Understanding Variation in Neighbourhood Environmental Inequalities: The Influence of Residential Segregation, Gentrification, and other City-Level Factors

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Abstract

Exposure to environmental burdens, such air and noise pollution or the lack of available green spaces, has been linked to a multitude of detrimental outcomes. Previous evidence indicates that poor residents and foreign minorities in European cities are disproportionately exposed to environmental burdens. However, there are substantial but ill-understood differences between European countries and between cities within countries. To address this limitation, we utilise fine-grained 1km-by-1km neighbourhood grid data on objective air and noise pollution as well as green space availability, enriched with administrative data on poverty rates and foreign minority shares from all German cities with at least 100,000 inhabitants in 2017. We examine whether poor residents and foreign minorities are more often affected by environmental burdens, how their exposure to environmental burdens differs between cities, and what city-specific contextual factors contribute to these between-city differences. We find evidence that foreign minorities are more likely to be exposed to environmental burdens, but poor residents are predominantly not. However, there is considerable variation between cities. The strongest explanatory factor for this variation is the extent to which disadvantaged groups live in central neighbourhoods, less so residential segregation of poor and foreign residents, or the scarcity of 'clean and healthy' neighbourhoods in a city. Against these results, we further explore empirically how the current wave of inner-city gentrification might ease environmental inequality in German cities.

Keywords

Environmental inequality; residential segregation; air pollution; noise pollution; green spaces; multiple environmental burden

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1. Introduction

Exposure to environmental burdens, such as air pollution and noise from traffic and industry, or the lack of accessible green and recreational spaces, has been linked to a multitude of detrimental outcomes. Poor environmental quality has been demonstrated to have negative impacts on physical and mental health (Currie *et al.*, 2014; Engemann *et al.*, 2019). Air pollution from different pollutants has led to an estimated 364,200 premature deaths and noise pollution to at least 12,000 premature deaths across the 27 member states of the EU in 2019 (EEA 2020a; EEA 2022). Exposure to environmental burdens also has substantial "non-health" effects, including impeding individuals' cognitive development and educational performances of children (e.g., Aguilar-Gomez *et al.*, 2022; Heissel, Persico and Simon, 2022; Bernardi and Conte Keivabu, 2023), labour market outcomes (Isen, Rossin-Slater and Walker, 2017), and social mobility (O'Brien *et al.*, 2018).

A substantial body of evidence indicates that individuals with lower socioeconomic status (SES) (Bell and Ebisu, 2012; Casey *et al.*, 2017) as well as racial and ethnic minorities (Downey, 2006; Clark, Millet and Marshall, 2014; Laurian and Funderburg, 2014; Rüttenauer, 2018b; Neier, 2021; König, 2024) in both the US and Europe face disproportionately low levels of environmental quality in the vicinity of their homes. Most prior research has focused on the socially unequal exposure to air pollution from industrial facilities and other sources (Crowder and Downey, 2010; Pais, Crowder and Downey, 2014; Ard, 2015; Rüttenauer, 2018b; Colmer *et al.*, 2020; Ard and Smiley, 2022). More recent work has provided initial evidence for similar patterns of *environmental inequality* in terms of noise exposure and the lack of green space and other natural environments (Casey *et al.*, 2017; Jünger, 2022; Diekmann *et al.*, 2023; König, 2024). The latter line of inquiry is yet emerging. Moreover, only few studies have jointly investigated different dimensions of neighbourhood environmental quality, let alone the possibility of exposure to multiple environmental burdens which has largely been ignored.

There is robust international evidence for the socially unequal distribution of air pollution in residential areas based on nationwide studies. Much less is known about whether these estimates of environmental inequality based on pooled data are a good representation of most cities and regions within a given country. Studies limited to individual regions (e.g., Bowen *et al.*, 1995; Downey, 2005, 2006; Grineski and Collins, 2008; Flacke *et al.*, 2016; Diekmann *et al.*, 2023; Neier, 2023) or presenting estimates of environmental inequality at sub-national levels (e.g., Downey, 2007) suggest that there is substantial regional variation in the extent of marginalised groups' environmental neighbourhood disadvantages. Such within-country regional variation in the extent of environmental inequality has rarely been studied in prior work but—if not solely driven by compositional differences of disadvantaged groups between regions—may provide an opportunity to investigate the role of local/regional contextual factors in shaping neighbourhood inequalities.

The present study makes three main contributions to the literature on environmental inequality: First, we study social disparities in the distribution of different dimensions of neighbourhood environmental quality (air and noise pollution, green space accessibility) and test whether poor residents and foreign minorities are more often affected by multiple environmental burdens. Second, we examine between-city variation in environmental neighbourhood disadvantages faced by those social groups. Third, we explore whether city-specific context factors contribute to regionally varying patterns of neighbourhood environmental inequality. To do so, we use fine-grained, objectively measured data on air pollution, noise pollution, and green space availability, combined with administrative grid data data (1km-by-1km) on neighbourhood shares of poor residents and foreign minorities for all German cities with at least 100,000 inhabitants.

Previous studies from Germany often rely on subjective measures of exposure to environmental burdens (Kohlhuber *et al.*, 2006; Best and Rüttenauer, 2018) or focus on individual cities or geographic regions (Raddatz and Mennis, 2013; Flacke *et al.*, 2016). We obtain administrative data for all 1km-by-1km grid cells located in German urban areas and provide estimates of nationwide environmental inequality by pooling across all German cities. To our knowledge, this is the first nationwide study to analyse whether disadvantaged urban neighbourhoods in Germany are disproportionately exposed to noise pollution or to multiple environmental burdens.

While the comparison of studies limited to single metropolitan areas or regions indicates that there is within-country regional variation in the nature and extent of residential environmental inequality, it is difficult to say whether observed differences are substantial or due to different data and methods. In addition to nationwide estimates of environmental inequality, we therefore also analyse these patterns of neighbourhood inequality for all large cities separately, to investigate within-country regional differences with coherent data and methods.

In a final step, we then consider urban contextual factors that potentially drive the differences in environmental neighbourhood disadvantages of poor residents and foreign minorities between German cities. We thereby add to a small but growing number of studies that shed light on cross-city variations in environmental inequality (Downey, 2007; Downey *et al.*, 2008; Padilla *et al.*, 2014; Diekmann *et al.*, 2023).

2. Theoretical background and previous findings

2.1 Neighbourhood environmental inequality

A substantial body of evidence indicates that both individuals with lower SES and racial minorities in the US are disproportionately affected by environmental hazards, including air and noise pollution, industrial hazards, a lack of access to green and recreational spaces, and less safe traffic infrastructure (e.g., Crowder and Downey, 2010; Sallis *et al.*, 2011; Ash *et al.*, 2013; Pais, Crowder and Downey, 2014; Mohai and Saha, 2015; Kodros *et al.*, 2022). The research on environmental inequality in Europe is much younger and yet emerging. Review articles by Hajat, Hsia and O'Neill (2015) and Fairburn et al. (2019) on exposure to air pollution found mixed evidence regarding a supposed link to SES. Estimates of environmental inequality by SES vary considerably both between and within European countries, and depending on the scale of the spatial unit of analysis. The evidence of environmental inequality by ethnic minority status—whether measured by nationality, migration background, or similar—in Europe tends to be more robust. It has been shown that ethnic minorities are disproportionately exposed to air and noise pollution (e.g., Glatter-Götz *et al.*, 2019; Neier, 2021; Diekmann *et al.*, 2023).

The number of studies on Germany that are nationwide in scope and based on objectively measured data is yet limited. Two ecological studies have shown that foreign minorities are, on average, exposed to higher levels of industrial air pollution and have lower access to urban green space (Rüttenauer, 2018b; König, 2024). Similarly, another two studies have investigated neighbourhood disadvantages in terms of exposure to key air pollutants from different sources (nitrogen dioxide, ozone, particulate matter) and land use (soil sealing, green space) based on geo-referenced survey data from the German General Social Survey (Jünger, 2022; Ehler *et al.*, 2023), again finding environmental inequality to the detriment of ethnic minorities. These studies further show that adjusting for SES does not substantially attenuate minorities' neighbourhood disadvantages. Studying whether neighbourhood income levels are linked to environmental quality, König (2024) finds no relationship once the share of non-nationals is held constant.

Until now, such studies have been lacking a comprehensive approach to the exposure to multiple environmental burdens. With regard to Germany, a case study of the city of Dortmund revealed a considerable degree of spatial overlap between different environmental burdens (Honold *et al.*, 2012). This suggests that environmental inequality should be assessed using multidimensional indices of exposure to environmental stressors in order to be properly identified.

Explanations of residential environmental inequality

Two principal mechanisms are posited to explain the emergence of environmental inequality: selective siting and selective migration. Selective siting refers to the phenomena that environmental burdens like industrial facilities, landfills, main traffic lines and the like are more often placed in disadvantaged neighbourhoods, owing to low land prices, discriminatory bias of decision makers (top-down), or a lack of socio-political capital and action of residents to prevent such placements (bottom-up). The evidence for selective siting remains limited and contradictory (Mohai and Saha, 2015; Rüttenauer and Best, 2021), in part due to the difficulty of gathering appropriate longitudinal data to test this mechanism.

Selective migration refers to processes of neighbourhood sorting by which residents belonging to disadvantaged groups tend to congregate in neighbourhoods that are burdened by environmental hazards, while other residents tend to relocate to areas with more favourable living conditions (e.g., Crowder and Downey, 2010). Selective migration has most prominently been attributed to affordability. The presence of noise and air pollution, as well as the accessibility of green spaces, have been demonstrated to influence housing and rental prices (e.g., Chay and Greenstone, 2005; Chen *et al.*, 2022; Kamtziridis, Vrakas and Tsoumakas, 2023). Housing market discrimination on behalf of landlords and real estate agents may further restrict housing opportunities for certain groups. This is particularly evident with regard to ethnic minorities in Germany and elsewhere (e.g., Auspurg, Hinz and Schmid, 2017; Christensen, Sarmiento-Barbieri and Timmins, 2022).

Finally, differences in preferences for residential environmental quality and other neighbourhood characteristics may affect environmental inequality. Despite the lower environmental quality of inner-city neighbourhoods, these areas attract urban residents for a number of other characteristics, including a broad cultural offering, proximity to workplaces and the presence of public infrastructure. The so-called "new" middle class, characterised not (only) by high household income but (additionally) by high educational attainment, appreciation of a broad cultural offering, and greater environmental awareness (Neckel *et al.*, 2018) especially has a preference for living in inner-city neighbourhoods (De Vos, Van Acker and Witlox, 2016; Florida, 2019; Reckwitz, 2019). Immigrants may further prefer to live in neighbourhoods with a high share of compatriots (e.g., Winke, 2018) since these neighbourhoods also provide dense ethnic infrastructure that is positively associated with migrant wellbeing (Wiedner, Schaeffer and Carol, 2022).

Hypotheses on environmental inequality within German cities

In light of previous studies, we assume that neighbourhoods with higher poverty rates (H1a) and higher shares of foreign minorities (H1b) are affected by higher levels of air and noise pollution, have more limited access to green spaces, and are more likely to be exposed to multiple environmental burdens.

