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Konrad-Zuse-Strasse 1 · D-18057 Rostock · Germany · Tel +49 (0) 3 81 20 81 - 0 · Fax +49 (0) 3 81 20 81 - 202 · www.demogr.mpg.de

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Poor air at school and educational inequalities by family socioeconomic status

Fabrizio Bernardi
Risto Conte Keivabu | contekeivabu@demogr.mpg.de

This working paper has been approved for release by: Emilio Zagheni (sekzagheni@demogr.mpg.de),
Head of the Laboratories of Migration and Mobility and Population Dynamics and Sustainable Well-Being.

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Fabrizio Bernardi,
Universidad Nacional de Educación a Distancia (UNED), email: fbernardi@poli.uned.es

Risto Conte Keivabu
Max Planck Institute for Demographic Research, email: contekeivabu@demogr.mpg.de

Abstract

In this paper we study social stratification in the impact of poor air quality on educational achievement. We address two main questions. First, are students from socioeconomically disadvantaged families more likely to attend schools with poor air quality? Second, is the effect of bad air quality for school results the same for children from high and low socioeconomic status families? We use a novel data set with test scores in math and reading for 456,508 students in 8th grade in a test administered nationally in Italy in 2019. We geocode the location of 6,882 schools based on their addresses and link the level of air pollution of the area around the school, using data on fine particulate matter provided by the Atmospheric Composition Analysis Group. To deal with possible confounders we use municipality fixed effects and control for an indicator of the characteristics of the school neighbourhood, using administrative fiscal data of the real estate values of the area around the school. We have three main findings. First, there is no SES gradient in the exposure to poor air at school. Second, we find a small but robust negative effect of particulate matter 2.5 (PM2.5) on test scores in math but not in reading. Third, this effect is mostly concentrated among low SES students. Conversely, high SES students are largely unaffected by exposure to poor air quality at school. We conclude that exposure to air pollution can exacerbate inequalities in education and the intergenerational transmission of disadvantage.

1. Introduction

There is a large body of evidence showing that exposure to air pollution negatively affects health, and children are more sensitive to air pollution exposure than adults due to several biological differences (Grineski, Collins and Adkins 2020, WHO 2018). Previous studies have also shown that there is a negative effect of exposure to poor air quality at school on children's educational achievement (Amanzadeh, Vesal and Ardestani 2020, Currie 2013, Requia et al. 2022, Stenson et al. 2021).

The quality of air in the area around a school is important as children spend many hours there and pollutants such fine particulate matter (PM2.5) of outdoor origin infiltrate and persist indoors (Chen and Zhao 2011, Jones et al. 2000, Pallarés et al. 2019). Moreover, it has been shown that high levels of pollution at school impair concentration and attention and thus affect learning during school hours (Gignac et al. 2021) and test performance (Amanzadeh, Vesal and Ardestani 2020). Similarly, poor air quality has a negative effect on school attendance (Currie et al. 2009) which can decrease children's learning trajectories during the school term (Passaretta and Skopek 2021). If evidence of a negative effect of poor air quality at school on educational outcomes is well established in the literature, only in a few studies has attention been paid to the impact of poor air at school on educational inequalities by parental socioeconomic status (SES) (Sunyer et al. 2015, Wen and Burke 2022).

From a social stratification perspective, the key question in this respect is whether the negative effect of exposure to poor air quality in the school surroundings contributes to educational inequalities arising from parental SES. This question can then be separated into two sub-questions that refer to the risk of exposure and heterogeneity in the effect of exposure on educational achievement: are low SES students more likely to attend schools in neighborhoods with poorer air quality? And second, is the negative effect of exposure to poor air quality on educational achievement the same for high and low SES children or, conversely, are high SES students more sheltered from the negative effect of exposure to poor air quality at school?

In order to address these questions, we use a unique data set with test scores in math and reading in a test administered nationally in 2019 among all 8th graders in Italy, a high-income country with one of the highest level of air pollution among OECD countries (OECD 2023). A total of 456,508 students are included in 6,882 schools. We geocode school locations based on their addresses and link the level of air pollution of the area around the school, using fine grained (1km x 1km grids) measures of particulate matter 2.5 (PM 2.5) provided by the Atmospheric Composition Analysis Group (ACAG) (Hammer et al. 2020). To deal with possible confounders we use municipality fixed effects and control for an indicator of the characteristics of the school neighborhood, using administrative fiscal data of the real estate values of the area around the school.

In remaining sections of the article, first we discuss the background literature on the effect of exposure to PM2.5 on educational achievement. We then present a conceptual framework based on social stratification literature to study how exposure to PM2.5 can contribute to educational inequalities by SES. We distinguish between *differences in exposure* and *heterogeneity in the effect* of exposure by parental SES. We discuss how differences in *sensitivity* and *parental responses* might account for a stronger impact of poor air quality on the educational achievement of low SES students. We then explain our research design and identification strategy, before presenting the data and methods used in the empirical analyses and our main findings. Finally, we discuss our findings and provide some concluding remarks.

2. Air pollution and educational achievement

Abundant academic evidence exists on the negative effect of air pollution on children's health and cognitive abilities. Importantly, these consequences of climate change pose challenges to children's educational performance. The existing studies relate the association between air quality and educational achievement to direct and indirect effects.

Direct effects of air pollution on educational achievement strictly refer to the impact of air quality on cognitive performance and development. The dimensions of cognitive abilities affected by air pollution are several. For example, studies have found PM2.5 to hinder the development of working memory (Alvarez-Pedrerol et al. 2017), to determine differences in brain structure (Cserbik et al. 2020), to reduce pattern construction (Milojevic et al. 2021), while one study documented air pollution as mediating the impact of neighborhood poverty on child cognitive development (Wodtke et al. 2022). Similarly, students attending schools located in the proximity of industrial facilities, power plants and highways have a higher risk of neurological diseases (Kweon et al. 2018, Zhang et al. 2022) and lower test scores (Persico and Venator 2019). These studies highlight how both short-term increases in air pollution, and long-term exposure to toxic air, affect cognitive abilities. In fact, a study in Iran showed how short-term increases in air pollution decreased test performance in math and reading (Amanzadeh, Vesal and Ardestani 2020). Conversely, studies in the United States showed how chronic exposure to low air quality during the school year is associated with worse test performance (Grineski, Collins and Adkins 2020, Mullen et al. 2020).

Indirect effects of air quality on educational achievement relate to decreases in school attendance or sleep quality. Air pollution increases the severity of several respiratory diseases such as asthma (Alotaibi et al. 2019) and worsens lung functioning (Barone-Adesi et al. 2015) increasing the number of school-days lost by students (Currie et al. 2009, Marcon et al. 2014). Moreover, air pollution can have a negative impact on sleep quality reducing the cognitive performance of children (Heyes and Zhu 2019). Based on these pathways, we can expect air quality to be particularly consequential for educational achievement.

