



Socioeconomic factors and environmental burden in a cohort from six Swedish cities

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ABSTRACT

Background: The association between socioeconomic status (SES) and environmental burden is context-dependent. Those with low SES may be more likely to live near major roads and industries where environmental exposures are high but may also be more likely to live further away from city centers. The aim of this study was to investigate the association between SES and environmental burden in Sweden.

Methods: The Swedish CardioPulmonary bioImage Study (SCAPIS) cohort recruited participants from six Swedish cities during 2013–2018. Residential environmental exposures (particulate matter <2.5 µm [PM_{2.5}], road traffic noise, and lack of greenspace) and neighborhood-level SES factors (proportions with low-income, low education, unemployment, rental units, foreign born) were assessed from participants' addresses in 2018. Individual-level SES factors (financial buffer, education, occupation, type of living, foreign born) were obtained from a questionnaire and neighborhood data from Statistics Sweden. Linear regression models were used to analyze the link between environmental exposures and SES factors. Correlations between SES factors were analyzed using Cramér's V and Spearman rank correlations.

Results: The study included 23 320 SCAPIS participants in 1939 neighborhoods. The explanatory power of SES factors differed substantially between factors and cities. A model with all ten SES factors could account for 25–88 %, 36–60 %, and 49–81 % of the spatial variance in PM_{2.5}, noise, and lack of greenspace respectively. Neighborhoods with more low-income earners, rental units and foreign born had more environmental burden. Neighborhoods with more inhabitants with low education and unemployment had less environmental burden. Associations were generally non-linear. Individual-level SES factors were not associated with environmental burdens after adjusting for neighborhood SES factors. Individual and neighborhood SES were weakly correlated.

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Conclusion: Neighborhood SES factors accounted for a large proportion of the variance in environmental burdens, whereas individual SES factors did not. The relationship between SES and environmental burden differed greatly between indicators and cities.

1. Introduction

The intricate relationship between health and environmental risk factors (“environmental burdens”) such as air pollution, transportation noise, and lack of greenspace is becoming increasingly evident. Ambient air pollution, for example, has been associated with systemic inflammation, cardiovascular disease, respiratory disease, and overall mortality (World Health Organization, 2016a). Exposure to road traffic noise is associated with sleep disturbance and annoyance, as well as cardiovascular and metabolic health (Clark & Paunovic, 2018; Sørensen et al., 2024; World Health Organization, 2018). A lack of green areas such as parks and forests can exacerbate these problems, contributing to reduced physical activity and increased stress, and heightened risk of cardiovascular disease, and mortality (World Health Organization, 2016b). Socioeconomic status (SES) is also closely connected with health, with consistent findings of higher disease burden and mortality among individuals with lower SES (Braveman & Gottlieb, 2014; Fiscella & Williams, 2004). The combination of environmental and SES factors can have a potent and multifaceted influence on public health (Laurent et al., 2007; O’Neill et al., 2003).

Studies of SES, and related concepts like socioeconomic deprivation often uses indicators to estimate societal position, to measure the uneven distribution of resources, constraints, and opportunities within a society (Svallfors, 2006). Examples of indicators include income, education, occupation, and type of residence. Because all these indicators try to estimate a similar concept and “reflect overlapping resources in terms of social standing” (Torssander & Erikson, 2010), they are often used interchangeably in medical and environmental research. They are, however, probably related to health through different mechanisms (Hasselgren, 2019). Each indicator provides different information, and their relevance can vary depending on the context (Bihagen & Halleröd, 2000; Galobardes et al., 2006). It is important to know how SES interacts with environmental burdens in order to gain a better understanding of who is most exposed and vulnerable, and where targeted preventive efforts should be focused.

A main goal of environmental justice is environmental equity, also known as environmental distributive justice; that is, the fair distribution of environmental burdens and benefits regardless of SES (Hughes, 2012). In research focusing on environmental justice and the health effects of environmental burdens, there seems to be a general explanatory framework emerging. Firstly, low SES areas/populations have more hazardous environmental exposure. Secondly, low SES have more vulnerability to environmental burdens via chronic stress, chronic disease, lifestyle factors, and so on, meaning that SES acts as an effect modifier to the health effects of environmental burdens. The combination of these two mechanisms makes low-SES areas more vulnerable to environmental burdens (Laurent et al., 2007; O’Neill et al., 2003).

The first part of this framework has mostly been based on research from North America (Hajat et al., 2015). However, it is becoming increasingly apparent that this may not be valid everywhere in the world. In many Asian contexts, for instance, there is an opposite trend of industrialization and urbanization, leading those with more resources to live in city centers with more air pollution, more noise, and a lack of greenspace (Hajat et al., 2015; Wang et al., 2022). In western Europe, the relationship between SES factors and environmental burdens shows mixed patterns, depending on country and city (Hajat et al., 2015). Sweden is frequently highlighted as an exceptional case in terms of systems and policies to reduce socioeconomic inequality (Esping-Andersen, 2014). However, several factors challenge this idea. Since the early 1990s, ethnic and socio-economic segregation have

increased, both contributing to the rise in residential segregation (Scarpa, 2015). At the same time, Swedish housing policy has been largely dismantled, leading to increased social and ethnic residential segregation (Gustafsson et al., 2017). In Swedish cities, poor neighborhoods are typically on the outskirts and are often ethnically diverse, unlike the downtown poor areas in the US (Scarpa, 2015). Non-linear patterns can emerge in some contexts and countries (Hajat et al., 2015; Kopas et al., 2020). In addition to the different associations between SES and environmental burden, it seems that individual SES and neighborhood SES can be considered as independent risk factors both for environmental burden and for disease (Meijer et al., 2012; Pickett & Pearl, 2001; Riva et al., 2007). There is a need for more research comparing the impact of individual and neighborhood SES (Laurent et al., 2007).

The overall aim of this study was to investigate the association between SES and environmental burden in Sweden. Specifically, we used the population-based SCAPIS (the Swedish CARDioPulmonary bioImage Study) cohort recruited in six Swedish cities to evaluate the difference in environmental burden depending on SES, and to assess the extent to which the variation in environmental burden can be accounted for by SES factors. We also analyzed whether there were any differences in the associations between neighborhood-level and individual-level SES factors on the one hand, and different environmental burdens on the other. Finally, we investigated correlations between individual-level and neighborhood-level SES factors.

2. Material and methods

2.1. Study participants

SCAPIS is a population-based cohort comprising 30 154 participants aged 50–65 years at recruitment, drawn from six study sites, encompassing Swedish cities: Malmö, Gothenburg, Linköping, Stockholm, Uppsala, and Umeå. Participants were recruited during 2013–2018, with a participation rate of 50.3 %. The primary objective of the cohort was to investigate early indicators or predictors associated with cardiovascular and pulmonary disease. A detailed account of the recruitment process and study design has been published previously (Bergström et al., 2015). A comprehensive two-day examination was conducted to obtain health information on participants, including a thorough clinical investigation. Participants were also required to complete a questionnaire detailing cardiovascular risk factors and SES factors such as occupation, place of residence, educational level, and financial buffer.

The overarching SCAPIS project was given ethical approval by the Regional Ethical Review Board in Umeå (ref: 2010-228-31M), and the current study was approved by the Swedish Ethical Review Authority (refs: 2019-06469, 2022-00789-02, 2024-00088-02).

2.2. Environmental burden assessment

Environmental burdens were defined as cohort participants’ exposure – or “burden” – to particulate air pollution (PM_{2.5} and PM₁₀), road traffic noise, and lack of residential greenspace in the year 2018. PM_{2.5} was used as the main air pollutant measure (results for PM₁₀ are reported in the supplement).

The air pollution modeling is described in depth elsewhere (Kilbo Edlund et al., 2024). Briefly, source-specific local and regional atmospheric dispersion modeling was performed covering all study sites. Local source-specific air pollutants (PM_{2.5} and PM₁₀) were estimated

using Gaussian-type dispersion modeling with a dynamic resolution ranging from 50×50 to 500×500 m². Local modeling was performed for Gothenburg, Linköping, and Umeå by the Swedish Meteorological and Hydrological Institute (SMHI), for Stockholm and Uppsala by the SLB-analys at the Environment and Health Administration of the City of Stockholm, and for Malmö by the Environmental Department of the City of Malmö. Regional modeling for long-range atmospheric transport was performed using the Eulerian model MATCH (Frohn et al., 2022) with a resolution of 5×5 km combined with measurements at background stations. All modeling was based on emission inventories covering the sites for the year 2018.

Noise burden was defined as the annual average road traffic noise exposure at the residential address, based on the European Union noise indicator L_{den} (day-evening-night noise level). This indicator measures the energy equivalent noise exposure over a whole day, with noise exposure during the evening (19:00–23:00) receiving a penalty of 5 dB and noise exposure during the night (23:00–07:00) receiving a penalty of 10 dB, as noise exposure during the evening and at night is considered more detrimental (European Commission, 2002). Noise burden was modeled using the Nordic Prediction Method, which takes traffic parameters and topographic factors into account (Bendtsen, 1999). A simplified approach was used for receiver positions in dense urban areas (Ögren & Barregard, 2016).

Lack of greenspace was defined as the inverse of the Normalized Difference Vegetation Index (iNDVI) for the year 2018 in a 500m-radius area surrounding a participant's residence. NDVI uses differences in light captured by satellite images to obtain a proportion of greenspace (Huang et al., 2021). In this study, lack of residential greenspace could theoretically range from iNDVI = 0 (indicating that all of the surrounding area consisted of green space) to iNDVI = 1 (indicating no green space in the surrounding area).

For each participant, residential address data for the year 2018 were collected from the Swedish Tax Agency and geocoded, and environmental burden data were assigned to participants using QGIS (QGIS Development Team v3.22, 2023).

2.3. Socioeconomic factors

Two different types of SES data were used for this study, individual-level and neighborhood-level.

