3. Consistent inequality across Germany? Exploring spatial heterogeneity in the unequal distribution of air pollution

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1. INTRODUCTION

Worldwide, air pollution is estimated to be responsible for 9 million premature deaths per year, thereby accounting for 16 per cent of all premature deaths (Landrigan et al., 2018). Also in Europe, the European Environment Agency attributes an estimated annual 400 000 premature deaths to air pollution (European Environment Agency, 2019). Despite the serious health impacts, research has also shown that the exposure to pollution can be linked to other social outcomes like education or economic performance (e.g. Persico, 2020). Yet environmental pollution is not equally distributed across society and disproportionately affects the poor and minorities. Because of its severe consequences for the population at risk, this unequal distribution of pollution constitutes an important dimension of social inequality.

As one of the first research studies on the topic of environmental inequality, the report of the United Church of Christ – Commission for Racial Justice (1987) demonstrated that minorities and the socioeconomically disadvantaged in the United States live disproportionately close to hazardous industrial facilities. Ever since, environmental inequality has been on the agenda of social science research in the US (e.g. Anderton et al., 1994; Been, 1994; Bryant and Mohai, 1992; Bullard, 1990). Within the past decades, various studies (for an overview, e.g. Banzhaf et al., 2019a; Mohai and Saha, 2015) have documented a persistently high pollution disadvantage of minority groups and the economically disadvantaged (Colmer et al., 2020). As Mohai et al. (2009, p. 406) put it: ‘Today, hundreds of studies conclude that, in general, ethnic minorities, indigenous persons, people of color, and low-income communities confront a higher burden of environmental exposure from air, water, and soil pollution from industrialization’.

Also in Europe, environmental inequality research has gained increasing interest over the past years. There are now several empirical studies documenting the unequal distribution of environmental hazards in Germany and other European countries (e.g. Best and Rüttenauer, 2018; Diekmann and Meyer, 2010; Flacke et al., 2016; Glatter-Götz et al., 2019; Kabisch and Haase, 2014; Kohlhuber et al., 2006; Padilla et al., 2014; Raddatz and Mennis, 2013; Rüttenauer, 2018b, 2019a). Still, as we will elaborate in detail below, results tend to disagree on the extent of environmental inequality in Europe. While some studies report substantial inequalities, others conclude that the social gradient in pollution is negligible. A possible reason for the inconsistent results in previous research might be the use of distinct types of pollution measures and the focus on different geographical areas. While some studies focus on industrial facilities, others use public green spaces or general air pollution as measures of environmental quality. Moreover, studies vary in geographical location and the spatial scale, ranging from case studies in single cities to countrywide comparisons. Weigand et al. (2019), for instance, provide a comprehensive overview of varying spatial scales and measures used in environmental inequality research, and discuss potential problems of commonly used data types.

In this study, we thus contribute to the current state of research in two ways. First, we investigate if conclusions on environmental inequality depend on the measure of pollution. Second, we follow an explorative approach to assess if the extent of environmental inequality changes with different geographical scales and locations across Germany. For this purpose, we use aggregated census data and two sources of pollution: point sources of industrial facilities and pollution estimates from diffusion models. Thus, we are able to calculate the correlation between the share of minorities and air pollution based on two different ways of measuring pollution. Furthermore, we employ geographically weighted regression techniques to calculate the extent of environmental inequality for a range of different locations in Germany and for various geographical scales.

In this chapter, we proceed as follows. We first provide an overview on potential theoretical explanations for the disproportionate exposure of disadvantaged groups to environmental pollution, and subsequently outline the current state of research in Europe. We then briefly describe the data which follows a previous study (Rüttenauer, 2018b), but extends previous analyses by additional pollution measures. We then compare the extent of environmental inequality across the distinct measures of pollution, and subsequently investigate the geographical heterogeneity in environmental inequality.

2. THEORETICAL BACKGROUND[1]

The environmental inequality literature distinguishes between two main causes for the unequal distribution of environmental pollution: selective siting and selective migration (e.g. Banzhaf et al., 2019a, 2019b; Been and Gupta, 1997; Crowder and Downey, 2010; Hamilton, 1995; Sieg et al., 2004). According to selective siting, industrial facilities are assumed to be sited in or close to areas with a high proportion of minorities and low-income households. The argument of selective migration, in contrast, states that minorities and low-income households have different likelihoods of escaping from and moving into polluted areas. Accordingly, one of the main concerns in environmental inequality research is the question of ‘which came first?’ (Pastor et al., 2001). The following sections will outline both theoretical arguments in more detail.

2.1 Selective Siting

The selective siting argument claims that hazardous facilities are disproportionately sited in neighbourhoods that already face a high proportion of minorities or low-income households (Been and Gupta, 1997; Mohai and Saha, 2015; Pastor et al., 2001; Saha and Mohai, 2005; Wolverton, 2009). Three sub-mechanisms might be at work here.

First, selective siting might be the result of taste-based discrimination. If decision makers belong predominantly to the majority group and are aware of the danger or the burden of industrial facilities, they might want to externalise unwanted facilities onto minority groups, while protecting members of their own group (Hamilton, 1995).

Second, the market explanation assumes that companies seek to minimise their land and housing costs when locating new unwanted facilities. Because of lower land prices and housing costs, low-income regions are seen as an attractive siting location for new facilities (Downey, 2005; Farber, 1998; Saha and Mohai, 2005; Wolverton, 2009, 2012). Furthermore, previous research indicates that low-income households have a lower ‘willingness to pay’ (in the sense of spending less money or not being able to spend money) for environmental goods (Banzhaf et al., 2012; Franzen and Vogl, 2013; Liebe et al., 2010; Meyer and Liebe, 2010). Potential compensation costs for environmental pollution are thus assumed to be lower in areas with predominantly low-income residents, thus adding to the likelihood of selective siting by profit-maximizing companies (Mohai and Saha, 2015; Saha and Mohai, 2005; Wolverton, 2009, 2012). Assuming that minorities are overrepresented in low-income areas, this also adds to their likelihood of receiving industrial disamenities in their residential neighbourhood.

