Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy

Yuyu Chen[a,1], Avraham Ebenstein[b,1], Michael Greenstone[c,d,1,2], and Hongbin Li[e,1]

[a]Applied Economics Department, Guanghua School of Management, Peking University, Beijing 100871, China; [b]Department of Economics, Hebrew University of Jerusalem, Mount Scopus 91905, Israel; [c]Department of Economics, Massachusetts Institute of Technology, Cambridge, MA 02142; [d]National Bureau of Economic Research, Cambridge, MA 02138; and [e]China Data Center and Department of Economics, School of Economics and Management, Tsinghua University, Beijing 100084, China

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This paper's findings suggest that an arbitrary Chinese policy that greatly increases total suspended particulates (TSPs) air pollution is causing the 500 million residents of Northern China to lose more than 2.5 billion life years of life expectancy. The quasi-experimental empirical approach is based on China's Huai River policy, which provided free winter heating via the provision of coal for boilers in cities north of the Huai River but denied heat to the south. Using a regression discontinuity design based on distance from the Huai River, we find that ambient concentrations of TSPs are about 184 μg/m^3 [95% confidence interval (CI): 61, 307] or 55% higher in the north. Further, the results indicate that life expectancies are about 5.5 y (95% CI: 0.8, 10.2) lower in the north owing to an increased incidence of cardiorespiratory mortality. More generally, the analysis suggests that long-term exposure to an additional 100 μg/m^3 of TSPs is associated with a reduction in life expectancy at birth of about 3.0 y (95% CI: 0.4, 5.6).

airborne particulate matter | unintended consequences of policy | premature mortality | health costs of coal combustion | Chinese environmental quality

Air quality in China is notoriously poor and recently has become an issue associated with increasing social unrest. Ambient concentrations of total suspended particulates (TSPs) between 1981–2001 were more than double China's National Annual Mean Ambient Air Quality Standard of 200 μg/m^3 (1) and five times the level that prevailed in the United States before the passage of the Clean Air Act in 1970. Furthermore, air quality is especially poor in Northern China, which is home to several of the world's most polluted cities (2). Following a career in the Southern China city of Shanghai, Premier Zhu Rongi reportedly quipped in 1999: "If I work in your Beijing [in Northern China], I would shorten my life at least five years" (3).

This paper examines the health consequences of these extraordinary pollution levels by exploiting a seemingly arbitrary Chinese policy that produced dramatic differences in air quality within China. During the 1950–1980 period of central planning, the Chinese government established free winter heating of homes and offices via the provision of free coal for fuel boilers as a basic right. The combustion of coal in boilers is associated with the release of air pollutants, and in particular emission of particulate matter that can be extremely harmful to human health (4, 5). Due to budgetary limitations, however, this right was only extended to areas located in North China, which is defined by the line formed by the Huai River and Qinling Mountain range (Fig. 1). Even today, the long-lived heating systems continue to make indoor heating much more common in the north.

This paper finds that the Huai River policy had dramatic impacts on pollution and human health. To the north of the Huai River, particulate concentrations are 184 μg/m^3 [95% confidence interval (CI): 61, 307], or 55% higher, and life expectancies are 5.5 y (95% CI: 0.8, 10.2) lower, almost entirely due to an increased incidence of cardiorespiratory mortality (and no effect on other causes). The estimates suggest that the 500 million residents of Northern China during the 1990s experienced a loss of more than 2.5 billion life years owing to the Huai River policy.

Furthermore, a research design based on this policy allows for a unique opportunity to estimate the effect of TSPs on human health, which can be applied to other countries, time periods, and settings. The resulting estimates suggest that long-term exposure to an additional 100 μg/m^3 of TSPs is associated with a reduction in life expectancy at birth of about 3.0 y (95% CI: 0.4, 5.6). This estimate is more than five times larger than the estimated impact of TSPs on life expectancy from fitting a conventional ordinary least-squares equation on the same data.

