European Sociological Review, 2023, **XX**, 1–15
https://doi.org/10.1093/esr/jcad046
Advance access publication 5 August 2023
Original Article

The air pollution disadvantage of immigrants in Germany: partly a matter of urbanity

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Several studies now document the disproportionate distribution of environmental pollution across different groups, but many are based on aggregated data or subjective pollution measures. In this study, we describe the air quality disadvantage of migrants in Germany using objective pollution data linked to nationally representative individual-level survey data. We intersect 1 × 1 km^2 grid geo-references from the German General Social Survey (ALLBUS) 2014, 2016, and 2018 with 2 × 2 km^2 estimates of annually averaged air pollution by the German Environment Agency for nitrogen dioxide, ozone, and particulate matter. Respondents with a migration background are exposed to higher levels of nitrogen dioxide and particulate matter than people of German descent. Urbanity of residence partly explains these differences, up to 81 per cent for particulate matter and about 30 per cent for other pollutants. A larger proportion of immigrants live in larger cities, which are more prone to high levels of air pollution. This is especially true for second-generation migrants. Income differences, on the other hand, do not explain the migrant disadvantage. In city fixed effects models, the patterns for migration background point unambiguously in the direction of environmental disadvantage for all pollutants except ozone. However, the within-municipality associations are weak.

Introduction

The general subject of environmental inequality research is the unequal distribution of environmental goods or bads—for example, air and water pollution, noise, or access to public green spaces—across different population groups.

Historically, the discussion on environmental justice originated in the 1970s in the United States (Pasetto, Mattioli and Marsili, 2019). Hazardous waste landfills were located near predominantly Black neighbourhoods or Native American reservations. Ever since, research on the racial and social gradients of environmental pollution has been accompanied by political activism for environmental justice (Bullard and Johnson, 2000). Environmental justice was less frequently addressed in other countries, and respective movements have remained comparatively small.

A large body of research in the United States shows that income and race are distinctly related to the amount of environmental pollution (Ash and Fetter, 2004; Ringquist, 2005; Crowder and Downey, 2010; Ash *et al.*, 2013; Pais, Crowder and Downey, 2014; Mohai and Saha, 2015). For Europe, fewer studies exist so far, and findings are less clear (Diekmann and Meyer, 2010; Hajat, Hsia and O'Neill, 2015; Best and Rüttenauer, 2018; Barnes, Chatterton and Longhurst, 2019; Fairburn *et al.*, 2019; Glatter-Götz *et al.*, 2019; Mannocci *et al.*, 2019; Diekmann *et al.*, 2022). Due to the comparatively high economic inequality (Piketty and Saez, 2014) and residential segregation (Musterd, 2005) in the United States, environmental inequality may follow different patterns in European countries. Moreover, the ongoing depopulation and abandonment of the older industrial urban cores—another driver of spatial inequality within larger US cities—is less pronounced in European cities (Raddatz and Mennis, 2013; Krehl and Siedentop, 2019). In European countries, city centres often host comparably attractive residential areas, leading to a spatial pattern of wealthy neighbourhoods which differs from many US cities. Besides, in conservative welfare states (Esping-Andersen, 1990) or coordinated market

Received: September 2021; **revised:** June 2023; **accepted:** July 2023

economies (Hall and Soskice, 2001) like Germany, economic activities—including how much pollution of the environment is tolerated—are more strictly regulated than in liberal economies like the United States. If effective, these policies should mitigate the abandonment of urban cores and inequalities in air pollution exposure. Results on environmental inequality thus cannot necessarily be transferred from US' liberal welfare state to a conservative European welfare state like Germany.

This study is the first to analyse environmental inequality in Germany based on a nationally representative individual-level survey and objective air pollution data. We focus on exposure to three pollutants among the six EPA Criteria Air Pollutants: nitrogen dioxide, ground-level ozone, and particulate matter (up to 10 µm diameter and up to 2.5 µm diameter).[1] We assess the extent of environmental inequality in Germany in terms of migration background by spatially matching geo-referenced cross-sectional survey data with small-scale estimates of air pollution. In Germany, studies on environmental inequality have mainly focused on subjective measures of air pollution (Mielck, 2004; Kohlhuber *et al.*, 2006; Best and Rüttenauer, 2018), have used aggregated data (Rüttenauer, 2018, 2019; Rüttenauer and Best, 2021), or focused on single geographic regions (Kindler, Weiland and Franck, 2011; Raddatz and Mennis, 2013; Flacke *et al.*, 2016). This has potential limitations. First, subjective assessment might differ between individuals, which might be correlated with other characteristics like income, education, or country of origin. Second, aggregate data do not allow us to test whether other individual-level characteristics can partially or even fully explain minority disadvantages. Third, case studies in large cities cannot capture the presumably important factor of urban versus rural living. Last, we provide a precise estimate of the pollution disadvantage in terms of nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$). This is particularly important in light of recent findings that exposure to these pollutants significantly affects health outcomes even at lower overall pollution levels (Meng *et al.*, 2021; Strak *et al.*, 2021).

In the following, we outline the theoretical background—selective siting and selective migration—before reviewing previous studies on environmental justice. We show that a nationwide micro-level study using objective pollution data from a conservative welfare state is lacking. We then describe the data, which we combine to assess air pollution inequality in Germany and present the relevant socio-demographic variables and pollutants along with their sources and effects on health. We give an overview of our analytical strategy and stepwise introduction of covariates in municipality-clustered regression models before presenting the results of our analyses.

Results reveal that people with a migration background are exposed to substantially higher levels of air pollution. The gross disadvantage in NO_2 and $PM_{2.5}$ is substantial and would, at a lower bound, translate into a 2.19 per cent higher mortality risk due to NO_2 and a 0.58 per cent higher mortality risk due to $PM_{2.5}$. Differences in income cannot explain this pollution gap, but it is mainly due to migrants living closer to major cities. Within this group, the impact of urbanity on exposure is mainly evident for second-generation immigrants. We conclude that the rural–urban divide is highly relevant for air pollution exposure and inequalities therein and that this divide partly mediates the migrant effect.

Theory and previous findings

Environmental inequality means that different parts of the population—income classes or racial/ethnic groups—are unequally affected by environmental pollution (e.g., air quality, clean water, noise) or have unequal access to environmental resources like green spaces (Mohai and Saha, 2015; Braun, Obenbrugge and Schulz, 2018; Jünger, 2022). On top of the exposure side of environmental inequality, less affluent people contribute less to environmental pollution in terms of car usage or consumption of industrial products and profit less from the returns of industrial production (Stephens, Bullock and Scott, 2001; Tessum *et al.*, 2019). This adds a further dimension of injustice. However, the aim of this study is to unveil and describe environmental inequalities, and we thus refer the interested reader to the broader discussions on the (in)justice aspect of environmental inequality (Schlosberg, 2007; Preisendörfer, 2014; Boyce, Zwickl and Ash, 2016).