2.3.1. Individual-level socioeconomic factors

Self-reported individual-level SES data were obtained at recruitment through the SCAPIS cohort questionnaire. “No financial buffer” was based on the participant's ability to find 20 000 SEK (Swedish kronor, ca. 2000 USD) in a week (yes/no). “Low education” was based on the participant's highest educational attainment, categorized into no high school (low), high school degree (medium), or post-secondary education (high). “Occupation” was obtained through occupational titles (current occupation, or longest held occupation if this was missing), and categorized according to the ISCO-08 skill levels (1–4) of the occupation, or as unemployed. Occupations with a skill level of 1–2 were then categorized as low-skilled, occupations with a level of 3–4 as high-skilled, and no occupation as unemployed. “Type of residence” was defined as owner-occupied house, owner-occupied apartment, rented apartment, or other. “Foreign born” was defined as a participant born outside of Sweden.

2.3.2. Neighborhood-level socioeconomic factors

Neighborhood-level SES data were obtained from Statistics Sweden for the year 2018. Statistics Sweden has divided Sweden into 5984 Demographic Statistical Areas (DeSO), each containing 700–2700 individuals, based on voting districts, population-dense areas, and geographic landmarks such as streets, waterways, and railways (SCB, 2023). These DeSO areas are henceforth referred to as neighborhoods. SCAPIS participants were nested within neighborhoods based on their

addresses in 2018 and assigned the neighborhood-level SES retrieved from Statistics Sweden using QGIS.

Five neighborhood-level markers of low SES were used: low income, defined as the proportion of the neighborhood population over the age of 20 with an income in the lowest nationwide quartile (<168 516 SEK [ca. 16 500 USD as of September 2024] per year); low education, defined as the proportion of the population aged 25–64 with less than high school education (i.e. <12 years); unemployment, defined as the proportion of the population aged 16–64 that were unemployed; and proportion of rental units, defined as the proportion of residential units that were rental units; foreign born, defined as the proportion of the population that was not born in Sweden. A neighborhood socioeconomic deprivation index composed of four of the neighborhood factors (all except neighborhood foreign born) was also used, in which the four SES factors were weighted using principal component analysis to predict death rates in Sweden: low income: 0.96, low education: 0.24, unemployment: 0.87, proportion rental units: 0.69, in accordance with Strömberg et al. (2021).

Neighborhoods were grouped in deciles for each neighborhood-level SES factor, with the distribution of that SES factor in the respective county used to define the deciles (i.e. all neighborhoods in Scania county were used to assess deciles for the Malmö study site, those in Västra Götaland for Gothenburg, those in Östergötland for Linköping, those in Stockholm county for Stockholm, those in Uppsala county for Uppsala, and those in Västerbotten for Umeå) in order to relate the SES of the neighborhood to the county it is situated in. For all SES factors, decile 10 corresponded to low SES (e.g. the highest proportion of low-income earners for “low income”) and decile 1 to high SES. Fig. 1 gives a visual presentation of neighborhood SES and Fig. 2 of environmental burdens. For descriptive statistics, neighborhoods were also grouped based on quartiles for each SES factor to simplify the presentation.

Statistics Sweden has classified neighborhoods by urbanicity in three categories: urban neighborhoods are densely populated areas located centrally in the municipality, suburban neighborhoods are densely populated areas that are not centrally located, and rural neighborhoods are areas outside of densely populated areas.

2.4. Statistical analysis

2.4.1. Exclusion and study sample

A complete-case analysis approach was employed, where participants with complete information on all SES factors and environmental burdens were included in the analysis (Figure S1). Participants were excluded from the current study if they died or moved to a non-modeled area before 2018 (255 participants out of 30 154) or had missing covariate data. As 85 % of SCAPIS participants were living in urban neighborhoods (Table S2), those in rural and suburban neighborhoods were excluded from the main analysis; this accounted for most exclusions (4020 out of 6834 exclusions), leaving 23 320 participants for our analysis (Figure S1). A comparison of sociodemographic characteristics was conducted between our study populations living in urban neighborhoods and the excluded participants living in rural or suburban neighborhoods, using *t*-tests or chi-square tests.

2.4.2. Model variance structure

A pre-analysis with a random-effects mixed model was performed to separate total variance into between-neighborhood and within-neighborhood variance. Since almost all the variance was between neighborhoods and very little within neighborhoods (Table S1), analysis was performed using multiple linear regression.

2.4.3. Regression models, R^2 values

The analysis used environmental burdens as the outcomes (dependent variables) and SES factors as the explanatory variables (independent variables). Multiple linear regression and the coefficient of determination (R^2) were used to investigate how much of the between-

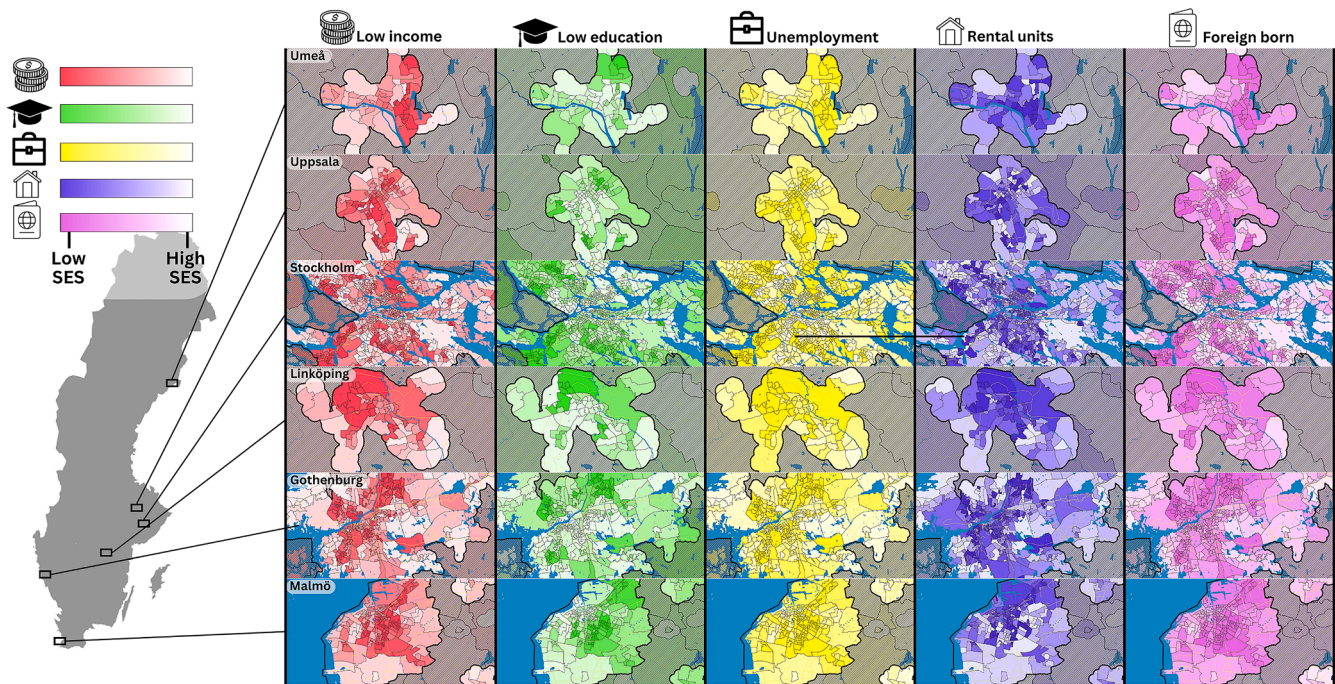


Fig. 1. Neighborhood socioeconomic status (SES) by city. Each column of maps is colorized based on neighborhood SES deciles within each county in Sweden. More intense colors indicate lower SES (decile 10) such as neighborhoods with a high proportion of low income earners, low education level, high unemployment rate, high proportion of rental units and high proportion of foreign born, respectively. Lighter or near-white areas indicate higher SES (decile 1) i.e. high income, high education level, low unemployment, low proportion rental units and Swedish-born. Only urban neighborhoods are included (outlined in black contour).

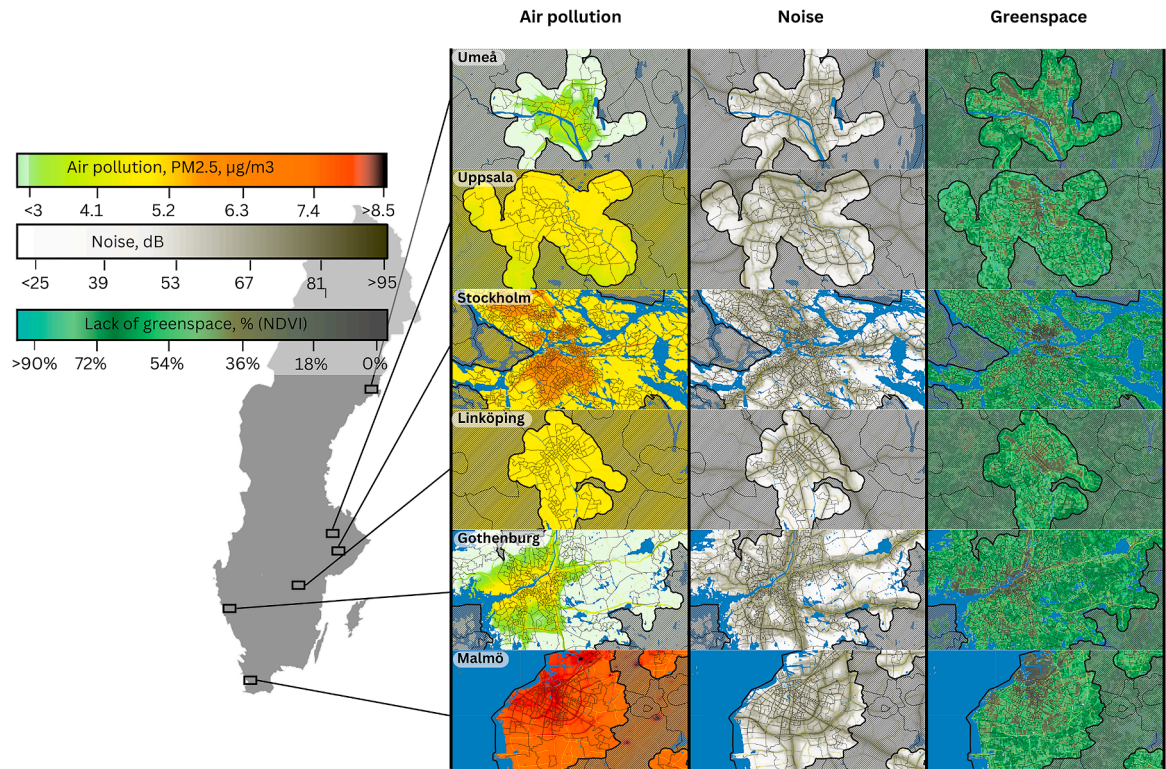


Fig. 2. Modelled environmental burdens by city. Only urban neighborhoods are included (outlined in black). Environmental burdens ordered from left to right: air pollution ($PM_{2.5}$), road-traffic noise, lack of greenspace. Cities are ordered from bottom to top: Malmö, Gothenburg, Linköping, Stockholm, Uppsala, and Umeå.

individual variance in environmental burden could be accounted for or “explained” by the models where SES factors were included as explanatory variables.