3. Analytical framework: differential exposure and heterogeneity of the effect of exposure by parental SES

The key question we intend to address in our analysis is whether the adverse effect of exposure to poor air quality for academic achievement documented by environmental, epidemiological and social science studies reviewed in the previous sections, contributes to the making of family inequalities in academic achievement.[i] To address this question, we employ an analytical framework used in social stratification and in life course studies that distinguishes between differences in *exposure* to a given stressor by parental SES and *heterogeneity* in the consequences associated with exposure by parental SES. This framework has been used to investigate the impact of a broad range of stressors on later educational and socioeconomic outcomes (Bernardi and Boertien 2017, Brady, Finningan and Hübgen 2017, Hogendoorn, Leopold and Bol 2020, Torche 2018). For the purpose of this paper we distinguish between *differential exposure* to poor air quality by SES and *heterogeneity* in the effect of exposure on school results by parental SES. With regard to the latter, we also suggest two mechanisms that might account for a more detrimental effect for low SES students: differential sensitivity and differential parental responses.

3.1 Differential exposure

We would observe differences in exposure if students from high SES families attended schools with a better air quality. That might happen if high SES parents choose schools taking into consideration the quality of the air at school or other characteristics of the schools that happen to be correlated to air quality. For instance, parents might choose a school with better and modern facilities located outside the city center, closer to green areas and, therefore, with better air quality. Differential exposure might also occur if high SES families live in neighborhoods with better air quality and bring their children to the school in proximity to their household. In the case of Italy, such scenarios are unlikely for three reasons.

First, SES residential segregation is much lower in Europe compared to the United States (US) (Andersson, Lyngstad and Sleutjes 2018, Friedrichs, Galster and Musterd 2003). In particular, in Italy high SES families often live in city centers and close to busy roads that are often the most polluted areas, as for example shown for Rome and Milan (Cesaroni et al. 2010, Tammaru et al. 2020). Second, children generally attend primary and lower secondary schools in the neighborhood where they live or close by. For example, a study on the cities of Bologna and Milan showed that children live on average at about 1.2 km from the school they attend (Mantovani, Gasperoni and Santangelo 2022). Third, until very recently, little was known about differences in air quality among schools. Information about school air quality is now becoming available and public concern and consciousness about the problem is likely to grow accordingly.[ii] However, we can exclude that parents of the children included in our analysis had access to any type of school rankings based on air quality as this information was not available. Consequently, we consider self-selection into schools due to their air quality to not be a concern for out study.

3.2 Differential sensitivity

Pre-existing conditions can make some children more vulnerable to the exposure to polluted air. As previously stated, poor air quality is particularly detrimental for children suffering from respiratory conditions such as asthma, as it can worsen existing health deficiencies (Guarnieri and Balmes 2014). What is relevant for our study is that the available evidence, mostly for the United States, suggests that children and adolescents from low SES families are more likely to suffer from asthma and have a lower respiratory function (Kozyrskyj et al. 2010, Kuruvilla et al. 2019, Rocha et al. 2019). Low SES students might then be more susceptible to the negative effect of exposure to air pollution, since chronic respiratory conditions are more prevalent among them (Gong et al. 2014). Similarly, studies have depicted air quality to be more consequential for school absences of low SES students (Conte Keivabu and Rüttenauer 2022). Thus in the Italian case we can expect that low SES children[iii] would be more likely to lose school days and have impaired concentration and attention for learning if subject to poor air conditions.

3.3 Differential parental responses

Parental responses to exposure to poor air at schools can come about in two ways. First, even if parents do not know the level of air pollution at school, they are likely to be more aware of the importance of good air for their children's development and health and organize their free time to enjoy less polluted environments. For example, a study in China showed that parents refrain from sending their children to preschool in polluted environments (Zhang 2022). Also, when provided with information on air quality, individuals are seen to change their behavior relating to free time (Yoo 2021). Considering the stratification of avoidance behavior as a mechanism, high SES families can enroll their children in extra-curricular activities in areas of the city with good air quality and spend more time during weekends and holidays in green areas. Alternatively, they could seek medical care more often if their child has an existing respiratory condition, such as asthma (Stingone and Claudio 2006).

Second, parental responses can be directed to school outcomes in order to compensate for low performance related to health issues triggered by poor air. More precisely, in the case of high school absences and of low educational achievement, parents can help their children with their homework and compensate for the disadvantages in learning that are associated with pollution at school (Bernardi and Graetz 2015).

3.4 Summary and hypotheses

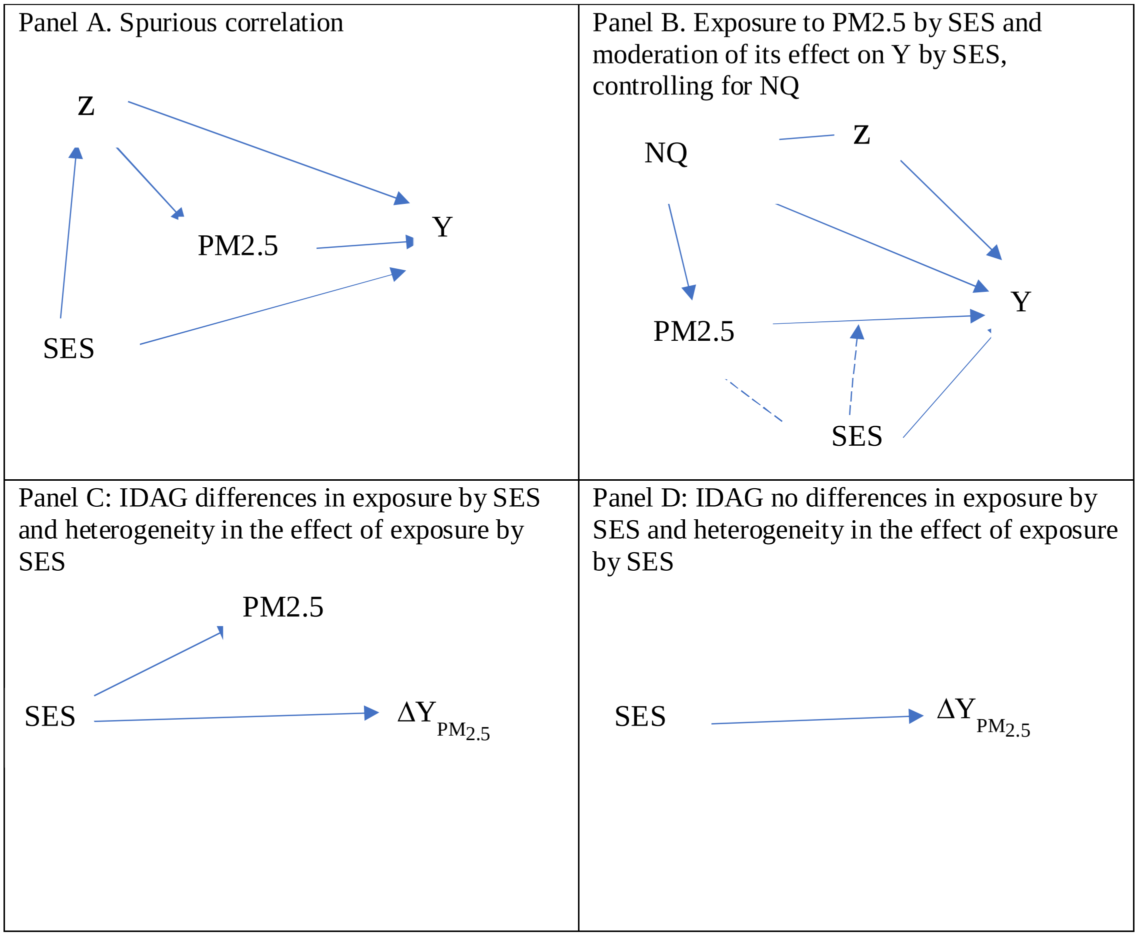
Given the relatively low level of residential segregation, the tendency of high SES families to live in the center of large cities,[iv] school regulations that favor enrolment in schools in the neighborhood of residence, and the lack of public information on the quality of air in Italian schools, we do not expect to find any socioeconomic gradient in the exposure to poor air quality at school (Hypothesis 1).

