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Socioeconomic Disparities and Air Pollution Exposure: a Global Review

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Abstract The existing reviews and meta-analyses addressing unequal exposure of environmental hazards on certain populations have focused on several environmental pollutants or on the siting of hazardous facilities. This review updates and contributes to the environmental inequality literature by focusing on ambient criteria air pollutants (including NO_x), by evaluating studies related to inequality by socioeconomic status (as opposed to race/ethnicity) and by providing a more global perspective. Overall, most North American studies have shown that areas where low-socioeconomic-status (SES) communities dwell experience higher concentrations of criteria air pollutants, while European research has been mixed. Research from Asia, Africa, and other parts of the world has shown a general trend similar to that of North America, but research in these parts of the world is limited.

Keywords Environmental justice · Environmental inequality · Criteria air pollutants · Air pollution · Socioeconomic status · Social disadvantage

Introduction

Several review articles related to inequalities in environmental hazards have been conducted over the years [1–9]. Existing reviews focus on a variety of important topics including the following: understanding the origins of environmental inequality [6], the policy implications of environmental justice (EJ) research [6], the interaction between the EJ advocacy movement and the research agenda [8], a methodological critique of the research [1], and finally the issue of whether environmental inequalities in the US disproportionately impact racial/ethnic minorities or populations of low socioeconomic status (SES) [7, 9]. The reviews of the existing body of research clearly highlight both the sheer volume of work around environmental inequalities and the complexity of the issues involved.

Although the terms EJ and environmental inequality are often used interchangeably in the literature, they do have distinct meanings. The concept of justice is normative, involving value judgments that can vary over place and time, while equality can be measured empirically and directly compared [10••, 11]. Inequalities can be defined across other domains such as process (equal access to the environmental decision-making process) and opportunity (equal opportunity to reduce or avoid exposures). These concepts, being difficult to measure, are not often found in empirical research (see Marshall [12••] and Clark [13] for papers that move beyond environmental inequality).

Beyond issues of fairness, environmental inequality research has important health implications. Several reviews

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focus on the relationship between environmental inequality and health [2–4, 14]. The triple jeopardy hypothesis states that low-SES communities face (1) higher exposure to air pollutants and other environmental hazards and (2) increased susceptibility to poor health (primarily as a result of more psychosocial stressors, such as discrimination and chronic stress, fewer opportunities to choose health-promoting behaviors and poorer health status) resulting in (3) health disparities that are driven by environmental factors [15–17].

The purpose of this paper is to review empirical data in the environmental inequality literature from the past 10 years and to broaden the scope of previous reviews by including research from around the globe. We define environmental inequality as the distribution of air pollution across different socioeconomic groups and focus on papers that address this issue, rather than the process or opportunity domains. Our review focuses exclusively on one important environmental hazard, air pollution, and will only review research related to the distribution of air pollutants by SES. We recognize that some researchers will think that the exclusion of research on environmental inequalities by race/ethnicity is a limitation of this work. However, racial/ethnic composition of populations is highly diverse, worldwide, as is patterning of socioeconomic factors by race/ethnicity. Further, some countries do not routinely record race/ethnicity in health data. Additionally, interpretation and conceptualization of research on race/ethnicity can be challenging [18]. Because of these factors and because we recognize that EJ is emerging as a critical issue in nations around the world, we decided to emphasize socioeconomic factors and not address race/ethnicity to allow for a more inclusive and generalizable global perspective.

Our focus on air pollution is further limited to the criteria air pollutants which are monitored and regulated by the US Environmental Protection Agency (EPA) and governmental agencies in other nations. Air quality standards for concentrations of particulate matter (PM, both particles <2.5 μm in aerodynamic diameter, $PM_{2.5}$, and <10 μm in aerodynamic diameter, PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and lead in outdoor air are set by the World Health Organization and individual governments around the world [19–21]. They are based on a review of the scientific evidence and are established to allow for an adequate margin of human health and safety, in light of the numerous health effects of criteria air pollutant exposure on human health [22–25].

