenues per capita in EURO (panel b, n = 153) for German cities. Panel (a) excludes Berlin, Bremen, Bremerhaven, and Hamburg due to lacking data on liquidity loans. Note that the axes of a partial correlation plot do not correspond to the original measurement scales and show correlations of the regression residuals.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster) and Bertelsmann Stiftung.

To conclude, our results show that changes in urban greening are generally small across German cities over our period of observation, but if surface covers changed, then mostly in the direction of higher sealing. None of our measures of socioeconomic needs are linked to greening; higher heat exposure, greater socioeconomic disadvantage, and population growth are all substantively very small at the spatial grid level. The same holds true for political aspects: a city adopting a heat plan or the political affiliation of municipal governments are irrelevant to greening in our data. The only factor that appears to be associated with greening is fiscal constraints: a higher

level of liquidity-relief loans and lower net trade tax revenue per capita go along with stronger declines in green space.

These findings are only partly mirrored in the literature. We confirm the existing evidence on sealing in Germany (Syrbe et al. 2025) and the correlation of city size and heat adaptation plans (Otto et al. 2021). However, our data do not support a connection between population growth and sealing or the loss of green spaces, in contrast to Behnisch, Poglitsch, and Krüger (2016), and we also do not find a link between political parties and greening, in contrast to Matuszczak et al. (2020). In both cases, this may be well due to the shorter time period covered by our data, but it might also be a result of changing trends or the high-quality nature of the CORINE Land Cover Plus Backbone data. Our key finding that fiscal capacity is associated with greening dynamics fits well with the evaluation in Bergs (2025), which finds that land development can create a self-reinforcing cycle of infrastructure investment, sealing, and additional local tax revenues, thereby incentivizing further land consumption. Bergs (2025) further suggests that differences in fiscal autonomy and local revenue incentives may contribute to divergent land-use trajectories based on a comparison of German county-free and county-affiliated cities.

Several limitations of this analysis should be borne in mind. First and foremost, this paper only investigates correlations and our data and empirical strategy do not permit causal inferences. While endogeneity may be a concern, we control for the level of baseline greening and assess spatial autocorrelation to reduce the risk that observed relations reflect pre-existing spatial patterns. Second, despite the exemplary accuracy of the novel CORINE Land Cover plus Backbone data, surface misclassifications cannot be fully ruled out. Nonetheless, they are likely balanced (Metsoja et al., 2025; Ursu et al., 2025). Third, the dataset not only contains public green spaces but also private ones. Since highly densely populated urban areas generally have only a small proportion of private green spaces, it can be assumed that including private green spaces will only have a limited impact on the results (Jänicke et al. 2025). Fourth, our observational period is brief due to data availability. Since it does not capture developments prior to 2018, our conclusions should be interpreted carefully since our non-results may be due to delayed effects. Yet, given the increasing urgency of heat adaptation, we would expect the tendencies that we aim to capture to be, if anything, more pronounced in recent years. Finally, our data only contains the quantity and not the quality or accessibility of urban green spaces. More fine-grained data, ideally complemented by qualitative research methods, would be required to adequately assess the full impact of (the lack of) green spaces.

4. Conclusion

This paper provides a broad descriptive picture of recent changes in green surfaces in German cities and investigates if they are linked to socioeconomic needs, political goals, and financial constraints. Using data for 153 German cities both the 1km grid and at the city level from the CORINE Land Cover Plus Backbone dataset and controlling for the level of baseline greening, it assesses spatial autocorrelation and examines the relationship between urban greening dynamics and spatial indicators of heat exposure, socioeconomic disadvantage, demographic structure, population size, local political characteristics, and fiscal capacity.

We find that German cities experienced more sealing than greening between 2018 and 2023, with only seven cities showing a net increase in green space. We do not find greening efforts to be concentrated in areas with higher needs as measured by higher heat exposure, greater socioeconomic disadvantage, or population growth at the spatial grid level. While we document a broad adaptation of heat plans, we do not find evidence that these, nor the political orientation of municipal governments, are associated with increased greening. Patterns at the city level, however, indicate that lower greening is linked to fiscal constraints as municipalities characterized by greater recourse to liquidity-relief loans and lower net trade tax revenue per capita tend to exhibit stronger declines in green space.

