China's War on Pollution: Evidence from the First Five Years

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Michael Greenstone, Guojun He, Shanjun Li, Eric Zou[1]

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Abstract

The decade from 2010 to 2019 marked a significant turning point in China's approach to environmental regulation and pollution. This article describes the recent trends in air and water quality, with a focus on the five years following the Chinese government's announcement of its "war on pollution" in 2014. We review the emerging literature that has taken advantage of recent improvements in data availability and accuracy to understand the social, economic, and health impacts of environmental pollution in China.

Keywords: air pollution, water pollution, government policy

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[1] Michael Greenstone: University of Chicago, mgreenst@uchicago.edu; Guojun He: University of Hong Kong, gjhe@me.com; Shanjun Li: Cornell University, SL2448@cornell.edu; Eric Yongchen Zou: University of Oregon, ericzou@uoregon.edu. We thank Claire Fan, Wenzheng Li, Yuhang Pan, and Luming Tan for excellent research assistance, Yazhen Gong for generous data sharing, and Cynthia Lin Lawell for comments. Financial support from the Center for Industrial Development and Environmental Governance (CIDEG) of Tsinghua University is greatly appreciated.

INTRODUCTION

China's unprecedented economic growth, heavy reliance on fossil fuels, and lax environmental regulations have significantly degraded the country's environmental quality during the past few decades (World Bank, 2007). Indeed, by 2010, China had become the world's largest consumer of energy and coal, largest automobile market, and largest emitter of carbon dioxide (CO_2) and sulfur dioxide (SO_2). Dubbed "airpocalypse" by the international news media,[2] severe air pollution episodes in large urban centers such as Beijing in the early 2010's resulted in a public outcry over the lack of basic, public information about pollution and the absence of effective government responses (Barwick et al. 2019).

Against this backdrop, China began to shift away from its long-standing strategy of prioritizing economic growth over environmental concerns. At the opening of the annual meeting of the People's Congress in March 2014, Premier Li Keqiang declared a "war on pollution," denouncing smog as "nature's warning against inefficient and blind development."[3] As a result, the central government undertook unprecedented regulatory changes on multiple fronts, including (1) recognizing fine particulate matter ($PM_{2.5}$) as a primary pollutant and establishing national maximum standards for $PM_{2.5}$ for the first time; (2) setting pollution reduction as one of the key bureaucratic targets in evaluating and promoting government officials; (3) launching a nationwide, real-time air quality monitoring and disclosure program; and (4) implementing a range of environmental policies, including piloting seven regional CO_2 cap-and-trade programs

[2] See for example: https://www.npr.org/2013/01/14/169305324/beijings-air-quality-reaches-hazardous-levels ; https://www.theguardian.com/cities/2014/dec/16/beijing-airpocalypse-city-almost-uninhabitable-pollution-china.
[3] https://www.reuters.com/article/us-china-parliament-pollution/china-to-declare-war-on-pollution-premier-says-idUSBREA2405W20140305

and promoting the electrification of the passenger transportation system (Barwick et al. 2019, Greenstone et al., 2020).

China has made significant progress in improving air quality since 2014. As we will discuss in this article, local air pollution levels have fallen significantly; five years after its peak in 2013, national-level $PM_{2.5}$ levels declined by about 40 percent, and SO_2 and CO concentrations fell by 65 percent and 33 percent, respectively. In comparison, the United States took at least a decade and two significant recessions to achieve comparable percentage reductions in air pollution following passage of the Clean Air Act in 1970.[4] Air pollution levels in China remain high despite the significant progress, suggesting that further efforts are needed to bring the country's environmental quality in line with international recommendations. For example, in 2018, the national average $PM_{2.5}$ concentration was 40.1 μg/m^3, which is still more than four times the level considered to be safe (10 μg/m^3 for the annual mean) by the World Health Organization (WHO).

This article, which is part of a symposium on China and the Environment, reviews the emerging literature on the economic, social, and health consequences of China's "war on pollution."[5] This literature has taken advantage of recent improvements in data availability and accuracy. We begin in the next section by describing recent trends in air and water quality in China. Then we review empirical evidence on the economic, social, and health impacts of pollution in China over the past decade and discuss compensatory responses. We conclude with a summary of our

[4] For data on pollution reduction trends in the US under the Clean Air Act, see https://www.epa.gov/air-trends.
[5] Vennemo et al. (2009) and Zheng and Kahn (2013) conducted earlier reviews of research on the causes and consequences of China's environmental challenges, with the former focusing on the status and trends and the latter focusing on the role of urbanization and the regulatory environment.

findings and a brief discussion of future research priorities. Together with the two other articles in this symposium — Karplus et al. (2021) and Auffhammer et al. (2021)[6] — we seek to provide readers with a one-stop shop for key economic insights on China's environmental and energy challenges.

RECENT TRENDS ON ENVIRONMENTAL QUALITY

This section describes national and regional trends in China's air and water quality during the 2010–2019 period.

