Coal, Smoke, and Death:

Bituminous Coal and American Home Heating

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Air pollution was severe in many urban areas of the United States in the first half of the twentieth century due to the burning of bituminous coal for heat. This paper estimates the effects of bituminous coal consumption for home heating on mortality rates in the U.S. during mid 20th century. Our identification strategy exploits changes in the costs of bituminous coal across states and years. Coal use for heating fell rapidly after 1945 as strikes, the end of the war, and expansion in pipelines cause the relative price of coal to rise. To further separate the effects of bituminous coal used for heating from the effects of bituminous coal used for other purposes, we exploit the fact that coal consumption for heating was highly seasonal and coal consumption for other purposes exhibited little seasonality. Our estimates suggest that reductions in the use of bituminous coal for heating between 1945 and 1959 decreased winter all-age mortality by 1.36 percent and winter infant mortality by 2.36 percent. Our estimates are likely to be a lower bound, since they primarily capture short-run relationships between coal and mortality.

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1. Introduction

Today, coal-related pollution is a serious concern in developing countries (Almond et al 2009, Cohen et al 2004). What has largely been forgotten is that until relatively recently, coal-related pollution was significant issue in many developed countries, including Britain and the United States. For example, London experienced killing 'fogs' from the 1850s onward. Thousands died in its most famous fog in December 1952. (Clay and Troesken 2010). The United States experienced severe coal-related pollution in cities in the 1930s and 1940s (Eisenbud 1978, Tarr 1996, Tarr and Clay 2012).

This paper estimates the effects of bituminous coal consumption for home heating on infant and all-age mortality rates in the U.S. during mid-twentieth century. Bituminous coal was both widely used and highly polluting compared to alternative fuels. In 1940, more than 55 percent of United States households and 64 percent of urban households used some type of coal for home heating. 75 percent of these households used bituminous coal. Further, use of bituminous coal for heating was generally more harmful than use of bituminous coal for others purposes. Many residential bituminous coal users were located in urban areas, burned bituminous coal at relatively low temperatures, and had low chimneys, all of which increased population exposure to pollution. Conversely, companies that used coal in manufacturing and electricity generation tended to be located away from the most densely populated areas, burned coal at high temperatures, and had higher smokestacks that allowed for dispersion of smoke across a much wider area.

Prior to 1945, temperature and proximity to bituminous deposits were the major determinants of the use of bituminous coal for heating. After 1945, coal use for heating fell rapidly. Coal strikes caused the price of coal to rise. At the same time, the price of oil and natural gas fell via as shipping became available to move heating oil and new long-distance pipelines began to move natural gas. Changing prices and the availability of low-cost conversion units for heating stoves and furnaces led to rapid switching. By 1959, only 12 percent of households used coal for home heating.

Exposure to coal-related pollution can lead to mortality across the population. For adults, air-borne particulates and associated pollutants such as carbon monoxide can cause atherosclerosis; heart arrhythmias; and pneumonia.[1] For infants, pollutants can cause premature delivery and low birth weight; respiratory disease; and cardiovascular disease.

The analysis draws on newly digitized historical mortality and coal data to examine the relationship between the use of bituminous coal for home heating and infant and all-age mortality. Data on all-age and infant mortality at the state-year and state-month level are taken from the annual *Vital Statistics* volumes. Fuel consumption data by use is from the *Historic Emissions of Sulfur and Nitrogen Oxides in the United States from 1900 to 1980.*[2] Additional data are from *Minerals Yearbook*. Data on state temperatures and state annual per capita income are from the United States Historical Climatology Network (USHCN) and U.S. Bureau of Economic Analysis.

The paper uses both difference-in-differences and triple difference approaches to identify the effect of bituminous coal on all-age and infant mortality. In the initial analysis a difference in difference approach is used that exploits changes in the costs of bituminous coal across states and years. To minimize issues of endogeneity, the analysis uses state per capita coal consumption in 1920 and interacts it with a post-1945 indicator variable or a post-1945 trend. To

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[1] See Lockwood (2012), Pope et al (2004), DelFino et al (2005), Curry and Walker (2011), Woodruff et al (2008), and Arceo-Gomez et al (2012).

[2] For more detail, see Chapter 2 of Gschwandtner et al (1983).

separate the effects of bituminous coal used for heating from the effects of bituminous coal used for other purposes, a triple difference approach is used that exploits the fact that coal consumption for heating was highly seasonal and coal consumption for other purposes exhibited little seasonality. Our hypothesis is that cold-weather spells would have larger impacts on mortality, via increased air pollution, in states located near bituminous coal deposits or time periods (post-1945) when alternative fuels were relatively cheaper. Both models include controls for state-by-month fixed effects to account for the possibility that states with greater access to coal also have different seasonal mortality patterns. To address the concern that changes in coal access over time are correlated with broader changes in public-health conditions, year-by-month fixed effects and state-specific trends are included. Some specifications also include controls for temperature and income.

Our estimates suggest that reductions in the use of bituminous coal for heating between 1945 and 1959 decreased winter (November-March) all-age mortality by 1.36 percent and winter infant mortality by 2.36 percent. The effects varied by region, because different regions experienced different changes in the use of bituminous coal. For example in the Midwest, the estimated effects were large, 2.5 percent for all-age mortality and 4.4 percent for infant mortality. In the Northeast, where bituminous coal was not widely used, the declines were 0.6 percent for all-age mortality and 1.1 percent for infant mortality. Our national and regional estimates are likely to be lower bounds, since they primarily capture short-run relationships between coal and mortality.

Our paper fills an important gap in the pollution-health literature. Specifically, most existing studies have examined contemporary settings where the levels of pollution were relatively low by historical standards. For example, Chay and Greenstone (2003a, 2003b), Currie and Neidell (2005), Currie, Neidell, and Schmieder (2009), Currie and Walker (2011), Knittel, Miller, and Sanders (2012) have examined the effect of pollution on infant mortality in the U.S. in the late 20th century. Arceo-Gomez, Hanna, Oliva (2012) present results from Mexico, where particulate levels are roughly twice the levels in the U.S. today. The closely related epidemiology literature (Pope et al 2002 and Laden 2006) also focuses on more recent data. In contrast, our paper examines infant and all-age mortality in a period when winter pollution levels were considerably higher. For example, the urban particulate was roughly eight times the levels in the U.S. and four times the levels in Mexico as measured in the late twentieth century. Importantly, the levels experienced in the historical U.S. were more comparable to those experienced in developing countries today (Almond et al., 2009, Cohen et al 2004).[3] Thus, our research can possibly offer more relevant estimates of the impact of high levels of coal consumption on human health in a developing country setting.

2. Coal

Background

Coal, and bituminous coal in particular, was important fuel for home heating from the late nineteenth century through the end of World War II. Using historical estimates from the U.S. Energy Information Administration, Figure 1 shows energy consumption by source in the U.S. economy as a whole. Until the 1880s, the primary source of fuel in the economy was wood.[4] Wood was surpassed by coal in the 1880s and coal remained the dominant fuel source through the 1940s, when it was surpassed by petroleum. In the late 19th century, anthracite coal from eastern Pennsylvania was dominant. As deposits west of the Alleghenies were developed and

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[3] This paper also contributes to the small but expanding historical literature on fuel use and fuel transitions (Wright 1964, Herbert 1992, Castaneda 1999).

[4] Shurr and Netschurt (1977) and *Mineral Yearbook* (various years) and *Mineral Resources of the United States* (various years).

transportation facilities improved, bituminous coal became dominant. As Figure 2a illustrates, bituminous coal consumption was already the dominant source of coal in 1900. As we discuss below, the use of bituminous coal is particularly harmful to public health.

To disentangle the effects of coal-related pollution from other factors that might effect health, our research design uses variation in heating-related coal consumption. Figure 3 provides evidence that residential coal use was much greater in winter (colder) months. The *Minerals Yearbook* only began reporting consumption by use by month in 1951.[5] January consumption for heating coal was more than three times the consumption in the lowest month, which typically falls in the May-July window. In comparison, other coal use was only slightly seasonal. Analysis of other years indicates that the seasonality of coal consumption was fairly stable across the 1950s.

In addition to leveraging seasonal variation in coal consumption, we also use variation in proximity to coal fields. Figure 4 shows the location of coal deposits in 1920. All of the deposits except the very small zig-zag ones in eastern Pennsylvania were bituminous. Figure 5 highlights that being close to a bituminous coal field was strongly correlated with bituminous coal consumption for heating in 1920. One exception, despite its proximity to bituminous deposits, was Pennsylvania. Pennsylvania was in the lowest quartile, because anthracite was widely used for heating due to its proximity to anthracite deposits.

Usage of coal varied widely by population density and by region. Household level data on fuel consumption was first collected in the 1940 Census of Housing.[6] In that year 55 percent of households used coal for heat (Figure 6). Although the census did not ask which type of coal

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[5] Unfortunately, there is no data on consumption by month for earlier time periods.

[6] There is some additional wartime evidence on the types of coal being used for heating. Reid (1943, p. 8) states that "In 1940, in the affected area - the New England and Middle Atlantic States and the District of Columbia - 1,600,000 dwelling units were heated with bituminous coal and 4,300,000 units were heated with anthracite."

households consumed, Figure 2b indicates that more than 75 percent of coal consumed for heating was bituminous.[7] The fraction of households using coal was high in urban (64 percent) and rural-nonfarm (54 percent) areas. Rural farm households still largely used wood (67 percent), although a modest fraction of households used coal (28 percent). In the North, which was populous, cold, and close to coal deposits, the fraction of households using coal in rural nonfarm (72 percent), rural farm (49 percent), and urban (79 percent) areas were much higher than the national average. The fraction of households using coal in urban areas in the South was much smaller (44 percent). In the West, households in urban areas were predominantly using natural gas (49 percent), as opposed to coal (24 percent). The energy mix in the West region reflected their proximity to natural gas fields in the Southwest.

Our identification strategy also exploits variation in the opportunity cost of coal over time. Figure 2c shows the trends in consumption of bituminous coal for heating and for non-heating uses (e.g. industrial production, electricity generation and rail transportation). Compared to heating, other uses exhibited greater declines during the Depression and greater gains during World War II. After the War, the two series diverge. The use of coal for heating declined continuously, while other uses decline between 1945 and 1950 and then recover. In the second half of the 1940s, cleaner fuels – natural gas and heating oil – quickly began to supersede coal for use in heating. The proximate cause of the switch appears to be relative prices. Figure 7 provides evidence that gas prices per BTU fell rapidly in the early 1940s, while the price of coal per BTU was increasing. Understanding the determinants of these price changes is crucial for interpreting our estimates.

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[7] Sales of anthracite coal by use are not available until the 1950s. At that point, they were 20 percent of heating coal sales on a tonnage basis (*Minerals Yearbook*). Estimates in the mid 1920s suggested that 65 percent of anthracite was being used for heating. Department of Commerce (1929), p. 6. The series in Figure 2b uses this 65 percent estimate.

The reasons for the decline in coal prices after 1945 are due to many factors. Coal strikes by the United Mine Workers throughout the 1940s raised the specter that a large strike could cause prices to increase and shortages to emerge. Strikes had occurred in the pre-war period, notably in 1939 and 1941. In the WWII period, government controls limited strike activity. The strikes in 1946 and 1949-1950 sharply restricted production, adversely affected coal stocks, and raised prices. In both cases, daily production fell from 2 million tons per day to well below 1 million tons per day.[8] These strikes idled manufacturing, prompted restrictions in electricity production (dimouts), and caused restrictions in freight shipments and travel. In response to the second strike in November 1946, the *New York Times* reported, "Further reductions in travel, heating, lighting and even cuts in the dispatch of mail were officially foreseen in the event of a prolonged strike."[9] The Public Buildings Administration ordered "reduce[d] heating temperatures to the wartime maximum of 68 degrees if they use coal." [10]A coal supplier in the New York area quoted in the *Wall Street Journal* in 1946 explicitly linked the strikes to switches in fuels "Every time John Lewis stages a coal strike I lose several score customers to oil."[11]

Switching

A major constraint on switching, prior to the 1940s, was the availability of alternative fuels.[12] Gas manufactured from coal was widely used for cooking in cities by the early 1940s, but was generally too costly to be used for heating. Two logistical problems had to be solved

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[8] Bituminous Coal section, *Mineral Resources*, 1939-1952. See also, *Statistical Abstract of the United States*, 1951, Table 825: Work stoppages in Anthracite and Bituminous Coal Mining Industries by Major Issues Involved, 1938 to 1950.