We interpret our findings to indicate that municipal governments appear to be aware of intensifying heat-related challenges as evidenced by their adoption of heat plans, but that their actions – such as increased sealing – are, if anything, likely to exacerbate heat exposure. Targeting greening in heat spots and to socioeconomically vulnerable groups is an obvious policy conclusion from our results. Monitoring and evaluating the impact of municipal land change decisions and of heat plans would be an important step in guiding policy-making. Such targeting need not necessarily conflict with the fiscal limitations that our data document. Nonetheless, equipping municipalities with the fiscal capacities to address extreme heat exposure is another policy recommendation arising from our findings. Whether this takes place through redistributions from the federal or regional budget, or through tax increases at the regional or municipal level such as inheritance or property taxes is a political question.

Finally, since our findings contribute to a field of research that is in its infancy, there are still many open questions that require further investigation. First, due to our brief observational period, future research will need to ascertain whether our findings hold over a longer timeframe during which adaptation measures can be implemented. Second, to develop a comprehensive understanding of heat adaptation, the implementation of other measures should be monitored

and compared to our results. Third, our results may serve as a stepping stone for future research that estimates the causal effects of city characteristics that lead to urban greening dynamics.

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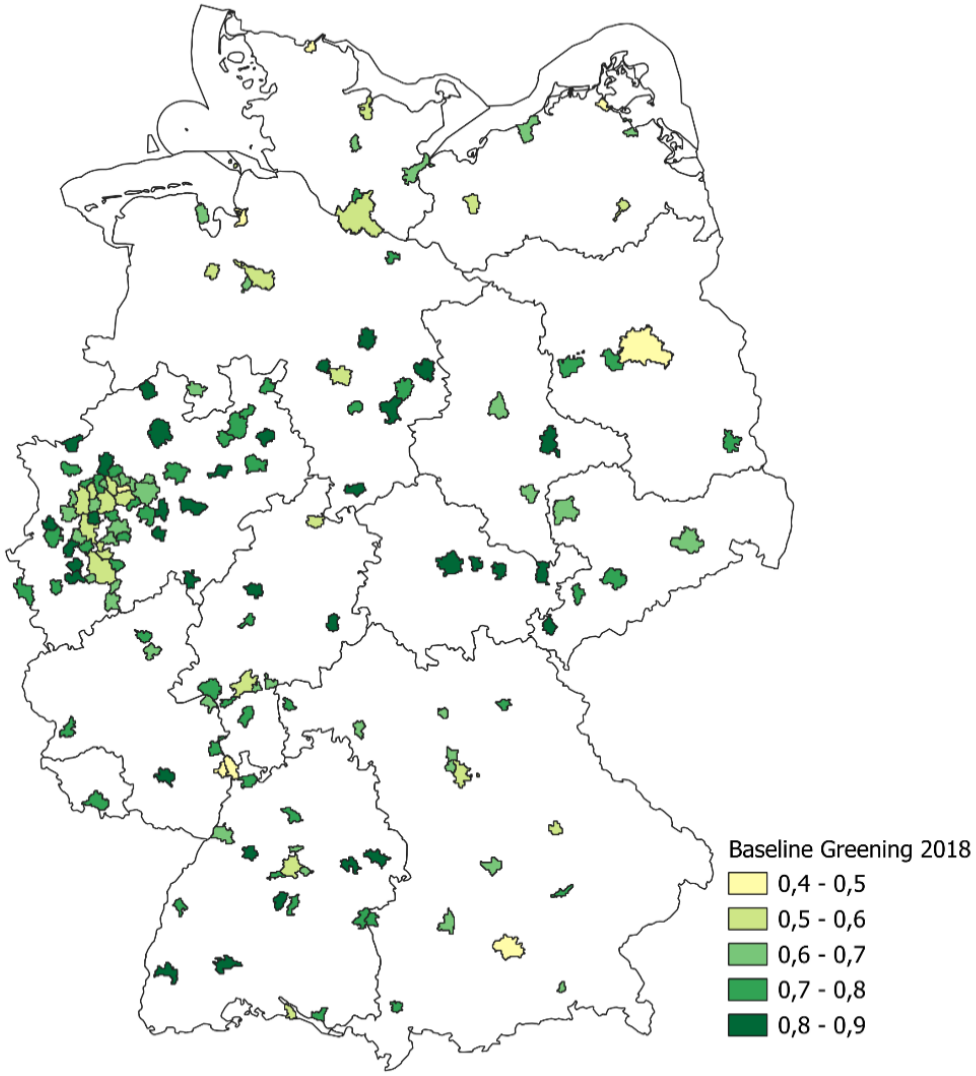
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Appendix A: Additional Results