The study addresses several shortcomings in our understanding about the health effects of air pollution. First, the research design provides estimates of the impact of long-run exposure to TSPs on life expectancy. The policy caused long-run differences in TSP concentrations between cities north and south of the Huai River (6). Moreover, during the period in question, the *hukou* (household registrations) system restricted mobility, so in general individuals will be observed where they lived most of their lives. In contrast, studies that use data for the United States or other developed countries must assume no migration, which is undermined by the high rates of migration in the United States and the potential selection of location based on air pollution concentrations, or alternatively assume that short-run variation in air pollution is informative about life expectancy (7, 8). Second, the availability of a regression discontinuity design based on the Huai River policy provides an appealing quasi-experimental approach that can help to move the existing literature from documenting a robust association between particulates and health toward documenting a causal relationship (9). Third, China's air is extremely polluted and we are unaware of any previous direct evidence on the impact of air pollution on life expectancy at these concentrations, although important research has applied results from the United States to the Chinese setting (10). Fourth, the analysis is conducted with the most comprehensive data file ever compiled on mortality and air pollution in China or any other developing country.

Data Sources

The dataset for this analysis is based on several sources. We collected information on annual daily average concentrations of

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[1]Y.C., A.E., M.G., and H.L. contributed equally to this work.

[2]To whom correspondence should be addressed. E-mail: mgreenst@mit.edu.

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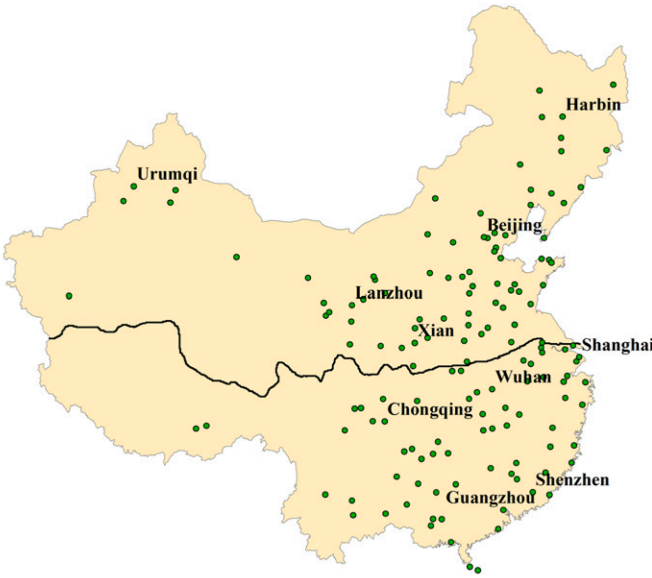

Fig. 1. The cities shown are the locations of the Disease Surveillance Points. Cities north of the solid line were covered by the home heating policy.

TSPs for 90 cities from 1981 to 2000. These data were compiled through a combination of hand entry from Chinese-language publications and access to electronic files (11). We obtained the data by combining the results of a World Bank project with information from hard copies of *China Environment Yearbook* to generate a single comprehensive file of air pollution across Chinese cities for our period.

Although there is recent evidence that air pollution readings in Chinese cities are manipulated by policymakers, with a tendency for officials to underreport pollution, we believe that manipulation was not a serious issue during the period we study (12). First, for the period of our study, government officials' evaluations were primarily based on economic growth rather than environmental indices (13). Second, the readings were also generally not widely available, which reduced the incentive to publish inaccurate information. Indeed, it has been reported extensively that Chinese officials monitored air pollution concentrations beginning in the late 1970s but this information was not publicly released until 1998 (14). Also, our analysis relies on testing for differences in air pollution readings near the Huai River, so unless the data were manipulated differently north and south of the river, mismeasurement would not bias the results in an obvious fashion. Moreover, even in the presence of manipulation of pollution concentrations, the estimates of the health impacts of living north of the Huai River will not be affected.

The mortality data are derived from China's Disease Surveillance Points (DSPs) system (15). The DSP is a set of 145 sites chosen to be nationally representative (benchmarked against the 1990 China census) so that it captures China's variation in wealth, urbanicity, and geographic dispersion. The DSP records all deaths and population counts at the sites and yields a nationally representative annual sample of deaths (16). The analysis will rely on the data taken from roughly 500,000 deaths recorded at sites between 1991 and 2000, and population counts by age and sex that are used to convert the recorded deaths into city-level mortality rates for ages 1, 5, and 10 y and 5-y increments through age 80. Additionally, these mortality rates are used to calculate an overall mortality rate based on China's age distribution in 2000 and life expectancy at birth, both measured annually for the 125 locations. In *SI Appendix*, we discuss why the results are unlikely to be driven by mismeasurement in a location's mortality rate from either migration or the transfer of sick rural residents to urban hospitals.