The SES factor models used are described in detail in Supplementary

file S1. In short, the following regression models were estimated to compare R² values: The first set of models (M1) included only one SES factor at a time: models M1.1 to M1.5 each included a single individual-level SES factor, and models M1.6 to M1.10 each included a single

neighborhood-level SES factor. The second set of models (M2) included multiple/ aggregates of SES factors. Model M2.1 included all individual-level SES factors. Model M2.2 included only the neighborhood-level deprivation index, and model M2.3 included the deprivation index along with all individual-level SES factors. To assess the added value of using the deprivation index as a proxy for neighborhood SES, we compared model M2.2 to model M2.4, which instead included the four individual neighborhood-level SES factors used to construct the index (income, education, unemployment, and rental housing). Similarly, model M2.5, which included these four neighborhood-level SES factors and all individual-level SES factors, was compared to model M2.3 to assess whether the deprivation index adequately captured relevant SES information. In addition to comparing R^2 values, models M2.2 and M2.4 were compared using the Akaike Information Criterion (AIC) to evaluate the deprivation index further. Lastly, model M2.6 included all five neighborhood-level and all five individual-level SES factors in one joint model and served as our main model. To account for possible variation in the relationship between SES and environmental burdens across different cities, all models were estimated separately by city.

2.4.4. Effect visualization

The pattern of associations between SES factor deciles and each environmental burden was first illustrated in graphs showing the mean environmental burden per decile. The main analysis was then performed using multiple linear regression models that allowed adjustment for other SES factors. It estimated the effect size in environmental burdens for M1.1–M1.10, the joint models M2.5 for the deprivation index, and M2.6 for all other SES factors. A stratified analysis (men/women) investigated gender-specific differences in socioeconomic deprivation using M2.5 (deprivation index and all individual SES factors). Significance testing was performed using type III F tests.

The correlation between SES factors was investigated using Cramér's V (for pairwise correlations of individual SES factors, and pairs with individual and neighborhood-level SES factors) or Spearman rank correlations (for pairwise correlation of neighborhood SES deciles). Correlations by Cramér's V were categorized into weak, moderate, and strong based on the SAGE thresholds for the phi-coefficient (Wiedmaier), but adjusting the thresholds based on the degrees of freedom of the cross-tabulation (Liebetrau, 1983).

3. Results

Descriptive statistics of neighborhoods and participants by city are presented in Table 1. In total, 23 320 participants were included within 1939 neighborhoods. The mean age of the study participants was 59 years, and there were approximately equal numbers of men and women. The individual SES of participants was high overall, with only 7 % of the participants having no financial buffer, 8 % having no high school degree, and 3 % being unemployed. Neighborhood SES varied between cities; Malmö generally had the lowest and Stockholm the highest neighborhood SES. For example, the mean neighborhood unemployment rate in the highest quartile of unemployment was 42 % in Malmö and 32–37 % in the other cities. The environmental burden also varied between cities, especially for air pollution, where the mean concentration ranged from 7.3 $\mu\text{g}/\text{m}^3$ PM_{2.5} in Malmö to 4.1 $\mu\text{g}/\text{m}^3$ PM_{2.5} in Umeå. There were relatively few participants in neighborhoods with more low-income earners and neighborhoods with low education.

When comparing participants living in urban neighborhoods to those living in rural or suburban neighborhoods, there were major differences in demographic factors, SES factors, and environmental burdens (Table S3). Participants in urban neighborhoods were less likely to have a financial buffer, more likely to live in a rented apartment and be foreign born, but more likely to have a higher education level and a higher-skilled occupation compared to participants in rural and suburban neighborhoods. Participants in urban neighborhoods also consistently had lower neighborhood SES and more environmental burdens.

3.1. Explanatory power of SES factors for variance in environmental burden

The analysis of how much variance in environmental burden between individuals could be accounted for by the different SES factor models revealed R^2 values that differed between cities and between models (Fig. 3 and Table S4). Most of the neighborhood SES factors had larger R^2 values than the individual SES factors, which were all small except for type of residence.

For the model including all individual and neighborhood SES factors (M2.6), R^2 varied between cities, ranging from 25 % to 88 % for air pollution (PM_{2.5}), 37 % to 60 % for noise burden, and 49 % to 81 % for lack of greenspace. Overall, the R^2 values for environmental burdens in Stockholm (25–49 %) were smaller in comparison to other cities, especially for air pollution.

For the models with separate neighborhood SES factors (M1.6–M1.10), proportion of rental units showed larger R^2 values than individual SES factors and at least one other neighborhood SES factor in all cities and was the single neighborhood SES factor that had the largest R^2 values in both Malmö (21–30 %) and Stockholm (9 %–19 %). Neighborhood low income had the largest R^2 values in Linköping (27–55 %) and Uppsala (15–26 %), neighborhood low education had the largest R^2 values in Umeå (24–53 %), while neighborhood foreign born had the largest R^2 value in Gothenburg (27–30 %). The deprivation index model (M2.2) did not have larger R^2 values than the models with its component neighborhood SES factors (M2.4) for any environmental burden or city. Furthermore, the models with the neighborhood SES factors making up the deprivation index had a better model fit (lower AIC scores) compared to the deprivation index models for all cities (Table S5).

Among the individual SES factors (M1.1–M1.5), lack of financial buffer, low education, occupation, and being foreign born had R^2 values close to 0 in all cities for all environmental burdens. This was also reflected in the model with all individual SES factors (M2.1), where R^2 values were equivalent to those of the model with only individual type of residence (M1.4). Moreover, individual type of residence had larger R^2 values than some neighborhood SES factors in all environmental burdens in all cities, particularly in Stockholm. R^2 values for the models with four neighborhood SES factors (M2.4) were equal to the R^2 values from the models with all individual and the four neighborhood SES factors (M2.5), even in cities where individual type of residence had large R^2 values.

3.2. Association between SES factors and environmental burdens

The pattern of the association between SES factors and environmental burdens in the regression models differed by SES factor and city (Fig. 4, Table S6 and S7 [including PM₁₀]). In general, neighborhoods with more deprivation, more low-income earners, more rental units, and/or more foreign born had more environmental burdens, while neighborhoods with low education and/or more unemployment had less environmental burden. All associations between neighborhood SES factors and environmental burdens were statistically significant (p-values from F-tests all <0.01). For particulate air pollution exposure, the variability between cities was larger than the variation by SES within cities (Figures S2 and S3), while for road traffic noise and lack of greenspace the variability by SES within cities was larger than that between cities. There were minimal differences in the association between neighborhood socioeconomic deprivation and environmental burdens stratified by gender (Figure S4).

For neighborhood SES factors, associations were similar in the separate SES factor models (M1.6–M1.10, Figure S5) and the joint model with the independent effect of each SES factor (M2.6, Fig. 4). In contrast, the effect estimates between environmental burden and individual SES factors were small and mostly non-significant in the joint model compared to separate SES factor models (M1.1–M1.5, Fig. 5 and Tables S6 and S7). Individual type of residence remained significant in

Table 1
Descriptive statistics for study participants and neighborhoods, divided by city.

