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DID FREDERICK BRODIE DISCOVER THE WORLD'S FIRST ENVIRONMENTAL KUZNETS CURVE? COAL SMOKE AND THE RISE AND FALL OF THE LONDON FOG

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ABSTRACT

In a paper presented to the Royal Meteorological Society, Brodie (1905) presented a data series that presaged the modern Environmental Kuznets Curve: in the decades leading up to 1890, the number of foggy days in London rose steadily, but after 1891, the fogs began to subside. Brodie attributed the rise and fall of the London fog to variation in emissions of coal smoke, arguing that before 1890 Londoners burned excessive amounts of soft coal, while in the years following, a series of legal, demographic, and technological changes mitigated the production of coal smoke. This paper asks two questions. First, are Brodie's underlying data trustworthy? Do other, independent sources of evidence same patterns Brodie identified? Was London's atmosphere becoming more polluted and foggy for most of the nineteenth century, only to improve around 1890? Second, if so, is Brodie's interpretation of the data correct? Can the changes in London's atmosphere be attributed to changes in the production of coal smoke, or were they the result of some broader meteorological phenomenon. The evidence we present here is consistent Brodie's data and interpretation.

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0. Introduction

In 1903, at a meeting of the Royal Meteorological Society, a British climatologist named Frederick J. Brodie presented a deceptively simple paper. Using data from the Brixton weather station in London, Brodie graphed the number foggy days per year between 1871 and 1903. His data, reproduced here in figure 1, revealed an inverted U-shaped pattern: the annual number of foggy days in London rose during the 1870s and 1880s; reversed trend sometime around 1888 or 1889; and then fell steadily during the 1890s and early 1900s. Brodie attributed the rise and fall of the London fog to variation in the production of coal smoke. During the 1870s and 80s, Brodie claimed, London businesses and homeowners burned coal with reckless abandon, filling the atmosphere with soot and giving rise to dense and dark fogs. After 1890, however, technological, legal, and social changes enabled, or forced, homeowners and businesses to burn coal more efficiently and cleanly. In particular, the expansion of gas for heating and cooking, and electricity for lighting curtailed domestic sources of smoke; and the London Coal Smoke Abatement Society lobbied local authorities to enforce the Public Health Acts which required manufacturers to adopt low-smoke technologies (Brodie 1905, pp. 15-20).

The criticisms of Brodie's paper were many. Multiple observers argued that the series Brodie had assembled was not believable because it focused on a single weather station, and fog data were based on subjective, non-instrumental observations. Brodie himself did not define what exactly was meant when a day was recorded as "foggy."[1] Were other weather

[1] According to Brazell (1968, p. 102), meteorologists did not construct a standardized definition of fog "until the development of aviation after the First World War."

stations in London revealing the same trend? Were other, more objective measures consistent with the reported decline in fog? If not, one could not even believe the underlying pattern Brodie was trying to explain, let alone his contentious interpretation. Other critics argued that changing wind speeds and directions could account for the rise and fall of the fog, in part because fog does not usually form in windy environments. H.L. Mill focused on the changing relationship between rainfall and fogs during the 1880s and on variation in atmospheric conditions over time. Another discussant wondered how the environs of London could possibly have been becoming less smokey over time, given the rapid growth in the city's population and manufacturing base. J.E. Clark believed one could ascribe at least part of the pattern observed by Brodie to the eruption of Krakatoa in Java in 1883, which had significant and lasting meteorological effects all over the globe. Clark seemed to suggest that Krakatoa might account for the increase in atmospheric haze in the immediate aftermath of the eruption, and also explain the decline in haze as the effects dissipated (Brodie 1905, pp. 21-27).

In this paper, we reconsider Brodie's data and his interpretation of those data. Specifically, we want to ask whether independent sources of evidence indicate smoke-induced changes in London's atmosphere over the course of the nineteenth and early twentieth century. Besides Brixton, do other London weather stations record a similar rise and fall in foggy days per annum? Do other measures of atmospheric conditions, such as hours of bright sunlight, also indicate improvement in London after 1890? Similarly, if London's air were becoming less polluted with coal smoke after 1890, this would have manifested itself in effects on human health, particularly deaths from respiratory diseases. To the extent that other sources of evidence corroborate Brodie's basic finding—that the incidence of fog and smoke in London was rising before 1890 and declining thereafter—we need to turn to Brodie's interpretation of that finding and ask why the atmosphere changed over time.

Four sorts of evidence will be considered. First, if smoke abatement efforts really were causing Londoners to burn coal more efficiently and adopt (relatively) smokeless technologies such as gas and electricity, this should be observable in data on coal consumption per capita and in data on gas and electricity production. Second, using a procedure we describe as a reverse-event study, we use large and unusual spikes in weekly mortality data to identify the frequency and severity fog-related events. Fog-related events were severe and persistent episodes of fog that culminated in spikes in mortality, particularly from respiratory diseases. The reverse event study is a center-piece of the paper, and the most novel part of our analysis. Third, we will construct a crude panel of cities and ask whether smoke abatement interventions in those cities also reduced pollution levels as manifested in deaths from respiratory diseases. Fourth, we will present a brief history of smoke abatement technologies and the enforcement of pollution control laws during the Victorian and Edwardian eras. This history will help establish a circumstantial case, for or against, the proposition that such actions helped make London a less smoky place.[2]

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[2]Ideally, we would like to get data on wind speed and direction, as well as the occurrence of anticyclones, a condition of extreme stillness that often produced fog, independent of the level of smoke in the air. Unfortunately, after much search, we have been unable to find such data. Nevertheless, some of the data and evidence we present below will provide indirect and qualitative information on the evolution of wind speed and the formation of fog in London.

The ostensible rise and fall of the London fog should interest economists and economic historians on at least two levels. First, the debate surrounding Brodie's paper prefigures current debates about the Environmental Kuznets Curve (EKC). Indeed, if Brodie's data and interpretations prove sound, he identified an archaic EKC. The construction of this early EKC might suggest pathways for studying the long-term evolution of the environment and environmental regulation. Other than a few metrics of water quality (e.g., bacteria counts and nitrate concentrations), governments before 1950 did not usually measure and report data on greenhouse gas emissions, air quality, or any of the inorganic environmental pollutants that interest us today.[3] One solution to this problem is to search for data that might serve as a proxy for environmental pollution. This paper provides, as far as we are aware, the first systematic attempt to implement and evaluate such proxies, in this case data on fogs and death rates. Along the same lines, when economists estimate the shape of the EKC, they must rely on cross-sections or very short time series from the late-twentieth century. While there is a venerable tradition of inferring the time series from cross-sectional relationships, recent empirical work suggests that such exercises are problematic in the context of the EKC (e.g., Deacon and Norman 2006; and De Bruyn 1997). A true historical time series would therefore be desirable. Documenting efforts by Western governments at an early stage of development to regulate coal smoke, this paper provides the beginnings of such a time series and helps to resolve some fundamental questions about the meaning of the EKC.

[3]See, however, List and Gallet (1999) who employ data on sulphur emissions in American states back to 1929.

Second, the basic question Brodie raised and attempted to answer is of no small historical moment: how could there have been a meaningful environmental movement in Victorian England? It seems a stretch. Smoke abatement technologies strike most of us as a distinctly late-twentieth century invention. Aside from a wholesale switch from coal to natural gas (which did not happen), what could be done in 1890 to reduce coal smoke? Whatever the available technology, surely it must have been much less efficient and more costly than today's abatement methods. How could a country that in 1890 was not much more wealthy than Mexico today, afford such an investment? The politics too seems all wrong. We tend to think of Victorian Britain as a place where the expedience of cholera and child labor trumped the expense of clean water and a decent wage, as a place where environmental and social degradation served as the handmaidens of avarice and economic development. Yet Brodie's paper suggests something quite different, as does even a cursory look at the political and economic history of smoke abatement. How can one reconcile all of this? There is, in short, much history to write and revise if Brodie turns out to be right, even partially right.[4]

1. What Was the London Fog?

The immediate causes of the London fog were evocatively described by the renowned nineteenth-century scientist Rollo Russell. According to Russell, the London fog began early in the morning around 6 a.m., when the city, or parts of the city, were enveloped by an "ordinary thick white fog." Soon after this, the city would awaken by lighting "about a million fires."

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[4]This paper spans the Victorian (1837-1901) and Edwardian (1901-1910) eras. As we show later, however, most of the interesting activity in terms of regulations, climate, and technology were products of the Victorian period.

These fires charged the atmosphere with "carbonaceous particles," which upon cooling, attached themselves to the spheres of water that constituted the fog. Ordinarily the warmth of the sun would have quickly dissipated the fog, but the smoke and an oily tar that surrounded the spheres of water impaired this process. In these conditions, city residents would not have sunlight until noon.[5] In an article in *Nature*, W.J. Russell (1891, p. 11) developed a similar line of thought, arguing that coal and sulphur particles induced the formation of fog by offering gaseous water a surface on which to condensate.[6] Late twentieth century scientists concur. For example, Brazell (1968, p. 102) writes: "London fogs are particularly obnoxious because the fog droplets tend to form on minute particles of atmospheric pollution which are usually produced by the combustion of coal, oil, and petrol."

While most of us use the word smog to describe the "cocktail of motor exhaust gases catalysed by sunlight and typically found over Los Angeles," the word is actually the product of nineteenth-century thinking about the unholy merger of smoke and fog. The person who first coined the term, or at least claimed credit for doing so, was H.A. Des Voeux, the Treasurer of the London Coal Smoke Abatement Society. In a letter to the *Times* (Dec. 27, 1904, p. 11), Des Voeux wrote that he wished to call London's fog problem by the name "smog" to show that it

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[5]This passage quoting Russell is from Hann's (1903) *Handbook of Climatology* , p. 78. A similar description is offered in Russell (1906).

[6]Russell (1891, p. 11) wrote: "The dust always present in the atmosphere offers this free surface to the gaseous water, and thus induces its condensation. This specific action of dust varies very considerably, first with regards to its composition, and second with regard to the size and abundance of the particles present. Sulphur burnt in the air is a most active fog producer, so is salt." For a similar statement regarding the origins and persistence of smoke-laden fogs, see Frankland (1882).

consisted "more of smoke than of true fog." Des Voeux believed that ordinary fogs were caused by the condensation moisture and that nothing could be done to eliminate them. Smog, on the other hand, was a different matter entirely. "Fog," Des Voeux wrote, was "incurable and infrequent" while "smog" was "curable and frequent." Brodie (1905, p. 20) expressed the same sentiment when he wrote colorfully about the benefits of an atmosphere purged of smoke: "With cleaner air . . . there is little doubt that fogs would diminish in frequency, and even when they did arise, the vapour particles would not be impregnated, as they are now, by the pestilential products arising from an imperfect and wasteful consumption of fuel."[7]

With or without the coal smoke, though, London would have been subjected to much ordinary fog. Describing London as "incorrigible" from a "meteorological point of view," Brodie argued that the city's geography and proximity to a large river made it "eminently favorable to the development of fog and mist." Two government reports issued in the early 1900s showed that the formation of fog in London was correlated with temperature, humidity, and wind-speed. Fogs were much more likely when the temperature in the city was below 40 degrees (no dense fog was observed when temperature was above 40), when humidity was high, and when the winds were calm. London fogs, these reports concluded, were of indigenous origin; they were not blown in from the countryside or nearby marshes, as many suggested (*Nature*, Jan. 12, 1905, p. 259). There was also a surprising inversion of temperatures during the most intense fogs. An article in *Nature* (April 9, 1903, p. 549) explained: "On March

[7]Martin (1906) presented data showing that London air contained higher carbon dioxide levels during fogs than during days without fog; per unit of air, carbon dioxide levels were 75 to 150 percent higher during "black fogs" than during clear moments.

7, during fog, the temperature in the streets of London was nearly 10° F. below that on the roof of the Meteorological Office, the elevated stations, and the surrounding country on the southern and western sides."

Britain's "latitudinal and continental position" was of special importance, because it left the whole country in the path of sequences of "migratory depressions" and anticyclones (Chandler 1965, p. 35). Anticyclones, and the temperature inversions that accompanied them, played a central role in the propagation of a certain kind of London fog. A short article in the journal *Notes and Queries* (March 2, 1878, p. 178) provides the clearest contemporary statement we have found on the significance of anticyclones. We quote it in full:

> These fogs are not caused by the rarefaction of the air, or by the consumption of gas, nor yet by the hills on the north, nor by the river. The peculiar atmospheric condition termed an anti-cyclone is the real cause of these annoying visitations; the wind is then blowing round a well defined circle, in the centre of which the air is tranquil, and consequently the smoke, condensed vapours, & c., cannot escape as they do when there is a direct onward movement of the wind. The pressure of the atmosphere at such times is almost invariably greatly in excess of the average in the midst of the anti-cyclone, which, by preventing the rise of the smoke, & c., increases the intensity of the fog. Whenever, therefore, an anti-cyclone occurs with London at or near the centre, there must necessarily be a `London fog,' the density of which will be in proportion to the smoke evolved at the time. The same phenomenon may be observed in other places within the anticyclonic circle, but of course in a less degree of density.

The most extreme and malignant forms of the London fog were those associated with anticyclones. In section 3, we will describe these fogs more fully and discuss their effects on human health. An econometric analysis of the excess deaths caused by such fogs will help us construct a measure of pollution that is independent of Brodie's fog counts.

2. Do Other Sources of Evidence Suggest a Decline in Fog?

In 1910, the *Times* of London published a short article entitled, "A Purified London Air." Although part of the article appears to have been based on Brodie's original paper, other parts of the article provide independent corroboration of Brodie's findings about the incidence of fogs and their connection to smoke. The opening paragraph began with the reporter's own assessment of the situation, an assessment he clearly believed was unassailable:

> The decrease in recent years, not only in the frequency but in the intensity of London fog, is a matter which admits no serious question. Persons who have reached middle age well remember the time when dense smoke fogs of the worst possible description were a common feature of the winter season, and lasted not infrequently for a week or more at a stretch.

In contrast to these earlier periods, "visitations" of smoke-laden fogs were "rare" by 1910, and "seldom" continued "without intermission for more than two or three days." The same article also presented data on the hours of bright sunshine in London, which presumably would have been inversely correlated with the incidence of fog. Sunshine, in contrast to fog, was measured instrumentally using a device known as the "Campbell Stokes Sunshine Recorder." The recorder consisted of a clear ball that magnified bright sunlight and gradually burned away a piece of cardboard. The sunshine data found in the *Times* are broadly consistent Brodie's data on the fog; they suggest that improvements in London's air began five to ten years earlier, during the early to mid 1880s as opposed to the early 1890s (*Times*, Dec. 27, 1910, p. 11).[8]

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[8]This was not the first time that the Times argued that London's atmosphere was becoming cleaner. In an editorial published a few months before Brodie's paper, the *Times* (Dec. 24, 1904) wrote: "we think no one whose experience of London extends over many years can entertain the slightest doubt that the fogs of the present day, even the worst of them, are

In a paper read before an international conference sponsored by the Coal Smoke Abatement Society in 1912, Rollo Russell presented a paper entitled, "Smoke and Fog." Russell echoed much of the *Times* report. Like the *Times* article, Russell began his paper by observing that London had become much less foggy in recent years. This was no mere impression; it was, he argued based on observations from London weather stations. While Russell and the *Times* agreed that London was becoming less smoky and foggy, they disagreed as to why. The paper subscribed to Brodie's view:

> The diminution of smoke which has taken place within recent years may be attributed in a large measure to a more vigorous enforcement of the smoke prevention clauses of the Public Health Act, but it has in all probability been materially aided by the increased use of gas fires for both heating and cooking purposes, and also by improved methods of lighting (*Times*, Dec. 27, 1910, p. 11).

Russell, in contrast, emphasized London's changing geography and broader weather patterns that were affecting the entire south of England.[9] For Russell, the declining incidence of fog was

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definitely less filthy and less opaque than those of the early or middle Victorian period. The change is commonly, and perhaps right, attributed to the extent to which the production of smoke in the metropolis has been diminished by legislation." See also, Schlicht (1907, p. 685), who in an article published in the *Journal of the Society of Arts*, wrote: "It must be said . . . that in recent years, thanks to admirable efforts of the Coal Smoke Abatement Society, and the exploitation of gas as a substitute for coal by the gas companies, the atmosphere of London is much less offensive than it was twenty-five or thirty years ago."