Importantly, the cause of death is also recorded after multiple validation checks. We classify causes of death as either cardiorespiratory or noncardiorespiratory. The cardiorespiratory causes of death that are those that have been linked to ambient air quality and include heart disease (17), stroke (18–20), lung cancer (21), and respiratory illnesses (22, 23). Causes of death presumably unrelated to air quality include other cancers, accidental or violent deaths, and various stomach ailments. Together, these two categories cover all causes of death.

We collected a range of determinants of mortality and life expectancy, besides TSPs, that are used as control variables in the subsequent statistical analysis. We obtained daily average temperature data for each location in the air pollution sample from the World Meteorological Organization that was used to calculate annual heating and cooling degree days (24). We also compiled a series of variables from China's 2000 census that are potentially related to health outcomes: average education of county residents, manufacturing's share of employment, the percentage of residents with urban registration, and the percentage of residents with access to tap water. The data file also includes an income variable taken from the DSP, which placed each site into one of four income categories.

To estimate the impact of long-run exposure to pollution, the location-level panel data are collapsed to a 125-observations, location-level, cross-sectional dataset, because the Huai River regression discontinuity design is fundamentally a cross-sectional design. This data file is obtained by averaging the annual location-specific measures of mortality rates, life expectancies, pollution concentrations, weather variables, and other covariates across the available years. Additionally, we used a geographic information system to identify the degrees latitude that each city centroid is north of the Huai River line and merged this information into the final dataset. *SI Appendix* provides more details on the procedure used to collapse the data file and the data sources.

Econometric Model

We use two approaches to estimate the relationship between TSPs and human health. The first approach is a "conventional" strategy that uses ordinary least squares to fit the following equation to the cross-sectional data file:

$$Y_j = \beta_0 + \beta_1 TSP_j + X_j \Gamma + \varepsilon_j, \qquad [1]$$

where TSP_j is the total suspended particulates concentration in city j, X_j is a vector of the observable characteristics of the city that might influence health outcomes other than air quality, and ε_j is a disturbance term. The dependent variable is Y_j, which is either a measure of mortality rates in city j or its residents' life expectancy, which is a simple function of age-specific mortality rates.

The coefficient β_1 measures the effect of TSP exposure on mortality, after controlling for the available covariates. Consistent estimation of β_1 requires that unobserved determinants of mortality do not covary with TSP_j after adjustment for X_j. Thus, the conventional approach rests on the assumption that linear adjustment for the limited set of variables available in the census removes all sources of confounding. With data from the United States, Chay et al. (9) have documented the sensitivity of the estimated TSP–adult mortality relationship to small changes in specification and sample, which is consistent with the possibility that omitted variables bias plagues the conventional approach.

The second approach leverages the regression discontinuity (RD) design implicit in the Huai River policy to measure its impact on TSP concentrations and life expectancy. The RD design was developed more than five decades ago and has been used successfully to test the causal nature of relationships in a wide range of fields including psychology, education, statistics, biostatistics, and economics (25, 26).

ENVIRONMENTAL SCIENCES

SUSTAINABILITY SCIENCE

Table 1. Summary statistics

Variable	South (1)	North (2)	Difference in means (3)	Adjusted difference in means (4)	*P* value (5)
Panel 1: Air pollution exposure at China's Disease Surveillance Points					
TSPs, $\mu g/m^3$	354.7	551.6	196.8***	199.5***	<0.001/0.002
SO_2, $\mu g/m^3$	91.2	94.5	3.4	−3.1	0.812/0.903
NO_x, $\mu g/m^3$	37.9	50.2	12.3***	−4.3	<0.001/0.468
Panel 2: Climate at the Disease Surveillance Points					
Heating degree days	2,876	6,220	3,344***	482	<0.001/0.262
Cooling degree days	2,050	1,141	−910***	−183	<0.001/0.371
Panel 3: Demographic features of China's Disease Surveillance Points					
Years of education	7.23	7.57	0.34	−0.65	0.187/0.171
Share in manufacturing	0.14	0.11	−0.03	−0.15***	0.202/0.002
Share minority	0.11	0.05	−0.05	0.04	0.132/0.443
Share urban	0.42	0.42	0.00	−0.20*	0.999/0.088
Share tap water	0.50	0.51	0.02	−0.32**	0.821/0.035
Rural, poor	0.21	0.23	0.01	−0.33*	0.879/0.09
Rural, average income	0.34	0.33	0.00	0.24	0.979/0.308
Rural, high income	0.21	0.19	−0.02	0.27	0.772/0.141
Urban site	0.24	0.25	0.01	−0.19	0.859/0.241
Predicted life expectancy	74.0	75.5	1.54***	−0.24	<0.001/0.811
Actual life expectancy	74.0	75.5	1.55	−5.04**	0.158/0.044