Air Quality

We use publicly available air quality data from the real-time monitoring and reporting system of China's Ministry of Ecology and Environment (MEE, formerly the Ministry of Environmental Protection (MEP).[7] More specifically, between 2013 and 2015, China rolled out a new nationwide air pollution program to provide real-time monitoring and reporting of six air pollutants: $PM_{2.5}$, PM_{10}, ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and SO_2. Hourly real-time pollution readings are available from about 1,600 monitoring sites spread across almost every city, covering 98% of the total population. Due to concerns about the accuracy and reliability of the previous monitoring system (see discussion below), we restrict our analysis to this more recent data. To accurately identify trends, we adjust for the differences in average pollution levels across cities that began monitoring at different times: the differences in the starting date of monitoring led to unbalanced city-level panel data sets. Using city- and day-

[6] These articles examine the history, structure, and performance of China's system of environmental regulation and China's renewable energy development and policy, respectively.
[7] http://www.cnemc.cn

level air pollution data, we estimate year-to-year changes in air quality separately for each pollutant.[8] More specifically, we estimate the changes in annual levels for each pollutant using variation within each city and over time. Because government monitoring data are available only for recent years, we complement these data with satellite-based $PM_{2.5}$ estimates for 1998-2018 (van Donkelaar et al., 2019). The satellite-based $PM_{2.5}$ measures provide similar findings.

As shown in panel (a) in Figure 1, with the exception of O_3, all air pollutant concentrations dropped sharply between 2013 and 2018.[9] $PM_{2.5}$ levels decreased by 27.7 μg/m^3, or about 41 percent. SO_2 concentrations fell the most, declining by over 65 percent. O_3 concentration *increased* by 8.5 percent, reflecting the complex nature of O_3 formation and the challenge of containing it given China's continued urbanization and motorization.[10] Overall, the evidence suggests that China achieved large reductions in air pollution in these five years.

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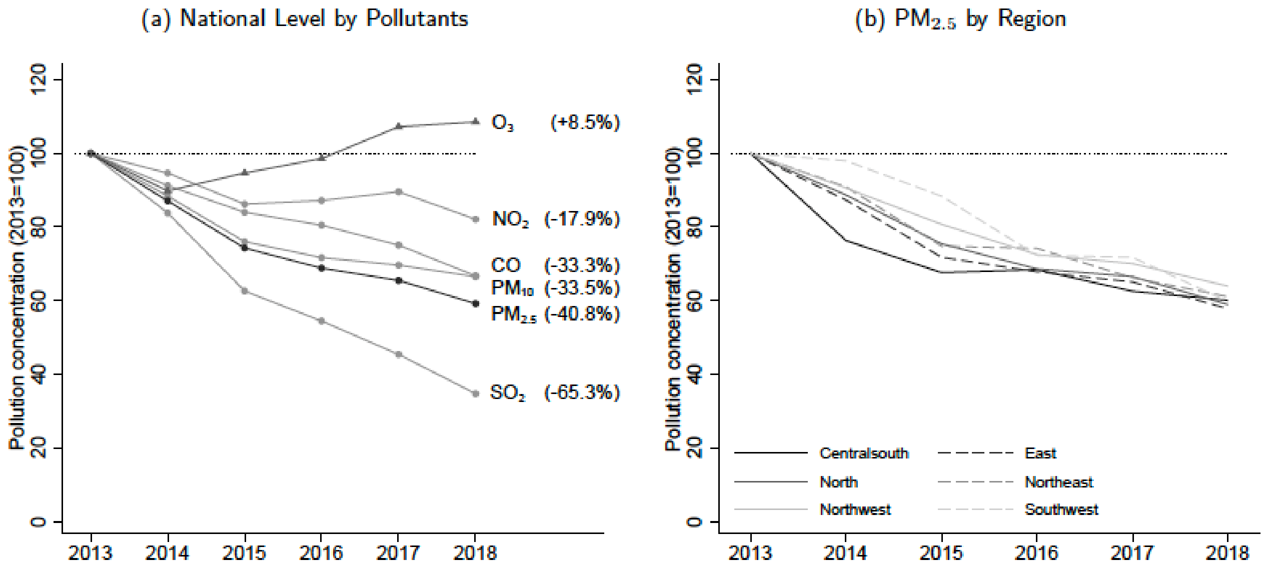
[8] We use the following equation: $Pollution_{ict} = \sum_{\tau=2013}^{2018} \beta_{i\tau}\, 1(y=\tau) + \alpha_{ic} + \varepsilon_{ict}$ (1) , where the dependent variable is the concentration of air pollutant *i* in city *c* on date *t* and the $\beta_{i\tau}$'s reveal the changes in annual levels for each pollutant using variation within each city and over time. When there are multiple monitors operating in the city-day, we take the average across the readings from these monitors. The trend estimates are similar if we conduct our analysis using monitor-level data (and controlling for monitor fixed effects). Because the initiation of real-time monitoring varies across cities, we include pollutant-by-city fixed effects (α_{ic}) to account for the differences in average pollution levels across cities in the unbalanced panel. As the *i* subscript indicates, the equation is estimated separately for each air pollutant.

[9] Figure A-1 in the on-line appendix shows the national annual average concentration levels for each of the six pollutants.

[10] O_3 is not emitted directly; rather it is produced by photochemical reactions between NO_x and volatile organic compounds (VOCs) via a nonlinear and non-monotonic relationship in the presence of sunlight (Sillman 1999). Thus, when VOCs are limited, a decrease in NO_x emissions could lead to an increase in O_3, as shown empirically by Salvo and Geiger (2014) and Zhang et al. (2017), for São Paulo and Bogotá, respectively.

