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COAL, SMOKE, AND DEATH:
BITUMINOUS COAL AND AMERICAN HOME HEATING

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ABSTRACT

Air pollution was severe in many urban areas of the United States in the first half of the twentieth century, in part due to the burning of bituminous coal for heat. We estimate the effects of this bituminous coal consumption on mortality rates in the U.S. during the mid 20th century. Coal consumption varied considerably during the 20th century due to coal-labor strikes, wartime oil and gas restrictions, and the expansion of gas pipelines, among other reasons. To mitigate the influence of confounding factors, we use a triple-differences identification strategy that relies on variation in coal consumption at the state-year-season level. It exploits the fact that coal consumption for heating was highest in the winter and uses within-state changes in mortality in non-winter months as an additional control group. Our estimates suggest that reductions in the use of bituminous coal for heating between 1945 and 1960 decreased winter all-age mortality by 1.25 percent and winter infant mortality by 3.27 percent, saving 1,923 all age lives per winter month and 310 infant lives per winter month. 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, especially China and India (Almond et al 2009, Cohen et al 2004). What has largely been forgotten is that until recently, coal-related pollution was also a significant public health problem in many developed countries, including Britain and the United States. Thousands died in London's most famous fog in December 1952 (Clay and Troesken 2010). While no single American incident rivaled the London Fog, the United States experienced severe coal-related air pollution in most Midwestern and Eastern towns and cities in the 1930s and 1940s (Eisenbud 1978, Tarr 1996, Tarr and Clay 2012). Examining historical periods when developed countries, like the United States, had high levels of pollution can offer important insights into the pollution-health relationship in countries at earlier stages of economic development.

This paper uses a triple-differences model to estimate the effects of bituminous coal consumption for home heating on infant and all-age mortality rates in the United States during the mid-twentieth century. We focus on the effects of bituminous coal for heating for three reasons.[1] First, bituminous coal was widely used for heating and highly polluting compared to alternative fuels, including anthracite coal. In 1940, approximately 41 percent of United States households and 48 percent of urban households used bituminous coal for home heating.[2] Second, bituminous coal used for heating was generally more harmful than bituminous coal that was used

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[1] In line with the *Minerals Yearbook*, we use bituminous coal to refer to lignite, sub-bituminous, and bituminous coal. Data from the *Coal Resources of the United States* (1950) show that lignite and subbituminous coal were produced in small quantities in western states. As of January 1, 1950, of all coal produced in the United States to that point, 97 percent was bituminous, 2 percent was subbituminous, and 1 percent was lignite.

[2] *1940 Census of Housing* Table 60, p. 101 available at http://www2.census.gov/prod2/decennial/documents/36911485v2p1ch1.pdf. The census asked whether the household used coal for heating, but it did not ask whether the household used bituminous or anthracite coal. Fifty-five percent of households and 64 percent of urban households reported using coal for heating. Estimates in the mid 1920s suggest suggested that 65 percent of anthracite was being used for heating. Department of Commerce (1929), p. 6. Taken together with data on consumption of bituminous and anthracite, this implies that 75 percent of coal consumed for heating was bituminous.

for other purposes. Residential bituminous coal users were primarily located in urban areas, burned bituminous coal at low temperatures thereby limiting the combustion of the coal, and had low chimneys, all of which increased population exposure to pollution.[3] Conversely, firms that used bituminous coal in manufacturing and electricity generation tended to be located outside urban areas, burned the coal at high temperatures thereby facilitating combustion, and had higher smokestacks that allowed for dispersion of smoke across a much wider area. Third, there was significant variation in the opportunity cost of bituminous coal during this time period. For example, the sale and repurposing of war-related oil pipelines for natural gas after World War II led to a decline in the relative price of natural gas. The percentage of households that used bituminous coal for home heating fell from 41 percent in 1940 to 9 percent in 1960.

The paper investigates the effects on both all-age mortality and infant mortality. Epidemiological evidence suggests that exposure to air pollution poses differential health risks across the age distribution. Infants are highly sensitive to current environmental conditions, and their outcomes almost certainly are related to recent exposure in the place in which they are observed. For infants, pollutants can cause premature delivery, low birth weight, respiratory disease, and cardiovascular disease.[4] For adults, air-borne particulates and associated pollutants such as carbon monoxide can cause atherosclerosis, heart arrhythmias, and pneumonia.[5]

There are several challenges to identifying the causal effects of burning bituminous coal for heating using simple cross-sectional or time-series correlations. States with greater access to bituminous coal may have different seasonal mortality patterns due to fixed differences in climate. (States with bituminous coal deposits tended to be colder.) Coal consumption for

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[3] It is difficult to optimize the mix of air and coal in small stoves or boilers, and so combustion is rarely complete. This leads to greater emissions of particulates. EPA (1995) and WHO (2012).

[4] See Arceo-Gomez et al (2012), Curry and Walker (2011), Lockwood (2012), and Woodruff et al (2008).

[5] See Lockwood (2012), Pope et al (2004), and DelFino et al (2005).

heating may be related to industrial coal consumption, which might affect health outcomes via changes in income or employment opportunities. Changes in access to coal over time might be spuriously correlated with improvements in public health at the national level, or convergence in health outcomes across states. Also, coal consumption for heating might increase in response to weather shocks that might influence health outcomes.

Our triple-differences model addresses these concerns in various ways. The treatment variable is the state-year bituminous coal consumption for heating *interacted with* whether the month of death is a "winter" month (November-March). State-by-month fixed effects account for the possibility that states with greater access to coal have fixed differences in seasonal mortality. State-year consumption is included as a main effect, which mitigates potential bias from omitted factors, like industrialization, that might be correlated with differences in mortality throughout the year. To address the concern that changes in coal access over time are correlated with broader changes in public-health conditions or convergence across states, year-by-month fixed effects and state-specific trends are included. Controls for temperature are included to account for climate-related changes in health conditions (e.g. cold spells) that might be related to coal consumption. Finally, controls for other non-heating forms of coal consumption are included, both as a main effect and interacted with winter months, to demonstrate that heating is the driving mechanism.

Our analysis draws on newly digitized historical mortality and coal data. The unit of observation is at the state-month level. Data on all-age and infant mortality at the state-month level are taken from the annual *Vital Statistics* volumes. Using data on annual national coal consumption and detailed survey and census data, we construct estimates of state-year bituminous coal consumption by type of use (e.g. heating, industrial, railroad). To the extent our state-year coal consumption includes classical measurement error, then the effect sizes are likely to be a lower bound.

Our estimates suggest that reductions in the use of bituminous coal for heating between 1945 and 1960 decreased winter all-age mortality by 1.25 percent and winter infant mortality by 3.27 percent. This translates into 1,923 fewer total deaths per winter month and 309 fewer infant deaths per winter month. The reductions in mortality varied considerably by region, because different regions had higher baseline levels of bituminous coal use. For example in the Midwest, the estimated effects suggest that the decline in bituminous coal consumption resulted in a 2.75 percent decline in all-age mortality and 7.27 percent decline in 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. Most existing studies have examined contemporary settings where the levels of pollution were relatively low by historical standards.[6] In contrast, our paper examines infant and all-age mortality in a period when winter pollution levels were high. Urban particulate levels in the U.S. in the 1930s and 1940s were similar to those experienced in developing countries today (Almond et al., 2009, Cohen et al 2004).[7] Specifically, they were roughly eight times the levels in the U.S. in the late twentieth century (Chay and Greenstone 2003b). Thus, our research can shed new light on the marginal effects of pollution when levels of pollution are high.

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[6] 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.

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

2. Coal

This section highlights the following historical facts about bituminous coal consumption in the United States: First, bituminous coal consumption was high through the 1940s. Second, there was considerable variation across states in the level of coal consumption. Third, the opportunity cost of using coal for home heating increased in the mid 1940s, leading to a decline in coal consumption. We leverage these facts, along with the fact that coal consumption is higher during the winter, in our identification strategy.