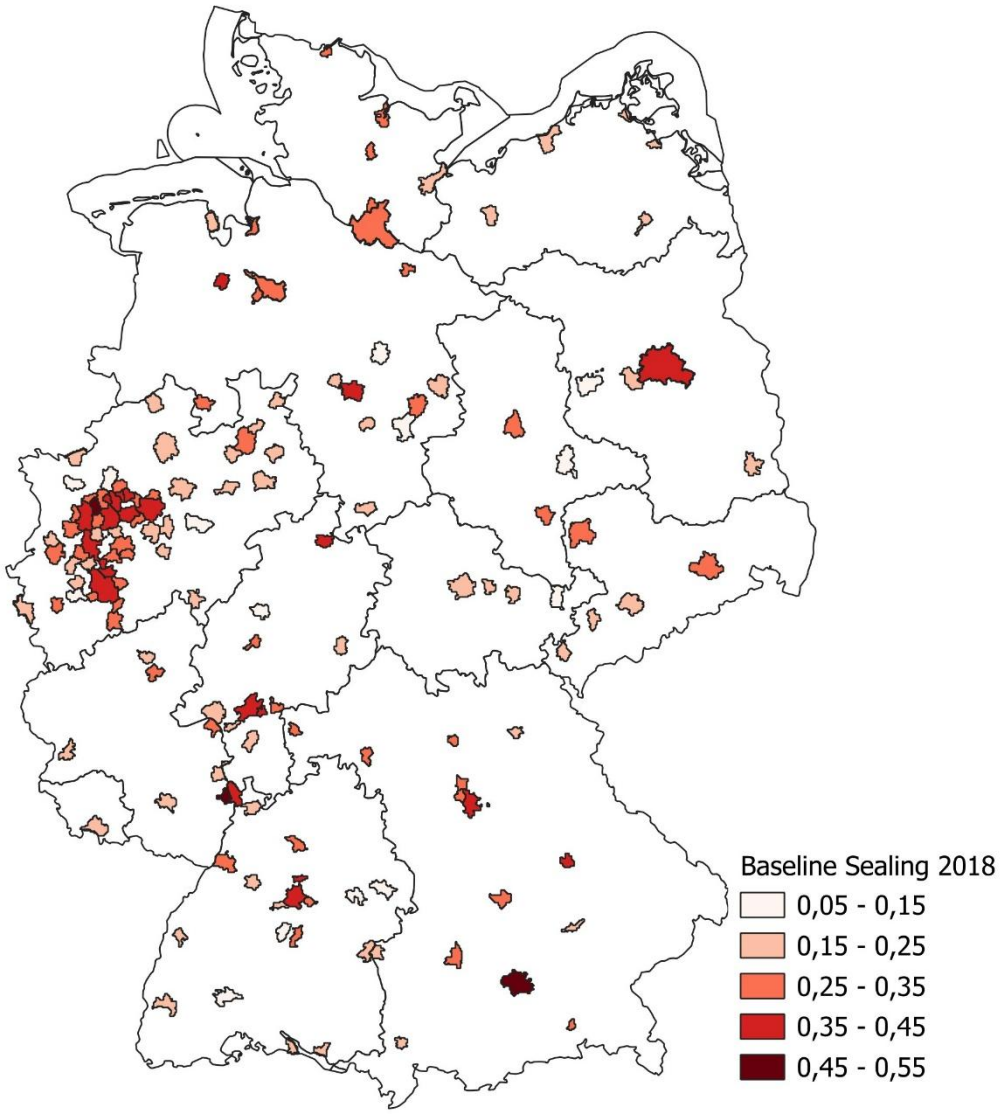
Figure A1: German cities and their baseline greening in 2018.



