AIR POLLUTION: A REVIEW OF ITS ECONOMIC EFFECTS AND POLICIES TO MITIGATE THEM

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Abstract

Air pollution is an increasing cause of concern among the scientific community, policymakers and the general public. This interest has led to a sharp increase in the number of scientific papers on air pollution. This paper provides a summary of the most prominent recent economic literature on the effects of air pollution, the main policy lessons that can be drawn from it, and the areas in which more research would be especially valuable. The literature has found sizable negative effects of air pollution on health and mortality. There is also some evidence that air pollution may have negative non-health effects, reducing labour supply and productivity, although the evidence is more mixed on the latter aspect. The literature also suggests that effects on both health and non-health dimensions may be heterogeneous in a number of dimensions, most prominently age, with more negative effects for the elderly. Finally, more research is needed on which policies to tackle air pollution would be more cost-effective.

Keywords: air pollution, health, labour supply, productivity.

JEL classification: I12, J22, J24, Q51, Q53.

Resumen

La contaminación atmosférica suscita un interés cada vez mayor entre la comunidad científica, los poderes públicos y la población en general, lo que ha llevado a un fuerte aumento en el número de artículos científicos sobre este asunto. Este documento proporciona un resumen de la literatura económica reciente más destacada sobre los efectos de la contaminación atmosférica, las principales lecciones de política que se pueden extraer de ella y las áreas en las que sería especialmente valioso centrar los esfuerzos de investigación. La literatura ha encontrado efectos negativos considerables de la contaminación del aire sobre la salud y la mortalidad. También hay alguna evidencia de que la contaminación del aire puede tener efectos negativos no relacionados con la salud, reduciendo la oferta laboral y la productividad, aunque la evidencia no es tan clara en el último aspecto. La literatura también sugiere que los efectos tanto sobre la salud como sobre aspectos no relacionados con ella pueden ser heterogéneos en varias dimensiones; sobre todo respecto a la edad, con efectos más negativos para los más mayores. Finalmente, el documento repasa la literatura sobre las políticas de reducción de la contaminación, como, por ejemplo, zonas de bajas emisiones, reducción de los límites de velocidad o rotación de matrículas. El documento concluye que se necesita más investigación sobre los efectos de las distintas políticas para abordar la contaminación.

Palabras clave: contaminación atmosférica, salud, oferta laboral, productividad.

Códigos JEL: I12, J22, J24, Q51, Q53.

Contents

1 Introduction

Air pollution is an increasing cause of concern among the scientific community, policymakers, and citizens in general. This interest has led to a sharp increase in the number of scientific papers on air pollution. Economists have also contributed to this literature by providing studies with credible identification strategies, such as those reviewed here.

In May 2008 the European Union published the "Directive on Ambient Air Quality and Cleaner Air for Europe" (2008/50/EC) in order to improve the quality of air in Europe and limit exposure to air pollution. This EU directive set value and threshold limits for ambient pollutant concentrations. The limits apply over differing periods of time because the observed health impacts associated with the various pollutants occur over different exposure times. This directive regarding the improvement of air quality has been transposed into Spanish law through Royal Decree 102/2011, of 28 January 2011.[1]

This review provides a summary of the most prominent recent literature on the effects of air pollution, the main policy lessons that can be drawn from it, and the areas in which more research would be especially valuable.

This paper is closely related to Aguilar-Gomez et al (2022), which reviews the economic research investigating the "non-health" effects of air pollution, that is, those economic outcomes other than health outcomes.[2] Our study goes further by covering not only the literature on effects but also that on the evaluation of policies aimed to reduce air pollution. Other surveys that the interested reader may consult are Graff Zivin and Neidell (2013), Zigler et al (2016), Schraufnagel et al (2019), and Lu (2020).

The rest of the paper is organised as follows. The literature on the effects of air pollutions is surveyed in Section 2. Specifically, its possible effects on mortality and health, housing prices, labour supply and human capital are considered. The study then reviews the literature on the effectiveness of different policies, in a variety of contexts, aiming to reduce pollution (Section 3). The review concludes by discussing some of the limitations of the literature and potential avenues for future research (Section 4).

1 This decree has been modified twice to transpose subsequent European directives, by Royal Decree 678/2014, of August 1, and by Royal Decree 39/2017, of January 27. In addition, two directives are of application. Directive 2004/107/EC of the European Parliament and of the Council, of December 15, 2004, regarding arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air; and Directive 2015/1480/CE, of the Commission, of August 28, 2015, regarding reference methods, data validation and the location of sampling points for the evaluation of ambient air quality. On December 12, 2011, Decision 2011/850/EU was approved, regarding the reciprocal exchange of information and the notification of ambient air quality to the European Commission. This decision applies from January 1, 2014 and establishes that the Member States will provide information on the evaluation system that must be applied in the following calendar year with respect to each pollutant in zones and agglomerations. Finally, in Spain, Order TEC/351/2019, of March 18, approves the National Air Quality Index.

2 We worked on this paper in parallel. Some differences between our document and theirs are that we review some work on mortality and other health effects of pollution, as well as on the evaluation of policies aimed to reduce the impacts of air pollution, while they provide a comprehensive scientific background on the channels and a conceptual theoretical model.

2 The Effects of Air Pollution

2.1 Measuring Air Pollution

'Pollutant' is defined as any substance present in ambient air and likely to have harmful effects on human health and/or the environment as a whole (see directive 2008/50/EC). Air pollutants may be categorised as primary or secondary. Primary pollutants are directly emitted to the atmosphere while secondary pollutants are formed from precursor ones through chemical reactions and microphysical processes.

Primary pollutants include particular matter (PM) of different sizes, carbon monoxide (CO), sulphur oxides (SO) or nitrogen oxides (denominated collectively as NOx). Many of the studies summarized in here deal with two particular sizes of Particular Matter: PM10 and PM2.5. The second set of pollutants (secondary pollutants) includes ozone (O_3) –see European Environment Agency, 2019.

Whether a pollutant is primary or secondary matters both for measurement and for assessing its impact. Following Neidell (2022), an important difference between pollutants like PM (a primary pollutant) and Ozone (a secondary one) is their ability to penetrate indoors. Ozone rapidly breaks down and disappears once it enters indoors. PM, however, can easily enter buildings. Hence, depending on the setting, different populations can be affected by each pollutant.

Because of their harmful effects, different countries have established different limits on the exposure to different pollutants. The EU specifically set limits on oxides of nitrogen, particulate matter (PM10 and PM2.5), carbon monoxide, ozone, and sulphur dioxide (NO_2).[3] Regarding PM2.5, the EU directive sets for an annual limit of 25 μg/m^3. The corresponding amount in the US is 10 μg/m^3, which is also the limit recommended by the World Health Organization (WHO). In the period spanning 2015 and 2017 between 6 and 8% of the European population were exposed to those yearly limits. If one considers the stricter limit set by the WHO, the fraction increases to 74-81% –see European Environment Agency op. cit.[4] For PM10 the limit is of 40 μg/m^3 per year and 50 μg/m^3 per day, which should not be exceeded more than 35 days per year. The EU estimates that 13-19% of the European population are exposed to those limits between 2015-2017. If one considers the WHO limit (20 μg/m^3), the fraction increases to 42-52% -see European Environment Agency, op. cit.