Figure 1: Trends in Air Pollutant Concentrations



Notes: Panel (a) reports the annual concentrations of six pollutants. The estimates are obtained from separate OLS regressions of city-daily pollution concentration on calendar year indicators (omitting 2013) and city fixed effects for each pollutant. Annual values are obtained by adding the regression constant back to the coefficients on the year indicators. Values are normalized to 100 in 2013. Panel (b) reports annual $PM_{2.5}$ concentration by region. The estimates are obtained from 6 separate OLS regressions (one for each region) of city-day $PM_{2.5}$ concentration on calendar year indicators (omitting 2013) and city fixed effects. Annual values are then obtained by adding the regression constant back to the coefficients on the year indicators.
Sources: Authors' calculations based on MEE data.

Although earlier studies suggest that in some cases, China's official air quality data was manipulated (e.g., Andrews, 2008; Chen et al., 2012; Ghanem and Zhang, 2014), the more recent data is less likely to be tampered with because the upgraded monitoring system automates the sampling and reporting process (Greenstone et al., 2020). Importantly, satellite-based pollution estimates also indicate a substantial decline in air pollution levels in China,[11] and the real-time $PM_{2.5}$ data from MEE seem to be consistent with those based on independent monitoring by the U.S. embassy and consulates in Beijing, Chengdu, Guangzhou, Shanghai, and Shenyang.[12] Note

[11] See Figure A-2 in the on-line appendix.
[12] See Figure A-3 in the on-line appendix.

that because the satellite $PM_{2.5}$ data are calibrated using ground monitor data, they are not an entirely independent benchmark. Nevertheless, if we examine direct satellite observations of aerosol optical depth, a key input of satellite-derived $PM_{2.5}$ measures, we also find a consistent downward trend since 2010.[13] We conclude that the readings from China's new monitoring system correspond well with independent measures, thus confirming the improvement in air quality.

To quantify the mortality benefit of the observed reduction in $PM_{2.5}$ concentration, we use the Air Quality Life Index (AQLI), which measures the potential gain in life expectancy from pollution reduction.[14] The AQLI is based on Ebenstein et al. (2017), who estimate the causal effect of sustained exposure to particulate pollution on life expectancy in China. Holding everything else equal, the AQLI predicts that if the observed reduction in $PM_{2.5}$ levels between 2013 and 2018 became permanent, it would generate a remarkable gain in average life expectancy of 2.7 years per person.

In order to understand regional heterogeneity, we examine $PM_{2.5}$ trends across six regions by estimating the year-to-year changes in PM2.5 concentrations separately for each region.[15] As shown in panel (b) in Figure 1, we find that although the initial speed of the reduction in $PM_{2.5}$ differed across regions, all six regions experienced similar $PM_{2.5}$ reductions in percentage terms by the end of 2018.[16]

[13] See Appendix Figure A-4 in the on-line appendix.
[14] AQLI was developed to measure and communicate the health risks posed by particulate matter air pollution around the world. See https://aqli.epic.uchicago.edu for more information.
[15] That is, we estimate the equation in footnote 8 separately for each region.
[16] See the on-line appendix for an examination of spatial heterogeneity at the city-level as well as the correlation between the city-level trends and city characteristics.

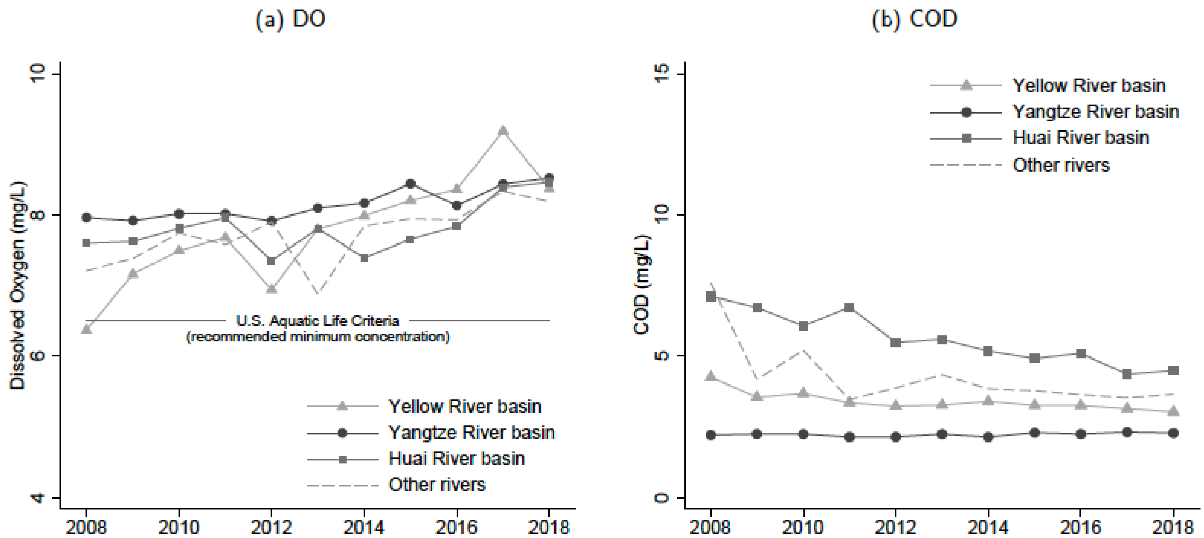
Water Quality

We use publicly available data from the MEE's Major River Basins Water Quality Reports, which contain weekly surface water quality data from about 110 monitoring stations.[17] These monitors cover major river basins in China and reflect surface water quality in river segments that are deemed important by the MEE.[18] We use water quality data from 2008 to 2018. There was no systematic real-time water quality reporting prior to 2008.