2.2 Differences in environmental inequality between cities

Segregation

A study of ethnic minorities in metropolitan areas across the USA found that segregation can both increase and decrease their exposure to environmental burdens (Downey *et al.*, 2008). This is not so much a contradictory finding as that it shows how much historical developments and path dependency matters in the emergence of both segregation and environmental inequality (Downey, 2007; Cesaroni *et al.*, 2010). In West Germany, numerous cities underwent significant demographic shifts in the late 1960s. At that time, a considerable number of unrenovated old buildings with substandard living conditions were present in West German city centres, offering affordable housing especially for newly arriving low-income immigrants and low-income natives alike (Reinecke, 2012). In contrast, the middle class relocated to the suburbs. This trend can also be observed in many American cities. These processes increased both income and ethnic segregation in (West) German cities and exposed poorer and immigrant populations to the higher environmental burdens associated with city centres. Higher social or ethnic segregation could therefore be a proxy for greater environmental inequality (Woo *et al.*, 2019). There is a paucity of empirical findings on the link between residential segregation and exposure to environmental burdens in German cities. However, Rüttenauer (2018a) found that residential segregation is not a significant factor in explaining the exposure of foreign minorities to industrial pollution in German cities.

Scarcity

The level of segregation in a city is influenced by the balance between housing supply and demand. When there is an increase in housing supply, native residents are more likely to self-segregate, whereas the segregation of migrants increases when there is a high demand for housing (Winke, 2018). In a similar manner, the supply of quiet neighbourhoods in close proximity to green and recreational spaces with clean air should affect the likelihood of disadvantaged social groups gaining access to these "goods". In the event that the supply is limited within a given city, competition is higher, and both economic forces, particularly high housing prices in these sought-after neighbourhoods, as well as discrimination, may negatively impact the accessibility of disadvantaged social groups to these neighbourhoods. If air and noise pollution, as well as the accessibility of green and recreational spaces, are generally high in a city, these amenities should not affect rent and housing prices to the same extent.

Centrality

A correlation can be observed between population density and environmental burdens in urban areas. While per capita emissions in densely populated neighbourhoods may be lower (Castells-Quintana, Dienesch and Krause, 2021) higher population density is associated with higher overall pollution levels. This is exemplified by the observation that pollution in large cities is highest in monocentric cities (Castells-Quintana, Dienesch and Krause, 2021), a phenomenon that is generally true of German cities. Furthermore, Rüttenauer (2018a) observed that in German cities where polluting facilities are situated in more central neighbourhoods, foreign minorities are more exposed to industrial pollution than in other cities. To the extent that higher population density is associated with higher poverty rates in German cities (Helbig, 2023), socially disadvantaged neighbourhoods may be more exposed to environmental burdens because of their centrality.

Hypotheses environmental inequality between cities

We expect that higher residential segregation of poor residents and foreign minorities is linked to a higher exposure to environmental burdens of low-income households and migrants, respectively (H2a). With regard to scarcity, we expect that the city-level proportion of high-quality neighbourhoods (absence of environmental bads, presence of environmental goods), is inversely linked to the extent of environmental inequality at the disadvantage of poor residents and foreign minorities (H2b). Regarding centrality, we anticipate that there will be a more pronounced correlation between poverty rates/ shares of foreigners and environmental burdens in cities where there is a stronger correlation between the population density of neighbourhoods and poverty rates/shares of foreign minorities (H2c).

3. Data and Methods

To test our hypotheses, we combine demographic and socio-economic data at the 1km-by-1km grid level with indicators of air pollution, noise exposure and urban green spaces from various sources. Information on the demographic and socio-economic composition of all 1km-by-1km grid cells in Germany is obtained from the German Federal Employment Agency (Bundesagentur für Arbeit) via a special inquiry, and from the GfK Geomarketing GmbH. Information on grid-level environmental quality is obtained from different sources. Data on air pollution at 2km-by-2km grids as well as spatial polygon data on noise pollution caused by aviation, road, and railway traffic are obtained from the German Federal Environment Agency. High resolution data on green spaces based on satellite imagery is obtained from the Urban Atlas (European Environment Agency, 2020).

While demographic, socio-economic, and air pollution data are available for all Germany, green space data are limited to cities and their commuting zones located within the 96 so-called Functional Urban Areas as defined by the OECD and the European Commission (Dijkstra, Poelman and Veneri, 2019). Among the cities located within German Functional Urban Areas are 69 cities that fall under the German Federal Environment Agency's definition of agglomeration centres (Umweltbundesamt, 2024) and have information on noise exposure available. All grid cells belonging to those 69 cities, which are the largest and most densely populated cities in Germany with at least 100,000 inhabitants each, constitute the sample for our analysis[1].

3.1 Measures

Neighbourhood social composition (grid-level)

In conducting our analysis, we utilise two grid-level dependent variables: the share of foreign minorities and the share of poor residents.

The Federal Employment Agency provided absolute figures of different social groups at the grid-level. This is administrative data routinely collected by the federal agency as part of the employment statistics and probably the most reliable source of information on the small-scale spatial distribution of foreign populations and poor residents in Germany. The total number of residents per grid as well as the number of residents in different age categories as of 2017 was obtained from GfK Geomarketing. This data, serving as the denominator, is only used to calculate grid-level variables in percentage terms and for population weighting of regressions later on.

To measure the **share of poor residents**, we calculate the proportion of individuals receiving social assistance for the unemployed or for low-income workers, as a percentage of all residents under age 65 for each grid in 2017. Eligibility for this type of assistance is generally restricted to individuals who have been unemployed for more than one year and low-income workers whose income is below the minimum subsistence level and who cannot cover living expenses from their own resources. Like previous studies, our index includes the working poor (e.g., Macintyre, Macdonald and Ellaway, 2008) but unlike others we exclude those that are "comfortable" between jobs.

To measure the **share of foreign minorities**, we calculate the grid-level percentage of working age residents (15-65) that have no German citizenship in 2017[2]. Following official statistics, we define the working age population as the group of employable people entitled to social benefits, consisting of employment subject to social security contributions and unemployment within this age range.

Neighbourhood environmental quality (grid-level)

Our index of **air pollution** exposure is calculated as the toxicity-weighted sum of the 2017 annual mean concentrations of nitrogen dioxide (NO_2), fine particulate matter ($PM_{2.5}$), and sulphur dioxide (SO_2), provided by the German Federal Environment Agency and based on emissions from various sources (e.g., traffic, industry, households) and estimated with the

[1] To assign grid cells to cities, we calculated the areal share of each 1 km^2 grid cell that lies within the borders of any city and restricted our sample to grid cells whose areal intersection with cities is at least 50 percent. The remaining grid cells were assigned to one specific city according to the largest area overlap.

[2] This excludes both citizens and non-citizens who are self-employed or, in the case of citizens, a special kind of permanent civil servant. Regarding non-citizens, it furthermore excludes stationary forces, diplomatic and consular representations, refugees and asylum seekers without a work permit, and non-citizens who, due to illness or disability, are unable to work at least three hours a day under normal working conditions for the foreseeable future.

REM-CALRGRID chemical transport model that accounts for geographic and meteorological conditions. Air pollution estimates are calibrated at around 400 air pollution monitors (Schneider *et al.*, 2016). To collapse pollutant-specific annual means into one measure of air pollution, we use the toxicity weights calculated by the Federal Environment Agency on the basis of the pollutant-specific health damage estimates (Matthey and Bünger, 2020).

We base our index of **noise pollution** on the annual mean level of exposure to noise from airports (Umweltbundesamt, 2018b), railway lines (Umweltbundesamt, 2018c), and roads (Umweltbundesamt, 2018a) in 2017. We used the source-specific noise maps provided by the Federal Environment Agency and calculated the fraction of grid-level residential areas affected by night-time noise of 50 dB or higher from each of the three sources. We then summed these source-specific traffic noise indices to obtain a single index of noise pollution.[3]

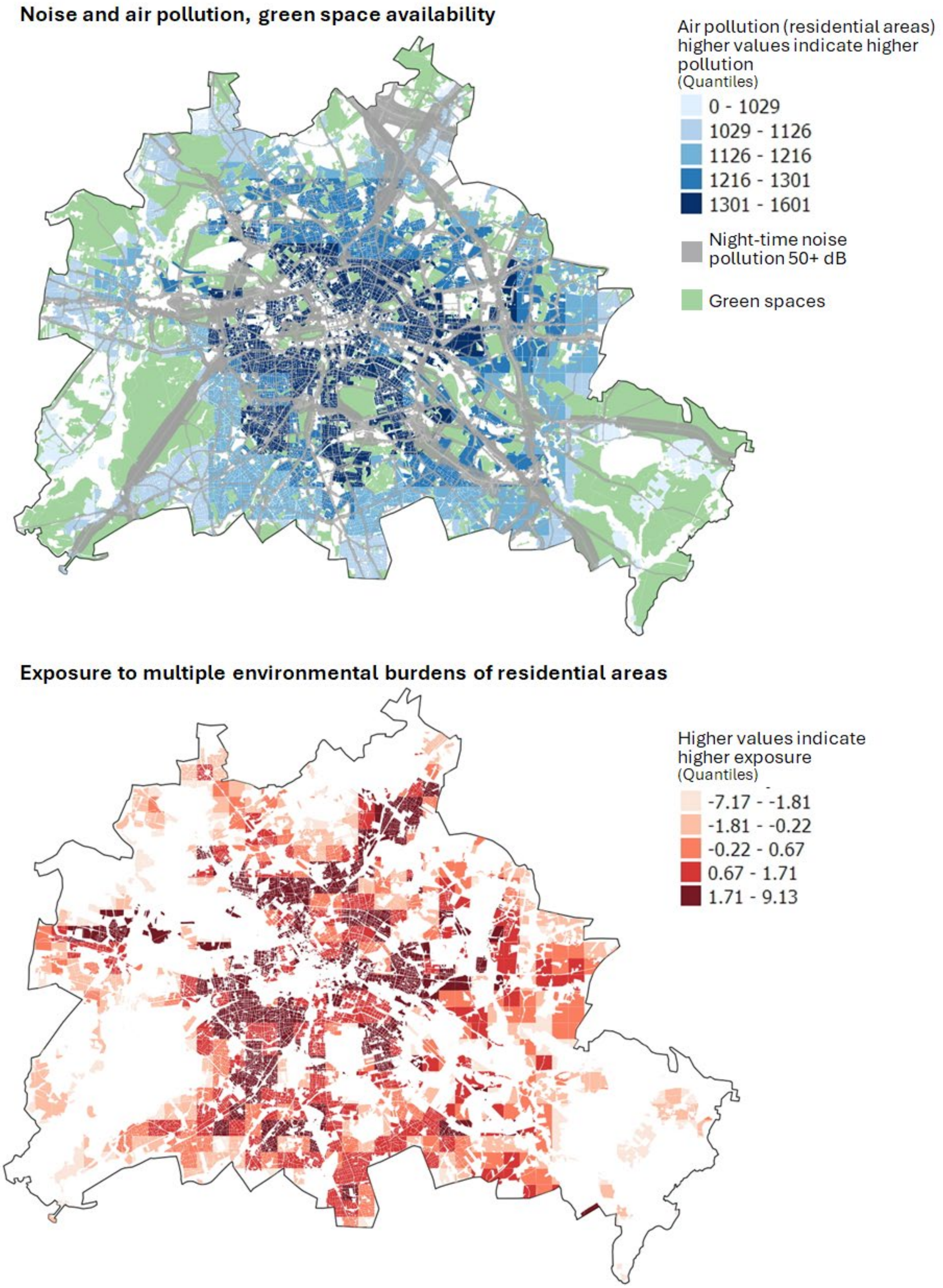
We measure residential **green space availability** as a grid cell's surface share covered by green space and other natural environments in percentage points. The measure is based on small-scale polygons of the following greenspace-related land use categories from the 2018 Urban Atlas: "green urban areas", "sports and leisure facilities", and "forests". Other types (e.g., arable land, permanent crops) are excluded since their desirability is ambiguous.[4] We further construct a **lack of green space** measure equal to 100 (percent) minus the surface share covered by green space to be used for the index of multiple environmental burdens.