At the same time, differential sensitivity and different parental responses are mechanisms that would bring about a more detrimental effect of exposure to poor air pollution for low SES students. These mechanisms are not exclusive or alternative and might actually operate in combination. While we cannot test them in this article, we discuss them to formulate the expectation that the effect of poor air will be stronger among students of socioeconomically disadvantaged families (Hypothesis 2).

4. Research design

To illustrate our research design, we present a series of graphs and directed acyclic graphs (DAGs) that represent the effect we want to estimate and the identification problems we face. In the DAG in panel A of figure 1, we have PM2.5 and family SES that have an effect on educational achievement Y. A major concern is for the effect of PM2.5 on Y to be confounded by another factor Z. For instance, it could be that PM2.5 at school only reflects whether the school is located in a urban/rural context. Within the same city the level of PM2.5 might also capture the quality of neighborhood where the school is located. For example, it could measure the absence of crime, affluency of the residents or presence of institutions that favour learning, such as public libraries. The observed effect of air pollution on school achievement could then be spurious and capture the effect of other factors correlated to air quality.

Figure 1. Directed acyclic graphs (DAGs) and directed acyclic graphs for interactions (IDAGs) for different patterns of relationship between SES, exposure to PM2.5 and results in test scores (Y)



Notes: Y= test scores; SES= family socio economic status; PM2.5= fine particulate matter; Z= unobserved factors such as crime or presence of institutions that foster learning; NQ = neighborhood quality; $\Delta Y_{PM2.5=}$variation in the effect of PM2.5 on Y

To deal with these possible biases we employ two strategies. First, in our analysis we employ municipality fixed effects and compare the effect of PM2.5 on school achievement for schools within the same municipality. Second, in our analysis we control for an indicator that directly measures the quality of the school neighborhood (NQ) (more information on the precise indicator used is given in the next section).

The graph in panel B illustrates the effects we aim to estimate in our analyses. First, there is the effect of SES on exposure to PM2.5 and the moderating effect of SES on the effect of PM2.5 on Y, expressed by the dotted arrow from SES to the arrow connecting PM2.5 to Y. By controlling for NQ we block a possible backdoor association between PM2.5 and Y. Formally, this graph is not a DAG and the dotted line is meaningless in a DAG framework. However, the figure in panel B graphically represents the idea of mediation of the effect of PM2.5 and moderation by SES at the core of our study.

Panel C and D present IDAGs, a recent proposal to depict interactions (the I in the IDAG acronym) within a DAG framework (Nilsson et al. 2021). In panel C, SES has an effect on PM2.5 and also produces a variation in the effect of PM2.5 on Y ($\Delta Y_{PM2.5}$). The arrow that goes from SES to $\Delta Y_{PM2.5}$ thus represents the interaction between SES and PM2.5. In panel D, accordingly, there is no effect of SES on PM2.5, and therefore no mediation of PM2.5 on SES inequalities in educational achievement. However, there is a moderation effect of SES on the effect of PM2.5 on Y ($\Delta Y_{PM2.5}$), in line with hypotheses 1 and 2 proposed at the end of the previous section.

5. Data, variables and methods

We use administrative data provided by the Italian National Institute for the Evaluation of Education (INVALSI) for 8th graders (ending lower secondary education) for the year 2019, amounting to 456,508 students and 6,882 schools.[v] We geocode the location of the schools based on their postal addresses, using data provided by the Italian Ministry of Education. We then link school-level data on the levels of air pollution and quality of the neighborhood with the INVALSI data.

Our dependent variables are test scores in standardized tests in math and language. These scores are standardized to have a mean of 200 and standard deviation of about 38, with a range from 66 to 366 in the case of math, and 35 to 364 for reading. Our key independent variable is parental socioeconomic status that is measured by the Economic, Social and Cultural Status (ESCS) index provided by INVALSI. This index is computed following international standards[vi] and combines into a single score different measures of resources that are available to the students (Avvisati 2020). The index is standardized with mean 0, standard deviation equal to one, a range from approximately minus 3 to 2. In the analysis we use alternatively a linear specification or quintiles.

With regard to the *level of air pollution* at school we use estimates of PM2.5 provided by the ACAG (Hammer et al. 2020). The ACAG provides data on PM2.5 at 1km x 1km resolution computed using a combination of satellite observations, *in-situ* monitors, and chemical transport modelling. The data has been shown to present some measurement error in the United States, leading to both overreporting and underreporting compared to local stations (Fowlie, Rubin and Walker 2019). However, full reliability of data from measurement stations is not assured (Zou 2021) and these are not equally present in all the Italian territory. Consequently, the ACAG data appears to be the most reliable data at our disposal. We compute the average yearly exposure to PM2.5 µg/m3 in each 1km x 1km grid and assign the value to the school that corresponds to the grid where it is located. In our analyses we use both measures with linear values in µg/m3 from minimum 4 to a maximum 24, in quintiles (Q1:9.5; Q2:13; Q3:14; Q4:18; Q5:22) and deciles (Q1:8; Q2:11; Q3:12; Q4:13; Q5:14; Q6:16; Q7:17;Q8:19; Q9: 21; Q10:22.6). Note that the World Health Organization (WHO) recently lowered the threshold value for air quality standard from PM2.5 equal to 10 µg/m3 to 5 µg/m3 (Hoffmann et al. 2021). The US standard is 12 µg/m3, while in the European Union (EU) this is much higher, equal to 25, although recently a proposal has been issued by the EU Commission to lower the limit to 10 µg/m3.[vii] This means that the level of pollution in the areas around Italian schools is below the limits recommended by WHO in only about 20 per cent of schools (first quintile) and below or just above US standards in about 40 per cent of schools (first and second quintiles). In other words, a great majority of Italian children attend schools where air pollution exceeds the limit set by the WHO and the US government, as well as that recently proposed by the EU Commission.