Coal, and bituminous coal in particular, was important fuel for home heating from the late nineteenth century through the end of World War II. Until the 1880s, the primary source of fuel in the economy was wood.[8] Wood was surpassed by coal in the 1880s, the majority of which was anthracite coal from eastern Pennsylvania. As bituminous deposits west of the Alleghenies were developed and transportation facilities improved, bituminous coal became the dominant form of coal by the end of the 19th century. Bituminous coal was the dominant fuel source through the 1940s. The 1940 Census of Housing reports that 55 percent of households used coal for heat. Approximately three quarters of these households, 41 percent, were using bituminous coal. The share for wood was 23 percent, gas was 11 percent, oil was 9 percent oil, and "other or none" was 2 percent.

States varied in their level of exposure to bituminous coal. As Figure 1 Panel A illustrates, states in the Midwest had much higher baseline consumption than other parts of the country. Two facts appear to be driving this cross-sectional variation.[9] First, high-bituminous consuming states tended to have colder winters. As a simple illustration of this fact, Appendix

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

[9] Interestingly, income does not appear to be strongly related to baseline coal consumption. See Figure A1 Panel B.

Figure A1 (Panel A) correlates the average daily temperature in January, February, and December of 1933 with the bituminous coal consumption in 1933, the first year for our data. Second, proximity to coal deposits is a strong predictor of consumption as well. Figure 1B shows the location of coal deposits, both bituminous and anthracite, in 1920. All of the deposits except for a small area in eastern Pennsylvania were bituminous. Comparing Figure 1A to Figure 1B, we see that being close to a bituminous coal field was strongly correlated with bituminous coal consumption for heating in 1933.[10]

Figure 2 plots national consumption of bituminous coal (for heating), natural gas, and heating oil annually for 1933-1960. Coal consumption began flat, fell somewhat in the late 1930s, and then rose rapidly until the mid-1940s. The fall in the late 1930s reflects both warmer winters and the adoption of oil and natural gas in some urban areas. The restrictions on the availability of oil and natural gas drove the rise through the mid-1940s. However, there was a large decline in bituminous coal consumption after 1945. As illustrated in Figure 2, an increase in natural gas and oil consumption accompanied the decline in bituminous coal consumption.

Several factors drove the decline in bituminous coal consumption after 1945. 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. Government controls limited strike activity in the WWII period. The strikes, which occurred in 1946 and during 1949 and 1950, sharply restricted production, adversely affected coal stocks, and raised prices. In both cases, daily production fell from 2

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[10] The data used to construct Figure 1A are described in the Data section. Pennsylvania is one important exception. Pennsylvania was in the second lowest quartile because anthracite was used instead of bituminous since anthracite deposits were relatively closer.

million tons per day to well below 1 million tons per day.[11] These strikes idled manufacturing, prompted restrictions in electricity production (dimouts), and caused restrictions in freight shipments and travel.[12]

In the late 1940s, the price of natural gas fell dramatically. Figure 2B illustrates this fact using a sample of cities from American Gas Association (1956). 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 before people could switch to natural gas for heating.[13] First, pipelines had to be built to move the gas from the Southwest to the Midwest and the East.[14] As of 1940, there were some pipelines, but the distances and capacity of those pipelines was quite limited. The federal government built the Big Inch and Little Big Inch pipelines from Texas to the East Coast during World War II to increase the security of the oil supply. In 1947, the pipelines were sold to the Texas East Transmission Company and were converted to natural gas.

Second, storage capacity had to be developed in order to successfully deliver gas to the end users. Winter demands for gas were much higher than summer demands, so gas had to be 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.[15]

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[11] 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.

[12] *Wall Street Journal*, September 26, 1946, p. 1. *New York Times*, November 22, 1946, p. 2.

[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] American Gas Association (1956).

Storage was primarily located in former gas, oil, or mixed oil and gas fields in Pennsylvania, Michigan, Ohio, and West Virginia.

Heating oil was primarily available in coastal cities prior to World War II. Supply was constrained in the early 1940s as shipping and railroad capacity became scarce. Rationing of heating oil, which began in October 1942, incentivized some oil users to switch 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 supply to residential users.

Switching heating fuels was not particularly costly. In 1940, 42 percent of households had central heat, 47 percent had a heating stove, and 12 percent had other or none, which included households with portable heaters, fireplaces, or kitchen stoves. 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 heating stove or furnace to burn gas or heating oil. Conversion from heating oil to coal, which occurred during heating oil shortages in World War II, cost approximately $50. Re-conversion cost roughly the same amount.[16] The total cost of switching from coal to natural gas after World War II was somewhat higher at $163. In 1950, the closest expenditure survey to the years of interest, average household current expenditure was $3925 and utility expenditure was $163.[17] Natural gas conversion was less than 5 percent of current expenditure and 100 percent of utility expenditure, and oil conversion was less than 2 percent of current expenditure and about 30 percent of utility expenditure.[18]

Given the increased availability and lower prices of oil and gas in the second half of the 1940s, consumers began to switch. Between 1940 and 1950, the share of households using gas

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

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

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

for heating increased from 11 percent to 29 percent, and the share using oil for heating increased from 9 percent to 23 percent.[19] In contrast, the share using coal fell from 55 percent to 35 percent, and the share using wood fell from 23 percent to 10 percent. As Figure 2A illustrates, oil consumption doubled between 1945 and 1960, and natural gas consumption went up by over 400 percent.

Given the confluence of events that occurred over this short time period, we cannot exploit any one historical event for causal identification. Instead, we rely on variation from year-to-year the opportunity cost of coal consumption at the national level. Arguably, this variation is driven by both exogenous factors (e.g. coal strikes) and endogenous factors (e.g. income shocks).[20] For this reason, we employ a triple-differences identification strategy. Specifically, we exploit variation over time in winter mortality relative to non-winter mortality. The key identifying assumption is that the omitted factors are not associated with changes over time in seasonal mortality patterns across states.

3. Background on Coal-Related Emissions and Mortality

Pollution in the United States

The level of pollution in the first half of 20th century United States was high by modern standards, something to be considered when relating our estimates to existing studies. Table 1 presents selected estimates of total suspended particulate pollution in the United States and

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[19] *1940 Census of Housing* and *1950 Census of Housing*. For 1940, Table 60, p. 101 available at http://www2.census.gov/prod2/decennial/documents/36911485v2p1ch1.pdf . For 1950, Table 20, pp. 127-130 available at http://www2.census.gov/prod2/decennial/documents/36965082v1p1ch1.pdf .

[20] Appendix Table A1 correlates changes in year-round bituminous coal consumption and log income per capita. There is no strong statistical relationship between log income per capita and bituminous coal consumption. However, we cannot rule out modest effect sizes. Nonetheless, any such income effects would have to have differential effects across seasons to bias our triple-differences estimates.

developing countries.[21] 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. By 1920, 175 municipalities had passed smoke control ordinances, suggesting that the problem was widespread.[22] 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 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 very few particulates when burned.[25]

Heating with bituminous coal is problematic in part because of 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

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[21] Particulates were not routinely measured in the United States until the late 1960s.
[22] Stern (1982)
[23] See Davidson and Davis (2005) for Pittsburgh and Eisenbud (1978) for New York.
[24] Butcher and Ellenbecker (1982), p. 380.
[25] EPA (1998)

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."[26]

Exposure to pollutants occurred both indoors and outdoors. In the nineteenth century, households burned fuel in open stoves or fireplaces in homes. By the early twentieth century, households had largely moved to closed stoves and furnaces. The primary vector of exposure from cooking and heating came through outdoor air pollution, which then migrated indoors through the opening and closing of doors and from drafts.[27,28] This is in contrast to the situation in developing countries, where indoor air pollution can be significantly higher than outdoor air pollution. Particularly in rural areas, cooking often takes place inside the home on open stoves or fires.[29]

Historical and contemporary evidence indicate that coal for heating was major contributor to winter air pollution. Ives et al (1936), which reported the results of a U.S. Public Health Service Study of 14 large U.S. cities 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."[30] An analysis of hours of winter solar

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[26] Eisenbud (1978), p. 1006.

