Pollution and Mortality in the 19th Century*

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Abstract

Mortality was extremely high in the industrial cities of the 19th century, but little is known about the role played by pollution in generating this pattern, due largely to a lack of direct pollution measures. I overcome this problem by combining data on the local composition of industries in Britain with information on the intensity with which industries used polluting inputs. Using this new measure, I show that pollution had a strong impact on mortality as far back as the 1850s. Industrial pollution explains 40% of the relationship between mortality and population density in 1851-60, and nearly 60% of this relationship in 1900. Growing industrial coal use from 1851-1900 reduced life expectancy by at least 0.57 years. A back-of-the envelope estimate suggests that the value of this loss of life was equal to 0.33-1.00 of annual GDP in 1900. Overall, these results show that industrial pollution was a major cause of mortality in the 19th century, and that industrial growth during this period came at a substantial cost to health. JEL Codes: N33, N53, I10, Q53

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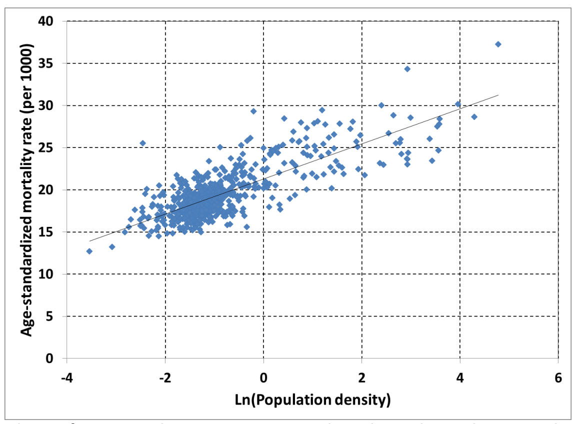
1 Introduction

In the 19th century, urban areas were incredibly unhealthy places to live. For example, Figure 1 describes the relationship between age-standardized mortality and district population density for 580 districts in England and Wales in 1851. Similar patterns have been shown for the United States (Cain & Hong (2009)), France (Kesztenbaum & Rosenthal (2011)), and other locations.

Figure 1: The Urban Mortality Penalty in England in 1851-1860



Mortality data for 580 districts in England and Wales, excluding London, averaged over 1851-1860 from the Registrar General's reports.

What caused the urban mortality penalty in the 19th century? One leading answer to this question is based on the disease environment. With a large population crowded closely together, the theory goes, infectious disease transmission increased. Particular emphasis has been placed on transmission through unsanitary water (Troesken (2002), Cutler & Miller (2005), Ferrie & Troesken (2008), Kesztenbaum & Rosenthal (2012), Alsan & Goldin (2014), Antman (2015)). A recent review suggests that the impact of the urban disease environment was so significant that, "The preponderance of the evidence suggests that the lack of improvement in mortality between 1820 and 1870 is due in large part to the greater spread of disease in newly enlarged cities" (Cutler *et al.* (2006), p. 102). A second potential cause may be poor nutrition, a channel emphasized by McKeown (1976), Fogel (2004), and Fogel & Costa (1997). If residents of larger cities were also poorer, or had less access to quality food, then poor nutrition may explain part of the urban mortality penalty.[1]

This paper highlights a third important determinant of mortality in the 19th century: industrial pollution. Pollution, particularly air pollution from coal burning in factories and homes, was a characteristic feature of British cities in the 19th century.[2] News reports complained that, "There was nothing more irritating than the unburnt carbon floating in the air; it fell on the air tubes of the human system, and formed a dark expectoration which was so injurious to the constitution; it gathered on the lungs and there accumulated."[3] A large literature studying pollution in modern economies has highlighted substantial health and mortality effects, primarily using data from the U.S. and Europe, where pollution levels are much lower than in the historical setting I consider.[4] Despite this evidence, pollution is often overlooked as an important determinant of mortality during the 19th century because we lack credible estimates of the magnitude of the impact of pollution during this period. This is largely because, outside of a few special cases, no direct pollution measures are available.

This paper makes four contributions to our understanding of the relationship between pollution and mortality. First, I construct a measure of local industrial pollution for Britain in the 19th century. The measure is based on data describing the local industrial structure together with information on the use of the main polluting input – coal – by each industry. This approach, which could be applied in a variety of settings, allows me to overcome the lack of direct pollution measures.

Second, I use this measure in order provide the first broad-based and well-identified estimates of the impact of industrial pollution on mortality in the 19th century. My baseline estimates, from 1851-1860, show that industrial pollution substantially raised mortality in the 19th century. A lower-bound estimate suggests that a one standard deviation increase in industrial pollution raised mortality by at least 0.8 percent. This impact is roughly similar to the total effect of major infectious diseases such as

[1]Nutritional deficiency may have been further exacerbated by the extra calories needed to fight infectious disease.

[2]Contemporary reports and the work of historians suggest that air pollution levels were extremely high in British cities during this period. Brimblecombe (1987) estimates that air pollution levels in London reached over 600 micrograms per cubic meter. For comparison, modern readings from Delhi, India are generally under 400 micrograms per cubic meter (Fouquet (2011)). Additional qualitative evidence comes from Mosley (2001), Thorsheim (2006) and others.

[3]*Times*, Feb. 7, 1882 p. 10, quoted from Troesken & Clay (2011).

[4]This literature is far too large to review here. Graff Zivin & Neidell (2013) provides a recent review of some of the literature in this area.

smallpox or diphtheria. This lowered life expectancy by at least 0.24 years. In heavily polluted cities, such as Manchester or Sheffield, the impacts would have been much larger.

Third, I show that industrial pollution explains roughly 40% of the urban mortality penalty in 1851-1860. Put another way, the impact of industrial pollution is about 70 percent as large as the impact of all other factors associated with population density, including infectious diseases. By 1900, industrial pollution explains nearly 60% of the urban mortality penalty, with an impact that is twice as large as other factors associated with density. These results show that one simply cannot understand urban mortality in the 19th century without accounting for industrial pollution.

Finally, this study provides evidence on the costs associated with rising industrial coal use from 1851-1900. Over this period, coal use increased by just under one ton per worker. Using long-difference regressions, I show that this reduced life-expectancy by 0.56 years. Back-of-the envelope estimates suggest that the monetary cost of the increased mortality associated with the increase in coal use intensity from 1851-1900 (a wealth effect) was equal to 0.33-1.00 of annual GDP in 1900. Thus, industry growth during this period came with important health costs.

In order to produce well-identified estimates, this study must address issues related to population sorting and omitted variables. One approach to dealing with these issues relies on the detailed cause-of-death information available in the data. In particular, I analyze the impact of industrial pollution on mortality due to respiratory diseases (bronchitis, asthma, etc.). Respiratory diseases are closely associated with the effects of airborne pollution and were also an important and growing cause-of-death in 19th century Britain. I define *excess respiratory mortality* as the percentage increase in respiratory mortality due to industrial pollution in excess of the percentage increase observed across all cause-of-death categories. This excess respiratory mortality will be free of selection concerns as long as those who select into more polluted areas are less healthy across a range of disease categories. Similarly, it will be free of omitted variables concerns unless those omitted variables specifically affect respiratory mortality.

As a second approach to dealing with population sorting issues, I look at variation in mortality patterns for workers holding the same occupation, using over 300 detailed occupational categories. Because occupation is a good reflection of income, education, and social class, looking within occupational categories should deal with most selection issues. Even within detailed occupational categories, I find strong evidence that mortality was higher in more polluted locations.

I also apply long-difference regressions over the 1851-1900 period. These allow me to estimate the impact of rising pollution on health while controlling for any fixed local features that may have influenced mortality in the cross-section. To deal with the possible endogeneity of local industry growth, I instrument for increasing industrial pollution intensity at the local level using each location's industrial composition in 1851 and national industry growth rates, as in Bartik (1991). This approach can be applied to both total mortality and excess respiratory mortality, allowing me to simultaneously address sorting and omitted variables concerns.

These results provide a new perspective on the sources of mortality during this important period of history. While current work emphasizes the role of the disease environment, my findings suggest that the impact of pollution should be given more weight. The evidence I provide fills an important hole in the historical literature and connects our understanding of historical mortality patterns to the substantial modern literature documenting the health effects of pollution.

Beyond improving our understanding of history, there are at least four reasons that the results documented in this paper are important. First, historical mortality experiences are regularly used to inform modern debates over pollution and health (see, e.g., Cutler *et al.* (2006) and Deaton (2013)). Second, when industrialization has substantial negative health effects, there may be important differences between measured GDP growth and actual welfare gains (Nordhaus & Tobin (1973)). In Britain, this will affect our assessment of the gains from increasing industrialization during the period I study, as well as the benefits of environmental improvements associated with the loss of heavy industry later in the 20th century. Documenting the health costs of rising industrialization in the 19th century is a first step towards a full accounting of these costs and benefits. Third, my results show that industrial pollution had an important impact on the spatial variation in health outcomes and may have generated population sorting. These historical patterns may be useful for understanding the roots of modern spatial inequality, a topic of current importance (see, e.g., Chetty *et al.* (2014)). Fourth, this study provides new evidence documenting the impact of pollution through both acute and chronic disease, over the long-run, in a high-pollution environment. This differs from most existing studies, which tend to focus acute effects and relatively low-pollution environments, though there are some important exceptions.[5]

This paper builds on a relatively small set of studies investigating the impact of pollution during the 19th and early 20th century. The closest of these, Troesken & Clay (2011), looks at the evolution of pollution in London in the late 19th century.[6] There is also an older line of related research debating the importance of pollution in 19th century cities ((Williamson, 1981b,a, 1982; Pollard, 1981)). For the mid-20th century, Barreca *et al.* (2014) show that the use of bituminous coal for home heating substantially increased mortality, while Clay *et al.* (2015) study the local impact of coal-fired power plants. In addition, a number of studies investigate the health impacts of particular pollution events in the 20th century (Townsend (1950), Logan (1953), Greenburg *et al.* (1962), Ball (2015)). Relative to existing contributions, this study extends our knowledge by providing evidence for an earlier period over a broad set of locations while accounting for a number of potential identification issues. My focus on industrial pollution also complements existing work, which has largely focused on residential pollution sources.

The next section provides background information on the empirical setting. Section 3 introduces the data. The analysis is presented in Section 4. Section 5 concludes.

2 Empirical Setting

2.1 Pollution in Victorian England

In England, pollution – particularly air pollution from coal burning – was a problem reaching back at least to the 17th century, when Evelyn published his Fumifugium (1661) decrying the smoke of London. This problem became much more acute in the 19th century, as industrialization took off and steam-driven factories expanded across

[5]Examples of studies looking at high-pollution environments include Greenstone & Hanna (2014) in India, Almond *et al.* (2009) and Chen *et al.* (2013) in China, Jayachandran (2009) in Indonesia, and Arceo *et al.* (forthcoming) in Mexico. Studies investigating the effects of pollution through chronic disease channels include Chen *et al.* (2013) and Anderson (2015).

[6]Other work focusing on pollution in the 19th century includes Fouquet (2011, 2012).

the country.[7]

In this study, much of the focus will be on pollution related to coal use. Coal was the main source of power during this period and the most important cause of industrial pollution. Domestic coal consumption in Britain rose from 60 million tons in 1854 to over 180 million tons in 1900.[8] Most of this coal was burnt by industry; data from Mitchell (1988) show that industrial consumption accounted for 60-65% of domestic coal use over the study period.[9] In addition to being the largest user of coal, industry was also geographically agglomerated, leading to substantial variation in industrial coal-use levels across locations.[10] Moreover, prior to electrification, power used in industry had to be generated on-site, so that most industrial coal use took place in urban areas. While industrial coal use tended to be less polluting, per ton, than other uses, the combination of concentrated production in urban locations and the high overall level of coal burnt suggests that industrial pollution was likely to have been an important contributor to overall pollution levels, particularly in urban areas.[11]

Of course, coal was not the only source of industrial pollution, nor was air pollution the only form that pollution took. Motivated by this, I will also consider a second approach to measuring industrial pollution, based on employment in a list of heavily pollution industries, which is not directly tied to coal use.

Despite high levels of pollution, regulation of polluting industries was limited (Thorsheim (2006), Fouquet (2012)). This feature was due to a combination of the strong laissez faire ideology that dominated British policy-making during this period

[7]Appendix A.1.1 describes estimated pollution levels in London starting in 1700 from Brimblecombe (1987) and Fouquet (2008).

[8]Coal prices in London and the main exporting ports were fairly constant over this period. This was despite increases in the pithead price of coal starting in the 1880's, which presumably were offset by falling transport costs. Graphs of coal consumption and prices are available in Appendix A.1.2. Data from Mitchell (1984) and Mitchell (1988).

[9]The 65% figure covers the industries included in my coal use measure, which span manufacturing and mining. Residential coal use accounted for roughly 25% of domestic coal consumption, while the remainder was used in utilities and transportation. See figure in Appendix A.1.2.

[10]It is worth noting that there was relatively little variation in the type of coal available across locations in England so we should not expect coal from different areas to imply substantially different levels of pollution. In contrast, in the U.S. some areas had large deposits of anthracite coal, which was cleaner than the bituminous coal available in other areas.

[11]Industrial use was cleaner relative to residential use because combustion was often more efficient and factory smoke-stacks deposited smoke at a higher altitude.

and the influence of local industrialists.[12] One consequences of lax regulation, together with generally low coal prices, was that industrial users had little incentive to invest in more efficient machinery or processes. As a result, contemporary sources such as the 1871 Coal Commission report suggest that there was substantial waste in industrial coal use through poor combustion, heat loss, and other channels (for details see Appendix A.1.3.

2.2 Mortality in Victorian England

Figure 2 describes the trend in overall mortality in England over the study period, as well as mortality due to the major infectious diseases and mortality due to respiratory diseases.[13] There are a couple of important patterns here. First, starting in the 1870s, overall mortality began to fall substantially, a pattern that continued through 1900. The reduction in overall mortality was driven by the fall in mortality due to infectious diseases, particularly tuberculosis, typhus, scarlet fever, and diarrhea & dysentery.[14] In contrast, mortality due to respiratory diseases, the category most closely associated with industrial pollution, was rising over most of the study period. This increase was particularly pronounced in the period before 1880, a period that also saw the greatest increases in coal use intensity (see Appendix A.1.2). By the 1891-1900 decade, respiratory mortality was accounting for as many deaths as all of the major infectious diseases combined.

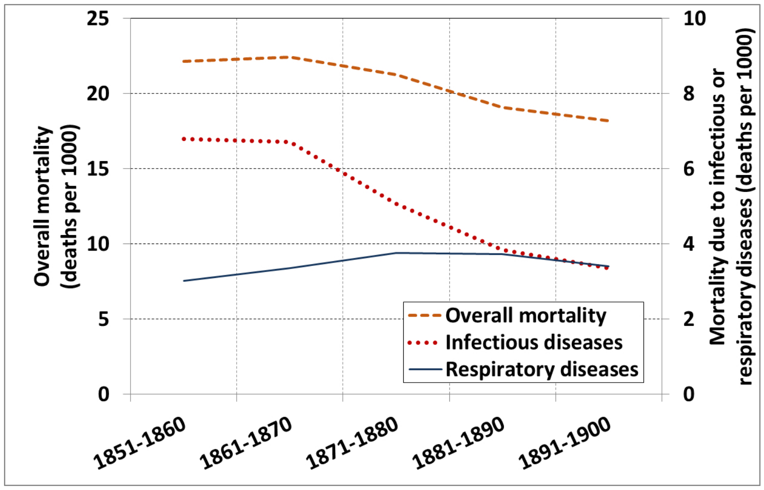
It is important to note that the increase in deaths attributed to respiratory diseases was rising from 1851-1870, before the major reductions in infectious diseases. This suggests that the rise in respiratory deaths was not a consequence of the fall in infectious disease mortality.

[12]While national acts regulating pollution were passed during this period, including the the Sanitary Act of 1866, the Public Health Act of 1875 and the Public Health (London) act of 1891, historical sources suggest that these measures had limited effectiveness, though there is some evidence that they began to influence outcomes in the last two decades of the 19th century.

[13]The respiratory disease category contains a variety of diseases, the most important of which are bronchitis, asthma, pneumonia, pleurisy, and influenza. This category may contain both non-infectious and some infectious diseases.

[14]A more detailed breakdown of the mortality patterns in specific cause-of-death categories is available in Appendix A.1.4.

Figure 2: Mortality in England & Wales, 1851-1900



The infectious diseases included are cholera, diarrhea & dysentery, diphtheria, measles, scarlet fever, smallpox, tuberculosis, typhus and whooping cough. The respiratory disease category includes a variety of diseases of the respiratory system, including bronchitis, pneumonia and asthma.

3 Data and Measurement

One unique feature of the historical setting I consider is that detailed mortality data are available from the Registrar General's reports. The data I use come from the decennial supplements and provide mortality averages by decade, from 1851-1900.[15] The data were collected by an extensive system aimed at registering every birth, marriage, and death in England and Wales. Of the data collected by the Registrar's office, those on mortality are considered to be the most accurate and comprehensive, the "shining star of the Victorian civil registration" (Woods (2000)).[16] While not

[15] These data were obtained from Woods (1997) through the UK Data Archive. The analysis ends in 1900 because after that point the cause of death categories change, making it difficult to construct consistent cause-of-death series beyond that point.

[16] For every death, registration with the local official (the "Registrar") was required within five days before the body could be legally disposed of. The Registrar was required to document the gender, age, and occupation of the deceased, together with the cause of death. The Registrar General's office put a substantial amount of effort into improving the registration of causes of death in the 1840s. This included sending circulars to all registrars and medical professionals, constructing a standardized set of disease nosologies, and providing registrars and medical professionals with standardized blank

perfect, relative to other mortality data available for the 19th century, these data provide a unique level of comprehensiveness, detail, and accuracy.

This study will focus primarily on all-age mortality. When doing so, I adjust for differential mortality patterns at different ages in order to generate age-standardized mortality values. The formula is $MORT_d = \sum_g^G MR_{gd} PS_g$ where $MORT_d$ is the age-standardized mortality rate for district d, MR_{gd} is the raw mortality rate in age-group g in district d and PS_g is the share of population in age-group g in the country as a whole. Thus, this formula adjusts a location's mortality rate to account for deviations in the age distribution of residents from the national age distribution.