We use the average real estate value as an omnibus measure of the quality of the neighborhood where the school is located, as this is common in urban studies (Ware 2017).[viii] We use administrative data on real estate values in the second semester of 2018 provided by the Italian fiscal agency. The polygons of each area vary depending on the location, smaller in large urban centers and bigger in rural areas, and provide the minimum and maximum values of properties in the area measured as the price per square meter. We connect the property value to the school based on the school location within each polygon.

We then measure the real estate value of the neighborhood where the school is located in quintiles, based on the *provincial distribution* of the average real estate value. In Italy there are 107 provinces and large geographical differences in the average cost of real estate. For instance, an average value of 3,000 euros per square meter corresponds to a relatively poor area in Milan, in the north of the country and to a relatively rich area in Alghero in the south. Using the actual real estate value of the neighborhood, or its position in the quintile distribution at the national level, one would primarily measure a North-South gradient in the real estate costs and more generally differences in the wealth levels across different areas of the country.

We also control for gender and whether the parents of the children are Italian nationals or migrants.[ix] In our analysis, we estimate Ordinary Least Square (OLS) regression with municipality fixed effects (FE) (n=4,446) with standard errors clustered at the school level.[x] In this way we compare the effect of PM2.5 on academic achievement within the same municipality. With this research design, we control for differences along the rural/urban dimension and for the overall level of economic development that might affect both the level of pollution and students' achievement. The problem of estimating municipality FE is that about 30 per cent of schools are lost, since there is only one school in small municipalities. As a robustness check we have also estimated province FE (n=107) and the findings (presented in the Appendix) are highly consistent with those based on municipality FE that we present in the text below.

Table 1: Descriptive statistics for the key variables used in the empirical analysis

Variable	Mean	Std. Dev.	Min	Max
Math	200.64	38.19	66.51	366.08
Reading	200.46	36.5	35.2	363.57
ESCS	.04	1	-3.06	2.15
Non-native	.1	.31	0	1
Female	1.49	.5	1	2
PM2.5	15.42	4.38	3.6	23.7
Real Estate Value	1,580.97	896.44	217.5	13,000
Tot. observations	456,508			

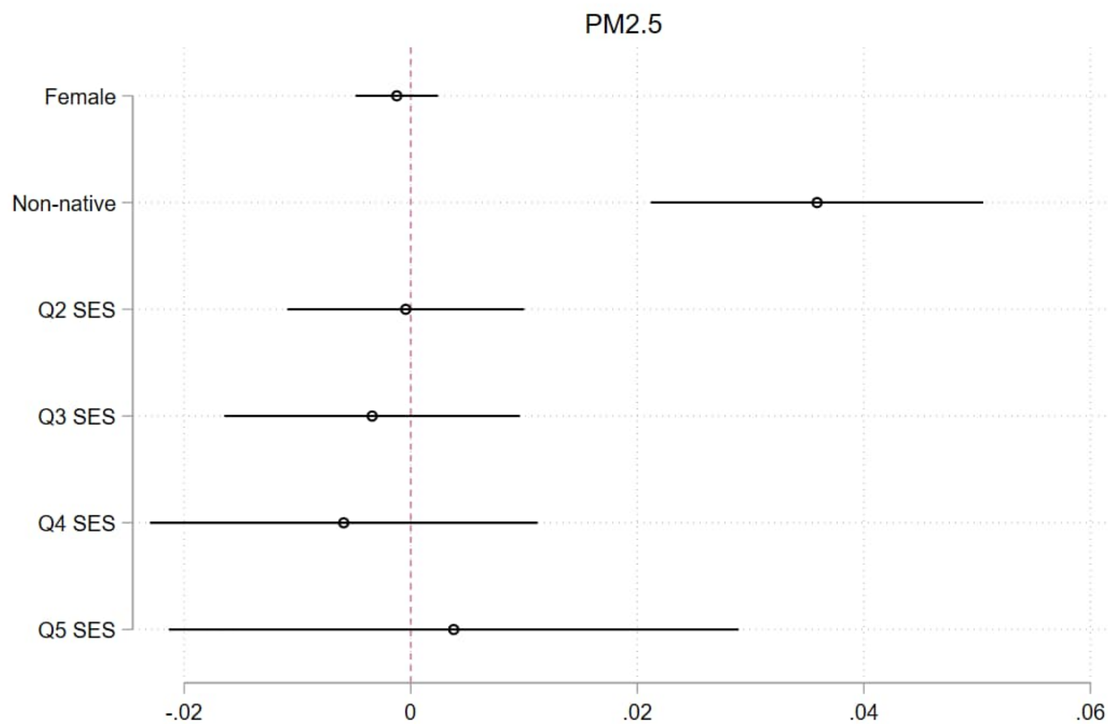
6. Results

In this section we present the results for the analysis of the SES gradient in exposure to poor air at school and discuss the findings of the moderation exerted by family SES on the effect of air quality on educational achievement.

6.1 Do low SES students attend schools with lower air quality?

Figure 2 shows the beta coefficients of an OLS regression with municipality fixed effects where the dependent variable is the average PM2.5 in the area around a school. All coefficients are close to 0, in particular those that refer to the SES quintiles. Considering that PM2.5 varies between about 3.5 and 24, we observe very small variations within municipalities, also when focusing on the effect for students with non-native parents (beta=0.04).

Figure 2. The association between child's characteristics and the level of PM2.5 of the school



Note: Coefficients of an OLS model where the dependent variable is the level of PM2.5 of the school that the child attends, with municipality FE and standard errors clustered at the school level. 95% confidence intervals are displayed.

We therefore find that there are no differences in exposure to poor air quality at school by SES. This result is in line with our expectation that there is no SES gradient in school attendance in more or less polluted areas, given the relatively low level of residential segregation by SES in Italy and Europe, more generally, compared to the United States. In addition to the relatively low level of residential segregation, one has to consider that school regulation in Italy favors enrolment in schools in the neighborhood of residence. Finally, until recently, public information on air quality around Italian schools has not been available, nor has there been a public debate on, and concern regarding, the possible detrimental effect of exposure to polluted air around schools.