Mechanisms explaining environmental inequality

Theoretically, inequalities in exposure to air pollution or environmental inequalities, in general, can be explained by two main mechanisms. One explanation is that industrial facilities, roads, and other sources of pollution are *selectively sited* close to neighbourhoods inhabited by ethnic minorities and low-income households. Reasons may include lower prices for building land, discrimination by decision-makers, or (expected) lower social and political capital of residents to oppose the nearby source of pollution (Hamilton, 1995; Mansfield, von Houtven and Huber, 2001; Boyce, 2007). Empirical evidence on selective siting is, however, mixed (Mohai and Saha, 2015; Ard and Fairbrother, 2017; Rüttenauer and Best, 2021). Moreover, Ard and Fairbrother (2017) have recently provided a first study using direct measures of social capital and found no mediating effect of social capital for differences in proximity to stationary sources of airborne toxins between Hispanics, African Americans, and the rest of the US population. A second explanation is *selective migration* out of or into polluted neighbourhoods. After sources of pollution have started impinging upon an area, those who can afford to will move to cleaner places (Pulido, 2000). Others—like minority households—are stuck in place. First, discrimination in the housing market reduces the moving options of minorities (Christensen, Sarmiento-Barbieri and Timmins, 2022), thus making them less likely to escape polluted areas.[2] Second, falling housing prices in the polluted area (Liebe, Preisendorfer and Meyerhoff, 2010) make these areas affordable to lower-income households. Third, minority households may have other priorities than avoiding pollution, such as a preference to live in a neighbourhood with a high share of compatriots (Rüttenauer, 2018; Winke, 2018).

Given the cross-sectional design of our study, we do not aim to test the resulting chicken-and-egg question of whether siting or migration is selective and causes environmental inequality. Rather, we assess descriptively if environmental inequality in air pollution exists in Germany and investigate the relevance of urban–rural differences. However, since we use individual data, we can still investigate hypotheses arising from the mechanisms discussed above.

The immigration history in Germany

Racial homogeneity is relatively high in Germany, but about a quarter of the population has a migration background. The status of immigrant minorities in society is quite diverse—from descendants of migrant workers ('Gastarbeiter') to cosmopolitan professionals—and hardly comparable to historical racial minorities in the United States. Minorities to large shares are much more recent immigrants, mainly from Turkey, Southern Europe, and later ex-Yugoslavia and Eastern Europe (Helbig and Jähnen, 2018). Their status and the discrimination they face are not directly comparable in terms of their underlying causes and consequences. Still, an international comparative meta-analysis by Auspurg, Schneck and Hinz (2019) has shown remarkable similarities in the extent of discrimination in the rental housing market between immigrant minorities in Germany and racial minorities in the United States. Moreover, Germany exhibits notable levels of residential segregation of immigrants and their descendants (Musterd, 2005; Schönwälder and Söhn, 2009; Helbig and Jähnen, 2018).

One particularity of the German migrant population is the spread across a large number of mainly West German cities. The settlement structures still reflect the labour demands of the 1960s and 1970s when immigration was mainly driven by an active guest worker program. An expanding industry recruited migrant workers from Southern Europe and Turkey to work in factories scattered throughout urban West Germany (Schönwälder and Söhn, 2009; Helbig and Jähnen, 2018). For those immigrants, Germany has not adopted an active assimilation policy and had a rather restrictive citizenship policy. This may be among the reasons why immigrants from Eastern Europe, Turkey, Italy, and Greece are still disadvantaged on the labour market, with only slight improvements in the second generation (Algan *et al.*, 2010). The labour market disadvantage of Turkish immigrants rather increased over the past decades (Wiedner and Giesecke 2022), thereby providing a pessimistic view on immigrants' economic assimilation over time. In the subsequent immigration phase during the early 1990s, Germany experienced large immigration flows of refugees from former Yugoslavia and other European countries. Another group of refugees from Syria, Iraq, and Afghanistan arrived in Germany since 2015 (BMI and BAMF 2023, see also Appendix Figure A9).

Despite comparatively low levels of deprivation (compared to the United States), German cities and immigrant groups vary substantially in the extent of ethnic segregation and spatial isolation (Musterd, 2005; Schönwälder and Söhn, 2009). The extent of residential segregation has been relatively stable over the past decade, with only modest declines (Helbig and Jähnen, 2018). Moreover, aggregated data do not provide patterns of assimilation in terms of place of residency. The over-representation of foreign minorities in metropolitan areas has been stable over the past 25 years, with the share of non-German citizens being approximately three times as high in metropolitan areas than in rural areas (Appendix Figure A9).

We might expect pronounced differences in environmental inequality by country of origin since, for example, housing preferences and the magnitude of experienced discrimination are quite diverse among these groups. For instance, there are substantial differences in the risk of cancer caused by air pollutants between groups of origin in the United States (Rubio *et al.*, 2020). In a European example, Diekmann and Meyer (2010) find greater exposure to air pollutants in Switzerland, especially for migrants of southern European origin (see also Diekmann *et al.*, 2022, for noise pollution). Moreover, the extent of residential segregation (Helbig and Jähnen, 2018) as well as the economic disadvantage (Algan *et al.*, 2010) differs between immigrants of different origins. Unfortunately, the sample size of our study does not allow for detailed comparisons of subgroups. We thus can only distinguish between immigrants originating from wealthy Western countries and those from other countries.

Resulting hypotheses

Our focus in this paper is on the environmental disadvantage of ethnic minorities, with the central hypothesis that immigrant minorities are exposed to higher levels of air pollution. Subsequently, we test several factors that could influence this association.

First, we can assess the role of income: if minority disadvantages persist after adjusting for income and other socio-economic factors, this indicates that the market-based explanation is insufficient to explain minority disadvantages. US studies at the household level have only partially confirmed the racial income-inequality thesis, which attributes the selective migration of racial minorities to more polluted areas to their lower incomes; a large part of the racial gap in moving behaviour cannot be explained by socio-economic factors (Crowder and Downey, 2010; Pais, Crowder and Downey, 2014). In Germany and Austria, economic indicators at the aggregate level do not substantially explain minority disadvantage (Rüttenauer, 2018; Glatter-Götz *et al.*, 2019; Neier, 2021). Although a recent study shows that income plays a role in the ability to escape perceived pollution (Rüttenauer and Best, 2022), others have shown that ethnic pollution disadvantages remain after accounting for income (Diekmann *et al.*, 2022).