[9] *New York Times*, November 22, 1946, p. 2.

[10] *New York Times*, November 22, 1946, p. 2.

[11] *Wall Street Journal*, September 26, 1946, p. 1.

[12] Railroads faced some of the same issues. As large carriers of coal, they could get preferential prices and carry or stockpile coal as needed. Switching relied on the availability of fuels. For some applications, railroad cars were electrified, but this only worked in urban areas. The larger move away from coal also relied on the commercialization of diesel railroad cars. Railroads rapidly switched from coal to diesel in the early 1950s.

before natural gas could be used for heating.[13] First, pipelines had to be built to move the gas from the Southwest to the Midwest and the East.[14] Figures 8a and 8b show Natural Gas Pipelines in 1940 and 1949. By 1940, some pipelines had been built. The distances that they moved gas and their capacity were still fairly limited. By 1949, major expansion of natural gas pipelines had taken place.[15]

Second, storage capacity had to be developed to store gas at the destination. Winter demands for gas were much higher than summer demands, so gas had to be to moved during the summer and fall and stored near population centers for use in the winter. The development of high-volume long-distance pipelines spurred the development of underground storage, which rose from 250 billion cubic feet in 1947 to 1,859 billion cubic feet in 1954.[16] Storage was primarily located in former gas, oil, or mixed oil and gas fields in Pennsylvania, Michigan, Ohio, and West Virginia.

Heating oil had been available in urban coastal cities prior to World War II. Supply was becoming an issue even before the United States entered the war as shipping and railroad capacity became scarce. Rationing of fuel oil beginning in October 1942 limited the ability of coal users to switch to fuel oil. It reportedly also incentivized some fuel oil users to switch back to coal, which was not rationed. The end of the war freed tanker and railroad capacity to be used for movement of heating oil, restoring the supply.

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[13] Hebert (1992) and Castaneda (1993).

[14] The first commercial liquefied natural gas plant was built in Cleveland in 1941. And the first trans-oceanic transport of LNG did not occur until 1959. LNG did not become common until the 1970s, and it remains a small share of world gas markets today.

[15] The sale and conversion of the Big Inch and Little Big Inch pipelines dramatically expanded the nation’s capacity to move natural gas. Early in World War II German submarines were routinely sinking ships carrying oil. Proposed in 1940, the pipelines were built in 1942-1943 to move oil from Texas to the East Coast. In 1947, the pipelines were sold to the Texas East Transmission Company and were converted to natural gas.

[16] American Gas Association (1956).

Switching heating fuels also involved some capital costs. In 1940, 42.0 percent of households had central heat, 46.6 percent had a heating stove, and 11.8 percent had other or none, which included households with portable heaters, fireplaces, or kitchen stoves.[17] Although households could purchase a new heating stove or furnace when they switched fuels, a more affordable option was a conversion burner, which allowed the existing stove or furnace to burn gas or heating oil. In 1950, the closest expenditure survey to 1945, average household current expenditure was $3925 and utility expenditure was $163.[18] The total cost of switching from coal to natural gas was $163, which is less than 5 percent of current expenditure and 100 percent of utility expenditure.[19] Conversion from heating oil to coal, which occurred during heating oil shortages in World War II, cost approximately $50, which was less than 2 percent of current expenditure and about 30 percent of utility expenditure.[20] Re-conversion cost roughly the same amount.

Given the lower prices of oil and gas and their increased availability in the second half of the 1940s, consumers began to switch. The shift is apparent in Figure 6, when one compares household fuels in 1940 and 1950. The share of households using gas for heating increased from 11.4 percent to 29.3 percent, and the share using oil for heating increased from 8.6 percent to 22.9 percent. In contrast, the share using coal fell from 55.1 percent to 35.1 percent, and the share using wood fell from 23.0 percent to 10.1 percent.

3. Background on Coal-Related Emissions and Mortality

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[17] By 1950, 50.4 percent of households had central heat, 36.0 percent of households had a heating stove or fireplace (other means with flue), 12.4 percent had portable heaters or electric baseboard heaters (other means without flue), and 1.4 percent did not have heat. By 1960, 65.7 percent of households had central heat or built in electric, 22.5 percent had heating stove or fireplace (other means with flue), 10 percent had portable heaters (other means without flue), and 1.7 percent had no heat.

[18] Jacobs and Shipp (1990), p. 22.

[19] Tarr (1981), p. 341.

[20] *New York Times*, September 12, 1945, p. 22 (continued from page 1).

Pollution in the United States

Heating with bituminous coal is considered to be a major contributor to winter air pollution. The reason why has to do with the height at which the pollution is emitted. In his analysis of pollution in New York City, Eisenbud (1978) writes: “It is a well-established principle of atmospheric physics that under most conditions the ground-level concentration from a point source of pollution is directly proportional to the quantity of pollutant emitted per unit time and inversely proportional to the square of the height above ground.” For large industrial stacks such as those used by power plants, the "height" of the stack is not only determined by its physical dimensions but by the temperature of the gases and the effects of buoyancy. All other things being equal, a power-plant stack with an effective height of 1,000 ft. will result in ground level concentrations that are 1% of the pollution resulting from a 100 ft. apartment house stack.”[21]

The level of pollution in the first half of 20th century United States was by modern standards high. Table 1 presents selected estimates of particulate pollution in the United States and developing countries.[22] While particulate pollution in the United States is currently low and has been at a relatively low level for a number of decades, it was high in the 1910s and 1930s. Additional evidence on levels of sootfall from New York and Pittsburgh suggest that levels remained high into the mid-1940s.[23] Notably, pollution levels in American cities in the 1910s and 1930s were similar to pollution levels in developing countries in the late twentieth century.

When burned for heating purposes, bituminous coal has a high particulate burden. Butcher and Ellenbecker (1982) examined particulates from wood, bituminous coal, and

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[21] Eisenbud (1978), p. 1006.
[22] Particulates were not routinely measured in the United States until the late 1960s.
[23] See Davidson and Davis (2005) for Pittsburgh and Eisenbud (1978) for New York.

anthracite coal when burned in heating stoves. They found that "Particulate emission factors for wood ranged from 1.6 to 6.4 g/kg (fuel) and were found to depend on the fuel load and the firing rate ... The average particulate emission factors for bituminous and anthracite coal are 10.4 and 0.50 g/kg."[24] The relative ordering for particulate emissions was likely to be bituminous coal, wood, and anthracite coal. Fuel oil is similar to wood in its particulate emissions. The precise values depend on the grade of heating oil. Natural gas emits almost no particulates when burned.

Exposure to pollutants occurred indoors and outdoors. At the beginning of the twentieth century, households burned fuel in open stoves or fireplaces in homes. By the 1920s and 1930s as households moved to closed stoves and furnaces. In both periods, indoor and outdoor air pollution tended to be highly correlated – air infiltration caused the two values to equilibrate.[25][26]

Historical and contemporary evidence indicate that coal for heating was major contributor to pollution. The Public Health Service study in the 1930s concluded based on analysis of time of day and day of the week pollution levels: "the nonindustrial pollution in the winter, resulting from the heating of residences, apartment houses, hotels, and other buildings, appears to be a greater factor than the year-round industrial pollution." [27] An analysis of hours of winter solar radiation – an indirect measure of air pollution in the United States – by Husar and

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[24] Butcher and Ellenbecker (1982), p. 380.

[25] Dockery and Spengler (1981).

[26] Indoor air pollution levels tend to be more stable over time, as increases and decreases in pollutants changed with a lag. The lag depends on the air change rate, which tended to be high historically and is lower today. Thus, indoor rates had lower lags historically (were close to outdoor rates) and have higher lags today. Nagada (1986). Air conditioning can reduce indoor particulates, but only became widespread after 1960 and was not typically used in the winter.

[27] Ives et al (1936), p. 47.) In 1930 the U.S. Public Health Service received an appropriation of $25,000 to study air pollution in cities. Given their limited resources, the goal of the 1930 study was solely to collect data on air quality in large American cities. Owens automatic air filters were run continuously in fourteen large U. S. cities beginning in July 1931. Total suspended particulates (TSP) were also sampled, although with lower frequency, because of the higher cost of data analysis. Analysis showed that TSP levels were highly correlated with the shade of the Owens automatic air filter. Winter air quality was nearly twice as bad as summer air quality. Average TSP in the winter months in these cities was 510. The study explored heating's contribution to pollution by examining pollution by time of day and by comparing Sundays, when most businesses were shut, to weekdays. Both analyses suggested that heating with coal was a major cause of pollution.

Patterson (1980) shows gains in the 1950s. In Dublin in 1990, following the ban on the sale of coal for heating, mean winter black smoke concentrations fell by 64 percent and overall concentrations fell 36 percent.[28] A 2005 E.U. study of pollution in Krakow concluded: "residential sources were also found to create the lion's share – beyond any single industrial source – of airborne PM measured near the ground."[29]

Particulates from Transportation and Cigarettes

Humans are exposed to particulates from a variety of sources, not just the burning of bituminous coal for heat or industrial purposes. Transportation was relatively minor source. Smoking, however, delivered far more particulates to smokers than pollution. As will be discussed in more detail in the next section, pollution remains relevant, because the dose-response relationship between particulates and mortality is highly non-linear. The marginal effects of particulates are large at small exposures associated with pollution and smaller but still positive at higher exposures.

Traffic particulates were a relatively small share of overall PM10 and PM2.5, although they were generally higher in cities. For example in 1940, the EPA estimates that on road vehicles accounted for slightly more than 1 percent of national PM10 emissions and in 1960, they accounted for about 2 percent of PM10 emissions.[30] Data for PM2.5 are only available beginning in 1990. In 1990, on road vehicles accounted for slightly more than 3 percent of PM2.5 and about 1 percent of PM10. Analysis of emissions in New York City suggests that traffic was 7-25 percent of TSP emissions from 1969-1975. The higher values reflect large declines in other sources of TSP and not increases in TSP due to transportation. In their analysis

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[28] Clancy et al (2002). Black smoke is a measure of light absorption of PM and is highly correlated with measures of PM10 and PM2.5

[29] Powell (2009), p. 8474, discussing Junninen et al (2009).

[30] EPA (2000).

of six U.S. cities from 1979-1988, Laden et al (2000) found that traffic accounted for 19 percent of PM2.5. Given that these estimates are for periods well after the declines in the use of coal, they suggests that automobile emissions were likely a small share of emissions in cities over the period 1920-1959.

Consumption of cigarettes and other burned tobacco products are a significant source of particulates for smokers and individuals exposed to second hand smoke. Smoking one cigarette delivers more particulates than (nonsmoking) individuals in highly polluted areas would be exposed to in one day. Per capita consumption of tobacco that was consumed in burned form (cigarettes, cigars, pipes, roll your own) was roughly 6 pounds in 1920 and 12 pounds in 1960. During the period 1920-1959, consumption was steadily rising, with the exception of a brief downturn during the Great Depression. In 1955, the first year for which detailed individual-level data is available, 55 percent of adult men and 25 percent of adult women reported being current cigarette smokers.[31]

The Pollution-Mortality Relationship

From the 19th century, public health officials and interested observers had suspected that air pollution was linked to mortality. The 1930s Public Health Service study notes: “No definite relation between smoke and health has, up to the present time, been shown to exist, and no attempt was made in the present study to investigate this phase of the subject, on account of the complexity of the problem and the limited amount of time and money available.”[32] Researchers continued to investigate the link. The main constraints were data and computation. Researchers needed access to detailed and accurate particulate and mortality data. They also had to wait for the development of powerful computers and appropriate statistical techniques to process the data.

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[31] http://www.cdc.gov/mmwr/preview/mmwrhtml/mm4843a2.htm

[32] Ives et al (1936), p. 1.

Despite the efforts of earlier researchers, it was not until the 1990s that the epidemiological literature convincingly documented the link between airborne particulates and mortality.[33][34] The studies use different measures of particulates and different samples. Measures include total suspended particulates (TSP), which are particles less than 25-45 microns, particulates less than 10 microns (PM_{10}), and particulates less than 2.5 microns ($PM_{2.5}$). In the United States, the main samples have been the Harvard Six Cities Sample (Laden et al 2006) and the American Cancer Society Cancer Prevention II study (Pope et al 2002). The studies began in the late 1970s and early 1980s, respectively. Their findings are based on tracking of sample participants, all of whom were adults when they entered the studies. The main outcome measure is all-age mortality, although the studies also track cause of death data. The reason the studies focus on all-age mortality is that cause of death is often subjective and attributions of cause of death may change over time.