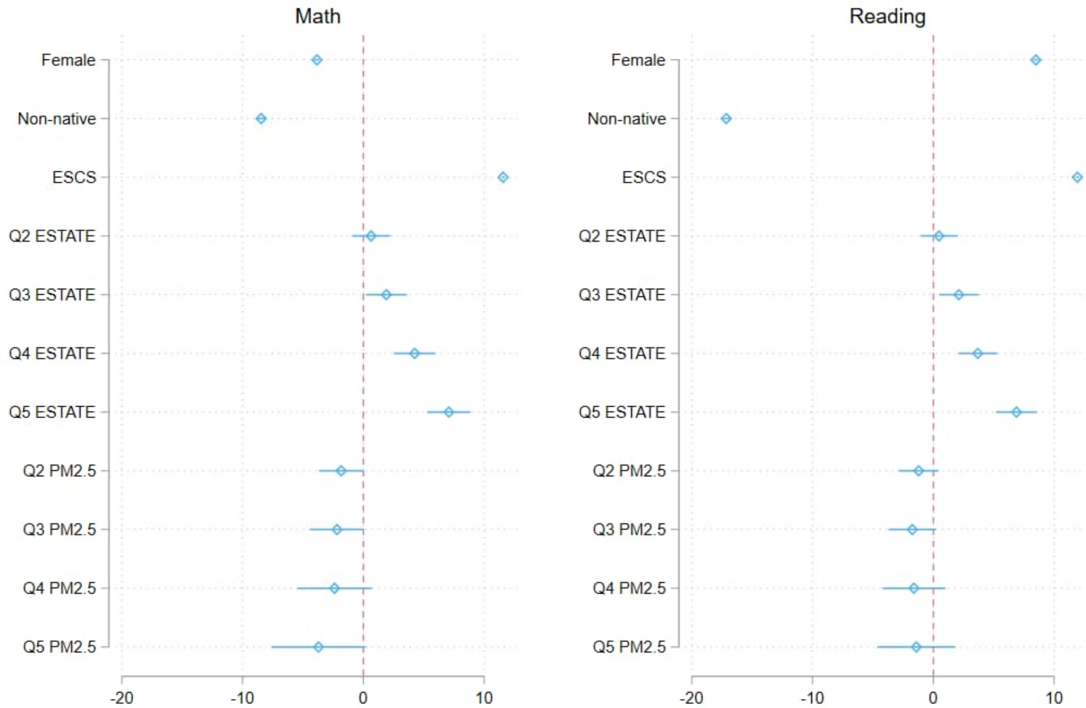
6.2 Does exposure to PM2.5 reduce educational achievement?

Figure 3 presents the beta coefficients of a municipality fixed effect OLS with test scores in reading (panel A) and math (panel B).We focus on the effects of PM2.5, observing that the effects of the other control variables are in line with what is known from previous literature, in particular the different patterns noted in some cases in the results for math and reading.[xi]

In line with previous studies that have documented a negative effect of the level of air pollution on academic achievement, we also find that students attending schools with a higher level of air pollution have a worse performance, in particular in math. Students attending schools with levels of PM2.5 in the fifth quintile perform on average 4 points lower in math test scores. In the linear specification, the beta corresponding to the effect of PM2.5 on math test scores is 0.4 (Appendix: Figure A1) and similar when using province FE (Appendix: Figure A2). Considering that the variation between the observed minimum and maximum values of PM2.5 is about 20 µg/m3, comparing these two extreme values we have a variation in math test scores of 8 points. Since the standard deviation in math test scores is about 38 points, the effect comparing the schools in the most polluted quintile of the distribution with those in the least polluted is about one ninth/one tenth of a standard deviation (4/38), while the effect comparing the highest value of PM2.5 (23 µg/m3) with the lowest (3 µg/m3) is about one fifth of a standard deviation (8/38).

These effects are not extremely large in size but are not trivial either. For instance, the 4-point reduction in math test score observed for students in the most polluted schools of the fifth quintile, is the same size as the observed penalty for girls compared to boys. Similarly, the 8-point reduction for those attending schools with the highest value of PM2.5 compared to those attending schools with the lowest value of PM2.5, are similar in size to the penalty for students with non-native parents. In turn, the effect of exposure to PM2.5 on reading is smaller in size and less precisely estimated.

Figure 3. The effect of children's and neighborhood characteristics on test scores in math and reading

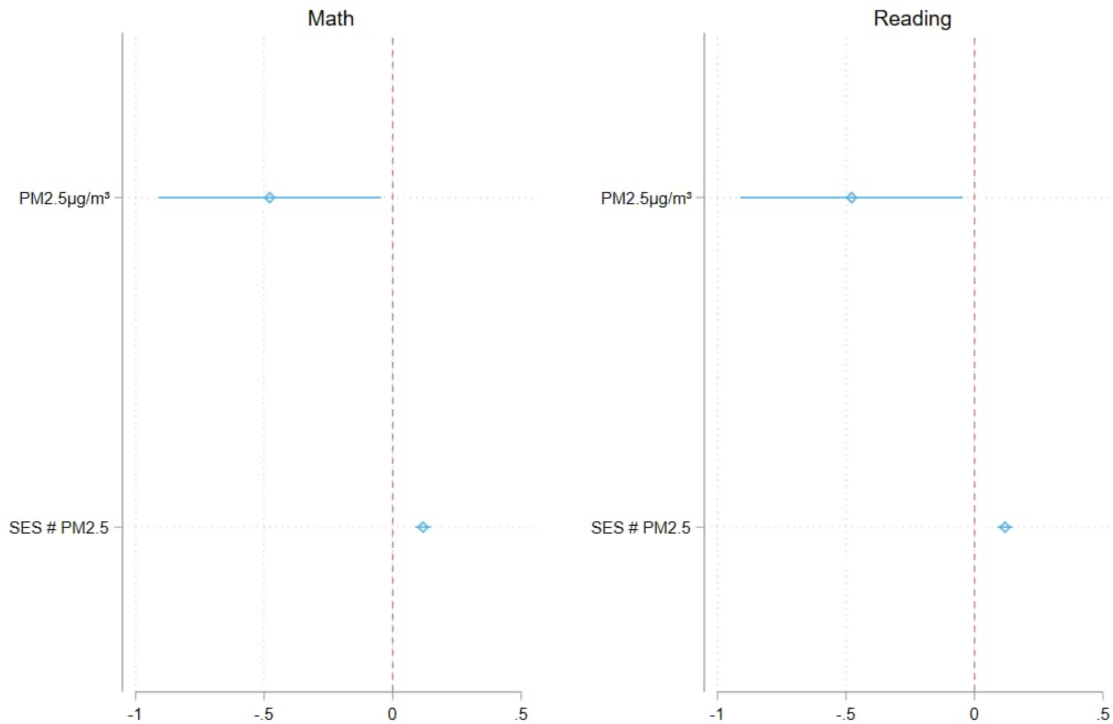


Note: Coefficients of an OLS model where the dependent variable are test scores, with municipality FE and standard errors clustered at the school level. 95% confidence intervals are displayed.
Q# ESTATE is the quintile in the provincial distribution of real estate value of the neighborhood
Q# Pm2.5 is the quintile in the distribution of the PM2.5 values of all schools