Second, we investigate the idea that immigrant minorities experience higher pollution levels due to their disproportionate representation in central urban areas, which would be reasonable to expect given the situation in Germany. Immigrants and their descendants tend to concentrate in larger cities (Brückner, 2016; Göttsche, 2018; Rüttenauer, 2018), presumably due to ethnic boundary-making, ethnic enclaves, and chain migration (Haug, 2000; Winke, 2018). The air pollution disadvantage of immigrants may thus be an unintended consequence (Szasz and Meuser, 2000) of their residence places' urbanity, a matter of rural–urban differences in pollutant concentration.

Third, we examine differences between first- and second-generation immigrants. This distinction may be relevant both to differences in discrimination faced by these groups and to differences in preferences and integration. In Germany, second-generation immigrants tend to be less segregated overall than first-generation immigrants (Janßen and Schroedter, 2007; Janßen and Bohr, 2018). Moreover, second-generation migrants still largely reside in urban and metropolitan areas, and a major share continues to live in the cities and regions where they grew up or their parents originally moved to, respectively (Schönwälder and Söhn, 2009). We could thus assume generally that first-generation migrants live in less favourable locations (e.g., due to discrimination or ethnic enclave migration), while the second generation is exposed to more pollution than the non-migrant population only because they disproportionately live in urban regions.

State of research

Research on environmental inequality has emerged around the world (Hajat, Hsia and O'Neill, 2015; Di Fonzo, Fabri and Pasetto, 2022; Shao, Liu and Tian, 2022) and in Europe in recent decades. Although many findings generally tend to support those from the United States, studies in Europe, in particular, give more mixed results (Fairburn *et al.*, 2019). For instance, ethnic minorities here are sometimes exposed to higher levels of pollution and sometimes to lower levels depending on the ethnic minority considered. In a European comparison from 2004 to 2008, Richardson *et al.* (2013) find a pollution disadvantage for low-income groups only in Eastern but not Western Europe. Nationwide studies in other German-speaking countries have so far concluded that immigrants, in particular, are more exposed and that other demographic or economic factors play a comparatively minor role. In Austria, people living near industrial sites are twice as likely to be immigrants (Glatter-Götz *et al.*, 2019). They are also more likely to be unemployed and to have lower education levels, but these differences are less pronounced. A recent study by Neier (2021) confirms these findings for foreign minorities but—contrary to expectation—indicates higher pollution levels with increasing income. Diekmann and Meyer (2010) find that immigrant minorities in Switzerland are disproportionately affected by pollution but report only modest pollution gradients in income and education, running opposite to the expected direction. Similarly, the exposure to noise pollution (Diekmann *et al.*, 2022) and green spaces (Jünger, 2022) differs primarily along ethnic lines, although conclusions vary across cities (Diekmann *et al.*, 2022).

Small-scale aggregate-level studies often yield less clear-cut results. For instance, Padilla *et al.* (2014) find contradictory results in four French cities, and Hajat *et al.* (2013) observe higher air pollution in some metropolitan regions for areas with a higher socio-economic status. This can be explained by the greater proximity to main transport routes. Analyses focusing on the distribution within individual neighbourhoods and areas appear particularly interesting in this context. Such analyses often yield different patterns than large-scale comparisons. For example, high SES districts in Rome are exposed to higher pollution levels (Cesaroni *et al.*, 2010), which the authors explain by the historical stratification within the city.

In Germany, most of the previous research supports the US conclusion by revealing a higher environmental burden of households with lower socio-economic status and migration background. Raddatz and Mennis

(2013) find that highly polluting factories in the city of Hamburg are less distant from neighbourhoods with a higher proportion of welfare recipients and foreigners. The only Germany-wide study (Rüttenauer, 2018) measuring objective environmental burdens finds higher burdens for areas with higher shares of foreigners, where clusters of high minority shares appear particularly disadvantaged. Greater minority environmental burdens are observed in urban and metropolitan areas, where the proportion of minorities is generally higher. Studies investigating disadvantages in access to green spaces (Jünger, 2022) or noise pollution Diekmann *et al.* (2022) generally corroborate these findings, although some cities show contradictory patterns in the sense that minority disadvantages are not observed (Rüttenauer, 2019; Diekmann *et al.*, 2022).

Although studies have concluded that the disadvantage of minorities persists after controlling for socio-economic characteristics (Raddatz and Mennis, 2013; Rüttenauer, 2018; Glatter-Götz *et al.*, 2019; Neier, 2021), these studies rely only on aggregate data. To investigate the interdependence of status and ethnicity with pollution (while holding other household characteristics constant), it is necessary to examine environmental inequality with micro-level data. The present study makes this contribution for Germany.

Data and methods

We combine data from two main sources, allowing us to examine the relationship between individual-level demographic data and residential air pollution for a random sample of the German population. We rely on three repeated cross-sectional waves of the German General Social Survey (ALLBUS) from 2014, 2016, and 2018 (GESIS, 2021a, 2021b). The data provide the locations of the respondents' residences, geo-referenced to evenly distributed grid cells of 1 × 1 km^2 (GESIS, 2021b). We combine data from 2014, 2016, and 2018 and pool them for all analyses, as meaningful trend analyses are not possible with only three points in time so close together. All analyses were conducted on-site at the GESIS Secure Data Center Cologne in order to guarantee the anonymity of the households surveyed.