Third, the social and political capital explanation presumes that minorities and low-income households face a lack of social and political capital. Hence, inhabitants of regions with a high minority share are less likely to organise collective actions against hazardous facilities (Hamilton, 1995; Mohai and Saha, 2015; Pastor et al., 2001). Low-income households have lower means to influence political decision makers, or to organise legal actions, for example to achieve a ban of hazardous facilities (Wolverton, 2009). In contrast, high-income residents (often in neighbourhoods with a low minority share), supposedly, are more likely to influence political actors due to their social ties and political engagement or civic activism, and they are able to afford expensive legal proceedings. To avoid protests or legal proceedings, the respective executive decision makers choose the ‘path of least political resistance’ (Saha and Mohai, 2005), and selectively locate unwanted facilities in socioeconomically disadvantaged neighbourhoods with a higher share of minorities.

2.2 Selective Migration

The second major explanation of environmental inequality proposes a competing mechanism based on selective migration or sorting processes. In general, this second approach extends the general literature of residential segregation and neighbourhood attainment (e.g. Alba et al., 1999; Crowder et al., 2006; Logan and Alba, 1993; South et al., 2016) by an environmental dimension. The selective migration or sorting hypothesis presumes that the disproportionate exposure of disadvantaged citizens stems from selective migration processes into and out of polluted areas (Banzhaf and McCormick, 2012; Banzhaf and Walsh, 2008; Crowder and Downey, 2010; Mohai and Saha, 2015; Pais et al., 2014; Sieg et al., 2004), thus assuming the opposite temporal order compared with the first set of mechanisms. Again, three different sub-mechanisms support this theory.

First, the ‘racial residential discrimination thesis’ states that minorities are steered into polluted areas because of discriminatory barriers in the housing market. On the one hand, housing agents or property owners may fear declining demand and housing prices due to minority in-migration. For instance, research has shown that the minority share is associated with the perception of neighbourhood crime rates above the objective crime rate (Massey and Denton, 1993; Semyonov et al., 2012). Hence, housing agents or property owners may prefer renters belonging to the majority group and discriminate against minority applicants (Turner and Ross, 2005; Yinger, 1986). Even though this explanation is based on housing discrimination against racial minorities in the US, recent research shows that ethnic minorities in Europe and Germany experience comparable levels of discrimination (Auspurg et al., 2019). On the other hand, housing agents may also spuriously anticipate that minorities have lower preferences for high environmental quality and thus restrict the respective housing offers to a subset of objects with lower quality (Ondrich et al., 2003; Turner and Ross, 2005). This explanation holds that the selective sorting patterns are a direct consequence of the minority status or race, and are independent of socioeconomic resources. Nevertheless, Logan and Alba (1993) also propose a weak and a strong version of place stratification theory, which justifies an interaction between minority status and income, as the extent of experienced discrimination might vary with the income level of applicants.

Second, the 'racial income-inequality thesis' explains minority disadvantages as a function of their lower economic resources. This follows Tiebout's (1956) model of the 'consumer-voter', in which households are assumed to have specific preferences for the provision of public goods and aim to satisfy these preferences by moving between neighbourhoods. Because households prefer a higher environmental quality to a lower one (Bayer et al., 2009), we expect a higher demand for clean neighbourhoods. Obviously, this also implies higher housing and land prices in areas with high environmental quality (Banzhaf and McCormick, 2012; Bayer et al., 2009; Farber, 1998). Given that households are 'willing to pay' more for a clean environment as their income rises (Banzhaf et al., 2012; Franzen and Vogl, 2013; Liebe et al., 2010; Meyer and Liebe, 2010), high-income households are more likely to move out of low-quality neighbourhoods (selective out-migration) because they can afford to do so. Simultaneously, low-income households are more likely to move into low-quality neighbourhoods (selective in-migration), as these neighbourhoods are more affordable and, thus, more attractive to low-income households. In sum, minorities sort into low-quality neighbourhoods because they cannot afford high-quality areas with high-priced housing opportunities. In contrast to the first explanation, the 'racial income-inequality thesis' posits that selective migration or sorting is a function of unequally distributed socioeconomic resources among racial or ethnic groups.

A third explanation for residential sorting processes can be based on unequal housing preferences and residential homophily (e.g. Krysan et al., 2009), or the more general course of immigrant assimilation (Logan and Alba, 1993; Massey and Denton, 1993). This is not to say that minorities prefer to live in polluted areas. However, there are reasons to assume that minority households have a preference for residential characteristics, which as a side-effect are connected to higher levels of environmental pollution. The ethnic enclave model, for instance, hypothesises that living among co-ethnic peers with similar migration experiences can help to integrate immigrant minorities into the society of the receiving country (Alba et al., 1999; Logan et al., 2002; Logan and Alba, 1993; Martén et al., 2019; Winke, 2018). Accordingly, central urban areas with a high share of ethnic minorities can be a favourable environment for cultural assimilation and integration into everyday life. Moreover, these areas offer potential networks for housing and job searches, which seems especially important for immigrant minorities not speaking the language of the receiving country. Likewise, research shows that speaking the language of the host country increases the probability of immigrant households moving from the central city to suburban districts (Alba et al., 1999; Logan et al., 2002). These integration processes thus restrict (immigrant) minorities' access to suburban or rural areas, which at the same time exhibit much lower levels of pollution. Even though the causal chain is not directly linked to pollution, the fact that ethnic enclaves are often located in central urban areas (Logan et al., 2002; Massey and Denton, 1988) can induce environmental inequality. The finding that urban clusters of high-minority areas in central cities at least partly drive the correlation between minority share and pollution in Germany (Rüttenauer, 2018b, 2019a) also supports this hypothesis.

3. PREVIOUS FINDINGS IN GERMANY AND EUROPE

Though environmental inequality research in Europe has received far less attention than in the US, several studies have investigated the unequal distribution of pollution in Europe and Germany (for an overview see e.g. Pasetto et al., 2019; Weigand et al., 2019). In most cases, these studies document the disproportionate environmental burden of minority residents and (somewhat less consistently) of socioeconomically disadvantaged households. Still, previous results in Europe are characterised by a large plurality of environmental measures, different levels of spatial aggregation, and various empirical research designs (Weigand et al., 2019).

One strand of research in the field, for instance, is mostly concerned with the unequal provision of public green spaces or related land use characteristics. For Germany, Kabisch and Haase (2014) show that foreigners experience a lower provision of public green space around their place of residence. Similarly, Jünger (2021) finds that migrants tend to live in areas with a significantly higher amount of soil sealing in their immediate surrounding. However, based on individual-level data of the German Socio-Economic Panel (GSEOP), Wüstemann et al. (2017) derive rather challenging results: neither migration status nor income is significantly associated with the distance to green spaces. In line with these inconsistencies, research in the UK demonstrates how conclusions vary when considering different measures of green space, like accessibility, area size, or population pressure (Mears et al., 2019). Therefore, even within this category of environmental measures – green space – results are relatively heterogeneous.