6.3 Does family SES moderate the effect of PM2.5 on educational achievement?

In the next step of our analysis, we include an interaction term between PM2.5 and SES. Figure 3 shows the results for the constitutive term of PM2.5 and the interaction between PM2.5 and SES (coefficients reported also in table A1 in the Appendix). In figure 4, the effect for PM2.5 refers to cases with SES equal to 0, namely the average value of SES since it is standardized. The estimate for the interaction SES # PM2.5 indicates that for higher values of SES, the negative effect of PM2.5 on educational achievement is moderated. This result is better visualized in figure 5, where we plot the average marginal effect of PM2.5 for different values of SES (panel A) and the average marginal effect of SES for different values of PM2.5 (panel B) (we replicate results with province FE in figure A3 in the Appendix).

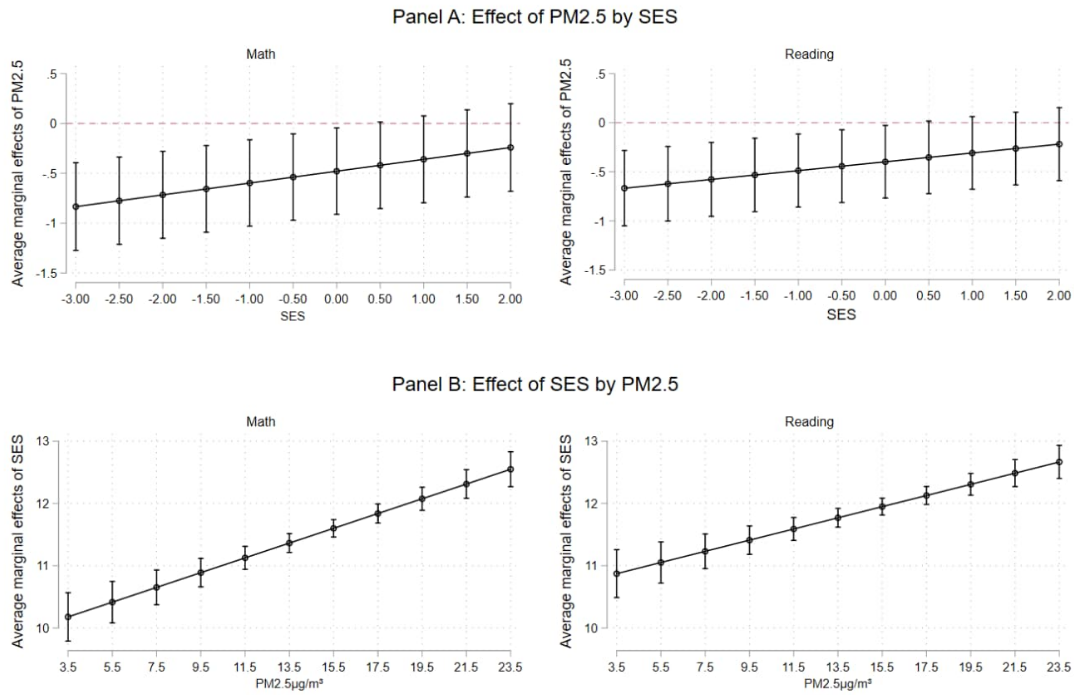
Figure 4. Estimates of the interaction between PM2.5 and SES on test scores in math and reading



Note: Estimates based on OLS models where the dependent variable are test scores with municipality FE and control variables for gender, migration status, real estate value as control and the interaction between SES and PM2.5. The effect corresponding to the constitutive term of SES is not reported in the graph because it is large in size (Beta=9.7) for math and its inclusion jeopardizes the visualization of the effects of PM2.5, but is estimated by the model.

From figure 5, panel A we see that the average marginal effect of PM2.5 is reduced for higher SES levels for both math and reading. For the highest level of SES, the effect of PM2.5 is almost 0. This means that high SES students are largely sheltered against the negative effect of exposure to PM2.5. Conversely, the effect of social background inequalities appears to be larger with higher levels of PM2.5.

Figure 5. Average marginal effect of PM2.5 by SES (panel A) and average marginal effect of SES by PM2.5 (panel B) on test scores in math and reading



Note: Each panel is based on an OLS model where the dependent variable are test scores, with municipality FE and control variables for gender, migration status, real estate value and the interaction between SES and PM2.5. Reported are the average marginal effects of the interaction with 95% confidence intervals.

7. Discussion and conclusion

In this paper we explored how exposure to air pollution affects inequalities in school achievement by parental SES. We first analyzed how the socioeconomic status of children in Italy stratifies exposure to the air pollutant PM2.5 at school. Our findings show that there are no substantial SES differences in the exposure to poor air quality at school. Secondly, we inquired how air quality differently affects math and reading test scores of students based on their SES. We found air pollution to be consequential for test scores and the effect to be largely concentrated among low SES students. Since our outcomes are test scores in low stakes tests, we cannot show whether the negative impact of air pollution has an impact on educational attainment and on later socioeconomic outcomes. We know, however, the results of the tests we have investigated in our study are strongly correlated to later educational transition (Aktaş et al. 2022). Consequently, we can assume that air pollution is a determinant of SES inequalities in educational attainment.

Compared to previous studies, we did not observe SES disparities in the exposure to air pollution at school. Such disparities have been found mainly in the United States (Cheeseman et al. 2022, Grineski and Collins 2018), but similar evidence is lacking for schools in other countries. Additionally, in Europe, studies on the association between neighborhood SES and air pollution has shown mixed results (Fairburn et al. 2019, Hajat, Hsia and O'Neill 2015). For Italy, the absence of an SES gradient in exposure to poor air at school is in line with the findings that residential segregation is lower compared to the US or Northern European countries and high SES individuals tend to live also in city centers that are more likely to have low air quality (Cesaroni et al. 2010, Forastiere et al. 2007).

We observe air pollution to be more consequential for low SES children's math and reading scores. These results are in line with a study in Barcelona (Sunyer et al. 2015) focused on traffic related pollution and with a study on wildfire smoke in the US (Wen and Burke 2022).[xii] We argued that these results can be explained by the higher prevalence of existing cardiorespiratory conditions in low SES children (Jans, Johansson and Nilsson 2018, Rocha et al. 2019) or parental responses that could help compensate for the negative effect of air pollution on high SES children (Bernardi 2014).