[9]Russell, it should be noted, did not entirely dismiss the possible roles of technological change and environmental activism, but he did assign them a clearly secondary role. Toward the end of his paper, he wrote: "Another influence tending to reduce the worst fogs is the increased use of gas. . . . Further, there are improved grates and kitcheners, and some extension of radiators and central heating, which reduces the smoke product per head. The efforts of the Coal Smoke Abatement Society have brought about an improvement in stoking, which is one of the most important of all factors, and a reduction in the emission of black smoke (Russell 1912, p. 22)."

not unique to London fog, but common to all cities and towns in the region.[10] This claim cuts to the heart of Brodie's argument and we will come back to it as our narrative proceeds.

Presenting a paper at the same conference, R.G.K. Lempfert introduced evidence inconsistent with the argument that London's atmosphere was improving solely because of broader, region-wide weather patterns. Lempfert was an accomplished climate scientist, and the Superintendent of the Forecast Division of the Royal Meteorological Office. Lempfert (1912, p. 23) described his paper as an empirical exercise. "It is my object," he wrote, "to examine the statistics of bright sunshine for London and other large towns to see whether they afford evidence of progressive amelioration or the reverse of the smoke nuisance." Lempfert's identification strategy was simple. If London's atmosphere was becoming more sunny because of purely meteorological phenomena, those same phenomena would have affected surrounding rural areas as well. If, however, London's atmosphere was improving because of innovations (both regulatory and technological) unique to metropolitan areas, London would have become increasingly sunny relative to the neighboring control areas. Furthermore, because far more coal was burnt during the winter months than the summer, if reductions in coal smoke were driving the improvement in London's atmosphere, one should observe

[10]Russell (1912, p. 21) wrote: "The last ten years have been remarkably free from dense fogs, not only in London but in the south of England generally. Meteorological conditions have been such that occasions for the development of dense ground fogs have been unusually few. This is not mere impression, but is derived from an examination of the Greenwich, Kew, Oxford, and other records. So rare have been the days and nights of calm, great cold, and dense fog, that we cannot know how the worst kind of London fog of the present would compare with one of thirty years ago. There can, I think, be little doubt that it would be somewhat less intense or less dark. It was not a very uncommon thing in the early eighties to be unable to see across a street."

greater relative improvement when we restrict the sample to the winter (Lempfert 1912).[11]

Table 1 reproduces the data from Lempfert's paper. In first two columns of data, the table expresses the duration of bright sunshine at two London weather stations (Westminster and Bunhill Row) as a proportion of the duration at four nearby "country" stations (Oxford; Cambridge; Marlboro; and Geldeston). Notice that for the first five year interval, 1881-85, London in the winter enjoys only 17 percent of the sunshine experienced in the control areas; by the last five year interval, 1906-10, London's relative sunshine rate has more than doubled, to 38 percent. There is evidence of improvement during the summer—the relative sunshine rate grows from 83 to 92 percent—but the improvement is much less pronounced than that observed during the winter months. The third and forth columns of data perform the same experiment for the weather station at Kew Gardens as the (placebo) treatment. The Kew station resided on the western edge of London (today, about ten miles directly east of Heathrow airport) and was relatively immune from the smoke problems that plagued the rest of the metropolis.[12] Kew shows little relative improvement in the duration of sunshine, in either winter or summer. The final two columns of data compare sunshine at the city stations to that observed at the Kew station. As when the country stations were used as controls, there

[11]Lempfert's argument—that if fogs (or a lack of sunshine) were generated by coal smoke, they would be more frequent and more severe during the winter months—was commonly made by climate scientists of the time. We will exploit this logic later in the paper.

[12]The word relative is important. Kew was not entirely immune from the effects of London smoke and there is a small literature that documents how the gardens were adversely affected by the city's production of coal smoke. See, for example, J.W. Bean's article, "A Note on Recent Observations of the Smoke Nuisance at Kew Gardens," presented at Coal Smoke Abatement Conference in 1912.

is evidence that the city stations became increasingly sunny relative to the station at Kew. Again the improvement is concentrated in the winter months, with the relative sunshine rate rising from 20 to 46 percent during the winter, and from 84 to 92 percent during the summer.[13]

The final part of Lempfert's paper contains data on fogs at the following weather stations in and around London: Greenwich; Kew; Tottenham; Camden Square; Westminster; and West Norwood. Figure 2 plots Lempfert's data from 1904 through 1911. Only one series (Greenwich) does not exhibit a secular downward trend in the number of foggy days per year;[14] the remaining five series all trend downward. Expanding on Lempfert's data, figure 3 juxtaposes a fog series for the West Norwood station with Brodie's original series for Brixton. The Brixton station was five miles south of the Thames; West Norwood was another ten miles south. Comparing the Brixton and West Norwood series suggests that Brodie was providing, if anything, a picture that understated the changes taking place in London's atmosphere. From peak to trough, Brixton falls from 80 days of fog per year to around 35; West Norwood falls from nearly 200 days of fog per year to around 45. Taken together, figures 2 and 3 call into question the argument that Brodie's data are unreliable because they were based on only a

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[13]Lempfert (1912, pp. 27-28) offered a caveat regarding instrumental measures of bright sunlight. The glass-balls employed in the Campbell-Stokes recorders began to yellow and became less sensitive to sunlight with time. Lempfert argued that this would lead observers to understate increases in the incidence of bright sunlight in London. Unfortunately, it would also have had the same effect in the control counties. Lempfert suggested that, whatever the bias, these effects would have been small, and that officials took steps to minimize the resulting measurement errors. Nevertheless, the caution should be noted.

[14]If the sample is restricted so that it covers only fog during the winter months, Greenwich does exhibit a downward trend, as do all of the other London stations.

single weather station. One might still argue that all fog data are unreliable because they were based on subjective (non-instrumental) observations. The difficulty with this line of thought is that the data on bright sunshine (which as explained above, were measured instrumentally) tell the same basic story.

3. Fog-Related Events: Identification, History, and Health Effects

Imagine London in the late nineteenth century. Although it is noon, the city is as dark as night. People must uses torches just to see a few yards ahead of them. Horse drawn carriages cannot move; trains crawl at a snail's pace, and in some instances, cease operating. The fog is so thick, justice must take a holiday. The courts cancel trials because witnesses cannot find their way. Thieves, on the other hand, enjoy the protection of a new found night. The fog even manages to penetrate inside buildings. At theater actors and audiences have difficulty seeing one another and shows have to be cancelled. In offices, workers have trouble concentrating and feel nervous and irritable because the "stinking fog." On the Thames, boat traffic is brought to a halt because of the darkness. Those who continue to move run into one another and fall from sidewalks, piers, and railway stops; others are thrown from their taxis, boats, and barges down to the curb or into the river. On one sad occasion, a young woman becomes disorientated and falls into the ice-cold Thames. She drowns before anyone can find her. On another, a railroad worker falls from a train and cracks his skull.

People described the darkness as fog because it was wet and heavy, and because it almost always occurred during unusually cold and calm conditions when fog was otherwise common. But it was also more than just fog. The darkness burned the eyes and throat. Deaths from all causes, but especially bronchitis and other acute respiratory diseases, spiked during such dense fogs and immediately after they lifted. First hand observes blamed the coal smoke trapped in the fog: "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 that dark expectoration which was so injurious to the constitution; it gathered on the lungs and there accumulated (*Times*, Feb. 7, 1882, p. 10)." Another observer wrote (*Medical Times*, March 11, 1882, p. 395): "After a fog the nostrils are like chimneys, and are lined with a layer of black smut. The expectoration is black from the amount of carbon arrested in the mucus of the air passages. For a day or two after exposure to a smut-laden atmosphere, black phlegm is brought up." During a cattle show in 1873, the fog was so thick that the Queen's prize bull dropped dead, as did several other large animals. If all this were not enough, imagine too that the fog went on for days at a time, and in some extraordinary cases, weeks. Although a composite of several of the most famous London fogs, these images convey what it was like to experience the most dense and persistent ones.[15]

After a severe fog in early February of 1882, the *Times* (Feb. 13, 1882, p. 10) published

[15]This composite is based heavily on a report in the *Times*, Feb. 6, 1882, p. 7. The quotation is from a talk by Dr. J.M. Fothergill recorded in the *Times*, Feb. 7, 1882, p. 10. Other articles in the *Times* that corroborate this picture, include: Jan. 21, 1861, p. 9; Nov. 19, 1862, p. 6; and Nov. 26, 1858, p. 10. That the Queen's prize bull was killed raises the question about how the monarchy and elite groups responded to the fog. Centuries before the Public Health Act was passed in 1891, the King had barred the burning of coal in London, and wealthy elites were at the forefront of smoke eradication; poorer groups were less concerned or opposed. This cross-sectional pattern is consistent the modern EKC, and in a political economy sense sounds plausible. To the extent that the costs of smoke eradication were born disproportionately by the poor, one would expect that the wealthy segments of society to have been the primary advocates environmental improvements.

the results of the coroner's inquest into several fog-related deaths. The results provide a window into the physiological mechanisms that made some fogs so deadly. James Smith, aged 60, was a wheelwright. According to his wife Ann, Smith "had been suffering from chest affection some time past." Although Ann "begged him" not go out in the fog, he went out anyway. The air was "highly charged with the fumes from numberless naphtha lamps used by the market people." When he returned, he was "very ill" and spent the next day in bed, coughing and vomiting. He tried to resume working, but died a few days later. The coroner ruled that "the fog had hastened his death very materially, increasing and developing bronchitis to an alarming extent." Alice Wright, aged 66, was married to a copper-plate printer. She went out when the "fog was the thickest, to fetch her mangling." Twenty-minutes later, a passerby found her lying in a passage and ran into the home to search out her daughter. Finding Wright unconscious, the daughter brought her inside and called for a doctor, "who found the poor creature dead." The *post-mortem* "showed that the fog had brought on effusion on the brain." William Henry Pepper, aged three months, was the son of a blacksmith. Although he had been a healthy baby, he took ill after he and his mother had ventured into the fog. The coroner concluded that "the child's lungs" were "to weak to resist the poison which had filtered into them." "Bronchial pneumonia" set in and "death resulted."

For convenience, we refer to extreme conditions like those just described as a "fog-related event." Fog-related events were an extreme form of smog. The available evidence indicates that they were associated with anticyclones and temperature inversions (Brodie 1891; Scott 1896; *Times*, Dec. 13, 1873, p. 7; Wise 2001, pp. 15-18). London's most famous fog-related event occurred in December 1952, and is documented in William Wise's popular book, *Killer Smog: The World's Worst Air Pollution Disaster*. The fog began on December 5, and did not lift for five days. Government officials estimated that there were roughly 4,000 excess deaths because of the fog, mostly due to respiratory complaints such as asthma and bronchitis. Although we might know this event best, that does not necessarily mean it was the worst. Earlier fogs lasted longer, and there is evidence that they took a heavier death toll. For example, the aforementioned cattle-show fog of 1873 lasted a week (Brazell 1968, p. 111). The December fog of 1879 lasted nearly two weeks, darkening London's skies from December 3 through December 27 (Brazell 1968, p. 111; Scott 1896). There was also the aptly named "anticyclonic winter" of 1890-1891, a two month interval of almost uninterrupted fog (Brodie 1891). Estimates presented below suggest that this event generated 7,405 excess deaths, nearly twice the number of excess deaths observed during the winter of 1952.

As the discussion above suggests, a defining features of a fog-related event is an unusually large number of deaths, especially from acute respiratory diseases. One the clearest contemporary statements on the spike in death rates that accompanied for-related events comes from a short article in the *British Medical Journal* (*BMJ*). The article described an event that occurred in February of 1880 (Feb. 14, 1880, p. 254):

> If one or two weeks during the cholera epidemic of 1849 and 1854 be excepted, the recorded mortality in London last week was higher than it has been at any time during the past forty years of civil registration. No fewer than 3,376 deaths were registered within the metropolis during the week ending Saturday, showing an excess of 1,657 upon the average number in the corresponding week of the last ten years.

Of these deaths, most were attributable to respiratory diseases, particularly bronchitis:

> The excess of mortality was mainly referred to diseases of the respiratory organs, which caused 1,557 deaths last week, against 559 and 757 in the two preceding two weeks, showing an excess of 1,118 upon the corrected weekly average. The fatal cases of bronchitis, which had been 531 in the previous week, rose to 1,223 last week.

The last time the weekly death rate in the metropolis had approached these levels was during the cattle-show fog of 1873. The *BMJ* called on scientists to isolate the factors that generated such unusual and unhealthy fogs:

> The terrible slaughter caused by these London fogs, and registered last week, should suggest a scientific inquiry as to how far the poisonous and suffocating qualities of these fogs are different from most fogs out of London—arise from causes which should be, if they are not, within the control of efficient sanitory authorities.

The article concluded by identifying smoke as the ultimate culprit and asking whether something could be done to minimize this nuisance: "It is smoke that makes the London fog so mischievous; and bearing in mind the disaster last week, it is worth inquiring whether anything cannot be done to mitigate the main cause of this remarkable mortality."

Ideally, we would like to have a complete history of all of the fog-related events in London during the late-nineteenth and early twentieth century. If we possessed such a history, and that history was independent of Brodie's fog observations, we could look at the frequency and severity of fog-related events before and after 1890. If Brodie's data were correct, we would expect to observe increasing frequency and severity in the years leading up to 1890, and decreasing frequency and severity in the years following. The difficultly, however, is that there is no formal history of fog-related events in London that claims to be comprehensive in any sense. The question, then, is how to construct such a history. One approach might be to return to the records of the Royal Meteorological Office (which Brodie used) and search for extended periods of dense fog. This approach is problematic because it is not fully independent of Brodie's data and because it would replicate much of the evidence already presented in section 2. More importantly, it would be much too crude: there were periods of persistent and dense fog in London that were not associated with unusually high mortality and would not fall under our definition of a fog-related event. As an alternative strategy, one might scour the *Times* of London and other contemporary news outlets for articles that described phenomena consistent with fog-related events. Besides the high search costs and subjectivity of this approach, one could never be certain of identifying all relevant events.

The *BMJ* article discussed above suggests an econometric strategy for identifying events. The article observed that deaths spiked during the weeks associated with fog-related events, and that these spikes were large and uncommon. Our identification strategy is an event study in reverse: we use spikes in the data to predict events, as opposed to using events to predict spikes in the data. To implement this strategy, we proceed as follows. We first collect weekly data on deaths in London during the late nineteenth and early twentieth centuries and calculate the weekly crude death rate. Using a simple regression framework—the weekly crude death rate is regressed against a few control variables—we then estimate a predicted death rate for the each of the weeks in our sample. From there, it is a simple matter to calculate a residual death rate for each week. The value of the residual establishes a necessary, but not a sufficient, condition to qualify as an event week. In particular, to be coded as an event week, the week must satisfy the following three conditions:

> (c.1) The residual death rate for the week must exceed .1. The choice of .1 as a threshold is not entirely arbitrary. Residuals above .1 are rare—they are 1.1 percent of the total sample—and as shown below, they are probably generated by a different set of forces than those below the threshold.
>
> (c.2) There must be supporting qualitative evidence in the *Times* indicating the presence of unusually dense and persistent fog during the week or sometime in the preceding week.
>
> (c.3) The preponderance of evidence must suggest that the spike of was not caused by something other than fog, such as an epidemic disease like cholera or influenza. If the weight of the evidence suggests an epidemic disease was present and important, the week is coded as a non-event week.[16] The on-line catalogues of the *BMJ* (at PubMed Central) and the *Times* are searched for such evidence.

As reported below, there are 32 weeks out of the sample that satisfy all three of these requirements and are coded as event weeks.

Before turning to the results of this exercise, a few points of clarification are in order. The data on deaths per week are gathered from the *Weekly Returns of the Registrar General*, which recorded deaths for several of England's largest cities including London. For years when the published volumes of the Registrar General are unavailable, the *Times* is consulted. After 1888, the *Times* regularly summarized the weekly returns of the Registrar General.[17] Death rates are calculated as deaths per 1,000 persons and are constructed using interpolated

[16]This happens only once in the early 1890s. If we re-coded the event and treated it as generated by a fog, the results and conclusions below would be unchanged.