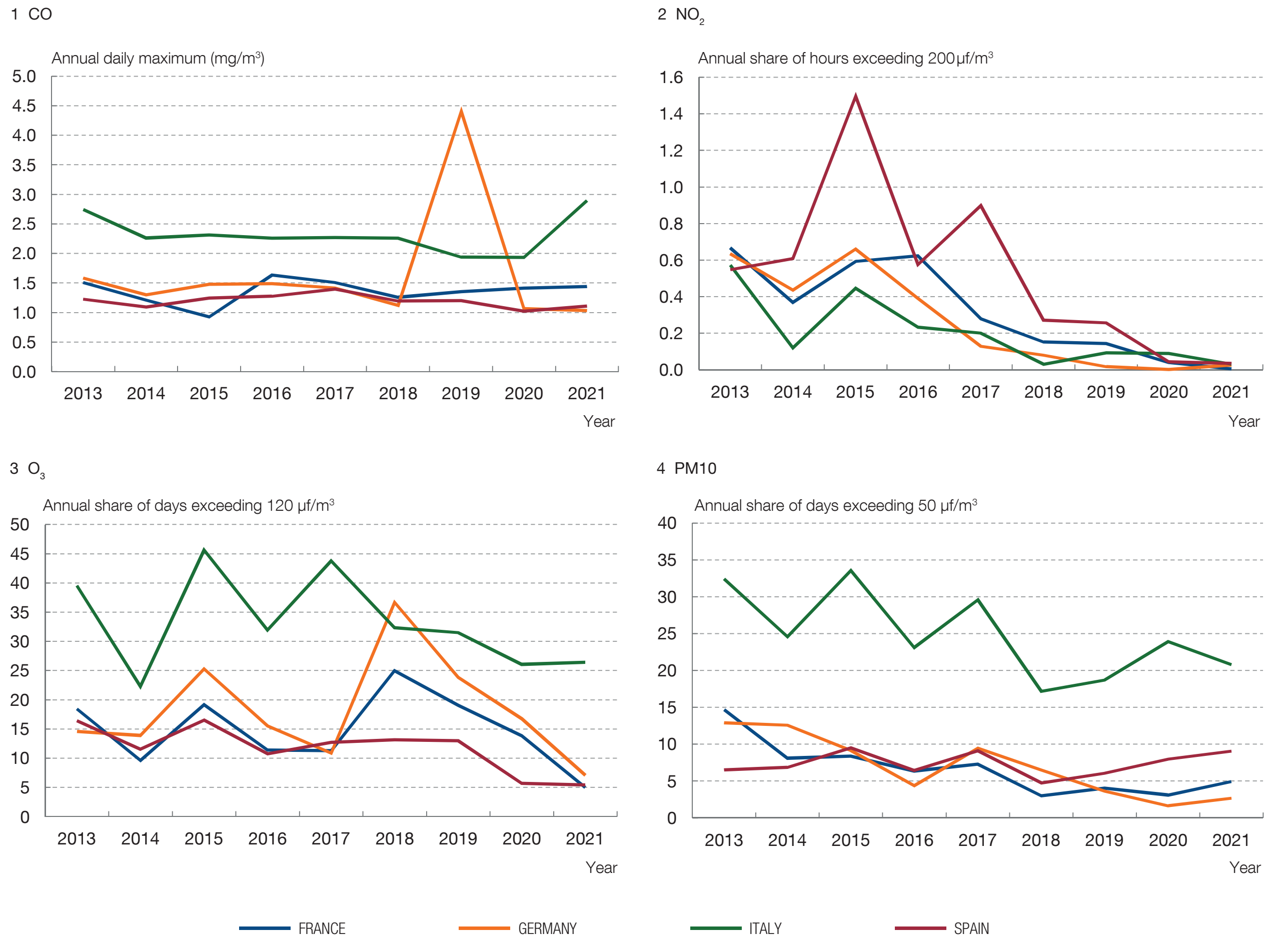
3 See Standards - Air Quality - Environment - European Commission (europa.eu). According to the Directive, 'Oxides of nitrogen' shall mean the sum of the volume mixing ratio (parts per billion volume) of nitrogen monoxide (nitric oxide) and nitrogen dioxide expressed in units of mass concentration of nitrogen dioxide (μg/m^3). Of particular interest for this study are PM10 and PM2.5. PM10 shall mean particulate matter which passes through a size-selective inlet as defined in the reference method for the sampling and measurement, EN 12341, with a 50% efficiency cut-off at 10 μm aerodynamic diameter; while PM2.5 shall mean particulate matter which passes through a size-selective inlet as defined in the reference method for the sampling and measurement of PM2.5, EN 14907, with a 50% efficiency cut-off at 2,5 μm aerodynamic diameter.

4 The daily limit is 35 μg/m^3 in the United States. EU does not have a pre-specified daily limit. See European Environmental Agency (2019).

Chart 1

EVOLUTION OVER TIME OF THE MAIN POLLUTANTS IN FOUR EUROPEAN COUNTRIES: FRANCE, GERMANY, ITALY AND SPAIN

The figure shows the evolution of the concentration in carbon monoxide (CO), ozone (O_3), particular matter (PM10), and nitogrn dioxide (NO_2). The levels of these pollutants are similar in France, Germany, and Spain, and higher in Italy (except for NO_2). A certain downward trend is observed in the four contries, more pronounced for NO_2 and PM10.



SOURCE: European Environment Agency.

Chart 1 shows the evolution over time of the main pollutants (CO, NO_2, O_3 and PM10) in four European countries: France, Germany, Italy and Spain. Specifically, the figure represents the number of hours in the day per year, or the number of days per year that the established thresholds are exceeded. For example, for PM10 the last panel indicates that around 10% of days exceed the limit of 50 µg/m³ in Spain. Overall, levels are similar in France, Germany and Spain and higher in Italy (except for NO_2). A certain downward trend is observed since 2015 in the four countries, more pronounced for NO_2 and PM10.

2.2 Mortality and Health

There is a sizable literature studying the effects of air pollution on mortality and health, see Table 1 for a selection of papers. Overall, the evidence points to the existence of

Table 1
SELECTED STUDIES OF THE IMPACT OF AIR QUALITY ON HEALTH OUTCOMES

Authors (Source)	Country	Pollutant	Main result	Most affected group
Panel A: Mortality				
1. Kenneth Y. Chay and Michael Greenstone (QJE 2003b)	United States	1. Carbon Monoxide (CO)	1. CO 1 pp reduction in Total Suspended Particles (TSP) reduces infant mortality by 0.35 pp	Disadvantaged
		2. PM10	2. Weak effects.	
2. Wolfram Schlenker and W. Reed Walker (RESTUD 2016)	United States	1. Carbon Monoxide (CO)	1. One standard deviation reduces a day of hospitalization due to coronary or respiratory problems	Individuals above 65 years of age or below 5
		2. Ozone/NO_2	2. Weak effects.	
3. Tatyana Deryugina, Garth Heutel, Nolan H. Miller, David Molitor, and Julian Reif (AER 2019)	United States	PM2.5	Exposure to 1 μg/m^3 of PM2.5 (10% of the average) for one day causes 0.69 deaths per million individuals above 65 during that day and the following two (a)	Concentrated among individuals with lower life expectancy
4. Michael L. Anderson (JEEA 2020)	United States	NO, CO	One standard deviation in time exposed to pollution increases mortality by 6% in the subsequent 3 years	Higher age
5. Jenny Jans, Per Johansson, and J. Peter Nilsson (JHE 2018)	Sweden	PM10	Thermal inversions increase daily PM10 by 25% (mean: 18.07μg/m^3) and children respiratory problems by 25% (b)	Low income children
PANEL B: Other health outcomes				
1. Anthony Heyes and Mingying Zhu (JEEM 2019)	China	1. Air Quality index	One standard deviation increase in AQI causes an 11.6% increase in sleeplessness	
		2. PM2.5	One standard deviation increase in PM2.5 (45μg/m^3) increases sleeplessness by 12.8% (a)	
2. Shuai Chen; Paulina Oliva; Peng Zhang (NBER WP 2018)	China	PM2.5	One-standard-deviation (18.04 μg/m^3) increase in average PM2.5 concentrations in the past month increases. The probability of having a score that is associated with severe mental illness by 0.33 standard deviations (a)	
3. Olivier Deschenes, Huixia Wang, Si Wang, and Peng Zhang (JDEV 2020)	China	PM2.5	1 μg/m^3 (1.54%) increase in average PM2.5 concentrations in the past 12 months increases body mass index by 0.27%, and overweight and obesity rates by 0.82 and 0.27 percentage points (a)	

NOTES: μg/m^3: micrograms per cubed meter. AER: American Economic Review, AEJ: EP American Economic Journal:Applied Economics, AEJ: EP American Economic Journal: Economic Policy, EJ: Economic Journal, JDEV: Journal of Development Economics, JEEA: Journal of the European Economic Association, JEEM: Journal of Environmental Economics and Management, JHE: Journal of Health Economics, JPUBE: Journal of Public Economics, LandEc: Land Economics, NBER WP: National Bureau of Economic Research working paper, PNAS: Proceedings of the National Academy of Sciences, QJE: Quarterly Journal of Economics, RESTAT: Review of Economics and Statistics, RESTUD: Review of Economic Studies.

a PM2.5: The yearly limit of exposure to PM2.5 in the EU is 20 μg/m^3 and in the US it is 10 μg/m^3. Between 2015 and 2017, 6-8% of the population in Europe was exposed to the yearly limit of PM2.5.
b PM10: The yearly limit of exposure to PM10 in the EU is 40 μg/m^3 adn the daily one is 20 μg/m^3.

negative effects of air pollution on these outcomes, but also to the presence of important heterogeneities. A first obstacle to establishing the impact of pollution on infant mortality is that individuals who are aware of the negative impact of pollution may move to cleaner areas, bidding up housing prices. Thus, simple comparisons of infant health outcomes between polluted and non-polluted areas might capture factors other than health, such as lower parental income. On the other hand, urban areas –more polluted- may have better health services, so simple rural-urban comparisons may also capture the effects of the quality of health care. We discuss below how different studies have addressed those identification issues –see Currie et al. 2009 for a discussion.