This study is not free of limitations and points to promising future avenues of research. First, our measure of air pollution has some limitations as it captures air quality in the year prior but not during the full school year and it can be biased by over- or underreporting (Fowlie, Rubin and Walker 2019). Nevertheless, air pollution has been shown to persist in the same neighborhoods over time (Colmer et al. 2020) making it unlikely for our estimates to change in relative terms. Moreover, fine-grained data provided by measurement stations is not available for the whole territory in Italy but is of increasing availability and could be leveraged in future research. Second, our data are cross-sectional and it would be important to expand our research using longitudinal data and measures of exposure over time. Third, our study focuses on Italy and cannot confidently be generalized to other contexts. However, Italy is a high-income country with high levels of air pollution providing an interesting case that can be considered similar to other urban contexts found in western countries (e.g. Barcelona, London, Madrid or Paris). Finally, we are unable to test the mechanisms underlying the heterogeneity in the effect of air pollution by SES that we have documented. Consequently, future studies could shed light on whether disparities in susceptibility or parental response determine the stratified impact of SES on our results.

To conclude, in this article, we provide evidence on the impact of air pollution on students' test scores and its stratified effect by SES. The result that the negative effect on academic abilities is largely concentrated among low SES students has important policy implications. As air pollution is more consequential for low SES students, policies to improve air quality, in particular at school, contributes to reduce socioeconomic inequalities in educational achievement. In this regard, policies such as congestion charges (Conte Keivabu and Rüttenauer 2022), information on air quality (Yoo 2021), advice from health professionals (Wynes 2022) and better infrastructure (Stankov et al. 2020) are also relevant tools to protect the poorest and reduce socioeconomic background inequalities.

Data availability

The data underlying this article were provided by INVALSI *(*https://www.invalsi.it/invalsi/index.php*)*. Restrictions apply to the availability of the INVALSI data with information of the school attended by the student, which were used under a special licence for this study. Data will be shared on request to the corresponding author only with permission of INVALSI.

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ENDNOTES

[i] Technically this question could be reformulated in terms of whether exposure to poor air quality *mediates* inequalities in achievement by family SES and/or whether family SES *moderates* the effect of exposure to poor air quality at school, so that – for instance – socioeconomic inequalities could be larger in case of exposure to poor air at school.

[ii] For the United Kingdom https://www.theguardian.com/environment/2021/jun/17/quarter-of-uk-pupils-attend-schools-where-air-pollution-is-over-who-limit; for Spain https://elpais.com/clima-y-medio-ambiente/2022-02-13/que-aire-respiran-los-ninos-de-madrid-y-barcelona-en-el-46-de-los-colegios-se-supera-la-contaminacion-permitida.html

We are not aware of similar recent articles in Italian newspapers.

[iii] See Chen, Martin & Matthews (2006) who show that acute respiratory conditions are more prevalent among low SES adolescents.

[iv] That are often the most polluted areas due to traffic congestion.

[v] From 2018, the test is computer-based to minimize the risk of cheating and better capture of cognitive abilities. It is compulsory for all students and in 2019 took place between 1 and 18 April. The test does not contribute to the final grade of graduation from middle school but attendance is a requirement to be able to sit the final exam that takes place in summer.

[vi] The ESCS score is based on the similar score defined by the OECD and used for the PISA test scores.

[vii] For the current EU limit value of PM2.5 set at 10µg/m3 see: https://environment.ec.europa.eu/topics/air/air-quality/eu-air-quality-standards_en. In October 2022 the European Commission published a proposal to reduce the limit value for PM2.5 to 10µg/m3, which is still double the limit suggested by WHO.

viii In doing this, we follow recent proposals in urban studies. For instance: “Residences on the high end of the property value distribution are likely proximate to valued goods, services, and social networks that provide access to material resources, knowledge, and skills. Conversely, properties with low values are more likely to be in high-crime neighborhoods.” (Ware 2017).

[ix] Since non-native families are concentrated in the low part of the SES distribution, and migrants might attend schools with worse air quality, it is important to control for this variable to avoid that the effect of family SES on exposure to PM2.5 captures the effect of being non-native. There is no proper reason for the inclusion of gender as a control for our identification of the mediating and moderating effect of family SES. If we exclude gender and immigrant status from our models, the results are virtually unchanged. Results available upon request.

[x] Estimating the municipality fixed effects model is feasible because there is variation in PM2.5 across schools within the same municipality. For instance, in the municipality of Venice the lowest level of PM2.5 is 14µg/m3 and the highest is 20.8µg/m3.

[xi] We observe a penalty in math and advantage for girls in reading: (Hyde and Mertz 2009). The penalty for students of non-native parents is larger in reading than in math, as would be expected as they are less likely to speak Italian at home (Wang 2021). As expected, the effect of the quality of the neighborhood is positive both on math and reading score (Vinopal and Morrissey 2020).

[xii] The results for the wildfire smoke showed to be more consequential also in high SES neighborhoods, but with a low prevalence of White students.

Appendix

Tables

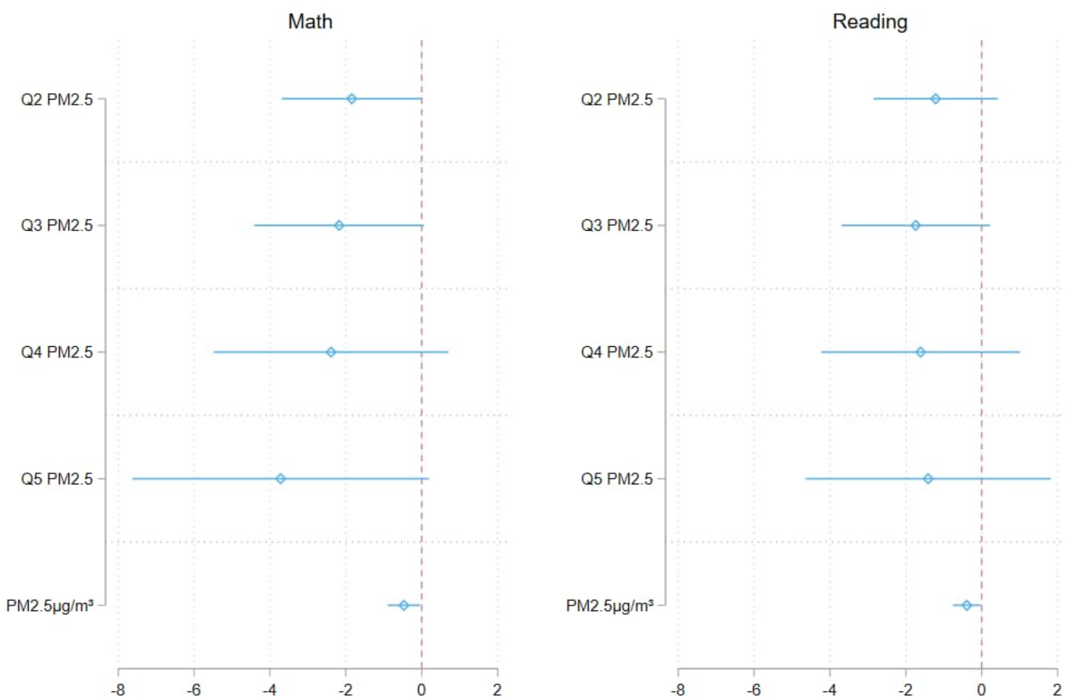
Table A1. The interaction between PM2.5 and SES on math and reading scores