Interestingly, most early studies controlled for smoking but did not directly examine the relationship between particulates from smoking and particulates from other air pollution sources. Recent epidemiological studies such as Pope et al (2011) indicate that the dose-response curve between particulates and mortality from cardiovascular disease is highly non-linear. At small exposures (less than 1 cigarette per day, which is the range in which most air pollution occurs) the marginal effects are large, while at high exposures (13+ cigarettes per day) the marginal

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[33] The studies examine mortality from particulate exposure at different frequencies, daily, monthly, and annually. One concern with the high frequency studies is that pollution is merely shifting the timing of mortality, but not affecting all-age mortality. While shifts in the timing, known as 'harvesting', are occurring for some individuals, the studies find that exposure to particulates also increases all-age mortality (Schwartz 2000, Pope et al 2009).

[34] Most of the discussion that follows will focus on particulates, since most of the early measurement of air pollution involved particulates, and most of the epidemiological work has been done on particulates. Particulates are highly correlated with other coal-related emissions such as carbon monoxide and sulfur dioxide. Some recent studies that use detailed monitor data are able to separately examine the effects of particulate, carbon monoxide, and sulfur dioxide on mortality. Monitor data is not widely available before the 1970s, so our analysis examines the effect of coal consumption on mortality directly.

effects are lower. Further, the available evidence suggests that increases in air pollution have positive effects on the mortality of never-smokers, former smokers, and current smokers (Pope et al 2004).

More recent studies using quasi-natural experiments also find strong links between particulates and mortality. Chay and Greenstone (2003a, 2003b), Currie and Neidell (2005), and Currie and Walker (2011) exploit permanent declines in pollution to measure the effects on infant mortality in the U.S. in the late 20th century. Epidemiological studies use quasi-natural experiments created by the shutdown of power plants and policy changes regarding the burning of coal.[35] Other papers utilize temporal or seasonal variation in pollution that are not permanent. Currie, Neidell, and Schmeider (2009) have very detailed data on pollution exposure of pregnant mothers, which varies over time and space, and subsequent mortality of infants. Most mothers are observed once, but a subset is observed more than once. These mothers almost always have different pollution exposures for different births. Knittel, Miller, and Sanders (2012) examine the effect of temporal changes in pollution caused by traffic shocks. Arceo-Gomez, Hanna, Oliva (2012) use a similar strategy to examine the link in Mexico. Clay and Troesken (2010) link variation in weather-related smogs to all-age mortality in London.

Research by Pope et al (2004) and DelFino et al (2005) suggest that particulates cause mortality in the adult population through three main mechanisms. The first is that particulates cause pulmonary and systemic inflammation and accelerated atherosclerosis. The second is that particulates adversely affect cardiac autonomic function, causing heart arrhythmias. The third, but less important, mechanism is through pneumonia.[36]

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[35] See Pope et al (1992), Clancy et al (2002), Hedley et al (2002), and Pope et al (2007).

[36] For a thorough and detailed discussion of the mechanisms for adults and children, see Lockwood (2012).

For infants, particulates cause mortality population through two main mechanisms. The first is prenatal. Curry and Walker (2011) use a natural experiment caused by the replacement of manual tolling with EZ Pass, which greatly reduced idling and local pollution. Their results show that higher levels of particulates were associated with greater likelihood of premature delivery and birth weight. Prenatal impacts are likely to be particularly important for much of our sample period, because successful interventions to help premature or low birth weight babies were extremely limited before 1959. The second mechanism is postnatal effects on respiratory and cardiovascular outcomes. Woodruff et al (2008) used U.S. infant birth and death records covering 1999-2002, demographic characteristics, and pollution data. They find a link between particulates and respiratory-related infant mortality. Recent work by Arceo-Gomez et al (2012) using data from Mexico supports the link between pollution and infant mortality from respiratory or cardio-vascular causes.

4. Data

Data on all-age and infant mortality at the state-year and state-month level are taken from the annual *Vital Statistics* volumes. States enter the National Center for Health Statistics sample of “registration states” slowly over time. Although all-age mortality reporting at the annual level began in 1900, the reporting of all-age mortality at the state-month level began in 1910, the report of infant mortality relative to live births began in 1915, and reporting of infant mortality by state-month began in 1939.[37]

Mortality rates were constructed using historical population estimates from the Decennial Censuses. These population estimates were linearly interpolated to construct state-year population estimates. Infant monthly mortality rates were constructed by dividing the monthly

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[37] There were 19 registration states (including the District of Columbia) in 1910, 34 registration states in 1920, and 49 registration states, the 48 continental states plus the District of Columbia, in 1933.

death counts by annual state-level birth data from 1940-1959.[38] Infant mortality rates are reported per 100,000 live births. Our dependent variable is the log of the all-age or infant mortality rate. Our results are robust to using the mortality rate in levels.

Heating degree days and other climatic data are from the United States Historical Climatology Network (USHCN) Daily Dataset.[39] Available weather variables include daily minimum and maximum temperature and total daily rainfall. Daily mean temperatures are the simple average of the minimum and maximum temperatures. The daily weather-station data is aggregated to the state-month level using population-distance weights.[40] The temperatures are used to construct "degree day" variables. We follow the convention and use heating-degree days with a base of 65 degrees Fahrenheit. A temperature of T would have heating degree days (HDD) with a base of 65 of 65-T for all values of T *less than* 65 and zero otherwise.

Fuel consumption data by use is from the *Historic Emissions of Sulfur and Nitrogen Oxides in the United States from 1900 to 1980.*[41] Gschwandtner et al (1983) constructed state-level estimates of coal use by type at 5 year intervals for 1900-1980 for the purpose of constructing estimates historic emissions of sulfur and nitrogen oxides.[42] An annual series of

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[38] Birth data were collected from Vital Statistics by Amy Finkelstein and Heidi Williams and are available from the NBER website.

[39] The USHCN data covers the period from the late 19th century to the present. The data set is comprised of approximately 1,200 weather stations, which were selected by the Department of Energy and the NCDC based on "length of record, percent of missing data, number of station moves and other station changes that may affect data homogeneity." This procedure involves three steps. The distance between each weather station and each county centroid is calculated for those weather stations that are within 50 miles of the county centroid. The variables are aggregated to the county-month level using inverse-distance weights. The county-month weather variables are aggregated to the state-month level using the county populations as weights. The county population data are from the decennial censuses and are linearly interpolated between census years.

[40] Humidity is not available for this period. Humidity is likely to be an important determinant of mortality (Barreca 2012). However, humidity and temperature are strongly correlated in nature. So long as humidity's independent effect on mortality is uncorrelated with state-year coal consumption then our results will be unbiased. That is, the temperature main effect includes humidity's impact.

[41] For more detail, see Chapter 2 of Gschwandtner et al (1983).

[42] For 1900-1945, estimates of state-level consumption were created by assigning state shares by use, which were available in 1889, 1917, 1927, and 1957, to national annual estimates by use from *Resources of the United States*

national coal use by type is available beginning in 1933 from *Minerals Yearbook*. Some specifications use this series.

Some specifications control for state annual per capita income. The data come from the U.S. Bureau of Economic Analysis and cover the years from 1929 to present. All income has been converted to real 2010$.

Table 2 presents summary statistics for high and low coal states, where high coal is defined as consuming more than one ton per capita for heating purposes. For the period 1920-1939, high and low coal states have different average heating degree days and bituminous coal consumption, but quite similar incomes, infant mortality, and all-age mortality.

5. Identification

Our hypothesis is that heavy-coal use states experienced a decline in mortality subsequent to 1945 relative to other states. To test this hypothesis, the following difference-in-differences model is estimated:

$$(1)\quad MORT_{sy} = \beta_1\, COAL20_s \text{ x } POST45_y + \eta_y + \theta_s + \lambda_s\, YEAR + \boldsymbol{\gamma}\, X_{sy} + \varepsilon_{smy}$$

where MORT is the log of the mortality rate (or log of the infant mortality rate) in state s in year y; COAL20 is the estimated bituminous coal consumption in state s in 1920; and POST45 is an indicator for whether year y is after 1945. Year fixed effects (η) mitigate biases from secular improvements in health conditions that occurred over time. State fixed effects (θ) account for fixed differences in mortality that are related to baseline coal consumption. State-specific trends mitigate bias from convergence in mortality rates that might be correlated with baseline coal

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and later *Mineral Yearbooks* to get state estimates by use at 5 year intervals. For the period 1950-1960, additional data was available that allowed improvement of the 1950, 1955, and 1960 estimates. The 1889 data is from Census of Manufacturing (1889). The 1917 data is from Lesher (1917). The 1927 data is from Tryon and Rogers (1927). The 1957 data is from U.S. Bureau of Mines (1957). For railroads, the data are from 1889, 1917, 1937 and 1947. The 1889 data is from the Census of Manufacturing. The 1917 data is from the U.S. Bureau of Railways (1917). The 1937 and 1947 for railroads are from *Minerals Yearbook*.

consumption. The error term (ε) is clustered at the state-level to account for time series correlation within states. All observations are weighted by the state-year population.[43]

Equation (1) assumes a discrete change in mortality subsequent to 1945 for the heavy-coal use states. In our preferred specification, mortality is allowed to decline linearly subsequent to 1945 depending on the level of treatment. Specifically, β_2 COAL20$_s$ x POST45$_y$ x YEAR is included in equation (1) above. As can be seen in Figure 2b, bituminous coal consumption peaked around 1945, then declined gradually. In addition, allowing for the treatment effect to increase over time potentially better captures the cumulative exposure to better air quality.

Figure 9 provides a graphic illustration of our identification strategy. Specifically, the average mortality rates over time are plotted by level of coal use in 1920. That is, states are assigned to be high (low) coal use if they have greater (less) than one ton per capita bituminous coal consumption in 1920. Panel A shows the raw data and Panel B shows the regression adjusted data. As Panel A illustrates, low coal states had a fairly stable decline between 1920 and 1955. However, high coal states had a relatively modest decline prior to 1942, a spike in mortality between 1942 and 1945, and then a steep decline subsequent to 1945. The differential mortality pattern in high coal states correspond to changes in coal consumption observed in Figure 2b.

The identifying variation in our model comes from changes over time in heavy-coal use states relative to other states. The model assumes that that the differences between heavy-coal use states and other states do not predict within-state changes in mortality after 1945 for reasons unrelated to coal use.

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[43] The unweighted estimates are qualitatively similar (results available upon request).

To assess the validity of this assumption, we add two sets of controls that are plausibly related to coal consumption in 1920. First, average annual heating degree days interacted with year dummy variables are added. Figure 10 Panel A shows that coal consumption was low in warmer states, even Appalachian states that are very close to coal reserves. Coal consumption was also highly variable in colder states. Some states were near bituminous coal deposits and used coal extensively, while other states were far from bituminous and used wood or anthracite instead. The inclusion of these controls allows us to flexibly control for changes in health conditions in cold states that are unrelated to changes in bituminous coal consumption. Second, average income in 1929 interacted with year dummy variables is added.[44] Figure 10 Panel B demonstrates that there is generally a weak correlation between income and bituminous coal consumption in the baseline period. Inclusion of these controls is unlikely to affect the estimates, although their precision may improve.

Equation (1) is supplemented with a triple differences model to account for potential time-variant unobservable variables in heavy-coal use states that are unrelated to baseline coal consumption. To apply this approach, we exploit the fact that heating (and coal consumption) is higher during winter months (Figure 3). Provided the mortality lag after exposure is within a short time frame, warmer months can be used as a second control group. Specifically, the following model is estimated:

$$(2)\quad MORT_{smy} = \beta_1\ COAL20_s \text{ x } WINT_m \text{ x } POST45_y + \beta_2\ COAL20_s \text{ x } POST45_y + \theta_{sm} + \eta_{my} + \lambda_s\ YEAR + \gamma\ X_{sym} + \varepsilon_{smy}$$

where MORT is now the log of the mortality rate in month m of year y in state s; WINT is an indicator for whether month m is between November and March (inclusive); θ_{sm} is a vector of

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[44] Income data are from the Bureau of Economic Analysis and 1929 is the first available year.

state-month fixed effects that account for the possibility that the seasonal mortality relationship is difference across states in a way that is related to baseline coal consumption; η_{my} are year-month fixed effects to control for secular improvements in health; and λ_s is a state specific linear time trend to account for potential convergence in health outcomes across states and seasons that may be spuriously correlated with baseline coal use. Note that our treatment window is larger than traditionally defined winters. This approach is used, because there may be a short-term lag in mortality effects of coal exposure. One data limitation with this strategy is that infant mortality statistics by month and state begin in 1939.