Following the example of earlier environmental inequality studies in the US, also studies in Germany and other European countries have used point locations of industrial facilities provided by the European Pollutant Release and Transfer Register (E-PRTR) to assess environmental inequality. In their case study of Hamburg, Raddatz and Mennis (2013) report a moderate correlation between the minority share and the distance to the nearest industrial facility (a 1 percentage-point increase in foreigners being associated with a 2 per cent lower distance to facilities, but with strong spatial multipliers). Based on aggregated census data, Rüttenauer (2018b) finds a relatively strong correlation between the share of foreign nationals and the level of hazardous emissions from industrial sites, which holds nationwide as well as within German municipalities (net of other controls, standardised total impacts of 0.123 and 0.227 respectively). Results also demonstrate that this correlation is stronger within metropolitan areas, and increases for cities with centrally located industrial facilities (Rüttenauer, 2019a). Though only speculative, this somewhat supports the idea that central-city residency of minorities and higher air pollution in inner cities adds to environmental inequality. Using the same pollution data, Glatter-Götz et al. (2019) also report a relatively strong disadvantage of minorities in Austria: areas with a higher share of immigrant minorities face an increased risk of hosting an industrial facility (9.9 per cent higher odds with a 1 per cent higher immigrant share). Moreover, this disadvantage reduces only slightly after controlling for the unemployment rate, education, and the living space per inhabitant, thus questioning the importance of economic resources as a causal pathway of environmental inequality.

Yet other studies have focused on the unequal distribution of general air pollution, which is estimated based on a variety of point and mobile emission sources, and distributed across space by the application of diffusion models. Diekmann and Meyer (2010) provided the first study in Switzerland connecting individual survey data to official estimates of ambient air pollution based on diffusion models. Though they find a moderate disadvantage of the non-native respondents in Switzerland (17 per cent of the urban–rural difference in particulate matter), the association with income is negligible (0.8 per cent of the urban–rural difference for 1000 CHF more income). Similar results seem to apply in France, where Padilla et al. (2014) find only weak evidence for an association between deprivation or the share of immigrants and inner-city nitrogen dioxide (NO_2) concentrations (significant in 3/4 and 2/4 of the cities respectively). For the city of Dortmund, Flacke et al. (2016) identify a moderate bivariate correlation between socioeconomic disadvantage and NO_2 as well as PM_{10} on the neighbourhood level (Spearman rank correlations of 0.32 and 0.26 respectively). For the UK, however, Mitchell et al. (2015) point to relatively strong disadvantages of deprived areas, with most deprived areas exceeding the least deprived areas by 40 per cent in NO_2 and by 11–14 per cent in particulate matter (PM_{10}). Though the results somewhat point to a lower inequality in general pollution as compared to industrial disamenities in central Europe, it is hard to derive robust conclusions given that previous studies differ in multiple dimensions. Furthermore, we are not aware of a nationwide empirical study in Germany relying on pollution estimates based on diffusion models of air pollutants.

In this study, we thus advance previous findings in Germany in two ways. First, we investigate if conclusions depend on the measure of pollution. As outlined above, studies based on point sources of industrial emissions in Germany and Austria both find a relatively strong disadvantage of immigrant minorities in terms of pollution levels and the likelihood of living close to environmental disamenities (Glatter-Götz et al., 2019; Rüttenauer, 2018b, 2019a). In contrast, the Swiss study by Diekmann and Meyer (2010) concludes that minorities face only moderate disadvantages based on pollution estimates of diffusion models, and the local study by Flacke et al. (2016) only identifies moderate associations with socioeconomic position. However, needless to say that these differences may stem from multiple sources: (a) different types of pollution measures; (b) different levels of aggregation (spatially aggregated vs individual-level data); or (c) existing differences between the countries. In this study, we thus compare the disadvantage of areas with a high share of minorities across different measures of air pollution. Therefore, we use (1) the emissions from (and the distance to) point sources of industrial facilities, and (2) pollution estimates of diffusion models including a wide range of stationary and mobile sources of emission as well as meteorological and topographical conditions. Doing so, we are able to test one possible explanation for the differences in previous findings.

Second, we scrutinise the spatial pattern of environmental inequality in Germany. Previous research in Germany (Rüttenauer, 2018b) has found that the disadvantage of areas with a high share of minorities is approximately twice as strong in urban municipalities as it is within rural municipalities. Furthermore, the pollution disadvantage seems more pronounced in areas with a high share of minorities clusters within cities, which points to an additional penalty in urban ethnic enclaves and the importance of the urban–suburban divide for environmental inequality (Rüttenauer, 2019a). However, the same study has also shown that conclusions vary quite strongly across geographical regions: while foreigners experience a substantial disadvantage in some cities, other cities exhibit a null-correlation or even negative associations between the share of foreigners and industrial pollution (for similar results in other countries see also Downey, 2007; Glatter-Götz et al., 2019; Padilla et al., 2014). Two important conclusions follow from these findings: (1) the spatial scale (i.e. nationwide, regional, or within-municipality) of analysis seems to play a role for the extent of environmental inequality, and (2) conclusions on the presence and extent of environmental inequality might vary across the geographical region under consideration.

To test these assumptions, we employ an explorative modelling technique and analyse the geographical dimensions of environmental inequality with various geographically weighted regressions (GWR). This modelling technique offers two decisive advantages over previous analyses based on the comparison of overall pooled and municipality-fixed effects models. First, we can vary the spatial scale of the study area around any given location, thereby obtaining results which are independent of arbitrary administrative boundaries (e.g. municipality boundaries). This seems especially important if we assume that some barriers restrict the access of minorities to cleaner suburban areas or agglomerations, as these are likely to form a distinct municipality according to administrative boundaries. Second, geographically weighted regressions provide us with an estimate of the minority-pollution disadvantage across space. Thus, for each possible location in Germany and its geographical surrounding of a given size, we can assess the pollution disadvantage associated with the share of foreigners.