A first group of studies focuses on child health, using different strategies to identify which children are affected by pollution. At the aggregate level, a first possibility is to identify counties in the United States that underwent a reduction in Total Suspended Particles (TSPs) because of the fall in pollution associated to the 1980-1982 recession. Different counties have different industrial specialization, and those with a higher share of manufacturing activity have higher levels of pollution. For that reason, a fall in economic activity diminishes the level of pollution relatively more in those counties with higher pre-recession levels of pollution. It is thus possible to compare data on pollution, birth weight and mortality aggregated at the level of those US counties to isolate the impact of pollution on the health outcomes mentioned. A generalization of this strategy examines how measures of pollution in a particular ZIP code deviate around its long-run trend.

Both strategies have been implemented using US data and suggest indeed that reductions in 1pp TSP in carbon monoxide associated to the 1980-1982 recession reduced infant mortality by 0.35pp. Similarly, it has been documented that when a zip code experiences unusually low temperatures, pollution due to carbon monoxide increases. During those episodes, child hospitalizations and the incidence of asthma also increase.[5] It is important to keep in mind that these results may not translate perfectly to today as, for example, the values of carbon monoxide measured between 1980 and 1982 (70 $\mu g/m^3$) were much higher.

A second possibility is to consider the individual-level exposure to air pollutants around the precise moment of child birth. Individual level information permits holding constant the influence of individual factors like race, child gender or maternal age, in addition to geographical and time characteristics. To further isolate for factors influencing mortality that are related to maternal background, individual level data on infants and their mother permits comparing the health outcomes of different siblings if they were born under different pollution episodes. This strategy yields that a decrease in exposure to CO by 1 parts per million (ppm) reduces infant deaths by 17.6 per 100,000 births. Those impacts happen even at low levels of pollution[6]. As a reference, the estimated impacts on infant mortality of a reduction of exposure to CO from 3ppm to 1ppm (as the observed in the sample of Currie et al. 2009) is equivalent to the impact of reducing mother's smoking from 10 cigarettes a day to none.

5 See Chay and Greenstone (2003b) for analysis of the fall in pollution associated to the 1980-1982 recession and Neidell (2004).

6 Geographical and time characteristics are implemented by introducing by month, year, zip code fixed effects, see Currie and Neidell (2005). Regarding the sibling comparison see Currie, Neidell and Schmieder (2009).

Finally, an alternative strategy is to identify sharp changes in the quality of air that are linked neither to the economic cycle (like the first strategy mentioned above) or to other climatic phenomena. To that end many studies have analysed "thermal inversions". These events consist of increases in pollutants at the ground level that happen when warmer air at higher altitude impedes the spread of air pollutants. Episodes of that type in Sweden increase the concentration of PM10 by 25%, resulting in the incidence of children respiratory problems by 5.5% (see Jans et al. 2018). Note that the mean PM10 in that study is 18 $\mu g/m^3$, below the limit in the European Union, but close to the WHO limit of 20 $\mu g/m^3$. As mentioned in Section 2.1, 42-52% of the European population is exposed to such levels of pollution.

Air pollution can also affect adult mortality. In particular, some studies have exploited the fact that exposure to pollution in certain areas changes because of sudden changes in the wind direction. Those events are interesting in the sense that wind changes are arguably uncorrelated with economic conditions and change the groups of the population exposed to pollutants quasi randomly. Those sharp episodes permit identifying high-frequency impacts of increases in pollution on the full population. Furthermore, the analysis can also be extended to estimate the impact of long-term exposure to air pollution on mortality.

The results from the episodes analysed are illustrative. In the United States, an increase of PM2.5 exposure for one day of 1 microgram per cubic meter ($\mu g/m^3$) (about 10 percent of the mean) causes 0.69 additional deaths per million elderly individuals over the three-day window that spans the day of the increase and the following two days. PM2.5 exposure increased mortality, visits to emergency rooms, hospitalizations and inpatient spending –see Deryugina et al. (2019). Those impacts are driven by individuals above 65 years of age. Note that the mean concentration of PM2.5 in their sample is 10 $\mu g/m^3$, well below the current daily limit of 35 $\mu g/m^3$ of PM2.5 in the US.

In another setting, in Los Angeles, similar quasi-random variation in pollution levels generated by wind patterns near major highways increased mortality rate (in the next 3 years) for individuals above 75 years of age.[7] Specifically, a one standard deviation increase in time spent downwind of a highway increases mortality by 6%.[8]

As has been mentioned, it is particularly informative to isolate episodes that lead to a sharp and temporary increase in pollution, as such instances permit the estimation of short and long-run impacts. A possible source of a dramatic worsening of pollution are traffic bottlenecks, or network delays around airports. Researchers have examined the length of taxi rides at three major airports in Eastern USA to identify how peaks in CO associated to network delays affect hospitalization rates for asthma, respiratory, and heart-

7 Deryugina et al (2019).

8 Anderson (2020).

related emergency admissions.[9] A one standard deviation increase in daily pollution levels leads to an additional $540 thousand in hospitalization costs for respiratory and heart-related admissions for the 6 million individuals living within 10 km (6.2 miles) of the airports in California.

Similar results are documented using the already mentioned episodes of thermal inversions. Deschenes et al (2020) examine the impacts of pollution peaks around thermal inversions and find that higher PM2.5 concentrations increase body mass index and obesity. In particular, 1 $\mu g/m^3$ (1.54%) increase in average PM2.5 concentrations in the past 12 months increases body mass index by 0.27%, and also increases overweight and obesity rates by 0.82 and 0.27 percentage points, respectively.

The impacts on health go beyond those of physical health and spill over to mental health and sleeplessness. Chen et al (2018) use episodes of thermal inversion in China and provide evidence that higher PM2.5 concentrations in the past month increase the probability of having a score that is associated with severe mental illness. In particular, a one-standard-deviation (18.04 $\mu g/m^3$) increase in average PM2.5 concentrations in the previous month increases the probability of having a score that is associated with severe mental illness by 6.67 percentage points, or 0.33 standard deviations. Szyszkowicz et al (2020) show that PM 2.5 and O_3 are associated with an increased risk for emergency visits for adolescents and young adults with diagnosed mental health disorders. Persico and Marcotte (2022) study whether air pollution increases suicide, employing detailed death certificate data from the U.S. for the years 2003-2010. Using sharp changes in daily pollution exposure associated to wind changes, they find that a 1 $\mu g/m^3$ increase in daily PM 2.5 leads to a 0.49% increase in daily suicides and 0.171 more suicide-related hospitalizations (a 50% increase). Finally, relying also on wind patterns, which are likely to cause a change in pollution that is arguably uncorrelated with other factors, Heyes and Zhu (2019) document that a one standard deviation decrease in an Air Quality Index (AQI) that includes various pollutants causes an 11.6% increase in sleeplessness. Similarly, an increase of one standard deviation in PM2.5 exposure increases sleeplessness by 12.8%.