The identifying variation in this model comes from differences over time in winter months in states with estimated high baseline coal use and use the non-winter months interacted with baseline coal use as additional controls (i.e. β_2). To the extent that reductions in coal consumption reduced summer time mortality, then this approach will underestimate the effects of coal on mortality. However, this model has the advantage of allowing us to control for idiosyncratic changes in year-round health in the treated states that may be spuriously correlated with time and baseline coal consumption.

As a simple illustration of our identification strategy, Figure 11 plots changes in the seasonal mortality relationship in states with relatively high coal usage in the baseline period. Specifically, states are classified as “high coal use” if per capita consumption is greater than one ton in 1920. As can be seen, the fall in mortality was much greater in the high coal states in the colder months than in the summer months. In low coal states, the fall in mortality was large in the winter and the summer months.

6. Results

Table 3 examines the relationships between annual coal use in 1920 and annual all-age and infant mortality before and after 1945. In column 1 of the top panel, the coefficient on COAL1920 x POST-1945 is negative and statistically significant. All-age mortality fell proportionate to coal consumption after 1945. In columns 2-5 the coefficient on COAL1920 x POST-1945 x YEAR is negative, statistically significant, and large across a variety of specifications. A state with per capita bituminous consumption for heating of 1 ton in 1920 had declines in mortality of 0.40-0.63 percent per year. In the bottom panel the effects for infant mortality are generally not significant and vary with the specification.

Table 4 replicates column 2 of Table 3 for a variety of data samples. The results are very similar to the results in column 2. The coefficient on COAL1920 x POST-1945 x YEAR is negative and statistically significant for all-age mortality and negative but not statistically significant for infant mortality.

One concern regarding Tables 3 and 4 is that the coefficient on COAL1920 may be capturing the effects of other omitted variables. One candidate is the use of bituminous coal in industry, electricity, and transportation. These are likely to be correlated with COAL1920. Other unobserved factors associated with health may also be correlated with COAL1920.

To address these concerns, Table 5 presents the results of the triple difference estimation. In columns 1-4 for all-age mortality, states with high coal consumption experienced statistically significantly larger declines in all-age mortality after 1945. In columns 1 and 2, the coefficient on COAL1920 x POST1945 is negative and significant, and in columns 3 and 4, the COAL1920 x POST1945 is negative and significant. This is consistent with Tables 3 and 4. The coefficients on WINTER x COAL1920 x POST1945 and WINTER x COAL1920 x POST1945 x YEAR are not statistically significant for all-age mortality. This suggests that the reductions in mortality were not disproportionately in the winter.

In columns 1-4 for infant mortality, states with high coal consumption experienced statistically significantly larger declines in winter mortality after 1945, which is consistent with coal-related pollution causing the mortality. The results suggest that in a state with per capita consumption of 1 ton, infant winter mortality fell 2.9-3.7 percent.

Using COAL1920 as the primary measure of coal has advantages and disadvantages. It is plausibly exogenous, which is attractive. At the same time, it does not very accurately capture the temporal variation in bituminous coal consumption observed in Figure 2b. Either COAL1920 is allowed to shift in 1945 (columns 1 and 2) or it is allowed to shift in 1945 and trend after 1945 (columns 3 and 4). Annual series of national coal consumption by use begin in 1933. A variable RETAIL is constructed by multiplying the 1920 state shares of national consumption by national retail coal consumption. Retail coal is predominantly used for heating residences and commercial buildings such as stores and office buildings.

Table 6 presents the results of the difference-in-differences using the RETAIL measure of coal. The patterns are generally similar to the patterns in Tables 2 and 3. Namely, the relationship between RETAIL and all age mortality is generally positive and statistically significant. The relationship between RETAIL and infant mortality is generally insignificant or even in column 4 negative and statistically significant.

Table 7 presents the results of the triple difference using the RETAIL measure of coal. The coefficients on WINTER x RETAIL are positive and statistically significant in 7 of the 8 specifications, suggesting that coal consumption was causally related to mortality. The coefficient on WINTER x RETAIL in the top panel suggests that a state with a decline in bituminous coal consumption between 1945 and 1959 of 1 ton per capita experienced a statistically significant decline in winter all-age mortality of 0.013-0.020. The coefficient on WINTER x RETAIL in the bottom panel suggests that a state with a similar decline experienced a statistically significant decline in winter infant mortality of 0.029-0.055.

Table 8 shows the effects nationally and by region, since some regions experienced much bigger declines in bituminous coal consumption than others. At the national level, winter all-age mortality fell 1.36 percent and winter infant mortality fell 2.36 percent. To contextualize the magnitudes, national winter all-age mortality fell 9.9 percent over the period 1945-1959 and infant morality fell 33.4 percent. In the Midwest, the estimated declines were substantially larger, 2.5 percent for all-age mortality and 4.4 percent for infant mortality. In the Northeast, where bituminous coal was not widely used, the declines were 0.6 percent for all-age mortality and 1.1 percent for infant mortality.

To get a clearer sense of the meaning of the magnitudes, it is also helpful to look at the related literature. Arceo-Gomez, Hanna, and Oliva (2012) present a table, which is reproduced in Table 9, showing the elasticities for particulate matter (PM_{10}) and infant mortality. Unfortunately, the measurement of particulates in the U.S. in the 1920-1959 period was very limited. Our back of the envelope estimate is that a reduction in consumption of bituminous coal for heating would yield a decline of 11-35 percent in winter particulates. The 11 percent estimate reflects the fact that bituminous coal for heating fell from 22 to 11 percent of bituminous coal between 1945 and 1959. The 35 percent estimate assumes that all of the increase winter particulates in the 1931-1933 study of pollution in large American cities was due to the use of coal for heating. The implied elasticity for winter infant mortality is fairly small relative to contemporary estimates: 0.067-0.214. In comparison, the elasticity for Mexico, where particulate levels were relatively high, was estimated to be approximately 0.325-0.415.

Our estimates are lower than the two other papers with high levels of PM10 and infant mortality (Arceo-Gomez et al 2012, Chay and Greenstone 2003a) largely due to the historical context. In our context, baseline infant mortality was high, and much of this mortality was from the deaths of premature or low birth weight babies. The share of babies dying from pollution was relatively low. In the later studies, the share of babies dying from pollution was higher, at least in part because of improvements in interventions that prevented the death of premature or low birth weight babies, which in turn lowered the baseline mortality rate.

Although the elasticities are low, the number of infant lives saved is large. For example, a 2.36 percent decline from an average infant mortality rate of 3,367 would result in a saving of 79 infants per 100,000 live births for 5 months out of every year or roughly 33 per 100,000 on an annual basis. For comparison in 2010, infant mortality from all causes was 615 per 100,000. Live births ranged from 2.9 million in 1945 to 4.3 million in 1959. A rough estimate suggests that for 3 million births, reducing coal-related air pollution from home heating saved about 1,000 infants per year.[45]

7. Conclusion

This paper found that the use of coal for home heating increased mortality during the period 1920-1959. Our regression results imply that reductions in the use of bituminous coal between 1945 and 1959 decreased winter all-age mortality by 1.36 percent and winter infant mortality by 2.36 percent. Our estimate is likely a lower bound, since it primarily captures short-run relationships between coal and mortality. For example, if exposure to pollution weakened

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[45] (79*30)*(5/12) = 988

population health, but affected individuals died in the summer from winter exposure, the triple difference approach would not capture their mortality.

If developing countries lower their pollution levels – as the United States did in the 1940s and 1950s – what types of declines in mortality would they experience? Needless to say, any answer would be highly speculative. In the United States context, the decline in consumption of bituminous coal for home heating between 1945 and 1959 accounted for a modest share of the decline in winter all-age mortality and a small share of the decline in winter infant mortality over the same time period. How this will translate into the developing world will depend on the baseline levels of all-age and infant mortality. For example, if infant mortality at or below the level of Mexico in the contemporary period, the realized elasticity may be higher than in the United States.   If infant mortality is closer to the level of the United States in 1945-1959, the realized elasticity may be low.

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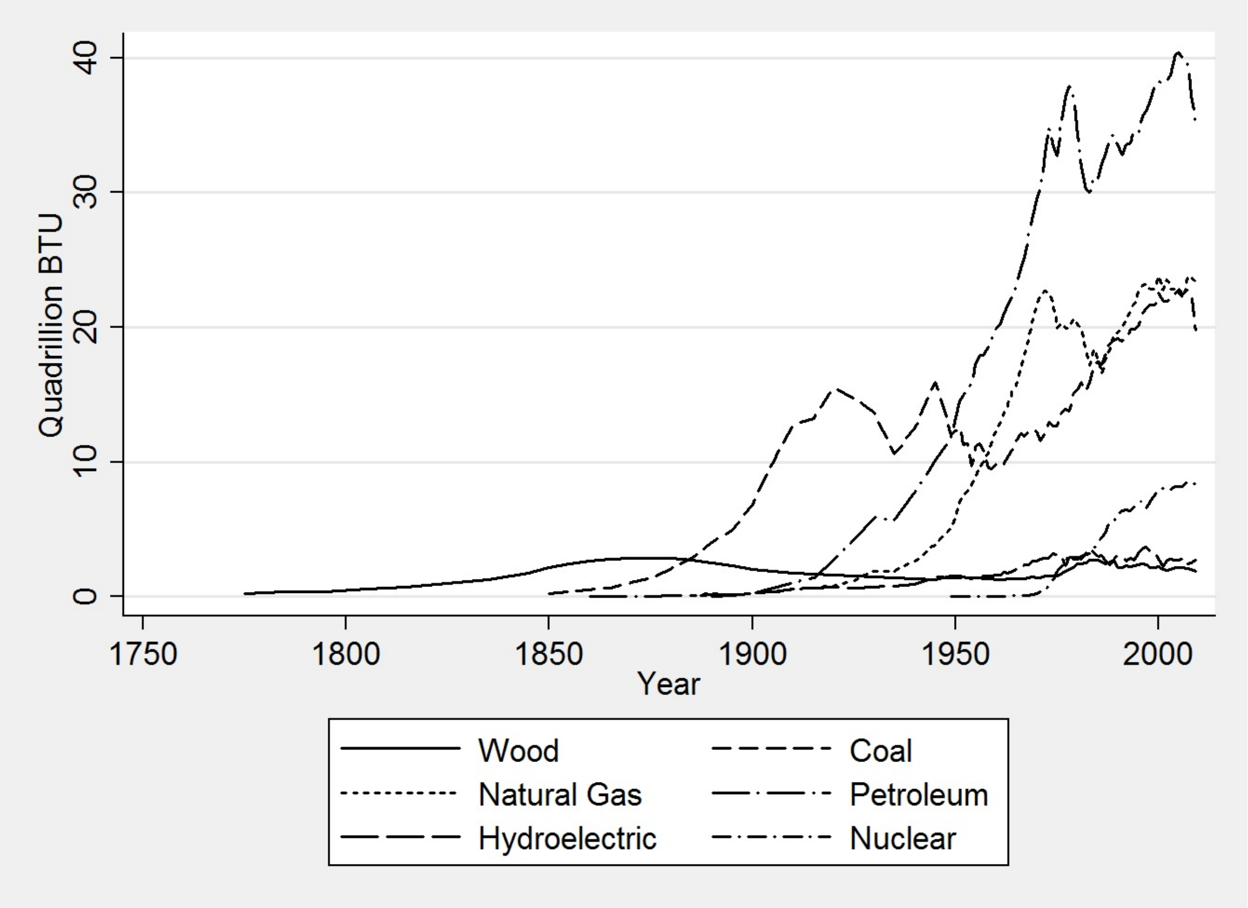
Figure 1: Energy Consumption in the U.S. Economy by Source, 1775-2009



Notes: Created from U.S. Energy Administration, History of Energy Consumption in the United States 1775-2009. http://www.eia.gov/todayinenergy/detail.cfm?id=10