[27] Dockery and Spengler (1981).

[28] 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).

[29] See Rylance et al (2010) and Alam et al (2012)

[30] 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

radiation – an indirect measure of air pollution in the United States – by Husar and 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.[31] A 2005 E.U. study of coal-related 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."[32]

Humans are exposed to particulates from sources other than coal, notably particulates from transportation and from smoking. Although important for interpretation of our estimates, it seems unlikely that transportation or smoking is biasing our results. [33] On-road vehicles were a small share of particulates – 1 percent of PM10 in 1940 and 2 percent in 1960. There does not appear to have been abrupt changes in the mid-1940s.[34] Cigarettes and other burned tobacco products were a significant source of particulates for smokers and individuals exposed to second hand smoke. The available evidence suggests, however, that consumption was trending up smoothly after the Great Depression.[35]

The Epidemiology of Pollution

During the period of our study, scientific evidence on the health costs of pollution was limited. From the 19th century, public health officials and interested observers had hypothesized

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in large American cities. 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.

[31] 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

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

[33] Other particulates could affect the local average treatment effect if the pollution-mortality relationship is non-linear.

[34] EPA (2000).

[35] During the period 1920-1960, consumption was steadily rising, with the exception of a brief downturn during the Great Depression. 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.

that air pollution was linked to mortality. It was not until the 1990s that the epidemiological literature convincingly documented the link between airborne particulates and mortality.[36,37] 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). Beginning in the late 1970s and early 1980s, the studies tracked sample participants, all of whom were adults. The studies measured all-age mortality and cause of death data. The primary focus was on all-cause mortality because cause of death coding tends to be unreliable in the absence of an autopsy. More recent studies using quasi-natural experiments also find strong links between particulates and mortality. [38]

Research by Pope et al (2004) and DelFino et al (2005) suggest that particulates cause mortality in the adult population through three 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. [39] The third, but less important, mechanism is through pneumonia.[40]

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[36] 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).

[37] Most of the discussion focuses 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.

[38] 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. Currie, Neidell, and Schmeider (2009) examine within-mother differences in birth outcomes since they have detailed data on pollution exposure of pregnant mothers, which varies over time and space. 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. See also Pope et al (1992), Clancy et al (2002), Hedley et al (2002), and Pope et al (2007).

[39] Recent 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

For infants, particulates cause mortality population through two primary 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 1960. 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 and cardiovascular causes.

4. Data

Data on all-age and infant mortality at the state-month level are taken from the annual *Vital Statistics* volumes. States entered the National Center for Health Statistics sample of "registration states" slowly over time. Reporting of all-age mortality at the state-month level began in 1900. The reporting of infant mortality at the state-month level began in 1939.[41] As we discuss in the methodology section, the monthly variation is important since we expect winter mortality to be disproportionately affected by bituminous coal consumption.

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range in which most air pollution occurs) the marginal effects are large, while at high exposures (13+ cigarettes per day) the marginal 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).

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

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

Mortality rates were constructed using historical population estimates from the Decennial Censuses. These population estimates were linearly interpolated to construct annual state population estimates. Infant monthly mortality rates were constructed by dividing the monthly death counts by annual state-level birth data from 1939-1960.[42] Infant mortality rates are reported per 100,000 live births. Our dependent variables are the log of the all-age and the log of infant mortality rate, respectively. Our results are robust to using the mortality rate in levels.

Climatic data are from the United States Historical Climatology Network (USHCN) Daily Dataset.[43] 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 are aggregated to the state-month level using population-distance weights.[44]

We construct state-year coal consumption data from two sources: (i) an annual series of national coal use by type from *Minerals Yearbook* for the years 1933 through 1960, and (ii) a United States Geological Survey (USGS) of state coal use by type conducted in 1917. The annual series on use by type, which began in 1933, is constructed based on detailed annual survey reports of production and consumption based on shipment data from railroads and reports of consumption by railroads, industry, electrical, and wholesale distributors. Unfortunately,

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

[43] 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.

[44] Humidity data are not available for our sample 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.

state-level data on coal use for heating is only available sporadically. The USGS survey was done in 1917 in conjunction with the allocation of bituminous coal to states during World War I.[45] The next USGS survey that covered heating was in 1957.[46] To construct our state-year consumption data, we multiply the annual national data by the state shares of national consumption in 1917. As a robustness check, we use the 1940 state shares of households using coal for home heating from the decennial census to allocate national consumption to states.[47]

Table 2 shows summary statistics for the full sample and by region. All age mortality is higher in the Northeast and Midwest and somewhat lower in the South and West. Infant deaths are similar across regions, with the exception of the South, which has higher infant mortality. Bituminous coal consumption for heating per capita was 0.55 tons, and varied from a high of 1.19 tons in the Midwest to a low of 0.18 tons in the Northeast. The fraction of households using coal was 0.53, and ranged from 75 percent in the Midwest to 18 percent in the West. Note that the high share of households using coal in the Northeast and the low per capita consumption of bituminous occurs because most households that burn coal are burning anthracite. Mean temperatures were 50 and 51 in the Northeast and Midwest and 62 and 56 in the South and the West. Per capita income is lowest in the South, as is urbanization.[48]

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[45] The 1917 survey followed an earlier 1915 survey and was considered more accurate. Lesher (1917), p. "Complete and absolutely accurate reports of distribution are impossible to obtain and any attempt to compile such statistics as this report contains must include estimates, but it is believed that these, data in all important respects are accurate and that some of the shortcomings of the statistics for 1915 have been overcome."

[46] A 1927 USGS survey covered most uses, but used the 1917 survey for heating.

[47] 1940 was the first year that the census asked about heating fuel. Similar data is available for 1950 and 1960. The censuses only asked about the use of coal for heating and not whether it was bituminous or anthracite. Nationally, three quarters of households were using bituminous coal, but we do not know the shares of the two coals that were being used in each state.

[48] The data on state annual per capita income are from the U.S. Bureau of Economic Analysis and cover the years from 1929 to present. All income has been converted to 2010 dollars. The urbanization measure is from the decennial census (Haines 2010).

5. Identification

Our hypothesis is that bituminous coal consumption for heating is associated with increased winter mortality relative to other months. To test this hypothesis, we estimate the following triple-difference model:

(1) $LNMORT_{smy} = \beta_1 \, BITCOAL_{sy} + \beta_2 \, BITCOAL_{sy} \times WINTER_m + \theta_{sm} + \eta_{my} + \lambda_s \, TIME + \boldsymbol{\gamma} \, X_{smy} + \varepsilon_{smy}$,

where LNMORT is the log of the mortality rate (or log of the infant mortality rate) in state s in month m and year y; BITCOAL is state s's share of bituminous coal consumption in 1917 multiplied by national consumption in year y. WINTER is a dummy variable for whether the month of death is between November and March. Month-year fixed effects (η) mitigate biases from secular improvements in health conditions that occurred over time. State-month fixed effects (θ) account for fixed differences in mortality that are related to baseline coal consumption. State-specific time trends mitigate bias from convergence in mortality rates that might be correlated with baseline coal consumption. In one specification we add state-by-calendar-month specific time trends to allow for differential convergence in mortality across states and seasons. X includes controls for unusually cold or warm temperatures in a given month that might be related to bituminous coal consumption. We also use lagged coal consumption in one specification to mitigate the possibility that contemporaneous cold weather is behind the estimated effects. X also controls for "other" non-heating forms of bituminous coal consumption, including a both a main effect and an interaction with the winter month dummy.