Hence, there is evidence that air pollution has a negative impact on mortality and health. At the same time, the evidence suggests that these effects may be heterogeneous. The most relevant aspect in this regard is age. In particular, it seems that older individuals and children may be more affected. Schlenker and Walker (2016) find stronger effects for elderly (+65) and children (-5). Deryugina et al (2019) find strong heterogeneity by life expectancy: there is a near-zero effect on mortality for about 75 percent of the elderly population but substantial effects for about 5 percent of this population. Anderson (2020) also finds strong heterogeneity by age, with all the negative impact concentrated on the elderly (+75) and no effects for younger population (50-75). In addition to age, some literature has also found more negative effects for black children -see Chay and Greenstone (2003a)- smokers and

9 Schlenker and Walker (2016).

older mothers -Currie et al (2009)- and low socio-economic-status children –see Neidell (2004); Jans et al (2018).

2.3 Labour Supply and Productivity

Concerns about air quality have traditionally been mostly about its effects on health and mortality, as these may represent the most visible impacts of pollution. Recent work suggests that pollution may have detrimental effects on other domains. One important such domain is the labour market. This review categorizes the literature on this point into two main outcomes: labour supply, i.e., the number of days or hours worked; and worker productivity, i.e., how much is produced per unit of time. Table 2 summarizes a selection of studies in this literature. It is important to emphasize that behavioural responses to limit the harms from pollution might interfere with labour market institutions (such as sick pay insurance), making causal attribution more complicated. For instance, measuring health outcomes due to pollution through sick leaves can capture individual choices to some extent, as sick leaves might be taken by healthy workers pretending to be sick (absenteeism) or not taken by sick workers pretending to be healthy (presenteeism). While absenteeism is a manifestation of moral hazard, presenteeism arises when workers fear adverse consequences of calling in sick, that would differ depending on labour market conditions of each position.

Regarding *labour supply,* the literature points at mostly negative effects of air quality, using a variety of methods and situations (including Norway, Mexico, Chile, Spain and China). One of the first studies on the issue is Hansen and Selte (2000). Using a logit model with data from a large office in Oslo, they find evidence that PM10 is associated with more sick leaves: an increase in the average level of PM10 by 1 μg/m^3 increases the number of sick-leaves by around 0.6 percent. However, they find no significant association of sick leaves with nitrogen dioxide (NO_2) or sulphur dioxide (SO_2). More recently, Hanna and Oliva (2015) examine the evolution of pollution and hours worked around the event of a closure of a refinery in Mexico City. In that study, SO_2 reduces hours worked the following week. More specifically, they find that one part per hundred million increase in SO_2 (or a 20% increase) results in a decrease of 1.04 to 1.30 in work hours per week (a 2.75 to 3.5% decline). Chan et al. (2022) use the exogenous incidence of wildfires between 2010 and 2018 in Chile to identify the causal impact of air pollution on labor supply. They find that a marginal increase of air pollution due to an extra smoky day leads to a 2.6 percent reduction in hours worked for the average Chilean worker. The effect is more substantial for male workers, mainly involved in outdoor tasks (such as agriculture) and poor households, where the negative effect of air pollution is up to four times higher.[10]

Holub et al (2021) study this question by using administrative data from Spain and using two strategies. The first is to follow the same individuals over time and then compare their absence rates when pollution levels deviate from the average in the city, year and

10 Following a similar strategy, Borgschulte et al. (2022) estimate that an additional day of smoke exposure in the US reduces quarterly earnings by about 0.1 percent. Extensive margin responses, including employment reductions and labor force exits, can explain 13 percent of the overall earnings losses.

Table 2

SELECTED STUDIES OF THE IMPACT OF AIR QUALITY AND SUPPLY AND PRODUCTIVITY

Authors (Source)	Country	Pollutant	Main result	Most affected group
Panel A: Labor supply				
1. Rema Hanna and Paulina Oliva (JPUBE 2015)	Mexico	Sulphur dioxide	An increase by 1 part per 100 million of sulphur dioxide (a 20% increase) reduces the number of hours worked on the following week by between 1.04 and 1.3 hours (between 2.75% and 3.75%)	Larger impacts for fixed salary workers
2. Felix Holub, Laura Hospido, and Ulrich J. Wagner (WP 2021)	Spain	PM10	A 10% reduction in pollution reduces sick leaves by 0.8% of the mean (b)	Larger impacts for workers with pre-existing conditions
3. Adam Isen, Maya Rossin-Slater, and W. Reed Walker (JPE 2017)	United States	TSP	The Clean Air Act reduced concentration of TSP by 10% and, for cohorts born in the year of the reduction, increased the numbers of quarters worked by age 30 by 0.7% and earnings by 1%	Larger impacts for individuals with lower expected earnings at birth
PANEL B: Productivity				
1. Joshua Graff Zivin and Matthew Neidell (AER 2012)	California	Ozone	An increase in concentration of ozone in 10 ppb (20 μg/m^3) decreases productivity by 5.5pp among fruit pickers ©	Men employed in jobs requiring physical effort
2. Tom Chang, Joshua Graff Zivin, Tal Gross, and Matthew Neidell (AEJ: EP 2016)	California	PM2.5	An increase in 10 μg/m^3 reduces productivity by $0.41 per hour among pear packers (6% of hourly wage) (a).	
3. Tom Chang, Joshua Graff Zivin, Tal Gross, and Matthew Neidell (AEJ: AE 2019)	China	PM 10	10 units decrease in an Air Quality index reduces calls handled in a call center by 0.35% (b)	
4. Jiaxiu He, Haoming Liu, and Alberto Salvo (AEJ: AE 2019)	China	PM 2.5	No immediate effects among indoor workers. 10 μg/m^3 during 25 days reduces output by 1% (a)	
5. Anthony Heyes, Nicholas Rivers, Brandon Schaufele (LandEc 2019)	Canada	PM 2.5	Exposure to 15 μg/m^3 causes a 2.3% reduction in the quality of MPs' speech (equivalent to a 2.6 month decrease in education) (a)	
6. Matthew E. Kahn and Pei Li (NBER WP 2019)	China	PM 2.5	1 pp increase in PM2.5 the case handling time by a given judge increases on average by 19.8% (a)	Stronger effects for older judges and for more complex cases
7. Xin Zhang, Xi Chen, and Xiaobo Zhang (PNAS 2018)	China	Index of air pollution (based on SO_2, NO_2 and PM10)	Exposure to 1 standard deviation (SD) on the index an over seven days reduces performance in verbal and math tests by 0.026 standard deviations. A 1 SD increase in the air pollution index over 3 years before the interview is associated with 0.108 SD drop in verbal test scores	The effect becomes stronger as people age, especially for less educated men

NOTES: μg/m3: micrograms per cubed meter. AER: American Economic Review, AEJ: EP American Economic Journal:Applied Economics, AEJ: EP American Economic Journal: Economic Policy, EJ: Economic Journal, JDEV: Journal of Development Economics, JEEA: Journal of the Europea Economic Association, JEEM: Journal of Environmental Economics and Management, JHE: Journal of Health Economics, JPUBE: Journal of Public Economics, LandEc: Land Economics, NBER WP: National Bureau of Economic Research working paper, PNAS: Proceedings of the National Academy of Sciences, QJE: Quarterly Journal of Economics, RESTAT: Review of Economics and Statistics, RESTUD: Review of Economic Studies.

a PM2.5: The yearly limit of exposure to PM2.5 in the EU is 20 μg/m^3 and in the US it is 10 μg/m^3. Between 2015 and 2017, 6-8% of the population in Europe was exposed to the yearly limit of PM2.5.

b PM10: The yearly limit of exposure to PM10 in the EU is 40 μg/m^3 and the daily one is 20 μg/m^3. ppb: parts per billion.

c Ozone (O_3): the 8-hour limit in EU is 120 μg/m^3. Between 8 and 19% of the population in Europe exposed to the limit.

quarter, holding constant weather conditions. The second strategy analyses instances when PM10 varies sharply because of dust storms coming from the Sahara. They find that PM10 presence increases absence rate of workers: a 10%-reduction in high-pollution events reduces the absence rate by 0.8% of the mean (2.79%).