Figure 2a: Per Capital Coal Consumption, Total

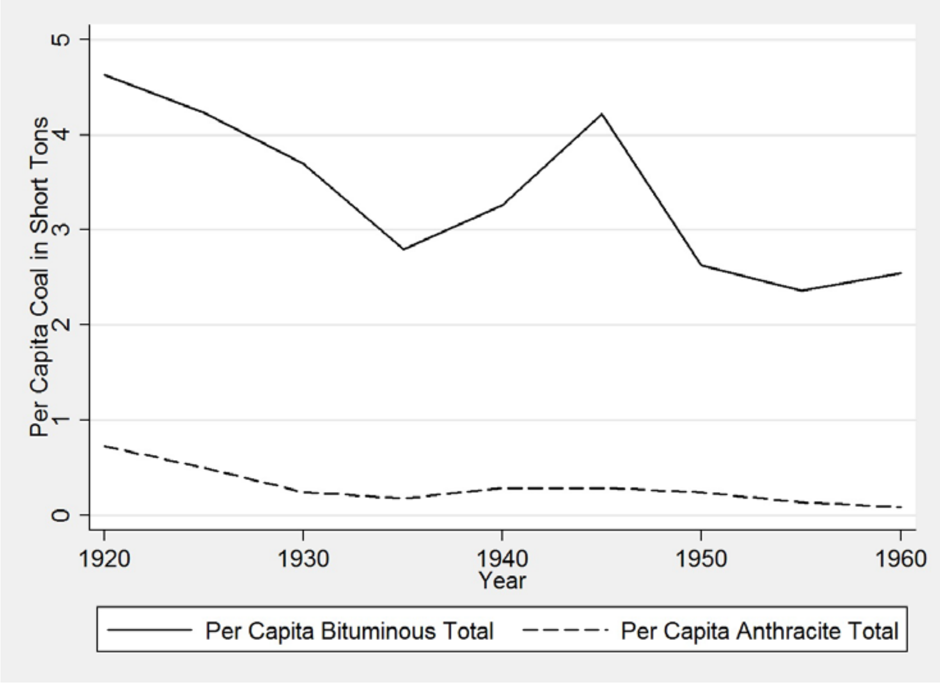


Figure 2b: Per Capita Consumption of Coal for Heating

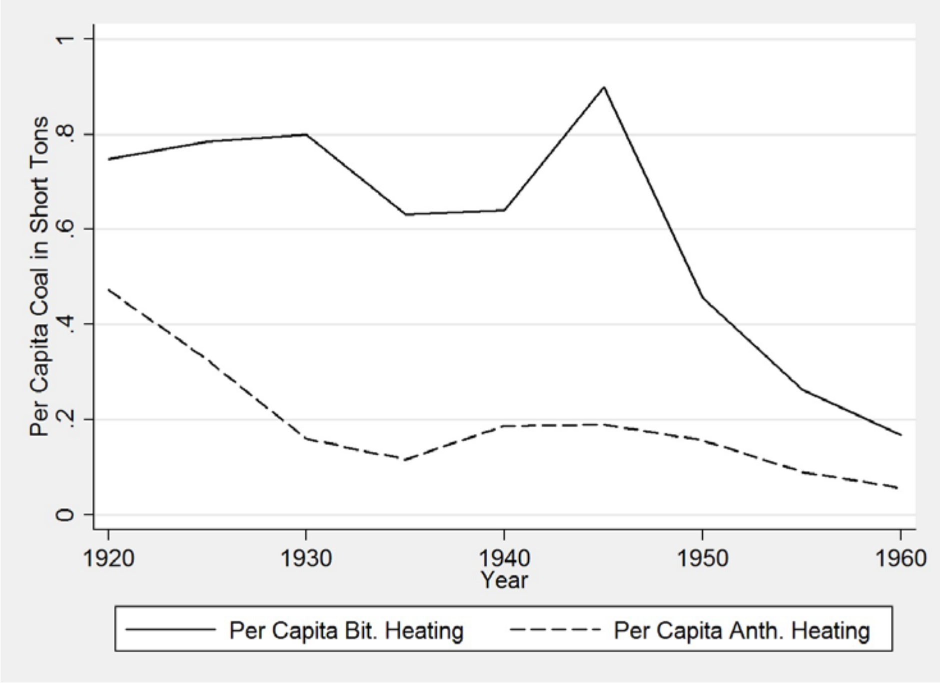
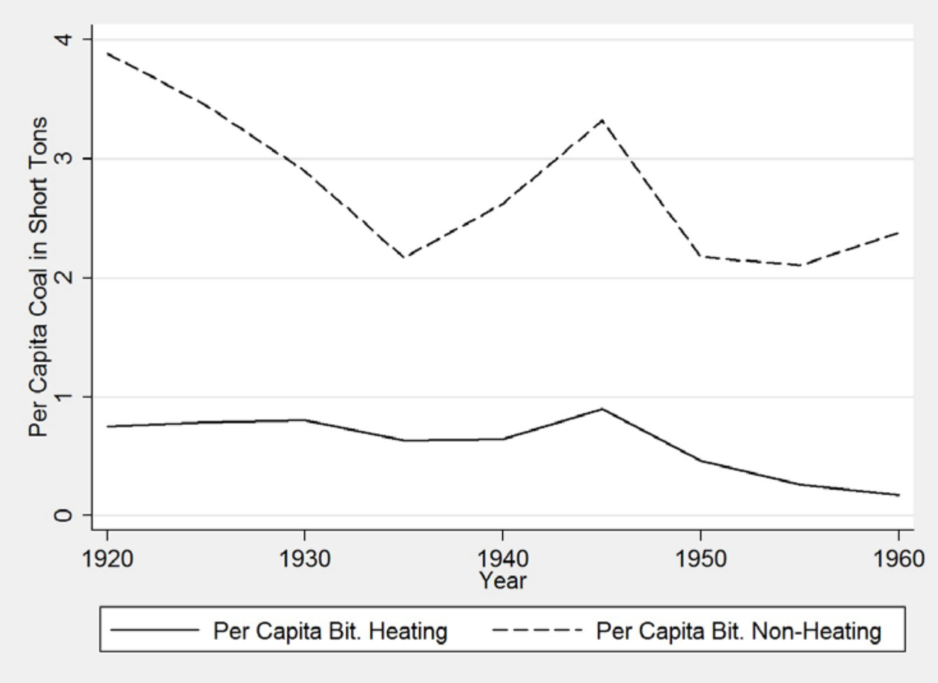
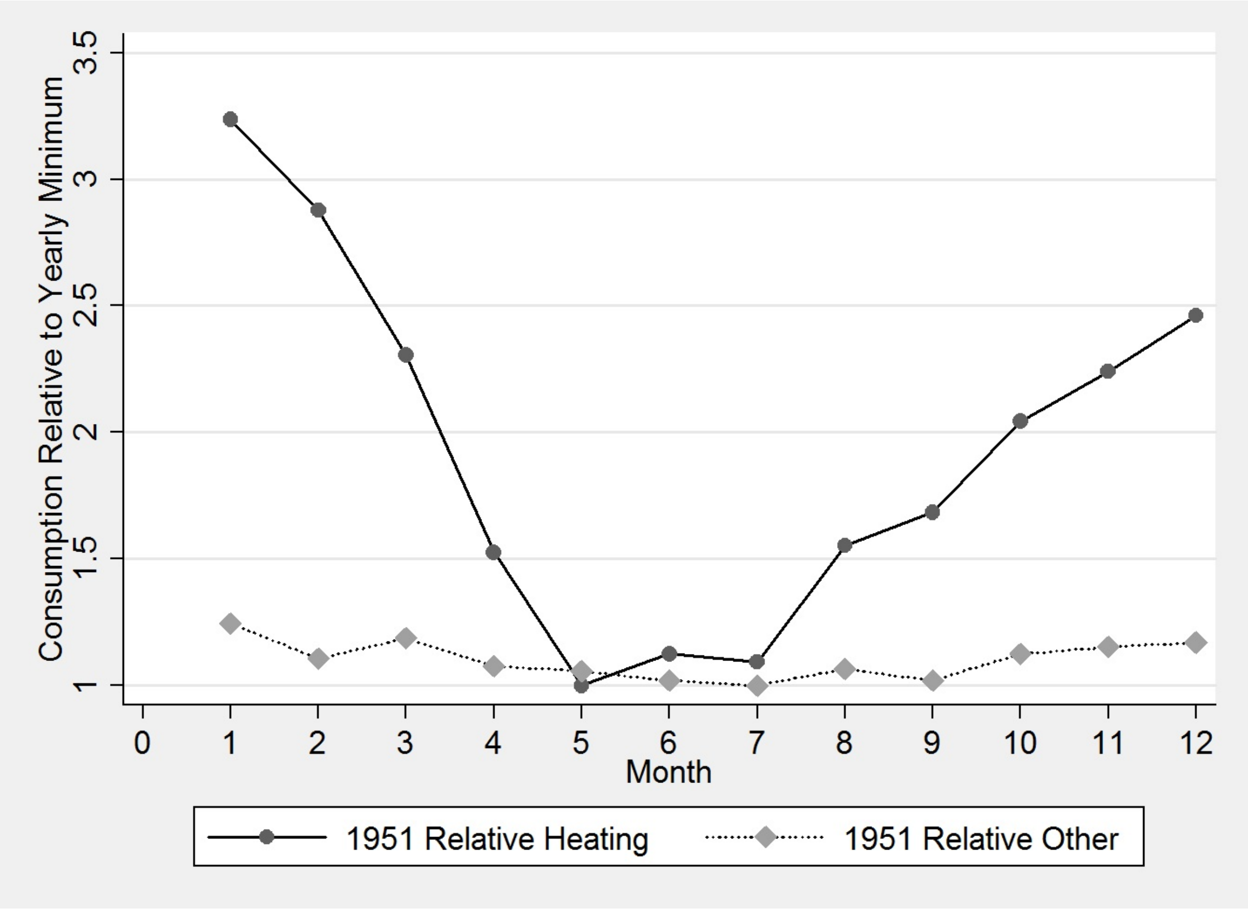


Figure 2c: Per Capita Consumption of Bituminous Coal by Use



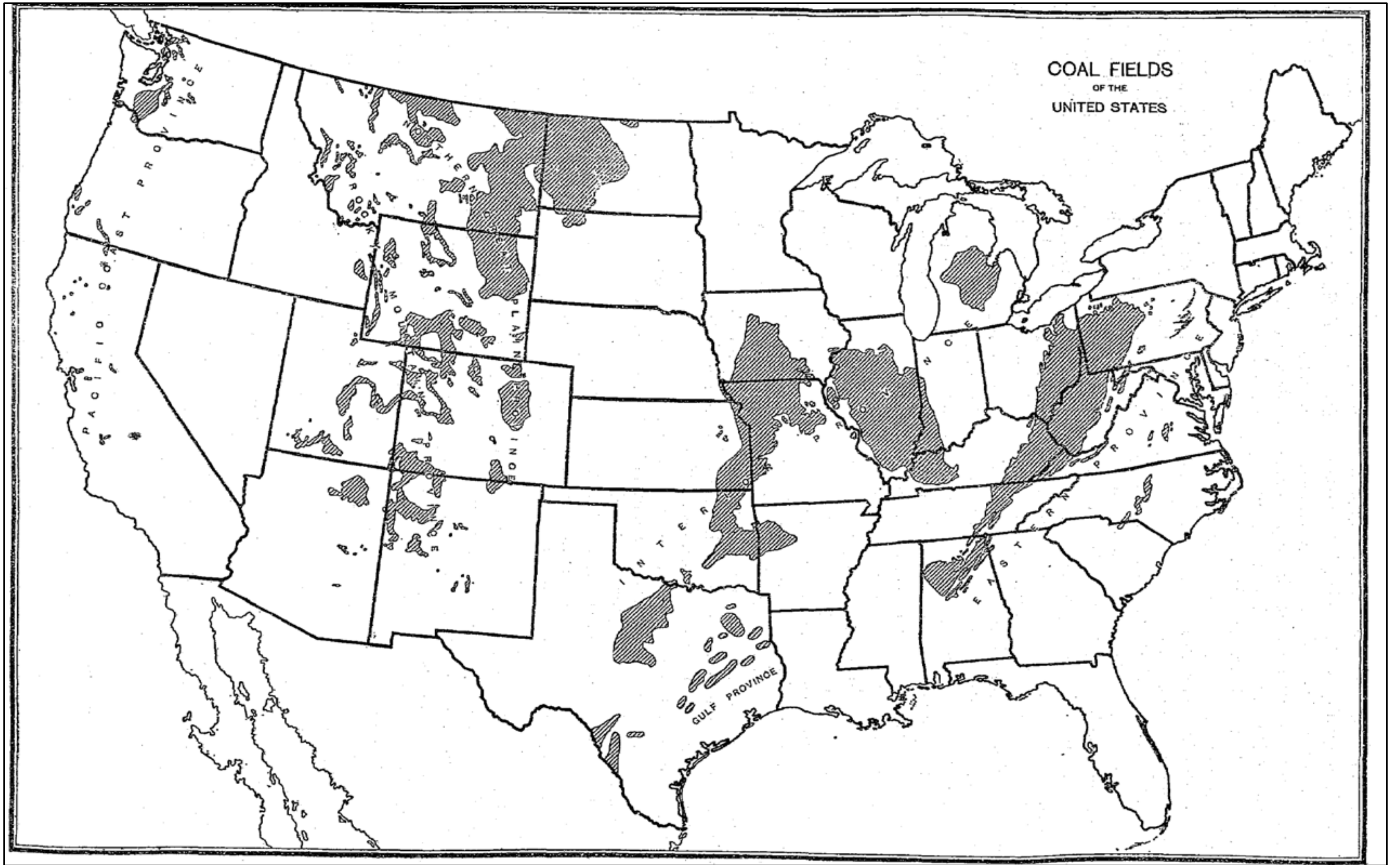
Notes: Values for bituminous and anthracite are from the *Historical Emissions Report* and are interpolated for years not ending in 0 or 5. National population values are from the Decennial Censuses and are interpolated for years not ending in 0. Sales of anthracite coal by use are not available until the 1950s. Estimates in the mid 1920s suggested that 65 percent of anthracite was being used for heating. Department of Commerce (1929), p. 6. The series in Figure 2c uses this 65 percent estimate.