[17]England's death registration system began in 1836, and included provisions that fined those who failed to report deaths.

population data from Mitchell (1988, p. 673). Note that we calculate and report a true weekly death rate, not an annualized weekly death rate. The sample period covers the 55 year interval extending from 1855 to 1910, yielding a maximum possible sample size of 2,860 (52 × 55). There are, however, 25 weeks for which data are unavailable. Dropping these from the sample, 2,835 observations remain. Regressing the crude death rate against week and year dummies and an overall time trend, we estimate the following model:

$$(1) \qquad d_{kt} = \alpha + \boldsymbol{w}_k \beta_1 + \boldsymbol{y}_t \beta_2 + \beta_3 N + e_{kt},$$

where d_{kt} is the overall death rate in London in week k ($k = 1, 2, \ldots, 52$) and year t ($t = 1, 2, \ldots,$ 55); $\boldsymbol{w}_k$ is a vector of week dummies; $\boldsymbol{y}_t$ is a vector of year dummies; N is an overall time trend ($N = 1, 2, \ldots, 2{,}860$); and e_{kt} is a random error term.[18]

The model has an adjusted-R^2 of .788. Even after including the week and year dummies, the time trend is significant at the .001 level. All of our results are identical when the time trend is excluded from the regression. We include the trend because there exists steep downward trend in the London death rate over the entire sample period, 1855 to 1910. (See figure 8.) In addition, the results reported below are robust to changes in our criteria that define event weeks. If, for example, we drop conditions (c.2) and (c.3) the same basic patterns and substantive conclusions emerge. The results are also unchanged if we lower or raise the

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[18]Ideally, it would be desirable to analyze data on cause-specific death rates for respiratory ailments such as bronchitis and pneumonia. Although we believe these data are available, the source in which they are reported is not easily obtained. We hope to acquire this source and analyze cause-specific death rates in subsequent research. Nevertheless, the anecdotal evidence presented elsewhere in the paper indicates that spikes in mortality were driven by respiratory diseases.

residual threshold by a modest amount. Our main results follow in a table and a series of figures.

Table 2 identifies the 32 weeks in the 1855-1910 interval that satisfy the conditions necessary to be designated as an event week. The first two columns indicate the year, and the week of the year in which the event took place. The final column, labeled documentation, provides citations to the month, day, and page of the *Times* corroborating the presence of a fog-related event. If the event has already been described in the secondary literature on the London fog, citations to representative secondary sources are provided. The third column, labeled "known," indicates whether the secondary literature already describes the weeks as involving fog-related events. Of the 32 event weeks, 22 are part of a sequence of continuous weeks. Events 1 and 2 involve the 4th and 5th weeks of 1855; events 3 and 4 involve the 47th and 48th weeks of 1858; and so on. The longest sequences are five weeks (events 22-26), and four weeks (events 29-32). The last event occurs in the second week of 1900. After that time, fog-related events cease for the period covered by our sample, which as said above ends in 1910.

It is notable how few of the event weeks we identify have been identified by the extant literature. For the period between 1855 and 1872, the reverse event study yields ten previously unknown events. The descriptions of these events found in the *Times* suggest the procedure is onto something. Describing events 6 and 7, the *Times* (Jan. 21, 1861, p. 9) observed:

> Last Thursday week, when the whole of the metropolis was enveloped in a dense fog, large numbers of person [*sic*] were stuck down as if shot. Dr. Lotheby, in his report to the city . . . says `the quantity of organic vapour, sulphate of ammonia, and finely divided soot in the atmosphere was unprecedented.'

The *Times* (Nov. 19, 1862, p. 6) characterized the fogs associated with event 8 this way: "There was a dense fog on Tuesday night, and on Thursday afternoon fog prevailed of a density that has not been equaled for several years." Of events 3 and 4, the *Times* (Nov. 26, 1858, p. 10) said, "it has been several years since we have seen so dense a fog." Events 12 through 15 are also missed by the current literature. Occurring one year after the cattle show fog, these events might have been overshadowed by their immediate predecessor, but newspaper accounts suggest an anticyclone and a series of dense and persistent fogs extending over weeks.[19] Of the previously unidentified fog of 1882 (event 19), the *Times* (Feb. 6, 1882, p. 7) wrote:

> By general consent the fog which prevailed over a great part of the metropolis during Saturday and Saturday night was one of the densest ever experienced. It was attended with all the usual inconvenience and incidents, intensified to an unprecedented degree. Trains were delayed, fog signals were heard in rapid succession on the railways, street lamps were lighted, street traffic was impeded and gradually suspended, many tramcars ceased to run, and businesses everywhere carried on by artificial light. In the streets, torches and lamps did not much expedite locomotion. Market carts failed to reach Covenant garden until many hours after they were due.

Lastly, it is important to point out that our procedure misses no fog-related event suggested by the existing secondary literature.

Figure 4 plots the residuals for event and non-event weeks. Event week residuals are given by black triangles; non-event week residuals by small, empty circles. To calculate the residuals, we estimate equation (1) using only non-event weeks. The difference between the

[19]On the Dec. 2, 1874, the *Times* quoted one observer as saying, "the most dense fog I ever saw in this locality." An editorial in the *Times* (Jan. 8, 1875) attributed the large number of deaths in the metropolis to cold and variable temperatures, but this observation, combined with the numerous reports of dense fog over a long period, suggest an anticyclone.

predicted and observed death rate equals the residual. The triangles are consonant with Brodie's data on the incidence of fog. The size of the residuals increase in the years leading up to 1891, and are more frequent before 1891 than after. There is a large and unusual spike in the non-event week residuals in the 8^{th}, 9^{th}, 10^{th}, and 11^{th} weeks of 1895. This is the result of an influenza epidemic (*Times*, March 9, 1895, p. 5). Note that the non-event residuals fall below −.100 only twice, when they reach −.111 and −.103. To the extent that we expect symmetry in the structure of the error term, one might plausibly argue that any residual greater than .1 is generated by a different process than that which produces the non-event residuals.

One objection to figure 4 is that the crude death in London falls by 50 percent over the course of the sample period. (See figure 9.) Given such a large reduction in the baseline death rate, one might argue that it is misleading to look at absolute deviations from trend; relative deviations could be preferable. Accordingly, figure 5 plots a measure of relative deviation, the residual death rate divided by the predicted rate. This change does not alter the basic pattern observed in figure 4: increasing severity before 1891, and more fog-related events before 1891 than after. Figure 5 does, however, provide a clearer picture of the effects of fog-related events on weekly death rates. The least severe events increased weekly death rates by 25 to 30 percent. The most severe events could double death rates, increasing them by 75 to 100 percent. Figure 6 provides a second look at the absolute effects of fog-related events. Plotting the excess number of deaths associated with event weeks, figure 6 again shows increasing severity before 1891, and declining severity and frequency thereafter. The excess deaths associated with the fog-related events of the 1850s and 1860s numbered around 500, but by

1891, these deaths neared 2,000. As in figures 3 and 4, it is significant that fog-related events cease after 1900.

Taken together, the results in table 2 and in figures 4-6 support Brodie's contention that London's atmosphere was worsening before 1890 and improving thereafter. These results, however, do not help us resolve the debate surrounding his interpretation. Perhaps fog-related events declined in frequency and severity after 1900 because there was a decline in anticyclonic activity; or, perhaps fog-related events disappeared, or became much less severe, because of smoke abatement efforts. Without additional evidence, we cannot be sure.

As an indicator of mortality, there is a concern with figures 4 through 6. Demographers call it "harvesting" and it occurs when adverse events strike heavily among the most vulnerable parts of the population. In the case of fog-related events, suppose that fogs killed only the frailest and most sickly individuals, people who would have died within a few days or weeks of the fog, whether or not the fog had ever occurred. If so, the data above would overstate the significance of fog-related events. There is anecdotal evidence to support this hypothesis. Witness, for example, the coroner inquests of James Smith, Alice Wright, and William Henry Pepper, discussed above.

To address this concern, we estimate the following variant of equation (1) using the full sample of event and non-event weeks:

$$(2) \qquad d_{kt} = \alpha + \boldsymbol{w}_k \boldsymbol{\beta}_1 + \boldsymbol{y}_t \boldsymbol{\beta}_2 + \beta_3 N + \psi_0 F_0 + \psi_1 F_1 + \psi_2 F_2 + \ldots + \psi_{12} F_{12} + e_{kt},$$

where, F_0 is a dummy variable that assumes a value of one for all event weeks, and zero otherwise; F_1 is a dummy variable that assumes a value of one for the week immediately following an event week, and zero otherwise; F_2 is a dummy variable that assumes a value of one for two weeks after an event week, and zero otherwise; and so on down to F_{12}, which assumes a value of one for twelve weeks after an event week, and zero otherwise. All other variables in equation (2) have the same definitions as in equation (1).

Figure 7 plots the estimated coefficients on F_0 through F_{12}. The black diamonds indicate a statistically significant coefficient at the 1 percent level; the empty circles indicate insignificant coefficients. The average fog-related event increased the weekly death rate by a statistically-significant .16 points. In the first and second weeks after the event, the death rate remained a statistically-significant .02 to .03 points above normal. Except for week four, all subsequent weeks are indistinguishably different from zero in terms of statistical significance. As for magnitudes, the point estimates are usually positive and are always very close to zero. Only weeks 5, 9, and 11 fall below zero, to −.002, −.003, and −.007, respectively. These patterns are inconsistent with the hypothesis that fog-related events merely rearranged deaths, only causing people to die a few weeks or days earlier than they otherwise would have.

Another concern is we do not control for rainfall and temperature in equation (1). To the extent that fogs were associated with low temperatures, and low temperatures were associated with excess deaths, this estimating procedure imparts an upward bias to the effects of fogs. Although we have not been able to code and analyze the weather data that would allow us to expressly control for such concerns,[20] we have located anecdotal evidence to

[20]It is our intention to use these data in subsequent research, but compiling the weather data and merging it the mortality data we use here is beyond the scope of this paper.

suggest that, absent dense fogs, extremely low temperatures did not have the same large effects on mortality. Intense cold alone raised the death rate, but not by the magnitudes we estimate for fogs and cold (*Times*: Jan. 16, 1867, p. 6; Dec. 14, 1897, p. 11; and Feb. 4, 1879, p. 3). Also, for variation in temperatures to explain the inverted U-shaped pattern we find in fog-related events reported in figures 4-6, temperatures in England and London would have had to follow that same pattern. We have examined temperature data for the whole of Central England from a variety of sources (e.g., Manley 1974) and find little evidence of this.

Finally, in those cases where fog and cold struck London simultaneously, the fog was unique to London but the cold was not; the latter affected surrounding areas as well. If it had been the cold causing the excess deaths, the spike in death rates would have occurred for all areas with cold. But when we consult the *Weekly Reports of the Registrar General*, and various accounts in the *Times*, both sources indicate that while the cold was a general event (affecting all cities and towns around London), the fogs and the spikes in mortality were not; they occurred only in London. Consider the following description of the role that cold temperatures played during the terrible fog of February, 1880, as highlighted by events 16-18 in table 2 :

> The weather was cold, and fogs had been dense and continuous. Cold alone does not account for the disaster, since in several of the English towns the cold was equally, and even more severe than in the metropolis, and yet their death rate was not unduly increased. The mischief appears to have been mainly wrought by fogs, heavily charged with the `London smoke,' or carbon in a minutely divided form, the properties of which are intensely irritant to the respiratory passages. (*Proceedings of the Medical Society of the County of Kings*, July 1880, p. 185.)

Similarly, in his study of the relationship between temperatures and the death rate in London, Dines (1894) argued that one should not be quick to attribute increased mortality during the winter quarter to reduced temperatures, but rather to increased crowding and a heavily polluted atmosphere.

4. A Kuznets Curve Too Far

A simple way to explore Brodie's hypothesis is to look at the annual death rate from bronchitis, which as explained above was highly responsive to fog-related events and presumably to smog in general. To the extent that the air of London was becoming more or less polluted, one expects that the death rate from bronchitis would have been positively correlated with such changes. For example, in a paper published in the *Journal of the Royal Sanitary Institute* in 1907, Louis Ascher presented fragmentary evidence linking the rise and fall of bronchitis and acute pulmonary diseases in the United States and Prussia to changes in exposure to coal smoke. Ascher also collected data for Manchester, England, which showed that between 1896 and 1905, the number of foggy days fell by 36 percent, while over the same period, the death rate from acute respiratory diseases fell by 18 percent. Ascher (1907, p. 89) hypothesized that both reductions might have resulted from smoke control: "From these statistics we see that the number of fog days has decreased, and we find a corresponding decrease in mortality from acute pulmonary diseases . . . . This decrease may, perhaps, be due to coal smoke abatement, which in Manchester is classical." While Ascher was clearly justified in his tentativeness, the hypothesis is intriguing, as was his suggestion that broad national changes in respiratory death rates in the U.S. and Prussia were driven by changes in coal smoke emissions. Schaefer (1907) presents evidence along these lines for Kansas City and St.

Louis.

Figure 8 plots the annual death rate from bronchitis in London from 1850 through 1920. The figure also plots the death rate from three respiratory diseases combined: bronchitis; pneumonia; and tuberculosis. Of the two series, we believe the bronchitis series is superior because bronchitis is more closely correlated with fog and inorganic pathogens. Pneumonia and tuberculosis, which have bacterial and viral origins, have weaker connections (Lawther 1959; Schaefer 1907; White and Shuey 1914). We include the latter series only because one might question the ability of nineteenth century physicians to distinguish among the three diseases. The bronchitis rate trends upward between 1850 and 1880, increasing by 67 percent, from around 150 deaths per 100,000 persons to 250. Notice that in 1880 the bronchitis rate spikes to 300, double the rate observed at the start of the series. This is the result of a fog-related event in February of 1880 (events 16 and 17 in table 2). After this event, however, the bronchitis rate reverses trend, and over the next three decades is more than halved, falling from 250 to 100. The death rate for respiratory diseases in general does not reveal the same sharp reversal in trend. Rather, the respiratory-disease death rate is flat between 1850 and 1880, and then begins a steep downward trend that parallels the trend for bronchitis. These patterns are an uneasy fit with Brodie's data. The bronchitis death rate maps out an inverted U-shape that is broadly consistent with the rise and fall of the London fog, but the inflection point occurs almost a decade before the inflection point observed in the fog data.

Are there interventions other than coal smoke abatement that might explain the sharp reversal in trend in the bronchitis death rate? One contentious line of thought attributes the decline in respiratory diseases (specifically tuberculosis) observed during this period to a rising standard of living, which resulted in better housing and improved nutrition (Wilson 2005). It is true that nutrition and wages were rising during the late nineteenth century, but to explain the break in trend observed here, they would have had to have been declining up to 1880 and then suddenly have started to improve. We are aware of no evidence to support such a conjecture.

A more plausible hypothesis builds on the idea that bronchitis might have been a common sequella to some other disease that experienced a highly effective intervention. The most logical candidate here is water. The Mills-Reincke phenomenon, identified independently by scientists in Massachusetts and Germany, posited that for every one death from typhoid fever there were four or more deaths from some other cause (not directly waterborne) that was the sequella of typhoid (Sedgwick and MacNutt 1910). Hence when cities began filtering water supplies, they not only reduced deaths from waterborne diseases like cholera and typhoid, they also reduced deaths from non-waterborne diseases like pneumonia, tuberculosis, kidney disease, and heart disease. There are two problems with this line of thought. In an econometric analysis of the Mills-Reincke phenomenon, Ferrie and Troesken (2008) find no evidence that bronchitis commonly followed typhoid (or enteric fever as it was called in England). And even if bronchitis had been a common sequella to typhoid, London began cleaning up its water supply long before 1880 (Tynan 2002).

Another possibility, akin to the sequella hypothesis, is that the rise and fall of bronchitis was part of a larger mortality transition taking place in London, a transition that saw a broad swath of diseases rise and fall between 1850 and 1910. This is not consistent with figure 9, which shows the crude death rate in London declining over the entire period after 1865. Before that time, the overall death rate is stagnant, except for two large spikes caused by cholera.