	Malmö	Gothenburg	Linköping	Stockholm	Uppsala	Umeå	All ¹
Individual-level demographics							
No of participants, n (%)	5387 (23 %)	5453 (23 %)	3155 (14 %)	4609 (20 %)	3279 (14 %)	1437 (6 %)	23 320 (100 %)
Age, mean (SD)	60 (5)	60 (4)	59 (5)	59 (4)	59 (5)	58 (4)	59 (5)
Sex, n (%)							
Men	2509 (47 %)	2578 (47 %)	1575 (50 %)	2293 (50 %)	1522 (46 %)	681 (47 %)	11,158 (48 %)
Women	2878 (53 %)	2875 (53 %)	1580 (50 %)	2316 (50 %)	1757 (54 %)	756 (53 %)	12,162 (52 %)
Recruitment year, mean (min–max)	2016 (14 - 18)	2015 (13 - 17)	2017 (15 - 18)	2016 (14 - 18)	2017 (15 - 18)	2017 (16 - 18)	2017 (15 - 18)
Individual-level SES factors							
Has financial buffer ² , n (%)	4802 (89 %)	4986 (91 %)	2986 (95 %)	4377 (95 %)	3096 (94 %)	1349 (94 %)	21 596 (93 %)
No financial buffer ² , n (%)	585 (11 %)	467 (9 %)	169 (5 %)	232 (5 %)	183 (6 %)	88 (6 %)	1724 (7 %)
Education, n (%)							
High (post-secondary education)	2253 (42 %)	2530 (46 %)	1434 (45 %)	2299 (50 %)	1885 (57 %)	704 (49 %)	11,105 (48 %)
Medium (high school degree)	2559 (48 %)	2367 (43 %)	1488 (47 %)	1978 (43 %)	1212 (37 %)	636 (44 %)	10,240 (44 %)
Low (no high school degree)	575 (11 %)	556 (10 %)	233 (7 %)	332 (7 %)	182 (6 %)	97 (7 %)	1975 (8 %)
Occupation, n (%)							
High-skilled (ISCO-08 skill level 3–4)	3020 (56 %)	3284 (60 %)	1912 (61 %)	3182 (69 %)	2245 (68 %)	834 (58 %)	14,477 (62 %)
Low-skilled (ISCO-08 skill level 1–2)	2077 (39 %)	1995 (37 %)	1153 (37 %)	1311 (28 %)	965 (29 %)	573 (40 %)	8074 (35 %)
Unemployed	290 (5 %)	174 (3 %)	90 (3 %)	116 (3 %)	69 (2 %)	30 (2 %)	769 (3 %)
Type of residence, n (%)							
Owner-occupied house	2027 (38 %)	2105 (39 %)	1433 (45 %)	1946 (42 %)	1270 (39 %)	742 (52 %)	9523 (41 %)
Owner-occupied apartment	2009 (37 %)	1590 (29 %)	827 (26 %)	1638 (36 %)	1457 (44 %)	378 (26 %)	7899 (34 %)
Rented apartment	1306 (24 %)	1719 (32 %)	883 (28 %)	993 (22 %)	536 (16 %)	308 (21 %)	5745 (25 %)
Other	45 (1 %)	39 (1 %)	12 (0 %)	32 (1 %)	16 (0 %)	9 (1 %)	153 (1 %)
Born in Sweden, count (%)	4162 (77 %)	4475 (82 %)	2902 (92 %)	3846 (83 %)	2794 (85 %)	1331 (93 %)	19 510 (84 %)
Foreign born, count (%)	1225 (23 %)	978 (18 %)	253 (8 %)	763 (17 %)	485 (15 %)	106 (7 %)	3810 (16 %)
Environmental burden							
Air pollution, mean ³ (SD), µg/m ³ PM _{2.5}	7.3 (0.2)	4.5 (0.5)	4.9 (0.2)	6 (0.3)	5.3 (0.1)	4.1 (0.3)	5.6 (1.1)
Road traffic noise, mean ³ (SD), dB	58 (6)	59 (6)	57 (6)	58 (8)	55 (8)	55 (5)	58 (7)
Lack of greenspace, mean ³ (SD), iNDVI 500 m radius	0.6 (0.11)	0.6 (0.14)	0.5 (0.12)	0.6 (0.13)	0.5 (0.11)	0.5 (0.11)	0.6 (0.13)
Neighborhood-level SES factors							
Neighborhoods/DeSO areas, n	258	368	88	1037	126	63	1939
% low-income earners, mean (min–max)							
Q1	19 % (14 - 22)	15 % (9 - 18)	15 % (12 - 18)	15 % (9 - 17)	17 % (12 - 19)	15 % (10 - 17)	16 % (9 - 22), <i>n</i> = 5824
Q2	24 % (22 - 26)	20 % (18 - 22)	20 % (18 - 23)	19 % (17 - 21)	20 % (19 - 23)	20 % (18 - 22)	21 % (17 - 26), <i>n</i> = 6061
Q3	29 % (26 - 33)	25 % (22 - 28)	26 % (23 - 29)	23 % (21 - 26)	26 % (24 - 28)	25 % (23 - 26)	26 % (21 - 33), <i>n</i> = 6153
Q4	43 % (33 - 76)	36 % (28 - 78)	39 % (29 - 66)	33 % (26 - 56)	37 % (29 - 83)	36 % (27 - 73)	38 % (26 - 83), <i>n</i> = 5282
% low-education ⁵ , mean (min–max)							
Q1	4 % (1 - 7)	5 % (1 - 7)	5 % (2 - 7)	3 % (1 - 5)	3 % (0 - 5)	4 % (2 - 6)	4 % (0 - 7), <i>n</i> = 11,491
Q2	9 % (7 - 11)	9 % (7 - 11)	8 % (7 - 10)	6 % (5 - 8)	7 % (5 - 10)	6 % (6 - 7)	8 % (5 - 11), <i>n</i> = 5880
Q3	13 % (11 - 16)	12 % (11 - 15)	12 % (11 - 14)	10 % (8 - 14)	11 % (10 - 13)	9 % (8 - 11)	12 % (8 - 16), <i>n</i> = 3398
Q4	22 % (16 - 51)	22 % (15 - 40)	24 % (15 - 34)	18 % (14 - 37)	17 % (14 - 26)	13 % (12 - 17)	20 % (12 - 51), <i>n</i> = 2551
% unemployment ⁶ , mean (min–max)							
Q1	19 % (15 - 21)	15 % (9 - 17)	17 % (13 - 17)	16 % (10 - 18)	17 % (15 - 18)	16 % (14 - 17)	16 % (9 - 21), <i>n</i> = 3686
Q2	24 % (21 - 25)	19 % (17 - 20)	20 % (18 - 21)	20 % (18 - 21)	20 % (18 - 22)	19 % (17 - 20)	20 % (17 - 25), <i>n</i> = 5990
Q3	29 % (25 - 33)	23 % (21 - 26)	24 % (22 - 28)	23 % (21 - 26)	25 % (22 - 29)	23 % (21 - 25)	25 % (21 - 33), <i>n</i> = 8238
Q4	42 % (33 - 72)	34 % (26 - 64)	37 % (28 - 62)	32 % (26 - 53)	37 % (29 - 64)	32 % (26 - 62)	37 % (26 - 72), <i>n</i> = 5406
% rental units ⁷ , mean (min–max)							
Q1	2 % (0 - 8)	3 % (0 - 9)	4 % (1 - 10)	2 % (0 - 7)	2 % (0 - 6)	4 % (0 - 8)	3 % (0 - 10), <i>n</i> = 5921
Q2	15 % (10 - 25)	18 % (9 - 29)	22 % (12 - 34)	15 % (7 - 27)	13 % (7 - 20)	26 % (19 - 33)	17 % (7 - 34), <i>n</i> = 4915
Q3	40 % (27 - 53)	46 % (31 - 59)	52 % (38 - 63)	38 % (27 - 52)	31 % (20 - 44)	43 % (34 - 53)	42 % (20 - 63), <i>n</i> = 6269
Q4	72 % (53 - 100)	80 % (60 - 100)	78 % (64 - 100)	71 % (52 - 100)	72 % (45 - 100)	66 % (53 - 100)	74 % (45 - 100), <i>n</i> = 6215
Deprivation index⁸, mean % (min–max)							
Q1 (lowest deprivation)	11 % (7 - 13)	8 % (6 - 11)	9 % (7 - 11)	9 % (5 - 10)	9 % (7 - 11)	8 % (7 - 8)	9 % (5 - 13), <i>n</i> = 5161
Q2	15 % (13 - 17)	13 % (11 - 16)	14 % (11 - 16)	13 % (10 - 15)	12 % (11 - 14)	14 % (11 - 16)	13 % (10 - 17), <i>n</i> = 5834
Q3	20 % (17 - 24)	19 % (16 - 23)	21 % (17 - 24)	17 % (15 - 20)	17 % (14 - 21)	19 % (17 - 21)	19 % (14 - 24), <i>n</i> = 6576

(continued on next page)

Table 1 (continued)

	Malmö	Gothenburg	Linköping	Stockholm	Uppsala	Umeå	All ¹
Q4 (highest deprivation)	32 % (25 - 54)	29 % (23 - 49)	30 % (25 - 48)	26 % (20 - 44)	29 % (21 - 51)	26 % (21 - 47)	29 % (20 - 54), n = 5749
% Foreign born ⁹ , mean (min-max)	9 % (6 - 11)	7 % (5 - 9)	6 % (6 - 6)	12 % (6 - 14)	8 % (7 - 10)	4 % (4 - 5)	10 % (4 - 14), n = 2486
Q1	14 % (11 - 17)	11 % (9 - 14)	9 % (6 - 11)	16 % (14 - 19)	12 % (10 - 14)	7 % (6 - 8)	13 % (6 - 19), n = 5757
Q2	22 % (17 - 28)	18 % (14 - 22)	14 % (11 - 19)	23 % (19 - 31)	17 % (14 - 23)	10 % (8 - 14)	18 % (8 - 31), n = 8740
Q3	40 % (29 - 71)	37 % (22 - 73)	30 % (20 - 58)	43 % (31 - 74)	33 % (23 - 72)	19 % (14 - 45)	36 % (14 - 74), n = 6337
Q4							

1 The column "All" shows the mean for SCAPIS participants from all the sites. As neighborhood SES quartiles were defined based on data from each entire county, the quartile thresholds varied between counties. Also the number of SCAPIS participants is not the same for all sites. Thus the min-max values overlap in the All column, and the number of SCAPIS participants in each quartile group is not 25 %.

2 Defined as inability to obtain 20 000 SEK within a week (ca. 2000 USD using the conversion rate as of 2024-08-29; 1 USD = 10.23 SEK).

3 Residential average, i.e. mean over SCAPIS participants in the city.

4 Proportion of the neighborhood population over the age of 20 with a low income. Low income was defined as an income in the lowest nationwide quartile (0–168 516 SEK, ca. 0–ca 16 500USD) in 2018. Divided into quartiles based on all neighborhoods in the relevant county (including neighborhoods without SCAPIS participants).

5 Proportion of the neighborhood population aged 25–64 with less than a high school education in 2018. Divided into quartiles based on all neighborhoods in the relevant county (including neighborhoods without SCAPIS participants).

6 Proportion of the neighborhood population aged 16–64 who were unemployed in 2018. Divided into quartiles based on all neighborhoods in the relevant county (including neighborhoods without SCAPIS participants).

7 Proportion of residential units within the neighborhood that were rental units in 2018. Divided into quartiles based on all neighborhoods in the relevant county (including neighborhoods without SCAPIS participants).