Finally, to construct our index of **exposure to multiple environmental burdens**, we created standardised variants (mean=0, SD=1) of the air pollution, noise pollution, and lack of green space measures (using grid population as weight when calculating means and standard deviations) and summed them up to obtain our composite index of environmental burdens. A grid cell characterised by average levels of air pollution, noise exposure, and (lack of) green space would, thus, result in an index value of 0. Using the example of Berlin, Figure 1 visualises the three components separately (top) and when collapsed into one index (bottom).

[3] The estimation of road and railway traffic noise is performed based on long-time sound pressure levels where the estimates of road traffic noise are based on a number of factors, including traffic flow, the categorisation of vehicles, speed, acceleration and deceleration, road gradient and condition. The estimates of railway noise consider the type of railway and railway vehicles. Aviation noise is estimated based on several factors, including the flightpath geometry, flights' speed and thrust profiles as well as airports' capacity utilisation to determine the localised noise levels emitted by airports. For details, see: https://www.bundesanzeiger.de/pub/publication/1FbcVABJ3TpUTOMTiS1?3 for details.

[4] Accessibility of these spaces may be limited, or they may be associated with odours and noise.

Figure 1. Environmental quality indicators mapped across Berlin



City context (city-level)

To investigate the role of local contexts in shaping neighbourhood environmental inequalities, we enrich the grid-level data with a number of city-level context factors.

In order to capture cities' extent of ethnic and socioeconomic **residential segregation**, we calculated the index of dissimilarity (Massey and Denton 1988), which is defined as:

$$\mathrm{d} = \frac{1}{2}\sum_{i=1}^{N}\left|\frac{a_i}{A} - \frac{b_i}{B}\right|,$$

Where a_i is the population of natives in a neighbourhood *i*, *A* the city-wide native population, b_i the foreign minority population in a neighbourhood *i*, and *B* the city-wide foreign minority population. Index *d* is a value between 0 and 100 that indicates the proportion of the city's population that must relocate in order to achieve an equal spatial distribution of foreign minorities and poor residents across a given city.

To measure **residential centrality** of foreign minority and poor residents, we utilise the city-wide correlation between the share of foreign minorities/poor residents and the grid population size. We thereby assume that grid population density is a reliable indicator of its centrality within a given city (Louf and Barthelemy, 2016). The **scarcity of desirable neighbourhoods** with low or non-existent environmental burdens is approximated using aggregated city-level measures of the various neighbourhood environmental quality indicators. Lastly, Information on a city's total population is obtained from the Federal Office for Building and Regional Planning and is, subsequently, used as a control variable when investigating the role of city-level contextual factors (see Section 3.2). Descriptive statistics for all indicators at the grid and city level can be found in the online supplement.

3.2 Statistical approach

We use fine-grained data at a 1-km-by-1km grid to approximate individuals' residential neighbourhoods. Spatial dependence, i.e., the tendency that nearby units exhibit similar characteristics, tends to be a more serious methodological challenge with small-scale spatial data, as an increasing number of spatial units for a given area may result in many observations clustered around the local mean. OLS regression models, assuming independence of observations, yield biased and inconsistent estimates when applied to spatially clustered data (LeSage and Pace, 2009). A common approach is to explicitly model spatial dependence by the inclusion of "spatial lags" (Anselin and Bera, 1998; LeSage and Pace, 2009).

We study the link between residential environmental quality and social neighbourhood composition in terms of poverty rates and shares of foreign minority residents. The different aspects of environmental quality considered here are likely to be spatially dependent since important sources of air and noise pollution (highways, railroads, flight paths etc.) as well as spatial footprints of urban green spaces are not confined to single grid cells. Calculating the index of spatial autocorrelation (Moran's I[5]) for the indicators of environmental quality indeed

[5] Moran's I is an index of spatial autocorrelation ranging from -1 (indicating that similar values reject each other) to +1 (indicating that similar values attract each other). It is based on the sum of cross products of adjacent neighbourhoods' deviations from the mean. If adjacent neighbourhoods tend to

suggests that urban green space availability, noise exposure, and the index of multiple exposures exhibit moderate levels of spatial dependence (Moran's I of 0.4, 0.32, and 0.54, respectively) and air pollution high levels of spatial dependence (Moran's I equal to 0.95; see Figure S1 in the OS).

To account for this spatial dependence we employ Spatially Lagged X Models (SLX, Vega and Elhorst, 2015). Which are defined as follows: $y = \alpha\iota + X\beta + WX\theta + \epsilon$,

where y is the N×1 vector of units' values of the dependent variable, α the model intercept, ι is a N×1 vector of ones, X a N×K a matrix of K independent variables, β is a K×1 parameter vector containing estimated direct effects of X on the dependent variable y (henceforth referred to as SLX main effect coefficients). θ is a K×1 parameter vector containing coefficient estimates of the spatial lag effect of adjacent grids (henceforth referred to as spatial lag effect). It represents estimated changes in unit i's dependent variable associated with changes in independent variables in adjacent units $j.W$ is the N×N spatial weights matrix, where $w_{ij} > 0$ for all grids j that are adjacent to i (sharing at least one common edge, queen contiguity criterion), $j \neq i$, and $w_{ij} = 0$ for non-adjacent units. Following standard practice, we row-normalize W by dividing each non-zero weight by the sum of all weights of unit i, which is the sum of the row: $w_{ij} \div \Sigma\, w_{ij}$. The spatial lag coefficient, thus, estimates the mean change in the dependent variable in i induced by an average increase in the dependent variable in all neighbouring units by one unit.

The analyses are divided into three parts: First, we examine whether disadvantaged social groups face disproportionately low levels of environmental quality at their place of residence. We do so by running a series of SLX regressions pooling 1km-by-1km grid cells across cities where we separately regress the two outcomes of interest (neighbourhood share of foreign minorities and poverty rate) on the environmental quality features (air pollution exposure, noise exposure, green space availability, multiple exposure index) and their spatial lag. To investigate whether potential neighbourhood inequalities persist when restricting to within-city variation, we run additional models including city-fixed effects for each treatment-outcome pair. SLX regressions are weighted by the total grid cell population. We estimate fully standardised coefficients. Standard errors are clustered at the city level.

Second, we generate subsamples of grid cells by city and re-run the same SLX regression for each subsample separately to study between-city differences in the extent of neighbourhood environmental inequality. As before, we weight all models by total grid cell population and estimate fully standardised city-level coefficients.

Third, we test whether the between-city differences in environmental inequalities can be explained by city-level contextual factors. To do so, we extract the city-specific main coefficient estimates of environmental neighbourhood disadvantage faced by foreign minorities or poor residents from the SLX regressions and regress them on the city-level contextual factors via an OLS regression[6]. For each city-level estimate of environmental inequality (e.g., estimate of foreign minorities' disproportionate exposure to air pollution), we run a single model including

positively/negatively deviate from the mean in similar ways, Moran's I is likely to be positive. If neighbouring units tend to differ in their deviations from the mean, Moran's I is likely to be negative.

[6] We opted for this approach since we are not aware of a way to run SLX models including cross-level interactions.

the city-level contextual factors of interest, i.e., centrality of residence, residential group segregation, scarcity of clean/healthy neighbourhoods. These multivariate OLS regressions additionally adjust for city size (log). Following King (1997), to account for the uncertainty of the first-stage (SLX) estimates, the second-stage OLS regressions are based on weights proportional to the inverse of the squared standard errors for environmental inequality coefficients estimated on the first stage. Greater weight is thereby given to observations with more precise estimates of city-level environmental inequality.

4. Results

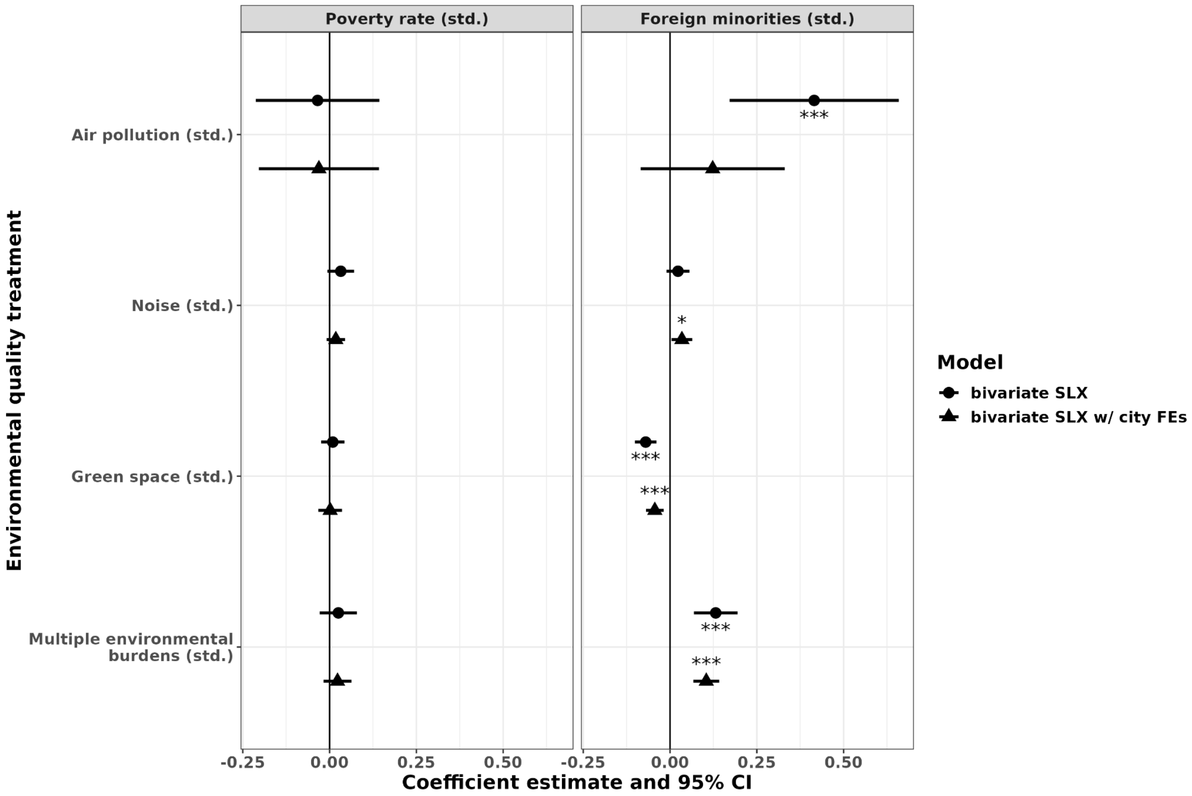
4.1 Social disparities in neighbourhood environmental quality

The first set of results is based on information about the social composition and environmental quality of urban neighbourhoods pooled across all German cities with at least 100,000 inhabitants. We assume that neighbourhoods with higher poverty rates (H1a) and higher shares of foreign minorities (H1b) are affected by higher levels of air and noise pollution, have more limited access to green spaces, and are more likely exposed to multiple environmental burdens.