In general, London is excluded from the analysis because it represents a substantial outlier in many ways. London was much larger than other British cities and extremely dense, with very high death rates in some parts of the city. In the robustness exercises I consider estimates obtained while including London and I find that this does not substantially impact the results.

The second key ingredient for this study is a measure of local industrial pollution. The pollution measures that I construct are based on the industrial composition of local areas. Data on the industrial composition is available from the Census of Population, which collected data on the occupation of each person (a full census, not a sample). The occupational categories generally correspond closely to what we think of as industries.[17] These data are reported for workers aged twenty and older for over 600 districts covering all of England and Wales 1851, and for 55 counties in each decade starting in 1851.[18] To obtain consistent series over time, I collapse the reported occupations into 26 industry categories covering nearly the entire private sector economy, including manufacturing, construction, services, and transportation, following Hanlon & Miscio (2014).[19]

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cause-of-death certificates. These efforts paid off with more accurate data in the 1850s and beyond. Thus, while there is surely some measurement error in the cause-of-death reporting, the error rates are not likely to be too large, particularly in the broad cause-of-death categories used in this analysis. Woods (2000) suggests that the statistics most prone to reporting error were live births and infant deaths. This is one motivation for focusing on all-age mortality in this study.

[17]Examples include "Cotton textile worker" and "Boot and shoe maker."

[18]District-level occupation data are reported only in 1851-1871, after which reporting at this level of detail was discontinued. There were around 600 districts in England and Wales, divided into 55 counties, with Yorkshire divided into the West Riding, East Riding, and North Riding.

[19]See Hanlon & Miscio (2014) and the online data appendix to that paper, available at `http://www.econ.ucla.edu/whanlon/appendices/hanlon_miscio_data_appendix.pdf`, for further details about the Census of Population Occupation data.

My primary measure of local pollution is based on industrial coal use. I model coal use at the district level in a particular year t as made up of three components: local employment in industry i in district d and year t, denoted L_{idt}, the coal use intensity in that industry θ_i, and a time-varying term representing efficiency gains in coal use, which I denote ψ_t. Putting these together, the overall level of coal burnt in a district in a year is,

$$COAL_{dt} = \psi_t \sum_i \theta_i L_{idt} \,, \tag{1}$$

District employment in industry i is available from the Census of Population occupation data, while industry coal use per worker is obtained from the 1907 Census of Production. The third term, ψ_t, reflects growth in coal use per worker over time. This is calculated by comparing data on national coal use to the coal use measure based on industry employment and industry coal use intensity.[20] Note that the ψ_t term will not play a role in cross-sectional regressions, where it will be absorbed into the constant, but it will matter in the long-difference regressions.

Implicit in this approach is the assumption that the *relative* coal intensity per worker across industries did not change substantially over time. In Appendix A.2.1, I provide evidence that this assumption is reasonable by comparing industry coal use intensity in 1907 and 1924.[21] As an additional test of the coal use measure, I use data on county-level industrial coal use in 1871 from the Coal Commission Report and show that my approach does a reasonable job of reproducing county-level industrial coal use in that year. Details of this check are available in Appendix A.2.2.

As a second measure of local pollution, I use a list of polluting industries constructed for the modern period by the Chinese government.[22] This list is consistent

[20] To be specific, this term is calculated using national-level data. The formula is $\psi_t = COAL_t / \sum_i L_{it}\theta_i$, where $COAL_t$ is national industrial coal use data obtained from Mitchell (1984), L_{it} is national employment in industry i, and θ_i is industry coal use intensity.

[21] Similar data are not available before 1907, so it is necessary to run this test on data after 1907. However, if anything we should expect larger changes between the 1907-1924 period than in the 1851-1907 period. This is because the sources of industrial power were fairly stable from 1851-1907, while the introduction of electricity means that we should see more changes in the 1907-1924 period. Thus, the fact that I find stable patterns in the 1907-1924 period suggests that the patterns were also likely to have been stable before 1907.

[22] Williamson (1981b) uses a somewhat similar methodology in which he focuses on only employment in mining and manufacturing. See Hanlon & Tian (2015) and the online appendix to that paper for further details.

with qualitative historical evidence on the main polluting industries during the period I study and also corresponds fairly closely to the set of heavy coal-using industries based on the 1907 Census of Production. Given the set of dirty industries D, this measure of pollution in a district is the level of district employment in these "dirty" industries, i.e., $DIRTYemp_{ct} = \sum_{i \in D} L_{ict}$.

Table 1 describes the polluting industries included in the database, their national employment, coal use per worker, and an indicator for whether they are on the list of heavily-polluting industries. Coal use per worker varies substantially across industries. The most intensive users, such as Earthenware & Bricks, Metal & Machinery, and Chemicals & Drugs, are often those that use coal to provide heat, for example to melt iron or fire bricks. Moderate coal-using industries such as Textiles, Mining, and Leather, use coal primarily to run engines for motive power. Industries such as Apparel, Tobacco, and Instruments & Jewelry, use very little coal per worker. Services, which are not on this list, are assumed to have a negligible amount of coal use per worker.[23] The last column of Table 1 shows that the list of heavily polluting industries corresponds fairly well to the list of coal-intensive industries.

The large variation in industry coal intensity means that locations specializing in industries such as iron and steel production will have much higher overall coal use than those specializing in services, trade, or light manufacturing. This variation is illustrated in Table 2, which describes various pollution measures for a set of districts with similar populations but widely varying levels of heavy industry. Coal use was substantially higher in districts specializing in heavy industry, such as Stoke-on-Trent, where pottery was a major part of the economy, and Durham, a coal mining and metals center. Districts such as Macclesfield and Norwich, which specialized in textiles and other light manufacturing, show moderate levels of pollution intensity. Bath, a resort district with an economy largely specialized in services, shows much lower levels of pollution intensity than the others.

[23] I also exclude public utilities when constructing the pollution measures. Some public utilities, particularly gas, were important coal users and did create local pollution. However, by converting coal into gas which was then pumped into cities, this industry may have actually decreased pollution in city centers. Thus, these industries are excluded because of their ambiguous effects on local pollution and local health.

Table 1: Industry employment in 1851, coal use, and pollution indicators

Industry	**National employment**	**Coal use per worker**	**Dirty industry?**
Earthenware, bricks, etc.	135,214	48.9	Yes
Metal and engine manufacturing	894,159	43.7	Yes
Chemical and drug manufacturing	61,442	40.1	Yes
Mining related	653,359	28.9	Yes
Oil, soap, etc. production	54,751	20.7	
Brewing and beverages	100,821	19.4	Yes
Leather, hair goods production	27,146	12.1	Yes
Food processing	220,860	12.0	
Textile production	1,066,735	10.1	Yes
Paper and publishing	226,894	9.7	Yes
Shipbuilding	169,770	6.1	
Wood furniture, etc., production	114,014	5.4	
Vehicle production	53,902	2.6	
Instruments, jewelry, etc.	43,296	2.0	
Apparel	243,968	1.6	
Construction	169,770	1.6	
Tobacco products	35,258	1.1	

Coal per worker values come from the 1907 Census of Production. The number of workers in the industry in 1851 come from the Census of Population Occupation reports.

Table 2: Pollution indicators for a set of districts of similar size, 1851-1860

District	**Mean District Pop.**	**District Pop. Density**	**Mortality Rate**	**Log Coal Use**	**Log Dirty Ind. Emp.**	**Coal use per worker**	**Dirty ind. emp. share**
Stoke-upon-Trent	64,625	2.84	28.1	13.16	9.34	26.41	0.58
Durham	63,113	0.30	22.7	12.44	8.99	14.33	0.46
Macclesfield	62,434	0.43	26.2	12.16	9.49	7.74	0.53
Norwich	71,317	9.38	24.3	11.94	8.85	5.66	0.26
Bath	69,091	1.37	21.6	11.41	7.85	3.23	0.09

I have also collected variables describing population density, district location, and several other factors that may have influenced health during this period.[24] Because of

[24]The district location data are based on geographic coordinates that were collected by hand.

the importance of clean water in influencing mortality during this period, I construct a control for the water services provided in each district. This variable is based on the number of persons employed in providing water services, either public or private, per 10,000 of district population, based on occupation data from the Census of Population. Similarly, I construct a variable representing the number of persons employed in medical occupations, per 10,000 of district population.[25] I also construct a control variable for the tonnage of imports passing through the major ports of Britain, based on data from the Annual Statement of Trade and Navigation for 1865. This is an important control because international trade played a role in the spread of disease. Summary statistics for all of these variables are reported in Appendix A.2.3.

4 Analysis

This section begins with a discussion of the main identification issues that must be addressed in the analysis and how I will deal with them. Next, I present baseline cross-sectional results using district-level data from 1851-1860. I then look at evidence on mortality for workers sharing the same occupational category, followed by an analysis of the causes-of-death. Last, I study the evolving relationship between pollution and mortality from 1851-1900 using county-level panel data.

4.1 Discussion of analysis issues

Selection: One potential issue in this analysis is the selection of less-healthy populations into more polluted areas.[26] This study offers two alternative approaches

These reflect the latitude and longitude for the main population or administrative center of each district. For a few very rural districts, where there was no clear population or administrative center, the geographic center was used.

[25]The occupations included in this category are physicians, surgeons, other medical men, dentists, nurses (not domestic) and midwives.

[26]Selection is a common identification concern in this literature. This issue is particularly important for the urban districts I study, which saw substantial in-migration from rural areas, as well as Ireland and Scotland. One approach for dealing with selection issues is to take advantage of sharp changes in local pollution levels and then look at the impact on health in the short-run, before the population has time to re-sort. Examples of studies of this type include Chay & Greenstone (2003) and Currie & Neidell (2005). However, it is difficult to capture the chronic effects related to long-term exposure with an approach of this type. A unique alternative approach is offered by Lleras-Muney (2010), who looks at health in military families, where compulsory relocation reduces selection concerns. A third approach, taken by Chen *et al.* (2013), is to study China, where gov-

to addressing potential selection issues. First, I analyze death patterns within occupation categories (Section 4.3). Since occupation is a good indicator of income, education, and class, this should substantially reduce selection issues. Second, I use information on causes-of-death and compare the increase in respiratory mortality, the category most closely associated with airborne pollution, to mortality due to all other causes (Section 4.4). These estimates will be free of selection concerns under the assumption that if less healthy populations select into more polluted areas, they will be unhealthy across a range of disease categories.[27]

Omitted variables: We may also be concerned that there are omitted variables that are correlated with the the local presence of polluting industries and also affect mortality. One way to deal with this issue is by exploiting the cause-of-death data. The cause-of-death results I present will be robust to omitted variables unless they specifically affect respiratory disease mortality. Further evidence against omitted variables is provided by the long-difference regressions (Section 4.5).

Acute vs. chronic effects: Pollution can have both chronic effects, such as lung diseases caused by long-term exposure to air pollution, and acute effects, such as heart attacks related to a particularly bad pollution day.[28] The mortality patterns documented in this study will reflect both of these channels. Separating the chronic and acute effects of pollution is an important direction for future research, but is beyond the scope of this study.

Migration: Migration and travel can potentially affect the results if people are exposed to pollution in one location but die in another. In general, migration will bias the estimated impact of pollution towards zero.[29] As a result, the estimates described in this study should be thought of as providing a lower bound on the true impact of pollution on mortality. A related issue is that people from healthy areas may travel into a more polluted area, die as the result of short-term pollution exposure, and

ernment restrictions reduce mobility between areas. For further discussion of selection issues in the modern pollution and health literature, see Graff Zivin & Neidell (2013).

[27]The use of cause-of-death data to address selection and omitted variables concerns in this context is similar to the approach taken in previous work by Galiani *et al.* (2005).

[28]A recent paper highlighting the acute effects of air pollution is Schlenker & Walker (2014).

[29]To see why, suppose that regardless of the location of exposure, the location of death is random. In that case I would estimate no relationship between pollution and mortality. In contrast, if the location of death matches the location of exposure exactly then there will be no bias in the estimated effects. In reality, my data will fall somewhere in between, implying that the estimated impact of pollution will be biased towards zero.

be counted in the mortality figures for that district. This would be captured in the estimated relationship between pollution and mortality, and rightly so, as it reflects the acute effects of pollution.

Income: We may be concerned that wage levels were lower in more polluting industries, which could influence mortality. This concern will be dealt with along with other selection effects. Moreover, evidence suggests that polluting industries tended to pay high wages, and that, even within occupation, higher wages were paid as a compensating differential in more polluted areas.[30] Thus, if anything income effects will exert a downward bias on the pollution effects I estimate.

On-the-job mortality: We may be concerned that the results are picking up other effects of industrial composition on mortality, such as on-the-job accidents. This concern will be addressed by both the analysis of mortality within occupation categories and by the cause-of-death results. A related issue is whether pollution exposure occurs on-the-job or elsewhere. In this study I do not seek to differentiate between these two types of exposure to pollution, though some evidence, such as mortality for the very young, will reflect only exposure outside of the workplace.

Residential pollution: Pollution from residential sources made a substantial contribution to overall pollution during this period, particularly in London. However, the results in this study are focused only on industrial pollution and should not be interpreted as including the impact of residential pollution. The impact of residential pollution will largely be captured by control variables, particularly population density, as well as controls for region and latitude, which will capture a variety of factors that can influence residential pollution levels including weather and local coal prices.

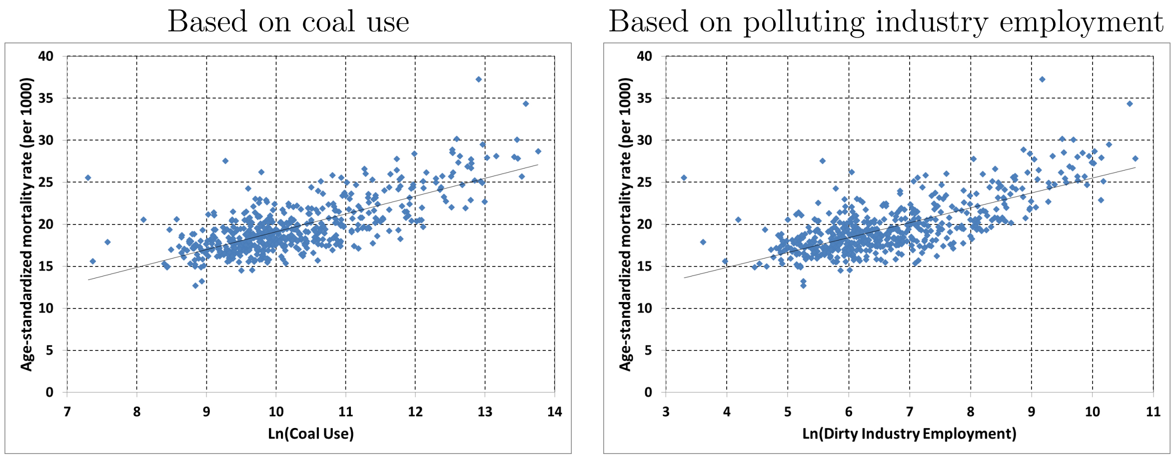
4.2 Baseline analysis, 1851-1860

The first step in the analysis is to decide upon the specific functional form used to represent the relationship between pollution and mortality. An ideal measure should reflect the intensity of the pollution exposure experienced by district residents. In the main analysis, I will use two main measures of local industry pollution inten-

[30]Wage data from Bowley (1972) are available in Appendix A.2.4. Evidence from (Williamson, 1981b, 1982) and Hanlon (2014) suggests that, even within occupations, workers were compensated for living in more polluted locations with wages that were higher relative to the local cost of living, though both of these studies find that the compensating differential was not too large.

sity: the log of coal use in a district and the log of dirty industry employment in a district.[31] Figure 3 describes the relationship between these pollution measures and age-standardized mortality at the district level. For both pollution measures we observe a strong positive relationship to mortality. Moreover, the relationship appears to be close to linear, suggesting that modeling pollution in this way is reasonable. In addition, I will examine a range of alternative pollution measures and show that these deliver similar results.

Figure 3: Pollution and mortality in England and Wales in 1851-1860



The pollution measures are based on the industrial composition of the districts in 1851. The mortality rate is age-standardized and calculated using data from 1851-1860. The two outliers in the top right of the graph are Liverpool and Manchester. The outlier in the top left of the graph is Hoo, a rural district at the mouth of the Thames, directly downstream and downwind from London. Districts in London are not included.

Figure 4 provides maps of district-level age-standardized mortality, population density, coal use, and dirty industry employment, the key ingredients in the present study. All of these variables display similar geographic patterns, with high levels in the industrial districts of Northwest England, as well as the areas around London, Birmingham, Cardiff, Bristol, Newcastle-upon-Tyne, and in Cornwall.

[31]Because the pollution measures are in logs, this suggests a concave relationship between pollution and mortality, which is consistent with existing evidence from Pope III *et al.* (2011) and Clay *et al.* (2015).

Figure 4: Maps of the pollution measures, density and overall mortality

Colors correspond to quantiles of each variable, where darker colors indicate higher values. I am grateful to the Cambridge Project on The Occupational Structure of Nineteenth Century Britain (funded by the Economic and Social Research Council) for their generosity in providing me with shapefiles for the 1851 Registration Districts.

Next, I undertake some simple cross-sectional regressions using pollution measures based on the industrial composition of districts in 1851 and mortality data for 1851-1860. The regression specification is,

$$MORT_d = \beta_0 + \beta_1 \ln(DENSITY_d) + \beta_2 \ln(POLL_d) + X_d\Lambda + R_d + \epsilon_d \,, \qquad (2)$$

where $MORT_d$ is the average age-standardized mortality rate over a decade in thousands of people per year in district d, $DENSITY_d$ is the population density, $POLL_d$ is one of the measures of local pollution, X_d is a vector of control variables, and R_d is a set of region indicator variables.[32]

To ease the interpretation of the results, I standardize the $\ln(DENSITY_d)$ and $\ln(POLL_d)$ variables, as well as the control variables for employment in water provision or medical services, to have a mean of zero and standard deviation of one. Because spatial correlation may be an issue here, I allow correlated standard errors between any pair of districts within 50km of each other, following Conley (1999).[33]

There may be a lag between the time at which pollution took place and when the effect on mortality appeared. In the cross-sectional regressions presented in this subsection this issue can largely be ignored because both pollution and mortality levels are fairly stable from one decade to another. Also note that, because the variables are in logs, the ψ_t term from Eq. 1 will be absorbed into the constant in Eq. 2.