8 Neighborhood deprivation index combining the proportions of low-income earners, people with less than a high school education, unemployed people, and residential units that were rented in 2018. These were weighted together using factor loadings 0.96, 0.24, 0.87, and 0.69, respectively.

9 Proportion of the neighborhood population born outside of Sweden in 2018. Divided into quartiles based on all neighborhoods in the relevant county (including neighborhoods without SCAPIS participants).

the joint model, but with reduced estimates (and smaller than neighborhood proportion of rental units).

The pattern of association between neighborhood SES factors and environmental burden was often non-linear, except in Stockholm and Malmö. Some cities, such as Gothenburg and Linköping, followed a right-skewed inverted U-curve pattern where neighborhoods with the least and the most deprivation and least and most low-income earners had the lowest environmental burden, and deciles 6–7 had the highest. The effect estimates varied by city, with the largest absolute magnitude by SES factor for PM_{2.5} ranging from 0.09 µg/m³ in Uppsala (deprivation index decile 5) to 1.27 µg/m³ in Gothenburg (low-education decile 10), noise ranging from 2.3 to 15.3 dB, and lack of greenspace ranging from 0.04 to 0.41 iNDVI. The coefficients between neighborhood SES factors and environmental burdens were proportionally larger for road traffic noise and lack of greenspace than for air pollution, for all cities and neighborhood SES factors. As there were major differences between cities, analysis of all cities together was not representative of the associations within each city.

3.4. Correlation between individual-level and neighborhood-level SES factors

The correlations between individual SES factors and the corresponding neighborhood factors were generally weak (Table 2). The exceptions were a strong correlation between individual type of residence and the neighborhood proportion of rental units, and a moderate correlation between individual and neighborhood foreign born in Gothenburg and Malmö.

4. Discussion

In this large population-based middle-aged cohort in six Swedish cities, neighborhood SES factors accounted for a substantial part (25–81 %) of the variance in environmental burden between participants within the same city. However, individual SES factors only accounted for a small part of the variance after adjustment for neighborhood SES. Both the size and direction of the associations differed between cities and between SES factors. Neighborhoods with more low-income earners, more rental units and/or more foreign born had more environmental burden, while neighborhoods with less education and/or more unemployment had less environmental burden. Neighborhoods with a higher deprivation index score had more environmental burden. The patterns of the associations between SES factors and environmental burdens were mostly non-linear and differed substantially between cities. However, within a city, the associations between each specific SES factor showed similar patterns for each part of the environmental burden (air pollution, traffic noise, or lack of greenspace). Air pollution concentrations varied more between cities than between different SES groups within cities, partly reflecting the influence by long-range transport, while road traffic noise and lack of greenspace varied more between SES groups within cities than between cities.

4.1. Differences in global patterns and implications for environmental justice research

Our results suggest that the statement in the environmental justice framework that low SES areas/populations have more environmental burden needs a more nuanced approach that accounts for social and geographical context. A previous systematic review of SES disparities in air pollution exposure reported that North American studies consistently found more air pollution burden in low SES settings, while studies in Asia generally found that low SES areas/populations had less air pollution burden (Hajat et al., 2015; Wang et al., 2022). In Europe, associations vary depending on country (Hajat et al., 2015; Richardson et al., 2013); for example, a study in London, UK, found that areas with low neighborhood SES had more nitrogen oxide (NO_x) burden

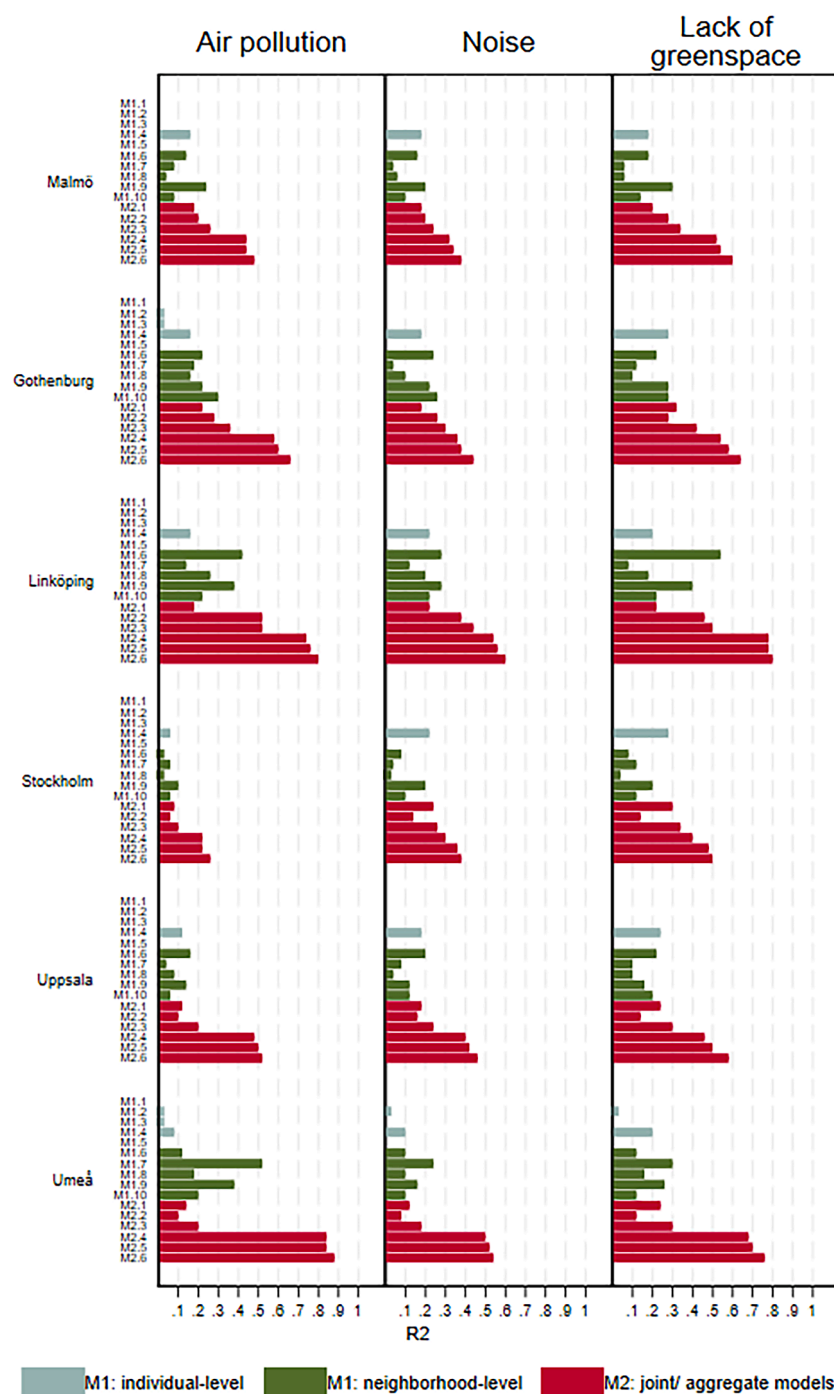


Fig. 3. Coefficient of determination (R^2) presented by city. The regression models including individual SES factors were M1.1 (lack of financial buffer), M1.2 (low education), M1.3 (occupation), M1.4 (type of residence), and M1.5 (foreign born); and the models including neighborhood factors were M1.6 (low income), M1.7 (low education), M1.8 (unemployment), M1.9 (proportion of rental units), and M1.10 (foreign born). Regression models including multiple/aggregate SES factors were M2.1 (all individual factors), M2.2 (neighborhood deprivation index), M2.3 (neighborhood deprivation index and all individual factors), M2.4 (four component neighborhood factors of the deprivation index; low income, low education, unemployment and proportion of rental units), M2.5 (four component neighborhood factors and all neighborhood SES factors) and M2.6 (all neighborhood and all individual SES factors). Air pollution was defined as $PM_{2.5}$, noise as road traffic noise (L_{den}), and lack of greenspace as the inverse of NDVI in a 500 m radius.

(Goodman et al., 2011). Another study in four French cities found that neighborhoods with more deprivation had more nitrogen dioxide (NO_2) in Lille and Marseille but less NO_2 in Paris (Padilla et al., 2014), similarly to our findings where the size and pattern of the association differed between cities. One previous study of children in Malmö, Sweden, reported more NO_2 burden in neighborhoods with low income (Chaix et al., 2006), in line with our results for Malmö. Another study in

Scania (the county encompassing Malmö) studying SES and NO_2 noted that size and direction of the association varied even between cities of the same county (Stroh et al., 2005).