Due to the limited number of monitoring stations, we are able to summarize water quality trends only for major river basins, including the Yellow, Yangtze, and Huai rivers. We aggregate the original station- and weekly-level data to compute year-to-year changes. Figure 2 presents two measures of water quality. The first measure is dissolved oxygen (DO in mg/L) concentration, which indicates the degree of the water's oxygen saturation and is thus a measure of the water's suitability for aquatic life. The second measure is chemical oxygen demand (COD in mg/L), which indicates the degree of oxygen depletion in the water as a result of bacteria actions and is thus a measure of water pollution.[19]

[17] For the location of these monitors, see panel (a) of Figure A-8 in the on-line appendix.
[18] Admittedly, the water quality data we collect are not representative of the entire country's water pollution because smaller rivers and lakes are generally more polluted. Unfortunately, water quality data from these less important monitoring stations are not systematically published by the MEE. This partially explains why there are fewer studies on water pollution. Over the past three decades, the MEE has significantly expanded the national water quality monitoring system, and by 2015, there were 972 national water quality monitoring stations across China, with the number expected to increase to more than 2,700 stations by 2020 (http://www.cnemc.cn).
[19] Figure A-8, Panel (b) in the on-line appendix plots a third measure of water quality: the fraction of Grade I, II, and III water – i.e., "swimmable" water. All three measures have been used in previous research on water quality in both China and the United States (e.g., Greenstone and Hanna, 2014; Kahn et al., 2015; Keiser, et al., 2019; Keiser and Shapiro, 2019; He et al., 2020).

Figure 2: Trends in Surface Water Quality in Major River Basins, 2010-2018



Notes: Panel (a) shows annual average dissolved oxygen concentration (higher is better). The "U.S. Aquatic Life Criteria" (6.5 mg/L) refers to the recommended 30-day minimum dissolved oxygen concentration criteria for cold water, non-early life stages aquatic lives by U.S. EPA Quality Criteria for Water (1986). Panel (b) shows annual average chemical oxygen demand (lower is better). We excluded the site in Yuncheng (Shanxi Province), where the COD level dropped from 110 to below 20 during the sample period.
Sources: Authors' calculations based on MEE data.

These figures reveal two key patterns. First, water quality steadily improved from 2008 to 2018 in all regions except the Yangtze River Basin, which had the highest initial water quality.[20] Second, there is a visible trend of convergence, with water quality in all river basins becoming similar. The water quality improvement is the largest in the Huai and Yellow River basins, which initially had the lowest water quality.

Publicly available data on drinking water and groundwater quality (which differ from surface water quality) are too limited to allow for similar analyses. However, based on the various annual reports of the MEE, we find that groundwater quality slightly deteriorated between 2010

[20] The average DO levels at the monitored locations are around 7.5 mg/L. This exceeds the U.S. EPA's recommended 30-day minimum concentration of 6.5 mg/L for aquatic life (U.S. EPA 1986).

and 2017.[21] The different trends for surface water and groundwater quality are likely due to the weaker regulations on groundwater. Groundwater pollution is less visible than surface water pollution and technically more challenging to address, and thus warrants future research.

THE IMPACTS OF POLLUTION ON HUMAN WELL-BEING AND PRODUCTIVITY

Given the magnitude of its pollution challenges, the rapidly changing policy environment, and the range of environmental policies implemented, China provides a unique and rich setting for studying the impacts of pollution on human well-being. In this section, we review the emerging literature that uses data from China, which can complement the extensive literature for developed countries. Because developing countries differ from developed countries in many ways, including regulatory environments, access to health care, and initial levels of pollution and population health, it is likely that the pollution impacts in developing countries are also different (Arceo et al. 2016; Greenstone and Jack 2015).[22] We focus here primarily on the more mature literature on air pollution, but we also briefly summarize the findings on water pollution. To facilitate the comparison across studies, we first outline the empirical framework and identification strategy used in the literature. We then discuss specific studies in the literature, focusing on physical health, mental health, and productivity, respectively.

Empirical Framework and Identification Strategy

[21] We plot groundwater quality in Figure A-9 in the on-line appendix. The MEE reports can be accessed via http://www.mee.gov.cn/hjzl/zghjzkgb/lnzghjzkgb/. Note that the groundwater quality standards are different from the surface water quality standards, even though both use a grade system to define different levels of water pollution.

[22] See Graff Zivin and Neidell (2013) and Currie et al. (2014) for reviews of studies that focus on the U.S. and other developed countries.

We first discuss the empirical framework and the commonly-used strategies for identifying the causal effects. The empirical studies generally estimate a linear equation in a panel data setting, with the dependent variable being the outcome of interest (e.g., mortality rate) and the key variable of interest being a measure of pollution exposure.