Figure 2 below shows estimated disparities in environmental quality between neighbourhood grids with varying poverty rates and shares of foreign minorities for all large German cities based on SLX models. As evident from the left column of Figure 2, we do not find evidence that neighbourhoods with high poverty rates are affected by low levels of environmental quality and, therefore, reject hypothesis H1a. The estimated coefficients of environmental inequality by poverty rates are small in magnitude and fail to reach statistical significance for all four dimensions of environmental quality. This holds true for models with and without city-fixed effects.

The right column of Figure 2 shows the same set of estimates with the grid-level share of foreign residents as outcome variable. Here, we do find a clear and rather consistent pattern of environmental neighbourhood disadvantage in support of hypothesis H1b. Based on the bivariate SLX model (without city-fixed effects), a one standard deviation increase in exposure to air pollution is linked to an increase in the share of foreign residents by .42 standard deviations which corresponds to an increase by 4.4 percentage points (10.47*.42). In terms of noise exposure, green space availability, and exposure to multiple environmental burdens are more moderate in size, but consistently indicate that foreign residents in German cities face poorer environmental conditions around their homes relative to the German majority population. Estimates based on the bivariate SLX model with no city-fixed effects indicate that a one standard deviation increase in exposure to noise, access to green spaces, and exposure to multiple environmental burdens is associated with a change in the foreign resident share by .02, -.07, and .13 standard deviations respectively. This implies, for instance, that a one standard deviation increase in our composite index of environmental burdens is associated with an increase in the share of foreign minority residents by around 1.4 percentage point (10.47*.13). Importantly, these neighbourhood disadvantages remain largely unchanged when restricting to within-city variation, while including city-fixed effects attenuates the disparities regarding air pollution which then fails to reach statistical significance.

Figure 2. Link between indicators of environmental quality and grid-level shares of poor and foreign residents



Notes. Coefficients based on SLX models with neighbourhood grids pooled across cities. * p.value<.05, ** p.value<.01, *** p.value<.001.

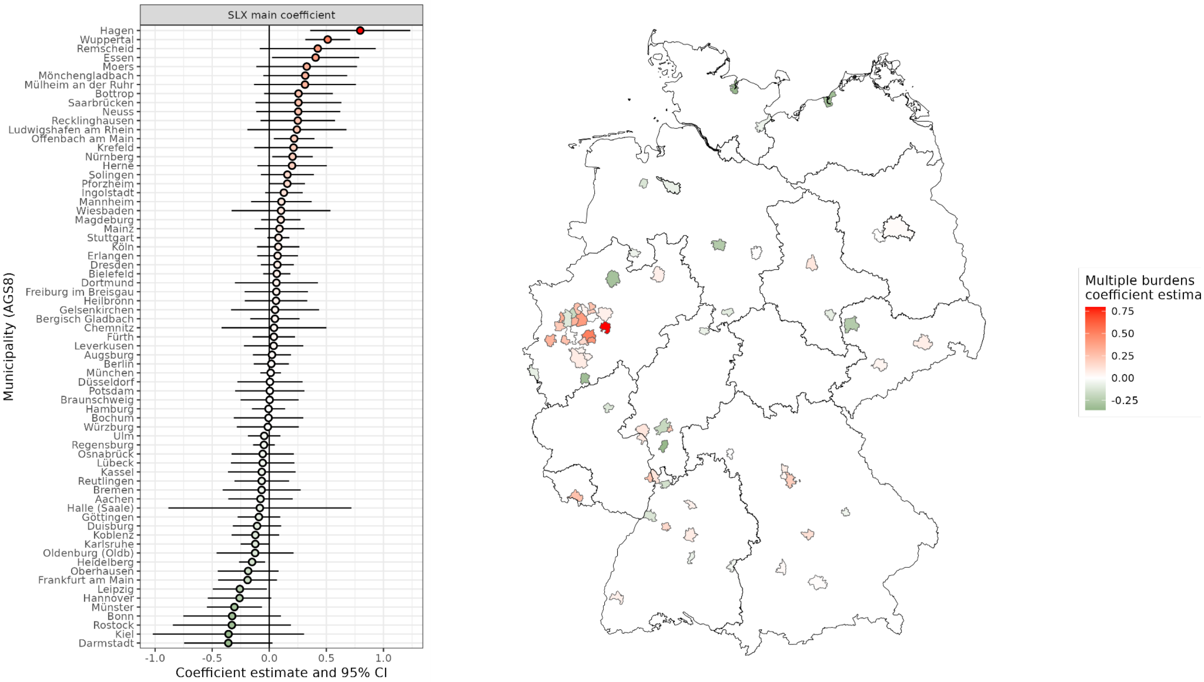
4.2. Differences in environmental inequality between cities

For the second part of the analyses, we generated subsamples of grid cells by city and reran the SLX regression models for each city separately to investigate whether the patterns and the extent of environmental inequalities differ between them. While we ran these analyses for all indicators of environmental inequality (air pollution exposure, traffic noise exposure, green space availability, exposure to multiple environmental burdens), we focus here the results for the index of exposure to multiple environmental burdens. Results for the other environmental quality indicators can be found in the online supplement.

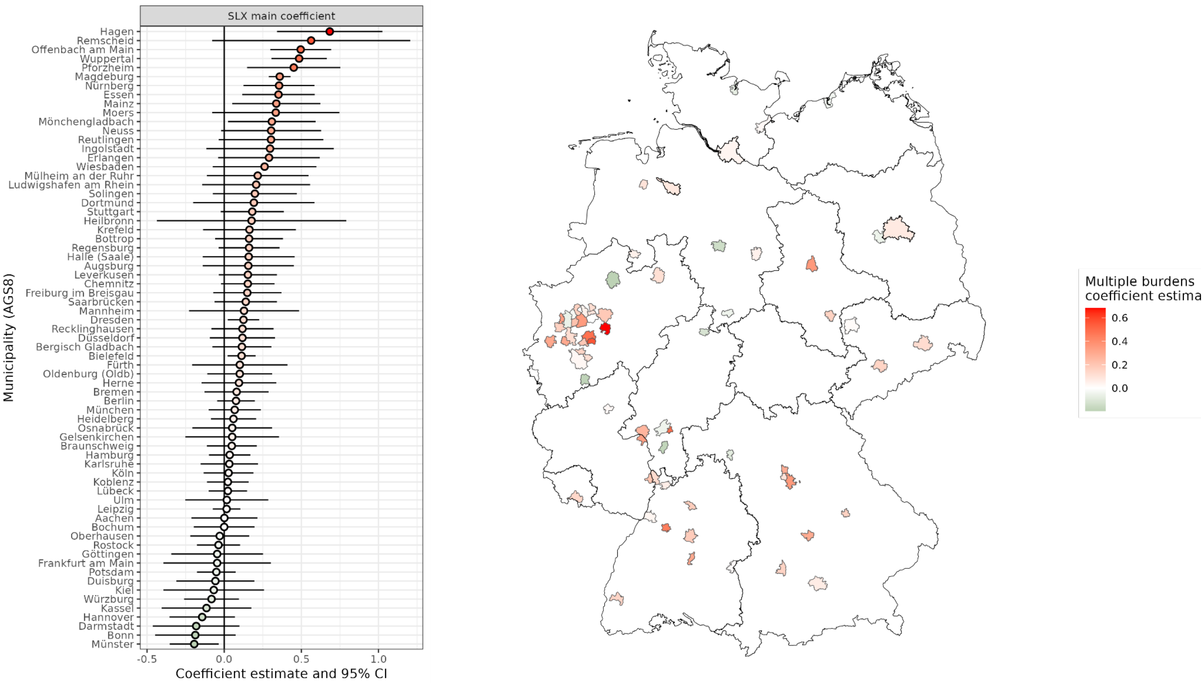
Figure 3a shows and maps the standardised, city-specific association between exposure to multiple environmental burdens and the poverty rate at the grid level (SLX main coefficient estimate). Positive coefficient estimates (coloured in shades of red) indicate that neighbourhood grids with high poverty rates are disproportionately exposed to multiple environmental burdens in a given city. Negative coefficient estimates (coloured in shades of green), on the other hand, imply that poor residents tend to live in less exposed neighbourhoods.

Figure 3. Link between exposure to multiple environmental burdens and neighbourhood poverty rates (panel a) and foreign minority rates (panel b) by city

a)



b)



Notes. Coefficients based on SLX models for each city. Interpretation example (based on 3a): An increase in the index of exposure to multiple environmental burdens by one standard deviation is linked to an increase in the poverty rate by about .5 standard deviations in the city of Wuppertal (2nd coefficient from the top).

For the majority of cities, the estimate of environmental inequality in relation to poverty rates is close to zero or even negative. Few cities mainly located in the west and south of Germany are the exception and show pronounced positive associations between a grid's exposure to multiple environmental burdens and the share of poor residents.

Figure 3b shows the same set of results for the share of foreign minorities as the outcome variable. We find substantial variation in the extent of foreign minorities' exposure to multiple environmental burdens. In contrast to the situation of poor residents, who are more likely to live in neighbourhoods with higher environmental quality in at least some cities, there are virtually no German cities in which foreign minorities enjoy residential environmental quality superior to that experienced by the majority population.

The two main takeaways from these city-level analyses of neighbourhood environmental inequalities are that i) the extent of neighbourhood (dis-)advantages faced by foreign minorities and poor residents varies substantially between cities, and, ii) that—in line with results based on pooled data (4.1)—we find somewhat stronger and more consistent evidence of environmental inequality by citizenship than by economic resources.

The breakdown of pooled data into city-level subsamples and the uncovered variation in estimates of spatial inequalities represents a promising opportunity to take a closer look at the role of local contextual factors at the city-level in shaping patterns of environmental inequality.