Differences between North America and Europe have also been observed for noise exposure. A recent systematic review of “sonic injustice” including 20 European and 12 North American studies showed that low SES was associated with more noise burden in North America

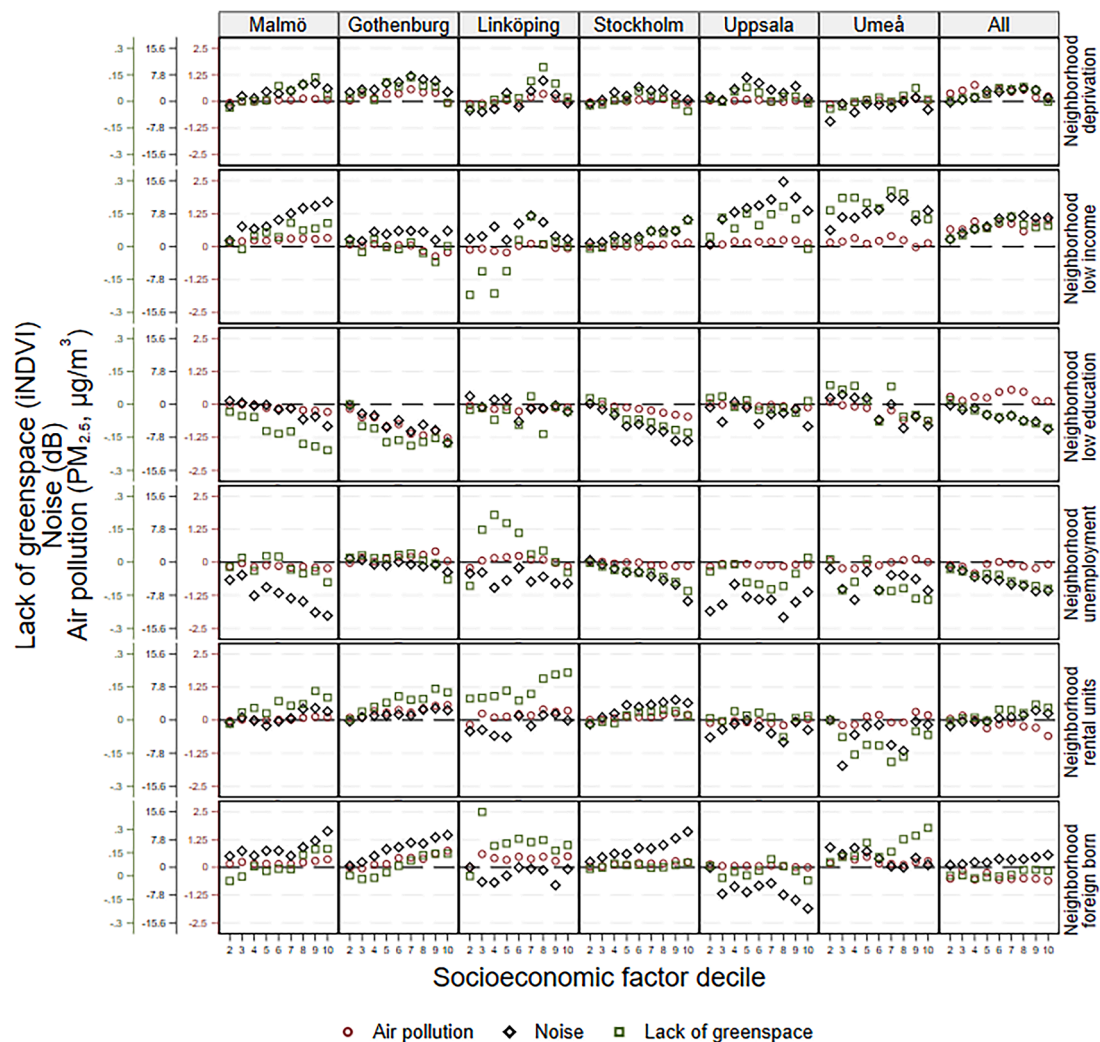


Fig. 4. Associations between neighborhood SES factors and environmental burdens, divided by city. The regression estimates show differences in environmental burden using SES factor decile 1 as reference. A low decile indicates a low neighborhood SES. The top row (deprivation index) is estimated using M2.3 (with neighborhood deprivation index and the 5 individual SES factors as the explanatory variables). The rest of the rows (income, education, etc.) are estimated using M2.6 (with 5 individual and 5 neighborhood SES factors), and show the independent effects of each neighborhood SES factor after adjustment for all other SES factors. P-values from type III F-tests were all <0.01 for all neighborhood SES factors, environmental burdens, and cities (Table S6). For example, low-income decile 7 (medium-low SES neighborhoods) in Linköping would have less greenspace (0.3 iNDVI, or 30 % less greenspace) compared to low-income decile 1 (high SES neighborhoods) after adjusting for other SES factors. Each of the three vertical axes are scaled to present the estimate relative to the range of the environmental burden, thus allowing a comparison of the magnitude of the association between environmental burdens. Air pollution was measured as $PM_{2.5}$, noise as road traffic noise (L_{den}), and lack of greenspace as the inverse of NDVI in a 500 m radius.

(60 % found low SES to be associated with more noise, 2 % found the opposite result, and 38 % found no significant association) but mixed results in Europe (31 % found low SES to be associated with more noise, 12 % found the opposite result, and 57 % found no significant associations) (Trudeau et al., 2023). The difference between Europe and North America was also echoed in the systematic review by Dreger et al. (2019). There were also differences between cities in the same countries, such as in the UK where the association between SES and noise differed by city (Peris & Arguelles, 2023).

For greenspace, the heterogeneity in terminology and methods is larger, but differences between regions have also been observed. Populations in the global south have less greenspace compared to the global north (Chen et al., 2022). Within Europe, there are also differences between regions, as countries in northern and western Europe have more greenspace compared to eastern Europe (EEA, 2019, 2022). Although these regional differences are not causal, they correlate with global socioeconomic differences between the global south/north and European east/west that are consistent with global socioeconomic differences.

Inequality by SES can also be seen within countries, where low SES is associated with less greenspace (Han et al., 2023). One study in Stockholm, Sweden, found that neighborhoods with low income have less greenspace, which is consistent with our results (Goldenberg et al., 2018). A recent cohort study in Uppsala, Sweden, also reported an association between lack of greenspace and neighborhoods with low income (Stucki et al., 2023), in line with our findings.

When viewing our results in combination with previous studies conducted throughout the world, we conclude that even when comparing cities in the same country, the local geographical context creates differences in the association between SES and environmental burdens. Furthermore, since a pooled analysis of many cities does not capture these differences (and, indeed, we observed reverse associations in some cities compared to the pooled analysis), city-dependent differences in associations should be allowed for when using SES as a possible confounder in studies of environmental risk factors and health.

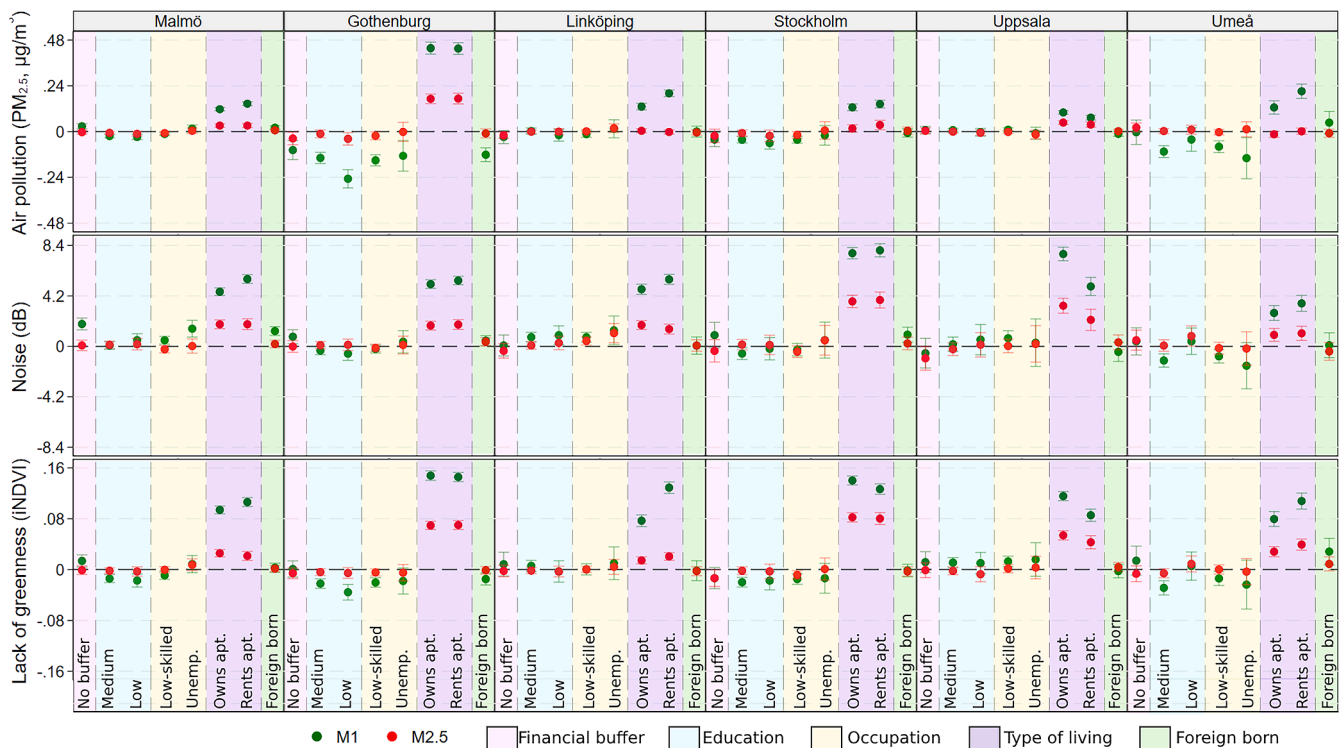


Fig. 5. Associations between individual SES factors and environmental burden, divided by city. Estimates are shown with 95 % confidence intervals. The red dots are estimates from M2.6, adjusting for 5 individual and 5 neighborhood SES factors. The green dots are from separate individual SES factor models (M1.1–M1.5), only adjusted for the respective factor. P-values are presented in Tables S6 and S7. The different color columns show, from left to right, estimates for the following SES factors: Financial buffer (ref: has financial buffer); Education (ref: high education); Occupation (ref: high-skilled occupation); Type of living (ref: living in an owner-occupied house); Foreign born (ref: born in Sweden). Air pollution was measured as $PM_{2.5}$, noise as road traffic noise (L_{den}), and lack of greenspace as the inverse of NDVI in a 500 m radius.