Figure 3: Seasonality of Heating and Other Coal Consumption in 1951



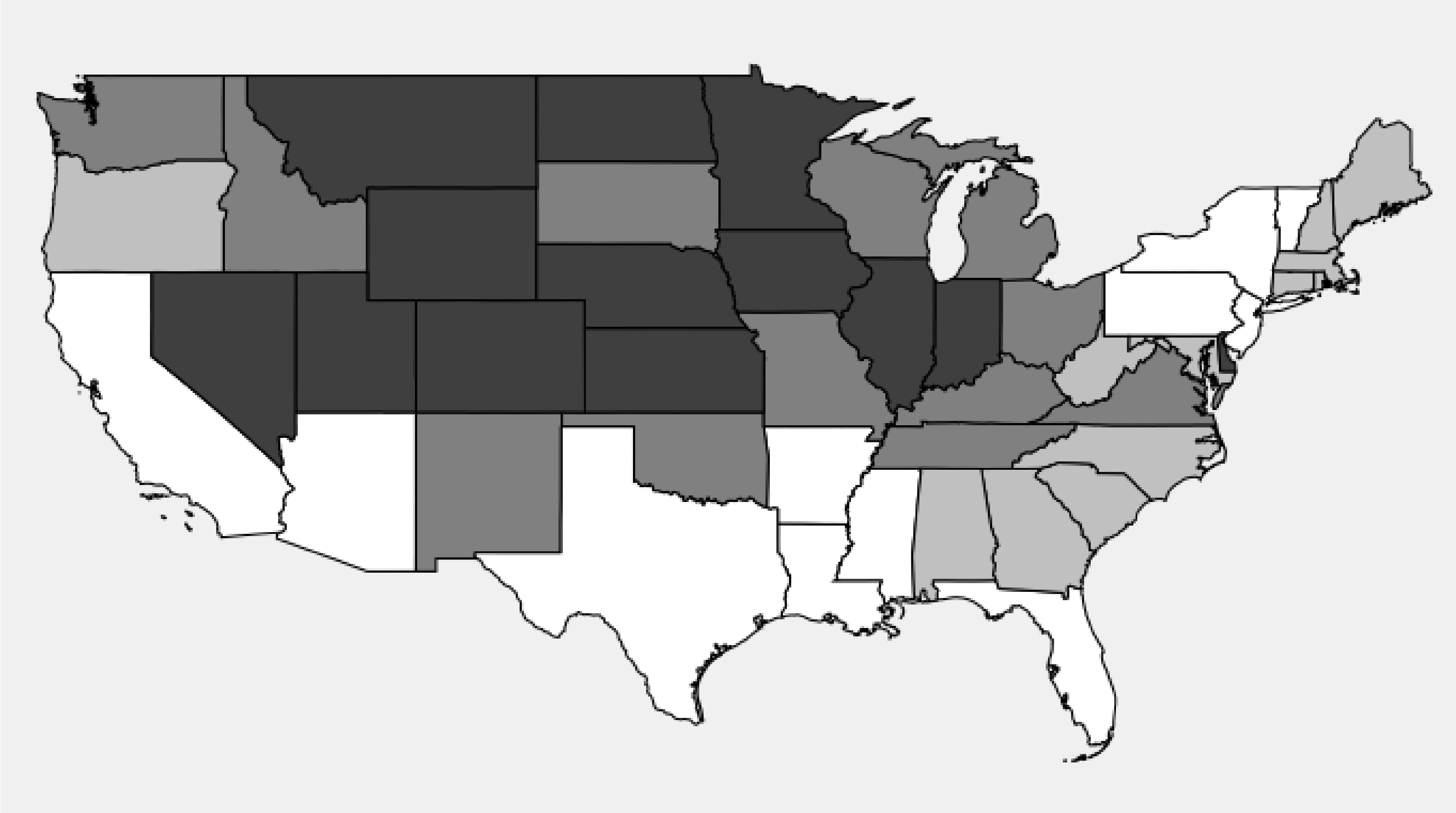
Source: *Minerals Yearbook* 1952. Other coal consumption includes bituminous coal used for electricity, industry, coke, and railroads.

Figure 4: Coal Fields of the United States



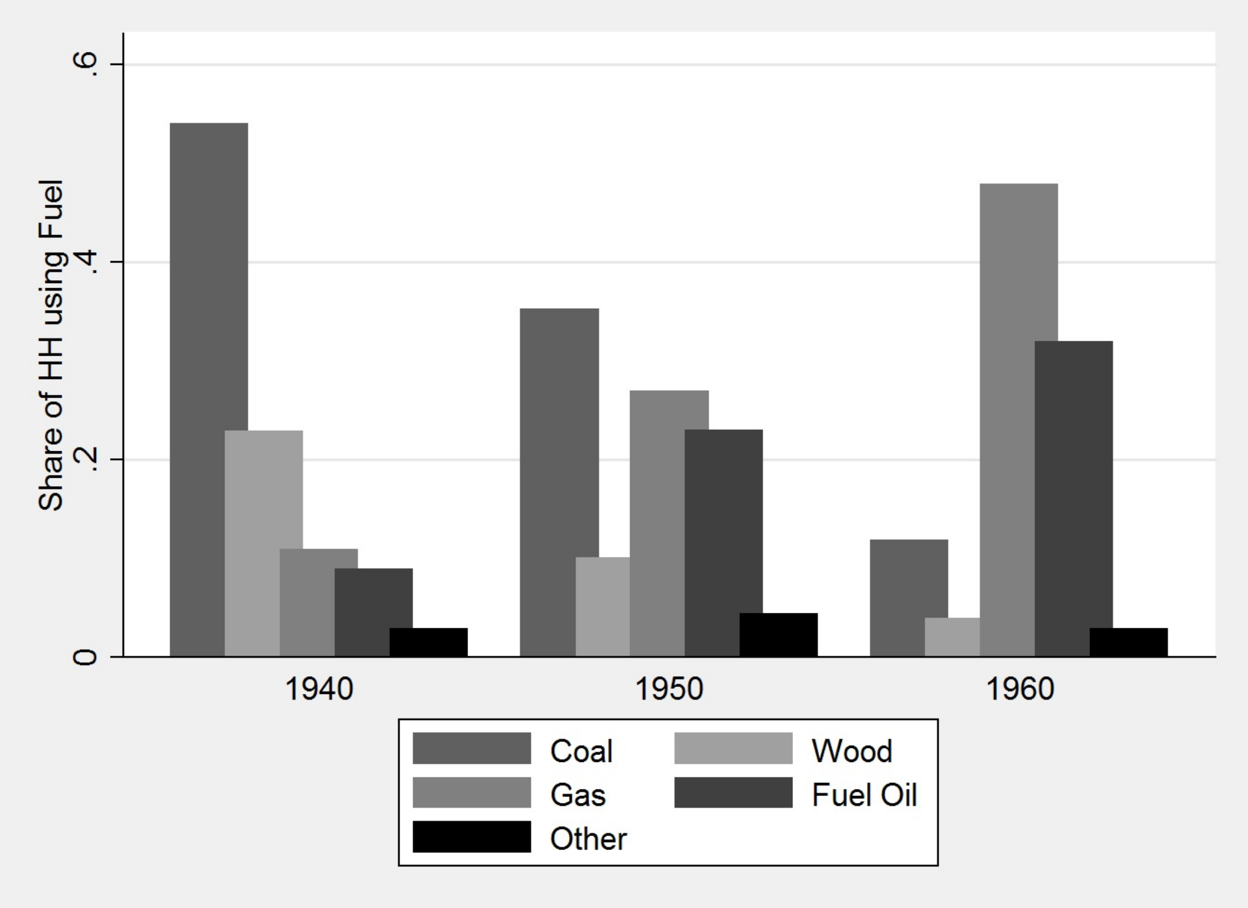
Notes: From *Fourteenth Census of the United States, Volume XI Mines and Quarries, 1919, General Report and Analytical Tables and Selected Industries*, p. 254. http://www2.census.gov/prod2/decennial/documents/23010460v11ch4.pdf

Figure 5: Quartile of Per Capita Bituminous Consumption for Heating in 1920



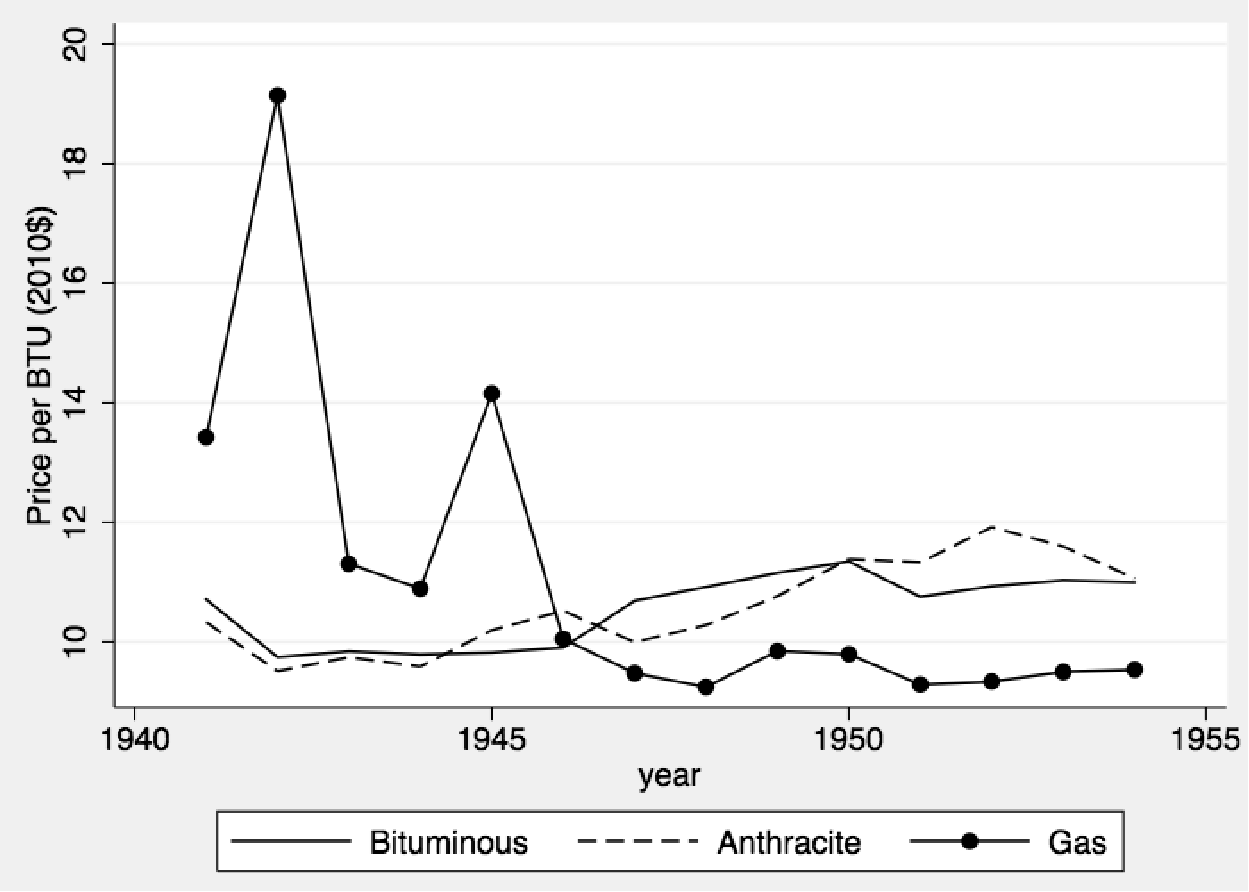
Notes: States were grouped into quartiles, with the shading ranges from lightest (Q1) to darkest (Q4).