Note: This figure shows the proportion of green surfaces within each city.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 (raster).

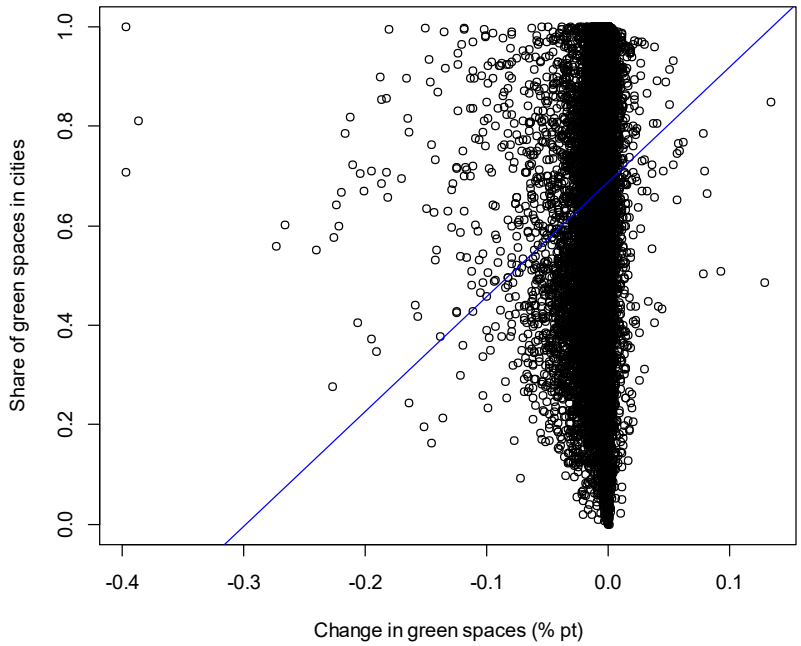
Figure A2: German cities and their baseline sealing in 2018.



Note: This figure shows the proportion of sealed surfaces within each city.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 (raster).

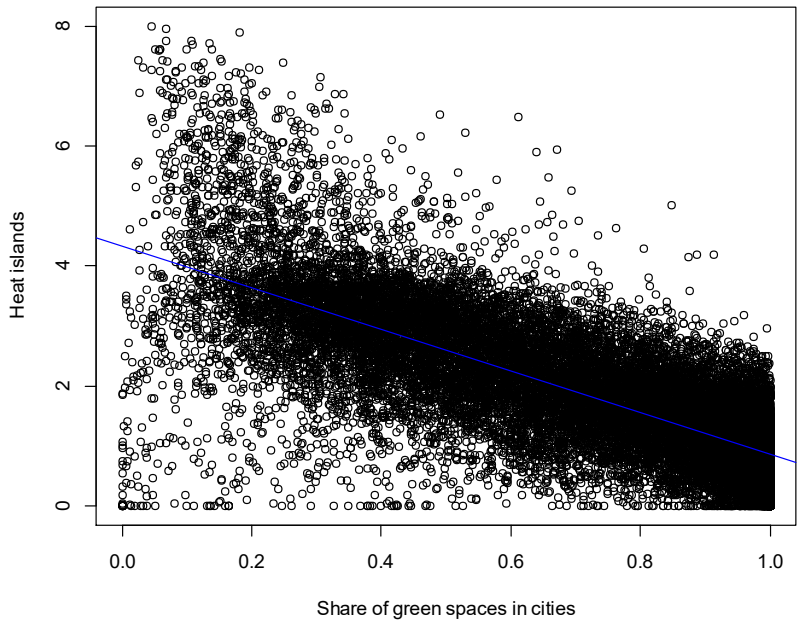
Figure A3: Level and change in the share of urban green space.