4.2. Differences between SES factors and the use of deprivation indices

When examining associations with environmental burden, we found major differences in both size and direction between different neighborhood SES factors. In London, UK, neighborhoods with less education have been shown to have less NO_x (similar to our associations between $PM_{2.5}$ and low education), while neighborhoods with more deprivation (using an index) had more NO_x (Goodman et al., 2011). Differences between SES factors were also found in four French cities; for example, in Lille, both neighborhoods with more white-collar workers (high SES) and neighborhoods with more deprivation (low SES, index score) had less NO_2 burden (Padilla et al., 2014). Our occupation-related SES factor showed the opposite pattern to Lille, as neighborhoods with more unemployment (low SES) had less air pollution burden. For noise, Trudeau et al. (2023) also noted that deprivation indices in different studies mostly had the same direction of the association (more deprivation associated with more noise), but that education and income, for example, had mixed patterns depending on the study. Dreger et al. (2019) also found differences between SES factors, where education had more mixed results compared to other factors. For greenspace, a study in the UK found mixed (depending on city/region) associations between crime rates and lack of greenspace, while those with low education consistently had less greenspace (Bao et al., 2023). Another study in multiple cities in Australia similarly found differences between socioeconomic factors, e.g. where foreign born participants had less greenspace while participants with lower education had more greenspace (Zhang & Luo, 2024). Our results suggest that the direction of the associations of one specific SES factor cannot always be applied, since the directions of the associations may differ by SES factors.

Our results also suggest that a deprivation index may not be better than separate SES factors in accounting for variation in environmental

burden. Using only a deprivation index may lead to misleading results, as it is not representative of the associations for the different factors within the index. As discussed above, Goodman et al. (2011) and Padilla et al. (2014) noticed a similar discrepancy; their main SES indicator was a deprivation index, but their associations with separate SES factors showed the opposite pattern to the index. There is also heterogeneity in how deprivation indices are constructed. For example, Goodman et al. (2011) used a deprivation index comprising employment, education, crime, barriers to housing and service, and environment, while we used a deprivation index including four neighborhood SES factors that was originally developed to predict death rates in Sweden (Strömberg et al., 2021). Caution may be needed when using the latter index outside its intended health-related context.

4.3. Non-linear patterns of association

Many of the associations between SES and environmental burden we observed were non-linear; for example, the inverse U-shaped association between environmental burden and neighborhood low income, where the largest environmental burden was seen in deciles 6–7 (for Gothenburg and Linköping). This is similar to the results of a study in India that showed inverted U-shaped patterns between exposure to air pollution from coal-fired power plants and illiteracy and poverty as markers of SES (Kopas et al., 2020). The authors of this Indian study theorized that this may have been due to the context in developing countries, where the most socioeconomically vulnerable populations are excluded from the consequences of industrial developments such as urbanization and increased traffic pollution (Kopas et al., 2020). Our results indicate that, although sociopolitical causes may differ, this pattern of association is not unique to developing countries.

Non-linear associations have also been observed in previous

European studies conducted in cities such as Strasbourg, where non-linear associations similar to our results were found between deprivation and NO₂ (Havard et al. (2009), and Helsinki, where a similar pattern was seen between median income and PM_{2.5} (Gosztonyi et al., 2023).

Right-skewed U-shaped patterns were also common in studies where high SES was associated with more noise (Trudeau et al., 2023). In France, while an approximately linear association was seen in Paris, the association was non-linear in Lyon (Padilla et al., 2014). We saw a

Table 2

Table and heatmap of different measures of correlation between different SES factors.

	Cramér's V					Spearman correlation				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Malmö										
Individual										
(1) No financial buffer										
(2) Low education	Weak									
(3) Occupation	Weak	Strong								
(4) Type of living	Moderate	Weak	Moderate							
(5) Foreign born	Weak	Weak	Weak	Weak						
Neighbourhood										
(6) Low income	Weak	Weak	Weak	Strong	Moderate					
(7) Low education	Weak	Weak	Moderate	Moderate	Moderate	0.72				
(8) Unemployment	Weak	Weak	Weak	Moderate	Moderate	0.85	0.73			
(9) proportion rental units	Weak	Weak	Weak	Strong	Weak	0.46	0.12	0.24		
(10) Deprivation index	Weak	Weak	Weak	Strong	Weak	0.83	0.47	0.65	0.84	
(11) Foreign born	Weak	Weak	Weak	Moderate	Moderate	0.85	0.79	0.81	0.19	0.6
Gothenburg										
Individual										
(1) No financial buffer										
(2) Low education	Weak									
(3) Occupation	Weak	Strong								
(4) Type of living	Weak	Weak	Weak							
(5) Foreign born	Weak	Weak	Weak	Weak						
Neighbourhood										
(6) Low income	Weak	Weak	Weak	Moderate	Weak	0.53				
(7) Low education	Weak	Weak	Moderate	Weak	Moderate	0.83	0.55			
(8) Unemployment	Weak	Weak	Weak	Moderate	Weak	0.88	0.55			
(9) proportion rental units	Weak	Weak	Weak	Strong	Weak	0.74	0.39	0.59		
(10) Deprivation index	Weak	Weak	Weak	Strong	Weak	0.89	0.49	0.77	0.95	
(11) Foreign born	Weak	Weak	Weak	Moderate	Moderate	0.74	0.71	0.7	0.5	0.64
Linköping										
Individual										
(1) No financial buffer										
(2) Low education	Weak									
(3) Occupation	Weak	Strong								
(4) Type of living	Weak	Moderate	Moderate							
(5) Foreign born	Weak	Weak	Weak	Weak						
Neighbourhood										
(6) Low income	Weak	Weak	Weak	Strong	Weak	0.34				
(7) Low education	Weak	Weak	Weak	Moderate	Weak	0.91	0.36			
(8) Unemployment	Weak	Weak	Weak	Moderate	Weak	0.71	0.26	0.67		
(9) proportion rental units	Weak	Weak	Weak	Strong	Weak	0.95	0.87	0.67		
(10) Deprivation index	Weak	Weak	Weak	Strong	Weak	0.92	0.32	0.86	0.92	
(11) Foreign born	Weak	Weak	Weak	Strong	Weak	0.68	0.57	0.64	0.6	0.7

(continued on next page)

Table 2 (continued)

Stockholm	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Individual										
(1) No financial buffer										
(2) Low education	Weak									
(3) Occupation	Weak	Moderate								
(4) Type of living	Weak	Weak	Weak							
(5) Foreign born	Weak	Weak	Weak	Weak						
Neighbourhood										
(6) Low income	Weak	Weak	Weak	Strong	Weak	0.48				
(7) Low education	Weak	Weak	Weak	Moderate	Weak	0.76	0.44			
(8) Unemployment	Weak	Weak	Weak	Moderate	Weak	0.58	0.28	0.28		
(9) proportion rental units	Weak	Weak	Weak	Strong	Weak	0.88	0.47	0.57	0.9	
(10) Deprivation index	Weak	Weak	Weak	Strong	Weak	0.63	0.37	0.47	0.9	0.58
(11) Foreign born	Weak	Weak	Weak	Strong	Weak	0.67	0.64	0.49	0.4	0.58
Uppsala	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Individual										
(1) No financial buffer										
(2) Low education	Weak									
(3) Occupation	Weak	Strong								
(4) Type of living	Moderate	Weak	Moderate							
(5) Foreign born	Weak	Weak	Weak	Weak						
Neighbourhood										
(6) Low income	Weak	Weak	Weak	Strong	Weak	0.33				
(7) Low education	Weak	Weak	Weak	Strong	Weak	0.79	0.15			
(8) Unemployment	Weak	Weak	Weak	Strong	Weak	0.63	0.37	0.57		
(9) proportion rental units	Weak	Weak	Weak	Strong	Weak	0.83	0.37	0.77	0.8	
(10) Deprivation index	Weak	Weak	Weak	Strong	Weak	0.77	0.9	0.9	0.9	0.66
(11) Foreign born	Weak	Weak	Weak	Strong	Weak	0.64	0.65	0.51	0.53	0.66
Umeå	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Individual										
(1) No financial buffer										
(2) Low education	Weak									
(3) Occupation	Weak	Strong								
(4) Type of living	Weak	Weak	Weak							
(5) Foreign born	Weak	Weak	Weak	Weak						
Neighbourhood										
(6) Low income	Weak	Weak	Weak	Moderate	Weak	0.36				
(7) Low education	Weak	Weak	Weak	Moderate	Weak	0.86	0.52			
(8) Unemployment	Weak	Weak	Weak	Moderate	Weak	0.56	0.12	0.53		
(9) proportion rental units	Weak	Weak	Weak	Strong	Weak	0.78	0.38	0.73	0.9	
(10) Deprivation index	Weak	Weak	Weak	Moderate	Weak	0.79	0.38	0.76	0.91	0.65
(11) Foreign born	Weak	Weak	Weak	Moderate	Weak	0.84	0.46	0.86	0.42	0.65

In the deprivation index, the four SES factors were weighted as follows: low income: 0.96, low education: 0.24, unemployment: 0.87, proportion rental units: 0.69. Correlations between SES factors were estimated using Cramér's V or Spearman rank correlation. Correlations by Cramér's V were categorized into weak, moderate and strong according to the SAGE thresholds for the phi-coefficient (Wiedmaier), where thresholds changed depending on the degrees of freedom of the cross-tabulation (Liebetrau, 1983). Spearman rank correlation coefficients are shown using a light to dark green gradient for negative correlations (darker means a stronger negative correlation) and a light to dark blue gradient for positive correlations (darker means a stronger positive correlation).

similar pattern in Malmö and Stockholm that had approximately linear patterns between income and environmental burdens. But in Uppsala we found non-linear associations with neighborhood income and this was also the case for other measures of SES in Malmö and Stockholm.

However, some studies have found linear patterns (Wang et al. (2022); Goodman et al. (2011)). This further emphasizes the need to take local differences into account, even within countries.

4.4. Urban settings

One way to interpret the mixed and non-linear associations between SES and environmental burdens is by understanding differences in the urban settings, especially socioeconomic segregation gradients. Road traffic noise, air pollution, and lack of greenspace are strongly connected to urbanicity. Air pollution, in particular, was shown to have an urban-suburban gradient both in our study (Fig. 2) and in other studies globally (Flacke et al., 2016; Goodman et al., 2011; O'Neill et al., 2003; Padilla et al., 2014).