Table 3 presents baseline cross-sectional results. The first three columns look separately at population density and the two pollution measures. Individually, each of these has a positive and statistically significant relationship to mortality. Columns 4 and 5 each combine the population density variables with one of the pollution measures. Columns 6-7 add in additional control variables for water and medical services in each district, the amount of seaborne trade, latitude, and a set of region indicator variables.

The results with the full set of control variables, in Columns 6-7, suggest that industrial pollution is associated with a mortality rate that is higher by just under one death per thousand. For comparison, the average age-standardized mortality rage across all districts (excluding London) was 19.6 deaths per thousand. The impact of

[32]The regions are Southeast, Southwest, East, South Midlands, West Midlands, North Midlands, Northwest, Yorkshire, Northern England, South Wales and North Wales.

[33]I implement this using code provided by Hsiang (2010). I have explored allowing spatial correlation over alternative distances and the results are not sensitive to reasonable alternatives. As an alternative, I have also calculated results clustering by county. This does not have any meaningful impact on the statistical significance of the results.

a one standard deviation increase in population density is just over 1.8 deaths per thousand. This suggests that the impact of industrial pollution is more than half as large as all of the other factors associated with density. Moreover, note that the coefficient on population density drops from 2.5 when industrial pollution is not included (Column 1) to 1.7-1.8 when industrial pollution is included in the regression (Columns 4-7). This suggests that industrial pollution is explaining roughly one third of the relationship between mortality and population density across districts. It is also worth highlighting that including just the population density and industrial pollution variables in the regression explains a substantial portion of the spatial variation in mortality rates during this period.

Table 3: Baseline cross-sectional regression results, 1851-1860

	DV: Age-standardized mortality						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ln(Pop. Density)	2.502***			1.724***	1.777***	1.846***	1.870***
	(0.251)			(0.127)	(0.120)	(0.112)	(0.0985)
Ln(Coal use)		2.321***		1.241***		0.980***	
		(0.254)		(0.216)		(0.189)	
Ln(Dirty emp.)			2.277***		1.227***		0.976***
			(0.234)		(0.200)		(0.183)
Water service emp.						-0.126	-0.107
						(0.110)	(0.110)
Medical service emp.						-0.247**	-0.209**
						(0.105)	(0.104)
Seaport tonnage						1.635***	1.863***
						(0.296)	(0.277)
Latitude						0.0882	0.0579
						(0.260)	(0.271)
Constant	19.58***	19.58***	19.58***	19.58***	19.58***	15.14	16.75
	(0.254)	(0.194)	(0.180)	(0.168)	(0.155)	(13.62)	(14.17)
Observations	580	580	580	580	580	580	580
R-squared	0.616	0.531	0.510	0.708	0.713	0.757	0.756

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, allow spatial correlation between districts within 50km of each other. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. The population density, coal use, dirty industry employment, water services, and medical services variables are standardized. Data cover all districts in England & Wales outside of London.

In the regressions described in Table 3, each district is treated as one observation with equal weight, regardless of district size. Alternatively, we may want to put greater weight on districts with larger populations. Appendix A.3.1 provides regression results obtained while weighting districts based on their average population size over the decade. Weighting has relatively little impact on the results, due largely to the fact that districts do not vary too much in size (as opposed to counties, where variation is more important). Given the similarity between weighted and unweighted regression results when using district data, for the remainder of this subsection I present only results from unweighted regressions.

In the results presented thus far, districts in London have been excluded because they represent substantial outliers along a number of dimensions relative to the rest of the country. In Appendix A.3.1 I present results mirroring those shown in Table 3 but including London. Results obtained when including districts in London are similar to the results described above. I have also generated results allowing more flexible population density controls. This does not substantially affect my findings.

We may be concerned that the strong relationship between industrial pollution and mortality observed in Table 3 is dependent on choices about the functional forms used for the pollution variables. To check this, Table 4 presents estimates based on a variety of alternative functional forms. Column 1 uses coal per worker. Column 2 uses the share of employment in heavily-polluting industries. Columns 3 and 4 use the log of coal use per acre and the log of dirty industry employment per acre, respectively. Columns 5 and 6 include, separately, variables representing employment in heavily polluting industries and in all other industries ("Clean emp.").[34]

All of these alternative functional forms suggests that industrial pollution had a significant impact on mortality. In general, the magnitudes are all similar to those obtained in Table 3, except that the results are particularly strong when using coal per acre or dirty industry employment per acre. This may be because these are better measures of pollution exposure in a district; however, because these variables are highly correlated with population density there is some concern that the pollution variables in Columns 3-4 are picking up some population density effects. In Columns 5 and 6, it is particularly interesting to see that, while employment in heavily polluting industries is associated with increased mortality, employment in relatively less polluting industries is strongly associated with lower mortality. This is consistent with the reduction in mortality that we would expect to be associated with increased

[34]Clean and dirty employment do not sum to district population because there is a substantial unemployed population in each district, including children, elderly, and non-workers.

income or work in healthier occupations such as agriculture.

Table 4: Results with alternative functional forms

	DV: Age-standardized mortality					
	(1)	(2)	(3)	(4)	(5)	(6)
Ln(Pop. Density)	2.023***	1.920***	0.0644	0.851***	1.902***	4.004***
	(0.144)	(0.112)	(0.341)	(0.213)	(0.101)	(0.947)
Coal per worker	0.866***					
	(0.145)					
Dirty emp. share		1.055***				
		(0.133)				
Ln(Coal per acre)			2.469***			
			(0.383)			
Ln(Dirty emp./acre)				1.722***		0.933***
				(0.286)		(0.339)
Ln(Dirty emp.)					1.172***	
					(0.180)	
Ln(Clean emp.)					-0.317***	
					(0.121)	
Ln(Clean emp./acre)						-2.541***
						(0.771)
Region controls	Yes	Yes	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	580	580	580	580	580	580
R-squared	0.762	0.771	0.760	0.752	0.760	0.760

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, allow spatial correlation between any districts within 50km of each other. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. Other control variables include employment in water services per 10,000 population in 1851, employment in medical services per 10,000 population in 1851, latitude and seaport tonnage in 1865. Population density and all of the pollution measures are standardized.

Regressions for specific age categories show that pollution effects are found among both adults and young children (see Appendix A.3.1). One way to summarize the impact of industrial pollution on mortality at different ages is by calculating the impact on life expectancy. To do so, I begin by estimating the impact of industrial coal use on mortality in the available age categories and then use the results to calculate life expectancy given the average level of coal use in the data and when coal use is one standard deviation above the mean.[35] This exercise suggests that in a

[35]The nature of the data means that these life expectancy calculations are somewhat rough. Data are only available at either five or ten-year age intervals. Also, I consider only years lived up to age 75 because the available mortality data become less reliable at older ages.

district with industrial coal use that is one standard deviation above the mean, life expectancy at birth is lower by 1.27 years while life expectancy at age twenty is lower by 0.18 years.[36]

The results presented in this section reveal a strong relationship between industrial pollution and mortality. This relationship may be due to the direct effects of pollution on health or to the selection of less healthy populations into more polluted areas. We may also be concerned about the role of omitted variables in this analysis. In the next two subsections I offer two approaches that help me deal with these concerns.

4.3 Mortality within occupational categories

One way to deal with potential selection issues is to look at the geographic variation in mortality for workers sharing the same occupational category. Information on mortality by occupation and location is available from a special section of the Registrar General's report for 1851. This report lists the number of living workers and number of deaths for 304 occupation categories for male workers aged twenty and above in 44 English & Welsh counties.[37] These occupational categories are quite detailed.[38]

To analyze these data I use the following regression specification,

$$MR_{ic} = \beta_0 + \beta_1 \ln(DENSITY_c) + \beta_2 \ln(POLL_c) + I_i + \epsilon_{ic}\,, \tag{3}$$

where MR_{ic} is the ratio of deaths in occupation i and county c per thousand living workers, I_i is a full set of occupation effects, and the other variables are defined as before. Standard errors are clustered at the county level.[39] These data do not include age information, so the dependent variable is not age-standardized. The regressions

[36]The difference between these values reflects the substantial impact of pollution on child mortality, as suggested by Table 20.

[37]The number of counties available in these data is smaller than the number available in some of the other county-level data sets because the Welsh data are reported only for North Wales and South Wales, rather than for specific Welsh counties. London is not included in the analysis.

[38]Some examples can be useful for illustrating this point. Within the legal profession, for example, the data differentiate between Barristers, Solicitors, Other Lawyers, Law Clerks, and Law Court Officers & Stationers. Among construction workers there are ten different categories, including Carpenters & Joiners, Bricklayers, Plumbers & Painters, Paperhangers, Slaters, Masons, and Plasterers. Among iron & steel workers there are separate categories for Anchorsmiths, Filemakers, Cutlers, Needle makers, Boilermakers and numerous others.

[39]Given the large sizes of the counties, using spatially correlated standard errors makes less sense in this context than when dealing with the district-level data.

are weighted based on the population of living workers in each occupation-county cell to account for the fact that observations will be noisier in cells with fewer workers.

Regressions are run on the full set of occupation data as well as on a more limited list of 89 non-industrial occupations that are found in substantial numbers in all locations. This list include various agricultural workers, national and local government workers, professionals (lawyers, doctors, teachers), businessmen, shopkeepers, innkeepers, domestic servants, and messengers & porters.[40] These occupations were less related to local industrial structure, yet these workers were still be exposed to the effects of local pollution.

Table 5 presents results using all occupations, in Columns 1-2, and the set of non-industrial occupations, in Columns 3-4.[41] These results suggest that, even within occupational categories, mortality was higher in counties with higher levels of industrial pollution. When all occupations are included I find that a one standard deviation increase in pollution raised mortality by 0.42-0.48 deaths per thousand among working men twenty and over, which is equal to over 3% of mortality for this population. My preferred results, in Columns 3-4, suggest that a one standard deviation increase in pollution was associated with an increase in occupation-specific mortality of 0.86-0.92 deaths per thousand. Thus, a one standard deviation increase in industrial pollution is associated with an 8% increase in overall mortality within these non-industrial occupations. In contrast, I find no evidence that density increased mortality among this working adult population. This is consistent with the age results, which show that most of the impact of density is concentrated among children and the elderly.

To assess the impact of population sorting in these findings, we can compare to results obtained while pooling workers from all occupations. These results, in Table 6, show that ignoring occupation leads to estimated pollution effects that are around three times as large as those estimated within occupational categories. Thus, the sorting of different types of workers into different locations has a substantial impact on the estimated relationship between pollution and mortality.

[40]The national government worker category does not include members of the military.

[41]London is not included in the results shown in Tables 5-6. For results with London included, see Appendix A.3.2.

Table 5: Impact of pollution on mortality when controlling for occupation

	DV: Deaths per 1000 workers within each occupation			
	All occupations (304)		**Non-industry occupations (89)**	
	(1)	(2)	(3)	(4)
Ln(Coal use)	0.423*		0.859***	
	(0.234)		(0.278)	
Ln(Dirty industry emp.)		0.478**		0.916***
		(0.224)		(0.266)
Ln(Population Density)	-0.242	-0.307	-0.289	-0.376
	(0.254)	(0.247)	(0.326)	(0.321)
Constant	73.40**	73.39**	73.10**	73.08**
	(30.44)	(30.44)	(30.28)	(30.28)
Occupation effects	Yes	Yes	Yes	Yes
Observations	11,647	11,647	3,766	3,766
R-squared	0.299	0.299	0.604	0.604

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered at the county level. Data cover working males aged twenty and over. Pollution measures are based on each district's industrial composition in 1851. Population density and both of the pollution measures are standardized. Regressions are estimated with analytical weights based on the number of living workers in each county-occupation cell. County-occupation cells with no living workers are dropped.

Table 6: Pooling workers from all occupational categories

	DV: Deaths per 1000			
	All occupations (304)		**Non-industry occupations (89)**	
	(1)	(2)	(3)	(4)
Ln(Coal use)	1.451***		2.763***	
	(0.318)		(0.335)	
Ln(Dirty industry emp.)		1.375***		2.793***
		(0.311)		(0.349)
Ln(Population Density)	-0.337	-0.382	-0.356	-0.568
	(0.291)	(0.304)	(0.404)	(0.396)
Constant	13.04***	13.09***	10.15***	10.20***
	(0.278)	(0.282)	(0.296)	(0.287)
Observations	44	44	44	44
R-squared	0.420	0.411	0.681	0.715

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parenthesis. Pollution measures are based on each district's industrial composition in 1851. Population density and both of the pollution measures are standardized. Regressions are estimated with analytical weights based on the number of living workers in each county-occupation cell. County-occupation cells with no living workers are dropped.

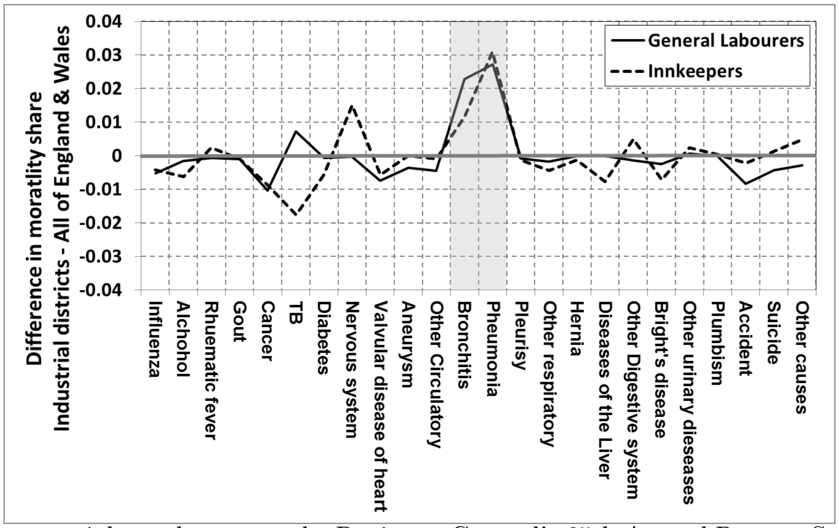
The occupation mortality data are explored in more detail in Appendix A.3.2. In particular, I provide estimates of the pollution effect for 19 groups covering the non-industrial occupation categories used in Columns 3-4 of Table 5. While data at the occupation level are noisy, for a number of occupations I find a statistically significant positive relationship to local industrial pollution, while none of the 19 show a statistically significant negative relationship. Some occupation groups provide particularly interesting examples. Among clergy, for example, I find strong evidence of higher mortality rates in counties with more industrial pollution. Similar results are found for a number of professional occupations including lawyers, teachers, local government employees, and businessmen. I also find statistically significant pollution effects in a number of working-class occupational categories, including domestic servants, agricultural laborers, and gardeners. Thus, the impact of industrial pollution does not appear to be confined only to the upper or the lower occupational classes.

A second set of data describing mortality rates within occupational categories is available for two types of workers, innkeepers and general laborers, for 1891-1900. These data are particularly interesting because they report the cause-of-death for these workers, information that is not available in the 1851 data. The data also indicate whether the worker was located in an industrial area of the country.[42] Thus, they allow me to look at how mortality patterns differed between industrial regions and the rest of England and Wales for workers within the same occupational category, by cause-of-death.

Using these data, I calculate the share of overall mortality for each cause-of-death and then plot the difference between the share represented by that cause in the industrial districts and the share due to that cause in England and Wales as a whole. The results are shown in Figure 5. We can see that, even within occupations, two respiratory-related causes of death – bronchitis and pneumonia – accounted for a much larger share of overall mortality in the industrial districts of the country than in the country as a whole. These results foreshadow the cause-of-death analysis presented next.

[42]These data were published in a special supplement included in the Supplement to the Registrar General's 65th Annual Report (1891-1900).

Figure 5: Relative importance of causes of death within two occupations



Data from a special supplement to the Registrar General's 65th Annual Report, Supplement II cover males aged 25-65. For two occupations, Innkeepers and General Laborers the data are reported for the industrial districts and the country as a whole. To generate this figure I calculate the share of total mortality represented by each cause of death in these two occupations, separately for the industrial districts and the country as a whole. I then plot the difference between the share of mortality represented by each cause of death in the industrial districts to that cause-of-death's share in the country as a whole for each available cause-of-death category.

4.4 Cause-of-death analysis

In this section, I use cause-of-death data in order to isolate one of the channels through which industrial pollution affected mortality in the 19th century. Specifically, I focus on excess mortality due to respiratory diseases, the category that is the most closely associated with the effects of airborne industrial pollution.[43] The first step in this analysis is to estimate the percentage increase in overall mortality associated with industrial pollution:

$$\ln(TOTmort_d) = a_0 + a_1 \ln(DENSITY_d) + a_2 \ln(POLL_d) + X_d\Lambda + R_d + \epsilon_d\,, \tag{4}$$

[43]See Rückerl *et al.* (2011) for one recent review of literature on this topic. For example, Pope 3rd (1989) studies the impact of the opening and closing of a steel mill in Utah Valley, in central Utah, on particulate pollution and health. He finds that elevated particulate pollution levels (PM10) were associated with increased hospital admissions for pneumonia, pleurisy, bronchitis, and asthma. These diseases are the most important components of the respiratory mortality category in my data.

where the $TOTmort_d$ is the overall age-standardized mortality rate in district d. This increase may be associated with the direct effects of pollution, selection effects, or omitted variables.

Next, I estimate the increase in the respiratory mortality category only, using,

$$\ln(RESPmort_d) = b_0 + b_1 \ln(DENSITY_d) + b_2 \ln(POLL_d) + X_d\Lambda + R_d + \epsilon_d \,, \tag{5}$$

where the $RESPmort_d$ is the age-standardized mortality rate in district d due to respiratory diseases. I then define the difference $b_2 - a_2$ as the excess increase in respiratory mortality due to the direct impact of pollution, i.e., the increase in respiratory mortality in excess of what we would expect given the patterns observed in all cause-of-death categories.[44]

In interpreting these results, it is important to remember that they reflect only one potential channel through which pollution affects mortality. However, they are valuable in that they allow us to isolate causal effects occurring through one important channel. They also provide a very conservative lower-bound estimate of the causal impact of industrial pollution on mortality during this period.