Figure 6: Household Heating Fuels in 1940, 1950, and 1960



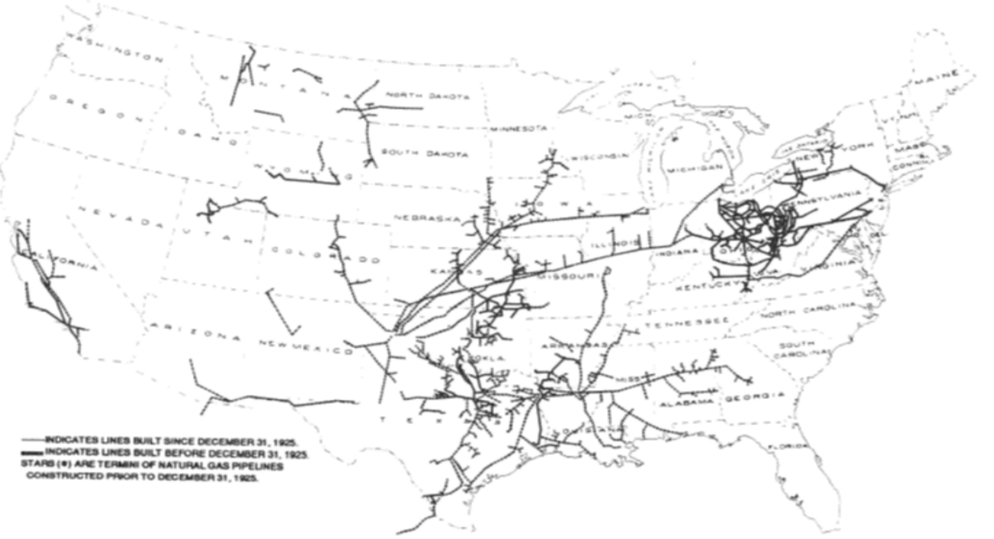
Source: *1940, 1950, 1960 Censuses of Housing*.
Notes: For 1940, Table 60, p. 101 available at http://www2.census.gov/prod2/decennial/documents/36911485v2p1ch1.pdf . For 1950, Table 20, pp. 1-26 available at http://www2.census.gov/prod2/decennial/documents/36965082v1p1ch1.pdf . For 1960, Table 7, pp. 1-29-1-33 available at: http://www2.census.gov/prod2/decennial/documents/41962442v1p1ch04.pdf . Other includes households with electrical (baseboard) heat and no heat.

Figure 7: December Price of Bituminous Coal, Anthracite Coal, and Gas in 20 Cities



Source: *Historical Statistics of the American Gas Association*, Table 231, p. 3
Notes: Prices are in cents per million BTU. The following 20 cities are in the sample: Atlanta, Baltimore, Boston, Chicago, Cincinnati, Cleveland, Detroit, Houston, Kansas City, Los Angeles, Minneapolis, New York, Philadelphia, Pittsburgh, Portland, San Francisco, Scranton, Seattle, St. Louis, Washington DC.

Figure 8: Natural Gas Pipelines in 1940 and 1949



Principal natural gas pipeline systems in the United States, 1940. Source: Federal Trade Commission Monograph no. 36 on Natural Gas Pipelines in USA. Published as Temporary National Economic Committee R[illegible]rt no. 76-3 (Senate Committee Print). Washington, DC: U.S. Government Printing Office, 1940.

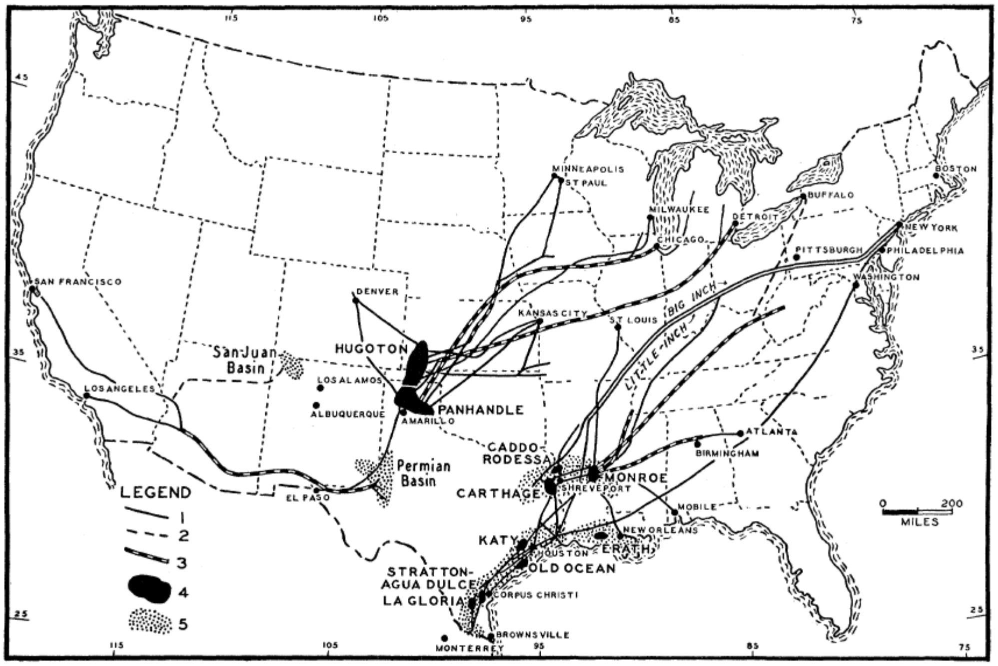
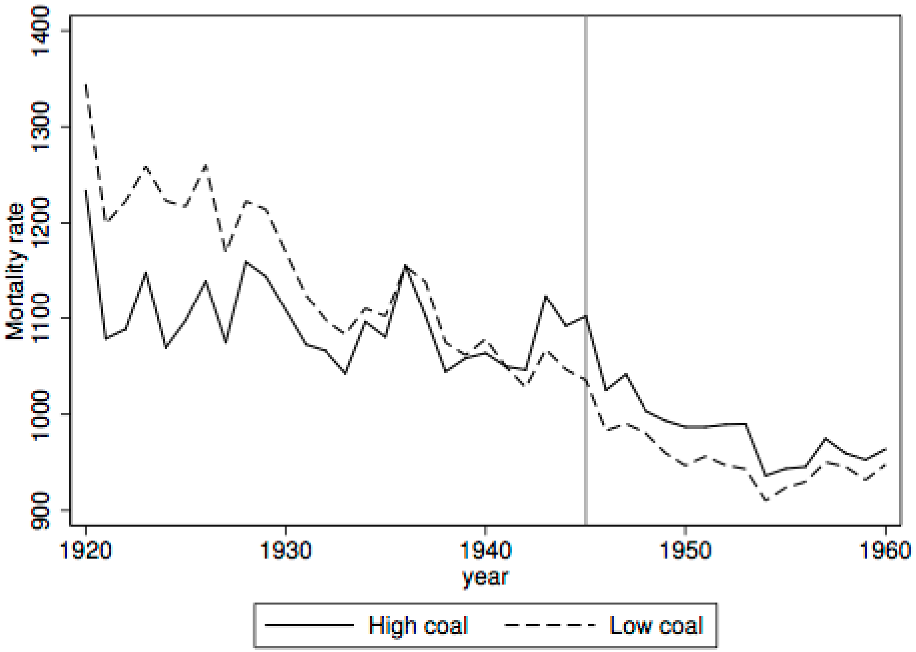


FIG. 1. Major interstate gas pipe lines in the United States, 1949. Legend: 1, pipe lines of 16-inch diameter or more originating in Mid-Continent and Gulf Coast areas; 2, pipe lines proposed or authorized; 3, double pipe lines; 4, principal gas fields; 5, other areas of scattered production supplying major interstate transmission lines.

Notes: 1940 Map: Federal Trade Commission Monograph no. 36 on Natural Gas Pipelines in the United States. Reproduced in Castaneda (1993) p. 19. 1949 Map: Parsons (1950), p. 165.

Figure 9: Mortality Rates For High-Coal And Low-Coal States

Panel A: Raw data



Panel B: Regression adjusted

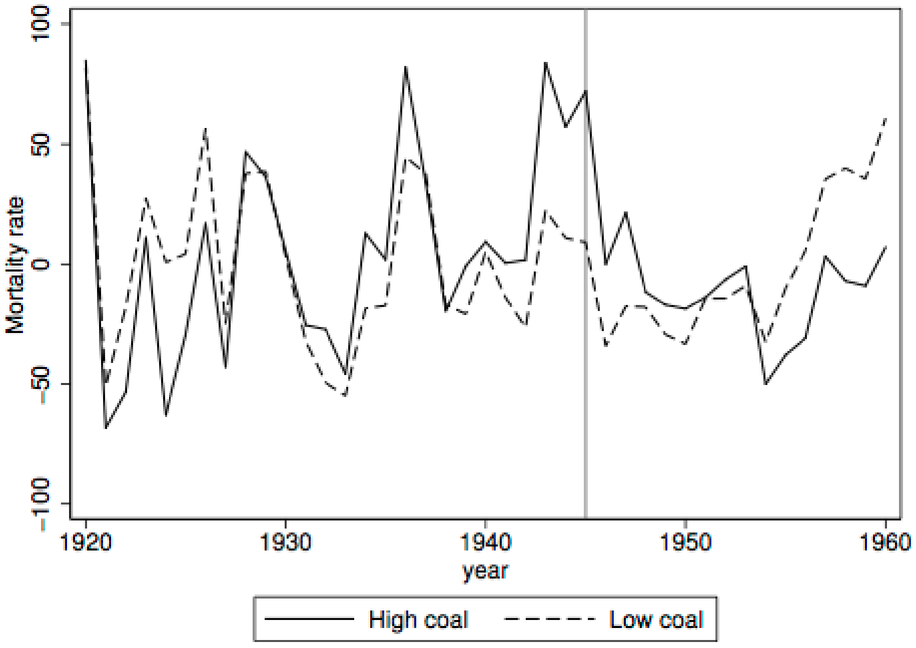
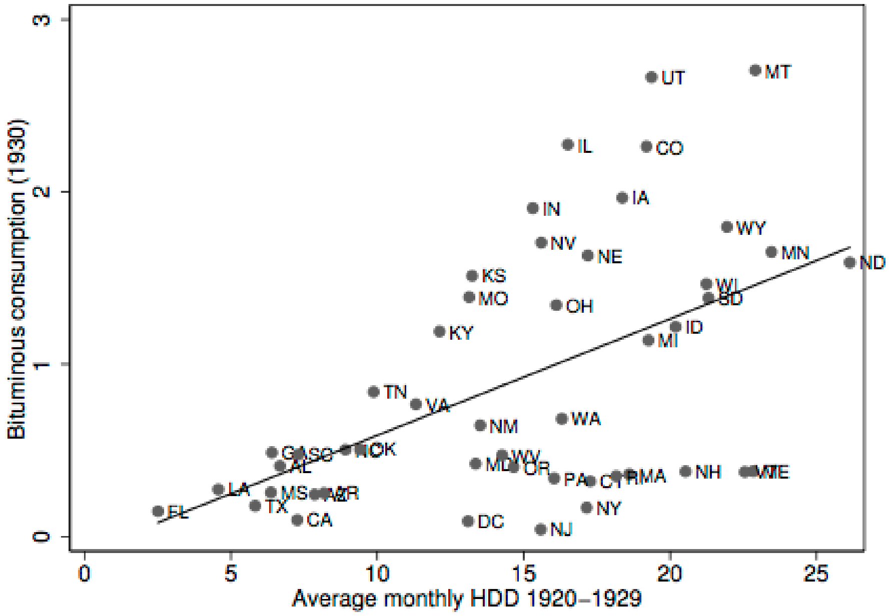