The final two hypotheses are the most plausible, but they also raise more questions than they answer. Consider figure 10, which plots the bronchitis death rate in London relative to the death rates in England and Wales in general. These data suggest that bronchitis rates were improving in the country as a whole, not just in London. One interpretation of this result is that there was some intervention other than smoke abatement that was common to all areas of England and Wales that caused death rates to start falling. The problem here is that we are no closer to understanding the ultimate cause of the change in trend. What exactly was this unidentified intervention? All we have done is push the question back to a higher level of aggregation.[21]

Another interpretation, for which there is supporting evidence, is that London was not alone in pursuing efforts to limit smoke emissions. All major cities in the England and Wales were pursuing these efforts and were subject to many of the same laws as was London (*BMJ*, Aug. 20, 1908, p. 615). We are not the first to suggest this possibility. More than one hundred years ago, Ascher (1907, p. 89) observed that bronchitis and pneumonia rates throughout

[21]One plausible hypothesis that we have not fully considered is that there was a nationwide shift in how physicians in England and Wales diagnosed bronchitis. We searched multiple online databases for articles in the history of medicine as well as contemporary journals such as the *Lancet* and the *BMJ* for evidence of such a shift, but found none. Moreover, even when we aggregated respiratory diseases (similar to what was done in figure 7, only for the whole of England and Wales) we found evidence of a change in trend taking place around 1880. This seems inconsistent with a story about physicians mistaking one respiratory disease for another.

England and Wales rose during the mid-1800s and then fell during the later part of the century. At the time Ascher suggested that "it would be a valuable work to examine whether" this pattern was the result of "coal smoke abatement."[22]

Ideally, we would like to construct a panel of British cities, some of which were subject to smoke abatement efforts, and some of which were not. With such a data set we could perform a more formal and standard fixed-effects estimation of the effects of smoke control on respiratory diseases. While we have identified a data source that would enable us to construct such a panel, we are unable at this stage compile and analyze the data. That is left for a later paper. Nevertheless, we can offer some preliminary observations. Though crude and subject to many caveats, these observations are suggestive and indicate that something was happening to bronchitis and respiratory disease rates in Britain and elsewhere, and that it is not implausible to believe that that something was caused by a reduction in coal smoke.[23]

In this preliminary context, we turn to the experiences of Glasgow in particular, and

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[22]Ascher's data do not agree with ours, though both came from the identical source, *The Annual Reports of the Registrar General*. Ascher (1908) suggests bronchitis and pneumonia rates in England and Wales were rising between 1866 and 1895, and fell thereafter. As already shown, our data suggest an earlier turning point.

[23]We have examined bronchitis rates in five American cities and one state (Chicago, Milwaukee, New Orleans, New York, Washington DC, and New Hampshire). Although we do not report these plots here, we found that in all of these places a sharp change in trend in bronchitis rates took place around 1890, ten years after the change observed in England and Wales. Several of these cities enacted smoke control ordinances during the 1890s. On smoke abatement efforts in Chicago, which closely paralleled those in London, see Bird (1911). For an overview of smoke abatement in Pittsburgh, see Meller (1926). Stradling and Thorsheim (1999) provide a nice overview of smoke abatement efforts in both America and Britain between 1860 and 1914.

Scotland in general. Glasgow was much like London. It too was a foggy place that sometimes experienced unusually dense and persistent fogs, apparently as a result of anticyclones and temperature inversions. For example, the *British Medical Journal* reported that during the first week of January 1875, the death rate in Glasgow rose 150 percent above its normal level for the week (Jan. 30, 1875, p. 153):

> Those who lived in Glasgow during the last three weeks of 1874 will hardly be surprised at the enormous death rate. There was a fog of no ordinary character. A fog is bad enough, but this one . . . could not only be seen, but tasted and smelt. The moisture was evidently impregnated with soot and chemical fumes in the highest degree.

Nor was this first time Glasgow had been enveloped by such a fog. Quoting a local physician, the *BMJ* explained that "every Glasgow citizen" had "of late" found themselves "in the midst of choking fogs." The *BMJ* concluded by observing that during Glasgow fogs, brass and metal plates on doors or any other exposed surface quickly oxidized. If this is what the fog did to polished metal, what, the journal wondered, did it do to an individual's bronchial passages?

> It is well known that when the wind blows from the east, it is almost impossible to keep the handles of doors, door-bells, or any polished metal from becoming quickly oxidised. And during the late fog it needed only an hour or two to darken the most brilliantly polished door-plate. The air was evidently impregnated with active chemical gases, and these, no doubt, acted on delicate bronchial tubes as well as the more enduring brass.

Describing a much later fog, the *Medical Press* (Feb. 22, 1899) observed: "On account of the dense fog in Glasgow a few days ago the death rate made a lead upward to 35 per 1,000 of the population, placing Glasgow in the unenviable position of having the largest death rate of any town in the United Kingdom." The last time death rates rose so high was five years prior, "when the frost and fog were intense." "Even then," however, "the same suffocating and throttling effect was not experienced as on the present occasion, when several instances of giddiness and vomiting in the street came under immediate notice." Offering a more general characterization, *Kirkwood's Dictionary of Glasgow and Vicinity* (1884, p. 60) wrote: "Although Glasgow fogs do not equal those of London . . . in the depth of winter, when the intensity of the frost prevents the lifting of smoke which always hangs over the city, the visitor or resident will doubtless consider them bad enough." The *Dictionary* lamented the fact that attempts "to force the public works to consumer their own smoke had "been in vain," but offered the following advice in consolation: "go out-of-doors as little as possible, and . . . keep the mouth as much as possible closed. Few things can be more hurtful than to take into the lungs and air-passages the exhalations and half-consumed floating carbon which, together, constitute a Glasgow fog."

Figure 11 plots bronchitis rates in Glasgow and Scotland from 1855 through 1905. The patterns are similar to those observed for London and for England and Wales. For Scotland as a whole, the bronchitis rate rises by a factor of 2.5 between 1855 and 1878, and then initiates a sharp downward trend, falling back to its original level by 1905. The data for Glasgow are not available before 1880, but after that date, they exhibit an even sharper downward trend. The death rate from bronchitis falls from a high of 400 deaths per 100,000 to just over 100, a reduction of nearly 75 percent. What distinguishes Glasgow's experience from London's, however, is the strong evidence of relative improvement. In 1880, Glasgow's death rate was roughly 60 percent greater than the death for the whole of Scotland; by 1905, the Glasgow bronchitis penalty vanished, and the city's death rate equaled that of the rest of the country.

Although we can not treat Glasgow's smoke abatement movement with the same level of detail that we will treat London's (see section 5), two observations can be made here. First, laws regulating coal smoke in Glasgow were passed in 1866, 1867, and 1892. There is evidence that the earlier laws were actively enforced by the late 1880s (Thomson 1894-95). Could these laws, and variation in their enforcement, account for the patterns we observe in bronchitis rates and fogs? Evidence presented below for London suggests this is a possibility.

Second, there are the short but remarkably perceptive letters written by William Tennant Gairdner, a prominent and widely-published Glasgow physician. Writing to the *Edinburgh Medical Journal* in January of 1875, Gairdner made an eloquent case that the only way to eliminate Glasgow's high fog-related mortality was to disperse the population and manufacturers over a broader area so that their smoke and noxious vapors became less concentrated.[24] After describing a December fog as bringing "Egyptian darkness into our houses at noonday," Gairdner plead his case:

> Hence the practical lesson to be derived from the late inordinate rate of mortality, is the necessity of diminishing the permanent rate; and this, I apprehend, can only be done by *the gradual dispersion of the town over a larger area*, thereby diminishing at once the concentration of noxious vapours, and the dangerously excessive density of the resident population [emphasis original].

Later in same letter, Gairdner made reference to Glasgow's Improvement Trust, which during

[24]Specifically, Gairdner published two consecutive letters. The first appeared under the heading, "Chemical Vapours, Fog, and the Death Rate," and was published on pp. 866-67 of the *Edinburgh Medical Journal*, Volume 20, Part 2, January-June 1875. The second appeared under the heading, "The Death-Rate in Glasgow—The Debate at the Police Board," and was published on pp. 867-68. The quotations below (with one brief exception) are from the second letter.

the late nineteenth century destroyed privately-owned tenement housing and replaced it with municipally-owned housing. These references are notable because they suggest the city had within its power the ability to use its police powers to force suburbanization, the very thing Gairdner advocated:

> The operations of the Improvement Trust have been very successful in clearing out some of the most densely peopled spots in the centre of the city, with great benefit alike to the health and morals of their immediate neighbourhood. . . . But the persons displaced by the City Improvement Act have not in all probability found their way to any extent into the suburbs—in other words, the Improvement Act, although greatly improving the spots which it affects, has not to any considerable extent *decentralized Glasgow*. And this is what we must aim at doing—gradually of course—if we are ever to have a purer atmosphere, a less overcrowded population, and a lower death rate [emphasis original].

Implicit in Gairdner's advocacy and analysis are the beginnings of an hypothesis: might suburbanization, a process that not only redistributed people but also smoke, help explain the rise and fall in bronchitis throughout the United Kingdom, as well as fogs in London? Data and evidence presented in section 5 will allow us to explore this possibility.

5. Victorian Environmentalism: Theory, History, and Evidence

Figure 12 plots two data series, one for fog and one for coal. The first series, given by the small hollow circles, is the number of foggy days in London from 1730 to 1910. A trend line is also plotted for this series.[25] The second series, given by the small black circles, is coal

[25]To create this series, we splice together three different data series on fog in London. The longest series is from Mossmann (1897), who gathered non-instrumental readings of London weather from 1713 through 1896 and then published his results in the *Quarterly Journal of the Royal Meteorological Society*. The next series is foggy days at the Brixton weather station, the series Brodie (1905) used. The third series is foggy days at the West Norwood Station. Part of this series is found in the discussion following Brodie's paper, and the other part of the

consumption per capita. We proxy consumption with imports of coal into London. Nearly all coal imported into London was consumed there. Before 1800 and the industrial revolution, the number of foggy days in London is stagnant, hovering around 12 days per year. Coal consumption per head shows only slight growth during the same period. After 1800 and the onset of industrialization, both series begin to rise, and after 1850 the growth is exponential. The foggy days measure rises threefold between 1850 and 1890, increasing from around 25 to more than 75 days per annum. Similarly, annual coal consumption rises by a factor of 2.5, from one ton per head in 1850 to 2.5 tons in 1890. Things change abruptly for both series around 1890. Foggy days per annum reverses trend, and plummets by around 85 percent within a twenty year interval. Although coal consumption does not reverse trend, it stagnates, showing no growth over the next thirty years.

Figure 13 plots a measure of total coal consumption over time, the natural log of tons of coal imported into London. The observed log is plotted by the empty circles. A vertical reference line is plotted at the year 1890 to indicate the inflection point in the fog series from figure 12. Figure 13 also includes several trend lines that identify changes in slope over different historical intervals. The flattest trend line indicates the growth rate in total coal consumption between 1700 and 1750; the next line indicates the growth rate between 1750 and 1800; the next to steepest line indicates the growth rate between 1800 and 1840; and the steepest line the growth rate between 1840 and 1880. As in figure 12, these lines show that over time,

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series is from Lempfert (1912). Although it does not change the picture much, we use simple regression techniques to make the separate series comparable over time.

the growth rate in coal consumption steadily increases. Not until sometime after 1890 does this pattern of increasing growth cease. There is clear evidence that after this point, for the next thirty years, coal consumption is well below trend.

At first blush, the patterns in figures 12 (and 13) seem broadly consistent with Brodie's explanation of the rise and fall of the London fog. When coal consumption in England grew slowly, and in some absolute sense, was not large, London fogs were much less frequent than they would later prove to be. Because it will be useful later in the analysis, we formalize this observation by saying that smoke-associated fogs will not emerge as long as the concentration or density of smoke, S^d, does not exceed some threshold, T. With the onset of industrialization in 1800, coal consumption continued to increase, and eventually, the concentration of smoke in London rose above the threshold T. At this point, the environment began to degrade, manifesting itself in a slow but observable increase in the number of foggy days per year. When coal consumption exploded after 1850, so too did the number of foggy days. Only when coal consumption stabilized around 1890 did the fogs begin to decline.

There is a problem here, however. How could stabilization in the per capita consumption of coal initiate a decline in fog? If increases in coal consumption per capita drove the increase in fog, the converse—that a decline in coal consumption in per capita drove the decrease in fog—would also have to be true, would it not? Moreover, to the extent that smoke density was determined solely by the amount of coal consumed, one should not even bother looking at coal consumption per head; all that should matter is total consumption of coal. By this logic, a reduction in smoke required a reduction in the total amount of coal consumed.

Without such a reduction there is no way we (or Brodie) could use smoke abatement to explain the demise of the London fog. And we know from figure 13 that total coal consumption did not fall. Its rate of growth slowed, but it did not reverse trend and begin to decline.

We think that this formulation misses three points. The first point builds on Gairdner's argument that Glasgow could have made its atmosphere cleaner by dispersing people and smoke over a larger area, in effect, diluting the smoke. The second point appeals to a *weak version* of Porter's conjecture that in the quest to abate pollution firms might discover new technologies and operating procedures that make them more productive.[26] The third point is that not all coals are equal; some create much more smoke than others. To make these points more clearly, we construct a simple model of smoke density, (S^d) in and around the area known as London, or more formally, as Greater London. After constructing the model, we engage in a crude calibration exercise. Using historical observation and some limited data, we give the model a plausible structure. In the context of that structured model, we argue that a policy change observed in 1891 could account for the patterns Brodie documented.

Before turning to the model, however, we need to more clearly define what is meant by the geographic descriptor "London." Today, London proper covers only 1.2 square miles; Greater London covers nearly 660 square miles. Thus far, all of our references to London have actually been to Greater London. We will continue this practice, but will also draw the distinction when appropriate. We did not raise this fine point of urban geography earlier

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[26]For empirical evidence consistent with the Porter hypothesis, see Berman and Bui (2001).

because it was not relevant until now.

Let smoke density in any year t in Greater London be determined by a simple function:

(3) $S^{d} = (\gamma C)/A$,

where A is a measure of the geographic area covered by Greater London in year t; C is the amount of coal consumed or burned in year t; and γ is a scalar, $\gamma \in (0,1)$. The scalar γ is the fraction of coal that is unburnt and escapes as soot and tar into the atmosphere during the firing and stoking process. The product of $\gamma \times C$ is smoke. Today, when we think about smoke abatement, we typically think about reducing γ through the installation of some sort of scrubber technology; or we might think about reducing C by switching from coal to some other fuel such as natural gas, solar, or nuclear power. Most people in the nineteenth and early twentieth century thought in a similar way. Nevertheless, one could also reduce S^{d} by increasing A. We explain these different mechanisms by giving the elements of equation (3) more structure.

Both A and C are strictly increasing functions of population. As population increases, the amount of coal consumed rises, which in turn increases the absolute amount of smoke and smoke density. But there is also a countervailing effect. As population increases, so too does the area of the city. New migrants do not only move to previously settled areas of the city; they also take up residence in outlying areas that were previously unsettled. This increases in A. One might even conceive of a world where population density in the central areas of the metropolis fall as residents of those areas move to less densely populated areas on the edge of the city, perhaps spurred by other migrants locating there. Redistributing population from a densely populated core to a less densely populated periphery would also change the distribution of smoke.

Under the right set of conditions, the redistribution of population and smoke might generate a reduction in smoke-associated fogs without any reduction in coal consumption, relative or absolute. In the simplest case, divide London into two parts, an old part that is densely populated, very smoky, and prone to smoke-associated fogs; and a new part that is sparsely populated, not smoky at all, and not prone to fog. Smoke density in the old part of the city is given by S^o, where $S^o > T$. (T recall is the fog threshold). Smoke density in the new part is given by S^n, where $S^n < T$. Let $R^o = (S^o - T)$ and $R^n = (T - S^n)$. Suppose the migration of households from the old part of the city to the new reduces smoke in the old area by R^o and increases smoke in the new area by the same amount. As long as $R^o \leq R^n$, the reduction in smoke in the old area would eliminate fogs there, while the associated increase in smoke in the new area would not be sufficiently large to generate fogs there. Smoke-related fogs would disappear. To the extent that population increases are associated with expansions in territory, and a dilution in the density of smoke, it seems appropriate to look at coal consumption per capita.