4.3 City-level contexts of environmental inequalities

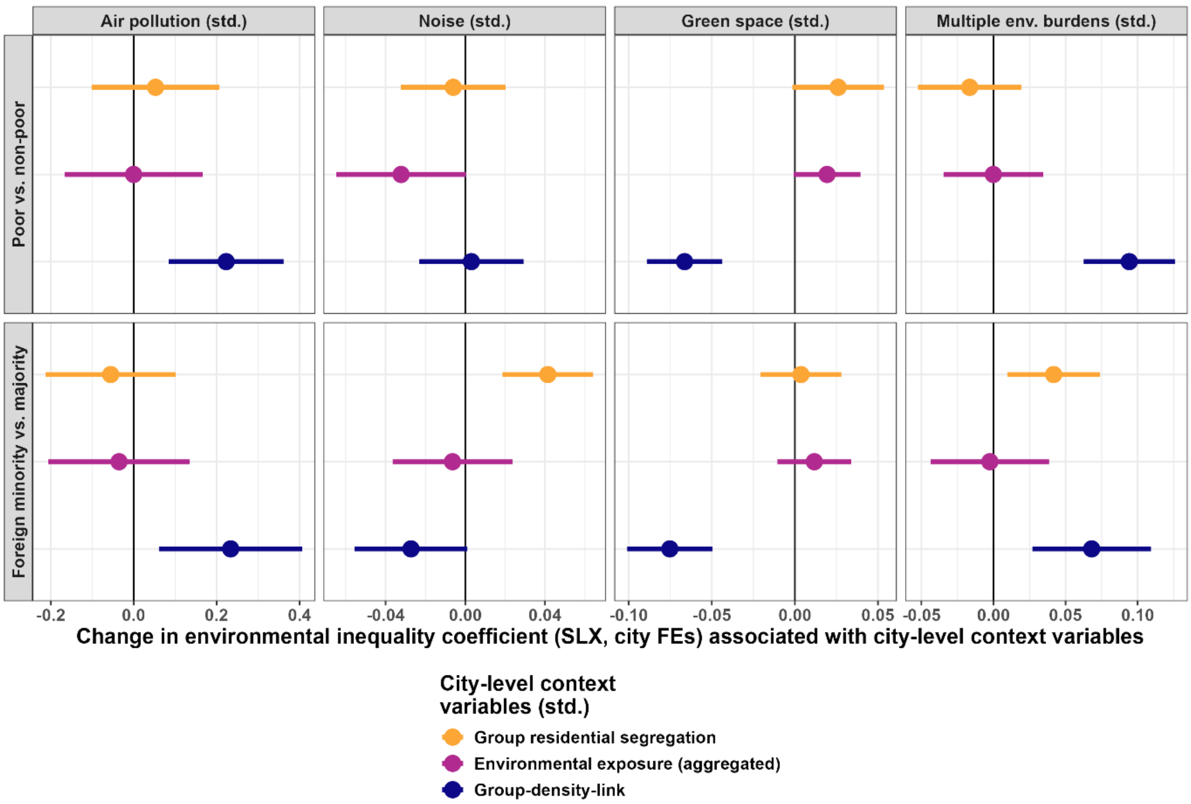
A certain degree of residential segregation is a necessary precondition for neighbourhood environmental inequalities. Building upon previous literature, we have argued that high levels of residential segregation might be linked to particularly large disparities in neighbourhood environmental quality (H2a). We have further argued that differences in the scarcity of environmentally desirable neighbourhoods (H2b) as well as the centrality of the residential location of different social groups (H2c) may explain the differences in neighbourhood environmental inequalities between cities. We have regressed the city-specific estimates of environmental inequality discussed in Section 4.2 (first stage) on these city-level contextual variables to investigate how they affect environmental inequalities (Figure 4).

With regard to the role of city-level residential segregation in environmental inequalities, we find mixed results. Higher levels of residential segregation of poor residents are not associated with (more pronounced) neighbourhood disadvantages in terms of exposure to air pollution and noise. In fact, poor residents tend to reside in greener neighbourhoods in cities characterised by high levels of residential segregation. For foreign minorities, we find the level of residential segregation to be linked to particularly pronounced disadvantages in terms of noise exposure but to be unrelated to neighbourhood disparities with regard to air pollution exposure and green space availability. The substantial and significant association with disparities in noise exposure also translate into a comparable pattern with regard to higher exposure to multiple environmental burdens.

Aggregated city-level measures of the different neighbourhood environmental quality measures serve to approximate the scarcity of desirable neighbourhoods with regard to the respective environmental features. Recall from Section 4.2 that positive coefficient estimates in case of an environmental bad (i.e., air pollution, noise, multiple environmental burdens) imply environmental neighbourhood disadvantages to the detriment of marginalised groups (poor residents, foreign minorities). In case of an environmental good (i.e., green space) such neighbourhood disadvantages are implied by negative coefficients.

If the scarcity of "clean" neighbourhoods within a city were actually linked to more severe levels of environmental inequality, increases in city-level exposure to environmental bads would need to be positively linked to estimates of city-level environmental inequality. This is, however, not the case. If anything, we find city-level increases in exposure to environmental bads to be linked to somewhat less pronounced environmental inequality between neighbourhoods. While the estimates for city-level noise exposure are statistically significant at the 95%-level, those for city-level air pollution fail to reach statistical significance. The city-level aggregate measure of exposure to multiple environmental burdens reaches statistical significance only with regard to neighbourhood disadvantages faced by foreign minorities.

Figure 4. Link between SLX estimates of within-city environmental inequality and city-level contextual factors



Notes. Estimates from OLS regression using city-level environmental inequalities (first-stage SLX main coefficients) as dependent variables.

If the scarcity of "green" neighbourhoods within a city was linked to more pronounced environmental inequality, on the other hand, increases in the city-level availability of green space (representing the opposite of scarcity) would again need to be positively linked to the city-level estimate of disparities in green space availability—which is what we actually find: A city-wide increase in green space availability is associated with a more positive association between the share of poor/foreign residents and green space at the grid level. Fewer available green space across a city is associated with worse availability of green spaces for marginalised groups. Taken together, we only partly confirm hypothesis H2b (based on results for the availability of urban green spaces).

Finally, we have studied whether a group's tendency to live in the city centre helps explain varying degrees of environmental inequality. We find strong evidence that marginalised group's residential centrality within a given city is linked to particularly poor levels of environmental quality in the vicinity of their homes, in support of hypothesis H2c. While residential centrality does not seem to affect disparities in noise exposure, the tendency to live in the city centre consistently predicts particularly large neighbourhood disadvantages to the detriment of both poor and foreign residents in terms of air pollution exposure, green space availability, and the risk of exposure to multiple environmental burdens. Compared to the degree of residential segregation and the level of scarcity of "clean and green" neighbourhoods, a group's residential centrality represents a substantially stronger predictor of environmental neighbourhood disadvantages. Estimates are statistically significant at the 95% level—again, with the exception of noise exposure.

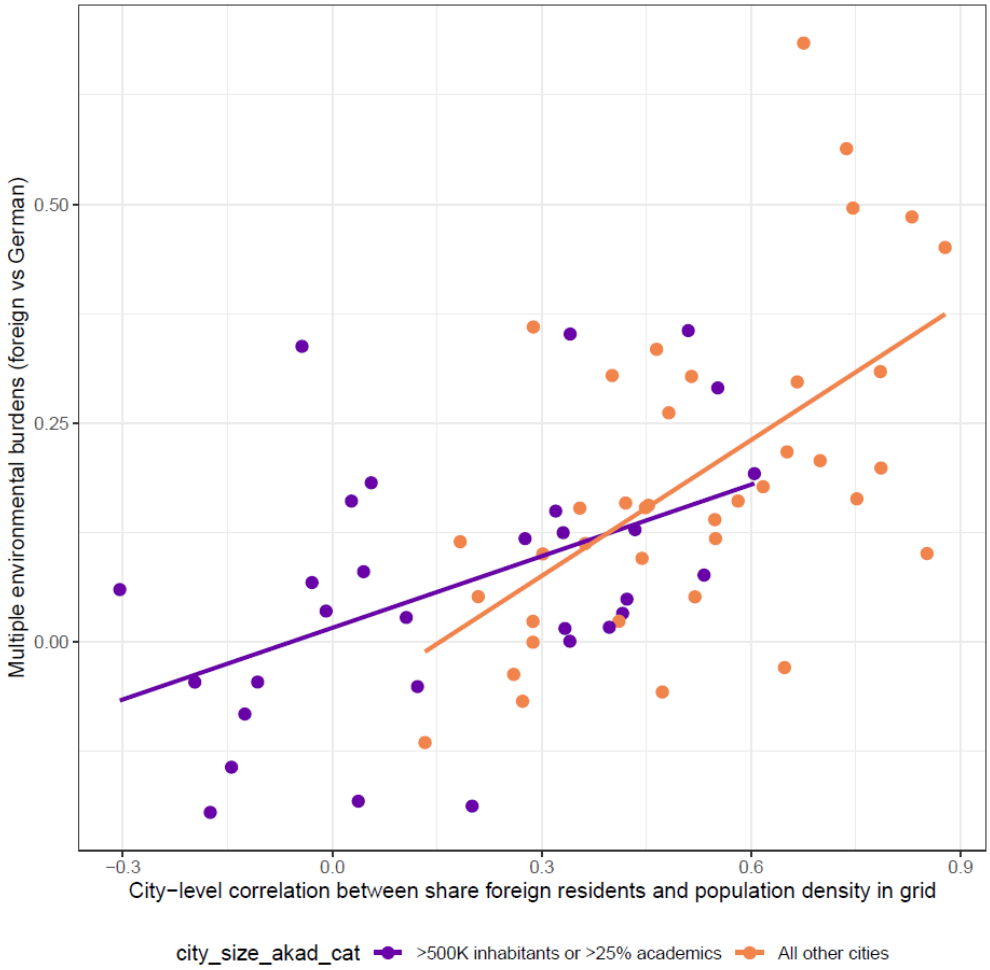
4.4 A levelling effect of gentrification on environmental inequality?

The preliminary conclusion regarding the role of city contexts is that, in contrast to prior work from the US (e.g., Woo *et al.*, 2019), the degree of socioeconomic and ethnic residential segregation does not persistently explain the varying degrees of neighbourhood environmental inequality between cities. The results regarding the scarcity of "clean and green" neighbourhoods are inconclusive or, if anything, they do indicate a correlation between a scarcity of environmentally desirable neighbourhoods and lower levels of environmental inequality. This may be due to two factors: Either a large proportion of neighbourhoods within a city affected by poor environmental quality implies exposure for a larger and more diverse group of residents; or because in competitive housing markets, it is not necessarily the most sought-after neighbourhoods that have high levels of environmental quality. Net of differences in the level of residential segregation, we found a group's tendency to live in densely populated grids, usually located in the city centre, to be a strong and consistent city level predictor of a group's environmental neighbourhood disadvantages.