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.[49]

The identifying variation in this model comes from differences over time in winter months in states with estimated high baseline coal use. In other words, we can use the non-winter months interacted with our coal consumption measure use as additional controls. We are able to provide support for our assumption using seasonal consumption data from the *Minerals Yearbook*, although such data are only available starting in 1951. As Figure 3 illustrates, January 1951 consumption for heating coal was more than three times the consumption in May 1951. Figure 3 plots seasonal consumption for 1954 and 1958, illustrating the fact that bituminous coal consumption fell more during winter months. Note that our empirical model imposes a constant "winter" effect for the months November through March since Figure 3 suggests that consumption was greatest during these months. We test the robustness of this modeling choice by including a series of interactions between BITCOAL and each calendar month, with July as the omitted month (see Figure 4 and related discussion below). To the extent that bituminous coal consumption also increases summer mortality, then this approach will underestimate the mortality effects. However, this model has the advantage of allowing us to control for idiosyncratic changes in year-round health that may be spuriously correlated with greater coal consumption.

6. Results

Core estimates

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

Table 3 presents the core estimates. The top panel shows the results for all age mortality and the bottom panel shows the results for infant mortality. Note that due to data limitations, the infant mortality span the years 1939 through 1960, while the all-age mortality estimates span the years 1933 through 1960.[50] Columns (1)-(3) present results for the log of mortality and (4)-(6) present the results for mortality rates in levels.

Table 3 provides four results worth noting. First, there is a positive relationship between coal consumption and mortality for the *average* month. Column (1), which does not include the winter interaction term, indicates that a one-ton increase in per capita bituminous coal consumption (BITCOAL) is associated with a 6.3 percent increase in all-age mortality and a 4.2 percent increase in infant mortality during the average month.

Second, as illustrated in columns (2) and (3), the mortality impact of BITCOAL was relatively greater in winter months. When controlling for year-month fixed effects, state-month fixed effects, and state-specific trends (column 2), a one-ton increase in BITCOAL leads to a 1.3 percent increase and a 4.5 percent increase in winter mortality relative to other months for all-age mortality and infant mortality. These estimates are statistically significant at the 10 percent and 1 percent level.

Third, point estimates are qualitatively similar when we add controls for the temperature and other uses of bituminous coal (column 3). For example, with all-age mortality as the outcome, the point estimate on WINTER x BITCOAL increases slightly from 0.013 to 0.017 when we control for the temperature and other uses of bituminous.

Finally, the estimates are qualitatively similar when the dependent variable is the mortality rate in levels (columns 4-6). For example, with the full set of controls (column 6), the

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[50] Our all-age mortality estimates are robust to restricting them to the 1939-1960 period.

impact of a one-ton increase in BITCOAL increases the winter mortality rate by 1.08 and 11.5 for all-age mortality per 100,000 and infant mortality per 100,000 births, respectively.

To provide a context for understanding the magnitude of our results, we calculate the number of winter deaths avoided due to the decline in coal consumption over the 1945-1960 period. This calculation is based on column (3) of Table 3 and the decline in per capita bituminous coal consumption over this time period. As reported in Table 4, the decline in the use of bituminous coal for heating accounted for 15 percent of the decline in winter all-age mortality and 10 percent of the decline in winter infant mortality nationally. The share is smaller for infant mortality than for all-age mortality because of rapid declines in infant mortality. Infant mortality fell 32.0 percent, while all age mortality fell 8.6 percent.[51] The number of lives saved per winter month was large:1,923 all-age lives and 310 infant lives.

The magnitudes of the share of the decline accounted for by coal varied considerably by region. In particular, the Midwest experienced the greatest improvements in health because of its high consumption of coal for heating at the baseline. In the Midwest, the decline in bituminous coal consumption between 1945 and 1960 accounted for 23 percent of the decline in winter all-age mortality and 22 percent of the decline in winter infant mortality. The number of lives saved per winter month in the Midwest was large: 1,084 all-age lives and 102 infant lives.

Robustness checks

To test the robustness of our WINTER dummy, Figure 4 estimates our triple-differences model with 11 separate interactions for each calendar month (with July being the excluded month). For all-age mortality, Panel A illustrates that the effects (relative to July) are largest in December and March, with second largest effects in January, February, and April. The effects

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[51] The fall in infant mortality is largely due to improvements in pre-natal care and treatment of low birth-weight babies.

appear to be small in November and modest in April, possibly due to a one-month lag in the effects from pollution. This finding suggesting that our winter designation (i.e. November-March) may be underestimating impacts on all-age mortality. For infant-mortality, the effects are monotonically increasing from July through December and from June back through January. These findings suggest our approach of designating November through March as “winter” is a sensible simplification.

Table 5 estimates a series of robustness checks for all-age mortality (Panel A) and infant mortality (Panel B). We do not report the main effects of the coal variables in the interest of presentation. Column (1) allows the effects of coal consumption to vary with the share of the state living in urban areas in 1930. One hypothesis is that the marginal impacts of coal consumption are increasing in population density. The coefficients on WINTER x BITCOAL are similar in sign and magnitude to our core specification. The coefficients on URBAN x WINTER x BITCOAL are actually negative, but statistically insignificant. This finding suggests that urban areas did not experience greater winter mortality beyond the effects captured in WINTER x BITCOAL. Given the plausible nonlinearity of the dose-response function and the high baseline exposure of urban residents, the marginal effects of pollution from home heating on mortality could well have been similar for urban and non-urban populations. It could also be that other important determinants of mortality such as nutritional intake may have varied by calendar month differentially for urban and rural areas. This could have affected the marginal health impacts of BITCOAL.

Column (2) in replaces the estimated state shares of bituminous coal consumption for heating with the 1940 state shares of households using any coal for heating from the census (COALHH). The results are qualitatively similar to our Table 3 specification. The magnitudes of the coefficients on COALHH are generally larger because of scaling. The mean for COALHH is 0.42 in 1933 and 0.16 in 1960, and BITCOAL was 0.61 in 1933 and 0.17 in 1960.

Column (3) correlates lagged coal consumption in year t-1 with current month's mortality. This robustness check addresses the possibility we have not adequately controlled for omitted factors that are correlated with high-frequency changes in coal consumption, like the weather. Our results are robust to this modification. Column (4) controls for state-by-calendar month time trends to account for possible convergence in seasonality across states by level of coal consumption. The all-age mortality estimates are robust to this modification. The infant mortality estimates diminish in magnitude and are only robust at the 10 percent level. However, the infant mortality estimates have fewer years of data, so the state-month specific trends potentially absorb useful variation. The fact that the standard errors have increased in magnitude (from 0.011 to 0.013) corroborates this hypothesis.

Columns (5) through (7) test the sensitivity of our results to changes in the sample. Column (5) drops the Western states, which had lower sulfur coal that was less harmful to human health. The magnitudes of the coefficients on WINTER x BITCOAL for all-age mortality are similar to Table 3. The infant mortality estimate diminishes slightly, although it is still statistically significant at the 1 percent level. Column (6) drops the 10 "warmest" states (see the Table 5 note for more detail). The coefficients on WINTER x BITCOAL for infant mortality diminishes slightly, but remains statistically significant. However, the coefficient on WINTER x BITCOAL for all-age mortality is close to zero and no longer statistically significant. One possible explanation is that there is non-classical measurement error in the exposure variable, per capita bituminous coal consumption, and the error was smaller in the least cold states. Though, it is unclear why this measurement error would affect the all-age mortality estimates, but not the infant mortality estimates. Column (7) stops the sample at 1955 instead of 1960. Both the all-age and infant mortality estimates increase in magnitude, suggesting that mortality effects from declines in coal consumption at low levels of consumption, as in the late 1950s, may have been small.