Methods

A systematic review was conducted to identify all published studies on SES and ambient air pollution exposure. First, a literature search was performed using Science Direct, Web of Science, Google Scholar, and PubMed for the following keywords: "socioeconomic injustice and air pollution," "environmental justice and air pollution," "environmental inequity and air pollution," "socioeconomic status and air pollution," and "disparity and air pollution and environment." These keywords yielded a total of 440 published papers after removing duplicates across databases.

We excluded papers from this review if (1) they were published prior to 2005, (2) they were mainly focused on quantifying the association between air pollution and a health outcome, with little attention to inequalities in exposure, (3) they did not conduct an empirical analysis (i.e., provided a framework or conceptual model), (4) they evaluated air pollutants other than the criteria air pollutants (e.g., hazardous air pollutants (HAPs), black carbon), (5) they used traffic-related metrics as a proxy for air pollution (e.g., distance to road, traffic density), (6) they combined several air pollutants (criteria and non-criteria) into an index without providing data on the individual ambient air pollutants themselves, and/or (7) they used only race/ethnicity classifications and not other socioeconomic factors to evaluate inequality. All papers were screened and reviewed by two study authors.

Ultimately, 37 studies met the inclusion criteria and were included in this review. Studies were organized by geographic location, with 22 North American studies, 10 European studies, and 5 studies from New Zealand, Asia, and Africa. Of these, some evaluated both criteria and non-criteria air pollutants and some evaluated both race/ethnicity and SES. Findings related to the non-criteria air pollutants and race/ethnicity are not described in the tables or text of this paper.

Given the differing methods used to assess the association between SES and air pollution, we did not attempt to quantify the overall magnitude of effect. Instead, we focused on describing the directionality of results to better understand if an overall trend emerges from the literature. We also discuss methodological issues, such as the analytic techniques employed to assess the association between SES and air pollution and the unit of analysis chosen by researchers. Furthermore, the different approaches used in air pollution exposure assessment and the types of SES metrics used are also discussed.

Results

The North American studies are outlined in Table 1. In general, these studies show a consistent finding: lower-SES individuals and communities are exposed to higher concentrations of criteria air pollutants. Comparison of magnitude of effects is difficult given differences across studies, but in those studies that used similar data sources and methods, we see relatively small increases in pollutant exposures associated with lower SES. For example, $PM_{2.5}$ concentrations were 0.14, 0.2, 0.47, and 0.9 $\mu g/m^3$ higher in census tracts in North Carolina [26], in the northeast USA [27], in six US cities [28•], and in