Better than coal consumption per capita, though, would be time series data on the distribution of London's population between the dense core and the sparse periphery. Figure 14 provides those data, plotting population density in London proper (the core) and the whole of Greater London from 1811 through 2001. Population density in London proper starts the series at a remarkable 400 persons per hectare and holds steady there until 1861, when it implodes. By 1911, population density in London proper falls to 103.6. Population density for Greater London rises from .6 persons per hectare in 1811 to 1.44 in 1861, after which it begins a more rapid ascent. By 1911, population density in Greater London rises to 3.5. These data suggest that one path to solving London's smoke problem began to emerge three decades before Brodie's inflection point around 1890. Poore (1893) indicated that it was not just London proper that experienced an outflow of people. The combined population of all five of London's central districts—Holborn; the Strand; St. Martins; St. Giles; and the city proper—dropped from a peak of 334,369 in 1861 to 247,140 in 1891.[27]

By driving people out of the center of the metropolis, the dense, smoky fogs of central London might have contained the seeds of their own demise. An article published in *Science* more than a century ago explained. Asking why the population density of Paris was so much higher than that of London, the unnamed author wrote (Feb. 19, 1886, pp. 173-74):

> The average density of Paris is more than double that of London, and yet the streets are brighter and cleaner. The question probably turns more upon the prevention of smoke than any thing else. If the fog and gloom could be removed, and free access provided for the sunlight, there is no pleasanter [sic] or healthier place to live than the west end of London; and many who now endure, morning and evening, forty minutes' journey through choking tunnels, and walk long distances to railway termini, would stay in town if they could be relieved from the depression which is the accompaniment of a murky atmosphere.

The idea that central London was, in a relative sense, an unhealthy place to live because of fog receives support from the available data on death rates. Figure 15 plots the trend in the crude

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[27]Poore (1893), it should be noted, believed that the increase in the area of the city was a cause of fogs.

death rate for London as a whole, and the observed crude death rate for London's five central districts. The death rate in London as a whole falls by around 25 percent between 1860 and 1890; the death rate in the central district remains flat.

While the data in figures 14 and 15 bear-out aspects of the suburbanization/smoke redistribution story, this story can not explain the sudden stagnation in the growth of coal consumption per capita observed in figure 12. Nor would it seem to do a very good job accounting for the sudden reversal in trend we observe for foggy days around 1890. The other components of equation (3), however, do provide a framework for explaining why foggy days started to trend down at the same time that coal consumption per capita stagnated. Recall the smoke term, γC. Advocates of smoke control suggested that γ and C were not independent of one another. On the contrary, as explained below, there was a large literature that claimed to demonstrate that as firms adopted technologies and operating procedures that mitigated smoke emissions, they would conserve on coal consumption because dense emissions of coal smoke contained a large amount of unburnt and unexploited coal. We formalize this idea by characterizing C as a weakly increasing function of γ:

(4) $C = c(\gamma)$ and $C_{\gamma} \geq 0$.

In a sense, γ is also a function of C. More precisely, firms and households in the nineteenth century had a choice between two types of coal, soft (bituminous) or hard (anthracite). The amount of smoke generated by coal depended upon which type was used. Soft coal, C^s, generated much more smoke than hard coal , C^h. Let h denote the proportion of coal used in London that was anthracite:

(5) $h = (C^h)/(C)$,

where $C = (C^s + C^h)$. The proportion of burned coal that escaped into the atmosphere was a negative function of how much of that coal was anthracite. We formalize this idea by characterizing γ as a strictly decreasing function of h:

(6) $\gamma = g(h)$ and $\gamma_h < 0$.

Barr (1900, pp. 9-48) provides a clear scientific explanation for this assumption. In London, two types of so-called "smokeless coals" were used. These were Welsh anthracite and Welsh steam coal, both of which contained more carbon and fewer volatile components than ordinary bituminous coal, though ash content was similar across all three types of coal.[28]

This set up give us a framework for understanding what happened in 1891. First we quickly summarize what we believe happened without providing any evidence; then we offer a longer historical discussion with evidence. In 1891, the British government passed the Public Health Act. This law empowered police in metropolitan London to fine manufacturers throughout the area for dense smoke emissions. Enforcement of this law encouraged firms to conserve on soft coal, setting in motion processes that drove up h, drove down γ, and at least put downward pressure on C^s. Although the absolute amount of coal (C) in London did not fall as a result of these processes, the relative amount stabilized as actors worked to economize

[28]In particular, Welsh steam coals were between 70 and 87 percent carbon, 12 to 20 percent volatile matter, and 1 to 4 percent ash; Welsh anthracite was 91 to 96 percent carbon, 3 to 8 percent volatile matter, and 1.5 percent ash. Ordinary bituminous coal from England was around 60 percent carbon, 38 percent volatile matter, and 4 percent ash. See Taylor and Haldeman (1855), p. 71.

on their use of soft coal. Complementing the actions of manufacturers, London homeowners also became more cognizant of ways to conserve on coal, and adopted gas for cooking and heating or purchased grates and boilers designed to minimize smoke emissions and wasted fuel. It is important to emphasize that none of this need to have been rational or profit-maximizing from a given firm's perspective. Logic suggests it must have cost firms more to economize on soft coal than the coal was worth, otherwise they would have adopted smoke abatement technologies and practices without the impetus of the Public Health Act.[29]

Although London had a long history of anti-smoke agitation (see Brimblecombe 1987, pp. 10-18, and 90-107), the movement began in earnest in 1880 with the creation of the National Smoke Abatement Institution (NSAI). A private institution located mainly in London but with ties throughout the United Kingdom, the NSAI organized exhibitions for inventors and manufacturers to display heating and cooking grates, stoves, steam boilers, smokeless fuels, and other devices designed to mitigate emissions of coal smoke. The group offered prizes for inventions deemed especially promising and created venues through which it sought to instruct manufacturers and homeowners in ways to conserve on coal. It also worked to dispel the widespread notion that coal smoke had disinfectant properties that destroyed airborne pathogens that would have otherwise carried diseases like tuberculosis and influenza (*Report of the Smoke Abatement Committee*, 1883, p. 183; and *Nature*, Feb. 9, 1888, pp. 356-68; *Transactions of the Sanitary Institute of Great Britain*, 1887-88, pp. 301-45).

[29] See also Booth (1898) for an informal discussion of the tendency for engineers in London to install bituminous-coal fired heaters rather than ones that used smokeless Welsh coals.

The members of the NSAI, like most participants in the late-nineteenth-century smoke abatement movement, embraced an early incarnation of the Porter hypothesis, the idea that environmental regulations and controls might spur productivity advances. The NSAI believed that the technologies it recognized and helped introduce to the world would not only make nineteenth-century cities cleaner and less polluted, they would make businesses more efficient and profitable. Arguing that dense smoke represented imperfect combustion and wasted fuel, the advocates of this early Porterism claimed that proper stoking methods, specially-designed coal grates, stoking machines, and various types of smoke consumers would enable manufacturers to conserve on coal (e.g., *Report from the Select Committee on Smoke Prevention* 1843; *Report of the Smoke Abatement Committee*, 1883, p. 183; *BMJ*, Aug. 20, 1908, p. 615).

Whether or not one is convinced by the claim that smoke abatement would make firms more profitable, participants in the smoke-control movement made a strong case that, whatever the cost of abatement, it would simultaneously economize on coal and reduce smoke. In his paper, "Wasteful Power Production: With Special Reference to Waste Due to Smoke," John S. Owens (1912, p. 93) explained:

> The production of dense smoke means that the burning gases are being extinguished, form some cause, before combustion is complete. This is often due to insufficient air supply to the combustion chamber while the gases are being distilled off and burnt. Insufficient air means not only smoke but the escape of unconsumed gases, and these are a source of considerable loss.

According to Owens, the simplest and easiest way to assure adequate air-flow was by stoking the coals properly:

> It is a very curious thing that so little effort is made to ensure a knowledge of the first principles of their calling in the men whose business it is to feed the fuel to a furnace. It has been shown that a bad stoker may burn 15 or 20 percent more fuel than a good one to get the same effect; and while doing so he usually produces a great deal more smoke than necessary. If fact, it is well known that smoke production and wasteful combustion go hand in hand. And although it might not pay a manufacturer to educate his stokers, or employ more skilled labour, in order to save the proportion of the fuel which is lost in soot alone; it would certainly pay him to see that the method of stoking is such as will give the best economy of fuel and the most perfect combustion.

This logic suggests that proper stoking reduced smoke, S^d, through two mechanism, one direct, the other indirect. The direct mechanism was that proper stoking itself reduced smoke. The indirect mechanism is that proper stoking also reduced coal consumption.

The idea that proper stoking prevented smoke and saved coal has a long history and was widely accepted, even among producers and manufacturers who were otherwise resistant to smoke abatement. In a paper read before the *Royal Sanitary Institute*, Caborne (1906) expressed the identical argument. Twenty year earlier in front of the same venue, Fletcher (1887-88) claimed to have stated the obvious when he discussed the efficacy of proper stoking. A survey conducted by the London Coal Smoke Abatement Society in the early 1900s also supports the idea that factory owners believed Owens's central message. Surveying 63 London factories who had not been cited for excessive smoke in the last six months of 1904, the society elicited 35 useful responses. Of the respondents, just over half (13) ascribed "their success in preventing the emission of smoke to careful stoking (Rideal 1906, p. 149)." The argument that proper stoking economized on coal by producing more heat from a given stock of coal lays an empirical and historical foundation for the assumption, $C_\gamma \geq 0$.

Arguably the most important factor driving down γ in the aftermath of the Public Health Act was the direct effect of having producers switch from soft coal to different varieties of hard coal. In the context of figure 11, the data on coal consumption per capita are for the consumption of all kinds of coal not just soft coal. We have found no data source that would allow us to construct separate times series for hard and soft coal. However, of the 35 firms responding to the aforementioned survey of the smoke abatement society, all but one used some variety of coke or anthracite. Seventeen firms used Welsh coal, a variety of anthracite (Rideal 1906). When miners in the south of Wales struck during the late 1890s, London factories that had been using Welsh coal were forced to use bituminous. Their furnaces ill-equipped for bituminous coal and unable to stoke their fires properly, the factory owners were "hauled up before sundry magistrates to show cause why they should not abate the smoke nuisance they [were] making (Booth 1898, p. 1064; *Public Health*, Aug. 15, 1898, p. 373)."

In the absence of legislation punishing smoke emissions, it is difficult to imagine that manufacturers would have switched from soft to hard coal, which all reports indicate was "much dearer" than soft coal and harder to light, though once lit it "was a splendid article" (*Medical Times*, March 11, 1882, p. 395; Booth 1898; Saward 1914, p. 156; Reynolds 1882, pp. 167-80). Figure 17 plots the relative price of Welsh steam coal and ordinary (Newcastle) bituminous coal over the course of the nineteenth century and early twentieth century. The underlying price series are based on the supply prices at the mine, not delivered prices in London. Over the long-term, the relative price of Welsh coal sold at a 20 percent premium throughout the period. This pattern rules out the possibility that the switch from soft to English coal to "smokeless" Welsh coal was driven by a reduction in the relative price of Welsh coal. On the contrary, the trend line indicates a non-trivial uptick in the relative price of Welsh coal sometime after 1885. This pattern is consistent with the hypothesis that demand for smokeless coals increased relative to the demand for ordinary bituminous coal as a result of regulatory or political pressures.

As manufacturers switched from soft coal to hard, they also indirectly helped reduce overall coal consumption. Once again, Owens (1912, pp. 93-94) provides a useful explanation of this mechanism. Because soot was a "very bad conductor of heat," when boiler plates became covered in soot, "the rate of heat transfer [was] reduced." Owens conducted a series of experiments to measure the amount of heat that might have been lost when factory owners and operatives allowed soot to build up on boiler plates. He found that a layer of soot 1/20 of an inch thick, reduced the transfer of heat by 15 percent. One way manufacturers could prevent the development of coal soot on boiler plate was to use hard coal intermittently or mixed with the bituminous coal. Because Welsh and anthracite coals generated less soot and tar than bituminous coal, even their intermittent use delayed the formation of soot on boiler plates and enabled workers to generate more heat than they otherwise would have when they used bituminous coal alone. It was not uncommon for manufacturers in turn-of-the-century London to use a mixtures of smokeless coal and bituminous coal (Rideal 1906). This pathway suggests another justification for the assumption, $C_\gamma \geq 0$.

Aside from the switch from bituminous to Welsh coal among manufacturers, there was also a more voluntary transition taking among consumers. An observer who placed heavy emphasis on the voluntary adoption of new technologies was Sir George Livesey, an officer of a large London gas company and leader of the city's smoke abatement movement. In a paper presented to the Royal Sanitary Institute, Livesey argued that London had become a less smoky place because more and more consumers, especially those among the working classes, were using gas stoves rather than coal for cooking. The spread of gas cookers among the poor was the result of two pricing strategies adopted by London gas companies: one was the practice of renting stoves to customers; the other was the coin-in-the-slot method of paying for gas. Of the 834,000 households in London that purchased gas from the city's three major gas companies, 70 percent used gas stoves for cooking, and that number would have been even higher if homes and apartments had had sufficient space for a gas stove and opposition from landlords had not been so strong (Livesey 1906). While one might dismiss Livesey's arguments and opposition to coal smoke as patently self-serving, ten years before he published his paper, the *British Medical Journal* (Aug. 22, 1896, p. 465) published data and evidence very much in keeping with his otherwise partisan observations. Surprisingly the *BMJ* suggested that it was the wealthy, not the poor, who were slow to adopt gas for cooking.[30]

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[30]The *BMJ* (Aug. 22, 1896, p. 465) wrote: "A new and unexpected agency is having a most beneficial effect in contributing to the abatement of the smoke nuisance in London. The relative clearness of the London atmosphere within the last twelve months has been plainly apparent, and the smoke cloud which obscures the London atmosphere appears to be progressively lightening. Mr. Ernest Hart, Chairman of the Smoke Abatement Exhibition in London, frequently pointed out that the greatest contributors to the smoke cloud of London were the small grates of the enormous number of houses of the poor, and a great deal of ingenuity had been exhausted with relatively little success in endeavoring to abate this nuisance. The use of gas fires was urgently recommended, but had hitherto been difficult,

6. Concluding Remarks

We motivated this paper with the simple question: did Frederick Brodie discover the world's first Environmental Kuznets Curve? The evidence presented above, though not conclusive, suggests that he did. The strongest single piece of evidence is the reverse event study, which shows that fog-related events—defined as unexplained spikes in weekly mortality rates—rose steadily in frequency and severity in the years leading up to 1891, and declined in frequency and severity thereafter. Furthermore, if one looks at sunshine measures, which in contrast to fog was measured instrumentally, there is evidence that sunshine rates in London were in decline relative to neighboring areas before 1891, and in ascension in the years following. In addition, qualitative evidence in the form of first-hand testimonials are presented throughout the paper to indicate that contemporary observers believed that London's atmosphere grew cleaner and more breathable in the wake of the Public Health Act. There is

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owing to its cost and want of suitable apparatus. The rapid and very extensive growth of the use of gas for cooking as well as lighting purposes by the working classes, due to the introduction of the `penny in the slot' system, is working a great revolution in the London atmosphere. During the last four years, the South London Gas Company alone has fixed 50,000 slot meters, and nearly 38,000 small gas cooking stoves in the houses of the working man. This movement is still making great progress, and we hope means may be found to extend it to the houses of the more comfortable classes. The enormous improvement in the London atmosphere, and the clearing away of a smoke pall which hangs over London, may then be anticipated." See also Ackermann (1906) who pleaded with London officials to promote the spread of producer gas (a cheap, low-grade type of coal gas appropriate for heating and cooking but not lighting) to replace coal. Martin (1906) presented data to indicate the threshold price at which it would be economical for households to switch from coal to producer gas. Fifteen years before the article in the *BMJ*, Aflred Carpenter, an independent scientist, proposed heavily taxing coal use in London, thereby encouraging homeowners and manufacturers to adopt gas for lighting, heating, cooking, and mechanical propulsion. See Carpenter (1880).

also some noisy evidence to suggest that annual bronchitis rates in London rose and fell with the incidence of fogs. Although we do not yet have the capacity to perform a full-blown analysis of panel data, evidence from other cities, particularly Glasgow, suggests that what was happening London was not unique: bronchitis rates grew increasingly frequent and severe with the rise of coal, and subsided only with reductions in coal smoke.

There are at least three plausible mechanisms through which Londoners might have successfully curtailed their production of coal smoke, or at least dissipated the smoke. First, the data above indicate the population of Greater London redistributed itself, as central districts became less densely populated and outlying districts more so. If smokey fogs formed only when smoke density rose above a certain threshold, redistributing population might have reduced the number of fogs experienced by the metropolis as a whole. (See sections 4 and 5.) Second, with passage of the Public Health Act in 1891, businesses were fined for failing to consumer their own smoke, or otherwise generating excess amounts of smoke. In response, manufacturers switched from bituminous coal from Newcastle and elsewhere in England to Welsh steam coal, a harder coal that generated much less smoke, though it was about 20 percent more expensive than ordinary soft coal. Businesses also adopted more efficient stoking and firing procedures so that they economized on coal and minimized emissions of unburnt soot and tar. Third, the expansion of gas for cooking and heating helped undermine demand for coal among homeowners, who otherwise burned much of the coal in London.