In what kind of cities, then, are poor and foreign residents mainly found in densely populated areas in the city centre? We believe that examining the processes of suburbanisation and gentrification that have historically and continue to influence neighbourhood inequality could prove an effective approach to this question. Low levels of environmental quality in city centres have prompted the development of post-war suburbanisation in numerous US metropolitan areas, with affluent and predominantly white groups relocating to suburban areas offering more living space and a buffer to industrial zones. While suburbanisation was less pronounced in European countries, the expansion of the knowledge-intensive service economy in many European cities, including Germany, in the 1990s has led to an increase in the number of highly educated individuals relocating to city centres in search of employment opportunities (Tammaru *et al.*, 2021; Viguié *et al.*, 2023). The processes of gentrification have since become a mass phenomenon in many high-income countries (Holm, 2014). The rate of gentrification is likely to vary depending on the presence of a knowledge-intensive service economy. Similarly, in highly competitive housing markets, there is a greater likelihood of social groups being displaced from city centres. Indeed, Helbig (2023) found that highly educated and high-income groups in Germany tend to cluster in the centres of university cities and large cities with populations of 500,000 or more.

Given the generally lower environmental quality of inner-city areas, we anticipate that the level of gentrification may be inversely correlated with the residential centrality of disadvantaged groups and environmental neighbourhood disadvantage. Furthermore, we posit that major cities that have the most competitive housing markets in Germany, as well as cities with high shares of academic employees, have undergone the most far-reaching gentrification processes.

Figure 5. Association between city-level environmental inequality by citizenship and residential centrality of foreign residents for two groups of cities



In order to evaluate these exploratory claims, we have identified a sample of German cities with a minimum population of 500,000 (major cities) and/or at least 25% of academic employees[7]. Figure 5 plots city-level estimates of the exposure to multiple environmental burdens by foreign minority shares against the link between foreign residents and grid population density. Figure S 8 in the supplementary material shows the same graph for environmental disadvantages faced by poor residents. Apparently, in cities that are

[7] The proportion of academics at the city level was measured as the proportion of employees with an academic degree among all employees in a city.

presumably more gentrified (shown in purple), there is less environmental inequality and a weaker link between residential centrality and environmental inequality. This evidence supports the idea that there is an inverse relationship between dynamic processes of gentrification and those environmental inequalities that negatively impact disadvantaged groups.

5. Limitations

The estimation of spatial inequalities is contingent upon the spatial scale of the underlying data, a phenomenon known as the Modifiable Areal Unit Problem. This can result in the ecological fallacy or aggregation bias. It has been demonstrated that the utilisation of more fine-grained spatial data can mitigate the potential for ecological bias by minimising within-unit and increasing between-unit variability in treatments, confounders, and outcomes (Dark and Bram, 2007). In the context of the present study, this suggests that our more detailed spatial units of analysis are more effective at aggregating comparable neighbourhood environments and categorising homogeneous groups of residents. However, it is not possible to eliminate the possibility of ecological bias entirely.

Since one potential mechanism underlying any potential association between the density of the neighbourhood foreign minority population and environmental burdens is discrimination, it would be advantageous to have information on naturalised residents, not only foreign minorities, since naturalised citizens might experience discrimination in the rental and housing market based on their ethnicity. However, the federal institute responsible for harmonising this data did not provide information about residents' migration background consistent across different cities.[8] Whether environmental inequalities faced by migrants closely match those faced by non-German citizens, thus, remains an open question.

6. Discussion and Conclusion

The present study investigated environmental inequality in German cities. We examined whether poor residents and foreign minorities are more often affected by air and noise pollution, lack of green space accessibility, and multiple environmental burdens (1). Furthermore, we analysed the variation in the exposure to multiple environmental burdens of these social groups in different cities (2). Lastly, we investigated whether city-specific contextual factors, i.e., residential segregation, the scarcity of environmental goods, and neighbourhood centrality contribute to these regionally varying patterns of neighbourhood environmental inequality (3). To this end, we employed fine-grained data on air pollution, noise pollution, and green space availability, combined with 1km-by-1km administrative grid data on poverty rates and the share of foreign minorities for 69 German cities with a minimum population of 100,000.

(1) In accordance with our hypothesis that neighbourhoods with higher poverty rates or higher proportions of foreign minorities are subject to elevated levels of air and noise pollution,

[8] The federal institute documents eight different methods of how cities in Germany collect data on naturalised citizens. Moreover, some cities have not provided information on their method or do not collect data on naturalised immigrants in the first place (Göddecke-Stellmann et al. 2022).

diminished access to green spaces, and increased exposure to multiple environmental burdens, our findings indicate that this is indeed the case for neighbourhood grids that are more densely populated by foreign minorities. However, there is no discernible link between elevated environmental burdens and neighbourhood poverty rates across the neighbourhoods of the 69 German we have analysed.

(2) Nevertheless, when the statistical correlation between poverty rates/the proportion of foreign minorities on the one hand and exposure to multiple environmental burdens on the other hand is calculated separately for each city, we find considerable variation between cities. With regard to foreign minorities, they are more exposed to multiple environmental burdens in most cities in our sample. While the majority of cities exhibit a negligible or even inverse correlation between environmental inequality and poverty rates, a few cities predominantly situated in the western and southern regions of Germany exhibit a pronounced positive association between a neighbourhood's exposure to multiple environmental burdens and the share of poor residents.

(3) We hypothesised that residential segregation, the scarcity of environmental goods, and neighbourhood centrality explain these differences between cities. We found that high residential segregation of foreign minorities in a city indeed renders them more likely to be exposed to noise pollution and multiple environmental burdens. This finding expands previous research indicating no correlation between residential segregation and exposure of foreign minorities to industrial pollution in German cities (Rüttenauer, 2018a). It suggests that there may be distinct underlying processes for different environmental burdens. Our expectations regarding the scarcity of 'clean and healthy' neighbourhoods were only confirmed with regard to green space availability. A reduced amount of green spaces available in a city is linked to a decline in the relative accessibility of green spaces in neighbourhoods with high poverty rates and high shares of foreign minorities. Lastly, we found that the tendency to live in city centres predicts particularly large neighbourhood disadvantages for both poor and foreign residents in terms of air pollution exposure, green space availability, and the risk of exposure to multiple environmental burdens.

The high relevance of centrality for explaining differences in the level of environmental inequality between cities compelled us to explore the link in greater depth. We find that in highly competitive housing markets, where high-income and highly educated residents are especially motivated to move to more central neighbourhoods (in large cities and university cities with a high share of academics), poor and foreign residents are less often exposed to environmental burdens. In this sense, social and environmental inequalities are a transient phenomenon that also reflects the level of development of an urban society. In the German Kaiserreich, a considerable number of working-class districts were constructed in close proximity to manufacturing facilities, which were typically situated in the eastern section of the city due to the prevailing wind patterns. Conversely, the western region witnessed the emergence of burgeoning bourgeois neighbourhoods and villa districts during this era (Harlander, Kuhn, and others, 2012; Heblich, Trew and Zylberberg, 2021 for England). In West Germany, numerous cities underwent significant social and demographic changes in the late 1960s and early 1970s. These changes often resulted in the emergence of immigrant neighbourhoods with a disproportionate concentration of economically disadvantaged individuals within the inner cities (Reinecke, 2012). With the advent of a knowledge-intensive service economy, cities with a high proportion of academics in their workforce are, once again, undergoing significant transformations.

In contrast to the early literature on gentrification (Glass, 1964), the gentrification of inner-city neighbourhoods no longer occurs in a fragmented manner, affecting specific quarters. Instead, it has become a global mainstream phenomenon (Holm, 2014). In contrast to the earlier notion of "islands of renewal in seas of decay," the current situation in many large cities is better described as "islands of decay in seas of renewal" (Holm, 2014). The varying rates of change result not only in different patterns of social segregation or gentrification, but also in differences in environmental inequality depending on the stage of development of the cities in question.

Nevertheless, despite the potential benefits of this new wave of gentrification in reducing environmental inequality, disadvantaged groups may still experience adverse effects. Empirical evidence from European cities suggests that inner-city gentrification negatively impacts the accessibility of public transportation for socioeconomically disadvantaged groups (e.g., Buettner *et al.*, 2013; Sterzer, 2017; Viguié *et al.*, 2023). Moreover, high-income and highly educated residents who relocate to inner-city neighbourhoods may leverage their resources and influence to increase the environmental quality of these areas. This could entail influencing urban planning, promoting green initiatives, or establishing low-traffic zones (Aldred *et al.*, 2021) which may have adverse effects on other neighbourhoods. The preliminary finding that ongoing processes of gentrification currently tend to reduce environmental inequalities and perhaps even promote residential integration may be a temporary snapshot. If socially disadvantaged groups that were once concentrated in city centres are forced to relocate to the periphery, this may also increase residential segregation in the future and subsequently lead to "selective siting" processes in disadvantaged neighbourhoods.

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Online supplement

A - Descriptive Statistic

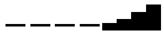
Table S1 shows descriptive sample statistics—weighted by the number of inhabitants per grid for it to be representative of German urban areas.

The average grid cell in German cities hosts around 2,600 inhabitants, around 14 percent of which qualify as poor (i.e., receive social assistance for the unemployed and low income workers) and around 17 percent of which are foreign minorities.

In terms of neighbourhood environmental quality, green space presence varies widely, including grids lacking any green space to grids fully covered by green space. Similarly, many grids' residential areas are not subjected to any noise from road, rail, or aviation noise, whereas other grids' residential areas are entirely affected by traffic noise from different sources. The indices of toxicity-weighted air pollution exposure (ranging from 561 to 1,687) and exposure to multiple environmental burdens are more complex and have a less intuitive interpretation—we will, therefore, report fully standardised coefficients later on.

City size ranges from slightly above 100,000 inhabitants (due to the sample restrictions outlined earlier) to around 3.7 million inhabitants (Berlin). The dissimilarity indices capturing residential segregation of foreign minorities and the poor range from 14 to 37 and 15 to 44, respectively. In terms of residential centrality of these groups, we see positive correlations between a grid's population density and the share of residents belonging to both groups. As evident from the last column of Table S1, city-level correlations—and, thereby, the spatial distribution of foreign minorities and poor residents across cities—vary substantially between German cities, ranging from around minus 0.3 to 0.9.

Table S1. Weighted descriptive statistics of neighbourhood- and city-level variables

	N	Mean	SD	[Min,Max]	Distribution
a) Grid level					
Grid population (unweighted)	9707	2565.3	3097.83	[1, 26668]	
Poverty rate	9707	13.97	10.44	[0, 100]	
Foreign minorities	9707	17.15	10.47	[0, 100]	
Air pollution, toxicity-weighted (PM25,NO2,SO2)	9707	1136.21	164.30	[560.64, 1687.24]	
Green space coverage (in %)	9707	16.96	14.10	[0, 99.23]	
Lack of green space (in %)	9707	83.04	14.10	[0.77, 100]	
Noise exposure (road, rail, aviation)	9707	11.87	13.42	[0, 200]	
Multiple_exposure_burden	9707	0.00	1.86	[-9.49, 14.12]	
b) City level					
City size (in 100K inhabitants)	9707	10.41	11.82	[1.04, 36.77]	
Segregation, poor residents	9707	30.31	4.06	[15.04, 44.03]	
Segregation, foreign minorities	9707	24.57	5.69	[14, 37.12]	
Residential centrality, SGBII	9707	0.20	0.27	[-0.32, 0.82]	
Residential centrality, immigrant-origin population	9707	0.31	0.27	[-0.3, 0.88]	

Notes. Descriptive statistics are weighted by neighbourhood grid population.