Table 1 North American studies of air pollution-SES inequalities

First author, year	Location	Unit of analysis	SES indicator(s)	Analytic method	Results						
					O_3	$PM_{2.5}$	PM_{10}	CO	NO_2	NO_x	SO_2
Canada											
Buzzelli, 2007 [30]	Toronto	CT	Ten inc, edu, occ indicators	OLS, logistic, SAR					↑↓[a]		
Carrier, 2014 [34]	Montreal	City block	Inc	SAR		–		–	↓	–	
Crouse, 2009 [32]	Montreal	CT	Eight inc, edu, occ indicators	CC					↑↓[a]		
Su, 2010 [57]	Seattle, WA, Vancouver, BC	CT	11 inc, edu, occ indicators	OLS, SAR, GAM					↓		
USA											
Bell, 2012 [29]	USA	CT (n=215)	Edu, pov, occ, inc	OLS and logistic		↓					
Brajer, 2005 [37]	SCABC	County	Inc, edu	CC	↓		↓				
Brochu, 2011 [27]	Six NE states	CT	Pov, edu, inc	GAM		↓*	↓*				
Clark, 2014 [13]	USA	BG	Pov, edu, inc	Means, Atkinson index					↓		
Gray, 2013 [26]	North Carolina	CT	Pov, edu, inc, NSES index	RE	↑	↓					
Grineski, 2007 [38]	Phoenix, AZ	Blocks	NSES index	OLS	↓			↓		↓	
Hajat, 2013 [28•]	Six US cities	Indiv and CT	Four indiv and five CT inc, edu, occ indicators, and NSES index	Spatial ICAR, RE, OLS		↑↓[b]				↑↓[b]	
Maroko, 2012 [31]	New York, NY	Parcel data	Pov and edu	Proximity analysis, logistic		↑↓[b]					
Marshall, 2008 [11]	SCABC	CT	Inc and edu	OLS	↑	↓					
Marshall, 2014 [12••]	SCABC	Blocks	Inc and race combined	% Difference, Atkinson index		↓					
Miranda, 2011 [35]	USA	BG, county	Pov	Logistic	↑	↓					
Molitor, 2011 [33]	LA, CA	CT	Pov	Cluster analysis, maps, means		↓~			↓~		
Rissman, 2013 [59]	Atlanta region	CT	Inc, edu, pov, NSES index	OLS, QR		↓OLS –QR					
Su, 2009 [61]	LA, CA	CT	Pov	Concentration index		↓			↓		
Su, 2011 [36]	LA, CA	One-fourth mile buffer around parks	Inc, edu, occupation	OLS	↑	–			↓		
Su, 2012 [60]	Alameda, SD, LA, CA	CT	Pov	Concentration index		↓			↓		
Yanosky, 2008 [56]	Worchester, MA	BG	Edu, inc, pov, crowding, index of all four indicators	Spatial RE					↓		
Zou, 2014 [58]	Dallas-Fort Worth, TX	BG, CT, zip code	Edu, inc	Logistic							↓

Locations: *SCABC* South Coast Air Basin of California which includes Los Angeles, Orange, Riverside, and San Bernardino Counties; *LA* Los Angeles; *SD* San Diego; *NE* Northeast; unit of analysis: *CT* census tract, *BG* block group; SES indicator: *inc* income, *edu* education, *occ* occupation, *pov* poverty, *NSES index* neighborhood SES index/neighborhood deprivation index, *indiv* individual, *nh* neighborhood; analytic method: *OLS* ordinary least squares regression, *SAR* spatial autoregressive models, *GAM* generalized additive model, *ICAR* intrinsic conditional autoregressive model, *RE* random effects/hierarchical model, *QR* quantile regression, *CC* correlation coefficients; results: ↓ higher-SES areas/groups/individuals associated with lower pollutant concentrations, ↑ higher-SES areas/groups/individuals associated with higher pollutant concentrations, ↑↓ mixed association—both positive and negative associations were found, – null association, * urban areas only, ~ non-linear association

[a] Association was dependent on which SES variable was used

[b] Association dependent on unit of analysis (e.g., cohort-wide vs city-specific or city-wide vs borough-specific)

selected census tracts around the USA [29], respectively, with an approximately 15 % greater population of persons with less than a high school education. For context, the EPA $PM_{2.5}$ standard is 12 μg/m^3 and the WHO guidelines aim for 25 μg/m^3.

A few exceptions to this pattern were seen. In New York City (NYC), Toronto, and Montreal, some SES indicators showed the opposite association: higher-SES census tracts had higher concentrations of pollutants [28•, 30–32]. In NYC, a borough-specific analysis revealed that the Bronx and Staten Island had these patterns [31], which is similar to what was found in the Multi-Ethnic Study of Atherosclerosis cohort among study participants who lived in the southern Bronx and northern Manhattan [28•]. These results may reflect the fact that these cities developed in such a way that high-SES individuals clustered around busy roadways which often run near rivers and lakes offering more scenic views and better access to urban amenities.