Variables

From the ALLBUS, the central factors we examine are migration background and income. A person has a migration background if they (first generation) or at least one of their parents (second generation) experienced immigration after 1949.[3] We distinguish between first- and second-generation migrants because we expect substantial differences between these groups, including differences in language skills and social integration. These differences could be crucial for disadvantages in their housing situation. Our income measure is the logarithm of the per capita equivalent net household income, calculated as the household income over the square root of the number of household members. Further variables derived from the ALLBUS are school education[4] and occupational prestige (ISEI based on ISCO-08, see Ganzeboom, 2010). To infer the degree of urbanity, we use the distance in kilometres from each household's corresponding ALLBUS grid cell centre to the centre of the nearest city with at least 100,000 inhabitants.[5]

We match ALLBUS data with geodata provided by the German Environment Agency on the annual mean concentration of the health-relevant criteria air pollutants. The pollutants are nitrogen dioxide (NO_2), ozone (O_3), and particulate matter (up to 10 μm diameter and up to 2.5 μm diameter) in micrograms per cubic metre. The values are based on emission data from traffic as line sources (TREMOD), industrial and agricultural production as point sources (PRTR), and area sources for the remaining agricultural production, trade, service industries, military, and residential heating systems.[6] To estimate the dispersion of the emissions across Germany, the German Environmental Agency uses a REM-CALGRID chemical transport model taking geographic and meteorological conditions into account, which they calibrate at around 400 measurement stations all over Germany (Schneider *et al.*, 2016). The data we use for our analysis are an interpolation of these modeled dispersion data to a nation-wide 2 × 2 km^2 grid projection. We calculate the value for each pollutant assigned to an ALLBUS grid cell as the average of all intersecting grid cells of the pollution data, weighted by its proportional intersection with the entire grid cell. Figure 1 shows the spatial distribution of the respective criteria air pollutants.

Pollutants sources, health effects, and distribution across Germany

The primary sources of nitrogen dioxide are combustion engines and firing systems for coal, oil, gas, wood, and waste. High concentrations of NO_2 in Germany are mostly found in densely populated areas and along busy roads and waterways. NO_2 can penetrate deep into the lungs and irritate the respiratory system, inducing various respiratory diseases (Manisalidis *et al.*, 2020). Furthermore, epidemiological studies provide strong evidence that NO_2 is associated with higher mortality from cardiovascular disease (Schneider *et al.*, 2018). The German Environment Agency estimates that between 6,000 and 8,000 premature deaths, or between 47,000 and 71,000 YLL (years of life lost) can be attributed to NO_2 pollution annually in Germany (Schneider *et al.*, 2018).

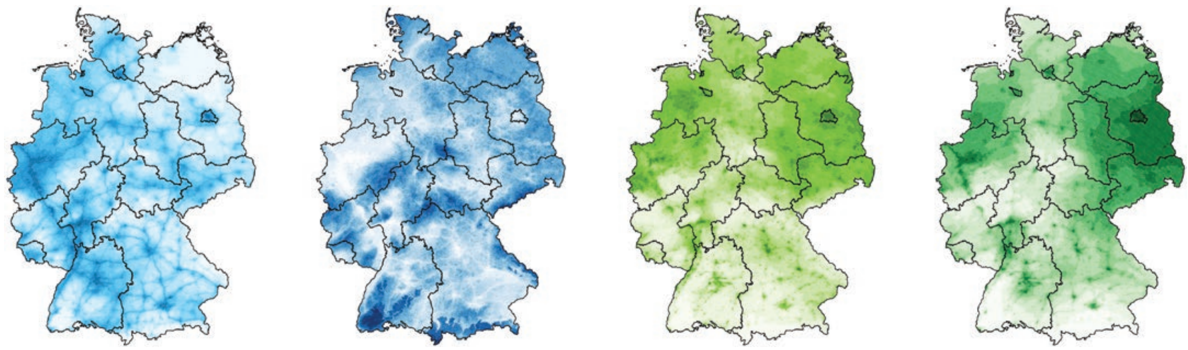

Figure 1 Pollutant concentration. Note: Local concentration of pollutants (from left to right): NO_2, O_3, PM_{10}, and $PM_{2.5}$, larger versions of the maps can be found in Supplementary Appendix A2. All values are averaged over 2014, 2016, and 2018.

Most of the precursors of ground-level ozone (O_3)—volatile organic compounds and nitrogen oxides (NO_2 and others)—are man-made. The main sources are again road traffic and power plants. In addition, there is a background ozone load resulting from hemispheric transport and natural formation processes. Methane and carbon monoxide emissions both contribute significantly to this background load due to their long atmospheric lifetime. Due to the so-called titration effect, O_3 concentrations are lower in urban traffic areas than in rural areas, leading to a negative correlation with many other pollutants. Short-term exposure to ozone can cause eye and respiratory irritation and headaches. When inhaled deeply and frequently, usually during physical activity, ozone reaches the lower parts of the lungs, where it can damage the tissue and induce inflammation. Evaluations of European and worldwide time series studies commissioned by the World Health Organization (World Health Organization, 2013) indicate an association between O_3 concentration and total daily mortality.

Particulate matter is also primarily produced by human activity: Primary particulate matter—that is, particles emitted directly at the source—is caused by emissions from motor vehicles, power, and district heating plants, furnaces and heating systems in residential buildings, metal and steel production and bulk material handling. It can also be of natural origin, for example, due to soil erosion. In conurbations, road traffic is the dominant source. Another important source is agriculture: emissions of gaseous precursors, especially ammonia emissions from animal husbandry, contribute to secondary particulate matter formation. In humans, PM_{10} can penetrate the nasal cavity, $PM_{2.5}$ can reach the bronchi and pulmonary alveoli, and ultrafine particles can enter the lung tissue and even the bloodstream. Depending on the particles' penetration depth, particulate matter's health effects vary. They range from irritation of the mucous membranes and local inflammation in the respiratory tract to increased plaque formation in the blood vessels and increased susceptibility to thrombosis or cardiac arrhythmia.

The pollution levels considered in this study are well within the health-relevant range. Recent studies show a fairly linear concentration–response function above 10 μg/m^3 NO_2 and above 5 μg/m^3 $PM_{2.5}$ for long-term exposure at the residence over nearly 20 years (Strak *et al.*, 2021) as well as short-term (Meng *et al.*, 2021) health effects such immediate cardiovascular and respiratory reactions. This is well below the average level of the study participants (see Appendices A1 and A2). This means that each additional microgram per cubic metre in NO_2 and $PM_{2.5}$ directly translates into worse health conditions. The relative marginal health effects are even stronger at lower levels of air pollution (Strak *et al.*, 2021).

To calculate differences in mortality risks we rely on average concentration–response effects of Strak *et al.* (2021), which are based on 325,367 adults followed over a period of 19.5 years. They estimate that a 5 μg/m^3 higher level of $PM_{2.5}$ is associated with a 13 per cent higher mortality risk and a 10 μg/m^3 higher exposure to NO_2 with an 8.6 per cent increased risk of mortality over the observation period. These concentration–response curves are nearly linear across normal values observed in Germany. We translate the observed pollution differences into respective mortality risk differences based on these estimates. Note that these are likely lower bound estimates, as recent results (Josey *et al.*, 2023) suggest that immigrant minorities are more susceptible to detrimental health consequences from NO_2 and $PM_{2.5}$ than non-migrants.