Discussion

The results in this paper raise two related questions. The first is: how do our estimates compare to modern studies on the pollution-mortality relationship? The second is: could government intervention have generated net social benefits by forcing households to switch to cleaner fuels earlier?

In the absence of monitor data, answering the first question is remarkably difficult. Data from the 1930s from large cities suggest that an 81 percent decline in bituminous coal consumption for heating would roughly have yielded a 45 percent decline in particulates.[52] In less densely settled locations, the average decline in particulates may well have been lower. If one takes 45 percent as roughly of the correct order of magnitude (which is arguably a strong assumption), the implied elasticities for the U.S. are 0.33 for all age mortality and 0.22for infant mortality.[53] If the actual declines in particulates were smaller, the implied elasticities would be larger.

Table 6 shows the elasticities for PM10 and infant mortality in a number of studies. The range of elasticities is very wide – 0 to 1.8. Compared to the two studies with the next highest

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[52] This is calculated by taking the difference between average values of the Owens shade meter at 8am, a time at which most households are burning fuel, in the five winter months and in the seven non-winter months and multiplying by 0.81. This assumes that the alternative heating fuel is to a first approximation non-polluting, which is roughly true of natural gas.

[53] The calculations use the values in row (4) from Table 4 for the United States and the 45 percent decline in particulates: All age = 0.15/0.45; Infant = 0.10/0.45.

levels of particulates and infant mortality, Chay and Greenstone (2003a) and Arceo-Gomez, Hanna and Oliva (2012), our infant mortality elasticity estimates are lower. This may reflect the high baseline infant mortality rate between 1939 and 1960. Alternatively, reductions in pollution may carry only modest benefits to health in cases where pollution levels are very high, as was the case of the mid-20th century.

For the second question, it is easiest to start with the marginal fuel costs and back out the threshold VSL for which it would have been socially beneficial to require switching. A conservative estimate of the marginal fuel cost can be obtained taking the retail cost of bituminous coal and noting that price per BTU of alternative fuels in the 1940s in Figure 2B was not more than 2x bituminous per BTU. According to American Gas Association (1956), in 1945 they were less than 1.5x bituminous per BTU. If the marginal fuel costs were 1.0x bituminous – that is alternative fuels were twice as expensive – the cost would have been 1.37 billion (1945$). If the marginal fuel costs was 0.5x bituminous – that is alternative fuels were 50 percent more expensive – the cost would have been 0.69 billion (1945$). Dividing this by 9,615 lives saved per year gives us a threshold value of $142,486 (1945$) per life at 1.0x bituminous and $71,243 at 0.5x bituminous.[54]

Next we need to know what the value of a statistical life was in 1945. We start by taking a current value of a statistical life of $7,000,000 (2012$), which is at the lower end of the conventional range.[55] We adjust it with a GDP per capita deflator, so $7,000,000 (2012$) is 221,000 (1945$).[56] The net benefit per life saved ranges from $78,514 for a marginal cost of fuel

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[54] Table 4, Panel A, row (5) calculates 1,923 lives saved per winter month. 1,923 lives/winter month x 5 winter months = 9,615 lives.

[55] The EPA now uses $7.4 million (2006$), adjusted to the appropriate year, which would be $8.4 million (2012$).

[56] The GDP deflator falls in between the CPI deflator and elasticity adjusted measures. The CPI deflator gives 549,000 (1945$). Costa and Kahn (2004) show that the elasticity of VSL with respect to real GNP per capita was

of 1x bituminous to $149,757 for 0.5x bituminous. By these metrics, it would have been socially beneficial for the government to intervene.

7. Conclusion

This paper provided new evidence on historical levels of air pollution in the United States and on one significant cause of decline in pollution, the rapid switch away from bituminous coal and towards cleaner fuels for home heating. Our regression results imply that reductions in the use of bituminous coal between 1945 and 1960 decreased winter all-age mortality by 1.25 percent and winter infant mortality by 3.27 percent. Our estimate is likely a lower bound, since it primarily reflects a short-run relationship between coal and mortality. For example, pollution exposure in the winter months may have ultimately resulted in higher mortality rates during the summer months due to a depleted stock of health capital.

Our results may be informative for developing countries since our historical setting is one where baseline pollution levels, changes in pollution levels, and baseline mortality levels were high relative to contemporary settings. Although we find more modest pollution-mortality elasticities, our cost-benefit analysis indicates that regulatory intervention in the 1940s would have generated net benefits. Despite the net benefits, federal intervention did not come about until the 1960s and 1970s. One explanation for the delay in intervention was that epidemiology had yet to convincingly show a causal relationship between pollution and mortality. For example, 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

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about 1.5. They offer estimates of VSL for 1940 and 1950 of $996,000 and $1,755,000 in 1990 dollars. In 1945 (CPI adjusted) dollars, these are $137,000 and $242,000. If we take the average, the value is $189,500.

study to investigate this phase of the subject."[57] Lave and Seskin (1970) published compelling evidence on the link in 1970, and their work was confirmed by large epidemiological studies in the 1990s.Without greater awareness of the dangers of pollution, intervention would have likely been politically unpopular, even by today's standards. Thus, the United States historical experience suggests that greater understanding about the health costs of pollution, as provided here, may help facilitate welfare-enhancing legislation in developing countries today.

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

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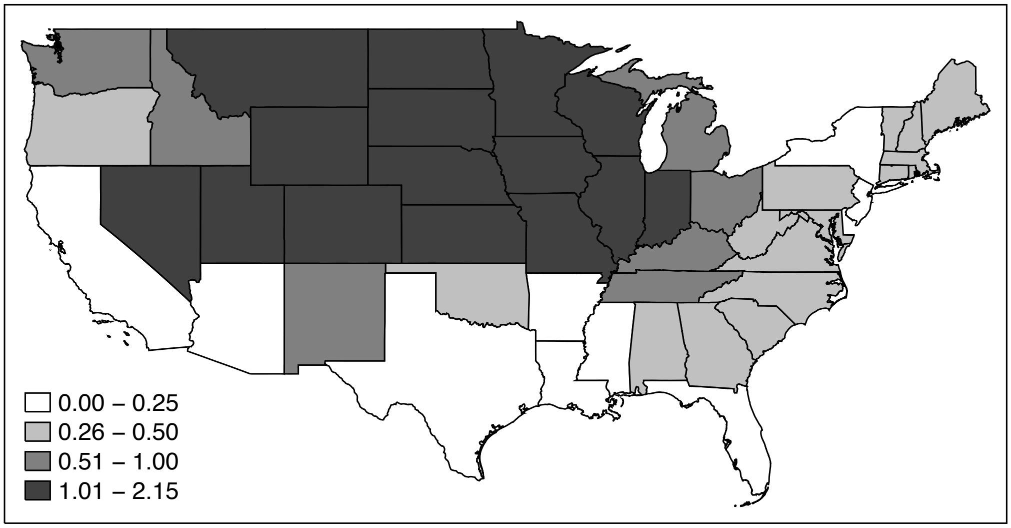
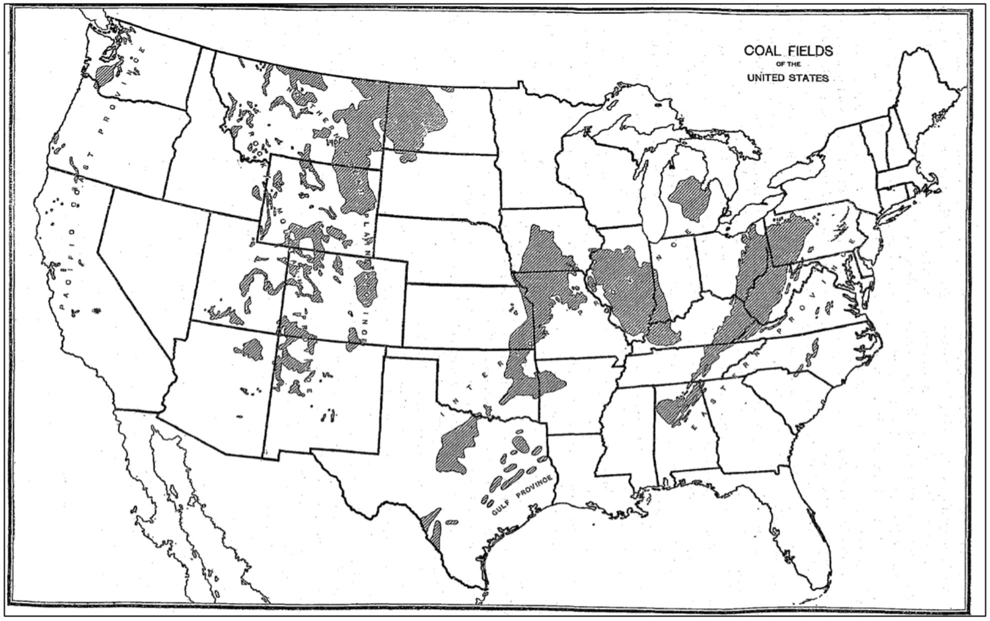
Figure 1: Bituminous coal consumption across states