4. DATA AND METHOD

4.1 Data

In this study, we combine three different data sources: (1) the German census 2011 (Statistische Ämter des Bundes und der Länder, 2015); (2) data on high-polluting industrial facilities from the European Pollutant Release and Transfer Register (E-PRTR; European Commission, 2006); and (3) pollution estimates of the REM-CALGRID diffusion models calculated by the German Environmental Protection Agency (EPA; Schneider et al., 2016). The German census is available at the level of a 1×1 km grid across Germany, and provides demographic information for 93 777 occupied grid cells, containing 778 inhabitants on average. The E-PRTR contains geo-coded information about all industrial facilities exceeding a pollutant-specific threshold (facilities below the threshold are missing). For 2011 this includes 4974 facilities, of which 1480 report emissions to air. The EPA pollution model comprises emissions from industrial activities (E-PRTR), household combustion, traffic and agriculture. The emissions are interpolated across Germany based on the emissions' point locations, meteorological data, and land use data to derive a geographically distributed estimate of the pollution, which are available at the level of a 2×2 km grid across Germany.

Note that the first two data sources have been used in Rüttenauer (2018b). However, we advance on this earlier study by adding pollution estimates of diffuse air pollution. Though E-PRTR data are also included in these diffusion models, the EPA data additionally includes emissions from private households and mobile pollution sources like traffic. This offers the possibility to assess whether earlier findings based on industrial point sources of emissions still hold when using a broader range of emission sources. To merge the E-PRTR data with the census grids, we apply a buffer method (e.g. Banzhaf and Walsh, 2008; Mohai and Saha, 2007) by constructing a 2 km circle around each industrial facility and allocate the toxicity-weighted emissions proportionate to the intersection between census cell and facility buffer (for more information see Rüttenauer, 2018b). Similarly, we intersect the 1×1 km census grid and the 2×2 km EPA pollution grid, and assign each census cell the weighted average across all intersecting pollution cells. In sum, this leaves us with a final dataset of 93 777 observations including information on population, industrial facilities, and estimates of pollution.

4.2 Variables

In this study, we rely on a range of different pollution estimates. Following Rüttenauer (2018b), we use the E-PRTR data to calculate the logarithmic toxicity-weighted level of industrial air pollution and the proximity to the nearest industrial facility. From the EPA diffusion model, we get the average estimated amount of nitrogen dioxide (NO_2), ozone (O_3), coarse particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$), and sulphur dioxide (SO_2), which are measured in $\mu g/m^3$. Figure 3.1 exemplarily shows the spatial distribution of NO_2 and PM_{10} across Germany. Both pollutants exhibit large-scale spatial patterns across the country, with NO_2 reaching high concentrations in the mid-west of Germany, and PM_{10} exhibiting high levels in East Germany and the Rhein-Ruhr area. Based on these pollution estimates, we additionally calculated a pollution index as the average across NO_2, $PM_{2.5}$, and SO_2. In this index, we exclude PM_{10} because of its multicollinearity with $PM_{2.5}$, and we omit ozone because of its natural negative correlation with the remaining pollutants (Diekmann and Meyer, 2010). We first standardised the single pollutants and subsequently calculated the mean, thereby assigning an equal weight to each pollutant.

The main demographic variables are derived from the 2011 census data. As the main indicator of minority residents we rely on the percentage of foreigners in each census cell, which are defined as the percentage without German nationality. Note that most empirical studies in the US are centred on racial minority groups. In Germany, however, recent immigrants and their descendants are the main focus of ethnic dissimilarities, and this group experiences comparable disadvantages in other dimensions to racial minorities in the US (e.g. Auspurg et al., 2019). Though we acknowledge that there are likely to be differences between distinct immigrant or foreign groups (see also Best and Rüttenauer, 2018), the best available indicator at this spatial level is given by nationality/ foreign status. As control variables, we further include the total

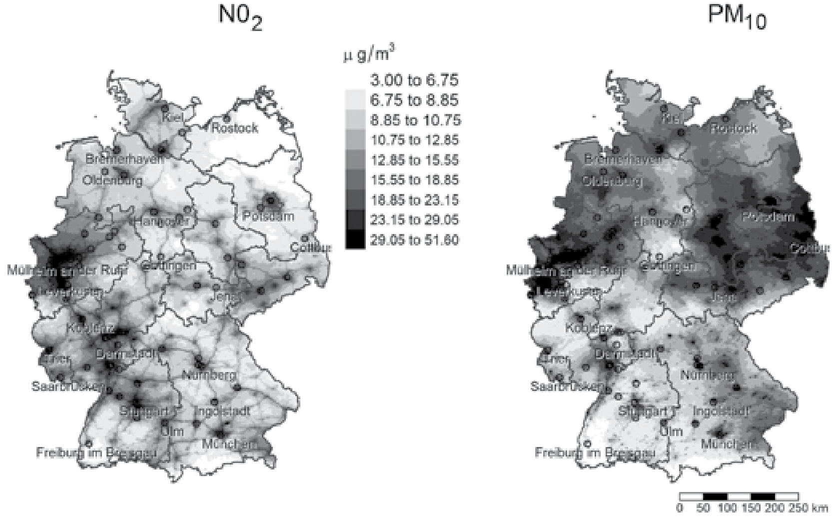

Figure 3.1 *Spatial distribution of NO_2 and PM_{10} estimates across Germany, based on EPA diffusion models*

number of inhabitants, the percentage at age 65 or older, the proportion of vacant housing, and the living space per inhabitant (for the theoretical motivation, see Rüttenauer, 2018b).

4.3 Analytical Strategy

In a first step, we will employ German-wide pooled and municipality-fixed effects spatial lag of X (SLX) models. The first set of pooled models assesses if the share of minorities correlates with the level of pollution across Germany in total. However, correlations might stem from large-scale spatial patterns, like minorities being overrepresented in West Germany. The second set of municipality-fixed effects models, in contrast, rules out between-municipality differences and measures the correlation within municipalities only (thus corresponding to local disadvantages). Further, we employ SLX models (Halleck Vega and Elhorst, 2015; Rüttenauer, 2019b) to account for spatial autocorrelation in the data and to identify clustering effects. Accordingly, Rüttenauer (2018b) has shown that industrial emissions tend to be high in areas where minorities spatially cluster. Formally, the SLX model is defined as:

$$y = X\beta + WX\theta + \varepsilon \tag{3.1}$$

where y is a $N\times1$ vector of the dependent variable, X a $N\times K$ matrix of K covariates, and ε a $N\times1$ vector of residuals (for $i = 1,\ldots N$ units). β and θ are $K\times1$ parameter vectors. W is a spatial weights matrix, which is constructed as a row-normalised contiguity ('Queens') weights matrix, where each element $w_{ij} = 1/n_i$ for all n_i units sharing a common border, and 0 otherwise. It follows that each row of WX contains the average values of X from the neighbouring units. A positive coefficient of the spatially lagged share of foreigners thus means that pollution is higher where grid cells with a high share of minorities spatially cluster. To estimate these SLX models we use the *R* package *spatialreg* (v.1.1-6, Bivand and Piras, 2015).