If one were to plot real wages for unskilled laborers in London against foggy days per annum the typical EKC would emerge. At low levels of development, pollution (as proxied by fog) rose with real wages, but at some real-wage threshold, the correlation reversed itself and rising wages were associated with reductions in foggy days per year. It is difficult to say what the EKC means in this context. Perhaps it reflects an income effect, or perhaps the correlation between income and pollution is spurious, the result of a threshold effect for pollution. Ordinary citizens and voters tolerate pollution as long as it is below some level, but begin actively lobbying for improvement once it crosses some threshold. The difficulty with the latter interpretation is that smoke abatements efforts in London had a long history, going back hundreds of years—though it was eventually repealed, the first statute prohibiting the burning of bituminous of coal in London was passed in 1273 (Martin 1906). It seems more likely that the metropolis had to reach some level income and technological advancement before it had the capacity to effectively deal with the coal smoke problem. This, however, is mere speculation. Fully resolving this question, and the other issues raised above, we leave for future research.

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	(London)/(country)		(Kew)/(country)		(London)/(Kew)	
Interval	winter	summer	winter	summer	winter	summer
1881-85	.17	.83	.85	.97	.20	.84
1886-90	.29	.85	.89	.96	.32	.87
1891-95	.32	.95	.83	1.02	.39	.94
1896-00	.35	.89	.97	1.03	.36	.86
1901-05	.32	.93	.88	1.04	.37	.89
1906-10	.38	.92	.81	.99	.46	.92

Table 1. Duration of Bright Sunshine at London Stations as a Proportion of the Duration at Neighboring Country Stations

Source: Lempfert (1912), p. 25.

Year	Week	Event #	Known[a]	Documentation (*Times* unless otherwise indicated)
1855	4	1	No	1/15, p. 10; 2/1, p. 5
1855	5	2	No	2/5, p. 10
1858	47	3	No	11/17, p. 10
1858	48	4	No	11/26, p. 10
1859	52	5	No	12/19, p. 6; 12/20, p. 10; 12/21, p. 12; 12/30, p. 9; 1/8, p. 6
1861	3	6	No	1/11, p. 9; 1/16, p. 10
1861	4	7	No	1/21, p. 10; 1/23, p. 12
1862	48	8	No	11/15, p. 11; 11/17, p. 10; 11/19, p. 6; 12/3, p. 12
1864	3	9	No	1/13, p. 12; 1/22, p.12
1871	50	10	No	11/18, p. 9; 11/19, p. 8; 12/20, p. 6
1873	51	11	Yes	12/19, p. 10; Brazell (1968), p. 111
1874	48	12	No	11/23, p. 5
1874	49	13	No	12/2, p. 10
1874	52	14	No	12/25, p. 7; 12/28, p. 5
1875	1	15	No	1/1, p. 11; 1/8, p. 9
1879	51	16	Yes	12/17, p. 8; Scott (1896); *Nature*, Nov. 5, 1891, p. 13
1880	5	17	Yes	*BMJ*, Feb. 14, 1880, p. 254; *Nature*, Nov. 5, 1891, p. 13
1880	6	18	Yes	same as above
1882	6	19	No	2/3, p. 6; 2/6, p. 7; 2/7, p. 10; 2/13, p. 10
1890	2	20	Yes	*Nature*, Nov. 5, 1891, pp. 14-15; Brodie (1891)
1890	3	21	Yes	same as above
1892	1	22	Yes	*Nature*, Nov. 5, 1891, pp. 14-15
1892	2	23	Yes	same as above
1892	3	24	Yes	same as above
1892	4	25	Yes	same as above
1892	5	26	Yes	same as above
1893	49	27	No	11/23, p. 8; 11/30, p. 8
1894	2	28	No	1/8, p. 6; 1/15, p. 6
1899	51	29	Yes	12/1, p. 11; 12/2, p. 5; 12/4, p. 13; 12/13, p. 11
1899	52	30	Yes	12/23, p. 12; 12/28, p. 5
1900	1	31	Yes	1/3, p. 8; Brazell (1968), p. 111
1900	2	32	Yes	same as above

Table 2. Fog-Related Events Identified by Reverse Event Study, 1855-1910

Sources: see text and final column of table.

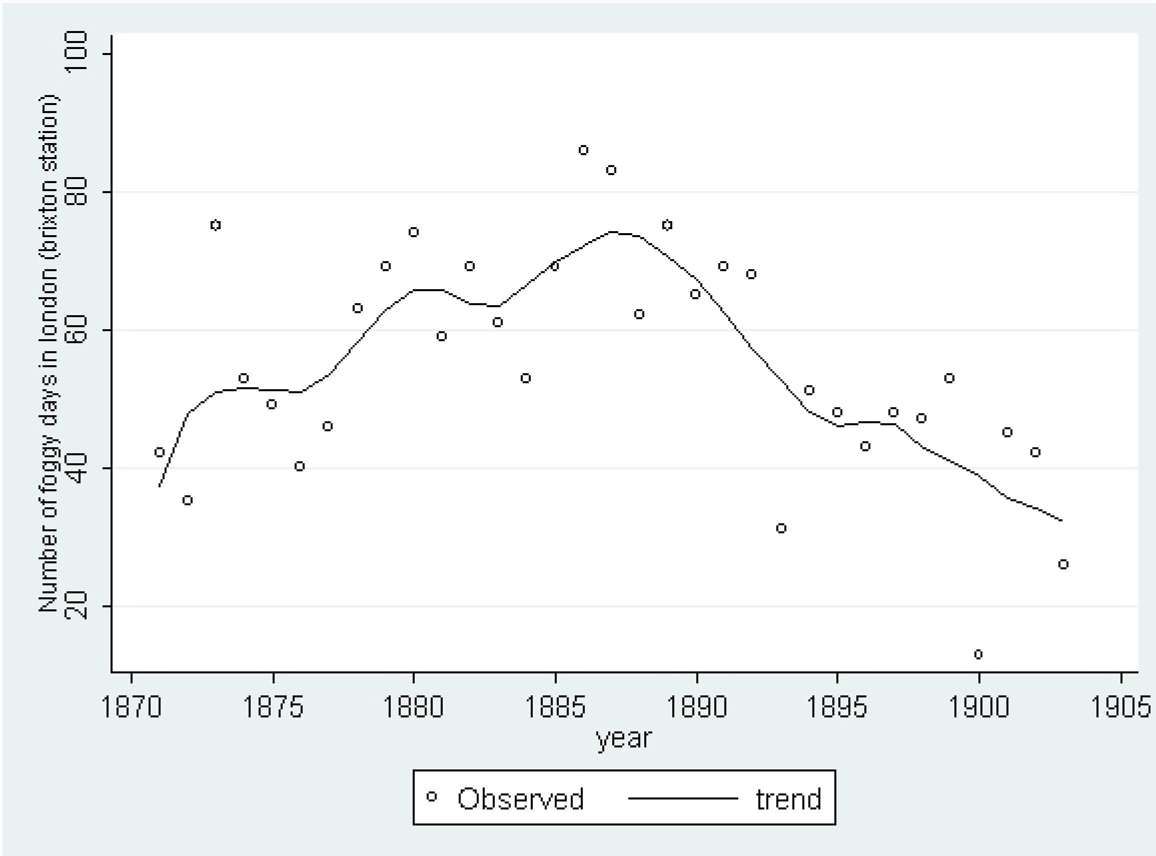

Figure 1. Brodie's graph (with a trend line)

Source: see text.

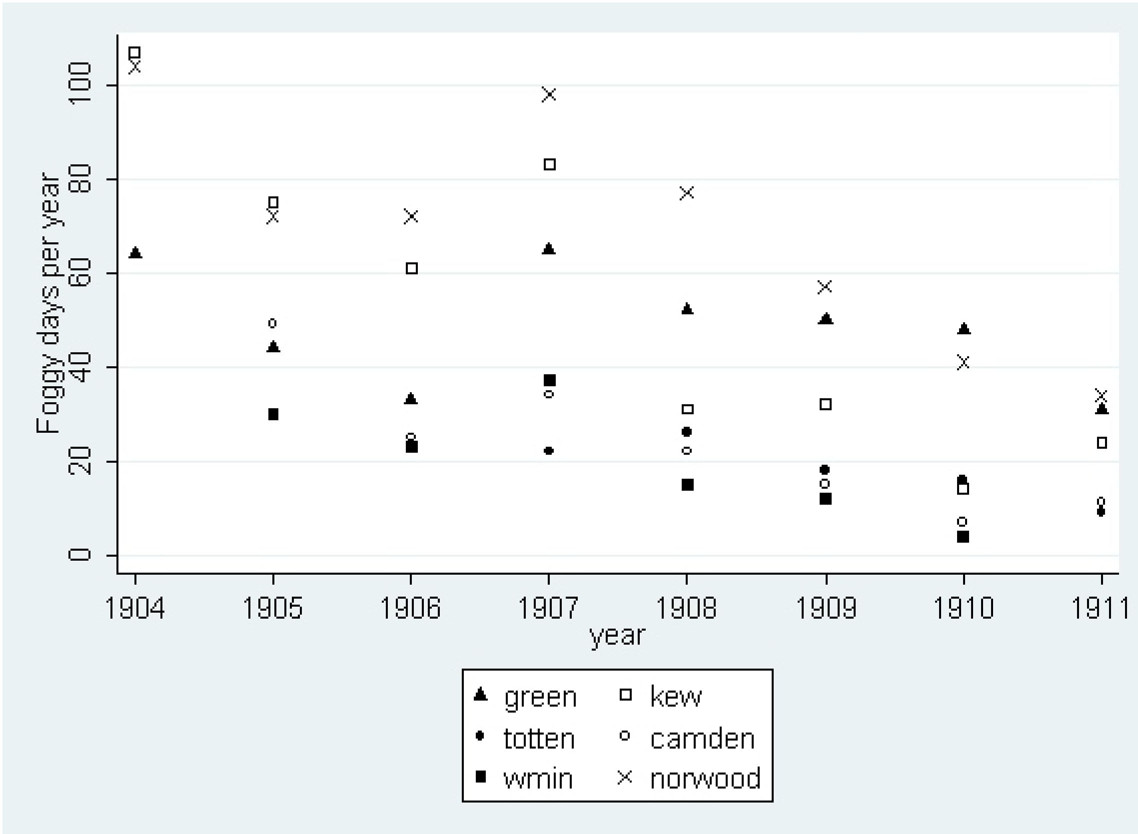

Figure 2. Foggy days at six london weather stations, 1904-1911

Source: Lempfert (1912).

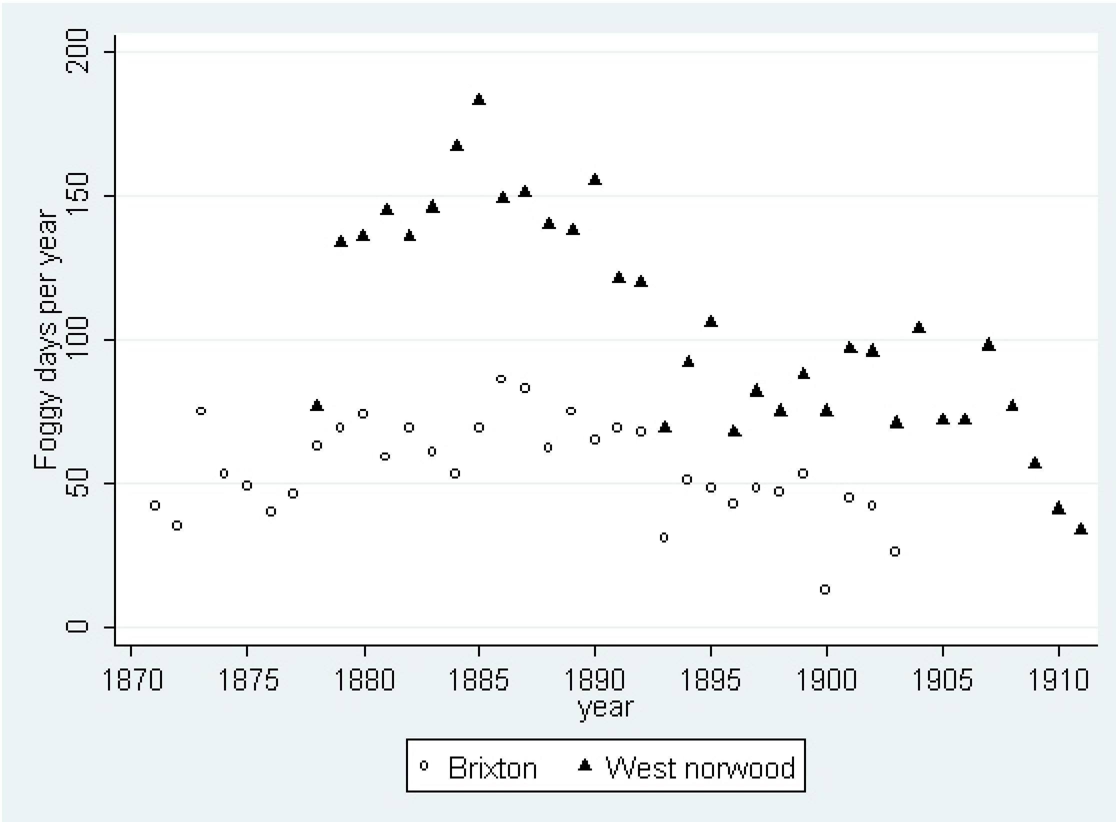

Figure 3. Foggy days in brixton and west norwood

Source: see text.

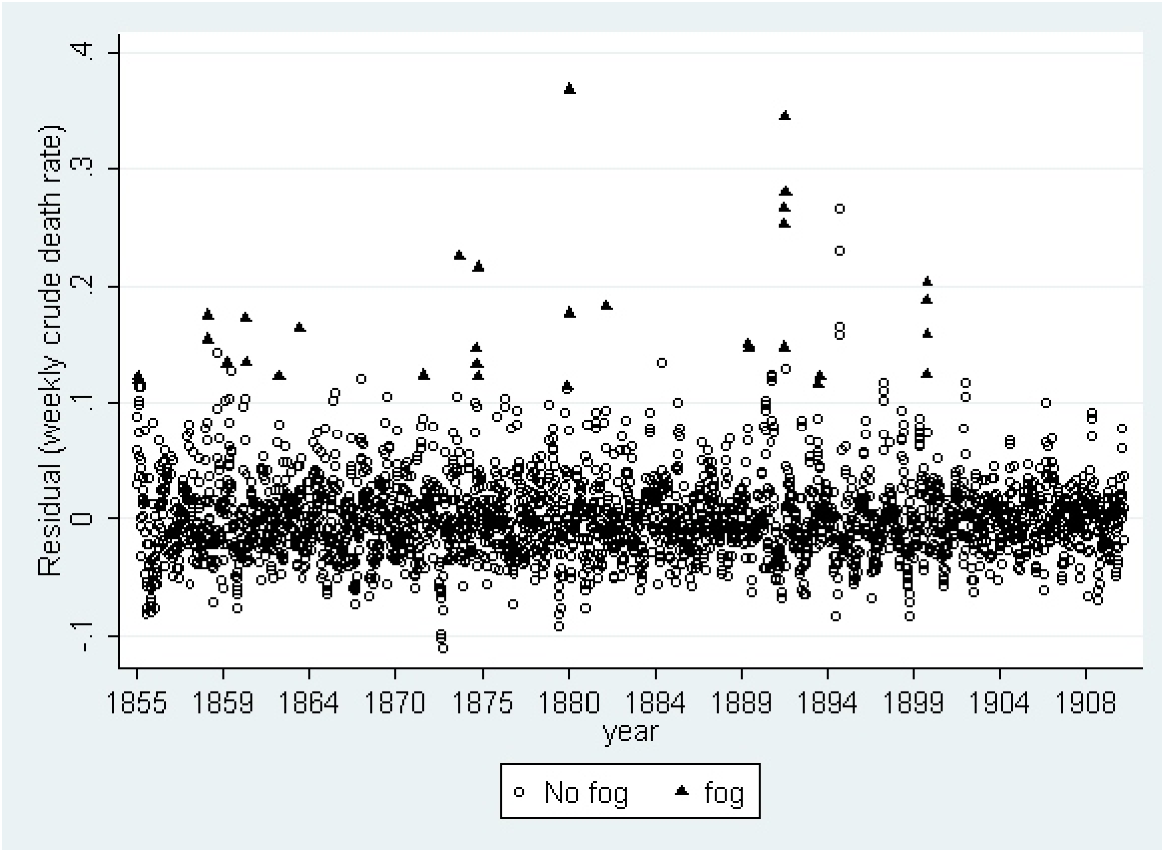

Figure 4. Deviation from predicted weekly crude death rate: 1855-1910

Source: see text.