The key challenge in estimating the causal impact of pollution on health (and many other outcomes) is that the pollution variable could be endogenous. First, unobservable social and economic factors (e.g., income) may be correlated with both air pollution and the outcome variables. Second, there could be measurement errors in pollution exposure because variables that are commonly used to indicate ambient pollution levels (ambient $PM_{2.5}$) may not be the same as pollution exposure.

The economic literature has mostly relied on quasi-experimental designs to credibly estimate the causal impact of air pollution (Greenstone and Gayer, 2009). In these designs, researchers typically leverage changes in meteorological conditions, regulations, and specific events or shocks to distinguish the pollution impacts from any confounding factors.

Several studies have explored changes in meteorological conditions (e.g., wind, thermal inversion) to estimate the impact of air pollution. For example, wind can disperse pollutants and exogenously change local air pollution levels. Under the assumption that unobservables from (time-varying) upwind areas are not correlated with local unobservables, wind direction is often used to generate a valid instrumental variable (IV) -- a variable that is correlated with the endogenous variable (pollution in this context) but not correlated with the error term. Thermal inversion is another common IV in the literature (e.g., Arceo et al., 2016). Thermal inversion occurs when warm air settles over cooler air. In such circumstances, air pollutants will be trapped from rising and dispersing, which can significantly increase ground-level air pollution concentrations.

Another source for causal identification comes from policy changes that, in principle, affect the outcome variables only through their impacts on air pollution. Notable examples that use this strategy include studies on the impacts of the U.S. Clean Air Act (e.g., Chay and Greenstone, 2005; Deschenes et al., 2017; Isen et al., 2017) and studies on the impacts of China's winter heating system policy (e.g., Chen et al., 2013; Ebenstein et al., 2017; Ito and Zhang, 2020).

Researchers have also explored various events and economic shocks that affect local pollution but are plausibly uncorrelated with unobservable determinants of the outcome to identify the pollution impact. For example, Schlenker and Walker (2016) use airplane network delays to generate exogenous changes in air pollution levels in the U.S. In the Chinese context, He et al. (2016) use changes in air pollution induced by the 2008 Beijing Olympic Games for exogenous variation. The literature has also relied on economic cycles and trade shocks (e.g., Chay and Greenstone 2003) to generate exogenous variation in local air pollution.

Impacts of Air Pollution on Physical Health

The impact of air pollution on human physical health has been studied extensively, with some estimates suggesting that seven million deaths around the world each year can be attributed to air pollution. Indeed, around 90 percent of the world's population is breathing air that is deemed harmful to human health.[23] We organize our discussion around studies that focus on the mortality

[23] https://www.who.int/phe/publications/en/

impact from short-term exposure, the mortality impact from sustained exposure, and the morbidity impact, respectively.

Mortality impact from short-term exposure

Although studies in the literature examine different empirical settings, they consistently show that air pollution can significantly increase premature deaths in China. For example, in a study n of China's acid rain policies, Tanaka (2015) finds that infant mortality significantly decreased in regions where SO_2 emissions are tightly controlled. He et al. (2016) examine pollution changes during the 2008 Beijing Olympic Games and find that a 10 percent decrease in monthly PM_{10} concentrations reduces the monthly standardized all-cause mortality rate by 8 percent. Focusing on China's trade-induced pollution, Bombardini and Li (2020) find that a one standard deviation increase in the pollution content of exports increases infant mortality by 4.1 deaths per thousand live births.

More recently, as better air quality data have become available, studies have shifted their focus to finer measures of air pollution, such as $PM_{2.5}$ and the Air Quality Index (AQI). For example, using the variation in the dates on which the coal-fired winter heating system is turned on across cities, Fan et al. (2020) estimate that a 10-point increase in the AQI due to winter heating leads to a 2.2 percent increase in mortality. He et al. (2020) examine farmers' straw burning practices and find that agricultural fires increase pollution and lead people to die prematurely from cardio-respiratory diseases, estimating that a 10 $\mu g/m^3$ increase in straw-fire-induced $PM_{2.5}$ increases the mortality rate by 3.25 percent. The magnitude of the estimated effect is similar in Fan et al. (2020) and He et al. (2020), but it is substantially smaller than the estimate in He et al. (2016). A plausible explanation for this difference is that He et al. (2016) use air pollution data from 2006 to 2010, a period in which the air pollution concentrations may have been under-reported (Greenstone et al., 2020).

Mortality impact from sustained exposure

The studies just discussed all examine the effect of pollution over a relatively short period of time (e.g., weekly, monthly, or, at most, annually). Credible evidence on air pollution's long-term impacts is limited both in China and elsewhere. To estimate the long-term impacts, researchers must address several empirical challenges, including identifying exogenous long-run variation in air pollution, collecting data on individuals' lifetime exposure to pollution, and finding a strategy to limit compensatory migration in response to air pollution differences. For example, richer people may move to areas with better air quality. Because these people may also have healthier lifestyles and better access to quality medical services, it is difficult to isolate the impact of air pollution from other factors. It is also possible that sicker people are more likely to move to areas with lower air pollution, leading to selection bias in another direction.