Fan and Grainger (2022) use survey data from China and also trace the same individuals over time. They compare individuals with similar age, education, marital status and employment and document a reduction of the average hours worked during episodes of higher exposure to PM2.5.[11] Namely, among the population aged 16-75, an increase of 1 μg/m^3 in PM2.5 reduces an individual's average hours worked by 14 minutes per week. Evaluated at the mean, a one percent increase in annual average PM2.5 concentration decreases hours worked by about one percent.

Finally, Hoffmann and Rud (2022) use hourly particulate matter air pollution data from ground monitoring stations in Mexico City to capture peaks in air pollution across days and localities. They also collect information on individual daily hours worked for each day in the reference week. They find that on an average day of extremely high PM 2.5 the probability of working is reduced by more than 5 percentage points, which implies an average reduction of same-day hours worked of 7.5%. This amounts to a loss of around 280,000 person-days of labor on a high-pollution day in the metropolitan area of Mexico City during the period analyzed (2005-2016). They include a comprehensive set of time-varying weather controls, variables to control for demographic and labor market characteristics, and a rich set of fixed effects to address unobserved, time-invariant and time-varying factors that could affect both air pollution and labor supply. Their results are also robust to using PM10 as a measure of pollution and a variety of specification checks, including analyzing localized increases in pollution levels associated to changes in wind speed and direction. Workers partially compensate for lost hours by increasing their labor supply on days that follow high-pollution days. Informal workers reduce their contemporaneous labor supply by working significantly less than formal workers on high-pollution days. Furthermore, informal workers also compensate less than formal workers with smaller increases to their labor supply in the following days.

In sum, albeit they are not documented for all pollutants, the negative effects of pollution on labour supply are documented in a variety of settings.

Assessing the impact of pollution on *productivity* is particularly challenging, as individual-level measures of productivity are very hard to obtain. For this reason, studies have focused on settings where high-frequency and good-quality measures of productivity are available. Not surprisingly, the estimates of the impact of air quality on productivity vary across types of jobs. Hence, we cluster studies according to the occupation of the affected group. An additional source of heterogeneity is that the results depend on the precise form of measuring pollution, as we will see below.

11 The study also conditions on the month when the individual is observed as well as for province-specific trends.

We start with mainly physical jobs, either in the agricultural or manufacturing sector. Graff Zivin and Neidell (2012) follow the performance of fruit pickers in a California farm and examine how daily variations in ozone (O_3) concentration affect their productivity. They find that a 10 parts per billion decrease in O_3 concentrations increases worker productivity by 5.5 percent, despite ozone levels being below regulatory thresholds.

Another study on the manufacturing activity in California conducted by Chang et al (2016) uses data from pear packing workers to study how pollution outdoors reduces productivity of *indoor* pear-packing workers. As in the previous study, the authors follow the same group of workers over time and conduct comparisons across workers that hold constant daily wind speed, temperature, dew point, rain, solar radiation, ozone, and day of the week. The study finds that an increase in PM2.5 concentration of 10 $\mu g/m^3$ reduces the productivity of workers by $0.41 per hour, approximately 6 percent of average hourly earnings. Those results are observed at pollution levels below federal limits and are consistent with the previous study on outdoor workers.

Conversely, in an industrial setting in China, He et al (2019) find different results. Their study uses a design similar to the previous work mentioned, i.e., they follow the daily evolution of pollution and worker output, and analyse how the average output of a worker reacts to deviations of pollution from the season-specific average. Contrary to the previous papers, He et al (2019) find that the pollutants they examine (PM 2.5 or SO_2) do not have an immediate effect on productivity in manufacturing sites. These authors do find some statistically significant but quantitatively small effects of longer exposure -a substantial 10 $\mu g/m^3$ PM2.5 variation sustained over 25 days reduces daily output by one percent. These authors attribute their differential findings to measurement issues: while most previous work had used outdoor measurement of pollution, which may be more prone to measurement error, they use indoor measurement.

The previous papers are mostly about physical or mechanical jobs. Some recent literature has looked at possible effects on jobs or tasks that are more cognitively demanding.

The studies considered also analyse longitudinal data on workers and atmospheric conditions to examine how measures of air pollution affect the productivity of workers conducting non-physical tasks. The occupations considered include call centre workers, umpires, Members of Parliament and judges. As it was the case in agriculture and manufacturing, those studies trace measures of the output of a given individual in periods over which there has been variation in his or her exposure to pollution. These studies examine if in periods when air quality falls below the sample mean, the productivity of a worker is also higher than his or her individual-specific average. While the precise measures of pollution and productivity vary across studies, the results are qualitatively similar and point at a detrimental impact of pollution on the productivity in cognitively demanding jobs.

A first study analyses desk jobs in call centres in China, a job requiring minimal physical effort and where productivity can be measured easily by the number of calls handled.

A 10-unit increase in the air pollution index (in their case, PM10) decreases the number of daily calls handled by a worker by 0.35 percent on average –see Chang et al, 2019. Also comparing locations and periods with differential exposure to pollution, the average baseball umpire is more likely to make an incorrect call in periods of higher concentration of CO and PM2.5 than in a period with lower one. For example, Archsmith et al (2018) document that a 1 ppm increase in 3-hour CO causes an 11.5% increase in the propensity of umpires to make incorrect calls and a 10 μg/m^3 increase in 12-hour PM2.5 causes a 2.6% increase.

A third study analyses the speeches of Members of Parliament (MPs) in Canada using text methods. The study finds that during periods with higher concentrations of PM2.5 the average MP reduces the complexity and quality of his or her speech relative to periods with lower concentration. More specifically, exposure to levels above 15 μg/m^3 causes a 2.3% reduction in the quality of MPs' speech (equivalent to a 2.6-month decrease in education time) –see Heyes et al, 2019.[12] Finally, a study measures the productivity of judges in China by the time that they take to reach a decision - Kahn and Li (2019). Then they relate the time it takes a decision to air quality (PM 2.5) and find that in periods and locations where there is a 1 pp increase in PM2.5 the case handling time by a given judge increases on average by 19.8%.

Finally, using employer-employee data and granular measures of air pollution in France from 2009 to 2015, Leroutier and Ollivier (2022) find that poor air quality negatively affects firms' sales. They exploit variation in air pollution induced by changes in monthly wind directions at the postcode level and detailed firm-level outcomes. The study finds that a 10% increase in monthly PM2.5 exposure increases worker absenteeism in the same month by 1%. In addition, the 10% increase, reduces sales in manufacturing, construction, and professional services, with different lags. Sales losses are several orders of magnitude larger than what we would expect if workers' absenteeism was the only factor affecting firms' performance. This suggests a potentially large effect of pollution on the productivity of non-absent workers.[13] The authors estimate that reducing air pollution in France in line with the World Health Organization's guidelines would have saved at least 0.3% of GDP annually in terms of avoided sales losses.

Turning to cognitive performance, various studies have examined the influence of air quality on verbal and mathematical tests as well as mistakes in chess tournaments. An advantage of examining tasks rather than productivity is that air quality may have an independent impact on the number of days of hours worked or the composition of the labour force. As the number of hours worked may affect productivity, it is not always obvious how to disentangle both factors –see Neidell, 2022. Conversely, examining tasks conducted by individuals alleviate somewhat that concern. As in the previous case, the following studies isolate the impact of air quality by following the same individuals over time and examining

12 The study documents that 2,6 months of education represent 0.21 grade levels.

13 An alternative channel would be the presence of demand effects, i.e. customers demanding less on more polluted days. Against this hypothesis, the authors find no effect on sales in business-to-customer services.

their performance both under high and low air quality. In China, Zhang et al (2018) study impacts at various horizons. In particular, they show that when an index of air pollution over seven days (based on SO_2, NO_2 and PM10) increases by one standard deviation prior to a survey-based cognitive test individuals' performance in the verbal and math assessments decreases by 0.278 points (0.026 standard deviations). Similarly, a 1 standard deviation (SD) increase in the air pollution index over 3 years before the test is associated with 1.132 points (0.108 SD) drop in verbal test scores. As a reference, in the education literature, a program or an intervention that increases test scores by 10% of one standard deviation is considered a moderate impact.