Figure 10: Correlations Between Bituminous Coal Consumption And Other Factors

Panel A: Heating degree days 1920-1929



Panel B: Income per capita in 1929

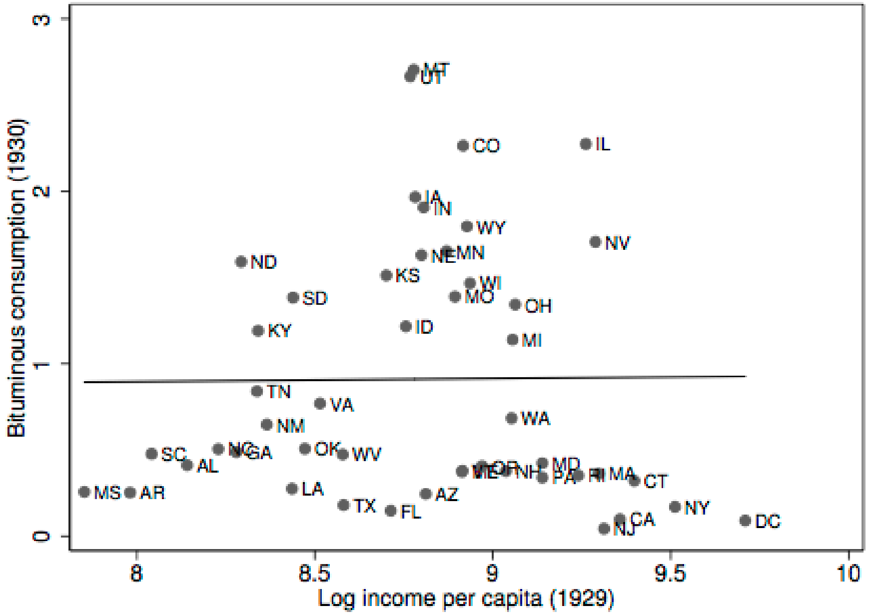


Figure 11: Changes In Seasonal Patterns Of Mortality In High And Low Coal States

Panel A: High coal states

Panel B: Low coal states

Table 1: Estimates of Total Suspended Particulates (TSP)

Location	*Time*	*TSP*	*Source*
Chicago	1912-1913	760	Eisenbud (1978)
14 Large US Cities	1931-1933, Winter	510	Ives et al (1936)
US Urban Stations	1953-1957	163	U.S. Department of Health, Education and Welfare (1958)
US Urban Stations	1960	118	Lave and Seskin (1972)
US National Average	1990	60	Chay and Greenstone (2003a)
58 Chinese Cities	1980-1993	538	Almond et al (2009)
Worldwide	1999	18% of urban pop > 240	Cohen et al (2004)

Notes: The original measurements were in TSP for all of the sources except for Cohen et al (2004). Cohen et al, Figure 17.3 (World), indicates that 18% of the urban population lived in locations where the PM10 was greater than 100. We translated the PM10 values to TSP using the following formula: PM10/0.417, where 0.417 is the empirical ratio of PM10 to TSP in their world data (Table 17.4). The estimate for 1990 is from Chay and Greenstone (2003a), Figure 1.

Table 2: Summary of means, 1920-1939

	All	Low coal	High coal
Annual deaths per 100,000	1,139	1,161	1,103
Infant deaths per 1,000 births	62.1	64.3	58.5
Heating degree days (base = 65)	13.8	12.1	16.9
Cooling degree days (base = 80)	0.23	0.272	0.155
Bituminous commercial + residential (1920)	0.732	0.303	1.51
Bituminous retail coal	0.596	0.24	1.25
Per capita income (real)	7,740	7,913	7,425
Number of states	49	30	19

Notes: Averages are weighted by state-year populations. High coal states are defined as those above one ton of per capita bituminous coal consumption in 1920. Delaware is missing coal consumption data and dropped from the analysis.

Table 3: Difference-in-Differences, 1920-1960

	(1)	(2)	(3)	(4)	(5)
	Panel outcome: Log all-age mortality (N=1,831)				
COAL1920 x POST1945	-0.02107 (0.00864)**	0.00239 (0.00799)	-0.00525 (0.00961)	0.00575 (0.00564)	0.00462 (0.00580)
COAL1920 x POST1945 x YEAR		-0.00583 (0.00148)***	-0.00398 (0.00095)***	-0.00632 (0.00148)***	-0.00589 (0.00158)***
	Panel outcome: Log infant mortality (N=1,779)				
COAL1920 x POST1945	0.02167 (0.03202)	0.03015 (0.01884)	0.00862 (0.01949)	0.04231 (0.01249)***	0.02787 (0.01217)**
COAL1920 x POST1945 x YEAR		-0.00234 (0.00434)	-0.00568 (0.00517)	0.00016 (0.00227)	-0.00030 (0.00282)
Year f.e.	Yes	Yes	Yes	Yes	Yes
State f.e.	Yes	Yes	Yes	Yes	Yes
State-specific trends	Yes	Yes	Yes	Yes	Yes
Weather controls	No	No	Yes	No	Yes
Income controls	No	No	No	Yes	Yes

Notes: * p<0.10, ** p<0.05, *** p<0.01. Standard errors are clustered at the state level. Regressions estimates are weighted by the total state-year population.

Table 4: Difference-in-Differences with Different Samples

	(1)	(2)	(3)	(4)
Sample:	1920-1955	1930-1960	No WWII	Cold states
	Panel outcome: Log all-age mortality (N=1,831)			
COAL 1920 x POST1945	0.00082 (0.00851)	0.00430 (0.00763)	0.00266 (0.02396)	0.00165 (0.00948)
COAL1920 x POST1945 x YEAR	-0.00554 (0.00141)***	-0.00577 (0.00244)**	-0.00592 (0.00180)***	-0.00491 (0.00093)***
	Panel outcome: Log infant mortality (N=1,779)			
COAL1920 x POST1945	0.02692 (0.02043)	0.03650 (0.01770)**	0.02803 (0.02880)	0.02231 (0.01796)
COAL1920 x POST1945 x YEAR	-0.00065 (0.00406)	-0.00156 (0.00425)	-0.00231 (0.00513)	-0.00466 (0.00471)
Year f.e.	Yes	Yes	Yes	Yes
State f.e.	Yes	Yes	Yes	Yes
State-specific trends	Yes	Yes	Yes	Yes

Notes: See notes to Table 3. The "no WWII" sample excludes years 1940-1945 inclusive. The "cold states" sample includes states with average heating degree days (base = 65) greater than 10.

Table 5: Triple Differences, State-Month Analysis

	(1)	(2)	(3)	(4)
Panel outcome: Log all-age mortality, 1920-1960 (N = 21,972)				
WINTER x COAL1920 x POST1945	-0.00958 (0.00596)	-0.00205 (0.00708)	-0.00988 (0.00678)	-0.00436 (0.00771)
COAL1920 x POST1945	-0.01755 (0.00905)*	-0.02069 (0.00801)**	0.00623 (0.00839)	0.00393 (0.00699)
WINTER x COAL1920 x POST1945 x YEAR			0.00004 (0.00055)	0.00057 (0.00049)
COAL1920 x POST1945 x YEAR			-0.00589 (0.00133)***	-0.00612 (0.00141)***
Panel outcome: Log infant mortality, 1940-1959 (N = 11,520)				
WINTER x COAL1920 x POST1945	-0.03633 (0.00870)***	-0.02910 (0.01186)**	-0.02887 (0.00987)***	-0.03717 (0.01406)**
COAL1920 x POST1945	0.04699 (0.01286)***	0.04397 (0.01488)***	0.02604 (0.01432)*	0.02950 (0.01623)*
WINTER x COAL1920 x POST1945 x YEAR			-0.00096 (0.00090)	-0.00429 (0.00259)
COAL1920 x POST1945 x YEAR			-0.00908 (0.00352)**	-0.00769 (0.00365)**
Year-month f.e.	Yes	Yes	Yes	Yes
State-month f.e.	Yes	Yes	Yes	Yes
State-specific trends	Yes	No	Yes	No
State-month specific trends	No	Yes	No	Yes

Notes: * p<0.10, ** p<0.05, *** p<0.01. Standard errors are clustered at the state level. Regressions estimates are weighted by the total state-year population.

Table 6: Difference-in-Differences Using Estimated Annual Consumption, State-Month Analysis

	(1)	(2)	(3)	(4)
	Panel outcome: Log all-age mortality, 1933-1958 (N = 14,976)			
RETAIL	0.06231	-0.00189	0.07470	0.02955
	(0.02540)**	(0.02377)	(0.02131)***	(0.01596)*
	Panel outcome: Log infant mortality, 1940-1958 (N = 10,944)			
RETAIL	0.01096	-0.00371	0.00844	-0.02923
	(0.02224)	(0.03004)	(0.01865)	(0.01731)*
Year-month f.e.	Yes	Yes	Yes	Yes
State-month f.e.	Yes	Yes	Yes	Yes
State-specific trends	Yes	No	Yes	No
State-month specific trends	No	Yes	No	Yes
Temperature distribution	No	No	Yes	Yes

Notes: * p<0.10, ** p<0.05, *** p<0.01. Standard errors are clustered at the state level. Regressions estimates are weighted by the total state-year population.

Table 7: Triple Differences Using Estimated Annual Consumption, State-Month Analysis

	(1)	(2)	(3)	(4)
Panel outcome: Log all-age mortality, 1933-1958 (N = 14,976)				
WINTER x RETAIL	0.01319	0.01751	0.02042	0.01811
	(0.00691)*	(0.00647)***	(0.00709)***	(0.00749)**
RETAIL	0.05667	0.05488	0.05402	0.05491
	(0.02343)**	(0.02436)**	(0.02275)**	(0.02320)**
Panel outcome: Log infant mortality, 1940-1958 (N = 10,944)				
WINTER x RETAIL	0.04874	0.02938	0.05571	0.03145
	(0.00924)***	(0.01768)	(0.00971)***	(0.01653)*
RETAIL	0.01753	0.02560	0.01336	0.02383
	(0.01777)	(0.01945)	(0.01705)	(0.01962)
Year-month f.e.	Yes	Yes	Yes	Yes
State-month f.e.	Yes	Yes	Yes	Yes
State-specific trends	Yes	No	Yes	No
State-month specific trends	No	Yes	No	Yes
Temperature distribution	No	No	Yes	Yes

Notes: * p<0.10, ** p<0.05, *** p<0.01. Standard errors are clustered at the state level. Regressions estimates are weighted by the total state-year population. Temperature distribution controls for the fraction of the month in a given 10-degree temperature band, following Deschenes and Greenstone (2009).

Table 8: Magnitudes of Effects (from Table 7, column 4)

1945-1959	Mortality	Change RETAIL 1945-1959	WINTER x RETAIL Coeff.	WINTER x RETAIL Effect
National	All-Age	0.75	0.01811	0.0136
National	Infant	0.75	0.03145	0.0236
Midwest	All-Age	1.4	0.01811	0.0254
Midwest	Infant	1.4	0.03145	0.0440
West	All-Age	0.9	0.01811	0.0163
West	Infant	0.9	0.03145	0.0283
South	All-Age	0.4	0.01811	0.0072
South	Infant	0.4	0.03145	0.0126
Northeast	All-Age	0.35	0.01811	0.0063
Northeast	Infant	0.35	0.03145	0.0110

Table 9: Elasticity of Pollution and Infant Mortality from Arceo-Gomez, Hanna, and Oliva (2012)

	Infant Mortality Rate per 100,000 live births	Mean Level PM10	Elasticity	Mean level CO	Elasticity
Arceo-Gomez, Hanna, and Oliva (2012)	1,987 (overall)	66.9	0.415	2.71	0.227
Arceo-Gomez, Hanna, and Oliva (2012)	1,899 (internal)	66.9	0.325	2.71	0.178
Barreca, Clay, and Tarr (2012)	3,367	100-300	0.067-0.214		
Chay and Greenstone (2003a)	1,179	35.3	0.284		
Currie, Neidell, and Schmieder (2005)	688	29.6	-0.008	1.58	0.040
Currie and Neidell (2005)	391	39.5	0.001	2.00	0.084
Knittel, Miller, and Sanders (2011)	280	28.9	1.827	1.01	0.146

Notes: Based on Table 8 of Arceo-Gomez, Hanna, and Oliva (2012).