To the best of our knowledge, the first quasi-experimental evidence on the impacts of sustained exposure to air pollution focuses on China (Chen et al. 2013 and Ebenstein et al. 2017). This evidence is characterized by two unique features that allow for causal identification. First, China's central winter heating system, which dates back to China's planning period in the 1950s, provided free winter heating for decades to people living north of the Huai River but not to those living south of the river. Because winter heating was generated from small coal boilers with few environmental controls, it significantly raised air pollution levels in northern China. Second, China's household registration (or Hukou) system has historically controlled migration across cities. This migration restriction makes it possible to identify individuals' lifetime exposure to pollution based on their current residence. Furthermore, the Hukou system, particularly prior to the 2000s, prevented most people from engaging in compensatory migration in response to local environmental quality.[24]

In their quasi-experimental studies, Chen et al. (2013) and Ebenstein et al. (2017) examine the impact of sustained pollution exposure on life expectancy, based on distance from the Huai River. The main difference between the two studies is that Chen et al. (2013) use mortality and pollution data from the 1990s while Ebenstein et al. (2017) use more recent and comprehensive data covering the 2004-2012 period. Both studies find that sustained exposure to air pollution significantly reduced life expectancy. In particular, Ebenstein et al. (2017) estimate that the winter heating policy raised PM_{10} levels by 46 percent in the region north of the Huai River between 2004 and 2012, causing a reduction in life expectancy of 3.4 years.

Morbidity impact

In addition to its impact on mortality and life expectancy, air pollution has been found to significantly increase certain diseases (morbidities). Unlike epidemiological studies, which generally focus on the correlation between pollution and the incidence of specific diseases, economic studies place greater emphasis on causality and the measurement of the economic costs of morbidity. In a comprehensive analysis of the morbidity cost of air pollution in China, Barwick et al. (2018) examine variation in $PM_{2.5}$ concentrations caused by wind patterns and find that a 10 $\mu g/m^3$ reduction in $PM_{2.5}$ would lead to an annual reduction in national healthcare spending of over \$9 billion, or about 1.5 percent of China's total healthcare spending in 2015.

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[24] The policy has been loosened in recent years. However, Ebenstein et al. (2017) find that cross-region migration did not appreciably alter people's lifetime exposure to air pollution.

Several other studies have assessed the morbidity impact of air pollution in China on a particular region or subpopulation. For example, Zhong et al. (2017) use Beijing's driving restrictions (which affect the number of vehicles on the road) to estimate the impact of pollution on morbidity. They find that the reduced traffic caused by these driving restrictions results in reductions in air pollution and lower demand for ambulance services. Using data on thermal inversion and disease and attendance records from more than 3,000 schools in Guangzhou city, Chen et al. (2018) find that air pollution has a sizable negative effect on school attendance due to its impact on respiratory diseases. Using data from international schools in north China, Liu and Salvo (2018) also find that air pollution significantly increases student absences.

A related strand of research examines the spillover effect of China's pollution on neighboring regions. Jia and Ku (2019) find that South Korea would have had 2,400 fewer cardiorespiratory deaths if China's AQI had been 12 points lower during the 2001–2010 period. Cheung et al. (2020) show that transboundary air pollution from mainland China's manufacturing increases air pollution in Hong Kong, which causes more people to die from cardiorespiratory diseases.

Impacts of Air Pollution on Mental Health, Happiness, and Cognitive Ability

Mental disorders have been found to be the second leading contributor to the global disease burden, accounting for 7 to 13 percent of disability-adjusted life-years (Vigo et al., 2016). Medical and epidemiological research has also documented that air pollutants (particularly particulate matter) can impair brain function and exacerbate depression and anxiety (e.g., Sørensen et al., 2003).

Chen et al. (2018), Xue et al. (2019), and Zheng et al. (2019) are among the first economists to assess how air pollution affects mental health and happiness in China.[25] Both Chen et al. (2018) and Xue et al. (2019) find that exposure to higher levels of $PM_{2.5}$ increases the probability of a self-reported mental illness,[26] confirming the epidemiological link between air pollution and mental health. However, the estimated effects are substantially larger in Chen et al. (2018) than in Xue et al. (2019). Based on an analysis of Chinese social media data, Zheng et al. (2019) find that air pollution is negatively associated with happiness in urban China.

Studies show that air pollution can also affect people's cognition and decision-making processes. For example, Zhang et al. (2018) find that long-term exposure to air pollution impedes individuals' cognitive performance on verbal and math tests and that the effects can be more pronounced as people age. Chang et al. (2018) find that elevated pollution increases the number of health insurance contracts sold on that day, and that better air quality during the cost-free cancellation period induces more cancellations of the insurance contracts. Based on laboratory experiments in 2012, Chew et al. (2019) find that high $PM_{2.5}$ levels lead to a variety of behavioral changes, including increased risk aversion to gains, risk tolerance of losses, and ambiguity aversion to gains, and greater impatience in temporal discounting.

Graff Zivin et al. (2019) study the impact of air pollution on the performance of high school students during high-stakes exams. Using data from the National College Entrance Examination for the 2005-2011 period, they find that straw burning leads to worse exam performance.

[25] We focus here on research that uses nationally representative data from China because studies that use data from local areas tend to generate mixed results.