Results are presented in Table 7. Columns 1-2 show that industrial pollution was associated with an increase in respiratory mortality of 11.9% and an increase in mortality in all cause-of-death categories of 5.3%. The difference between these implies an excess increase in respiratory mortality of 6.6%. The average impact of respiratory mortality across all districts is 2.36 deaths per thousand. Given this, the implied direct effect of a one standard deviation increase in industrial pollution through excess

[44]An alternative approach would be to compare the increase in respiratory mortality to the increase in all non-respiratory causes of death. This would suggest larger effects than those described in this section. The reason that I compare to total mortality rather than to non-respiratory mortality here is that we may be concerned that increases in respiratory mortality could have resulted in a decrease in other types of mortality, because people who died of respiratory diseases could not die from other causes. By including respiratory deaths in the comparison group, the results I report are not subject to a potential of upward bias through this channel. This is related to a larger issue of competing risks. The competing risks concern is that the increase in respiratory mortality may be due entirely to reductions in other types of mortality. This is a very difficult issues to fully address, however, given that pollution is associated with increased mortality across many cause-of-death categories this is unlikely to be a major concern in the context I study. The issue of competing risks is revisited in Section 4.5.

respiratory mortality alone is equal to 0.16 additional deaths per thousand, or 0.8 percent of overall mortality. The results in Columns 3-4 suggest impacts of a similar magnitude. Similar results are obtained using alternative measures of industrial pollution (see Appendix A.3.3).

Table 7: Impact of industrial pollution on respiratory and total mortality

	DV: Ln(Age-standardized mortality)			
Category:	Respiratory mortality	Total mortality	Respiratory mortality	Total mortality
	(1)	(2)	(3)	(4)
Ln(Pop. Density)	0.139***	0.0822***	0.147***	0.0836***
	(0.0197)	(0.00556)	(0.0175)	(0.00514)
Ln(Coal use)	0.119***	0.0529***		
	(0.0329)	(0.00945)		
Ln(Dirty emp.)			0.111***	0.0526***
			(0.0293)	(0.00918)
Region effects	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes
Observations	580	580	580	580
R-squared	0.583	0.730	0.577	0.729

*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, allow spatial correlation between any pair of districts within 50km of each other. Mortality data are from 1851-1860. Pollution measures are based on each district's industrial composition in 1851. Other control variables include employment in water services per 10,000 population in 1851, employment in medical services per 10,000 population in 1851, seaport tonnage in 1865, and latitude. The population density and industrial pollution variables are standardized.

I have also investigated the impact of pollution on respiratory mortality at different age levels (see Appendix A.3.3). For children under five, I find that industrial pollution was associated with an excess increase in respiratory mortality of 8.8%. For adults twenty and over, the effect is 7.6%. Using age-specific estimates of excess respiratory mortality, I also calculate the impact of industrial pollution on life expectancy through the excess respiratory mortality channel only. These estimates suggest that a one standard deviation increase in industrial coal use reduces life expectancy at birth by 0.24 years through this channel, and reduced life expectancy at age twenty by 0.11 years. I will think of these figures as conservative lower bounds on the causal impact of industrial pollution on life expectancy during this period.

The results presented in this section isolate one direct channel – respiratory diseases – through which pollution effects mortality. Under reasonable assumptions, these results will be free of bias due to population sorting or omitted variables. Even when focusing solely on this channel, the implied impact of industrial pollution in locations such as Birmingham and Manchester, relative to the average district, amount to three quarters of a year of life expectancy at birth.

4.5 Changing patterns over time, 1851-1900

Next, I examine how the impact of industrial pollution evolved over the second half of the 19th century. To study this evolution I draw on county-level panel data covering 54 English and Welsh counties from 1851-1900.[45] These data allow me to construct a complete panel of pollution measures, mortality, and additional control variables.

The analysis begins with cross-sectional regressions for each decade from 1851-1900. These regressions are similar to the district-level results shown previously except that, because of the smaller number of observations available, I apply a more parsimonious expression that does not include region effects. Regressions are weighted by county population to account for the substantial heterogeneity in county size. To allow some serial correlation, standard errors are clustered by region.[46]

Results obtained using the coal-use measure of industrial pollution are presented in the top panel of Table 8.[47] These results show that the impact of population density on mortality was consistently declining across this period. By 1900, the impact of population density on overall mortality had fallen by more than half, reflecting substantial gains in improving health in British cities. In contrast, the impact of industrial pollution does not show a clear pattern of decline over the period. There is some evidence that the impact of pollution rose between 1851 and 1880 and then began slowly falling.[48] The bottom panel of Table 8 shows the estimates obtained

[45] London is excluded because it is a substantial outlier during this period. Robustness results including London are reported in the Appendix.

[46] The eleven regions are the Southwest, Southeast, South Midlands, West Midlands, North Midlands, East, Northwest, Yorkshire, North, South Wales and North Wales. Regions were official designations for sets of similar and geographically proximate counties so this seems like a reasonable unit for clustering. Calculating spatially correlated standard errors based on the location of the main population or administrative center makes less sense in the context of counties, which are larger, often contain multiple cities, and vary in size more than districts.

[47] Results using the dirty industry employment measure are available in Appendix A.3.4.

[48] This inverse U-shape is suggestive of an environmental Kuznets curve. However, this pattern is dependent on the pollution measure used.

when I do not control for local industrial pollution. These estimates show the urban mortality penalty falling across this period. Comparing the estimated effect of density in the top and bottom panel shows that accounting for local industrial pollution explains just under 40% of the relationship between mortality and population density in 1851-1860 and nearly 60% of this relationship in 1891-1900.

Table 8: County-level cross-sectional regressions for each decade from 1851-1900

	DV: Age-standardized mortality				
	1851-1860	**1861-1870**	**1871-1880**	**1881-1890**	**1891-1900**
Ln(Pop. Density)	1.383***	0.977*	0.741*	0.577**	0.525**
	(0.317)	(0.461)	(0.376)	(0.259)	(0.208)
Ln(Coal use)	0.986***	1.204**	1.401**	0.954***	1.108***
	(0.305)	(0.503)	(0.447)	(0.274)	(0.249)
Other controls	Yes	Yes	Yes	Yes	Yes
Observations	54	54	54	54	54
R-squared	0.930	0.923	0.889	0.951	0.941
	DV: Age-standardized mortality				
	1851-1860	**1861-1870**	**1871-1880**	**1881-1890**	**1891-1900**
Ln(Pop. Density)	2.168***	1.938***	1.809***	1.172***	1.276***
	(0.236)	(0.316)	(0.351)	(0.155)	(0.130)
Other controls	Yes	Yes	Yes	Yes	Yes
Observations	54	54	54	54	54
R-squared	0.715	0.731	0.713	0.808	0.752

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered by region. The pollution measures, as well as the water and medical services controls, are based on each district's industrial composition at the beginning of each decade. Seaport tonnage is based on data from 1865. Regressions are weighted by county population. Regressions are weighted by county population.

It is also possible to use cause-of-death patterns to identify the direct impact of industrial pollution on mortality in each decade, following the approach introduced in Section 4.4. Results obtained using the coal use measure of industrial pollution are presented in Table 9.[49] Columns 1-2 present coefficient estimates for the impact of industrial pollution from regressions where the dependent variables are total mortality and respiratory mortality, respectively.[50] Column 3 gives the difference between these estimates, which is the implied increase in respiratory mortality in excess of

[49]Results using the dirty industry employment measure, available in Appendix A.3.4, show similar patterns.

[50]Full regression results are available in Appendix A.3.4.

the increases experienced in all other mortality categories. Columns 4 converts this percentage increase into an increase in deaths per thousand. Column 5 describes the increase in mortality due to excess respiratory mortality relative to average overall mortality in that decade.

Table 9: Estimated pollution effects on total and respiratory mortality, 1851-1900

	Pollution coefficient from mortality regression for all causes	Pollution coefficient from respiratory mortality regression	Difference: Excess increase in respiratory mortality	Mortality impact of one s.d. more pollution through excess respiratory channel (deaths/1000)	Impact relative to average overall mortality
1851-1860	0.0471**	0.116*	6.9%	0.161	0.80%
	(0.0157)	(0.0631)			
1861-1870	0.0561**	0.131**	7.5%	0.192	0.97%
	(0.0232)	(0.0512)			
1871-1880	0.0667***	0.113***	4.6%	0.136	0.73%
	(0.0210)	(0.0255)			
1881-1890	0.0525***	0.104**	5.2%	0.153	0.91%
	(0.0151)	(0.0361)			
1891-1900	0.0643***	0.109***	4.5%	0.122	0.76%
	(0.0160)	(0.0285)			

Columns 1 and 2 present estimated coefficient on the log of coal use variable for regressions in which the dependent variable is the log of the total mortality rate and the log of the respiratory mortality rate, respectively. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, are clustered by 11 regions. Column 3 describes the excess increase in respiratory mortality (Column 2 minus Column 1). Column 4 describes the implied impact of the excess respiratory mortality in deaths per thousand. Column 5 is Column 4 divided by the overall mortality rate in each decade.

In all decades there is evidence of a direct impact of industrial pollution on mortality through respiratory causes, even after adjusting for the increase in all other cause-of-death categories. The impact through this direct respiratory channel appears to have fallen only slightly over time, while the share of total mortality due to excess respiratory mortality was stable across this half-century.[51]

[51] These findings provide evidence against the concern that respiratory mortality may have been over-reported in locations that were more polluted. If this type of misreporting were behind the respiratory disease patterns I observe, then the impact of respiratory disease should be falling over time as improved medical practice led to better cause-of-death reporting. The fact that the impact of respiratory disease as a share of overall mortality was fairly stable over this 50 year period, which saw

The patterns described in Tables 8-9 can help us think about the relationship between pollution and infectious diseases, and the role of competing risks, in this setting. There are two ways that falling infectious disease mortality can interact with pollution. On one hand, if respiratory diseases due to pollution and infectious diseases are competing risks, then a fall in infectious disease mortality should increase the impact of pollution through respiratory deaths. On the other hand, it may be the case that encountering infectious diseases increases people's susceptibility to pollution-related respiratory diseases later in life (or vice-versa), so that falling infectious disease rates should reduce the impact of pollution. The patterns described in Tables 8-9 are more consistent with the latter of these two alternatives, i.e., pollution and infectious diseases are likely to be complementary factors in generating mortality. This also suggests that competing risk issues are not likely to be a major concern for my results.

Next, I exploit the time variation available in the data in order to assess the impact of rising industrial coal use on mortality from 1851-1900 while controlling for fixed locational features. The regression specification is,

$$\Delta_{t-\tau,t}MORT_{dt} = \alpha_0 + \alpha_1 \Delta_{t-\tau,t}POLL_{dt} + \Delta_{t-\tau,t}X_{dt}\Gamma + e_{dt} \tag{6}$$

where $\Delta_{t-\tau,t}$ is a difference operator between periods $t-\tau$ and t, $POLL_{dt}$ is the industrial pollution measure, and X_{dt} is a set of control variables. Ideally, τ should be as large as possible to limit the impact of $POLL_{d,t-\tau}$ on $MORT_{dt}$, which could bias estimates of α_1. Thus, I run this regression using the longest available difference, so t indicates the decade 1891-1900 and $t-\tau$ indicates the decade 1851-1860. Regressions are weighted by county population and standard errors are clustered by region. I consider only the pollution measure based on coal use in this analysis because it is the only measure that allows for changes in pollution intensity within industries over time.

I use pollution per capita as the key explanatory variable in these regressions. This is because, if I were to include separate coal use and population variables in the long-difference regressions, these are both certain to be endogenously affected

huge improvements in medical practice, suggests that misreporting is not driving the cause-of-death patterns I observe.

by the change in the mortality rate.[52] This issue will be less severe when focusing on local pollution intensity per capita, where both the numerator and denominator will be affected in a similar way. Moreover, as I will discuss below, it is possible to construct a sufficiently strong instrument for pollution per capita, while no reasonable instrument is available when the level of coal use and the level of population are included separately.[53]

To deal with potential endogeneity issues, I use an instrumental variables approach following Bartik (1991). The instrument is,

$$\Delta \text{ Predicted coal per worker} = \frac{PredCOAL_{d1891}}{PredWORKPOP_{d1891}} - \frac{COAL_{d1851}}{WORKPOP_{d1851}}$$

where $COAL_{d1851}$ is coal use in county d in 1851, $WORKPOP_{d1851}$ is the working population of the county in 1851, and the predicted coal use and working population variables are given by,

$$PredCOAL_{d1891} = \sum_i \theta_i L_{id1851} GR_{i,-d}$$

$$PredWORKPOP_{d1891} = \sum_i L_{id1851} GR_{i,-d}\,.$$

Here L_{id1851} is employment in industry i in county d in 1851 and $GR_{i,-d}$ is the growth rate of industry i from 1851-1891 in all counties other than d. The first-stage regression results shown in Table 10 show that this procedure generates a sufficiently strong instrument.

[52] The link between mortality and population growth is clear, while mortality will also affect coal use by impacting local labor supply (Hanlon (2014)).

[53] As suggested by Hanlon (2014), the Bartik approach does not provide a valid instrument when the level of population in a county and the level of coal use are included as separate variables because coal use generates an endogenous disamenity that negatively affects city growth, which in turn has consequences for the growth of polluting industries.

Table 10: First-stage regression results using Bartik instrumentation

Dependent variable:	**Δ Coal per capita**
Δ Predicted coal per worker	0.2005**
	(0.0654)
Constant	0.3661*
	0.1783
Observations	54
F-statistic	9.38

*** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered by by 11 regions. Coal per capita is the tons of coal per county resident based on actual county employment and population levels. Predicted county coal use is calculated as described above.

Table 11 presents the long-difference regression results. Columns 1 provides basic OLS estimates of the impact of rising coal use on overall mortality. These results suggest that rising coal use intensity from 1851-1900 had a statistically significant impact on overall mortality. Column 2 presents results for respiratory mortality only. These estimates suggest that the impact of industrial pollution on respiratory mortality, in percentage terms, was much stronger than the impact on all other causes of death. Columns 3-4 present similar results but adding in controls for the change in water and medical services employment at the county level. Adding these additional controls has a negligible impact on the results.

Column 5-6 present IV results using the Bartik instrument for the change in county coal use intensity.[54] The results in Column 5 suggest that rising coal use had a somewhat stronger impact than the OLS results suggested. The fact that the IV estimates are larger than the OLS estimates suggest that there were omitted factors, such as local regulation, that generated a negative relationship between mortality and local coal use intensity. Column 6 presents IV results for respiratory mortality. The coefficient estimate suggests that industrial pollution had a larger impact on respiratory mortality than on overall mortality, but this estimate is not precise enough to draw strong conclusions. However, when I estimate results for respiratory mortality in specific age categories I observe statistically significant increases in mortality at every age from 25 to 75. Additional results are available in Appendix A.3.5.

[54]It is not possible to include controls for water or medical services in these regressions because these variables are likely to be endogenous and no instrument is available. However, the results in Columns 1-4 suggest that omitting these controls is not likely to have a substantial impact on the estimated pollution coefficient.

Table 11: Long-difference regression results

	OLS regressions				IV regressions	
Dependent variable:	Δ Log total mortality	Δ Log respiratory mortality	Δ Log total mortality	Δ Log respiratory mortality	Δ Log total mortality	Δ Log respiratory mortality
	(1)	(2)	(3)	(4)	(5)	(6)
Δ Coal per cap.	0.0630***	0.129***	0.0590**	0.0957*	0.0881**	0.208
	(0.0188)	(0.0398)	(0.0217)	(0.0461)	(0.0389)	(0.142)
Constant	-0.277***	-0.00266	-0.261***	0.133	-0.300***	-0.0743
	(0.0222)	(0.0459)	(0.0376)	(0.0981)	(0.0340)	(0.110)
Other controls			Yes	Yes		
Observations	54	54	54	54	54	54
R-squared	0.287	0.142	0.300	0.239	0.241	0.089

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered by 11 regions. Columns 1-2 present OLS regressions for total mortality and respiratory mortality, respectively. Columns 3-4 include controls for the change in medical and water services employment. Columns 5-6 present IV regression results in which a Bartik instrument based on initial county industrial composition interacted with the growth rate of industries in all other counties and then interacted with industry coal use intensity is used as an instrument for the change in industrial coal use at the county level. Good instruments are not available for the change in water or medical services so these are not included in the IV regressions. Regressions are weighted by 1851 county population.

To interpret the magnitude of these estimated effects it is helpful to know that the population-weighted rise in county coal use per person over this period was 0.91 tons.[55] Thus, my preferred results, from Column 5, imply that rising coal use increased overall mortality by 8%. The overall reduction in mortality over this period was 22%. This suggests that the fall in overall mortality could have been substantially larger in the absence of the increase in coal use intensity.

An alternative way to look at the impact of rising coal use is to consider life expectancy. A rough estimate suggests that life expectancy at birth increased by 4.9 years between 1851-1900, while life expectancy at age twenty increased by 1.8 years.[56] Using the estimated impact of coal use on mortality by age category obtained from long-difference regressions, we can compare these figures to the gains that might have

[55] Full summary statistics for the variables included in the long-differences regressions are available in Appendix A.2.3.

[56] I refer to these as rough estimates because they use only the mortality rates for ages available in each of those years, which are often only available in ten year intervals. These calculations also do not include life expectancy gains at ages over 75, where the mortality data are less reliable.

been achieved had the increase in coal use been smaller.[57] If Britain had managed to hold coal use per capita at the levels observed in 1851 while all other factors affecting health remained unchanged, estimates based on the IV specification suggest that life expectancy at birth would have risen by 5.7 years while life expectancy at age twenty would have increased by 3.1 years. Put another way, the IV results suggest that eliminating the growth in coal use per worker, all else equal, would have increased life expectancy at birth by an additional 0.77 years and life expectancy at age twenty by an additional 1.26 years. Most of these effects are due to respiratory disease mortality.

If, instead, I consider only the impact of coal use through excess respiratory mortality, I estimate that holding coal use intensity at 1851 levels would have increased life expectancy at birth by an additional 0.57 years and life expectancy at age twenty by an additional 0.35 years, on top of the gains actually achieved from 1851-1900. This suggests that rising coal use offset over ten percent of the life expectancy gains that might have been achieved during this period. These estimates should be largely free of concerns related to selection and omitted variables.