Panel A: Bituminous coal consumption for heating (tons per capita), 1933



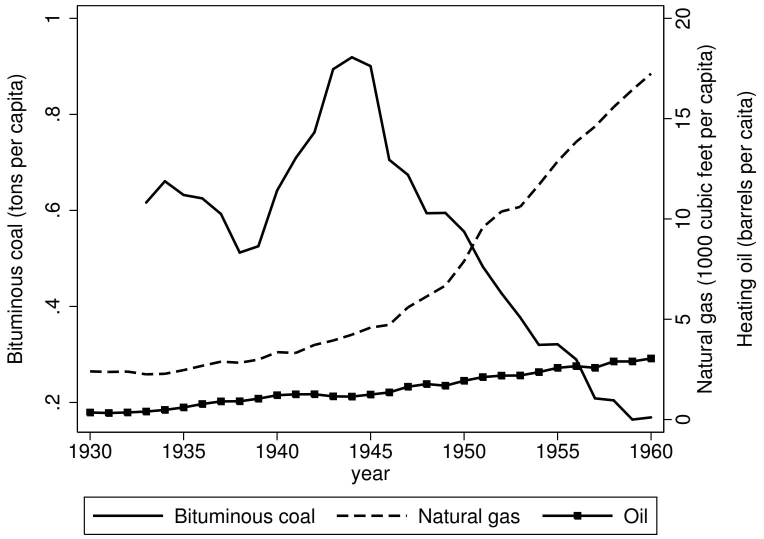
Panel B: Location of coal deposits (c. 1919)



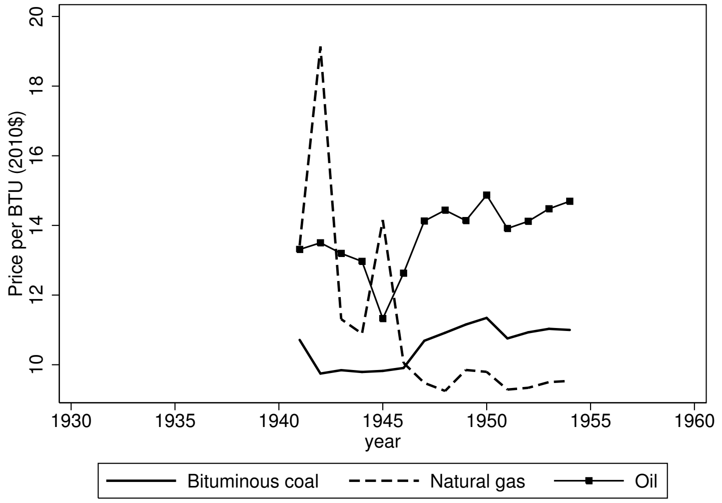
Notes: Panel A data are constructed using coal consumption shares from 1917 (Lesher 1917) and annual nation consumption estimates from *Minerals Yearbook* (various years). Panel B map is from the Fourteenth Census of the United States, Volume XI Mines and Quarries, 1919, General Report and Analytical Tables and Selected Industries, p. 254. http://www2.census.gov/prod2/decennial/documents/23010460v11ch4.pdf .

Figure 2: Consumption of fuels for heating, c. 1930-1960

Panel A: Consumption, entire United States

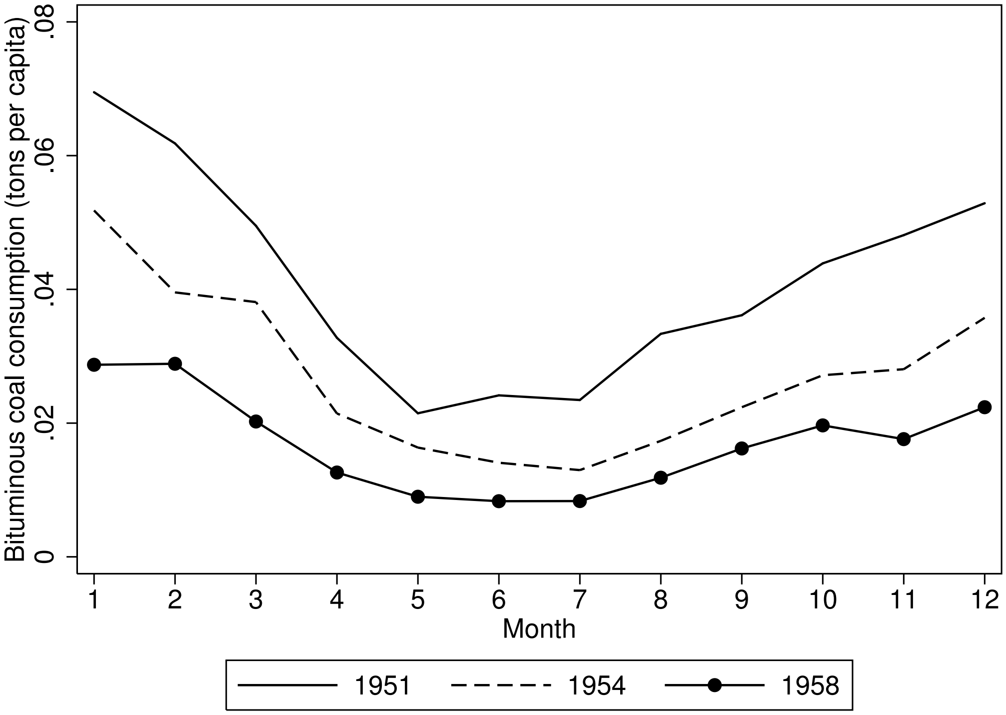


Panel B: Price per BTU, various cities



Notes: Panel A data are from Minerals Yearbook (various years). Data on bituminous coal consumption are only available for the 1933-1960 period. Panel B data come from American Gas Association, Bureau of Statistics. Historical Statistics of the Gas Industry. 1956. These data are only available for the 1941-1954 period. The cities included in the sample include: Atlanta, Baltimore, Boston, Chicago, Cincinnati, Cleveland, Detroit, Houston, Kansas City, Los Angeles, Minneapolis, New York, Philadelphia, Pittsburgh, Portland, St. Louis, San Francisco, Scranton, Seattle, and Washington D.C. Bituminous prices are not available for Boston, Houston, Los Angeles, New York, Philadelphia, Scranton, or Washington D.C. Oil prices are not available for Atlanta, Cincinnati, Cleveland, Houston, Los Angeles, Pittsburgh, St. Louis, San Francisco, or Scranton. Gas prices are available for all the aforementioned cities.