[26] Both studies use nationally representative data from the China Family Panel Studies (CFPS), in which individuals self-report their mental health along many dimensions. Chen et al. (2018) use data from 2014 to 2015 and leverage thermal inversions to instrument local air quality; Xue et al. (2019) use data from 2010 to 2014 and rely on fixed effects models to identify the pollution impact.

Leveraging the spatial dispersion of air pollutants due to exogenous wind directions, Lai et al. (2021) show that $PM_{2.5}$ emissions from upwind straw burning have a negative impact on the cognitive functions of the elderly and that the impact is transitory and caused by contemporaneous $PM_{2.5}$ emissions on the day of cognitive testing.

Using data from the financial market, two recent studies show that air pollution also affects financial decision-making. Li et al. (2019) show that air pollution significantly increases the disposition effect of investors -- the tendency of investors to sell assets that have appreciated in price while keeping assets that have depreciated. Rui et al. (2019) find that poor air quality during corporate site visits by investment analysts is associated with earning forecasts that are lower than realized earnings and suggest that this is due to pollution-induced pessimism.

Impact of Air Pollution on Productivity

Thanks to the recent availability of high-frequency production data, there is a growing literature that examines the impact of air pollution on the productivity of Chinese workers. Manufacturing jobs are generally labor-intensive and require workers to be physically healthy. To estimate the impacts of air pollution on manufacturing workers' productivity, He et al. (2019) assemble daily worker-level output data from two Chinese textile firms and daily air quality data. They find that the current-day impact of air pollution on worker productivity is largely negligible, while prolonged exposure to air pollution results in a modest decline in output. Specifically, a 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentrations sustained over 25 days reduces daily output by one percent.

Chang et al. (2019) study workers in the service sector, where jobs may be more cognitively demanding than those in the manufacturing sector. Using daily performance data for workers in two call centers in China, the authors estimate that a 10-unit increase in the Air Pollution Index (API) decreases the number of daily calls handled by a worker by 0.35 percent. The magnitude of the estimated effect is similar in Chang et al. (2019) and He et al. (2019). Although workers in call centers rely largely on mental skills rather than physical skills, such work is generally not difficult to master. Kahn and Li (2020) focus on highly skilled workers – judges working in the government -- and find that increases in $PM_{2.5}$ significantly increased the time a judge took to adjudicate a case.

While the studies discussed above shed light on the relationship between air pollution and productivity, they focus on specific lines of work and specific sectors, and thus their representativeness and long-term validity are less clear. Fu et al. (2019) use a nationally representative sample of all Chinese manufacturing firms from 1998 to 2007 to estimate the effect of air pollution on productivity. They find that a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ increases productivity by 8.2 percent, which is an order of magnitude larger than the estimates in Chang et al. (2019) and He et al. (2019). In another study that uses the Huai River winter heating policy, Ebenstein and Greenstone (2020) find that childhood exposure to air pollution leads not only to reduced educational attainment but also lower wages as an adult.

Impacts of Water Pollution

Most environmental pollution studies focus on air pollution, in part because air quality data are generally readily available. In contrast, systematic data on water pollution are rare, and thus there have been relatively few studies of water pollution. In one of the first studies to estimate the impact of surface water pollution on health, Ebenstein (2012) finds that a one-grade decrease (on a six-grade scale) in surface water pollution increases the digestive cancer death rate by 9.7

percent. He and Perloff (2019) find that surface water pollution has a non-monotonic effect on infant mortality: as water quality degrades, infant mortality first goes up and then goes down.[27] Lai (2017) studies the impacts of exposure to pollution in drinking water by comparing the outcomes for people who drink surface water and groundwater in regions with different intensities of rice pesticide use. He finds that increased use of pesticides adversely affects the health outcomes of rural residents 65 and older.

A parallel line of research examines the impacts of clean drinking water. While these studies do not directly measure water pollution, they all suggest that clean drinking water has large health benefits. For example, using village-level data, Zhang (2012) shows that introducing piped water into villages improves the health status of both adults and children. Similarly, in a study of China's rural drinking water program, Zhang and Xu (2016) find that providing clean drinking water to children increases their educational attainment in the long run. Fan and He (2019) show that piped water provision significantly reduced infant mortality.

COMPENSATORY RESPONSES TO POLLUTION

Individuals facing high levels of pollution can take preventive measures to reduce exposure and mitigate the impact. These risk-compensating behaviors include avoidance actions and defensive spending in the short run and household location choices (i.e., sorting) in the long run. Early empirical evidence on avoidance behavior was based on data from the U.S. (e.g., Neidell 2009). Research on avoidance behavior based on data from China has been undertaken only recently. In

[27] They argue that when surface water becomes slightly degraded, people do not notice the pollution and continue consuming it; however, as the pollution worsens, people become more aware of it, and thus reduce their consumption of surface water. Such avoidance behavior helps to explain the non-monotonic relationship between water pollution and infant mortality in China.

this section, we first discuss the role of pollution information in fostering compensatory responses to pollution and then summarize the empirical evidence on how people in China protect themselves against pollution, such as through defensive spending and migration.

Pollution Information

Before 2013, public access to real-time pollution measures was absent in most Chinese cities. Although the MEE began compiling the API for major cities in 2000 and has gradually expanded the cities covered, the MEE did not initially control the monitoring stations. Instead, local environmental bureaus, whose leaders were appointed by local governments, gathered and reported the data. There is evidence that before 2013, local governments in many cities manipulated the API data(e.g., Andrews, 2008; Ghanem and Zhang, 2014; Greenstone et al., 2020).