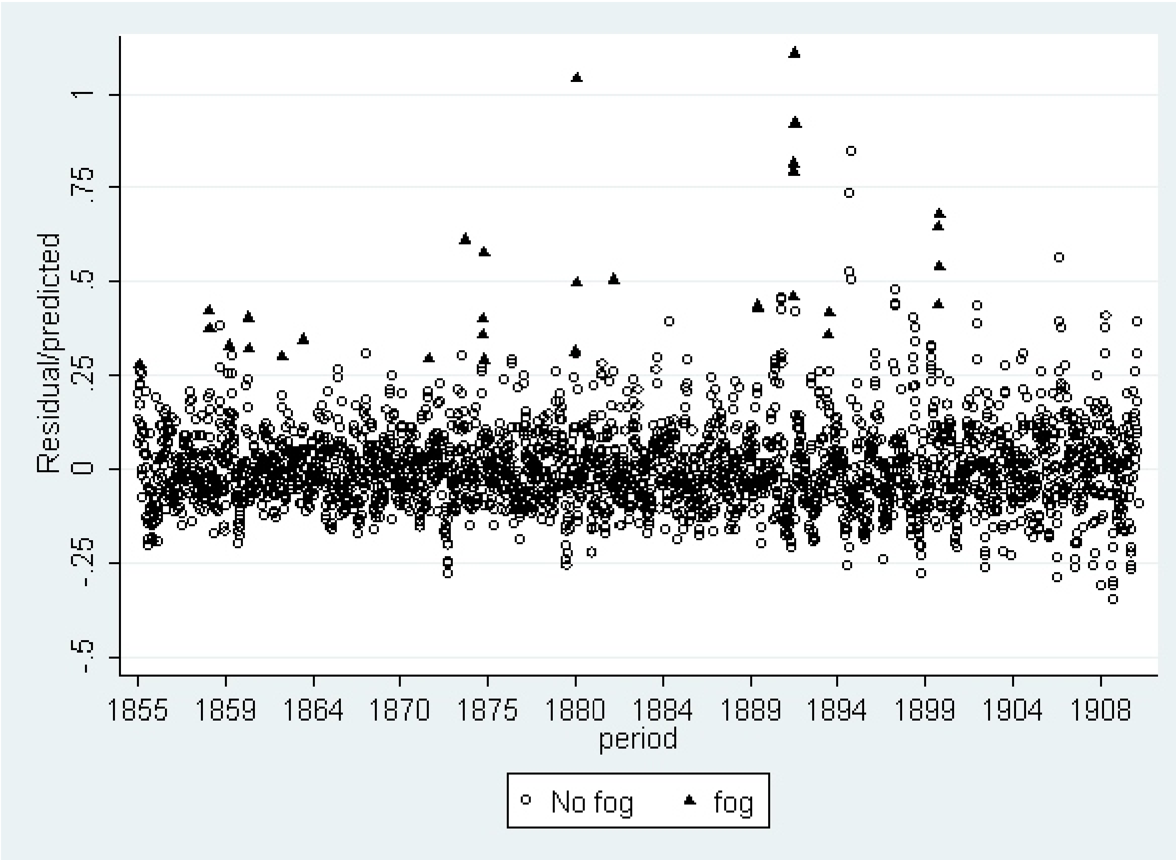

Figure 5. Percentage deviation from predicted weekly crude death rate: 1855-1910

Source: see text.

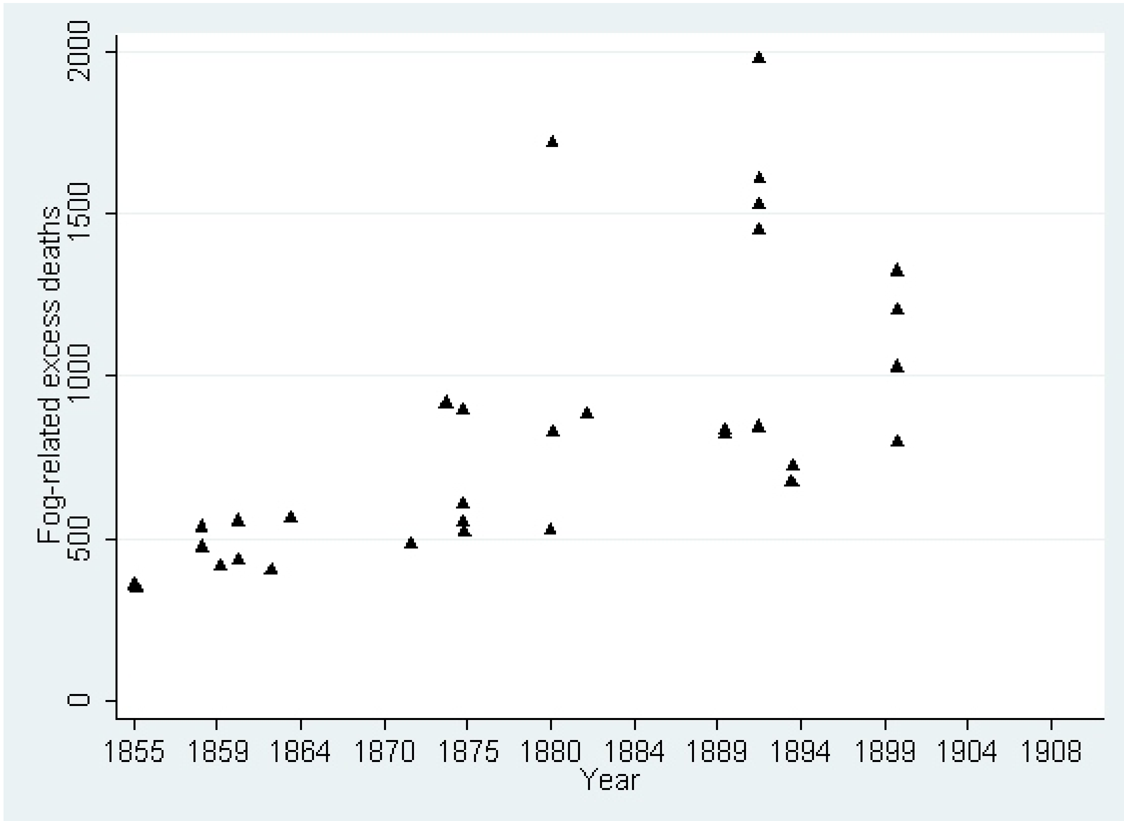

Figure 6. Excess number of deaths during fog-related events

Source: see text.

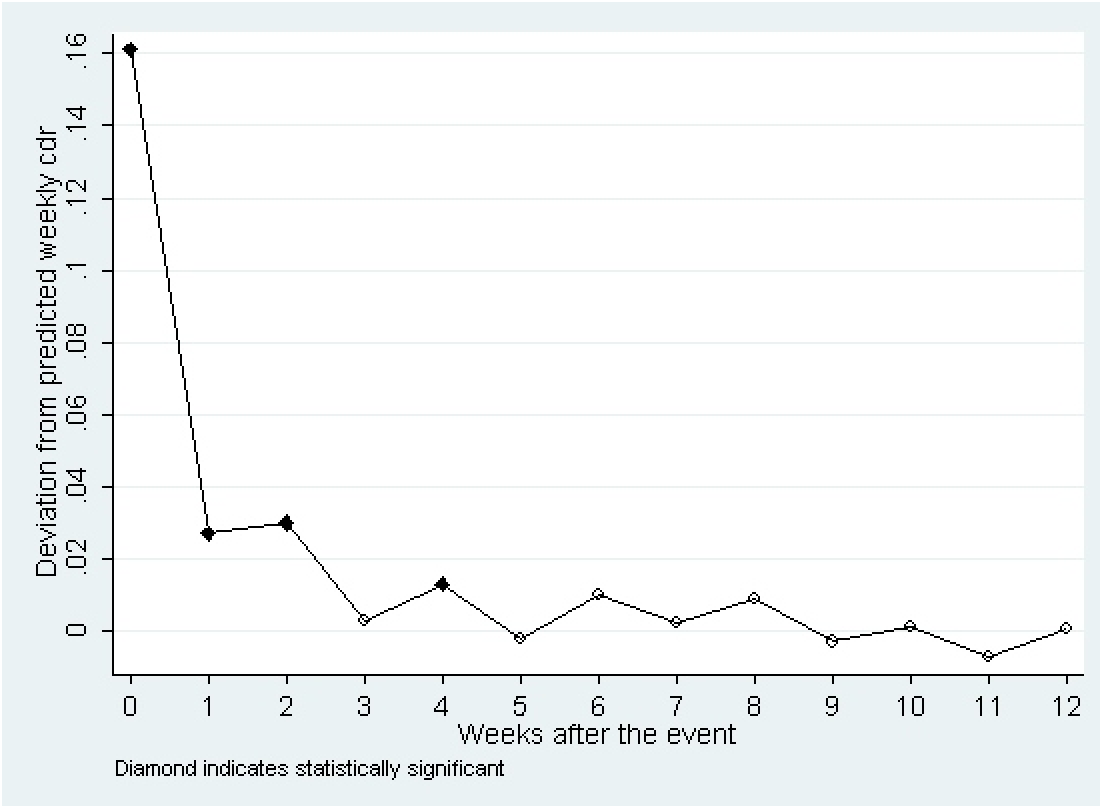

Figure 7. Deviation from predicted death rate in weeks following fog-related events

Source: see text.

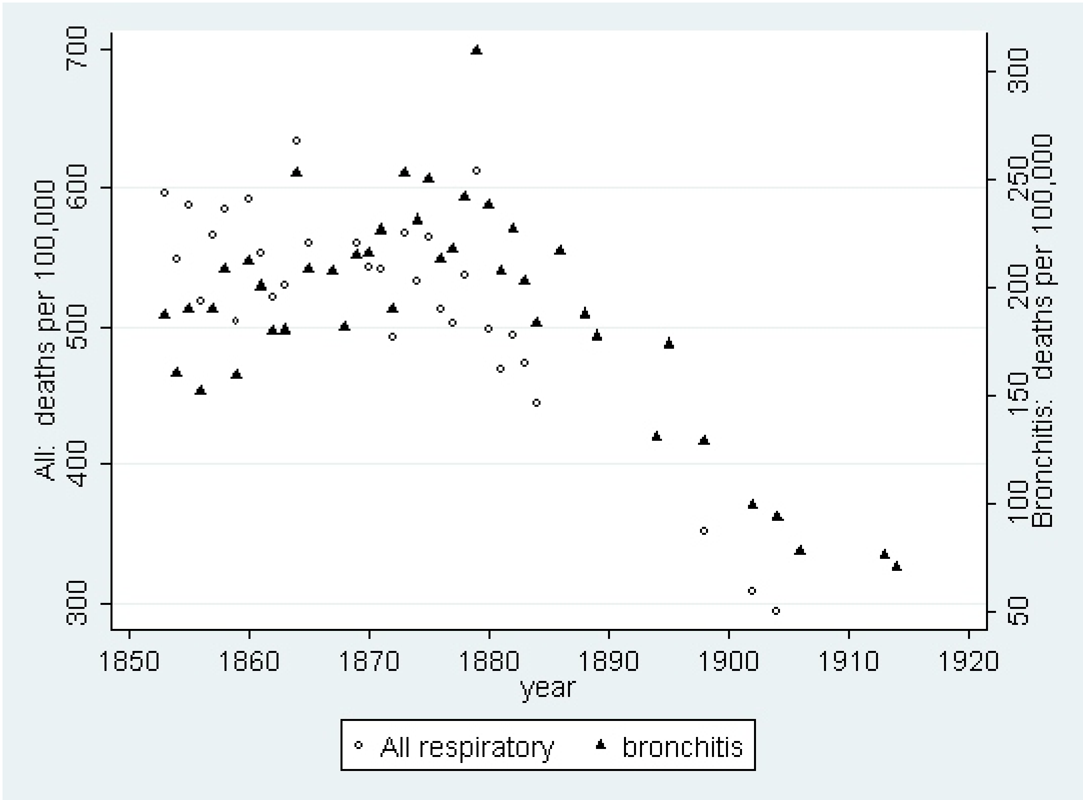

Figure 8. Deaths from respiratory diseases in london: 1850-1920

The category "all respiratory" includes: pneumonia, phthisis (tuberculosis), and bronchitis

Sources: *Annual Reports of the Registrar General* (England and Wales), various years; and *London Statistics*, various years.

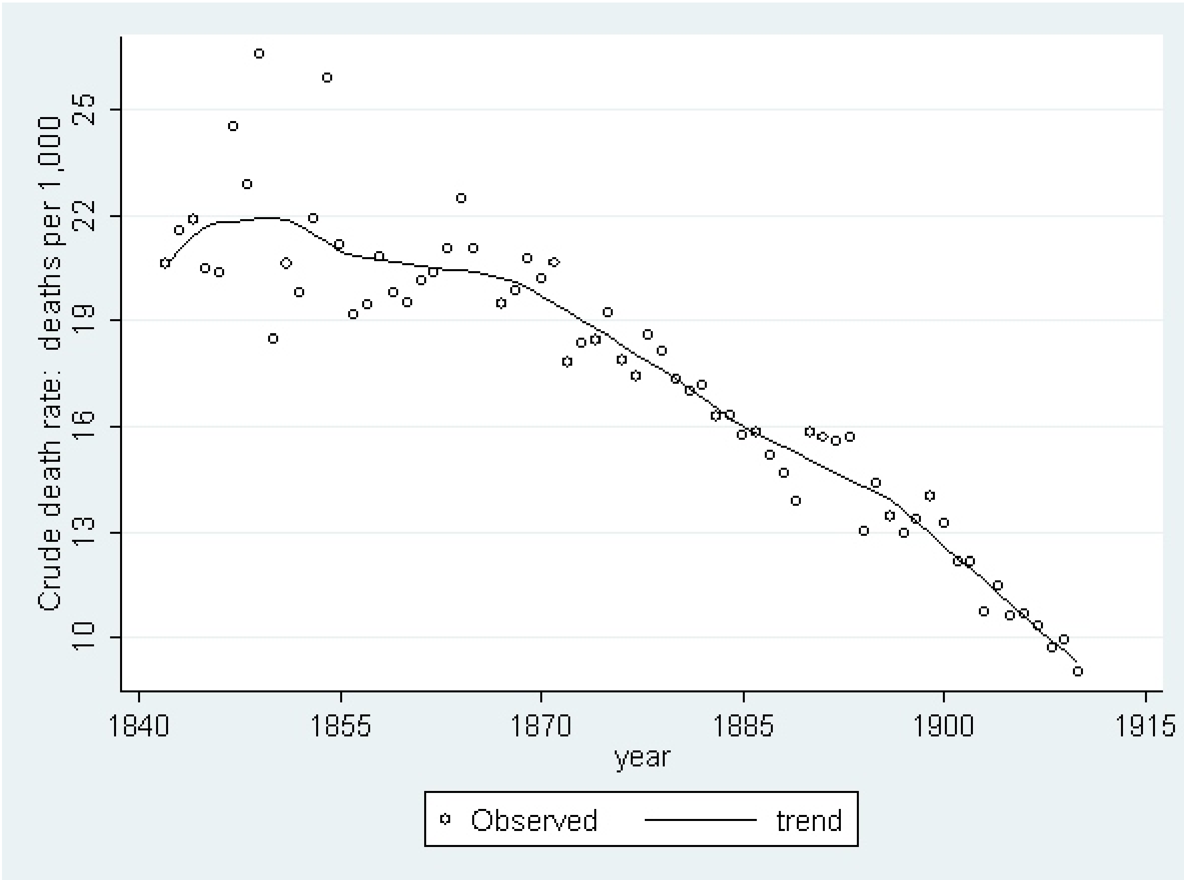

Figure 9. Crude death rate in london, 1840-1915

Sources: *Annual Reports of the Registrar General* (England and Wales), various years; and *London Statistics*, various years.