The sample (n = 125) is restricted to DSP locations within 150 km of an air quality monitoring station. TSP ($\mu g/m^3$) in the years 1981–2000 before the DSP period is used to calculate city-specific averages. Degree days are the deviation of each day's average temperature from 65°F, averaged over the years 1981–2000 before the DSP period. The results in column (4) are adjusted for a cubic in degrees of latitude north of the Huai River boundary. Predicted life expectancy is calculated by OLS using all of the demographic and meteorological covariates shown. All results are weighted by the population at the DSP location. One DSP location is excluded due to invalid mortality data. *Significant at 10%, **significant at 5%, ***significant at 1%. Sources: China Disease Surveillance Points (1991–2000), *China Environment Yearbook* (1981–2000), and World Meteorological Association (1980–2000).

This paper's RD design exploits the discrete increase in the availability of free indoor heating as one crosses the Huai River line (with no availability to the south and, in principle, complete availability north of the line). Specifically, we separately test whether the Huai River policy caused a discontinuous change in TSPs at the river and a discontinuous change in life expectancy. The respective necessary assumptions are that any unobserved determinants of TSPs or mortality change smoothly as they cross the river. If the relevant assumption is valid, adjustment for a sufficiently flexible polynomial in distance from the river will remove all potential sources of bias and allow for causal inference.

In practice, we estimate the following equations to test for the impacts of the Huai River policy:

$$TSP_j = \alpha_0 + \alpha_1 N_j + \alpha_2 f(L_j) + X_j\kappa + \nu_j \qquad \textbf{[2a]}$$

$$Y_j = \delta_0 + \delta_1 N_j + \delta_2 f(L_j) + X_j\phi + u_j, \qquad \textbf{[2b]}$$

where j references a city or location in China. TSP_j is the average annual ambient concentration of TSPs in city j over the period 1980–2000 and Y_j is a measure of city j's mortality or life expectancy at birth. N_j is an indicator variable equal to 1 for locations that are north of the Huai River line, $f(L_j)$ is a polynomial in the degrees north of the Huai River, and X_j is a vector of the demographic and city characteristics, other than air quality, that are associated with mortality rates (*SI Appendix* gives details).

This design can also be used to develop estimates of the impact of TSP concentrations on life expectancy. Specifically, if the Huai River policy only influences mortality through its impact on TSPs, then it is valid to treat Eq. **2a** as the first stage in a two-stage least-squares (2SLS) system of equations. An important appeal of the 2SLS approach is that it produces estimates of the impact of units of TSPs on life expectancy, so the results are applicable in other settings. The second-stage equation is

$$Y_j = \beta_0 + \beta_1 T\hat{S}P_j + \beta_2 f(L_j) + X_j\Gamma + \varepsilon_j, \qquad \textbf{[2c]}$$

where $T\hat{S}P_j$ represents the fitted values from estimating (Eq. **1**) and the other variables are as described above. The 2SLS approach offers the prospect of solving the confounding or omitted

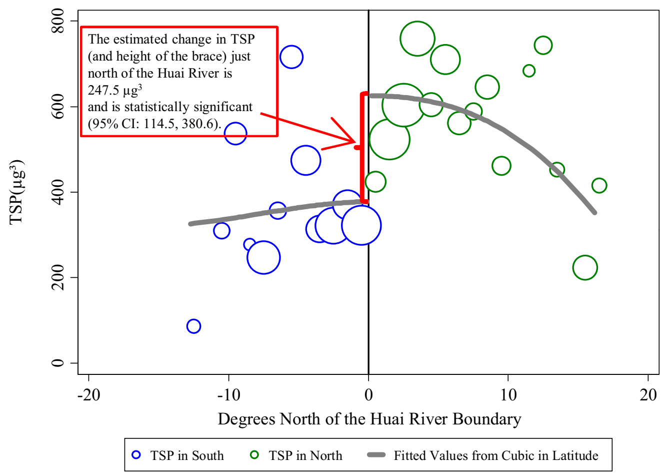

Fig. 2. Each observation (circle) is generated by averaging TSPs across the Disease Surveillance Point locations within a 1° latitude range, weighted by the population at each location. The size of the circle is in proportion to the total population at DSP locations within the 1° latitude range. The plotted line reports the fitted values from a regression of TSPs on a cubic polynomial in latitude using the sample of DSP locations, weighted by the population at each location.