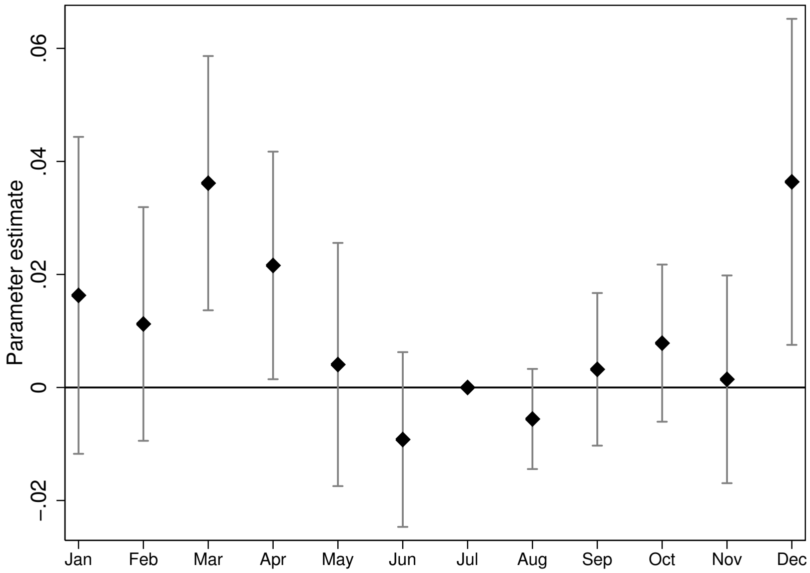
Figure 3: Coal consumption by month of year, 1951, 1954, and 1958



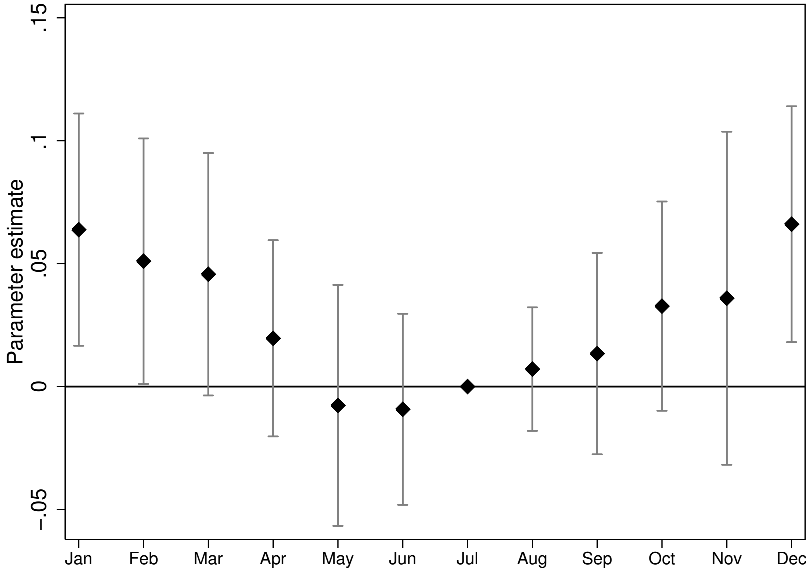
Notes: Data are from *Minerals Yearbook* (various years). Other coal consumption includes bituminous coal used for electricity, industry, coke, and railroads. Seasonal bituminous coal consumption data are not available prior to 1951.

Figure 4: Triple-difference model with calendar month interactions

Panel A: Log all-age mortality



Panel B: Log infant mortality



Notes: The y-axis scales differ between panel A and panel B. The point estimates are the diamond shape and the brackets represent two standard errors. The estimates are from one model where we have BITCOAL as a main effect and interactions BITCOAL with each calendar month where July is the omitted month. Thus, the coefficients can be interpreted as the mortality difference between a given calendar month and July in state-years with higher bituminous coal consumption for heating. All other controls are the same as Column (3) of Table 3.

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. D.H.E.W. (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)
18% of cities worldwide	1999	> 240	Cohen et al (2004)

Notes: 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 by region, 1933-1960

Sample:	All states	Northeast	Midwest	South	West
Monthly deaths per 100,000	84.5	91.2	86.1	78.3	82
Monthly infant deaths per 100,000 births	272	241	246	327	261
Bituminous coal consumption (tons per capita)	.553	.176	1.18	.322	.412
Fraction households using coal for heating (1940)	.53	.698	.749	.317	.179
Mean temp (F) < 30	.108	.149	.173	.0313	.053
Mean temp (F) 30-40	.125	.168	.153	.0785	.0872
Mean temp (F) 40-50	.151	.162	.14	.141	.177
Mean temp (F) 50-60	.17	.16	.144	.165	.268
Mean temp (F) 60-70	.192	.19	.175	.191	.243
Mean temp (F) 70-80	.182	.15	.168	.242	.129
Mean temp (F) 80-90	.0694	.0212	.045	.147	.0359
Mean temp (F) $>= 90$	.00252	.0000814	.00181	.0035	.00703
Mean temp (F)	54.7	50.2	50.6	62	55.7
Fraction of population urban (1930)	.406	.583	.43	.224	.432
Number of states	48	9	12	16	11

Notes: Averages are weighted by state-year populations. Delaware is missing coal consumption data and dropped from our sample. Infant mortality data are unavailable prior to 1939. Urban places are those with greater than 25,000 inhabitants.

Table 3: Core estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Panel outcome:	(A) Log all-age mortality (N=16,128)			(B) Mortality rate per 100,000 (N=16,128)		
BITCOAL	0.063	0.058	0.039	5.400	5.000	3.360
	(0.025)**	(0.023)**	(0.021)*	(2.294)**	(2.117)**	(1.956)*
WINTER x BITCOAL		0.013	0.017		0.960	1.080
		(0.007)*	(0.006)***		(0.647)	(0.501)**
Panel outcome:	(C) Log infant mortality (N=12,672)			(D) Infant mortality rate (N=12,672)		
BITCOAL	0.042	0.023	0.012	21.176	16.454	11.543
	(0.014)***	(0.013)*	(0.013)	(7.091)***	(6.800)**	(6.384)*
WINTER x BITCOAL		0.045	0.044		11.335	11.500
		(0.010)***	(0.011)***		(3.331)***	(3.569)***
Year-month f.e.	Yes	Yes	Yes	Yes	Yes	Yes
State-month f.e.	Yes	Yes	Yes	Yes	Yes	Yes
State-specific trends	Yes	Yes	Yes	Yes	Yes	Yes
Temperature distribution	No	No	Yes	No	No	Yes
Other bituminous	No	No	Yes	No	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. BITCOAL is the estimated state-year bituminous consumption for heating. WINTER is a dummy for calendar months November through March (inclusive). This variable is constructed by interacting the states' 1917 share of national bituminous consumption with the annual measure of coal consumption for heating. Temperature distribution controls for the fraction of the month in a given 10-degree temperature band, following Deschenes and Greenstone (2009). We also control for per capita bituminous coal used for electricity, industry, coke, and railroads, and its interaction with the WINTER dummy variable. The all-age mortality estimates span the 1933-1960 time period, while the infant mortality estimates are for the 1939-1960 time period.