In the setting of chess tournaments in Germany, Künn et al (2019) analyse how the frequency of erroneous moves in a chess game relates to air quality. To isolate that impact, the study compares the frequency that the average player makes an error when the air quality is worse, effectively comparing that frequency to his or her average performance in all tournaments in the same year, in the same round and move of the game. To isolate other confounding environmental factors that may concur with worse air quality and that also have an impact on the frequency of chess mistakes, the study also compares days with similar environmental conditions. An increase in the indoor concentration of PM2.5 by 10 $\mu g/m^3$ increases a player's probability of making an erroneous move by 26.3%. However, they find smaller and mostly insignificant effects for other pollutants, like carbon dioxide (CO_2). Finally, La Nauze and Severnini (2021) examine how increases in PM2.5 associated to changes in daily local wind direction affect standardised scores in brain games. They find that exposure to PM2.5 at levels above 25 $\mu g/m^3$ reduces standardized scores in brain games by approximately 0.18 standard deviations.

In sum, the literature has found some evidence that air pollution may decrease labour supply and productivity. Some papers have also looked for potential sources of heterogeneity. Age appears, as with the health effects, as the most relevant aspect. However, there is conflicting evidence. In the context of chess tournaments Künn et al (2019) and in the context of survey-based cognitive test Zhang et al (2018) find evidence that pollution effects are more negative for older individuals. By contrast, La Nauze and Severnini (2021) find that effects of pollution on performance in brain training games aimed at improving attention are larger for younger individuals (those below 50). Another aspect that has been found to matter is how "demanding" the task is, with larger impacts for more physically demanding tasks (Graff Zivin and Neidell, 2012), more complex judicial cases (Kahn and Li, 2019), or more time pressure or facing a difficult opponent in chess tournaments (Künn et al., 2019).

2.4 Human capital

This section reviews some literature that studies whether air pollution in key moments in life –such as year of birth or around the moment of high stakes exams– can be detrimental to the acquisition of human capital and have long-term consequences.

Regarding high-stakes exams and in the context of Israel, Lavy et al (2014) implement alternative designs with either city, school, and student fixed effects to estimate the effect of pollution exposure on standardized test scores between 2000 and 2002. In particular, they analyse performance in a test and the probability of getting a certificate needed for college entrance. They find that a 10-unit increase in the ambient concentration of fine particulate matter (PM2.5) reduces test scores by 0.46 points, or roughly 1.9% of a standard deviation, and a 10-unit increase in CO reduces test scores by 0.85 points, or roughly 3.5% of a standard deviation. In this same context, Ebenstein et al (2016) implement a design with student, cohort, month, day of the week, and exam proficiency level fixed effects and document that exposure to PM2.5 decreases students' performance in exams and postsecondary educational attainment. Namely, a 1 standard deviation increase in PM2.5 is associated with a decline in student performance of 0.93 points, or 3.9 percent of a standard deviation. Even more strikingly, they go further and find an effect on earnings 8-10 years later: an additional ten units of PM2.5 exposures across the student's multiple exams is associated with a 1.64-unit decline in a student's score. The study then follows those students over time and find that ten additional units of PM2.5 result in a 0.15 decline in years of education at a university, and a $30 decline in monthly salary.

Roth (2020) uses data from a UK university and implements an OLS design with subject and student fixed effects, temperature and humidity controls, and CO_2 as a proxy for human activity and behaviour. He finds that PM10 measured indoors reduces test scores of students: a one-unit increase in PM10 ($\mu g/m^3$), or being above the World Health Organization (WHO) guidelines, reduces students' test scores by 0.3 and 13.5 percent of a standard deviation respectively.

Gilgraine and Zheng (2022) estimate the relationship between air pollution and test scores in school districts in the US. To account for the possible biases coming from other factors behind student achievement being correlated with air quality, they include detailed controls capturing aspects like local economic conditions or weather. Furthermore, they leverage variation coming from nearby power plants, which generate roughly thirty percent of particulate matter pollution in the US, and that is presumably unrelated to factors that affect both test scores and pollution. Their findings reveal that each microgram per cubic meter ($\mu g/m^3$) increase in PM2.5 concentrations causes a 0.02 standard deviation decline in test scores.

Isen et al (2017) provide additional evidence on long-term effects. They use a feature of the Clean Air Act (CAA) in the USA to identify counties with very similar pollution levels but where an intervention led a subset of them to reduce pollution dramatically. In particular, the CAA requires a set of interventions once pollution levels exceed a ceiling level. In that case, the Environmental Protection Agency (EPA) declares the county as a "non-attainment" one. Thus, a natural strategy to analyse the impacts of policy-induced reduction in pollution compares counties that barely passed the ceiling that triggers the EPA intervention to different counties where, because they were close but below the threshold, no intervention was implemented. As the unit of the analysis is the county, one can compare the long run impacts of interventions aimed at improving air quality. For example, one can compare cohorts born after the time of the intervention, who were unexposed to bad air quality at birth to previous ones. The outcomes of interest are time worked and earnings, both measured around age 30. Specifically, they find that the CAA led to an over 10 percent reduction in ambient total suspended particle levels in nonattainment counties in the 3 years after the regulation went into effect (ie, the intervention was indeed effective), and that this regulation-induced reduction in air pollution is associated with a 0.7 percent increase in the annual number of quarters worked and a 1 percent increase in mean annual earnings for affected cohorts.

While the channels behind these results need more investigation, one possible such channel is the impact of air pollution on school attendance. In this regard, Currie et al (2009) implement a triple-difference design focusing on variations in pollution by school-year-attendance period cells, and find evidence that exposure to CO increases school absenteeism in Texas. In particular, an additional day between 75% and 100% of the recommended threshold for CO increases absenteeism by 5 percentage points, while an additional day with a CO level above the threshold increases absenteeism by almost 9 percentage points. However, they find no effects for PM10 and O_3. Another possible channel is that air pollution may hinder the acquisition of knowledge or skills even conditional on attending class, which would be consistent with some of the evidence reviewed in Section 2.3 on the detrimental effects of air pollution on the performance on cognitively-demanding tasks. Research on this regard would be especially valuable.

Finally, there is some evidence of heterogeneous effects. Three papers find that effects are more negative for men (Lavy et al. 2014; Ebenstein et al. 2016; Roth, 2020); but Isen et al (2017) find no heterogeneity by gender. There is also some evidence that the effects may be non-linear, with more negative effects for worse students (Lavy et al. 2014; Ebenstein et al. 2016; Roth, 2020). Also, Isen et al (2017) find stronger effects for individuals with lower predicted incomes.

2.5 Other effects

The literature has also studied the effects of air pollution on many more outcomes, such as housing values, migration flows, and crime. Without aiming to be exhaustive, here we review some of the most prominent papers doing that.

First, the effects on housing values have been studied in the United States. As house prices are determined in equilibrium and have a strong location component, studies in this area focus on variation across counties. As mentioned in Section 2.4, in the United States, small variations in air quality across counties may trigger very different interventions from the government. This happens to be the case because of the already commented features of the Clean Air Act Amendments (CAAAs) in 1970, by which initiatives to reduce air quality only happen once a certain ceiling of pollution concentration is reached and the county is declared to have a “non-attainment” status. Thus, Chay and Greenstone (2005) compare the evolution between 1970 and 1980 of the price of houses with similar characteristics across both sets of counties. To quantify the success of the intervention, they also track the evolution of TSPs (Total Suspended Particles). It is estimated that if nonattainment counties experience a reduction in TSPs concentrations housing prices increase.

A second strategy is adopted by Bayer et al. (2009), who also analyse the evolution of the price of dwellings with similar characteristics but compare counties with different distances to the source of local pollution. They find that prices close to the local source of pollution are lower, which implies that individuals in the U.S. are willing to pay for a reduction in average ambient concentrations of particulate matter.