	(1) Math	(2) Reading
PM2.5	-0.478*	-0.398*
	(0.221)	(0.188)
SES	9.763***	10.560***
	(0.250)	(0.246)
SES#PM2.5	0.119***	0.090***
	(0.015)	(0.015)
Observations	456,496	456,466
R-squared	0.219	0.230

Note: The coefficients are based on a regression where the dependent variables are test scores, with municipality FE and control variables for gender, migration status, real estate value. Standard errors clustered at the school level. Standard errors in parenthesis. Control variable and constant are included in the model but not reported here. *** $p<0.001$, ** $p<0.01$, * $p<0.05$

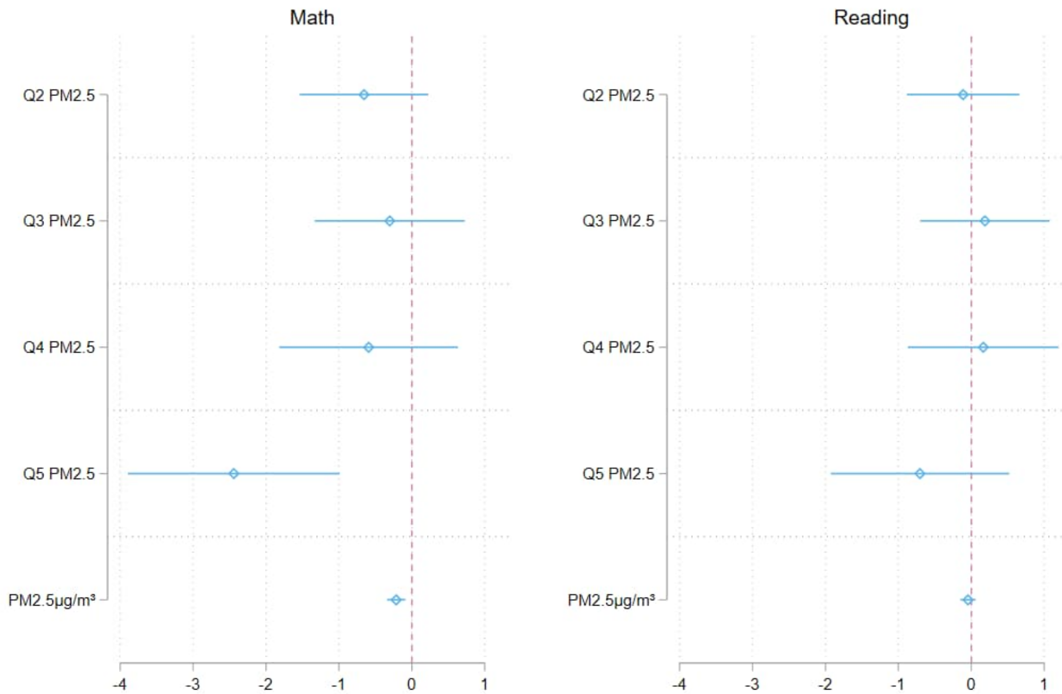
Figures

Figure A1. The effect of PM2.5 specified as continuous and categorical with municipality FE on math and reading



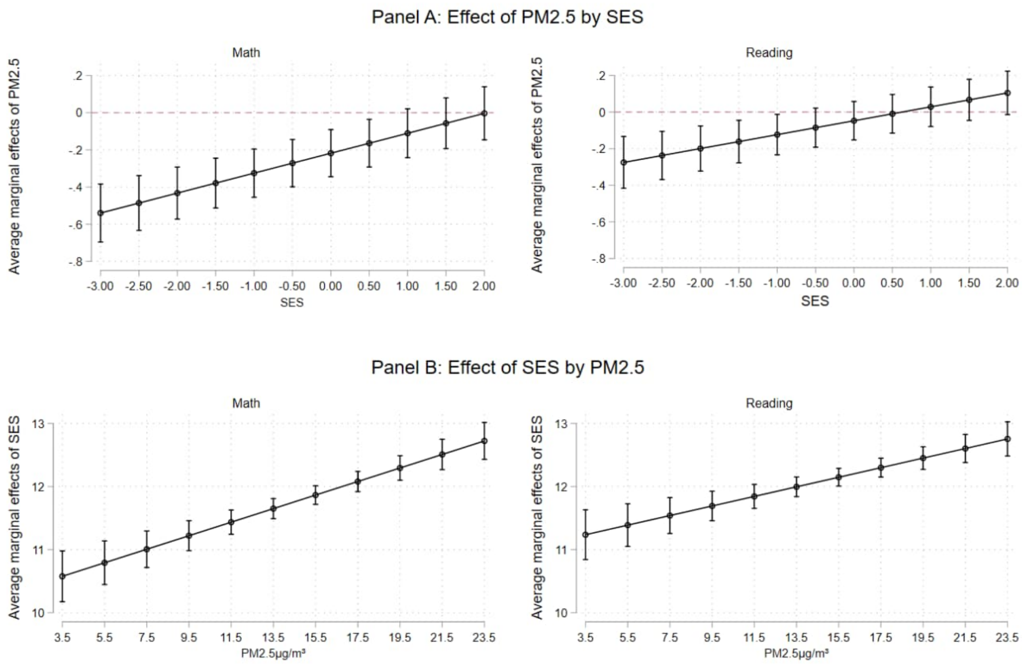
Note: The coefficients for PM2.5 as a *categorial* variable in quintiles and as a *continuous* variable are based on separate regressions with *municipality* FE and standard errors clustered at the school level..95% confidence intervals are displayed.

Figure A2. The effect of PM2.5 specified as continuous and categorical with province FE on math and reading



Note: The coefficients for PM2.5 as a categorial variable in quintiles and as a continuous variable are based on separate regressions with *province* FE and standard errors clustered at the school level. 95% confidence intervals are displayed.

Figure A3. Average marginal effect of PM2.5 by SES (panel A) and average marginal effect of SES by PM2.5 (panel B) on test scores in math and reading with province fixed effects



Note: Each panel is based on an OLS models with province FE and control variables for gender, migration status, real estate value and the interaction between SES and PM2.5 on math and reading. Reported are the average marginal effects of the interaction with 95% confidence intervals.