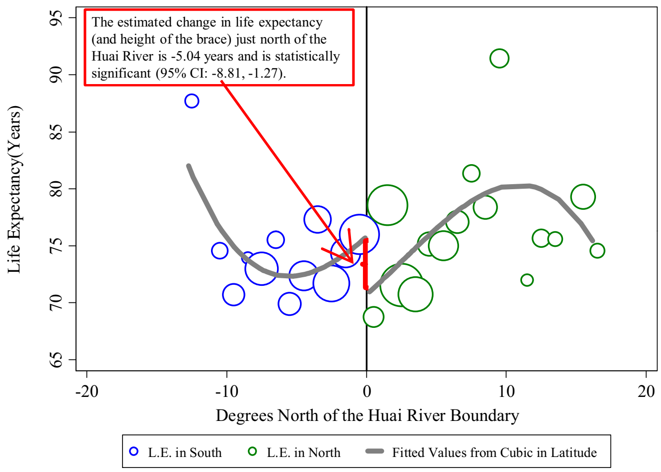

Fig. 3. The plotted line reports the fitted values from a regression of life expectancy on a cubic in latitude using the sample of DSP locations, weighted by the population at each location.

variables problem associated with the estimation of the air pollution–health effects relationship and is a solution to the attenuation bias associated with the mismeasurement of TSP.

Results

Summary Statistics. Table 1 reports the summary statistics for several of the key determinants of mortality rates and provides evidence on the validity of the RD design. Columns (1) and (2) report the means in cities south and north of the Huai River line. Column (3) reports the mean difference between the North and the South. Column (4) also reports the difference, but this time it is adjusted for a cubic polynomial in degrees north of the Huai River so that it is a test for a discontinuous change at the Huai River line. A direct test of the RD design's identifying assumption that unobservables change smoothly at the boundary is, of course, impossible, but it would nevertheless be reassuring if observable determinants change smoothly at the boundary. (This is analogous to the test in randomized control trials that observable determinants of the outcome are independent of treatment status.) Column (5) reports the P values associated with the tests that the differences in columns (3) and (4) are equal to zero.

Two key points emerge from this table. First, there are large differences in TSP exposure among Southern and Northern Chinese residents, but not for other forms of air pollution (e.g., sulfur dioxide and nitrous oxides) owing to the greater distances that they travel. Second, there are substantial differences in the determinants of mortality rates (e.g., temperature and predicted life expectancy) between the South and North, but adjustment for the cubic polynomial in latitude greatly reduces these differences and causes them to become statistically insignificant. This finding supports the validity of the RD design and the 2SLS approach to inferring the causal relationship between TSPs and life expectancy.

Graphical Analysis. The paper's primary findings are presented graphically in Figs. 2–4. Fig. 2 plots cities' TSP concentration against their degrees north of the Huai River boundary. The line is the fitted value from the estimation of the first-stage Eq. **1**, without adjustment for X_j. The circles represent the average TSP concentration across locations within 1° latitude distance bins from the Huai River; each circle's size is proportional to the number of DSP locations within the relevant 1° bin. The discontinuous change in ambient TSP concentrations to the north of the border indicates that the Huai River policy increased TSP concentrations in the North by about 200 μg/m^3. In contrast, *SI Appendix*, Figs. S1 and S2 graphically confirm that sulfur dioxide and nitrous oxide concentrations are approximately equal on the two sides of the Huai River.

Fig. 3 repeats the graphical exercise in Fig. 2, except here it plots life expectancy against degrees north of the Huai River boundary. The striking finding is that there is a discrete decline in life expectancy at the border of roughly 5 y, which mirrors the increase in TSPs. Together, Figs. 2 and 3 reveal a sharp increase in TSPs and a sharp decline in life expectancy at precisely the location where the Huai River policy went into effect. The results in Fig. 3 are also evident in *SI Appendix*, Fig. S3 in the sample of DSP sites within 5° latitude of the Huai River.