In a second step, we employ geographically weighted regression models (GWR; Brunsdon et al., 1996; Gollini et al., 2015). GWR is an explorative tool for spatial data analysis in which we estimate equation (3.1) at different geographical points. For L given locations across Germany, we thus receive L different coefficients of the form:

$$\widehat{\beta}_l = (X^{\intercal} M_l X)^{-1} X^{\intercal} M_l Y \tag{3.2}$$

$$\hat{\theta} = [(WX)^{\intercal} M_l WX]^{-1} (WX)^{\intercal} M_l Y \tag{3.3}$$

for each location $l = \{1,\ldots, L\}$. The $N\times N$ matrix M_l defines the weights at each local point l, assigning higher weights to closer units. For these local weights, we use a boxcar kernel density function with a predetermined bandwidth b around each point l (see e.g. Gollini et al., 2015), thereby assigning a weight of zero to all observations outside the bandwidth b and a weight of 1 to all observations within the bandwidth b. Intuitively, this means that we estimate the regression model of equation (3.1) for selected geographical subsamples within Germany, thus changing the observations contributing to the model. For instance, GWR with a bandwidth of 40 km tells us if the share of foreigners in the focal (β_l) and adjacent grid cells

(θ_l) correlates with the pollution based on all grid cells within an area of 40 km radius around the chosen mid-point. No matter the geographical bandwidth, the spatially lagged term WX is always based on the adjacent units ('Queens' neighbours) of each grid cell.

To analyse how the extent of environmental inequality changes with the geographical scale of the analysis, we estimate the GWR for a range of different bandwidths, going from 9 km to 600 km around each location. While the area of 9 km radius approximately equals the size of medium to large German municipalities like Frankfurt am Main, a 600 km radius measures environmental inequality at a very large spatial scale, thus approaching a global overall model as in (3.1). Note that we naturally expect the GWR with a bandwidth of 600 km to estimate coefficients for each location, which are similar to the results obtained from the pooled model of equation (3.1). To simplify the computational effort as well as the visualisation of the resulting L coefficients, we here use a 100×150 cell grid over Germany to determine our regression locations l. Further, we reduce these grid-points to locations with at least 40 census cells and 1000 inhabitants within a radius of 9 km. There is a trade-off between choosing a small starting radius and restricting the sample to areas which still exhibit enough data points and relevant variance within this radius (to avoid singularities). However, additional analyses have shown that starting with a smaller radius does not provide additional insights. This leaves us with 7285 regression locations at which we estimate equation (3.1) based on a subsample within the bandwidth. We use the *R* packages *GWmodel* (v.2.1-4, Gollini et al., 2015) for GWR regressions and *tmap* for visualisation (v.3.1, Tennekes, 2018).

5. RESULTS

We first test if conclusions regarding environmental inequality depend on the measure of environmental pollution, or put differently: are minorities disproportionately exposed to air pollution across different measures of pollution? Figure 3.2 plots the coefficients of the share of foreigners across various measures of pollution as outcome variable (the full results are shown in the Appendix). All models include the above-mentioned controls, and we report the direct effect of the focal unit and the indirect effect of neighbouring units, which gives an estimate of spatial clustering effects.

The first two lines of Figure 3.2 correspond to what we already know from Rüttenauer (2018b): in a German-wide comparison as well as within municipalities, a higher share of foreigners is positively correlated with the amount of toxic emissions and the proximity to industrial facilities. Direct coefficients of 0.04 and 0.12 (0.06 and 0.13 within municipalities) standard deviations indicate a small to medium disadvantage. However, the indirect clustering effects of 0.08 and 0.17 in the pooled German-wide models, and 0.17 and 0.22 within municipalities indicate a relatively strong disadvantage of broader areas in which foreigners spatially cluster, especially within municipalities. As a comparison, metropolitan areas on average have a 0.25 standard deviations higher level of industrial pollution and 0.38 standard deviations higher proximity than municipalities below 100 000 inhabitants. The effect of a one standard deviation (or 5.44 percentage points) higher share of foreigners – in the focal and the surrounding units – thus seems substantial in comparison. Especially within municipalities, industrial pollution and the proximity to environmental disamenities is disproportionately higher in minority areas.

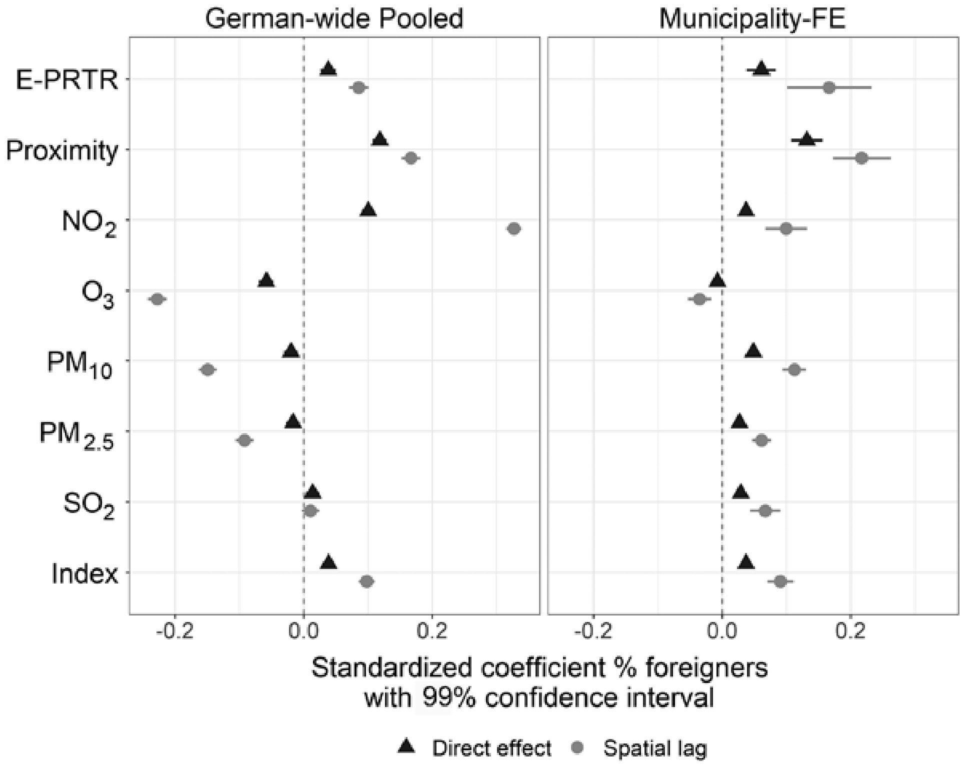

Figure 3.2 *Standardised effect of percentage foreigners and spatially lagged percentage foreigners*

Notes: Included controls: population, percentage 65 and older, percentage vacant housing, average living space per inhabitant (all also included as spatial lag), and city dummy in case of pooled models. $N = 93777$ census cells. E-PRTR: toxicity weighted air pollution of industrial facilities; Proximity: proximity to nearest E-PRTR facility. Index: mean of NO_2, $PM_{2.5}$, SO_2.