Estimation strategy

Given the descriptive purpose of our paper, statistical control for all possible mechanisms and relevant confounders is less critical than in a longitudinal, causal study. Importantly, we cannot control for mechanisms related to the life course, such as moves due to changes in family structure, for example, births or divorces.

Table 1 Statistical associations of migration background and local air pollution

Pollutant (mean in µg/m³)	NO_2 (15.57)	O_3 (48.72)	PM_{10} (15.77)	$PM_{2.5}$ (11.53)
Adjusted for survey year only	2.55***	−1.40***	0.47***	0.22**
With socio-economic controls	2.60***	−1.41***	0.42**	0.20*
Soc. dem. + distance to city	1.85***	−0.96***	0.20+	0.04
Soc. dem. + city fixed effects	0.12+	−0.06	0.09**	0.03+

Note: We report unstandardized coefficients and significance levels from standard errors clustered by municipality (267 clusters, 266 degrees of freedom) obtained from linear regressions weighted by sampling probability. Independent variable: migration background (respondent or at least one parent has immigration experience). Socio-economic controls: per capita equivalent net household income (log), schooling, occupational status (ISEI), survey year. The sample size is 8,311 for all regressions.
***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, +$P < 0.1$.

Instead, we want to assess the overall magnitude of inequality in air pollution exposure in Germany and decompose it into different parts due to migration background, socio-economic factors such as income, and spatial structure. To do this, we need a sample that is as representative as possible of the population.

In our analyses, we regress air pollution on migration background, varying the dependent variable across the different types of pollution. We then include additional controls in a stepwise design. No single pollutant can provide a complete picture of health-relevant air pollution exposure. Especially ground-level O_3, which is more concentrated in rural areas, is expected to lead to different conclusions than the other pollutants. Still, also NO_2 and particulates differ in their causes and health impacts. We, therefore, run the models separately for each pollutant. In the first set of models, we assess the overall level of inequality concerning migration background. Here, and in all subsequent models, we control for the survey year, as the share of immigrants increased while air pollution decreased from 2014 to 2018. In the second step, we control for socio-economic factors. We then run another set of models using two different approaches to account for the expected differences between more urban and more rural areas: In one model, we simply add a control for the distance to the centre of the nearest major city[7]; in another, we use municipality/city fixed effects (see Supplementary Appendix A7.4 for a robustness check using group mean centred RE models). After excluding cases with missing geodata and missing data on the variables examined, 8,311 cases are included in the analysis.[8] Since ALLBUS uses disproportionate sampling for Eastern and Western Germany, sampling weights are applied accordingly in all analyses. The error variance is estimated in all models clustered by municipality.[9]

Results

In the following, we present correlations between background and air pollution, introduce socio-economic controls, adjust for distance to the nearest major city as a measure of urbanity, and examine the relationships within each community using city fixed effects models.

The models controlling only for survey year (Table 1, first row)[10] show that the air is distinctly cleaner where people without a migration background live (except for ozone). People with migration background in Germany are, on average, exposed around their home to 16.4 per cent more nitrogen dioxide ($P < 0.001$), 2.9 per cent less ozone ($P < 0.001$), 3.0 per cent more particulate matter up to a diameter of 10 µm ($P < 0.001$), and 1.9 per cent more particulate matter up to a diameter of 2.5 µm ($P = 0.008$) than people without migration background.[11]

This corroborates previous results at the spatially aggregated level and indicates a substantial disadvantage. Using average concentration–response estimates in European cities, this would translate into a 2.19 per cent higher long-term[12] mortality risk due to NO_2 and a 0.58 per cent higher mortality risk due to $PM_{2.5}$ for people with a migration background. This disadvantage in mortality risk is likely an underestimate, as according to Josey *et al.* (2023) minorities experience higher than average health impacts from pollution exposure.

One might speculate that people with a migration background are exposed to higher air pollution mainly because their lower incomes force them to sort into more polluted, lower-rent neighbourhoods. This idea is misleading, as Table 1 (second row) and Figure 2 (left panel) show. Adjusted for socio-economics, the inequalities concerning migration background remain unchanged, indicating that the relationship between migration background and air pollution is independent of a household's socio-economic position.

The influence of urbanity

Urbanization and the spatial sorting of immigrants near large cities is another possible explanation for environmental inequality (Table 1, third row, or Figure 2,

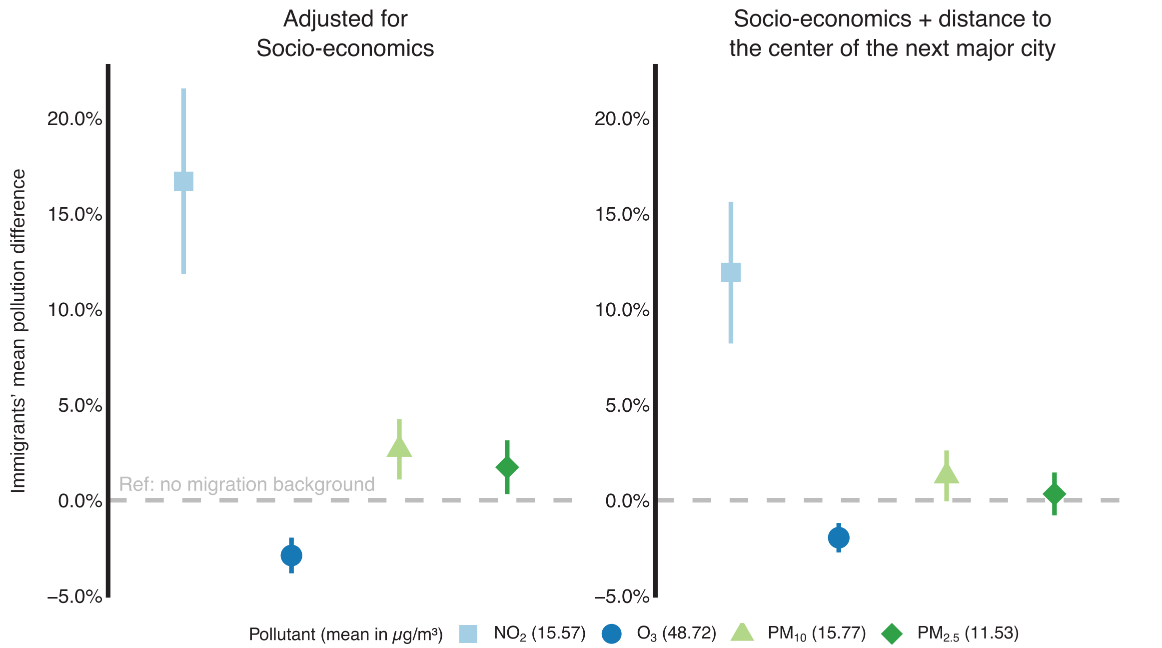

Figure 2 Statistical associations of migration background and local air pollution. Note: We plot predicted percentage differences relative to mean air pollution obtained from linear regressions weighted by sampling probability and 95 per cent confidence intervals from standard errors clustered by municipality. Dependent variables: pollutants NO_2, O_3, PM_{10}, and $PM_{2.5}$. Independent variable: migration background: interviewee or at least one of their parents has immigration experience, reference: no migration background. Socio-economic controls: per capita equivalent net household income (log), schooling, occupational status (ISEI), survey year.