Figure 10. Death rate from bronchitis in london and england & wales, 1850-1920

Sources: *Annual Reports of the Registrar General* (England and Wales), various years; and *London Statistics*, various years.

Figure 11. Death rate from bronchitis in glasgow and scotland, 1850-1920

Sources: *Annual Reports of the Registrar General* (Scotland), various years.

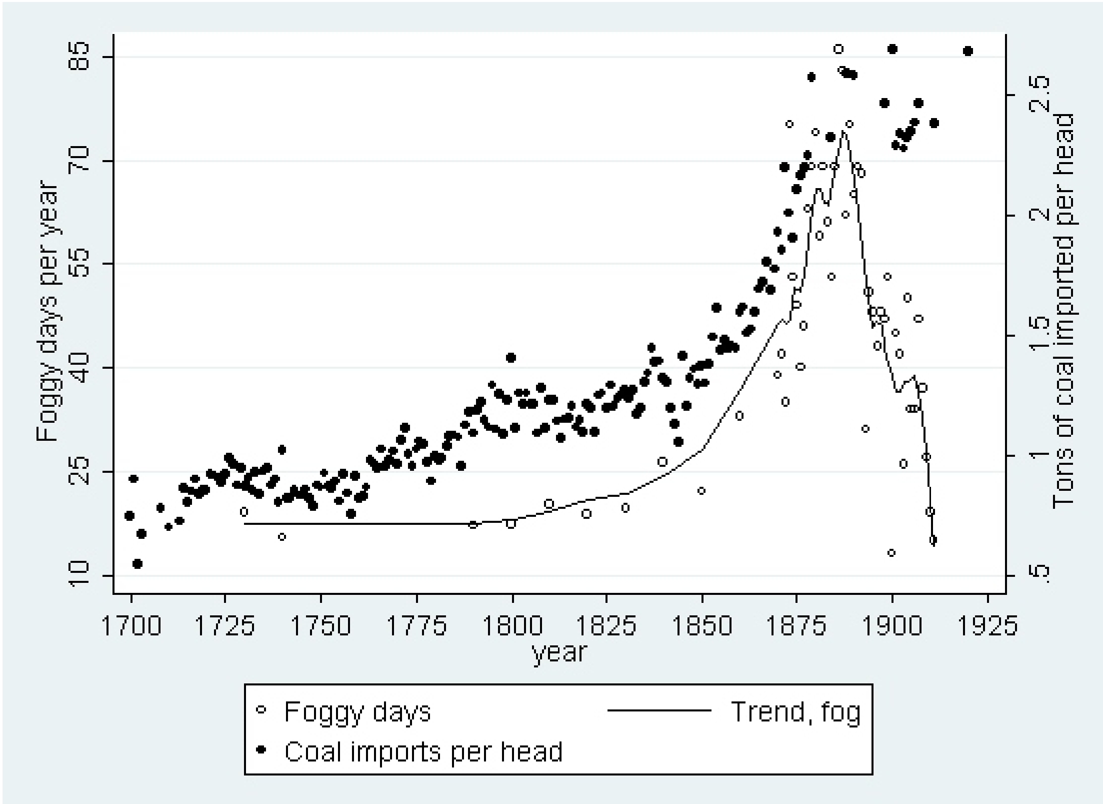

Figure 12. Coal consumption per capital and foggy days in london, 1700-1925

Sources: the coal data are from the 1899, 1908, and 1919 volumes of *The Coal Trade* by Saward (editor); the *Times*, July 23, 1901, p. 11; Dec. 1, 1913, p. 26; Aug. 11, 1927, p. 20; *Nature*, Nov. 5, 1891, p. 12; and for earlier years Mitchell (1988), a source which also provides data on London's population. The fog data are derived from the sources described in the text, especially Brodie and Mossman.

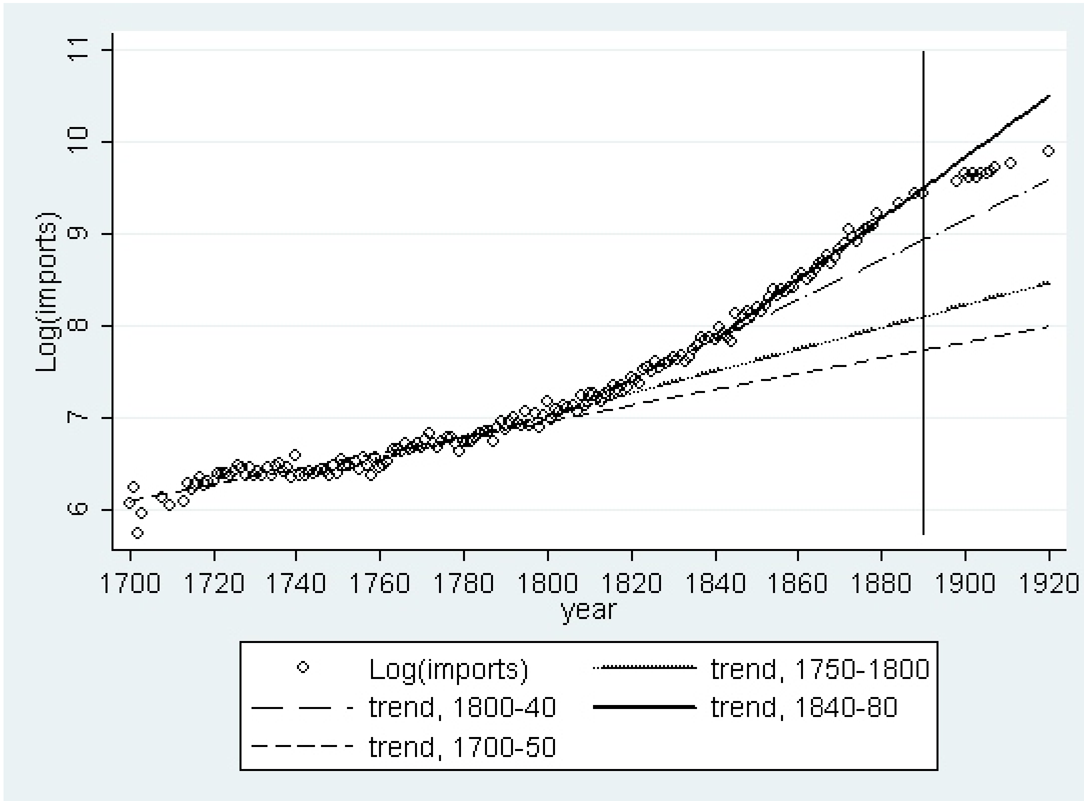

Figure 13. Total coal consumption in london (in logs): 1700-1920

Source: see note to figure 12.

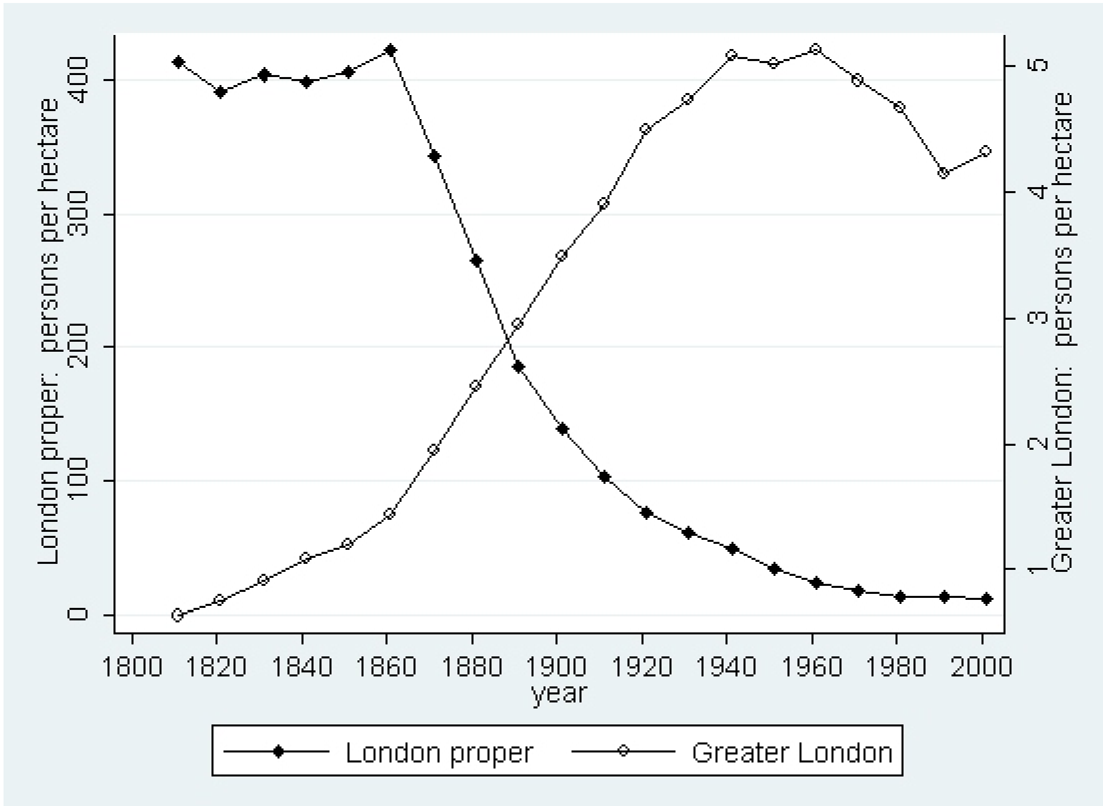

Figure 14. Population density in london proper and greater london, 1801-2001

Source: Poore (1883) for nineteenth century; *London Statistics* various years.

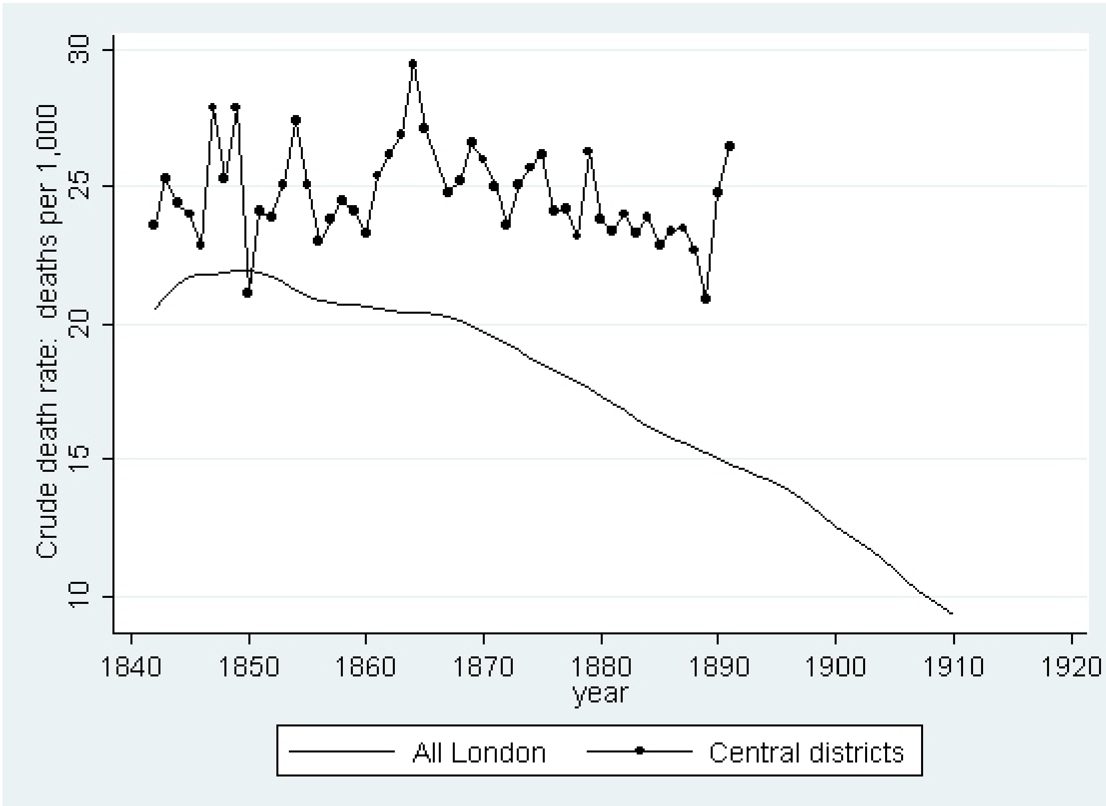

Figure 15. Crude death in greater london and five central districts, 1840-1920

Source: Poore (1883); *London Statistics*, various years.

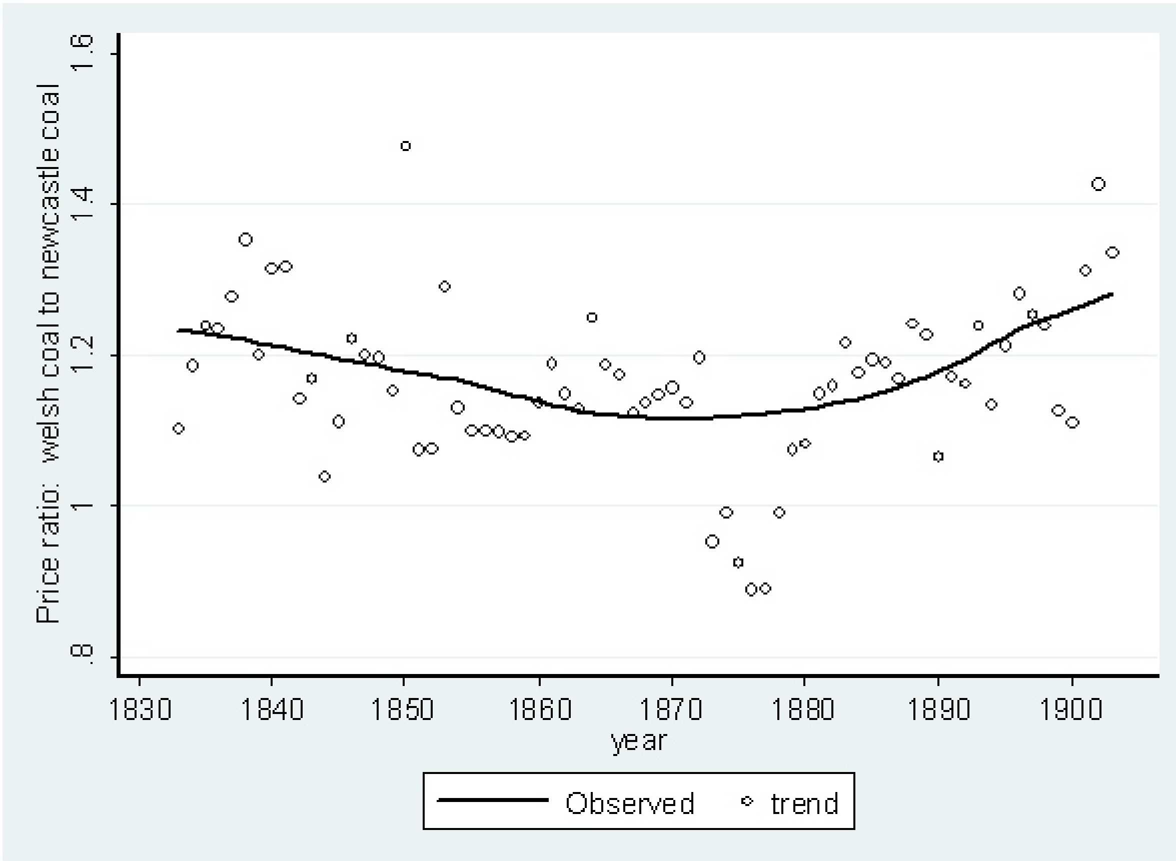

Figure 16. Price of Steam Coal in Swansea (Wales) Divided by Price of Bituminous Coal in Newcastle

Note: trend line estimated with STATA using a running line smoother, bandwidth of .8, and lowess option.

Sources: price series are from Wright (1905), pp. 409-20. Alternative price series which yield similar patterns can be found in Great Britain, Board of Trade (1903), pp. 12-19.