The impact of pollution on migration flows has also been studied in China and in the European Union. The challenge in this case is to identify an event of pollution that sparks migration above and beyond the flows observed in other occasions. Two studies Chen et al. (2017) and Dechezleprêtre et al. (2019) identify the already mentioned episodes of thermal inversions as factors that can only affect migration behaviour through pollution and not through other concurrent factors. In China, Chen et at. (2017) relate their results to the labour force and find evidence that the marginal effects of PM2.5 on net outmigration for the three educational categories considered (junior high school or below, high school, and college or above) is monotonically increasing by education level. Dechezleprêtre et al. (2019) estimate that a 1μg/m^3 increase in PM2.5 concentration (or a 10% increase at the sample mean) causes a 0.8% reduction in real GDP that same year. Ninety-five per cent of this impact is due to reductions in output per worker.

Finally, we summarize a nascent literature linking short-term air pollution to crime, a behaviour that is particularly costly from a societal perspective. Bondy et al. (2020) show that air pollution increases crime in London. They use the air quality index (AQI), a composite measure of air pollution based on multiple pollutants, and compare the crime rates in different neighbourhoods of the city. To isolate the impact of air pollution, they use the already mentioned episodes of thermal inversions and wind directions. Furthermore, it is important to hold constant neighbourhood-specific characteristics. As a result, they gauge the impact of air quality on the crime rate by examining if the average crime rate in a neighbourhood departs from its sample average in periods when thermal inversions or wind directions worsen air quality. Those comparisons suggest that air pollution has a positive impact on several major crime categories, including the ones with economic reasons. Burkhardt et al. (2019) apply a similar strategy in a US county using a daily panel of observations on crime and air quality. They find that a 10% increase in fine particulates (PM2.5) is associated with a 0.14% increase in violent crimes, and a 10% increase in ozone with a 0.3% increase. They find no relationship with non-violent crime. Herrnstadt et al (2021) provides quasi-experimental evidence that air pollution affects violent criminal activity. They study crime in the city of Chicago from 2001 to 2012. Using episodes of decreased air quality associated to wind-direction, they estimate that a one-standard deviation decrease in PM10 pollution is associated with a 2.9 percent reduction in violent crime, but not property crime.

Those findings are consistent with research from biology and medicine that link air pollution and aggression. Also, these effects on crime manifest at pollution levels that are well below regulatory limits, consistent with the findings of pollution effects on productivity.

3 Policies

The interest of policy makers to manage traffic congestion and reduce pollutant emissions has led to the development and introduction of several environmental measures in urban areas. According to United Nations estimations, in 2050, two-thirds of the world´s population will live in urban areas. There are a wide range of policies that may lead to different results depending on the chosen measures and the countries or cities where they are implemented. This section reviews some studies that analyse and assess the effects of these policies, distinguishing between the type of tool implemented.[14] See Table 3 for further detail on a selection of papers.

A first measure with relatively little success is the introduction of driving license plate restrictions, implemented in Mexico and Bogotá. Davis (2008) analyses the effect of the *Hoy No Circula* (HNC) policy implemented in 1989 in Mexico, which includes bans to drivers from using their vehicles depending on the last digit of their license plate. Using data on gasoline sales and vehicles registrations the study concludes that HNC has not yielded the expected outcomes. On the contrary, it has led to an increase in the number of vehicles in circulation and has also increased the percentage of high-emission vehicles. Zhang et al. (2017) find comparable effects of a similar restriction in Bogota, Colombia. These authors study the air quality changes caused by the license-plate driving restrictions using information about the sources and chemistry composition of different air pollutants. In the case of Bogotá, the study detects a substitution effect associated to the purchase of a second car or to alternative modes of transportation that, under some circumstances, may even increase air pollution. Also, Zhang et al. (2017) find different results by air pollutant due to the heterogeneity in its sources and its atmospheric chemical composition, with a significant decrease in NO and a significant increase in NO_2, NOx, and O_3 after the implementation of the measure.

A second policy are Low Emission Zones (LEZs). They are defined as access restricted areas for certain road vehicles depending on the emission standard for which the vehicle was constructed. LEZs have been used in many countries with different results. Holman et al. (2015) evaluate the effects of LEZs in five countries of the Europe: Denmark, Germany, Netherlands, Italy and United Kingdom. The study obtains mixed results, possibly because LEZs may impose different degrees of restrictions and because it is also difficult to isolate the direct effect of LEZs from other policies. For the case of Germany, they observe that the country complies with the annual achievement for the EU limit values of concentration but that once confounding factors are taken into account the reduction in air pollution associated to LEZs is limited. Boogaard et al. (2012) evaluate the change in air pollution at the street level before and after the implementation of LEZ for trucks in five cities in Denmark. They do not find a significant decrease in air pollution concentrations in streets and urban locations subjected to LEZ when compared with the suburban locations taken as controls.

14 We do not consider the wide literature that considers taxes & subsidies –see Knittel and Sandler (forthcoming).

Table 3

SELECTED EVIDENCE ON POLICIES AIMED AT IMPROVING AIR QUALITY

Authors (Source)	Country	Main result (pollution)	Main result (other)
Panel A: Introduction of driving license plate restrictions			
1. Lucas Davis (JPE 2008)	Mexico	No effect on air quality of reform that bans most drivers from using their vehicles one weekday per week on the basis of the last digit of the vehicle's license plate	
2. Wei Zhang, C.-Y. Cynthia Lin Lawell, Victoria I. Umanskaya (JEEM 2017)	Colombia	Decreases NO and increases NO_2, NOx, and O_3	
PANEL B: Low emission zones			
1. Hendrik Wolff (EJ 2014)	Germany	Reduction of concentration of PM10 by 9%	The estimated health benefits of nearly 2 billion dollars have come at a cost of just over 1 billion dollars for upgrading the fleet of vehicles
2. Markus Gehrsitz (JEEM 2016)	Germany	Low emission zone decreases average levels of fine particulate matter by about 4 percent and by up to 8 percent at a city's highest-polluting monitor. Low emission zones also reduce the number of days per year on which legal pollution limits are exceeded by three	Reductions too small to translate into substantial improvements in infant health
3. Jose Enrique Galdon-Sanchez, Ricard Gil, Felix Holub, Guillermo Uriz-Uharte (JEEA 2022)	Spain	Low-emission zone (Madrid Central) reduces congestion and pollution	
4. Rafael Salas, Maria J.Perez-Villadoniga, Juan Prieto-Rodriguez, Ana Russo (TR, 2021)	Spain	Madrid Central LEZ, NO2 concentration set historical records well below the annual European Union established threshold of 40 $\mu g/m_3$	
PANEL C: Polution warnings			
1. Joshua Graff Zivin and Matthew Neidell (JEEM 2009)	United States	Alerts impact attendance at two popular outdoor venues in Los Angeles	
2. Aguilar-Gómez (WP 2020)	Mexico	Alerts do not affect air quality until the mitigation component, which limited transport emissions, was introduced	Alerts do not affect health outcomes until the mitigation component, which limited transport emissions, was introduced
PANEL D: Clean air act			
1. W. Reed Walker (QJE 2013)	United States	Significant reallocation costs, but below quantified health benefits	

NOTES: $\mu g/m_3$: micrograms per cubed meter. AER: American Economic Review, AEJ: EP American Economic Journal:Applied Economics, AEJ: EP American Economic Journal: Economic Policy, EJ: Economic Journal, JDEV: Journal of Development Economics, JEEA: Journal of the European Economic Association, JEEM: Journal of Environmental Economics and Management, JHE: Journal of Health Economics, JPUBE: Journal of Public Economics, LandEc: Land Economics, NBER WP: National Bureau of Economic Research working paper, PNAS: Proceedings of the National Academy of Sciences, QJE: Quarterly Journal of Economics, RESTAT: Review of Economics and Statistics, RESTUD: Review of Economic Studies, TR: Transportation Research.