right panel). The correlation between air pollution and migration background becomes remarkably weaker once we control for the distance to the nearest city centre as a measure of urbanity: the migration background gap in pollution is reduced by 29 per cent for nitrogen dioxide, by 32 per cent for ground-level ozone, by 52 per cent for PM_{10}, and by 81 per cent for $PM_{2.5}$. This indicates that the spatial sorting of immigrants closer to city centres plays an important role in the disadvantage of people with a migration background.[13]

Although urbanity contributes significantly to environmental inequality, previous research has documented disadvantages even within municipalities. Within municipalities (Table 1, fourth row), all the relationships are very weak, but the patterns are the same as in the pooled models. Also within municipalities, people with a migration background are, by trend, exposed to more nitrogen dioxide and particulates of both sizes (PM_{10} and $PM_{2.5}$).

Overall, the disadvantage of the immigrant population in air quality is not an effect of impoverishment but largely a result of the sorting of immigrants into more urbanized regions and immigrants' concentration in more polluted neighbourhoods. Likewise, we find only small associations between income and air pollution: although the correlations between income and particulate concentration are significant, the size of this pollution gap is negligible (Supplementary Appendix A5), supporting previous interpretations (Glatter-Götz *et al.*, 2019; Neier, 2021; Diekmann *et al.*, 2022). A replication of the analyses presented here, using pooled data from the 2008 to 2018 waves of the German Socioeconomic Panel (GSOEP) instead of the ALLBUS yields very similar results (see Supplementary Appendix A6).[14]

Comparing migrant generations and origin groups

As we argued earlier, there may be considerable heterogeneity among immigrants. Thus, we also computed two additional sets of models differentiating by immigrants' characteristics (see Figure 3). First, we look at the distinction between first- and second-generation migrants, as there may be differences in opportunities and discrimination between these two groups. Second, we apply a rough classification of origin countries into Western and non-Western countries to investigate the unequal conditions of migrant groups of different origins while still ensuring sufficient statistical power of the analysis.[15]

The first examination shows slightly less environmental disadvantage for German-born descendants of immigrants – second generation migrants (Figure 3,

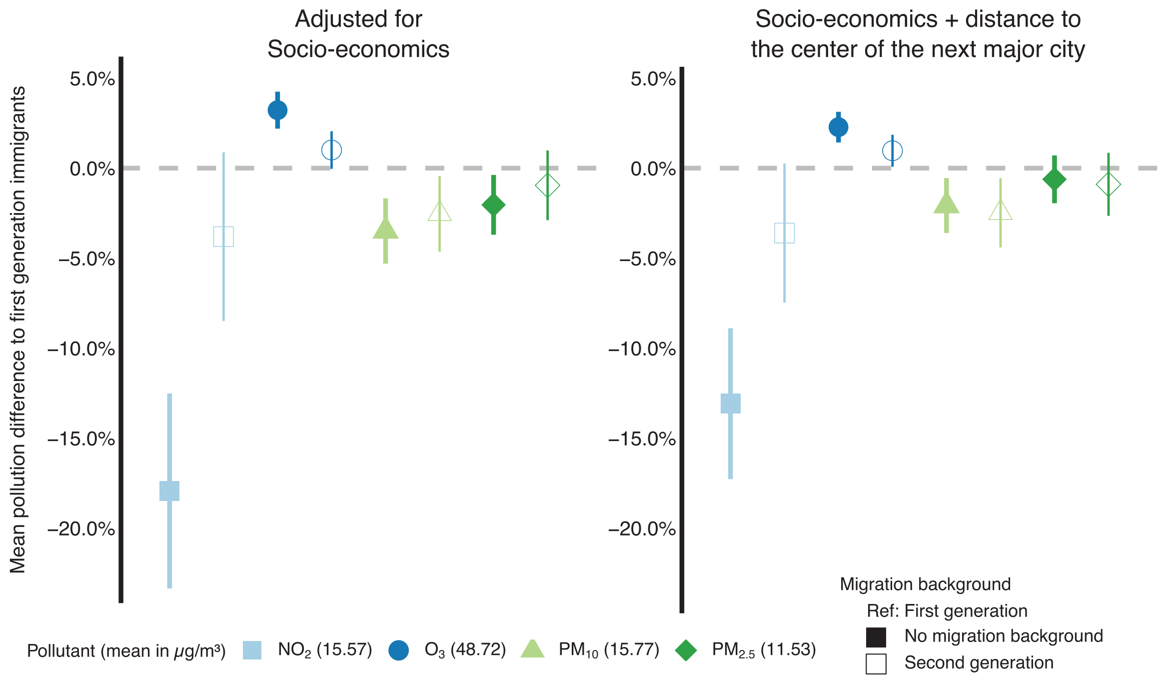

Figure 3 Statistical associations of immigrant generations with local air pollution. Note: We plot predicted percentage differences relative to mean air pollution obtained from linear regressions weighted with sampling probability and 95 per cent confidence intervals from standard errors clustered by municipality. Dependent variables: pollutants NO_2, O_3, PM_{10}, and $PM_{2.5}$. Socio-economic controls: per capita equivalent net household income (log), schooling, occupational status (ISEI), survey year. Immigrant generations: reference (0 line): first-generation immigrant (interviewee has immigration experience). ■: no migration background. □: second-generation migration background (at least one of interviewee's parents has immigrated).

empty markers, and Supplementary Appendix A7.2). They are exposed to significantly less particulate matter of 10 micrometres diameter than first-generation immigrants (reference category) and do not differ much from people without a migration background in this respect. Differences between the first and second generation for the other pollutants are relatively small. Despite these overall small differences, it is striking that controlling for urbanity through distance to the nearest metropolitan centre (right panel) makes second-generation immigrants and non-migrants appear more similar.