Of course, it may be unrealistic to consider a counterfactual in which the growth of coal use intensity was eliminated while assuming that health was not affected through other channels, such as rising income. A full accounting of the health effects of reducing industrial coal use requires an estimate of the impact through these other channels, something that is beyond the scope of this study. However, as the 1871 Coal Commission Report makes clear, there was substantial scope for efficiency gains in industrial coal use during this period (see examples in Appendix A.1.3). While the costs required for such gains were modest, this report argues that manufacturers had little incentive to invest in more efficient processes and technologies because of the cheapness of coal and lack of effective pollution regulation.

Finally, it is possible to construct a simple back-of-the-envelope calculation of the monetary cost of the additional mortality associated with rising industrial pollution. As a starting point, I draw on value of life estimates for 1900 from Costa & Kahn (2004) and Kim & Fishback (1993). These studies suggest a value of life ranging from 1,180-3,529 in 1900 GBP.[58] Given a life expectancy of 44 years in 1900, this implies

[57]The estimated coefficients by age category that go into these calculations are available in Appendix A.3.5.

[58]To be more specific, these studies suggest a value of life in 1900 ranging from 100,000 to 300,000 in 1990 US dollars. I convert these to 1900 GBP using the CPI deflator and taking the average of the values obtained using the average annual exchange rate in each of the intervening years. The

a value of a life-year of 27-80 in 1900 GBP, equal to 60-175% of GDP per capita in that year. Given my estimates for the causal effect of the increase in industrial pollution intensity through excess respiratory mortality alone, this implies that the monetary cost of the increase in coal use intensity from 1851-1900 was equal to at least 0.33-1.00 of annual GDP in 1900. Note that this cost is equivalent to a wealth effect, while GDP is a flow variable. If instead I use the estimate of the relationship between industrial pollution and total mortality, the cost ranges from 0.45-1.35 of annual GDP in 1900.

5 Conclusions

Due in part to lack of evidence, recent surveys of health and mortality during the 19th century have largely ignored the role of pollution. Cutler *et al.* (2006), for example, discusses the health effects of urbanization in Britain, but never directly addresses pollution. In Deaton (2013), pollution merits only a passing remark (p. 94). Szreter (2005) spends just one out of four hundred pages (p. 126) discussing the role of pollution, and draws primarily on anecdotal evidence. Focusing on the U.S., Costa (2013) describes Pittsburgh skies darkened by pollution, but argues that the lack of reliable particulate data limit our ability to measure the impact of pollution, or to assess the benefits generated as air quality improved. This study fills this gap in the literature by providing broad-based and well-identified evidence of the impact of industrial pollution on mortality in the 19th century. I find that industrial pollution substantially increased mortality in 1851-1860, and that these effects grew as coal use intensity rose from 1851-1900.

How do the effects I measure compare to those observed in modern studies? In general, it is difficult to answer this question because I do not observe direct measures of pollution, the main explanatory variable in most modern work. However, it is possible to conduct a rough comparison to the impacts found by Chen *et al.* (2013), one of the few studies available for a highly-polluted environment. They estimate that increased coal use for heating north of the Huai River in China from 1990-2000 reduced life expectancy by 5.5 years, which is equal to roughly 7.8% of total life expectancy in China. Using my estimates for the relationship between industrial

deflators are available from measuringworth.com.

pollution and total mortality in 1851-1860, a one s.d. increase in coal use lowered life expectancy by 1.27 years, or 3.3% of total life expectancy. A three s.d. increase, as was found in cities such as Manchester and Birmingham, lowered life expectancy by 3.8 years, or 9.8% of total life expectancy. Thus, these figures seem to be of similar magnited to those observed by Chen *et al.* (2013) for China. However, these figures may be influenced by substantial sorting effects; if I focus only on excess respiratory mortality, the impact of a one s.d. increase in coal use is equal to .24 years or 0.6% of total life expectancy. A three s.d. increase in coal use is associated with a loss of 0.72 years of life, or 1.8% of total life expectancy. Relative to these conservative causal estimates, the findings of Chen *et al.* (2013) seem high.

While this paper documents the effects of local pollution, it is also likely that pollution in one area may have affected mortality in other nearby districts. This could have further implications for population sorting and the political economy of pollution regulation. Understanding these spillovers is one promising direction for future research.

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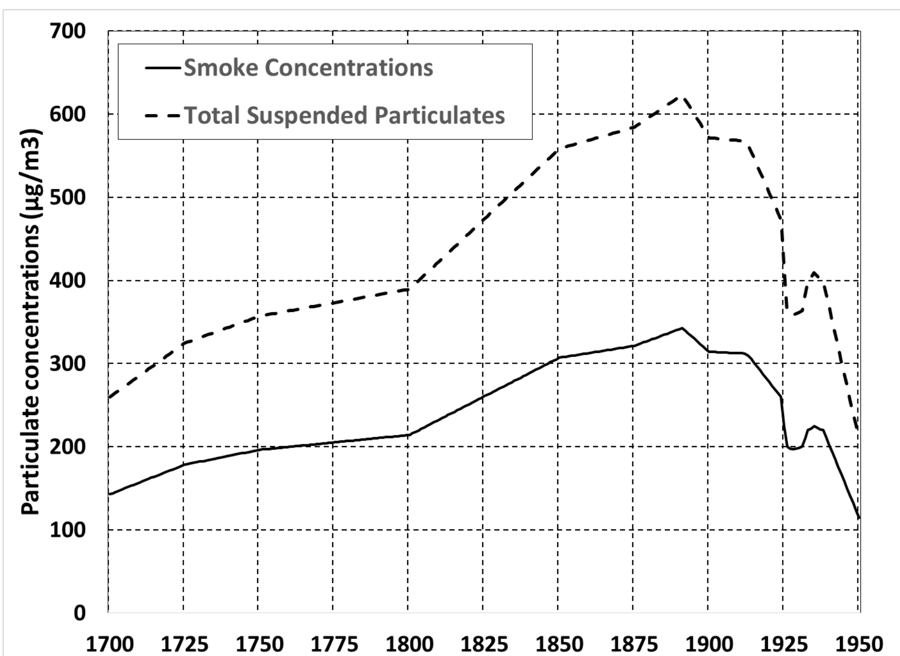
A Appendix

A.1 Empirical setting appendix

A.1.1 Estimated pollution levels in London from 1700

While broad direct measures of pollution are not available for the historical period, Brimblecombe (1987) has produced estimates of smoke concentrations for London starting in 1700.[59] These have been converted to total suspended particulate (TSP) values, a standard pollution measure, by Fouquet (2008). Figure 6 plots these values. These show that the period covered by this study covers the highest pollution decades for London.

Figure 6: Estimates of historical smoke concentrations and TSP levels for London

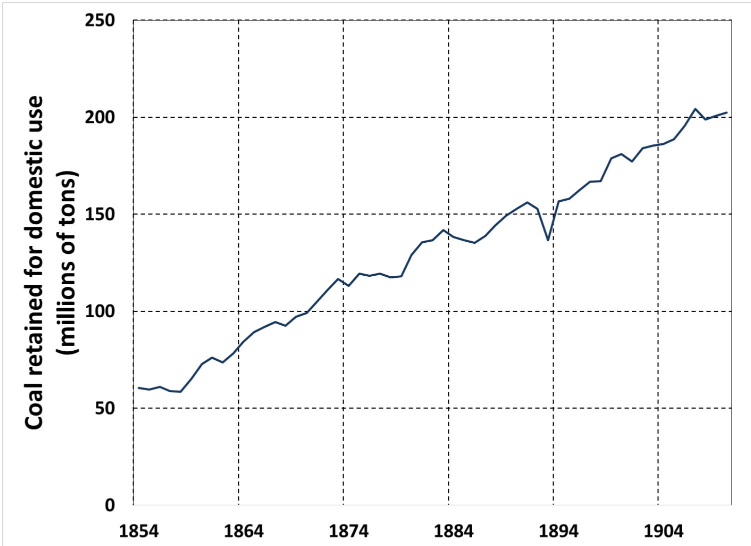


Smoke concentration estimates from Brimblecombe (1987) converted to TSP levels by Fouquet (2008).

[59]Brimblecombe's measures are constructed using data on imports of coal into London.

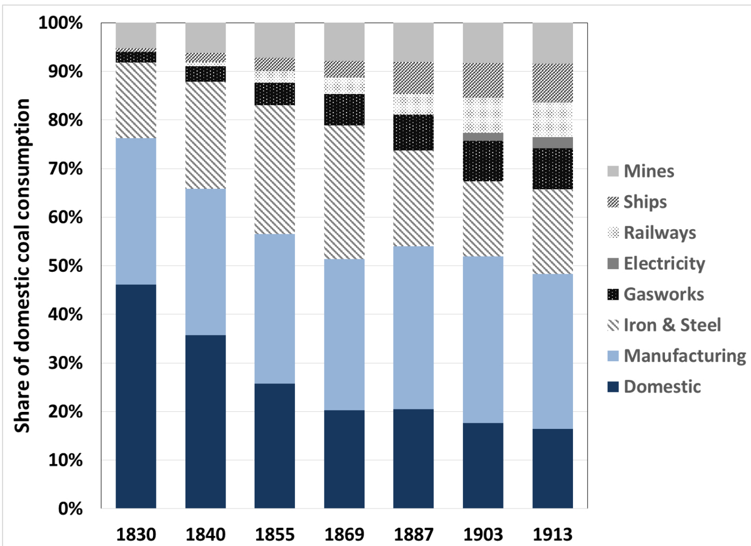
A.1.2 National coal use patterns and prices

Figure 7: Domestic consumption of coal by all users



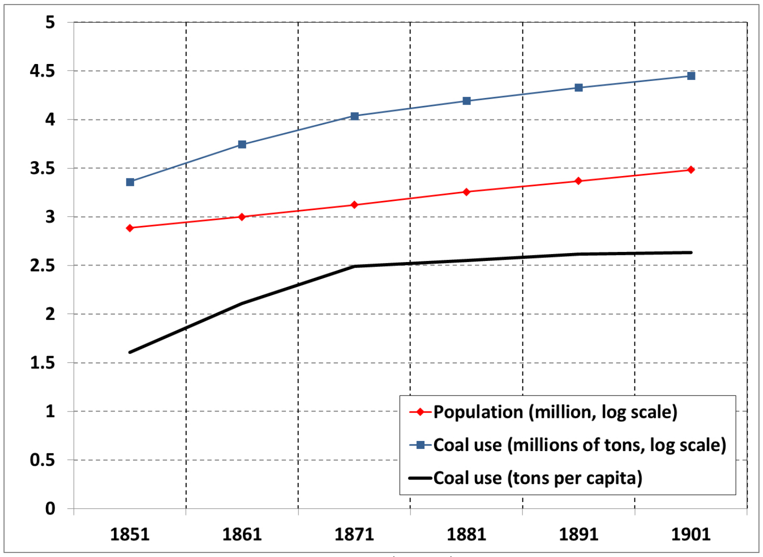
Data from Mitchell (1988).

Figure 8: Coal usage shares for the U.K.



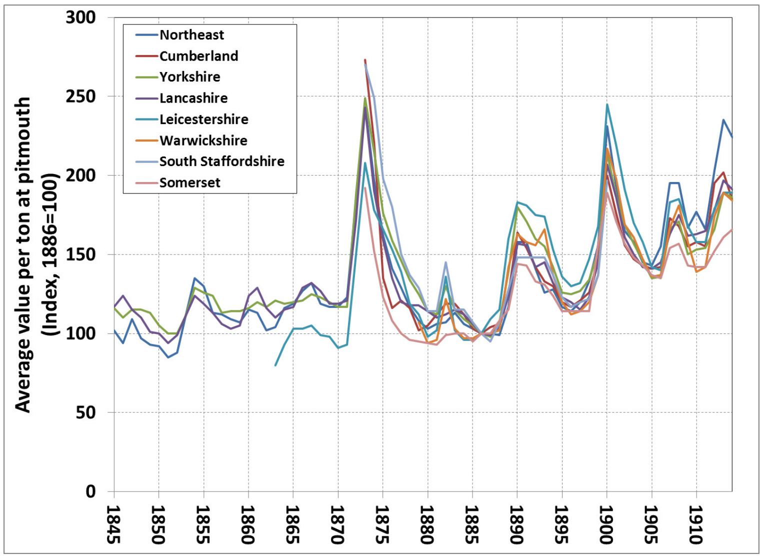
Data from Mitchell (1988).

Figure 9: Industrial coal use per capita



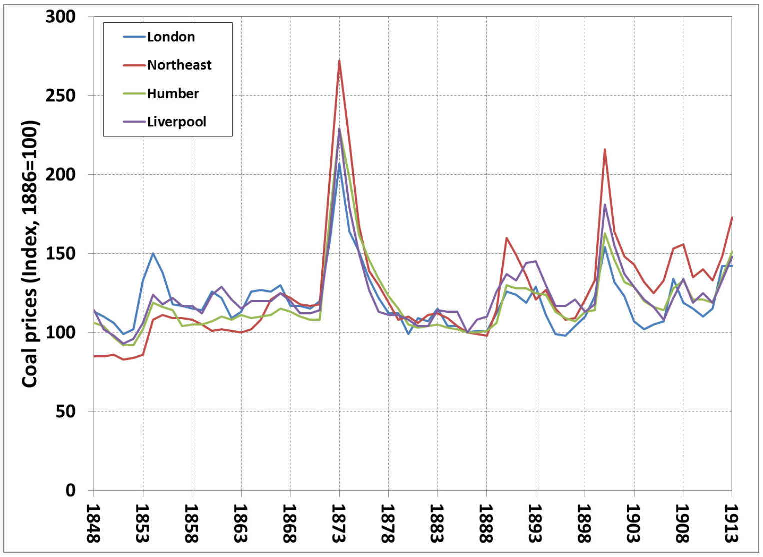
Coal data from Mitchell (1988). Population data from the Census of Population.

Figure 10: Pithead price indexes for coal from the major English coalfields



Data from Mitchell (1984).

Figure 11: Coal price indexes for London and the major exporting ports



Data from Mitchell (1984).

A.1.3 Details from the 1871 Coal Commission Report

The 1871 Coal Commission report, which stretches to over 1300 pages, was commissioned by Parliament in response to fears of a coal shortage in the early 1870s (which ultimately turned out to be unfounded). This appears to be by far the most comprehensive and detailed study of British coal mining and use undertaken during the period I study. While much of this report is dedicated to estimating available coal reserves, Committee B was chosen to, "inquire whether there is reason to believe that coal is wasted by carelessness or neglect of proper appliances for its economical consumption" (p. 93). Below I describe some of the most relevant findings of this report.

This Committee's report begins by reviewing the substantial progress that had been made in improving coal use efficiency among iron and steel producers, the largest coal users in Britain. The report that substantial progress was made in this area:

> *All the evidence collected from the witnesses examined...go to prove, that in one way and another a saving of not less than 20 per cent. has been effected in the smelting of iron during the last ten years, and all the indications are, that yet increased economy will be effected in the future.* (p. 99)

At the same time, one witness, Mr. William Siemens, a civil engineer, suggests that there was still huge scope for improvement through adoption of more efficient technologies:

> *...there appears to be a saving of fuel [from using regenerative furnaces], which amounts in many cases to nearly 50 per cent. The cost however, of erecting the regenerative gas furnace is rather more than double that of the ordinary furnaces...it must be remembered, that of the 6,243 puddling furnaces at work in 1869 a very small number of them had adopted any arrangement for utilizing the waste heat, consequently even at the lowest estimate the loss of heat must be enormous.* (p. 101)

The committee then turns to the use of coal for generating steam power, which was the main industrial use outside of the metal trades. Here the committee finds substantial evidence of waste and inefficiency:

> *...we feel called upon to notice the enormous waste of heat, and consequently wasteful consumption of fuel, in a very large majority of the steam boilers used in this country; most especially such as are used in collieries and iron workers, through their being left to the influence of every change in the atmospheric conditions, quite exposed to winds, rains, and snows, when a slight covering of a non-conducting substance would, by protecting them, improve their steam producing power, and save a considerable quantity of coal.* (p. 103)

They go on to state that,

The careless and wasteful manner of stoking in most of the coal-producing districts is not only a source of vast waste, but of extreme annoyance to all the surrounding neighborhood. Coal is piled upon the fire without any discretion, producing dense volumes of the blackest smoke, which is so much fuel actually thrown away; nor is the waste the worst part of it; vegetation is destroyed, or seriously injured, for miles, and that which acts so seriously on the plant cannot fail to be injurious to man. (p.103)

They also find that efficiency gains could have been achieved given the technologies available at the time. Simple changes in the procedure for generating combustion could have important effects:

Without traveling beyond known principles, it was thought that a considerable saving of fuel could be effected. Imperfect combustion must be regarded as the first essential loss. The air is supplied so unskillfully that much passes into the chimney as hot air, carrying with it the vast quantity of unconsumed carbonaceous matter which we see escaping in black clouds from the top of the chimney. This imperfect combustion may be traced to the bad construction of the fireplaces, and to the reckless way in which coal is thrown into, and over, the mass of ignited matter in the fireplace. (p. 104)

Gains could also be achieved through insulating steam engines so to limit heat loss and through improved boiler construction. For example, another witness, Mr. John Hicks, M.P., provided evidence that (p. 104), "careful construction and a good system of steam jacketing, a saving of something like 30 per cent. is said to be effected."

A.1.4 Mortality background

Additional details on the changing mortality patterns in the second half of the 19th century are provided in Table 12, which is adapted from Woods (2000). The first two columns describe the number of deaths in England & Wales in different categories. The third and fourth columns describe the number of years of life that would have been gained had the cause of death been completely eliminated, which takes into account both the number of deaths associated with the cause and the age at which these deaths occurred. Some of the causes listed in Table 12 are specific to major diseases, such as tuberculosis, typhus, scarlet fever and measles. Many of the remaining deaths are gathered into general categories related to the systems that they affected, such as respiratory diseases, neurological diseases, cardiovascular diseases, and gastrointestinal diseases. These categories will include a variety of non-infectious causes of mortality and they may also include some infectious diseases. For example, the respiratory disease category includes bronchitis, pneumonia, influenza, etc.