B - Further results

B.1 Spatial dependence

Moran’s I is an index of spatial autocorrelation based on the sum of cross products of adjacent units’ deviations from the mean. It ranges from -1 to +1 and is i) likely positive if neighbouring units tend to deviate from the mean in similar ways (both above/below mean with regard to variable of interest), that is, if similar values spatially cluster, and, ii) likely negative if neighbouring units deviate tend to deviate from the mean in different directions. A positive Moran’s I statistic, therefore, indicates spatial dependence/autocorrelation (i.e., the coincidence of value similarity with locational similarity).

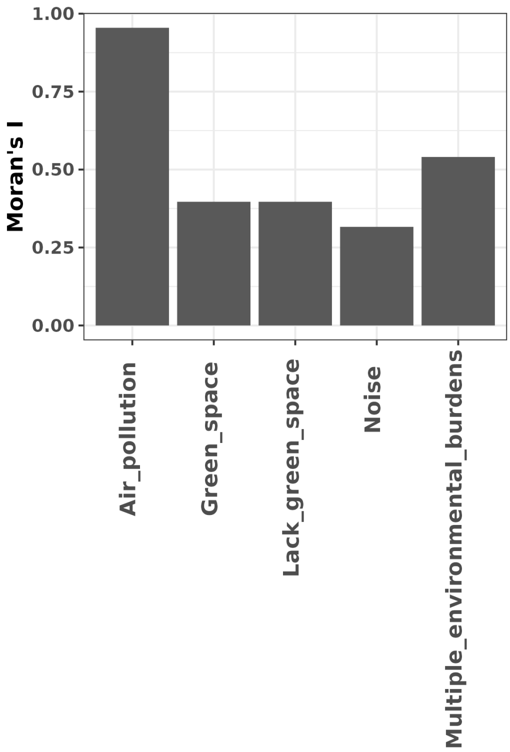


Figure S1: Moran’s I statistic for environmental quality variables.

As evident from Figure S1, the environmental quality variables used in our analyses exhibit substantial degrees of spatial dependence as indicated by the Moran’s I statistic. The toxicity-weighted measure of air pollution exposure based on air quality data by the German Environmental Agency exhibits extremely high spatial autocorrelation while our measures of (lack of) green space presence, noise exposure as well as the composite index of exposure to multiple environmental burdens exhibit moderate levels of spatial autocorrelation.

B.2 City-level estimates of environmental inequality for air pollution exposure, noise exposure, and green space presence

Poverty rate

Figure S2. Link between grid-level air pollution exposure and poverty share in all German cities.

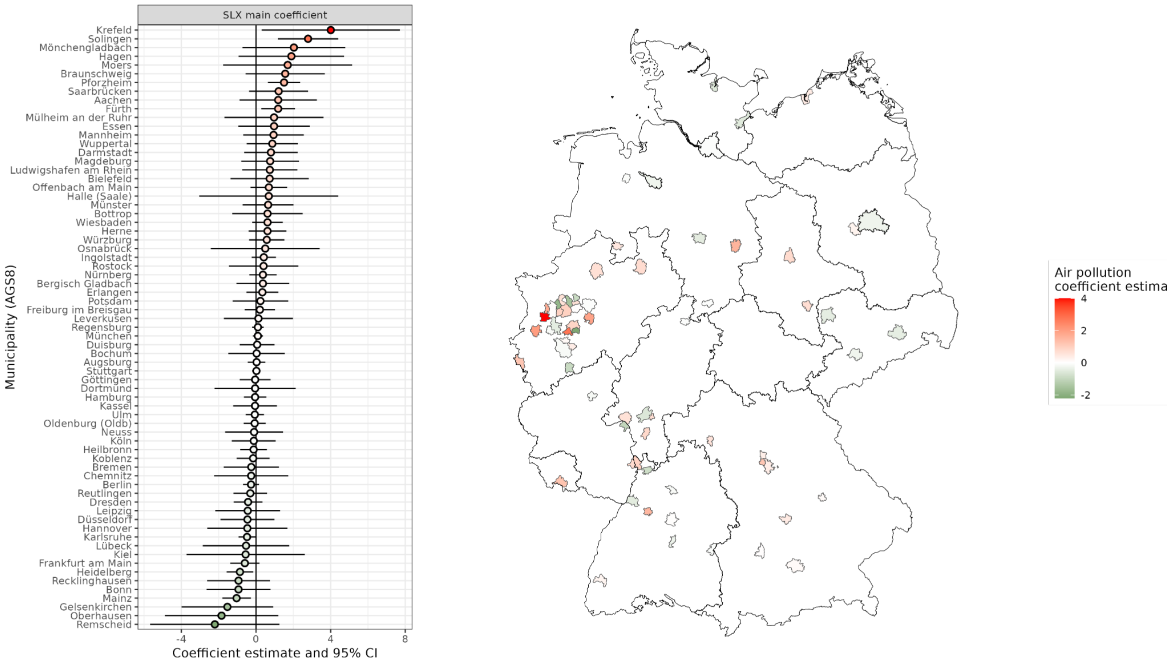


Figure S3. Link between grid-level noise exposure and poverty share in all German cities.

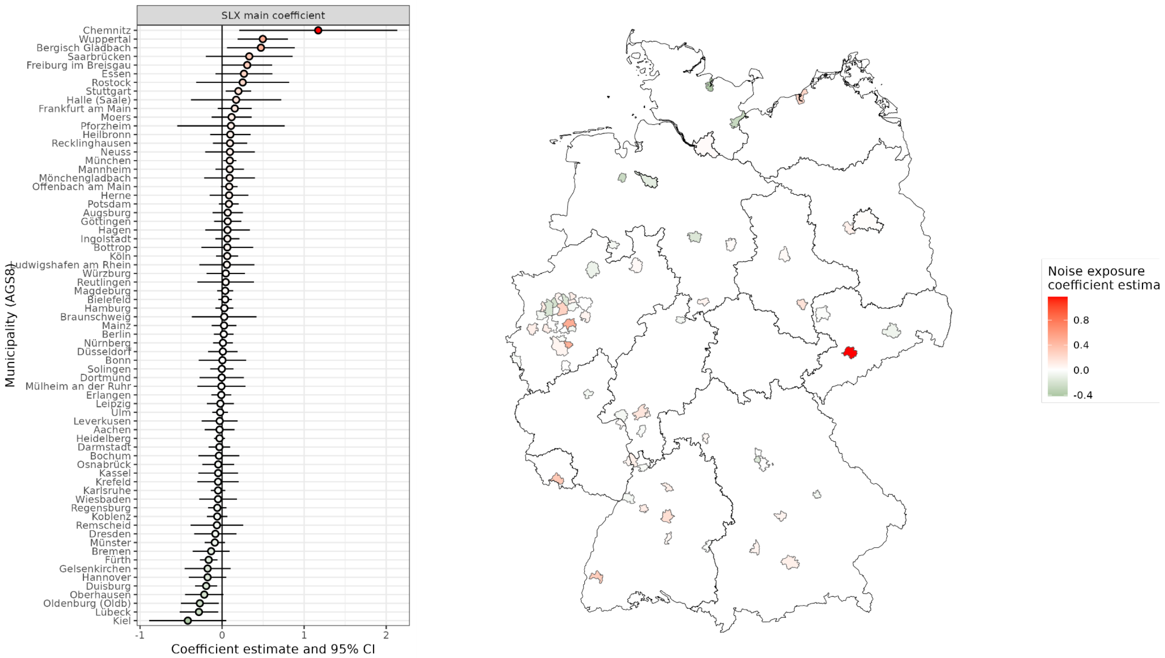
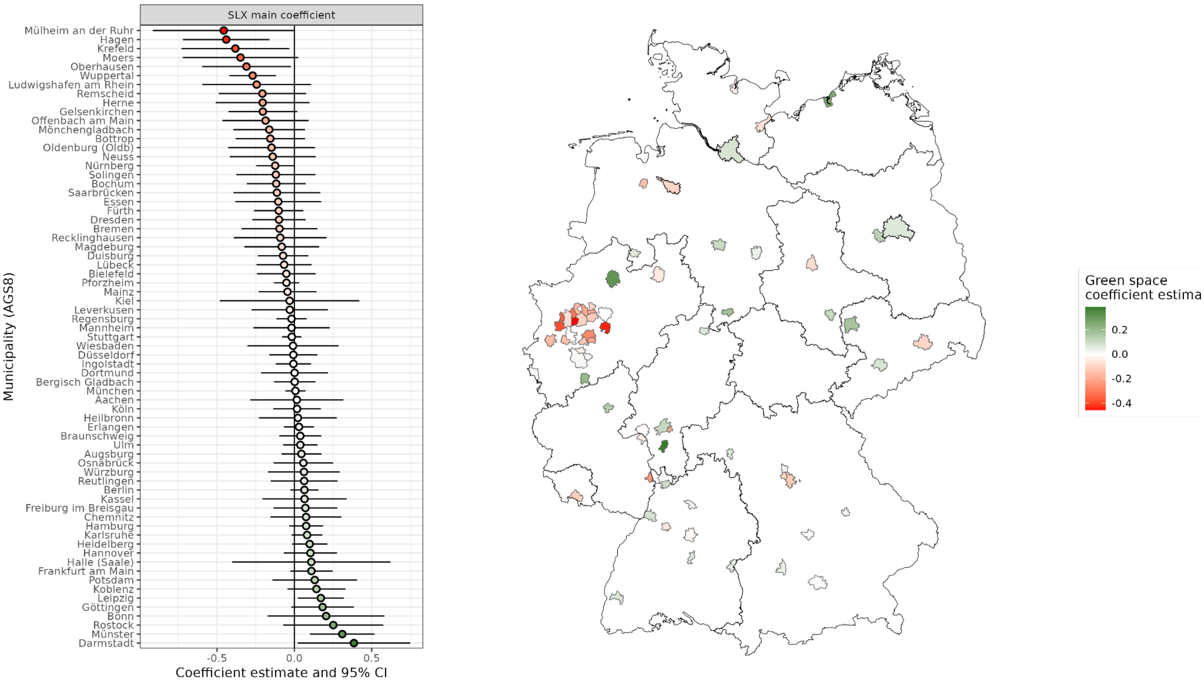


Figure S4. Link between grid-level green space availability and poverty share in all German cities.



Foreign minorities

Figure S5. Link between grid-level air pollution exposure and foreign minority share in all German cities.