Nevertheless, more recent studies do find that LEZs do increase air quality. Some of those studies use the fact that the introduction of LEZs was staggered across German cities between 2007 and 2016. The fact that different areas introduce LEZs in different moments permits disentangling the impact of the policy from other regional trends affecting both air quality and health outcomes. Firstly, Cyrys et al. (2014) assess the impact of 48 LEZ in Germany, finding a reduction of up to 10% in PM10 mass concentration. These authors highlight the decrease in soot concentration measured along major roads by 52% in 2010 in Berlin (with reference year 2007), and by 63% in 2012 (with reference year 2007) in the same city. PM10 is composed of several particles with different degrees of toxicity, but since diesel soot is the most dangerous for human health, the effects of LEZ may have had a greater positive effect on health than expected when only reduction of PM10 mass concentration was considered. Wolff (2014) also carries on a study about LEZs in Germany and estimates a cost for updating the fleet of vehicles of 1 billion dollars, which is compensated by health benefits of approximately 2 billion dollars and a reduction of particulate emissions by 9% after the entrance of the measure. Gehrsitz (2017) conducts a study about LEZs and its effects on air quality and birth outcomes in Germany. He compares the evolution of those outcomes around the introduction of LEZs exploiting the staggered adoption of the LEZs across the country and documents an average reduction in PM 10 by 4%. The effect increases to up to 8% when the city's monitors in the more highly polluted locations are considered. Nevertheless, the results cannot be translated to an improvement in infant health since they are too small to lead to a substantially improvement. Finally, Pestel and Wozny (2019) also find that the implementation of LEZs in Germany reduced the levels of air pollution in urban areas and detect a decrease of respiratory and cardiovascular diagnoses associated to pollution in hospitals located in or close to the LEZs. On the other hand, the introduction of LEZs did not have a discernible impact on birth weight. That finding is consistent with that of Gehrsitz (2017) and suggests that while LEZs may have positive impacts on the general population, there is weak evidence (at most) for an impact on infant health.

LEZ has also been implemented in Madrid, whose restricted area is known as "Madrid Central". Overall, the literature finds that "Madrid Central" has helped to reduce pollution within its boundaries, but there is not clear evidence on its effect on traffic outside them. Galdon-Sanchez et al. (2022) estimate a reduction in congestion and pollution by 15% and a change in the consumption pattern of customers affected by the regulation, who substitute their expenditures from brick-and-mortar to online shopping. This suggests that the rise in transportation costs caused by the policy may have been mitigated by e-commerce. Moreover, no significant effect is found on consumption spending inside the banned area. Salas et al. (2021) find a reduction of pollution (NO_2) in the "Madrid central" area. Furthermore, stations located near Madrid Central also exhibit significant, though smaller, reductions in NO_2 levels. Hence, the authors suggest that there may have been a positive spillover effect and that pollution was not transferred from the city centre to other nearby areas.

Another possible policy is the introduction of speed limits, but the results are again inconclusive. A possible reason is that the impact of speed limit reductions on local air quality is hard to predict, as the relationship between vehicle speed and pollution may not be monotonic.

Bel et al. (2015) found a reduction of NOx and PM10 following the introduction of an 80 km/h fixed speed limit in the Barcelona metropolitan area (where the previous maximum limit ranged from 100 to 120 km/h). The study shows statistical significance at the 90th quantile for NOx and at the 5th quantile for PM10.

Folgerø el al. (2020) study the impact of speed limits on local air pollution using a series of date-specific speed limit reductions in Oslo over the 2004–2011 period. They find that lowering the speed limit from 80 to 60 km/h reduces travel speed by 5.8 km/h. However, they find no evidence of reduced air pollution as measured next to the roads affected by speed limits. Their findings imply that policy makers may need to consider other actions than speed limit reductions to improve local air quality.

As a restrictive legislation worth highlighting is the Clean Air Act in the U.S. Chay and Greenstone (2003b) examine the effects of the CAA on air quality and infant health. As mentioned above nonattainment counties were required to adopt initiatives to lower pollution levels, while no action was needed in attainment counties. In that sense, attainment counties can be used to construct a counterfactual evolution of non-attainment counties had no intervention been adopted. If one compares nonattainment counties near to the federal ceiling to attainment counties below the target of the regulation, the first experimented a greater reduction in their emissions. Chay and Greenstone (2003b) find that a reduction by 1% in TSPs led to a decline in 0.5% in infant mortality rate from 1971 to 1972. However, to the extent that actions to reduce pollution entail firm closures the forced reallocation of workers can be costly. Walker (2013) precisely analyses those transitional costs of reallocating workers from regulated industries to other economic sectors after the implementation of the environmental policy. Taking the worker as the unit of analysis, he finds a statistically significant cost of CAA on labour. First, displaced employees in new regulated plants suffer from an increase in unemployment. Second, they perceive lower earnings in future employments. Those losses amount to more than 5.4 billion dollars for workers in the following years after the policy is introduced. Clay et al (2021) compare the evolution of attainment and non-attainment areas and, find that the CAA led to large and persistent decreases in output and productivity, but only for plants that opened before 1963, when the original CAA was introduced. They also find that the aggregate productivity losses of the CAA borne by the power sector were substantially mitigated by the reallocation of output from older less efficient power plants to newer plants.

In addition to environmental policy measures that focus on reducing pollution externalities through mitigation, other measures aim at reducing the harms from exposure by encouraging adaptation. These policies focus on encouraging people to reduce their emissions, on the one hand, and avoid exposure, on the other. The evidence about its efficacy is mixed. A first policy are pollution warnings. Graff Zivin and Neidell (2009) use turnstile data to show that alerts impact attendance at two popular outdoor venues in Los Angeles (Los Angeles Zoo and The Griffith Observatory) especially amongst those with children. However, if alerts are issued on two consecutive days, there is no statistically significant reduction on the second day. Noonan (2014) uses data from a small-scale survey of people passing two park benches in a 35-day period in Piedmont Park in Atlanta. He gets mixed results, finding no impact of alerts on the aggregate use of a major park but evidence consistent with reduced use by older people and joggers. In the case of air quality alerts in Sydney, estimates using administrative data indicate a reduction in cycling between 14% and 35%, depending on the econometric method used. On the contrary, Welch et al. (2005) find that the Ozone Action Days in Chicago do not significantly change subway ridership. Finally, Aguilar-Gomez (2020) studies the Mexico City Environmental Alerts Program in Mexico City. Before 2016, the program provided only information about high pollution levels in the form of alerts. In 2016, warnings were issued at the same pollution levels, but now mitigation measures were also undertaken. In particular, driving restrictions were to be put in place every time an alert was issued, forcing a number of vehicles (which depended on the level of the alert) to stay off the streets.

In conclusion, several measures can be implemented to improve air quality with generally positive results for those based on LEZs, mixed results for alert program used in isolation, and negative outcomes in the case of policies based on restrictions by driving license's plate. The findings vary across studies when these policies are linked to health improvement. It is also noticeable the need to increase data collection and its accuracy.

4 Final Remarks

This paper has reviewed the literature on the effects of air pollution, focusing on three main areas: mortality and health, labour supply and productivity, and human capital. It has also reviewed the evidence on some of the policies implemented to reduce air pollution, such as low emission zones.

Overall, the literature indicates that air pollution has detrimental health effects, especially for the elderly. Beyond that, there is also some evidence that air pollution may have negative non-health effects, reducing labour supply and productivity, although the evidence is more mixed on the latter aspect. Finally, there is no consensus on which policies to tackle air pollution may be more cost-effective.

Much progress has been made in recent years in identifying the causal effects of air pollution. The older papers usually relied on simple comparisons between the health outcomes of residents in areas exposed to pollution and the rest. However, these simple comparisons of outcomes might capture other characteristics of the neighbourhood, such as the income level or the provision of health services. More recent papers have been using better identification strategies, like sharp increases in pollution associated to changes in wind direction or intensity, that are arguably unrelated to confounding factors. Our reading of the literature, however, is that there are still several hurdles to overcome. First, one may worry about the existence of a "publication bias" in favour of those studies that find significant negative effects of air pollution. Second, and related to the first issue, there are many different pollutants and time frames to look at. This creates potential problems of "p-hacking" and multiple hypothesis testing. Finally, it has been hard to credibly establish the existence of non-linearities in the effects of air pollution, and whether there are clear thresholds in air pollutants that could be used as guidelines for policies. Some of these challenges are not specific to the air pollution literature, yet it is important to keep them in mind while evaluating it.

More research on air pollution is needed. In particular, more knowledge on the productivity effects of air pollution and the differences between indoor and outdoor activities (where the evidence has been mixed) and the non-linear and heterogeneous impacts of air pollution would be especially valuable.

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