Other North American studies found differences by pollutant. For example, high-poverty clusters in Los Angeles had similar NO_2 and $PM_{2.5}$ concentrations compared to low-poverty clusters but had higher concentrations of other pollutants [33]. These pollutant-specific results were also seen in a study from Montreal, where higher NO_2 concentrations were associated with low-income populations, but no differences across populations were found for $PM_{2.5}$, CO, and NO_x [34]. Several North American studies also found that higher SES groups are exposed to higher concentrations of O_3 compared to lower-SES groups [11, 26, 35, 36]. This is likely because of the scavenging of O_3 by nitric oxide (NO) which can result in lower O_3 levels near roadways (where low-income populations are more likely to live) and higher levels further away from them. However, two US studies found O_3 levels to be higher among low-SES groups [37, 38].

Although research from other parts of the world is limited, studies from New Zealand (NZ), Asia, and Africa also showed negative associations between SES and air pollutants (Table 2). The three studies from NZ found that low-income and high-deprivation neighborhoods had higher concentrations of PM_{10} compared to higher-SES areas [39–41]. The lone study to address air pollution inequalities in Africa was from Ghana [42•]. That study found that community SES was inversely associated with both $PM_{2.5}$ and PM_{10}. Lastly, a study from Hong Kong explored a municipality with a strong social safety net which had direct bearing on air pollution inequalities [43•]. The government of Hong Kong provides public housing for low-income residents, while higher-income families obtain housing through the private housing market. Among those living in private housing, the lower-SES population had higher exposure to PM_{10} compared to the high-SES population. No such inequality was found for residences of public housing. The authors indicate that similar results were found for several other air pollutants. The differential location of public housing facilities appears to be reducing residents' exposure to traffic-related air pollution.

Findings in the European literature were quite mixed (Table 3). Several studies found non-linear patterns of inequality [44–46]. In Strasbourg, France, only the high-SES quintile had lower NO_2 concentrations, compared to the other four quintiles that had similar concentrations [45]. Similarly, a European-wide analysis uncovered non-linear trends where middle-income populations had lower PM_{10} concentrations compared to both higher- and lower-income groups, depending on if analyses focused on Eastern or Western Europe [46]. In London, some high-SES groups had similar NO_x concentrations to low-SES groups when using a small-area SES metric [44]. Other studies found that the choice of SES metric was relevant to findings, where some SES measures were positively associated with air pollution and others negatively [44, 47, 48]. A pilot study of several cities in the Czech Republic found pollutant-specific results: smaller cities with larger low-SES populations had higher PM_{10} and SO_2 concentrations, while larger cities with larger high-SES populations had higher concentrations of NO_2 [49]. Lastly, a Spanish study of pregnant women found no association between individual-level SES and NO_2 [50].

A few European studies from England and Sweden found patterns of inequality similar to those seen in the USA [51–53]. Two UK-based studies found that low-SES groups were exposed to worse air quality [52, 53], and a study of a city in Sweden found that low-income children were exposed to higher levels of NO_2 compared to children from higher-income families [51]. Patterns similar to those seen in New York and Toronto were also seen in the Netherlands, where low-SES groups were exposed to better air quality compared to high-SES groups [52].

Methodological Issues

As described above, results from air pollution inequality studies vary depending on place. The methodological approaches used can also result in differences in findings. Previous authors have discussed how some methodological approaches in such studies can yield higher-quality research while avoiding common limitations [1, 54].

The appropriate unit of analysis and the accompanying modifiable areal unit problem (MAUP) in environmental inequality studies have been discussed [1, 17, 54, 55]. MAUP refers to the situation where using different units of analysis results in contradictory findings. Several scholars advocate for using smaller levels of geography in order to improve reliability and accuracy of the study [1, 54]. Very few studies in this review rely exclusively on larger geographic units such as counties [37], cities [49], or regions within a nation [46]. Most of the studies use something similar to or smaller than a US census tract. A few studies use very small geographic

Table 2 New Zealand, Asian, and African studies of air pollution-SES inequalities