This indicates that urban living explains a larger share of the second-generation disadvantage than it does for first-generation migrants. The fact that there are generally no major differences between the generations may indicate that issues such as integration and language skills are less important than ascriptive discrimination in the housing market, which would affect both groups. However, based on our cross-sectional analyses, we cannot clearly attribute the moderating effect of urbanity to a specific causal mechanism.

Taking into account the countries of origin of people with migration background does not reveal systematic differences (Figure 4, and Supplementary Appendix A7.3). Immigrants from Western countries (unfilled markers) tend to be more similar to non-immigrants, but do not differ significantly from other immigrants (reference category) for any of the pollutants.

Discussion

In our study, we observe environmental inequality in objective air pollution in Germany. Migration background is consistently associated with higher levels of air pollution. This disadvantage is substantive, as it can be translated into an increased long-term mortality. The association is not attributable to income or other socio-economic factors. The higher exposure of migrants to nitrogen dioxide and particulate matter is largely due to their spatial sorting into more urban areas. Within municipalities, we find much weaker but still significant associations with migration background for NO_2 and PM_{10}. This contrasts with results from the United States, where racial differences are also quite distinct within cities.

Our finding that inequality by migration background is not related to socioeconomic status can be interpreted as evidence against the racial/ethnic

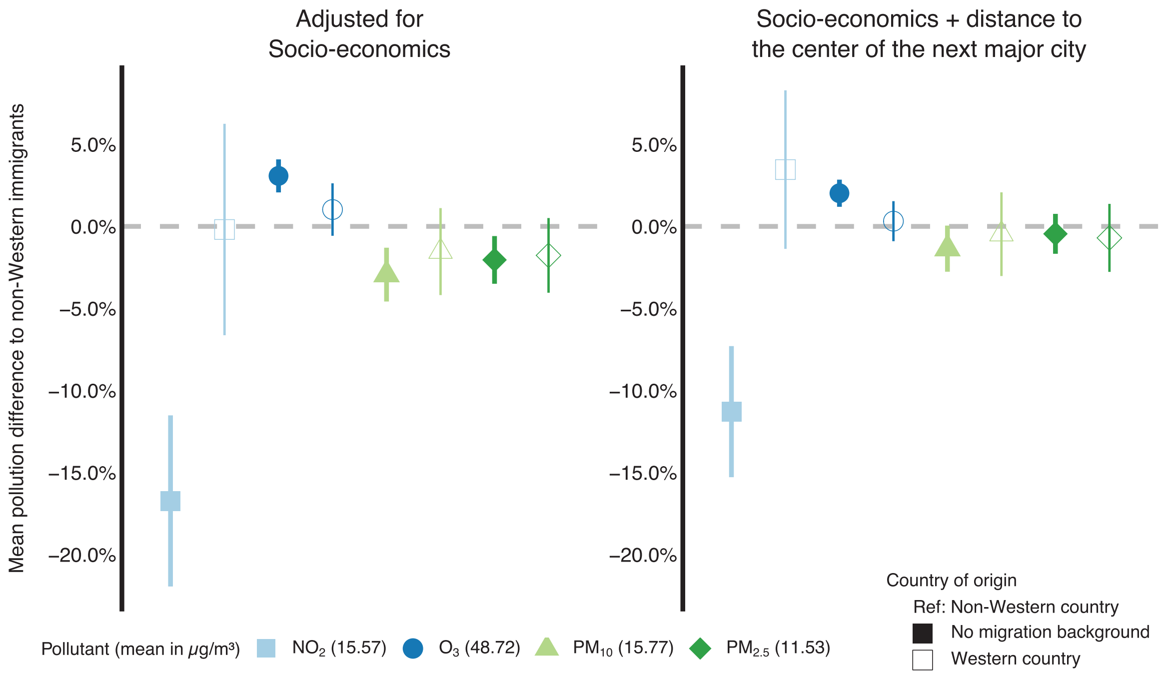

Figure 4 Statistical associations of immigrants' countries of origin with local air pollution. Note: Countries of origin: reference (0 line): immigrant from non-Western country. ■: no migration background. □: immigrant from Western country. Western countries include: Austria, Belgium, Cyprus, Denmark, Finland, France, Greece, Italy, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland, Spain, United Kingdom, Australia, Canada, and the United States.

income inequality thesis, although it is possible that migrants systematically have a smaller share of their income at disposal, for example, due to payments to relatives in their country of origin. Second, the distinction between first- and second-generation migrants may allow for conclusions about the role of discrimination in environmental inequality, albeit to a limited extent, since discrimination based on name (Christensen, Sarmiento-Barbieri and Timmins, 2022) and ascriptive characteristics such as skin colour should be very similar in both generations. However, factors such as citizenship, level of integration, and language proficiency are also important in this context and should lead to less disadvantage in the second generation. If discrimination were the main driver, we would not expect substantive differences in pollution exposure between the two generations. We find that people of second-generation migration background are only slightly better off than first-generation immigrants. Moreover, the role of urbanity seems relatively similar across the generations. This points to discrimination based on ascribed characteristics as a potential reason for the pollution gap. Still, further research is needed to test this conclusion more rigorously.

Some restrictions should be considered when interpreting our results. First, the spatial resolution of the pollution estimates used is relatively coarse, with grid cells of 2×2 km^2. Therefore, the pollution data are suboptimal for spatial comparisons within municipalities and may lead to an underestimation of exposure differences. However, they are the most fine-grained nationwide pollution data available for Germany to date. Second, the cross-sectional survey data from ALLBUS have the advantage of providing first-rate population samples and high representativeness, but impose some limitations on the study of causal mechanisms. Taking these limitations into account, we control for rural/urban context and socio-economic factors such as income, but deliberately refrain from including control variables that reflect life-cycle changes. To adequately account for such variables, longitudinal data are required. Controlling for them in this study using only cross-sectional data may introduce overcontrol bias without shedding light on the mechanisms. Therefore, future causal research should link longitudinal data with air pollution data to delve deeper into the mechanisms of environmental inequality formation (see, e.g., Rüttenauer *et al.*, 2023).