Note: This Figure shows a linear regression line correlating the unweighted level (baseline greening in 2018) and the change in green space from 2018 to 2023 on the 1km grid level ($r = 0.15$; $p < 0.01$).

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster).

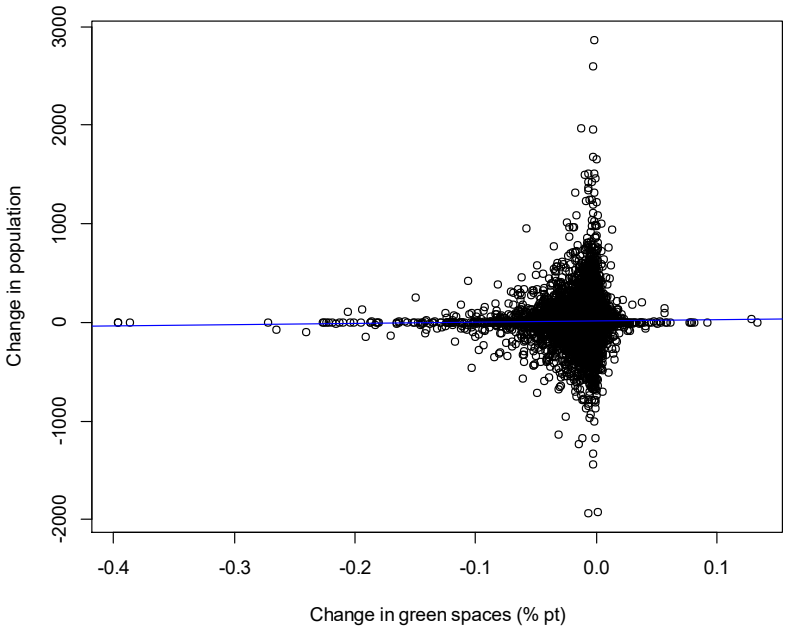
Figure A4: Level of urban green space and heat islands.



Note: This Figure shows a linear regression line correlating the unweighted level (baseline greening in 2018) and the urban heat islands on the 1km grid level ($r = -0.75$; $p < 0.01$). Note that sealed surfaces are one indicator of calculating urban heat islands.

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 (raster) and German Weather Service 2024.

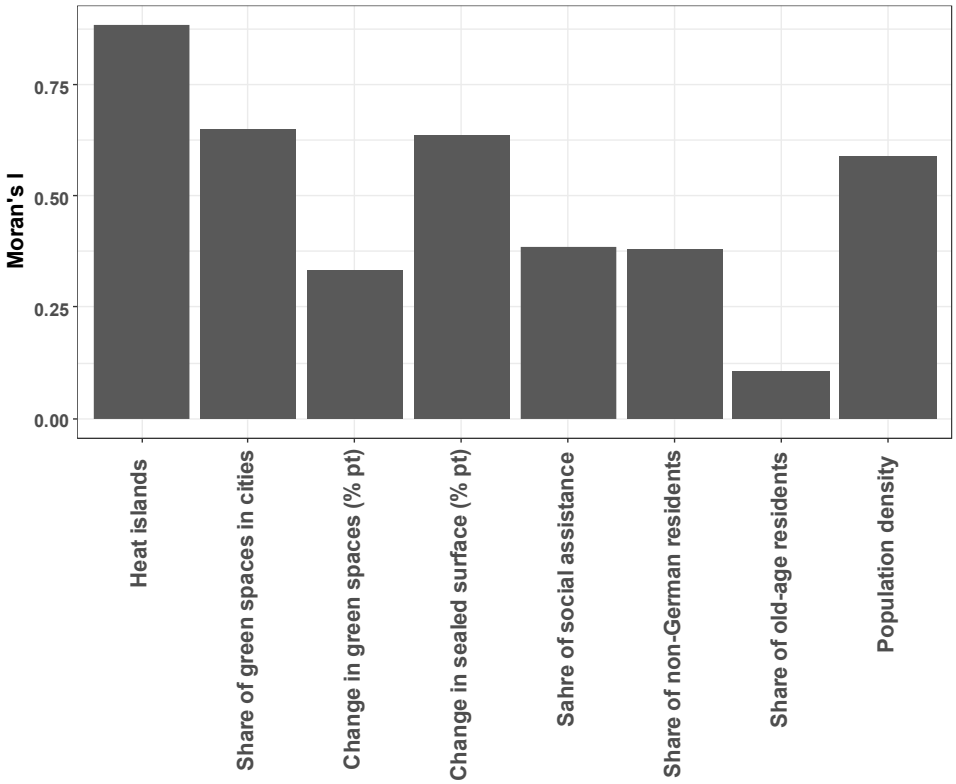
Figure A5: Changes in the share of urban green space and changes in population.