Turning to the EPA pollution estimates – which additionally account for other non-industrial sources of emissions – we however observe a relatively heterogeneous picture in the German-wide pooled models (left panel). For NO_2, conclusions align with the E-PRTR measures. Foreigners are exposed to higher NO_2 levels, and the strength of the spatial lag even exceeds findings of industrial emissions. The direction of the effect is similar for SO_2 and the combined index, but the strength of the disadvantage is much lower. For O_3, PM_{10}, and $PM_{2.5}$, conclusions in contrast differ drastically: those pollutants are lower in areas with a higher share of minorities. For O_3 we would expect this finding given its negative correlation with other pollutants and its high value in rural and suburban regions. Though results for particulate matter seem surprising at first inspection, this negative correlation is a result of the high levels of particulate matter in East Germany (see Figure 3.1), where foreigners are historically under-represented. Because of these large-scale patterns of particulate matter, foreigners live in regions with lower than average particulate matter.

Accordingly, the negative correlation with particulate matter vanishes once we take these large-scale differences into account by estimating municipality-fixed effects models (right panel). Except for ozone, all measures point to a positive correlation between the share of foreigners and the amount of air pollution. Within municipalities, minorities tend to live in neighbourhoods, which have a higher level of air pollution across all measures except ozone. In terms of substantive magnitude, this disadvantage is lower than the disadvantage estimated by relying on information from industrial facilities only. For the combined index of pollution, for instance, the within-city effect in standard deviations corresponds to 0.04 for the focal and 0.09 for the spatial lag. Though the results do not differ greatly from the coefficients of E-PRTR pollution in terms of standard deviations (0.06 and 0.17), there seems to be a pronounced difference in substantive significance. Net of common controls, the pollution index level in urban areas exceeds the average non-urban level by 1.01 standard deviations (0.25 for E-PRTR pollution). The total within-city disadvantage associated with a 5.44 percentage point higher share of foreign minorities (direct + spatial lag) thus equals 12 per cent of the disadvantage of living in an urban area. For hazardous E-PRTR emissions, in contrast, we find a minority effect, which corresponds to 93 per cent of the urban pollution disadvantage. Even though the conclusion of a disadvantage of foreign minorities remains unchanged across all measures (except ozone), the extent of environmental inequality in substantive terms seems sensitive to the measure of environmental pollution.

As we have argued earlier, another dimension which might influence the conclusions of empirical environmental inequality studies is the geographic location and scale of the analysis. To test this hypothesis, we estimate a series of GWR models for a wide range of spatial bandwidths. To simplify the presentation of results, we focus on the pollution index as dependent variable, averaging across NO_2, $PM_{2.5}$, and SO_2. Results are depicted in two different ways.

First, Figure 3.3 shows how the median conditional correlation between the percentage of foreigners and the pollution index changes over the range of geographical bandwidths, thus indicating how environmental inequality varies with the geographical scale. The shaded area furthermore depicts the standard deviation of the coefficients across the 7285 regressions in each bandwidth. All models include the above-mentioned controls except the city dummy, which we need to omit because of potential singularities. The strength of the direct coefficient first increases from 0.03 at 9 km up to a bandwidth of 100 km, reaching a value of 0.06, and subsequently decreases again. Considering the standard deviation within each bandwidth, local levels below 20 km exhibit a high amount of heterogeneity in the disadvantage of foreigners. With broader bandwidths, the median coefficient of the GWR obviously approaches the coefficient of 0.04 from the overall pooled model (Figure 3.2). By trend, the spatially lagged or clustering effect follows a similar path: starting at a value of 0.06 at 9 km, the coefficient reaches its maximum of 0.17 at a bandwidth of 100 km, before it approaches the overall effect of 0.10 standard deviations.

In sum, this provides us with two important insights: (1) there is strong variation in the disadvantage of foreigners at the more local level (≤ 20 km) across Germany; and (2) the average pollution-disadvantage in Germany reaches its maximum when considering medium-scaled areas with a bandwidth of around 100 km. To give a reference point, the area of Berlin (891 km^2) approximately fits into a circle with a bandwidth of 17 km. The results thus indicate that the relative disadvantage of minorities is strongest at a spatial scale far beyond the level of municipalities or cities. Obviously, the result on this scale may be driven by the differences in pollution between metropolitan and rural/ suburban areas, with minorities being

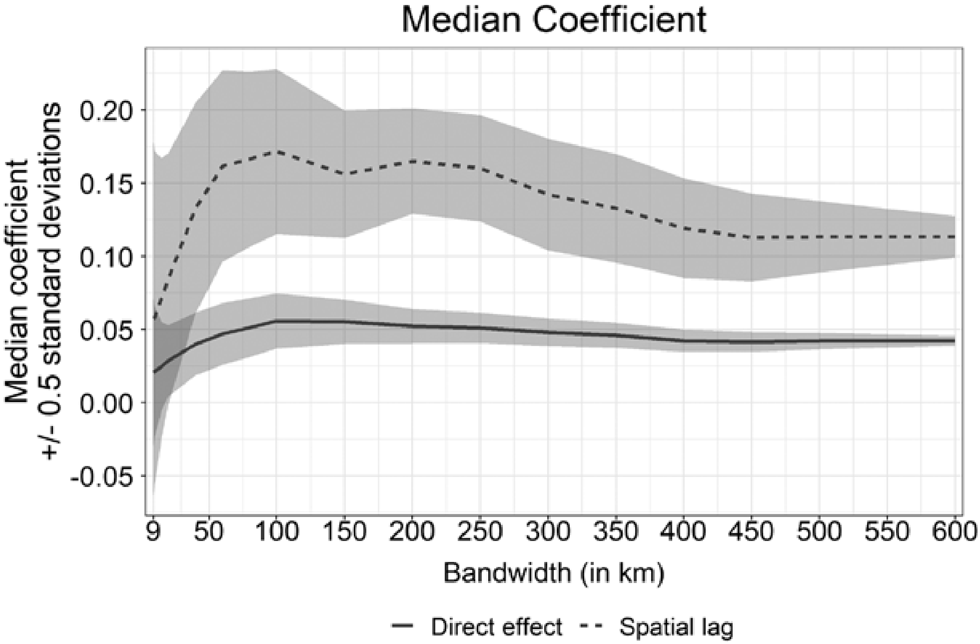

Figure 3.3 *Median coefficient of share of foreigners and spatially lagged share of foreigners from GWR models across a range of kernel bandwidths*