Table 4: Fraction of winter mortality decline explained by bituminous coal consumption, 1945-1960

	US	Northeast	Midwest	South	West
		Panel A: All-age mortality			
(1) Percent decline in winter mortality (1945-1960)	8.60	12.43	12.20	-2.22	12.92
(2) Decline in coal consumption (1945-1960)	0.73	0.24	1.59	0.41	0.54
(3) Percent decline in winter mortality due to (2)	1.25	0.41	2.75	0.70	0.93
(4) (3) as a fraction of (1)	0.15	0.03	0.23	-0.32	0.07
(5) Lives saved each winter month in 1960	1923.05	170.05	1230.78	322.71	194.41
		Panel B: Infant mortality			
(1) Percent decline in winter mortality (1945-1960)	31.98	32.12	33.10	29.82	33.89
(2) Decline in coal consumption (1945-1960)	0.73	0.24	1.59	0.41	0.54
(3) Percent decline in winter mortality due to (2)	3.27	1.05	7.27	1.82	2.43
(4) (3) as a fraction of (1)	0.10	0.03	0.22	0.06	0.07
(5) Lives saved each winter month in 1960	309.88	20.52	182.66	66.91	33.45

Notes: Based on the coefficient estimates from column (3) of Table 3. Coal consumption is tons per capita.

Table 5: Robustness checks
Outcome: Log of all-age mortality
Years 1933-1960 (unless otherwise noted)

Specification:	(1) Urban interaction	(2) Household measure	(3) Lagged coal	(4) State-month trends	(5) Drop Western states	(6) Drop warm states	(7) 1939-1955 sample
Panel A outcome: Log all-age mortality							
WINTER x BITCOAL	0.018 (0.009)**			0.015 (0.006)**	0.016 (0.007)**	0.004 (0.004)	0.024 (0.007)***
URBAN x WINTER x BITCOAL	-0.002 (0.018)						
WINTER x COALHH		0.090 (0.019)***					
WINTER x BITCOAL (Y-1)			0.016 (0.005)***				
Panel B outcome: Log infant mortality							
WINTER x BITCOAL	0.061 (0.017)***			0.025 (0.013)*	0.045 (0.013)***	0.034 (0.012)***	0.065 (0.013)***
URBAN x WINTER x BITCOAL	-0.046 (0.037)						
WINTER x COALHH		0.098 (0.043)**					
WINTER x BITCOAL (Y-1)			0.038 (0.009)***				
Main effect of coal variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month f.e.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State-month f.e.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State-specific trends	Yes	Yes	Yes	No	Yes	Yes	Yes
State-month specific trends	No	No	No	Yes	No	No	No
Temperature distribution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other bituminous	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: See notes to Table 3. Urban is the fraction of the state population living in a city with over 25 thousand people in 1930. COALHH is the fraction of state households with coal stoves in 1940 interacted with the annual variation in bituminous coal consumption for heating (in 100,000 tons). The mean for COALHH is 0.42 in 1933 and 0.16 in 1960. Column (3) excludes data from 1933 since we do not have (lagged) information on coal for 1932. The Western states, as defined by the U.S. Bureau of Census, include: AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, and WY. The "warm" states were determined by the average heating degree days (base = 50) over the 1920-1929 time period. The 10 states include: AL, AR, AZ, CA, FL, GA, LA, MS, SC, and TX.

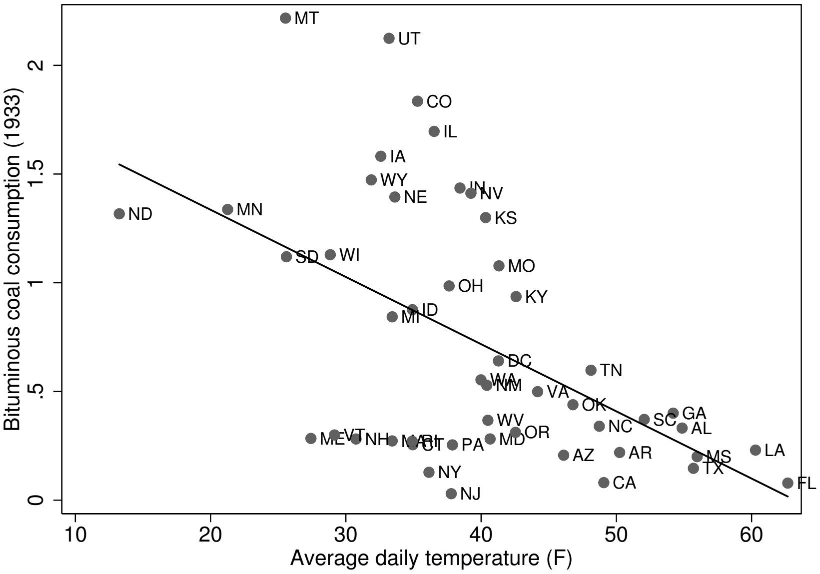
Table 6: Elasticity of Pollution and Infant Mortality from Arceo-Gomez, Hanna, and Oliva (2012)

Study	IMR per 100,000 births	Mean Level PM10	Elasticity	Mean level CO	Elasticity
Barreca, Clay, and Tarr (2013)	3367	100-300	0.22	NA	NA
Arceo-Gomez, Hanna, and Oliva (2012)	1987 (overall)	66.9	0.415	2.71	0.227
Arceo-Gomez, Hanna, and Oliva (2012)	1899 (internal)	66.9	0.325	2.71	0.178
Chay and Greenstone (2003a)	1179	35.3	0.284	NA	NA
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

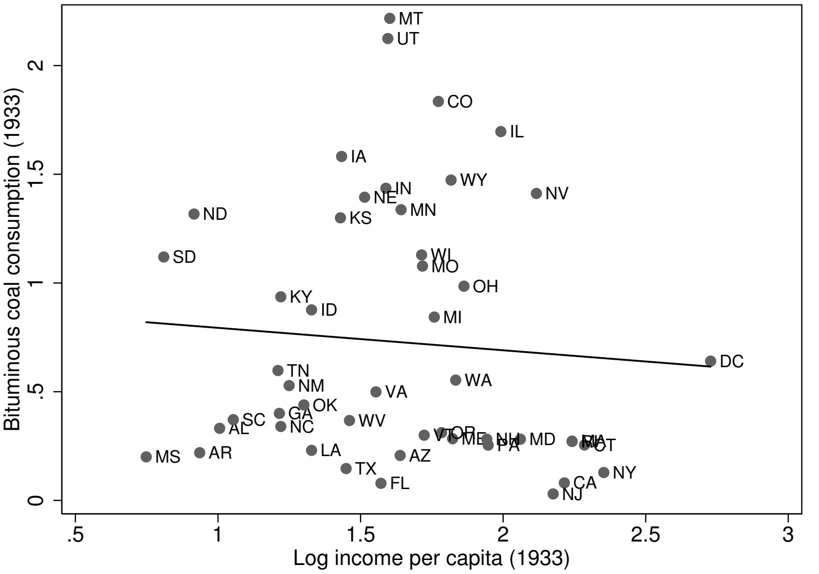
Notes: Based on Table 8 of Arceo-Gomez, Hanna, and Oliva (2012). NA = not available.

Figure A1: Correlation between coal consumption in 1933 and other factors

Panel A: Average daily temperature in January, February, and December of 1933



Panel B: Income per capita in 1933



Notes: Line represents a linear prediction from an unweighted regression. Coal consumption is in tons per capita. Average daily temperature is constructed from daily weather station records from the USHCN. The 1933 The income estimate comes from the Bureau of Economic Analysis (2012).

Table A1: Estimated effect on income per capita, 1933-1960

	(1)	(2)
Outcome:	Log income per capita	
BITCOAL	-0.025	0.054
	(0.025)	(0.040)
Year f.e.	Yes	Yes
State f.e.	Yes	Yes
State-specific trends	No	Yes
Observations	1,344	1,344

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. Unit of observation is state-year. Income per capita is in 2010$. The data come from the Bureau of Economic Analysis (2012).