Concluding remarks

Our study highlights a substantial pollution disadvantage for people with a migration background in Germany, as they are exposed to 2.55 µg/m^3 more

NO_2 and 0.22 μg/m³ more $PM_{2.5}$ compared to the native population. This elevated level of air pollution is estimated to result in a higher long-term mortality risk of 2.19 per cent due to NO_2 and 0.58 per cent due to $PM_{2.5}$, which is likely an underestimate as Josey *et al.* (2023) suggest that minorities are more susceptible to the adverse effects of air pollution. We consider this a severe disadvantage with far-reaching consequences for a marginalized group. However, we also acknowledge that there are larger urban–rural differences in air pollution levels than the minority disadvantage we identify (see Appendix A3). For example, the pollution disadvantage associated with living in a major city with respect to NO_2 is 3.52 times greater than the minority disadvantage we have identified, for $PM_{2.5}$ it is even 11.59 times larger. Nevertheless, it is important to recognize that the minority pollution disadvantage is likely not a matter of choice but rather appears to be a systematic penalty imposed on an entire social group because of where they were born.

Much of this minority disadvantage can be attributed to urban–rural differences. Inequality within cities, on the other hand, appears to be very low. However, this could be due to the resolution of the pollution data, which may need to be higher to detect within-city differences. In terms of broader justice discussions, this finding needs to be weighed against other advantages (labour market opportunities, shopping possibilities, transportation, cultural offers, social networks, potentially fewer experienced discrimination), and disadvantages (higher exposure to crime and noise, limited access to green spaces) of urban life for migrants and non-migrants, and considered in a differentiated way that also takes into account preferences. It is also important to know the reasons for the greater concentration of people with a migration background in metropolitan cities. Differences in labour market opportunities, for which discrimination may also be responsible, chain migration (Haug, 2000), and ethnic clustering (Winke, 2018) could be at the root of such segregation processes.

There are two clear lines of action to address environmental inequality in Germany. First, efforts to improve air quality in cities should be intensified, for example, by implementing low-emission zones (Margaryan, 2021) or establishing car-free cities. Second, rural living could be made more appealing to immigrants through initiatives such as social inclusion and community bridging projects in smaller municipalities or efforts to strengthen inter-ethnic social networks in local associations in rural areas. Both of these directions would require policies aimed at reducing the exposure of marginalized groups to air pollution and creating more equitable living conditions.

Notes

1. We do not have all-encompassing data for Germany on carbon monoxide and lead. Fortunately, sulfur dioxide in Germany had already fallen to negligible levels before the period under study.
2. On discrimination against immigrants in Germany's housing market in general, see Auspurg, Hinz and Schmid (2017), Auspurg, Schneck and Hinz (2019).
3. We do not assign migration background to respondents from former eastern territories of Germany.
4. School education is simply operationalized as low (graduation from 'Hauptschule' or less), middle (graduation from 'Realschule'), and high education ('Fachabitur' or 'Abitur').
5. We derived the coordinates of the city centres from Open Street Maps.
6. The distinction between point, line and area sources is about the cartographic representation of the data in the model. Point sources enter the model as point coordinates to which a pollution value is assigned, line sources as line coordinates and area sources in the form of a polygon.
7. See Supplementary Appendix A4 for a robustness check adjusting for municipality sizes.
8. Univariate statistics on the distribution in our sample of all variables used can be found in Supplementary Appendix A1.
9. The R-package estimateR, which is used for all regression analyses, provides several methods for variance estimation. We use Stata-style cluster-robust variance estimation for all models, as only this method allows both weights and fixed effects to be applied. Where applicable, other methods of variance estimation do not produce results that would alter our conclusions.
10. Full tables for all models can be found in Supplementary Appendix A7.1.
11. The fact that ozone is negatively related to migration background is not surprising, as immigrants tend to be concentrated in larger cities, and ground-level ozone is decomposed by nitrogen monoxide, which is more densely concentrated in more trafficked urban areas. Diekmann and Meyer (2010) also find a similar deviation from the overall pattern for ozone in Switzerland.
12. Here, long-term means that the overall mortality risk increases by this percentage for the corresponding difference in annual average pollution exposure, in contrast to short-term effects, where an association between short-term measured exposure (e.g., daily) and daily mortality is established with a fixed lag.
13. In Supplementary Appendix A3, we show that larger municipalities and places closer to the centre of a major city exhibit remarkably higher pollution levels. In Supplementary Appendix A4, we employ another way of dealing with the sorting of people according to the degree of urbanization: we control for the categorized number of the municipalities' inhabitants. Here, coefficients for particulates even turn negative (significant for $PM_{2.5}$), that is, people with a migration background tend to live in neighbourhoods with cleaner air than native Germans with comparable socio-economic status in municipalities of a similar size. These effects might be due to the arbitrary cutoffs of municipality sizes.

14. Despite its larger sample size, GSOEP is less suitable for the descriptive purpose of this paper. Cases within each household over the waves are not independent, and the sample represents the composition of society when the panel started (partly 'updated' by refreshment samples), but not the current society like the repeated cross-sectional random samples of ALLBUS.
15. The Western country category includes Western European countries, North America, and Australia.

Supplementary Data

Supplementary data are available at *ESR* online.

Acknowledgements

We thank Michael Friedrich for excellent research assistance. We are grateful to GESIS, especially to Pascal Siegers, and the German Environment Agency, especially to Stephan Nordmann, Alfred Trukenmüller and Dirk Wintermeyer, for providing the data and helpful guidance.

Funding

This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) [418939357].

Conflict of Interest

All authors declare that they have no conflicts of interest.

Author contributions

Ingmar Ehler (Conceptualization [Equal], Data curation [Equal], Formal analysis [Supporting], Investigation [Equal], Methodology [Supporting], Project administration [Equal], Resources [Equal], Software [Equal], Supervision [Equal], Validation [Equal], Visualization [Equal], Writing – original draft [Lead], Writing – review & editing [Lead]), Felix Bader (Conceptualization [Equal], Data curation [Equal], Formal analysis [Lead], Investigation [Equal], Methodology [Lead], Project administration [Equal], Resources [Equal], Software [Equal], Supervision [Equal], Validation [Equal], Visualization [Equal], Writing – original draft [Equal], Writing – review & editing [Supporting]), Tobias Rüttenauer (Conceptualization [Equal], Data curation [Equal], Funding acquisition [Equal], Methodology [Supporting], Resources [Lead], Software [Supporting], Supervision [Supporting], Validation [Equal], Visualization [Supporting], Writing – original draft [Supporting], Writing – review & editing [Supporting]), and Henning Best (Conceptualization [Equal], Formal analysis [Supporting], Funding acquisition [Lead], Investigation [Supporting], Methodology [Supporting], Project administration [Supporting], Software [Supporting], Supervision [Equal], Validation [Equal], Writing – original draft [Supporting], Writing – review & editing [Equal])

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