Note: The shaded areas show the standard deviation of the coefficients across 7285 location points in each bandwidth.

over-represented in polluted inner-city regions and under-represented in rural and suburban regions.

Second, we look at how the association varies with location. Figure 3.4 graphically shows the extent of environmental inequality across the 7285 regression mid-points for two bandwidths: 40 km in the top panel and 100 km in the bottom panel. At the local level of 40 km, coefficients range from negative values of −0.20 to positive values of 0.53 (−0.46 to 1.13 for the spatial clustering effect). This highlights that there are regions in which minorities actually have a pollution advantage, but other areas with a strong disadvantage for minorities (which is in line with previous results, e.g. Padilla et al., 2014; Rüttenauer, 2019a). However, at this spatial scale, it is hard to detect a general spatial pattern. Across all regions, we observe some areas with a weaker and others with a stronger correlation. Nevertheless, the top panel of Figure 3.4 provides some indication for higher levels of environmental inequality around larger cities (as indicated by the circles). Especially high spatial clustering effects (right side) can be found around metropolitan areas, for instance in the Rhine-Ruhr metropolitan region or around Munich and Nuremberg. This provides further support for the hypothesis that urban–suburban differences in pollution and the share of foreigners add to the unequal distribution of pollution.

The bottom panel of Figure 3.4 depicts large-scale differences in environmental inequality across Germany. Though this is the scale at which we observe the strongest average disadvantage of minorities (Figure 3.3), there are large differences across Germany. In some regions – mainly North Rhine-Westphalia, Saxony, Saxony-Anhalt, and Thuringia – GWR estimates correlations that are either slightly negative or close to zero. Foreign minorities are not exposed to a pollution disadvantage in those regions compared to observations within a reach of 100 km, though they are on a smaller scale inside those regions (upper panel). In contrast, minorities experience a relatively strong disadvantage in central and northern parts of Germany on this large spatial scale. In those regions, areas with a higher share of minorities also exhibit a higher than average level of air pollution. These large-scale patterns of environmental inequality are unlikely to be driven by general population patterns, as North Rhine-Westphalia shows low levels of environmental inequality despite a high population density.

This second set of results offers a range of implications. First, the extent of environmental inequality depends on the spatial scale of the analysis. In contrast to previous assumptions (Rüttenauer, 2018b), the strongest average disadvantage does not occur on a within-municipality level, but rather when analysing larger geographic areas, potentially including urban and rural areas. Second, some areas show low levels of inequality on a large scale, but still exhibit environmental inequality on the local scale. By trend, environmental inequality on the local level seems larger around urban areas, which again speaks for a causal channel operating through differences in residency between urban core-areas and suburban regions. Nevertheless, it is important to keep in mind that these findings are descriptive, and hypotheses about the generating process remain speculative.

6. DISCUSSION

Air pollution is known to have strong adverse health effects and is likely to influence other dimensions of social life. Thus, it comes as no surprise that social sciences in Europe have seen increasing interest in the topic of environmental inequality. Though previous studies in Germany and other European countries have shown that minorities are on average exposed to higher levels of pollution, there is strong variation in the extent of this disadvantage. In this study, we test two possible explanations for diverging results in previous studies: (1) the use of different pollution measures; and (2) the spatial scale and location of the analysis within Germany.

Our results show that conclusions of nationwide analyses depend heavily on large-scale pollution patterns. While foreign minorities are over-represented in areas with higher levels of industrial pollution as well as NO_2 and SO_2, they tend to be less affected by particulate matter and ozone. Within municipalities, in contrast, foreign minorities tend to live in areas with a higher amount of air pollution across all measures employed in this study, with the only exception of ozone. The finding of a pollution disadvantage of minorities within municipalities is thus strikingly consistent. The substantive strength of this disadvantage varies, however, across the different measures. When using the difference between urban and non-urban areas as a reference, the disadvantage seems substantial in terms of industrial emissions and the proximity to industrial disamenities, but it is rather weak regarding pollution estimates of various sources of emissions.

Further, we show that conclusions regarding the strength of environmental inequality in Germany depend on the spatial scale of the study. While the average disadvantage is rather small at the local level, it increases to its maximum at a large regional level of around 100 km.

Figure 3.4 *Direct and spatially lagged coefficient of percentage of foreigners based on geographically weighted regressions for different bandwidths*

Notes: Dependent variable is the pollution index of NO2, PM2.5 and SO2. Controls as in Figure 3.2.

This large-scale disadvantage is more pronounced in central Germany, and less so in Western and Eastern parts. However, regions with a low level of large-scale environmental inequality can still exhibit some hotspot areas of environmental inequality at a lower geographical level. At the local geographical level, we find that the unequal distribution of air pollution is especially high around metropolitan areas. Even though these results are only explorative, the spatial patterns support the idea that minorities experience a pollution penalty because of the residency in inner-city areas. As argued earlier (e.g. Alba et al., 1999; Logan et al., 2002; Winke, 2018), inner-city districts are likely to provide beneficial opportunity structures for immigrant-minorities. At the same time, barriers on the housing market restrict the access of minorities to cleaner suburban or rural areas. Regardless of the reason, the tendency of living in urban core areas seems a plausible contributor to the disproportionate exposure of minorities to environmental pollution.