The gradient of SES segregation in the US, where those with high SES are found in the suburbs, creates a suburban-urban SES gradient, and consequently low SES is associated with more environmental burdens (Massey & Tannen, 2018; Sharp & Iceland, 2013). In Europe, the geographical gradient of socioeconomic segregation is more mixed. For example, the study of four French cities found that those with low SES lived in suburbs in Paris but more centrally in Lille, and consequently that low SES was associated with more NO₂ in Lille but with less NO₂ in Paris (Padilla et al., 2014). Most of the socioeconomic segregation gradients in the six cities in our study were similar to the situation in Lille (low SES centrally), which may explain why our results were more consistent with those from Lille than those from Paris (Padilla et al., 2014). However, several of the cities in the present study also have suburbs with low SES; for example, Gothenburg has suburbs with both very high and low SES, and urban neighborhoods with medium-low SES. This socioeconomic segregation pattern is likely the cause of the right-skewed U-shaped pattern of associations between SES and environmental burden pattern in Gothenburg. In Lyon, the socioeconomic segregation gradient was mixed, with very low and very high SES neighborhoods in suburbs, and medium SES centrally, and Padilla et al. (2014) found similar results to Gothenburg.

The differences between SES factors can also be viewed in this manner. If we examine neighborhood low education, the pattern is the complete opposite, with low-education neighborhoods having an urban-suburban gradient in which high education is found in the urban center (Fig. 1); this may explain the differences in the directions of the associations between low education and low income. Overall, examining urbanicity and specific urban settings may give some understanding of our results, as well as results in similar studies.

4.5. Differences between environmental burdens

For each SES factor, we found similar associations with all included environmental burdens, similar to previous studies in Dortmund, Germany (low SES was significantly associated with more air pollution and lack of greenspace, and non-significantly associated with noise), and Ghent, Belgium (low SES was associated with more air pollution and noise) (Flacke et al., 2016; Verbeek, 2019). Interestingly, the results from those two studies indicated weaker associations between SES and noise, whereas the sizes of our associations were proportionally greater for noise compared to air pollution. Furthermore, the German and Belgian studies found that the associations with noise did not vary much between SES factors in their respective cities, but in Sweden we found similar R² values for environmental burdens and larger variability by SES within cities compared to between cities. A difference between our study and most others is that we used particle matter to assess air pollution burden (PM_{2.5} and PM₁₀), while many others used NO₂/NO_x (Flacke et al., 2016; Goodman et al., 2011; Padilla et al., 2014; Verbeek, 2019). NO_x arises from more local sources of air pollution, making local variability more noticeable compared to PM. We opted to use PM as our air pollution indicator as it is more clearly related to health outcomes (World Health Organization, 2021).

While our results suggest that inequality in environmental exposure for different burdens will follow the same pattern for any specific SES factors, more studies using multiple environmental burdens are needed to properly understand the connections. Multiple environmental

burdens likely increase the risk of negative health effects, especially in low SES groups (EEA, 2019; Morello-Frosch et al., 2011; Solomon et al., 2016).

4.6. Individual and neighborhood SES factors, and correlation between SES factors

We found that neighborhood SES factors were more clearly associated with environmental factors, in comparison to individual SES factors. Similarly, Goodman et al. (2011) found that the association between individual SES and NO_x became weaker in joint models with neighborhood SES. Wang et al. (2022) found a significant association between individual SES and air pollution, but the association was weaker than the one found for neighborhood factors. A Swedish study based on women living in Uppsala (Stucki et al. (2023) mostly used individual SES factors, but also included neighborhood median income as an SES factor. In contrast to our results, that study found larger effect sizes for most of the individual factors (education, civil status, age) than for neighborhood income, but individual/household income did not have a strong effect compared to neighborhood income. One reason for the difference between those results and ours may be that the Uppsala study did not include other neighborhood factors. For example, when we compared M2.2 (deprivation index) and M2.3 (deprivation index + individual factors), the R² value for M2.3 was substantially higher, whereas R² values for M2.4 (with four neighborhood factors) and M2.5 (with all individual and the component neighborhood factors) were almost the same. Our findings suggest that when multiple neighborhood SES factors are already accounted for, the addition of individual SES factors may not contribute much to SES factor models investigating associations with environmental burdens.

One important finding was the low correlation between individual and neighborhood SES. The lower R² values and magnitudes of association indicate that individual SES may not be as important as neighborhood SES for the association with environmental burden. Individual type of residence was an exception, but this was correlated to the neighborhood type of residence. The model with individual type of residence might therefore have captured the explanatory effects of neighborhood type of residence, as shown by the similar R² values in the joint models M2.4 and M2.5. Our results suggest that in Sweden, individual SES factors are often independent of neighborhood SES. This may be relevant to other contexts outside of environmental research.

The weak association between environmental burden and individual SES factors may not be applicable to other contexts, such as when looking at how SES affects the association between environmental burden and health effects. While our results suggest that neighborhood factors are more important for distributive environmental justice, the meta-analysis by Laurent et al. (2007) noted the opposite; that is, studies using individual SES showed clearer environmental burden-SES interaction effects in their association with mortality. Individual SES is likely more important in studies of the health effects of environmental exposures than it is when investigating distributive environmental justice.

4.7. Strengths and limitations

There are several limitations to our findings. Firstly, our study only included participants living in urban neighborhoods, as there were too few rural/suburban participants for separate analyses. Since local context seems to matter in the association between SES factors and environmental burdens, generalizing our results outside of urban environments should be done with caution.

Secondly, although the SCAPIS cohort is population-based, it is not fully representative of the general population. The overall participation rate in the SCAPIS pilot study was 50 %, but a pilot study indicated that it was lower in low-SES neighborhoods (Björk et al., 2017). In our data, the distribution of the neighborhood SES of our population indicated that there were fewer participants in low-SES neighborhoods. Combined

with the pilot SCAPIS study findings, this would indicate that socio-economically vulnerable participants may have participated to a lower extent and thus be underrepresented in our study. Selection into a study can be viewed as a collider problem when estimating the effect of X (here SES) on an outcome (here environmental exposure). If both X and Y affect participation, then participation is a collider, and analysing only those who participated leads to collider bias (Nohr & Liew, 2018). In our analysis, it seems likely that X could affect participation. But it seems less likely that Y=exposure affects the choice to participate. However, the high nonresponse rates could have skewed our results and must be considered in the interpretation.

Thirdly, our model with all SES factors (M2.6) included highly correlated factors, which may have introduced multicollinearity. Generally, including highly correlated explanatory variables produce estimates with higher uncertainty, as reflected in wider confidence intervals for the estimates. However, the estimates from the multivariate models are generally unbiased, which is not the case for the single explanatory variable model, as this single variable becomes a proxy for the joint effect of the correlated variables. In a regression analysis with the aim to adjust for SES, we would likely have included only one SES factor. However, in our analyses, different aspects of SES were the main interest. We also reported estimates from univariate models (M1.1–M1.10), which were not considerably different from the separate effect estimates from M2.6. Therefore, we believe the joint model provides more robust and interpretable estimates overall. Nonetheless, the high correlation between predictors should be considered when interpreting these results.

Finally, we did not take spatial autocorrelation into account, which could have led to overestimated effect estimates and worse model fit, as observed in previous studies comparing models adjusting/not adjusting for spatial autocorrelation (Bao et al., 2023; Havard et al., 2009; Verbeek, 2019). The reason we decided not to use a multilevel model structure was that we found almost no within-neighborhood variation in air pollution.

This study also has several strengths. We analyzed several environmental exposures to get a comprehensive view of the association between SES and environmental burden, using high-quality individual and neighborhood data from a well-characterized cohort. The cohort was used to study associations between environmental burden and health, making these analyses directly relevant to future studies using the cohort. Another key strength is the availability of data for multiple urban sites in Sweden with exposure and outcome data obtained through similar methodology, allowing detailed and accurate comparisons due to homogeneity between the data sets.

5. Conclusions

In this large population-based middle-aged cohort in six Swedish cities, we found that SES factors were associated with environmental burdens, but with major differences between cities and between SES factors. Putting our findings within the context of previous studies, the main take-home messages are as follows:

- 1) There are major differences between cities in Sweden when it comes to the associations between SES and environmental burden. Both the pattern and strength of the association may differ, although the directions were the same for all six cities in this study. Non-linear associations were common in our analyses. Future multi-city studies of environmental risk factors and health that adjust for SES should allow for city-specific differences and for non-linearity.
- 2) Interventions for environmental justice need to consider who is most affected in their specific local contexts. In some settings, areas with the most environmental burden are not always the areas with the most social vulnerability.
- 3) Different measures of neighborhood SES (income, education, unemployment, etc.) have substantially different and sometimes

opposite associations with environmental burden. It is therefore difficult to capture these differences in simple indices of deprivation.

- 4) Area-level and individual-level SES should be seen as independent factors, and area-level SES seems to be more important for explaining variance in environmental burden. Individual and area-level SES are generally weakly correlated.
- 5) The pattern of association with SES seems to be similar for different environmental burdens.

CRedit authorship contribution statement

Mehjar Azzouz: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Johan Sommar:** Writing – review & editing, Conceptualization. **Martin Tondel:** Writing – review & editing, Methodology. **Lars Barregard:** Writing – review & editing, Conceptualization. **Charlotta Eriksson:** Writing – review & editing. **Mare Löhmus:** Writing – review & editing. **Mikael Ögren:** Writing – review & editing. **Cecilia Bennet:** Writing – review & editing, Data curation. **Jenny Lindvall:** Writing – review & editing, Data curation. **Susanna Gustafsson:** Writing – review & editing. **Marta A. Kisiel:** Writing – review & editing. **Petter Ljungman:** Writing – review & editing. **Stefan Ljunggren:** Writing – review & editing. **Erica Nordlander:** Writing – review & editing. **Anna Oudin:** Writing – review & editing. **Göran Pershagen:** Writing – review & editing. **Leo Stockfelt:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Eva M. Andersson:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data statement

The data used for this study cannot be shared publicly due to the privacy of SCAPIS cohort participants. Data are however available from the authors with permission from SCAPIS. Ethical approval from The Swedish Ethical Review Authority is needed to access the data.

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Supplementary materials

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