First author, year	Location	Unit of Analysis	SES indicator(s)	Analytic method	Results		
					$PM_{2.5}$	PM_{10}	NO_x
Fan, 2012 [43•]	Hong Kong	Building group	Education, occupation, crowding, income, NSES index	Decile, logistic regression		↓* —**	↓* —**
Kingham, 2007 [39]	Christchurch, NZ	Census area unit	Income, NSES index	Means		↓	
Pearce, 2006 [41]	Christchurch, NZ	Census area units	Income, NSES index	Means, OLS		↓	
Pearce, 2008 [40]	Urban areas NZ	Census area unit	Income, NSES index	OLS		↓	
Rooney, 2012 [42•]	Accra, Ghana	Household	NSES index	RE accounting for temporal and spatial autocorrelation	↓	↓	

Location: *NZ* New Zealand; SES indicators: *NSES* index neighborhood SES/deprivation index; analytic method: *OLS* ordinary least squares regression, *RE* random effects/hierarchical model; results: ↓ higher-SES areas/groups associated with lower pollutant concentrations, ↑ higher-SES areas/groups associated with higher pollutant concentrations, — null association, * private housing only, ** public housing only

areas such as parcel data [31], building of residence [51], or British postcode (mean of 14 households) [44].

Some statistical methods used in environmental inequality research may produce biased findings [1, 5]. Although a variety of methods are used to evaluate inequality, many researchers use a regression-based approach to quantify the magnitude and direction of the inequality. In the studies reviewed here, air pollution is the outcome or dependent variable. Ordinary least squares (OLS) regression (i.e., linear regression) assumes that outcomes are independent. Since air pollution often displays a pattern of spatial autocorrelation, it is important to evaluate spatial autocorrelation and use a spatial analytic technique if autocorrelation is present. This will ensure that the independence of observations assumption is not violated.

Many of the studies reviewed do use a spatial regression approach to evaluate the association between SES and air pollution: both spatial generalized additive models (GAM) and spatial autoregressive (SAR) models (i.e., spatial lag or spatial error models) were popular choices. In addition, a few papers used a hierarchical or random effects model that accounted for between neighborhood correlations [26, 44] and, in some cases, specified a spatial covariance structure [42•, 56]. A few studies use both spatial and aspatial approaches to underscore differences across models and find that parameter estimates from OLS models tend to overestimate the magnitude of effect compared to spatial approaches (i.e., GAMs or SAR) [28•, 30, 45, 57]. One study compared aspatial multilevel models to a spatial approach and found little difference between the two [28•]. Unfortunately, among studies using regression methods, many do not use methods that account for the clustering of air pollutants across space [11, 26, 29, 32, 35–38, 43•, 44, 46, 49, 50, 52, 58, 59]. Furthermore, these same studies do not report the degree of autocorrelation present in the data, so it is unclear if their choice of model is justified.

Regardless of the use of spatial or aspatial regression approaches for addressing autocorrelation, the issue of adjusting for additional confounders is an important one. It seems plausible that factors such as population density and land use could be important confounders of the air pollution-SES association. However, only a few studies adjust for potential confounders [11, 27, 28•, 35, 40, 42•, 52], leaving parameter estimates subject to bias. The amount of bias will depend on the number and strength of the confounders adjusted for. In the few studies that provide data for both adjusted and unadjusted models, it appears that controlling for several confounders attenuates the parameter estimates [28•, 52]. We recognize that confounders may be specific to the study population at hand; thus, future research should explore this issue on a case-by-case basis. Exploring the possibility of potential confounders may result in future environmental inequality studies that provide a less-biased measure of the magnitude of effect.

A related issue pertains to whether air pollution inequality studies pool data (or combine effect estimates) across locations or conduct stratified analyses. A few papers reviewed here provide examples of pooling data within the context of a single study, and all show that pooled analyses tend to mask potentially important patterns found in stratified models [28•, 46, 52, 57]. For example, data from an English study show that in the cities of Leeds and London, PM_{10} and NO_2 concentrations increase as SES declines, whereas the association is similar for SES groups in Liverpool and Bristol [52]. These patterns were masked in the country-wide analyses. Understanding the locality-specific patterns will be relevant for policy makers and those considering interventions to reduce the health effects of air pollution.