Table 12: Cause-specific mortality in England & Wales, 1861-1870 to 1891-1900

Cause	Deaths by cause 1861-1870	Deaths by cause 1891-1900	Years of life gained if cause eliminated 1861-1870	Years of life gained if cause eliminated 1891-1900
Respiratory diseases	719,601	1,044,719	4.66	5.82
Neurological diseases	595,747	426,224	3.75	3.45
Tuberculosis	529,425	426,224	3.56	2.16
Cardiovascular diseases	288,447	507,730	1.56	2.27
Diarrhea & Dysentery	230,201	226,143	1.45	0.33
Digestive diseases	209,744	365,484	1.17	1.92
Scarlet fever	207,867	48,290	1.57	0.31
Typhus	189,285	55,996	0.36	0.01
Violence	163,840	202,363	1.03	1.03
Whooping cough	112,800	115,670	0.81	0.74
Measles	94,099	126,841	0.70	0.83
Scrofula	93,529	189,782	0.63	1.15
Cancer	82,820	232,178	0.63	0.96
Other causes	1,277,095	1,368,714		

Data adapted from Woods (2000) p. 350.

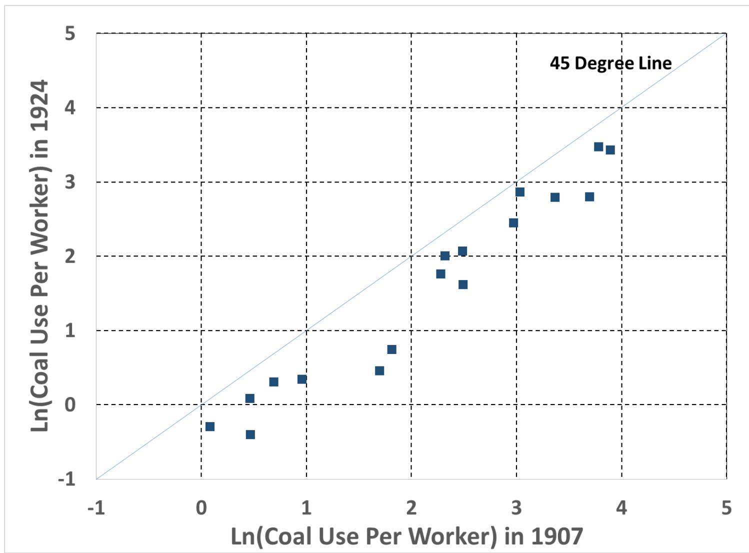
One important message from Table 12 is that, while the major infectious diseases were important causes of mortality, they are not the whole story. Other causes, particularly respiratory diseases, were also important.

A.2 Data appendix

A.2.1 Assessing the stability of relative industry coal use

This appendix provides an analysis of the stability of relative coal use intensity across industries. This is done by comparing industry coal use intensity in 1907 to values from the next Census of Production, which was taken in 1924. Using these two Census observations, Figure 12 looks at how much the relative coal intensity of industries changed over time. We can see that coal use per worker has shifted down for all industries, but that the slope is indistinguishable from zero, suggesting that there has been no clear change in relative industry coal use intensity over this period. I.e., while efficiency gains were made in overall coal use, the relative coal intensity of industries was remarkably stable over time.

Figure 12: Comparing industry coal use in 1907 and 1924



	DV: Coal per worker in 1924
Coal per worker in 1907	1.021***
	(0.0612)
Constant	-0.623***
	(0.151)
Observations	17
R-squared	0.949

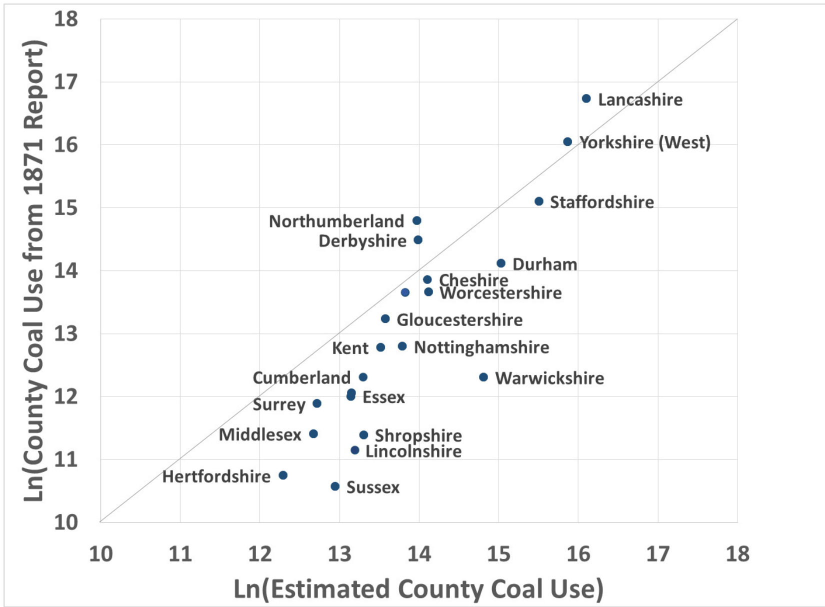
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

A.2.2 Comparing to 1871 county-level coal use

As an additional check of the coal use measure I have constructed, I compare county-level industrial coal use calculated using my methodology to estimates for 1871 based on data from the House of Commons, *Report of the Commissioners Appointed to Inquire into the Several Matters Relating to Coal in the United Kingdom*. That report, which was prompted by fears of a coal shortage in the early 1870s, included a survey of industrial coal use in a selection of English counties. Within each county, circulars were sent to firms asking them about their coal use. Using the resulting reports, and adjusting for the number of circulars returned in each county, I am able to calculated industrial coal use levels in the counties surveyed, though these figures will be imperfect because only major industrial establishments were surveyed. I then compare these estimates to results obtained by applying my methodology to county-level industrial employment data from the 1871 Census of Population combined with industry coal use intensity measures from the 1907 Census of Production.

Figure 13 describes the results for the set of available counties. In this graph, the y-axis describes county-level coal use constructed from the 1871 Coal Commission report while the x-axis gives the county coal use estimated using the methodology introduced in this paper. In general, the points lie close to the 45 degree line, suggesting that my methodology does a reasonable job of matching the estimates obtained using the data from the Coal Commission report. The methodology used in this paper does particularly well for the larger and more industrial counties. The greatest differences occur in the more rural counties with low levels of coal use, where my methodology overestimates industrial coal use relative the the figures from the 1871 Coal Commission report. However, these are also the counties where the figures from the Coal Commission report are most likely to understate county coal use because smaller industrial establishments, which were omitted from the Coal Commission report, are likely to form a more important coal user in less industrialized counties. Overall, these results provide additional evidence that the methodology used to calculated industrial coal use in this paper delivers reasonable results.

Figure 13: Comparing county industrial coal use in 1871



Another way to compare these two measures of coal use is to look at their relationship with mortality. This is done in Table 13, where I run cross-sectional regressions of mortality in 1871-1880 on each of the two coal use measures. Because of the small number of available observations, I do not include additional controls in these regressions.

Columns 1-2 present results for total mortality using, respectively, the coal use measure introduced in this paper and coal use based on the 1871 Coal Commission Report. We can see that these two coal use measures deliver very similar results. Note that these estimates differ somewhat from those shown in Table 8 because we observe only a subset of English & Welsh counties. Columns 3-4 present results for respiratory mortality only. Again, the results are very similar. Overall, these findings suggest that regressions run using the coal use measure introduced in this paper deliver results that are very similar to those obtained using coal use estimates based on the 1871 data.

Table 13: Comparing the mortality impact of different coal use measures

	DV: Total mortality		DV: Respiratory mortality	
	(1)	(2)	(3)	(4)
Ln(Pop. Density)	0.0392	0.210	0.240***	0.307**
	(0.464)	(0.362)	(0.0801)	(0.112)
Ln(Coal Use) – my measure	2.344***		0.505***	
	(0.346)		(0.0867)	
Ln(Coal Use) – Coal commission report		2.306***		0.437***
		(0.254)		(0.0912)
Constant	19.80***	19.80***	3.304***	3.304***
	(0.315)	(0.294)	(0.0780)	(0.0871)
Observations	22	22	22	22
R-squared	0.739	0.773	0.788	0.736

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parenthesis. Mortality is age-standardized.

A.2.3 Summary statistics for analysis data

Table 14 describes summary statistics for data used in the district-level analysis. Table 15 provides summary statistics for the data used in the long-differences analysis.

Table 14: Summary statistics for district-level variables

Variable	**Obs.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Age-standardized mortality	19.582	3.187	12.711	37.276	
Age-standardized respiratory mortality	2.358	0.867	0.59	7.398	
Ln(Coal use)	10.257	1.099	7.3	13.762	
Ln(Dirty industry emp.)	6.704	1.277	3.296	10.707	
District population in 1851 census	26,809	26,272	2,493	258,236	
Population density (per acre) in 1851	0.940	4.017	0.015	67.651	
Ln(Population density)	-1.47	1.189	-4.171	4.214	
Water service emp.	0.87	1.966	0	28.567	
Medical service emp.	37.769	19.854	1.907	131.857	
Seaport tonnage	0.017	0.147	0	2.653	
Ln(Coal per acre)	-0.532	1.529	-3.528	5.875	
Ln(Dirty ind. emp. per acre)	-4.085	1.669	-7.117	2.148	
Coal use per worker	4.972	3.906	1.087	26.405	
Dirty industry share of local employment	0.164	0.154	0.021	0.693	
Ln(Clean industry emp.)	8.643	0.601	6.617	11.37	

Table 15: Summary statistics for long-difference regression variables

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Δ Ln(Total mortality)	-0.22	0.065	-0.375	0.04
Δ Ln(Respiratory mortality)	0.115	0.188	-0.203	0.940
Δ Coal per worker	0.91	0.55	-0.266	2.761
Δ Water services	1.272	7.109	-0.631	115.8
Δ Medical services	10.733	6.056	-0.241	32.2

A.2.4 Industry wage data

Table 16 contains data from Bowley (1900), *Wages in the United Kingdom in the Nineteenth Century* (p. 132), describing relative industry wage levels over time. We can see that the most polluting industries on this list, iron and mining, paid relatively high wages compared to less polluting industries.

Table 16: Relative industry wage levels over time

Industry	1850	1860	1870	1880	1891
Cotton	52	62	72	82	97
Wool	69	76	84	96	87
Construction	122	138	160	173	177
Mining	108	124	132	128	183
Iron	142	150	170	176	187
Sailors	100	119	123	120	168
Agriculture	71	87	92	104	100

Wages are indexed with agriculture in England in 1891 = 100.

A.3 Analysis appendix

A.3.1 Additional results for district mortality in 1851-1860

Table 17 presents regression results where each district is weighted by district population (Columns 1-2) or the log of district population (Columns 3-4). In general we can see that these results suggest pollution impacts that are fairly similar, though slightly larger, than those reported in the main text.

Table 17: Weighted cross-sectional regressions for 1851-1860

	DV: Age-standardized mortality			
	Weighted by district pop.		Weighted by log district pop.	
	(1)	(2)	(3)	(4)
Ln(Pop. Density)	1.801***	1.844***	1.843***	1.870***
	(0.151)	(0.146)	(0.144)	(0.138)
Ln(Coal use)	1.232***		1.009***	
	(0.247)		(0.222)	
Ln(Dirty emp.)		1.228***		1.003***
		(0.255)		(0.217)
Water service emp.	-0.141*	-0.120	-0.130	-0.110
	(0.0796)	(0.0783)	(0.0832)	(0.0819)
Medical service emp.	-0.360***	-0.324***	-0.257**	-0.220*
	(0.0959)	(0.105)	(0.103)	(0.110)
Seaport tonnage	1.575***	1.807***	1.620***	1.847***
	(0.150)	(0.187)	(0.200)	(0.209)
Latitude	0.143	0.111	0.0922	0.0605
	(0.349)	(0.369)	(0.313)	(0.325)
Constant	12.19	13.91	14.93	16.61
	(18.27)	(19.28)	(16.42)	(17.02)
Observations	580	580	580	580
R-squared	0.881	0.880	0.774	0.774

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered at the county level. These are used in place of spatially correlated standard errors, which are more difficult to calculate in weighted regressions. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. Analytical weights are based on average district population over the decade. The population density, coal use, dirty industry employment, water services, and medical services variables are standardized.

Table 18: Results allowing more flexible density controls

	DV: Age-standardized mortality			
	(1)	(2)	(3)	(4)
Ln(Coal use)	1.284***		0.987***	
	(0.221)		(0.193)	
Ln(Pop. Density)	1.547***	1.603***	1.829***	1.875***
	(0.216)	(0.202)	(0.216)	(0.203)
Ln(Pol. Density) Squared	0.0822	0.0822	0.00676	-0.00200
	(0.0745)	(0.0743)	(0.0651)	(0.0659)
Water service emp.			-0.126	-0.107
			(0.111)	(0.112)
Medical service emp.			-0.246**	-0.209**
			(0.104)	(0.103)
Seaport tonnage			1.617***	1.868***
			(0.304)	(0.295)
Latitude			0.0858	0.0586
			(0.266)	(0.276)
Constant	19.50***	19.50***	15.26	16.71
	(0.186)	(0.168)	(13.92)	(14.43)
Ln(Dirty emp.)		1.268***		0.974***
		(0.205)		(0.181)
Observations	580	580	580	580
R-squared	0.710	0.715	0.757	0.756

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, allow spatial correlation between any districts within 50km of each other. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. Analytical weights are based on average district population over the decade. The population density, coal use, dirty industry employment, water services, and medical services variables are standardized.

Table 19 presents estimates from cross-sectional regressions on data from 1851-1860 while including London districts in the data. In general these results are quite similar to those reported in the main text, suggesting that my findings are not sensitive to excluding London from the analysis. Also note that the standard errors in these regressions tend to be larger, reflecting the fact that several of the London districts are substantial outliers in the data.

Table 19: Cross-sectional regression results including districts in London, 1851-1860

	DV: Age-standardized mortality						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ln(Pop. Density)	2.956***			2.255***	2.297***	2.719***	2.707***
	(0.325)			(0.119)	(0.118)	(0.167)	(0.135)
Ln(Coal use)		2.520***		1.173***		0.849***	
		(0.187)		(0.323)		(0.273)	
Ln(Dirty emp.)			2.461***		1.187***		0.890***
			(0.156)		(0.289)		(0.247)
Water emp.						-0.317	-0.301
						(0.254)	(0.259)
Medical emp.						0.482	0.522
						(0.522)	(0.508)
Seaport tonnage						0.231	0.358
						(1.113)	(1.193)
Latitude						0.170	0.138
						(0.321)	(0.328)
Constant	19.99***	19.99***	19.99***	19.99***	19.99***	10.90	12.64
	(0.307)	(0.308)	(0.332)	(0.190)	(0.174)	(16.79)	(17.15)
Observations	616	616	616	616	616	616	616
R-squared	0.561	0.408	0.389	0.618	0.624	0.665	0.667

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, allow spatial correlation between any districts within 50km of each other. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. The population density, coal per acre, dirty industry employment, water services, and medical services variables are standardized.

Table 20 provides additional results looking specifically at the impact of pollution on children under age five and adults aged twenty and over. These results show that pollution was associated with higher mortality both for children and adults. The increase in mortality per thousand is much larger for children, who have much higher mortality overall. Relative to the average overall mortality rate for children (54.8 per thousand), a one standard-deviation increase in local coal use is associated with roughly a 16% increase in mortality. For adults, where the average age-standardized mortality rate is 16.9, the same increase in coal use is associated with a 6% increase in overall mortality.

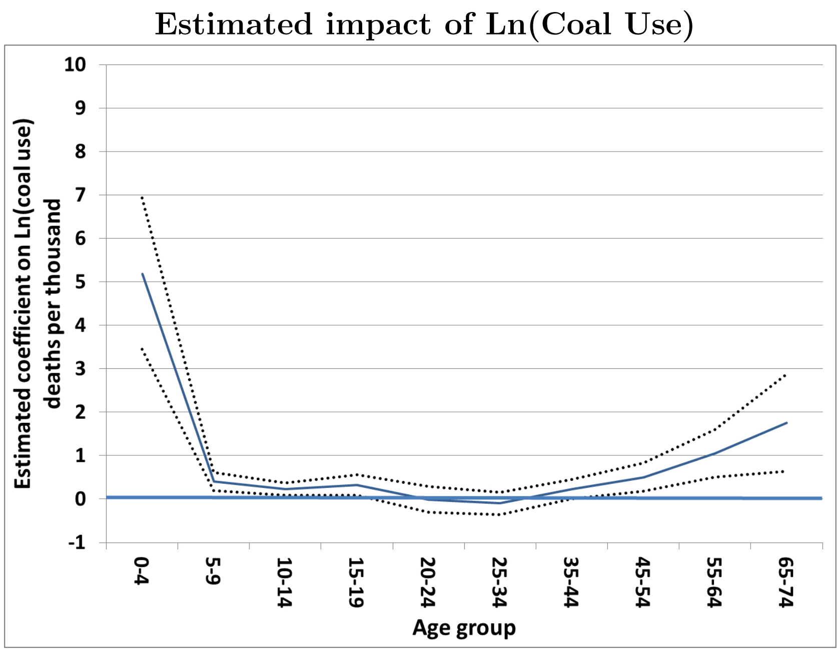
Table 20: Results for children and adults

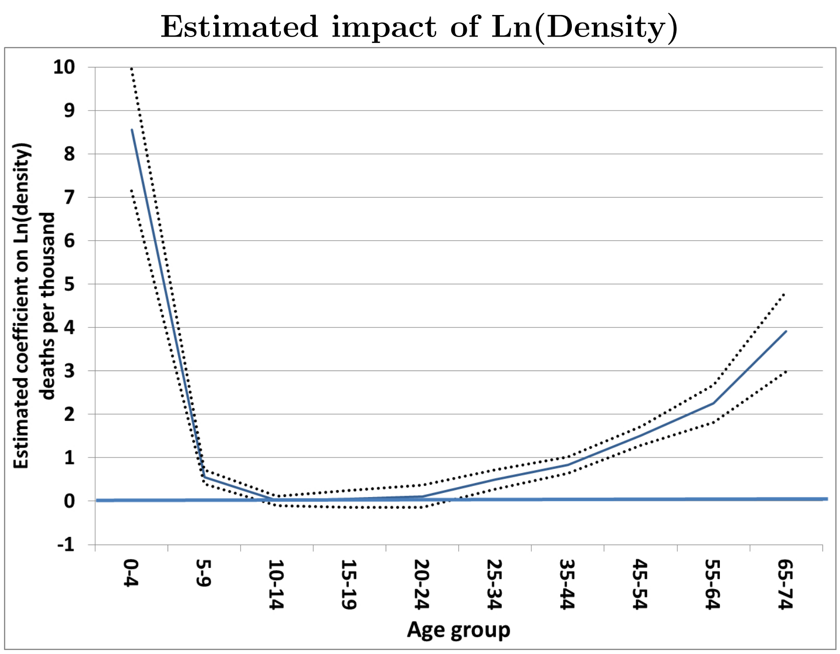
	Children under 5		**Adults 20 and over**	
	DV: Mortality rate		**DV: Age-std. mortality**	
	(1)	(2)	(3)	(4)
Ln(Population Density)	8.554***	8.997***	0.999***	0.947***
	(0.716)	(0.622)	(0.0822)	(0.0766)
Ln(Coal use)	5.187***		0.339**	
	(0.888)		(0.145)	
Ln(Dirty industry emp.)		4.677***		0.430***
		(0.864)		(0.151)
Region controls	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes
Observations	580	580	580	580
R-squared	0.773	0.767	0.518	0.524

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, allow spatial correlation between any districts within 50km of each other. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. Other control variables include employment in water services per 10,000 population in 1851, employment in medical services per 10,000 population in 1851, latitude and seaport tonnage in 1865. Population density and both of the pollution measures are standardized.