Note: This Figure shows a linear regression line correlating the change in green space from 2018 to 2023 and the change in population size from 2018 to 2022 on the 1km grid level ($r = 0.01$; $p = 0.038$).

Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster) and Federal Employment Agency (Helbig 2023).

Figure A6: Moran's I statistic for key variables.



Source: own calculations, data: CORINE Land Cover plus Backbone 2018 and 2023 (raster), Federal Employment Agency (Helbig 2023), Census 2022 and German Weather Service 2024.

Table A1: Research Area Cities.

Aachen	Greifswald	Neubrandenburg
Aalen	Grevenbroich	Neumünster
Arnsberg	Gütersloh	Neuss
Aschaffenburg	Hagen	Neu-Ulm
Augsburg	Halle (Saale)	Neuwied
Bamberg	Hamburg	Norderstedt
Bayreuth	Hamm	Nürnberg
Bergheim	Hanau	Oberhausen
Bergisch Gladbach	Hannover	Offenbach am Main
Berlin	Heidelberg	Offenburg
Bielefeld	Heilbronn	Oldenburg (Oldenburg)
Bocholt	Herford	Osnabrück
Bochum	Herne	Paderborn
Bonn	Herten	Pforzheim
Bottrop	Hildesheim	Plauen
Brandenburg an der Havel	Hürth	Potsdam
Braunschweig	Ingolstadt	Ratingen
Bremen	Iserlohn	Recklinghausen
Bremerhaven	Jena	Regensburg
Castrop-Rauxel	Kaiserslautern	Remscheid
Celle	Karlsruhe	Reutlingen
Chemnitz	Kassel	Rheine
Cottbus/Chóśebuz	Kempten (Allgäu)	Rosenheim
Darmstadt	Kerpen	Rostock
Delmenhorst	Kiel	Rüsselsheim am Main
Dessau-Roßlau	Koblenz	Saarbrücken
Detmold	Köln	Salzgitter
Dinslaken	Konstanz	Schwäbisch Gmünd
Dormagen	Krefeld	Schwerin
Dorsten	Landshut	Siegen
Dortmund	Langenfeld (Rheinland)	Sindelfingen
Dresden	Leipzig	Solingen
Duisburg	Leverkusen	Stralsund
Düren	Lippstadt	Stuttgart
Düsseldorf	Lübeck	Trier
Erfurt	Lüdenscheid	Troisdorf
Erlangen	Ludwigsburg	Tübingen
Essen	Ludwigshafen am Rhein	Ulm
Esslingen am Neckar	Lüneburg	Velbert
Flensburg	Lünen	Viersen
Frankfurt am Main	Magdeburg	Villingen-Schwenningen
Freiburg im Breisgau	Mainz	Weimar
Friedrichshafen	Mannheim	Wesel
Fulda	Marburg	Wiesbaden
Fürth	Marl	Wilhelmshaven
Garbsen	Minden	Witten
Gelsenkirchen	Moers	Wolfsburg
Gera	Mönchengladbach	Worms
Gießen	Mülheim an der Ruhr	Wuppertal
Gladbeck	München	Würzburg
Göttingen	Münster	Zwickau

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