A few studies have begun using inequality metrics such as the concentration index, Atkinson index, and the slope index of inequality to quantify the inequality present in the data [12••, 13, 53, 60, 61]. These metrics were first developed by econometricians to assess inequality in income across populations but have since been applied to health and environmental studies [62–64]. Inequality metrics are useful in order to directly compare inequality across groups but may also be useful in assessing high-risk individuals within a population of interest.

Table 3 European studies of air pollution-SES inequalities

First author, year	Location	Unit of analysis	SES indicator(s)	Analytic method	Results					
					O_3	PM_{10}	CO	NO_2	NO_x	SO_2
Branis, 2012 [49]	Czech Republic	City (*n*=39)	Education, unemployment rate, income	PCA of SES indicators and air pollution variables		↓*		↑**		↓*
Briggs, 2008 [47]	England	Neighborhood (SOA), wards, districts	NSES index, domains of index (income, education, employment)	GAM	↑↓[a]	↑↓[a]			↑↓[a]	↑↓[a]
Chaix, 2006 [51]	Malmo, Sweden	Individual and neighborhood	Income	Spatial scan statistic, RE				↓		
Fecht, 2015 [52]	England, Netherlands	Neighborhood (lower SOA, buurt)	Income	OLS		↑↓[b]		↑↓[b]		
Fernandez-Somoano, 2014 [50]	Northern Spain	Individual	Education, occupation	OLS				–		
Goodman, 2011 [44]	London, England	Individual, postcode (mean 14 households), neighborhood (SOA)	Individual level: education, income, Post-code level: lifestyle/consumer index, SOA level: NSES index	RE					↑↓[a,b]~	
Havard, 2009 [45]	Strasbourg, France	Census block	NSES index	OLS, SAR				↓~		
Padilla, 2014 [48]	Four French cities	Census block	Education, occupation, income indicators, NSES index	GAM				↑↓[a,b]		
Pearce, 2010 [53]	United Kingdom	Wards	Income	Means, slope index of inequality		↓	↓	↓		↓
Richardson, 2013 [46]	21 European countries	Region	Income	Means, CC		↑↓[b] ~				

Unit of analysis: *SOA* super output areas; SES indicators: *NSES index* neighborhood SES index/neighborhood deprivation index; Analytic method: *PCA* principal component analysis, *OLS* ordinary least squares regression, *SAR* spatial autoregressive models, *GAM* generalized additive model, *RE* random effects/hierarchical model, *CC* correlation coefficients; results: ↓ higher-SES areas/groups/individuals associated with lower pollutant concentrations, ↑ higher-SES areas/groups/individuals associated with higher pollutant concentrations, ↑↓ mixed association—both positive, negative and null associations were found, ~ non-linear association, * small cities only, ** large cities only, – null association

[a] Association was dependent on which SES variable was used

[b] Association dependent on unit of analysis and country (e.g., England vs Netherlands, city-specific vs nationwide, postcode vs individual)

Furthermore, these metrics show much promise in quantifying inequality across time, e.g., before and after a policy is implemented [10••]. The studies using inequality metrics in this review were all cross-sectional in nature. We hope that future studies will apply these metrics to health effects studies to better understand if inequality in the distribution of air pollution is related to environmental health disparities.

Overall, air pollution inequality studies have become more analytically sophisticated over time. Given the important policy ramifications of this work, this is a welcomed development.

Air Pollution Exposure Assessment

Air pollution exposure assessment has evolved over the past several decades. The move from between-city to within-city estimation has allowed for a reduction in measurement error and the identification of significant variability of air pollution within small geographic areas [65]. The ability to predict air pollution at fine spatial resolution may also be useful for explaining the mixed results seen previously. That is, the ability to incorporate fine-scale variability in air pollution across space may allow researchers to unmask some of the homogeneity seen in past studies, creating a more nuanced picture of the air pollution-SES association. Furthermore, the advances in exposure assessment may also help us better understand the differing patterns of SES by pollutant, i.e., O_3 vs NO_2, which have different spatial distributions.