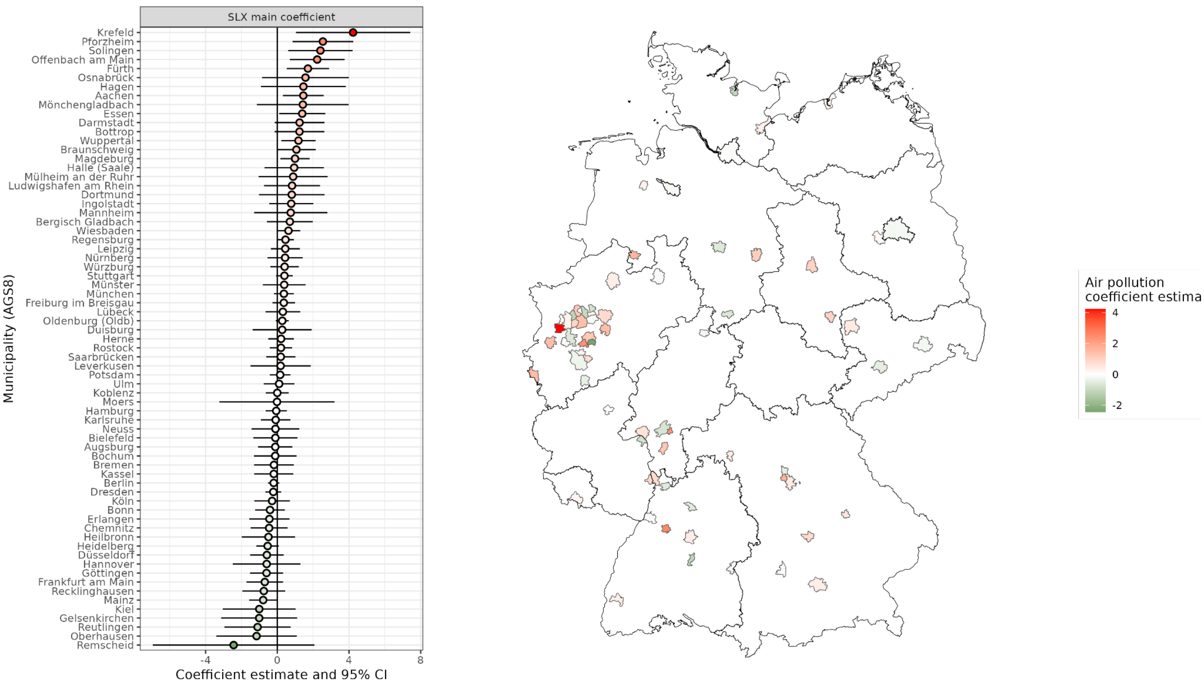


Figure S6. Link between grid-level noise exposure and foreign minority share in all German cities.

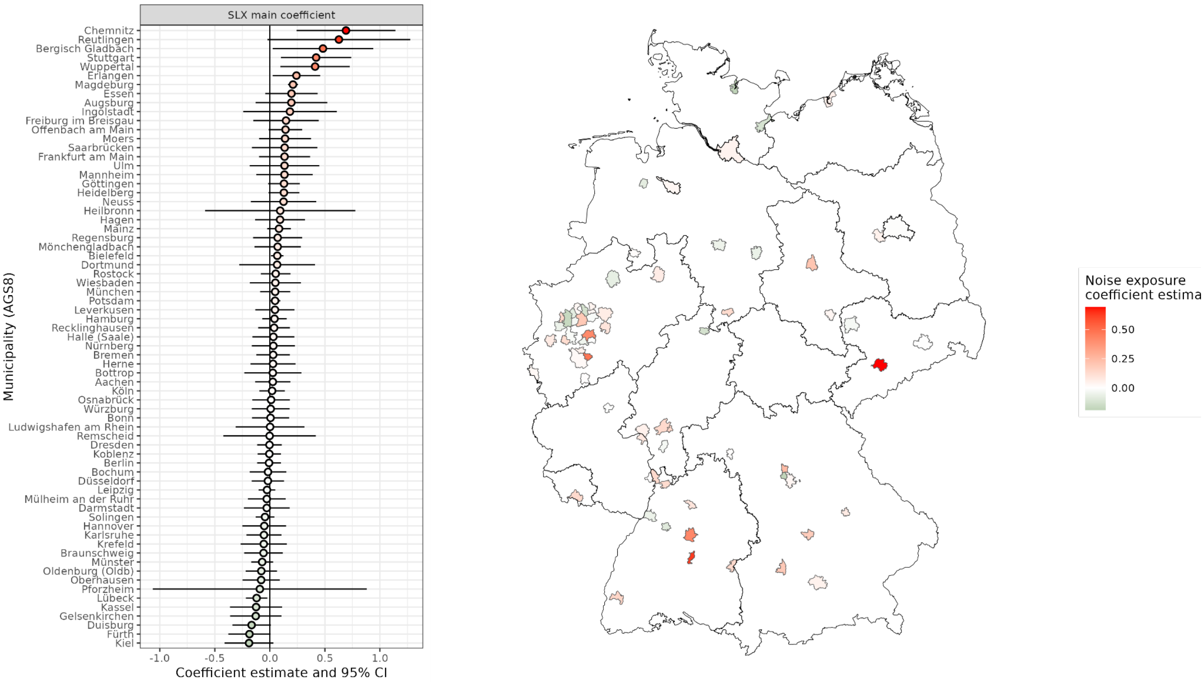


Figure S7. Link between grid-level green space availability and foreign minority share in all German cities.

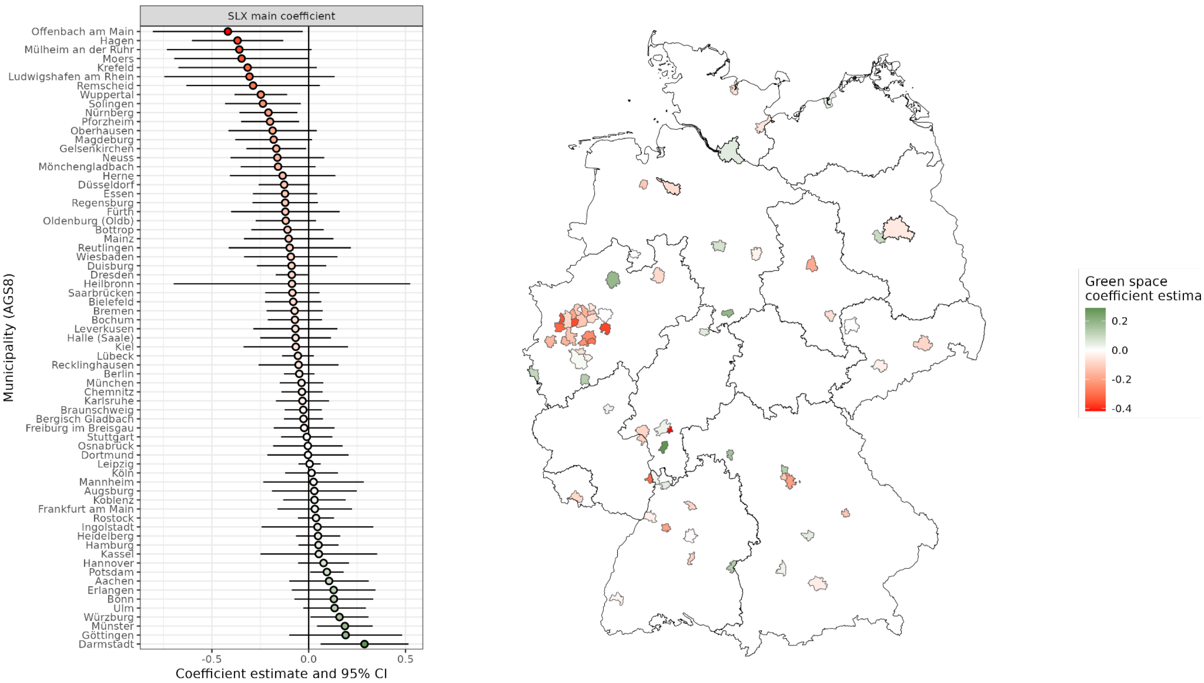
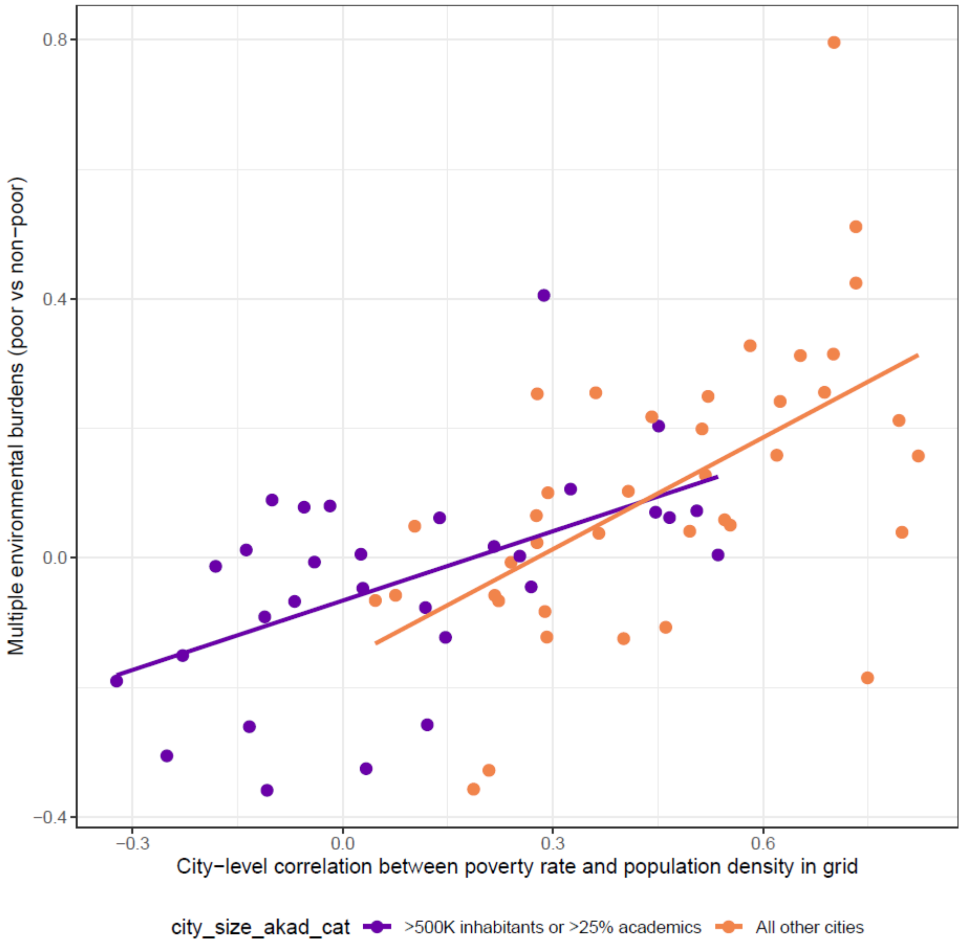


Figure S8. Association between city-level environmental inequality by poverty rates and residential centrality of poor residents for two groups of cities



D - Further material

Figure S9. Labelled map of German cities investigated.