Figure 14 presents the estimated coefficients on the coal use and density terms from regressions run within each available age category. These results show that industrial pollution increased mortality both for children and for adults over 35. Population density shows a similar pattern of effects, but with larger impacts for the very young.

Figure 14: Age-specific regression results, 1851-1860





These figures present coefficient estimates and 95% confidence intervals for regressions looking at mortality within specific age categories. The regressions include control variables for water services employment, medical services employment, seaport tonnage, latitude, and region controls. The density and coal use variables are standardized. Standard errors allow for serial correlation for districts within 50km of each other.

A.3.2 Additional results for mortality within occupation categories

This subsection presents additional results for mortality within occupational categories. Table 21 presents results for a number of specific non-industrial occupation groups that are found in substantial numbers across most locations. Because mortality in these categories comes from only one year, there will be substantial noise in the data. Despite this, a number of these non-industrial categories display statistically significant increased mortality in locations with more industrial coal use. At the same time, not one of them shows a statistically significant lower mortality rate associated with industrial pollution. Also, once I control for occupation, I find very little evidence that density substantially affected mortality among the working age males in these data.

The effects of pollution appear among low-skill occupation categories, such as agricultural laborers and domestic servants, as well as high-skill categories such as clergy, lawyers, teachers, and local government officials. This suggests that the effects of pollution were not limited only to the lower classes.

From the coefficients estimated on the constant terms we can see that the underlying level of mortality varies substantially across these different groups. One factor that will contribute to this variation is the fact that it is not possible to age-standardize the data. Variation in the average age across occupations can help explain why we observe such low mortality rates in occupations like agricultural laborers and domestic servants, where most of the workers would have been young men or young women, respectively, and higher rates among occupations requiring more years of education, such as lawyers and doctors.

Table 22 and 23 provide some additional results calculated while including London in the data. The magnitude of the estimated pollution effects are reduced in these results. This is likely due to the fact that, while London had very high death rates, the level of industrial pollution was low compared to what we would expect given the population size.

Table 21: Mortality results for non-industrial occupation categories

	DV: Ln(Age-standardized mortality)									
Category:	Agricultural laborers	Domestic servants	Messengers & porters	Farmers	Shepherds, etc.	Gardeners	Millers & grocers	Butchers, etc.	Innkeepers & publicans	Writing & publishing
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Ln(Coal use)	0.910**	1.542*	1.837	0.245	0.724	1.814**	0.768	-1.299	2.168	-1.498
	(0.379)	(0.880)	(2.872)	(0.750)	(1.422)	(0.858)	(0.689)	(0.805)	(2.307)	(1.564)
Ln(Population Density)	-0.747	-0.0521	-1.840	1.742	0.386	-0.936	-0.0642	-0.308	-1.527	0.133
	(0.474)	(0.779)	(2.328)	(1.242)	(1.184)	(0.841)	(0.581)	(0.645)	(1.914)	(1.592)
Constant	1.932***	12.97***	22.39***	18.52***	17.96***	17.64***	16.90***	21.22***	29.82***	19.27***
	(0.242)	(0.727)	(2.216)	(1.455)	(0.968)	(0.749)	(0.551)	(0.822)	(1.884)	(1.539)
Observations	44	44	44	44	44	44	44	44	44	44
R-squared	0.140	0.130	0.015	0.182	0.031	0.100	0.054	0.137	0.018	0.031

	DV: Ln(Age-standardized mortality)								
Category:	Druggist /chemist	Law clerk	Businessmen	Teacher	National government	Local government	Clergy	Doctors	Lawyers
	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
Ln(Coal use)	1.219	-0.0141	2.352***	3.115***	3.678	4.229***	2.058*	2.911	4.182**
	(1.853)	(2.643)	(0.868)	(0.998)	(3.194)	(1.058)	(1.210)	(2.141)	(1.732)
Ln(Population Density)	-1.273	0.577	-1.549**	-1.279	-1.442	-1.667	-0.856	-2.501	-0.718
	(1.648)	(2.173)	(0.666)	(0.855)	(2.699)	(1.014)	(1.118)	(2.087)	(1.624)
Constant	15.30***	18.30***	20.40***	16.73***	16.37***	12.41***	13.00***	21.69***	17.72***
	(1.757)	(2.045)	(0.724)	(1.026)	(2.642)	(1.211)	(0.906)	(1.601)	(1.476)
Observations	44	44	44	44	44	44	44	44	44
R-squared	0.010	0.003	0.165	0.160	0.059	0.210	0.086	0.056	0.169

*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, are clustered at the county level. Pollution measures are based on each district's industrial composition in 1851. Population density and both of the pollution measures are standardized. Regressions are estimated with analytical weights based on the number of living workers in each county-occupation cell in order to account for the fact that observations based on cells with fewer workers will be noisier. Note that when using all occupation categories some county-occupation cells have no living workers and are dropped. The national government worker category does not include members of the military.

Table 22: Impact on mortality within occupational categories with London

	DV: Deaths per 1000 workers within each occupation			
	All occupations (304)		**Non-industry occupations (89)**	
	(1)	(2)	(3)	(4)
Ln(Coal use)	0.267*		0.774***	
	(0.151)		(0.175)	
Ln(Dirty industry emp.)		0.270**		0.756***
		(0.118)		(0.136)
Ln(Population Density)	0.0226	0.0264	-0.190	-0.172
	(0.0837)	(0.0784)	(0.117)	(0.119)
Constant	56.07**	56.06**	55.92**	55.91**
	(26.78)	(26.78)	(26.60)	(26.60)
Observations	11,950	11,950	3,855	3,855
R-squared	0.294	0.294	0.598	0.598

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered at the county level. Data cover working males aged twenty and over. Pollution measures are based on each district's industrial composition in 1851. Population density and both of the pollution measures are standardized. Regressions are estimated with analytical weights based on the number of living workers in each county-occupation cell. County-occupation cells with no living workers are dropped.

Table 23: Regressions for all working males aged twenty and over with London

	DV: Deaths per 1000			
	All occupations (304)		**Non-industry occupations (89)**	
	(1)	(2)	(3)	(4)
Ln(Coal use)	0.859***		2.227***	
	(0.259)		(0.259)	
Ln(Dirty industry emp.)		0.721***		2.028***
		(0.243)		(0.169)
Ln(Population Density)	0.659***	0.716***	0.586***	0.680***
	(0.123)	(0.115)	(0.129)	(0.131)
Constant	13.24***	13.29***	10.39***	10.46***
	(0.282)	(0.286)	(0.317)	(0.314)
Observations	45	45	45	45
R-squared	0.629	0.618	0.761	0.766

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parenthesis. Pollution measures are based on each district's industrial composition in 1851. Population density and both of the pollution measures are standardized. Regressions are estimated with analytical weights based on the number of living workers in each county-occupation cell. County-occupation cells with no living workers are dropped.

A.3.3 Additional cause-of-death analysis results

This subsection presents some additional regression results related to the analysis of causes-of-death. In Table 24, I look at the impact of industrial pollution on respiratory and other mortality causes separately for adults twenty and over and children under five. For both of these age groups, industrial pollution had a stronger impact, in percentage terms, on respiratory mortality than on other mortality causes.

Table 24: Impact of pollution on respiratory and total mortality for adults and children

	Children under 5		**Adults 20 and over**	
Category:	Respiratory mortality	Total mortality	Respiratory mortality	Total mortality
	(1)	(2)	(3)	(4)
Ln(Pop. Density)	0.137***	0.119***	0.143***	0.0411***
	(0.0339)	(0.0128)	(0.0187)	(0.00476)
Ln(Coal use)	0.187***	0.0990***	0.0906***	0.0145*
	(0.0600)	(0.0143)	(0.0280)	(0.00771)
Region controls	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes
Observations	580	580	580	580
R-squared	0.605	0.692	0.485	0.367

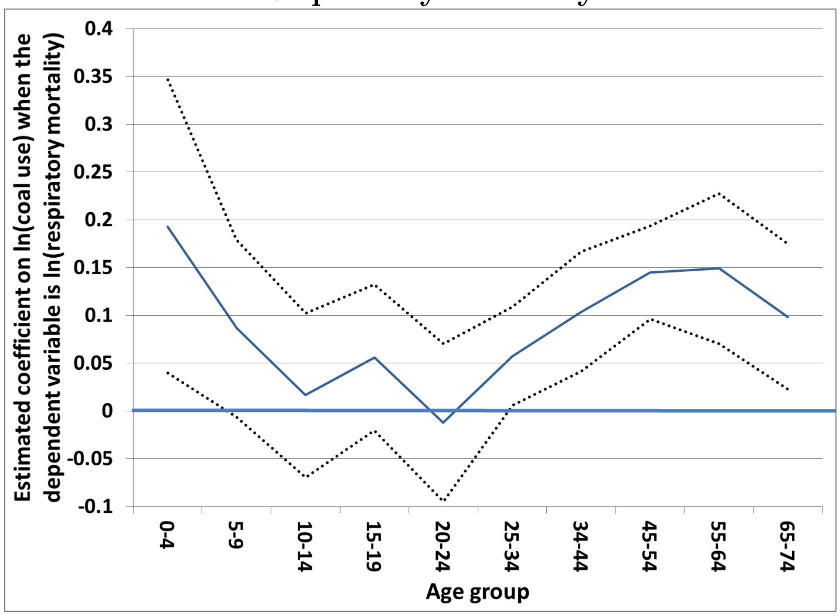
*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, allow spatial correlation between any districts within 50km of each other. Mortality data for the decade 1851-1860. Pollution measures are based on each district's industrial composition in 1851. Other control variables include employment in water services per 10,000 population in 1851, employment in medical services per 10,000 population in 1851, seaport tonnage in 1865, and latitude. The population density and pollution variables are standardized. Adult mortality is age-standardized.

Figure 15 presents age-specific estimates of the effect of pollution on respiratory and total mortality. Together, these values are used to obtain the age-specific excess respiratory mortality effect of pollution which is then used in calculating the impact of excess respiratory mortality on life expectancy.

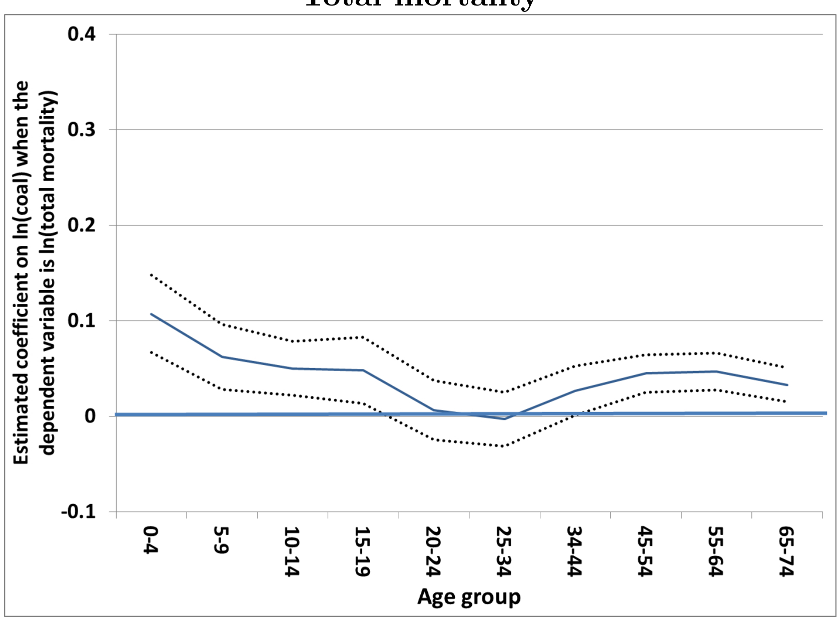
Table 25 describes results for total mortality and respiratory mortality obtained using an alternative pollution measures.

Figure 15: Age-specific cause-of-death regression results

Respiratory mortality



Total mortality



These figures present coefficient estimates and 95% confidence intervals for the estimated coefficient on Ln(Coal use) in age-specific regressions. The top panel presents results when the dependent variable is Ln(Respiratory mortality) while the bottom panel presents results when the dependent variable is Ln(Total mortality). The difference between these two coefficients is age-specific excess respiratory mortality.

Table 25: Cause-of-death results with alternative pollution measures, 1851-1860

	DV: Ln(Age-standardized mortality)							
Category:	Respiratory mortality (1)	Total mortality (2)	Respiratory mortality (3)	Total mortality (4)	Respiratory mortality (5)	Total mortality (6)	Respiratory mortality (7)	Total mortality (8)
Ln(Pop. Density)	0.153***	0.0931***	0.154***	0.0880***	-0.103	-0.0134	0.0251	0.0292***
	(0.0174)	(0.00561)	(0.0180)	(0.00465)	(0.0780)	(0.0164)	(0.0493)	(0.0108)
Coal per worker	0.118***	0.0444***						
	(0.0287)	(0.00694)						
Dirty emp. share			0.117***	0.0537***				
			(0.0299)	(0.00621)				
Ln(Coal per acre)					0.326***	0.133***		
					(0.0827)	(0.0187)		
Ln(Dirty emp./acre)							0.202***	0.0923***
							(0.0543)	(0.0142)
Region effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	580	580	580	580	580	580	580	580
R-squared	0.600	0.731	0.591	0.742	0.594	0.734	0.576	0.724

*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, allow spatial correlation for districts within 50km. The pollution measures, as well as the water and medical services controls, are based on each district's industrial composition in 1851. Population density and the pollution measures are standardized. Other controls includes water service employment, medical service employment, seaport tonnage and latitude.

A.3.4 Additional cross-sectional results for each decade from 1851-1900

This subsection presents additional results looking at the evolution of the mortality effects of pollution from 1851-1900 using cross-sectional regressions. Table 26 presents regression results for each decade from 1851-1900 using county level data and the pollution measure based on dirty industry employment. As in the main results, we observe a consistent decrease in the impact of population density on mortality over time. The impact of industrial pollution remains stable over this period, but unlike the results presented in the main text, we do not observe evidence of an inverted U-shaped relationship in the impact of industrial pollution over time.

Table 26: County-level cross-sectional results using dirty employment, 1851-1900

	DV: Age-standardized mortality				
	1851-1860	**1861-1870**	**1871-1880**	**1881-1890**	**1891-1900**
Ln(Pop. Density)	0.941**	0.904**	0.758*	0.566**	0.467**
	(0.382)	(0.402)	(0.412)	(0.206)	(0.183)
Ln(Dirty emp.)	1.128***	0.778**	0.843**	0.755***	0.948***
	(0.286)	(0.334)	(0.297)	(0.113)	(0.128)
Water service emp.	0.142	1.572	1.733	2.356	-0.0462
	(1.194)	(2.521)	(1.757)	(1.477)	(0.0283)
Medical service emp.	-0.497**	-0.810*	-1.382***	-0.888***	-0.976***
	(0.200)	(0.369)	(0.298)	(0.110)	(0.119)
Seaport tonnage	1.081***	1.452***	0.985***	1.191***	0.829***
	(0.241)	(0.121)	(0.271)	(0.109)	(0.203)
Constant	19.92***	19.81***	18.12***	16.87***	16.44***
	(0.240)	(0.333)	(0.254)	(0.138)	(0.243)
Observations	53	53	53	53	53
R-squared	0.810	0.766	0.754	0.851	0.815

*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, are clustered by region. The pollution measures, as well as the water and medical services controls, are based on each district's industrial composition at the beginning of each decade. Seaport tonnage is based on data from 1865. The population density, dirty industry employment, water services and medical services variables have been standardized. Regressions are weighted by county population.

Table 27 presents regression results for each decade from 1851-1900 including London. These results show similar patterns to those documented in the main text.

Table 27: Cross-sectional results with London, 1851-1900

	DV: Age-standardized mortality				
	1851-1860	**1861-1870**	**1871-1880**	**1881-1890**	**1891-1900**
Ln(Pop. Density)	0.869***	0.512*	0.670**	0.499**	0.487***
	(0.237)	(0.265)	(0.289)	(0.178)	(0.135)
Ln(Coal use)	1.394***	1.609***	1.610***	1.108***	1.288***
	(0.287)	(0.364)	(0.404)	(0.206)	(0.220)
Water service emp.	1.542	4.240	2.921*	3.487*	0.00408
	(1.225)	(2.820)	(1.385)	(1.618)	(0.0337)
Medical service emp.	-1.146***	-1.131***	-1.459***	-1.007***	-0.889***
	(0.214)	(0.332)	(0.436)	(0.208)	(0.147)
Seaport tonnage	0.813***	1.255***	0.791***	1.048***	0.694***
	(0.105)	(0.177)	(0.231)	(0.0537)	(0.0892)
Constant	20.36***	19.95***	17.87***	16.81***	16.11***
	(0.292)	(0.404)	(0.271)	(0.233)	(0.332)
Observations	55	55	55	55	55
R-squared	0.927	0.929	0.898	0.954	0.943

*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Standard errors, in parenthesis, are clustered by region for 11 regions. The pollution measures, as well as the water and medical services controls, are based on each district's industrial composition at the beginning of each decade. Seaport tonnage is based on data from 1865. The population density, coal use, water services and medical services variables have been standardized. Regressions are weighted by county population.