Though we find that conclusions are to some extent sensitive to pollution measures and spatial scale, we can only speculate on the reasons of this heterogeneity. For instance, actual pollution levels are hard to observe, while industrial disamenities are easily visible. Thus, selective migration processes may be more reactive to industrial facilities than to average levels of air pollution. Still, the relative coarseness of the pollution estimates (2×2 km) may also mask important differences within municipalities. To test these theoretical explanations, further research needs to combine longitudinal migration trajectories to pollution estimates and the location of environmental disamenities. In addition, individual-level survey data and pollution estimates should be used to assess the substantive strength of environmental inequality across different measures in Germany. It is also important to gain insights on how the air pollution gap connects to other dimensions of inequality, like health inequalities or educational achievement gaps. In sum, we are confident that much can be learned from future research connecting the aggregated level of environmental hazards to individual-level data over time.

NOTE

1. This section is based on a more extensive theoretical discussion in Rüttenauer (2018a).

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APPENDIX: SLX REGRESSION RESULTS

Table 3A.1 Pooled SLX models

% Foreigners	0.038^{***}	0.118^{***}	0.100^{***}	-0.058^{***}	-0.020^{***}	-0.017^{***}	0.014^{***}	0.039^{***}
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
W % Foreigners	0.085^{***}	0.167^{***}	0.327^{***}	-0.228^{***}	-0.149^{***}	-0.092^{***}	0.011^{*}	0.098^{***}
	(0.006)	(0.006)	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)	(0.005)
Population	−0.006	-0.035^{***}	0.022^{***}	0.024^{***}	0.032^{***}	0.038^{***}	0.042^{***}	0.041^{***}
	(0.005)	(0.005)	(0.004)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)
W Population	0.001	0.179^{***}	0.245^{***}	-0.036^{***}	0.301^{***}	0.304^{***}	0.218^{***}	0.306^{***}
	(0.007)	(0.007)	(0.005)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)
% 65 and older	0.003	0.014^{***}	0.010^{***}	0.057^{***}	0.041^{***}	0.045^{***}	0.039^{***}	0.037^{***}
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
W % 65 and older	0.006	0.020^{***}	0.007^{*}	0.136^{***}	0.076^{***}	0.085^{***}	0.073^{***}	0.066^{***}
	(0.005)	(0.004)	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
% Vacant	0.009^{**}	0.016^{***}	-0.008^{**}	0.028^{***}	-0.030^{***}	-0.012^{***}	-0.007^{*}	-0.011^{***}
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
W % Vacant	0.010^{*}	0.005	-0.040^{***}	0.078^{***}	-0.083^{***}	-0.045^{***}	-0.020^{***}	-0.042^{***}
	(0.005)	(0.004)	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Living space	-0.034^{***}	-0.039^{***}	0.011^{***}	-0.051^{***}	-0.084^{***}	-0.092^{***}	-0.044^{***}	-0.050^{***}
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
W Living space	-0.076^{***}	-0.069^{***}	0.025^{***}	-0.125^{***}	-0.172^{***}	-0.200^{***}	-0.095^{***}	-0.108^{***}
	(0.005)	(0.004)	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Urban	0.245***	0.379***	0.883***	−0.378***	0.723***	0.810***	1.005***	1.076***
	(0.013)	(0.012)	(0.010)	(0.013)	(0.012)	(0.012)	(0.012)	(0.010)
R^2	0.032	0.173	0.460	0.123	0.203	0.262	0.253	0.411
Adj. R^2	0.032	0.173	0.460	0.123	0.203	0.262	0.253	0.411
Num. obs.	93777	93777	93777	93777	93777	93777	93777	93777

Notes: $^{**}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.
All variables are standardized except city dummy. Standard errors in parentheses. W is specified as row-normalized contiguity weights matrix. E-PRTR: toxicity weighted air pollution of industrial facilities; Prox: proximity to nearest E-PRTR facility. Index: mean of NO_2, PM_{10}, $PM_{2.5}$, SO_2.

Table 3A.2 Municipality-fixed effects SLX models

% Foreigners	0.061***	0.131***	0.037***	−0.008***	0.048***	0.026***	0.029***	0.037***
	(0.009)	(0.009)	(0.003)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)
W % Foreigners	0.166***	0.217***	0.099***	−0.035***	0.112***	0.061***	0.067***	0.091***
	(0.026)	(0.017)	(0.013)	(0.007)	(0.007)	(0.006)	(0.009)	(0.008)
Population	−0.010	−0.044***	0.018***	0.032***	0.016***	0.027***	0.036***	0.032***
	(0.007)	(0.009)	(0.003)	(0.006)	(0.003)	(0.003)	(0.004)	(0.003)
W Population	−0.040	0.078***	0.102***	0.061**	0.092***	0.101***	0.113***	0.126***
	(0.023)	(0.013)	(0.011)	(0.022)	(0.011)	(0.006)	(0.010)	(0.006)
% 65 and older	−0.005	0.004	0.002	0.013***	0.001	0.001	0.002*	0.002**
	(0.004)	(0.002)	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
W % 65 and older	−0.008	0.006	−0.000	0.023***	−0.001	−0.001	0.001	−0.000
	(0.007)	(0.004)	(0.003)	(0.004)	(0.002)	(0.001)	(0.002)	(0.002)
% Vacant	0.014**	0.016***	−0.001	0.008***	0.001	−0.000	0.003*	0.001
	(0.005)	(0.003)	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
W % Vacant	0.020*	0.010	−0.014***	0.021***	−0.011***	−0.010***	−0.003	−0.011***
	(0.008)	(0.005)	(0.002)	(0.004)	(0.002)	(0.002)	(0.003)	(0.002)
Living space	−0.012**	−0.036***	−0.008***	0.002	−0.013***	−0.008***	−0.009***	−0.010***
	(0.004)	(0.004)	(0.001)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
W Living space	–0.036***	–0.064***	–0.015***	0.001	–0.023***	–0.015***	–0.018***	–0.019***
	(0.007)	(0.007)	(0.003)	(0.005)	(0.004)	(0.004)	(0.004)	(0.003)
R^2	0.019	0.069	0.197	0.030	0.244	0.300	0.216	0.309
Adj. R^2	−0.031	0.022	0.157	−0.019	0.206	0.265	0.176	0.274
Num. obs.	93777	93777	93777	93777	93777	93777	93777	93777

Notes: $^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.
All variables are standardized except city dummy. Cluster-robust standard errors (municipality level) in parentheses. W is specified as row-normalized contiguity weights matrix. E-PRTR: toxicity weighted air pollution of industrial facilities; Prox: proximity to nearest E-PRTR facility. Index: mean of NO_2, PM_{10}, $PM_{2.5}$, SO_2.