Most of the studies reviewed here used either dispersion models, land use regression (LUR) models, or a hybrid approach which combines a variety of techniques such as LUR and geostatistical interpolation (e.g., kriging) to predict air pollution at unmeasured locations (all except [29, 35, 37, 49]. Very few studies use proximity-based or proximity-weighted approaches [29, 35, 37, 47, 49, 53]. In most cases where these approaches were taken, collecting additional data was not feasible because these studies were interested in providing an assessment of air pollution inequality for the entire nation.

A particularly interesting exposure assessment approach was implemented in Ghana. In light of the lack of government air pollution monitoring in Ghana, the authors undertook an extensive mobile monitoring campaign coupled with the placement of several fixed site monitors and a census of wood and charcoal stoves along the mobile monitoring route. These data were combined to produce detailed exposure maps which showed significant spatial variability both within and between the neighborhoods under study [42•, 66]. Such extensive efforts may be required to characterize inequality in less-industrialized nations where routine ambient air quality monitoring is lacking.

Some studies looked at specific sources of air pollution (e.g., road versus industrial) [11, 33, 58] or components of a more complex mixture [29]. Source-specific studies may guide regulations and other interventions which may have a more direct impact on reducing air pollution inequalities.

SES Measures

SES is a complex construct that has been operationalized with a variety of different measures, including income, education, and occupation [67]. SES measures take different forms in less-industrialized countries where housing type, water and electricity access, and assets in the form of cattle and televisions are often used [68]. In terms of area-level measures of SES, the British have led the way in articulating the need for a deprivation index, an index composed of several individual metrics to measure a relative lack of resources along several dimensions (social, material) [69].

Many authors agree that using only one indicator of SES (e.g., income) may not sufficiently capture the broader construct of SES. For example, some US health studies ask one question on income or education and assume that item sufficiently measures (with minimal measurement error) this relatively complex construct. However, it is also widely acknowledged that indicators of SES tend to be highly correlated, and thus, using multiple measures within a single model is not recommended. SES indices based on principal components analysis or a similar dimension reduction technique are intended to address this issue. Fourteen studies in this review use some sort of SES index [26, 28•, 38–41, 42•, 43•, 44, 45, 47, 48, 56, 59]. As a part of the nationwide multidomain deprivation index, a few studies from the UK used several indicators such as number of families receiving income support or some other means-tested benefit offered by the government to better capture the concept of income deprivation [70]. To date, only air pollution inequality studies from Canada have not embraced the use of an SES index.

Another important methodological issue with implications for health effects studies is the use of both individual- and area-level SES metrics. To better understand the role of SES as a confounder of the air pollution-health association, data at both individual and area levels are needed. Only a few studies have included both levels of data [28•, 44, 51], and all have found stronger associations with air pollution for area/neighborhood-level SES compared to individual-level SES. Because of the relatively limited knowledge based on how both levels may singly and/or jointly influence air pollution exposures and associated health outcomes and because preventive interventions often differ by level, future studies should evaluate the role of both individual- and area-level SES metrics in their specific populations.

Conclusions

Much, but not all, of the environmental inequality literature from North America, NZ, Asia, and Africa, to date, has shown that low-SES communities face higher concentrations of criteria air pollutants. The European research, on the other hand, is quite mixed. Some studies found that SES was positively associated with air pollution, while others found a negative association, and still, others found patterns suggesting similar levels regardless of social class. These results suggest the need for further, more rigorous examination of the air pollution-SES association in Europe. Overall, there is a paucity of environmental inequality research from nations outside the USA, but the concepts of EJ and inequality are taking hold around the world, and we anticipate more research in years to come. In particular, rapidly developing nations like India and China are understudied assessing if economic development distributes air pollution unequally across these population may have sizeable impacts for population health.

Although several methodological advances in this body of research have occurred, future researchers may want to consider some methodological areas of particular importance. First, understanding the spatial structure of the air pollution data is a critical first step in choosing an analytic approach. Secondly, researchers may want to explore the possibility of confounders of the air pollution-SES association. Methodological improvements in both these areas will provide more accurate point estimates and standard errors.