Fig. 4 graphically assesses the validity of this paper's approach by testing whether predicted life expectancy, calculated as the fitted value from an ordinary least-squares (OLS) regression of life expectancy on all covariates except TSPs (just as in Table 1), differs at the Huai River's border. Specifically, this equation includes all of the covariates listed in panels 2 and 3 of Table 1, and these variables collectively explain a substantial portion of the variation in life expectancy ($R^2 = 0.265$). It is evident that predicted life expectancy is essentially equal just to the north and south of the border (Table 1 reports a P value of 0.81 from a test of equal life expectancy). Also note that *SI Appendix*, Table S2 demonstrates that dietary and smoking patterns are similar in the North and South, suggesting that these determinants of life expectancy are unlikely to explain the sharp decline in life expectancy north of the border.

Regression Results. Table 2 reports the results from the application of the conventional OLS approach. The estimation of Eq. **1** with four different dependent variables is reported: the overall mortality rate, the cardiorespiratory mortality rate, the noncardiorespiratory-related mortality rate, and life expectancy. The set of controls are reported at the bottom of the table. The first three rows indicate that a 100 μg/m^3 increase in TSPs is associated with a statistically significant 3% increase in the mortality rate that is entirely due to an increase in cardiorespiratory causes of death. The column (2) specification in the final row indicates that a 100 μg/m^3 increase in TSPs is associated with a loss in life expectancy of about 0.52 y (95% CI: 0.07, 0.97).

Table 3 presents the RD results from the estimation of Eqs. **2a** and **2b** in panel 1 and the 2SLS results from Eq. **2c** in panel 2. In column (1), the specification includes a cubic in distance from the Huai River (measured in degrees of latitude). Column (2) adds the available covariates to the specification. Column (3) uses an alternative RD approach, which limits the sample to locations within

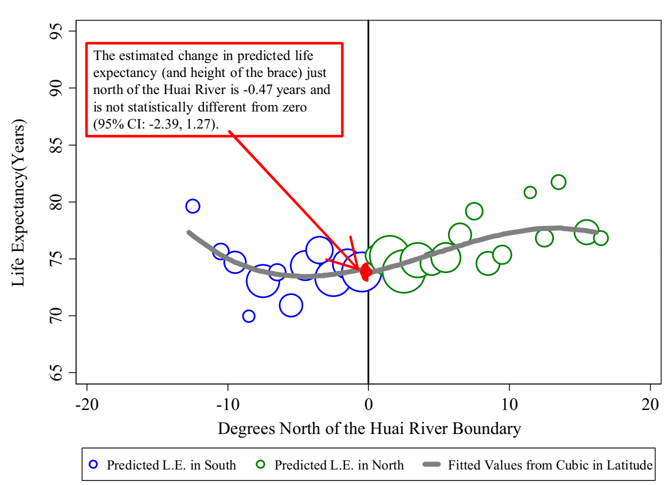

Fig. 4. The plotted line reports the fitted values from a regression of predicted life expectancy on a cubic in latitude using the sample of DSP locations, weighted by the population at each location. Predicted life expectancy is calculated by OLS using demographic and meteorological covariates (excluding TSPs).

Table 2. Impact of TSPs (100 μg/m^3) on health outcomes using conventional strategy (ordinary least squares)

Dependent variable	(1)	(2)
ln(All cause mortality rate)	0.03* (0.01)	0.03** (0.01)
ln(Cardiorespiratory mortality rate)	0.04** (0.02)	0.04** (0.02)
ln(Noncardiorespiratory mortality rate)	0.01 (0.02)	0.01 (0.02)
Life expectancy, y	−0.54** (0.26)	−0.52** (0.23)
Climate controls	No	Yes
Census and DSP controls	No	Yes

n = 125. Each cell in the table represents the coefficient from a separate regression, and heteroskedastic-consistent SEs are reported in parentheses. The cardiorespiratory illnesses are heart disease, stroke, lung cancer and other respiratory illnesses. The noncardiorespiratory-related illnesses are violence, cancers other than lung, and all other causes. Models in column (2) include demographic controls and climate controls reported in Table 1. Regressions are weighted by the population at the DSP location. *Significant at 10%, **significant at 5%, ***significant at 1%. Sources: China Disease Surveillance Points (1991–2000), *China Environment Yearbook* (1981–2000), and World Meteorological Association (1980–2000).

5° latitude of the Huai River and reduces the sample size from 125 to 69. With this smaller sample, latitude is modeled with a first-order polynomial. The specification details are noted at the bottom of the table.