Table 28 presents regression results by cause-of-death for each decade from 1851-1900. The estimated coal use coefficients from these regressions correspond to the coefficients reported in Table 9 in the main text. Table 29 presents similar results using the dirty industry employment measure of industrial pollution.

Table 28: Impact of coal use in each decade for respiratory and all diseases

Decade:	1851-1860		1861-1870		1871-1880		1881-1890		1891-1900	
COD:	All causes	Resp.	All causes	Resp.	All causes	Resp.	All causes	Resp.	All causes	Resp.
Ln(Pop. Density)	0.0621***	0.174**	0.0430	0.149**	0.0363	0.120***	0.0315*	0.0852**	0.0297*	0.0796***
	(0.0174)	(0.0559)	(0.0239)	(0.0489)	(0.0203)	(0.0239)	(0.0156)	(0.0293)	(0.0134)	(0.0246)
Ln(Coal use)	0.0471**	0.116*	0.0561**	0.131**	0.0667***	0.113***	0.0525***	0.104**	0.0643***	0.109***
	(0.0157)	(0.0631)	(0.0232)	(0.0512)	(0.0210)	(0.0255)	(0.0151)	(0.0361)	(0.0160)	(0.0285)
Water service emp.	-0.0242	0.129	0.137	-0.00754	0.127	-0.0554	0.137	-0.0340	-0.00105	-0.00120
	(0.0550)	(0.285)	(0.150)	(0.159)	(0.103)	(0.0895)	(0.0938)	(0.215)	(0.00203)	(0.00323)
Medical service emp.	-0.0393***	0.0136	-0.0472***	-0.00553	-0.0703***	-0.0532	-0.0531***	-0.0721**	-0.0503***	-0.0842***
	(0.00887)	(0.0312)	(0.0139)	(0.0287)	(0.0199)	(0.0333)	(0.0108)	(0.0280)	(0.00846)	(0.0199)
Seaport tonnage	0.0261***	0.00171	0.0426***	0.0146	0.0276***	0.0155	0.0440***	0.0500***	0.0275***	0.0223*
	(0.00658)	(0.0300)	(0.00877)	(0.0104)	(0.00741)	(0.0177)	(0.00437)	(0.0147)	(0.00838)	(0.0106)
Constant	2.999***	0.908***	2.985***	0.936***	2.881***	1.005***	2.814***	1.039***	2.774***	0.971***
	(0.0128)	(0.0302)	(0.0199)	(0.0188)	(0.0143)	(0.0212)	(0.0122)	(0.0276)	(0.0222)	(0.0359)
Observations	54	54	54	54	54	54	54	54	54	54
R-squared	0.912	0.781	0.908	0.866	0.880	0.863	0.940	0.919	0.926	0.919

*** $p<0.01$, ** $p<0.05$, * $p<0.1$ Standard errors clustered by region for 11 regions. The pollution measures, as well as the water and medical services controls, are based on each district's industrial composition at the beginning of each decade. Seaport tonnage is based on data from 1865. The population density, coal use, water services and medical services variables have been standardized. Regressions are weighted by county population.

Table 29: Impact of dirty industry employment in each decade for respiratory and all diseases

Decade:	1851-1860		1861-1870		1871-1880		1881-1890		1891-1900	
COD:	All causes	Resp.	All causes	Resp.	All causes	Resp.	All causes	Resp.	All causes	Resp.
Ln(Pop. Density)	0.0586***	0.173**	0.0311	0.127**	0.0249	0.0944**	0.0297*	0.0752**	0.0322**	0.0757***
	(0.0177)	(0.0574)	(0.0229)	(0.0449)	(0.0251)	(0.0324)	(0.0139)	(0.0259)	(0.0139)	(0.0238)
Ln(Dirty emp.)	0.0455***	0.103*	0.0636***	0.141***	0.0757***	0.136***	0.0537***	0.116***	0.0573***	0.108***
	(0.0136)	(0.0546)	(0.0198)	(0.0403)	(0.0217)	(0.0316)	(0.0122)	(0.0338)	(0.0148)	(0.0286)
Water service emp.	-0.00744	0.165	0.167	0.0581	0.141	-0.0296	0.118	-0.0916	-0.00235	-0.00332
	(0.0562)	(0.279)	(0.145)	(0.161)	(0.102)	(0.0877)	(0.0866)	(0.190)	(0.00196)	(0.00324)
Medical service emp.	-0.0375***	0.0153	-0.0414**	0.00531	-0.0613**	-0.0337	-0.0501***	-0.0619**	-0.0506***	-0.0804***
	(0.00910)	(0.0342)	(0.0147)	(0.0245)	(0.0202)	(0.0362)	(0.00821)	(0.0260)	(0.00800)	(0.0200)
Seaport tonnage	0.0252***	-0.000164	0.0411***	0.0113	0.0246***	0.0101	0.0413***	0.0439***	0.0249**	0.0179
	(0.00748)	(0.0357)	(0.00708)	(0.0137)	(0.00410)	(0.0138)	(0.00470)	(0.0124)	(0.0104)	(0.0132)
Constant	2.990***	0.888***	2.982***	0.931***	2.888***	1.016***	2.821***	1.047***	2.786***	0.986***
	(0.0115)	(0.0342)	(0.0175)	(0.0162)	(0.0131)	(0.0204)	(0.0112)	(0.0270)	(0.0195)	(0.0350)
Observations	54	54	54	54	54	54	54	54	54	54
R-squared	0.914	0.777	0.918	0.876	0.892	0.881	0.943	0.927	0.924	0.922

*** $p<0.01$, ** $p<0.05$, * $p<0.1$ Standard errors clustered by region for 11 regions. The pollution measures, as well as the water and medical services controls, are based on each district's industrial composition at the beginning of each decade. Seaport tonnage is based on data from 1865. The population density, coal use, water services and medical services variables have been standardized. Regressions are weighted by county population.

A.3.5 Additional long-difference regression results

This subsection presents additional long-difference regression results. Table 30 provides results when London is included in the data. In general these result are similar to those described in the main text, though I now find statistically significant evidence that respiratory mortality increased as a result of rising industrial coal use when using the IV specification.

Table 30: Long-difference regression results with London

	OLS regressions				**IV regressions**	
Dependent variable:	Δ Log total mortality	Δ Log respiratory mortality	Δ Log total mortality	Δ Log respiratory mortality	Δ Log total mortality	Δ Log respiratory mortality
	(1)	(2)	(3)	(4)	(5)	(6)
Δ Coal per cap.	0.0584***	0.150***	0.0550***	0.136**	0.0714**	0.241*
	(0.0166)	(0.0433)	(0.0173)	(0.0510)	(0.0310)	(0.129)
Constant	-0.270***	-0.0350	-0.252***	0.0403	-0.281***	-0.113
	(0.0189)	(0.0452)	(0.0271)	(0.0959)	(0.0274)	(0.0922)
Other controls			Yes	Yes		
Observations	55	55	55	55	55	55
R-squared	0.270	0.190	0.293	0.236	0.257	0.119

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered by 11 regions. Columns 1-2 present OLS regressions for total mortality and respiratory mortality, respectively. Columns 3-4 add in controls for the change in medical and water services employment. Columns 5-6 present IV regression results in which a Bartik instrument based on initial county industrial composition interacted with the growth rate of industries in all other counties and then interacted with industry coal use intensity is used as an instrument for the change in industrial coal use at the county level. Good instruments are not available for the change in water or medical services so these are not included in the IV regressions. All regressions are weighted by 1851 county population.

Table 31 presents results from unweighted long-difference regressions. These regressions deliver similar, but generally larger, estimates of the impact of rising coal use on mortality.

Table 31: Long-difference regression results without weights

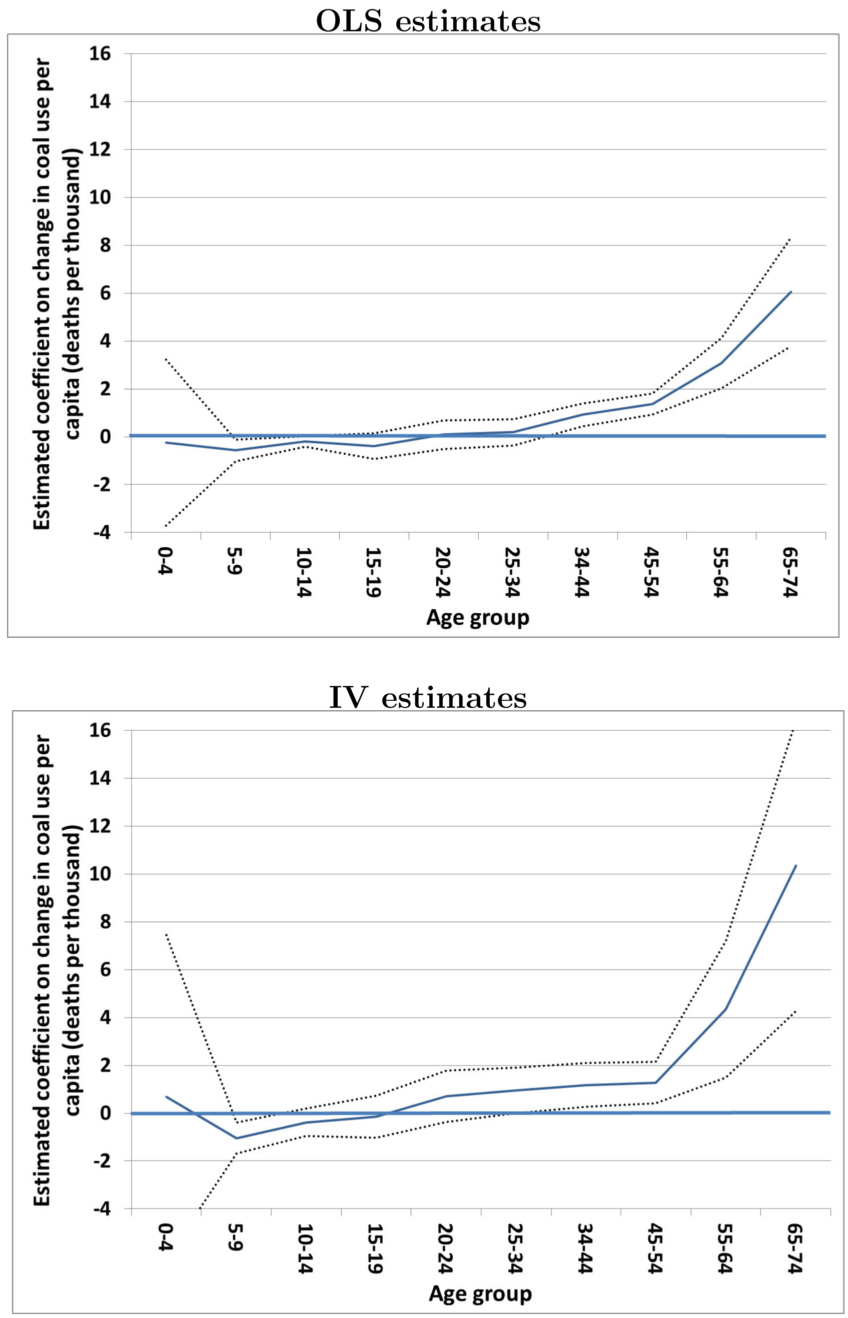
	OLS regressions				IV regressions	
Dependent variable:	Δ Log total mortality	Δ Log respiratory mortality	Δ Log total mortality	Δ Log respiratory mortality	Δ Log total mortality	Δ Log respiratory mortality
	(1)	(2)	(3)	(4)	(5)	(6)
Δ Coal per cap.	0.0767**	0.144**	0.0725**	0.118*	0.141**	0.364*
	(0.0277)	(0.0515)	(0.0296)	(0.0543)	(0.0582)	(0.200)
Constant	-0.274***	0.0688	-0.244***	0.251	-0.322***	-0.0947
	(0.0349)	(0.0978)	(0.0517)	(0.144)	(0.0469)	(0.144)
Other controls			Yes	Yes		
Observations	54	54	54	54	54	54

*** p<0.01, ** p<0.05, * p<0.1. Standard errors, in parenthesis, are clustered by 11 regions. Columns 1-2 present OLS regressions for total mortality and respiratory mortality, respectively. Columns 3-4 add in controls for the change in medical and water services employment. Columns 5-6 present IV regression results in which a Bartik instrument based on initial county industrial composition interacted with the growth rate of industries in all other counties and then interacted with industry coal use intensity is used as an instrument for the change in industrial coal use at the county level. Good instruments are not available for the change in water or medical services so these are not included in the IV regressions.

Figure 16 describes age-specific long-difference regression results. These estimates show that increasing coal use raised mortality, and that these effects were concentrated in older age categories. It is somewhat surprising that we don't see any evidence that rising coal use intensity affected mortality among young children. The most likely explanation for this pattern is that one of the main impacts of coal use on the mortality of children was through increasing their vulnerability to infectious diseases. Because infectious diseases fell dramatically over the 1851-1891 period, the impact of coal use on child mortality through this channel would have been substantially reduced. Some support for this hypothesis is provided by Figure 17, which focuses only on mortality due to respiratory diseases. The fall in infectious disease mortality should not have had much effect on mortality due to respiratory causes. The estimates in Figure 17 provide evidence that rising coal use did increase child mortality due to respiratory diseases, though the IV estimates for child mortality are imprecise.

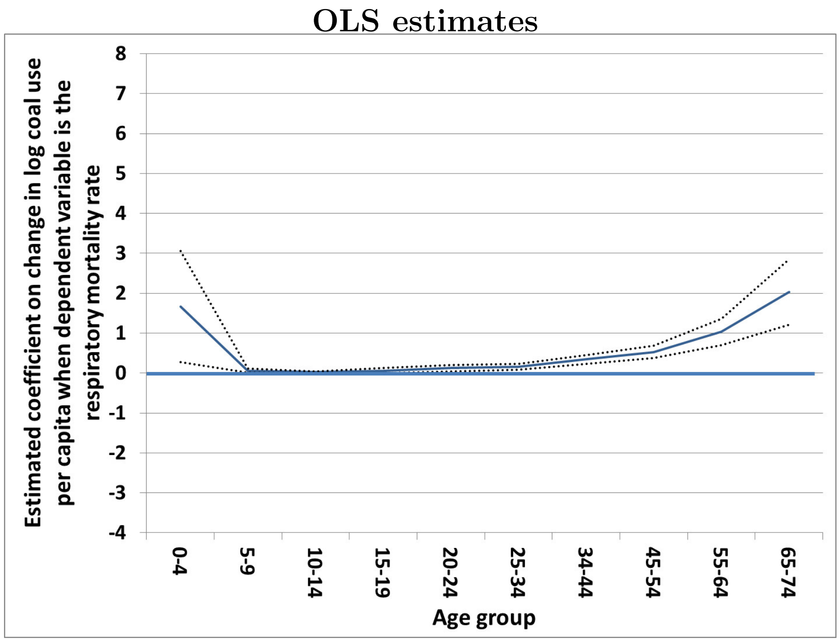
The estimates shown in these figures are used to calculate the impact of rising coal use on life expectancy through either total mortality or excess respiratory mortality.

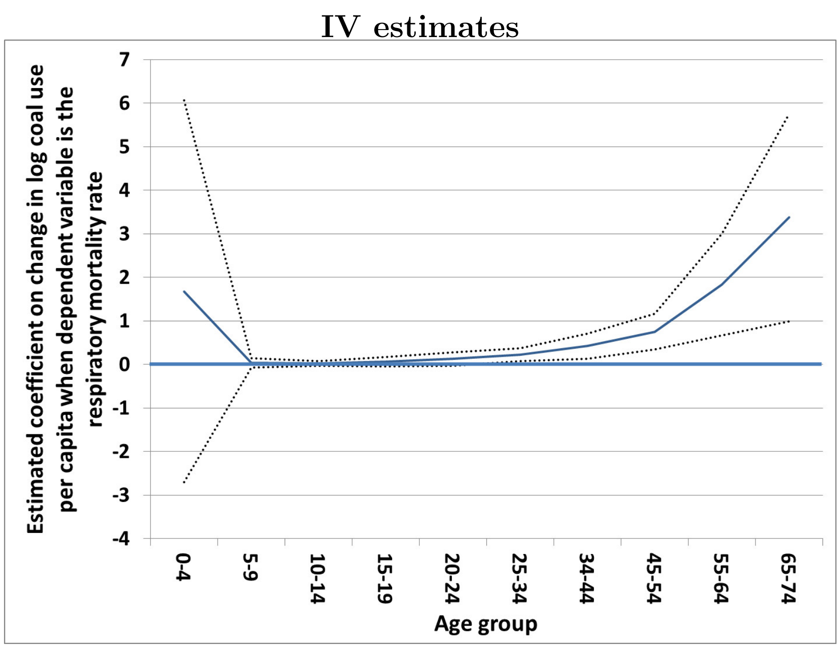
Figure 16: Age-specific long-difference regression results



These figures present coefficient estimates and 95% confidence intervals for the Δ Coal per capita coefficients estimated using long-difference regressions. The dependent variable is the change in the log mortality rate for residents within a particular age category. The top panel panel presents results from OLS regressions. These correspond to the specification used in Column 1 of Table 11 to study all-age mortality. The bottom panel presents IV results. These correspond to the specification used in Column 5 of Table 11.

Figure 17: Age-specific long-difference regression results – respiratory mortality only





These figures present coefficient estimates and 95% confidence intervals for the Δ Coal per capita coefficients estimated using long-difference regressions. The dependent variable is the change in the log mortality rate for residents within a particular age category. The top panel presents results from OLS regressions. These correspond to the specification used in Column 2 of Table 11 to study all-age mortality. The bottom panel presents IV results. These correspond to the specification used to study all-age mortality in Column 6 of Table 11.