Environmental inequality research has implications for health effects analyses. First, it is important for health researchers to know if individual- and/or area-level SES confounds the air pollution-health outcome association. SES, like air pollution, can be highly variable from place to place, and researchers should carefully consider what it represents in the context of health studies. Environmental inequality studies can provide an in-depth look at one piece of the confounding triangle, but only if both individual- and area-level SESs are explored. Few studies, to date, have tackled this question [28•, 44, 51].

More importantly, the question of whether differential exposure to air pollution is driving environmental health disparities is relevant from a regulatory and public health perspective. In the USA, evidence supports that many (but not all) low-SES communities bear a disproportionate burden of air pollution. For these communities, it is plausible that differential exposure to air pollution may be a contributor to higher associations between air pollution and health than seen in better-off populations. In some European studies, however, higher air pollution concentrations were found among higher-SES populations, but the health effects of air pollution were still distributed disproportionately among the poor [71–74]. The observation that communities where high-SES groups live have higher concentrations of air pollution does not necessarily mean that the residents are more exposed. High-SES individuals have access to more resources that can protect them from increased exposure, such as private transportation versus public, indoor versus outdoor work environments, better constructed housing and, potentially, access to climate control, including filtration, for indoor environments [71, 75]. Alternatively, environmental health disparities in Europe could be driven by other environmental hazards, such as noise, second-hand smoke, or other work- or housing-related indicators, many of which are also linked to the social environment and disproportionately impact the poor [19]. Additional research into the social distribution of air pollution in Europe will require a rigorous, area-specific approach to shed light on what is likely to be a quite nuanced reality.

Understanding how environmental inequality is created may help explain air pollution and inequality research and has implications for policy. It has been hypothesized that low-SES communities with limited political power and influence are unable to stop locally undesirably land uses (LULU), such as factories and roads, from being built in their communities. That is, poor communities lack social capital, a necessary prerequisite for mounting an effective campaign against placing a LULU in one's community. On the other hand, it has been suggested that industry is motivated solely by economic factors: building a LULU on cheap land is economically prudent. The presence of a LULU will then result in the decline in property values which makes an area more accessible for low-SES and minority populations [6, 76]. Both of these theories point to the importance of class- and race-based residential segregation in creating inequality in air pollution concentrations across space. It should be noted that much of the research about causes of environmental inequalities has focused on the US context. Given the importance of historical, economic, and social contexts in understanding inequality, other nations may have very different explanations for why environmental inequalities exist.

One strength of the environmental inequality literature as reviewed here is its truly interdisciplinary nature. Researchers from a diverse set of fields bring their own tools and lenses to the question of inequality, making this body of research primed for innovation. In the studies reviewed here, authors were from a wide array of disciplines including the following: geography, sociology, economics, epidemiology, urban studies, environmental health sciences, environmental studies, and civil engineering.

Several open research areas and knowledge gaps exist. First, very few studies have examined changes in inequality over time [37, 48]. Since levels of air pollution have declined over time, particularly in North America, it is of interest to understand if the unequal distribution of air pollution is widening or narrowing. Specifically, as air pollution policies and regulations (both related and unrelated to inequality) are put into place, it is important to understand if these policies impact inequality. Another policy-relevant issue is that of which sources or components are most unequally distributed. Although a few studies have begun to examine this question, inequalities may be driven by local sources of pollution, thus necessitating more research. Finally, although this review did not specifically address race/ethnicity, understanding how these factors relate to socioeconomic factors in terms of location-based variability in air pollution concentrations is important for EJ.

Research that pursues these and other questions that directly inform policy changes to enhance environmental quality and health equity is essential in continuing global efforts to improve health and provide safe environments for all.

Compliance with Ethics Guidelines

Conflict of Interest Anjum Hajat, Charlene Hsia, and Marie S. O'Neill declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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