The first row of Table 3, panel 1 confirms that the impact of the Huai River policy on TSPs is robust to adjustment for the covariates and the alternate RD approach (*SI Appendix*, Fig. S3). The remaining rows suggest that this policy increases mortality rate by 22–30% and that this is almost entirely due to higher rates of mortality among cardiorespiratory causes. The estimates in the final row indicate that there is a discontinuous decrease in life expectancy of ∼5 y to the north of the boundary.

Panel 2 in Table 3 reports on the 2SLS estimates. Column (2) estimates suggest that a 100 μg/m^3 increase in TSPs is associated with an increase in the overall mortality rate of 14% or 0.14 ln points (95% CI: 0.005, 0.275) and a decline in life expectancy of 3.0 y (95% CI: 0.39, 5.61). Again, the results seem to be driven entirely by higher mortality rates from cardiorespiratory causes of death.

The heterogeneity in the results across the population is explored in *SI Appendix*. *SI Appendix*, Table S3 reveals that the mortality and life expectancy findings hold for men and women. *SI Appendix*, Table S4 and Fig. S4 demonstrate that the impacts on cardiorespiratory mortality rates are generally evident over the entire course of the life cycle, not just for the young and old.

The basic results are also robust to a wide variety of specification checks. *SI Appendix*, Tables S5 and S6 document that the results are qualitatively unchanged by using alternative methods to assign TSP concentrations to DSP locations. *SI Appendix*, Table S7 shows that the panel 1 results are qualitatively unchanged by expanding the sample to the full set of 144 DSP locations (with valid mortality data) from the 125 locations with TSP data. Further, the results are unchanged by adjustment for distance from the coast (*SI Appendix*, Table S8).

We additionally explored the robustness of the results to alternative approaches to implementing the RD design. *SI Appendix*, Table S9 reports a set of goodness-of-fit tests that lead us to emphasize modeling distance from the Huai River with a cubic polynomial in latitude. *SI Appendix*, Table S10 documents that a first- or second-order polynomial in latitude best fits the data in the sample that is restricted to locations within 5° latitude of the river, and that the results are qualitatively similar using either approach. *SI Appendix*, Table S11 reports on specifications that allow the polynomial to differ to the north and south of the river. The goodness-of-fit statistics support separate quadratics north and south of the Huai River, and this specification suggests a somewhat smaller increase in TSPs at the border but a larger decline in life expectancy.

A natural concern related to the research design is that the government used the Huai River as the demarcation line for changes in other government policies related to public health, and this would confound the estimates of TSPs on health. This possibility is mitigated by the fact that the Huai River is not a border used for administrative purposes. The Huai River follows the January 0° average temperature line (Celsius), and this was in fact the basis of its choice as a method to divide the country for free heating. Further, local policies generally hew to administrative boundaries associated with cities and provinces; indeed, the Huai River cuts through several provinces. Nevertheless, we compiled some additional variables on city-level policies that are plausibly related to health from the *China City Statistical Yearbook*. We examine whether there is any discontinuity in these variables at the

Table 3. Using the Huai River policy to estimate the impact of TSPs (100 μg/m^3) on health outcomes

Dependent variable	(1)	(2)	(3)
Panel 1: Impact of "North" on the listed variable, ordinary least squares			
TSPs, 100 μg/m^3	2.48*** (0.65)	1.84*** (0.63)	2.17*** (0.66)
ln(All cause mortality rate)	0.22* (0.13)	0.26* (0.13)	0.30* (0.15)
ln(Cardiorespiratory mortality rate)	0.37** (0.16)	0.38** (0.16)	0.50*** (0.19)
ln(Noncardiorespiratory mortality rate)	0.00 (0.13)	0.08 (0.13)	0.00 (0.13)
Life expectancy, y	−5.04** (2.47)	−5.52** (2.39)	−5.30* (2.85)
Panel 2: Impact of TSPs on the listed variable, two-stage least squares			
ln(All cause mortality rate)	0.09* (0.05)	0.14** (0.07)	0.14* (0.08)
ln(Cardiorespiratory mortality rate)	0.15** (0.06)	0.21** (0.09)	0.23** (0.10)
ln(Noncardiorespiratory mortality rate)	0.00 (0.05)	0.04 (0.07)	0.00 (0.06)
Life expectancy, y	−2.04** (0.92)	−3.00** (1.33)	−2.44 (1.50)
Climate controls	No	Yes	Yes
Census and DSP controls	No	Yes	Yes
Polynomial in latitude	Cubic	Cubic	Linear
Only DSP locations within 5° latitude	No	No	Yes

The sample in columns (1) and (2) includes all DSP locations (*n* = 125) and in column (3) is restricted to DSP locations within 5° latitude of the Huai River boundary (*n* = 69). Each cell in the table represents the coefficient from a separate regression, and heteroskedastic-consistent SEs are reported in parentheses. Models in column (1) include a cubic in latitude. Models in column (2) additionally include demographic and climate controls reported in Table 1. Models in column (3) are estimated with a linear control for latitude. Regressions are weighted by the population at the DSP location. *Significant at 10%, **significant at 5%, ***significant at 1%. Sources: China Disease Surveillance Points (1991–2000), *China Environment Yearbook* (1981–2000), and World Meteorological Association (1980–2000).

Huai River in *SI Appendix*, Table S12. The results demonstrate that the null hypothesis that these variables are equal on both sides of the Huai River generally cannot be rejected. We also reestimate our Table 3 specification with the addition of these variables in *SI Appendix*, Table S13. We find that the addition of these variables to the Table 3 specifications leaves our results largely unchanged, and even suggests modestly larger losses of life expectancy than those reported in Table 3.

Interpretation. The 2SLS estimates suggest that a 100 $\mu g/m^3$ increase in TSPs leads to a decline in life expectancy of 3.0 y (95% CI: 0.4, 5.6). This estimate is more than five times larger than one obtained from the application of a conventional least-squares approach to the same data. The difference suggests that the OLS estimates understate the true effect owing to some combination of omitted variables bias (e.g., unobserved factors that improve health and are positively correlated with TSPs, such as income and hospital quality) and measurement error. Further, it is about half the magnitude of the estimated impact of an equal unit of particulate matter smaller than 2.5 μm ($PM_{2.5}$) from the pioneering study of Pope et al. (27). There are at least three important differences between the studies that complicate direct comparisons: (*i*) $PM_{2.5}$ is believed to be more lethal than the larger particles that also qualify as TSPs; (*ii*) the setting for the $PM_{2.5}$ results is the United States between 1980 and 2000, when particulate concentrations were just a fraction of current concentrations in China; and (*iii*) this study's results are based on a RD design, which can produce causal estimates in nonexperimental settings.

A related issue is whether the Huai River heating policy caused behavioral responses that amplify or mitigate the estimated mortality impacts of TSPs. For example, the heating policy very likely leads people in the North to spend more time indoors, where temperatures are presumably higher; this would be protective of human health. Alternatively, the greater time indoors may cause people to reduce their exercise and increase their exposure to indoor air pollution that would be harmful to health. Further, the free provision of coal is an in-kind transfer that increases households' disposable income, and this may cause northern households to alter their consumption patterns in ways that are protective (e.g., medical care) or harmful (e.g., tobacco or alcohol) for health. In the case where these behavioral responses affect mortality, the 2SLS estimates of the impact of TSPs on mortality would be invalid, although the estimated mortality effects of the Huai River heating policy (e.g., panel 1 of Table 3) would still be valid. Ultimately, the estimated impacts of TSPs on mortality should be interpreted with these caveats in mind because the necessary data to test for these behavioral responses are unavailable.

Conclusions

The analysis suggests that the Huai River policy, which had the laudable goal of providing indoor heat, had disastrous consequences for health, presumably due to the failure to require the installation of sufficient pollution abatement equipment. Specifically, it led to TSP concentrations that were 184 $\mu g/m^3$ higher (95% CI: 60, 308) or 55% higher in the North and reductions in life expectancies of 5.52 y (95% CI: 0.8, 10.2) in the North due to elevated rates of cardiorespiratory mortality.

The population in Northern China between 1990 and 2000 exceeded 500 million. Consequently, our results imply that the Huai River policy led to a staggering loss of over 2.5 billion life years. Furthermore, data from 2003 to 2008 indicate that PM_{10} (particulate matter smaller than 10 μm) concentrations are 22.9 $\mu g/m^3$ higher (95% CI: 13.5, 23.3) or 26% higher north of the Huai River, suggesting that residents of the North continue to have shortened lifespans. The TSP concentrations that prevailed during the study period greatly exceed the current concentrations in developed countries but are not atypical for many cities in developing countries today, such as India and China. These results may help explain why China's explosive economic growth has led to relatively anemic growth in life expectancy. More broadly, this paper's results may be useful in forming policy as developing countries search for the optimal balance between economic growth and environmental quality (28).

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