China's real-time pollution monitoring and disclosure program (henceforth, the information program) was launched in 2013 and marked a turning point in pollution information access and awareness. Under this program, the central government installed more than 1,600 U.S. Environmental Protection Agency (EPA)-grade monitoring stations, each equipped with automated, real-time monitoring devices that track concentrations for multiple pollutants. In about two years, the monitoring network had managed to cover the entire country. The central government also established a parallel data streaming system, whereby the pollution information from these monitors stream in real time to city-, province- and central-level governments.

Greenstone et al. (2020) find that the automation of the information program has the potential to address China's environmental monitoring principal-agent problem, where the central government is the principal (who wants accurate information and pollution reduction) and local officials are the agents (who tend to hide such information because they place a greater emphasis on economic growth). Using detailed data on a wide array of outcomes, including pollution awareness, short- and long-run economic activities, and health outcomes, Barwick et al. (2019) show that the information program has had profound impacts on pollution awareness and behavior (such as defensive spending and outdoor activities) among Chinese residents.

Avoidance Actions and Defensive Spending

Many studies have also examined how changes in pollution levels affect avoidance behaviors. For example, Sun et al. (2017) analyze the relationship between daily air pollution and the sales of face masks and air purifiers, and find that people buy more face masks and air purifiers when ambient pollution levels exceed alert thresholds. Based on data on online sales and day-to-day changes in air quality across cities, Zhang and Mu (2018) examine people's investment in face masks. They estimate that a 10-point increase in the AQI increases the purchase of all masks by 5.5 percent and the purchase of anti-$PM_{2.5}$ masks by 7.1 percent. This suggests that if China could eliminate 10 percent of heavy pollution days, the country could save approximately $187 million on face masks alone. Barwick et al. (2018) find that elevated $PM_{2.5}$ levels are positively associated with increased spending on healthcare but reduced spending in supermarkets, suggesting avoidance behavior. Barwick et al. (2019) find that the reduction in consumer spending is greater for deferrable categories (such as restaurant dining) and smaller for scheduled or less-deferrable categories (such as paying bills and business-to-business transactions). Sun et al. (2019) estimate a positive correlation between air quality and daily consumption activities in restaurants and shopping malls.

Several recent studies document intercity trips as a short-term strategy for pollution avoidance in China. For example, Chen et al. (2018) use cell phone data to track consumer movement across cities and Cui et al. (2019) use smartphone-based location data to show that consumers travel from polluted cities to cleaner cities to avoid pollution. Barwick et al. (2020) trace consumer locations based on credit and debit transactions and find that improved transportation infrastructure (such as high-speed rail and air connections) facilitates pollution avoidance through intercity travel.

Data on consumers' revealed preferences through the marketplace would allow researchers to identify willingness-to-pay (WTP) for improved air quality. Based on sales data on air purifiers, Ito and Zhang (2020) estimate that a household is willing to pay $13.4 annually to remove 10 $\mu g/m^3$ of PM_{10} and $32.7 annually to eliminate the increased pollution caused by China's winter heating policy. The authors suggest that these could be lower-bound estimates of the true WTP for several reasons, including the limited information on pollution levels and lack of consumer awareness of the health impacts of air pollution, especially before 2013.

Multiple studies have found that income levels are important determinants of people's WTP for clean air (e.g., Sun et al., 2017; Ito and Zhang, 2020). Because wealthier people can better protect themselves against pollution, they may partially mitigate the negative effect of air pollution through actions such as defensive spending. In fact, both Fan et al. (2020) and He et al. (2020) find that air pollution has a greater impact on mortality in low-income areas than in high-income areas. Similarly, Cheung et al. (2020) find that the effect of air pollution has significantly decreased in Hong Kong in the past two decades and attribute this lower impact to the improvement in the city's medical system. Liu and Salvo (2018) find that air pollution has a small impact on school attendance among high-income children, whose parents and principals are better informed.

Household Location Choices

Households choose where to live (i.e., they vote with their feet) based on housing prices and the provision of local amenities such as public goods and environmental quality (Tiebout 1956). There are two main approaches to analyzing such household sorting when it comes to environmental quality. The first approach, which is based on neighborhood-level data (such as census tract), examines the relationship between the changes in population size and changes in environmental quality in a linear regression framework. The second approach examines how households sort across different locations using a discrete choice framework. Both approaches face the same identification challenge: that unobserved factors are correlated with both household location choices and environmental quality. Such unobservables could be public goods such as school quality, crime rates, access to public transit, and other neighborhood quality measures.

Empirical evidence for the U.S. generally confirms that households indeed choose locations to seek better environmental quality (e.g., Kahn, 2000; Chay and Greenstone 2005; Banzhaf and Walsh, 2008; Greenstone and Gallagher 2008; Bayer et al., 2009). A small but growing literature also finds evidence of such household sorting with respect to environmental quality in China. For example, using population census data, Chen et al. (2017) find that air pollution significantly affects cross-city migration in China and that the effect is driven mostly by well-educated people and young professionals.

Using a household-sorting model that is similar to Bayer et al. (2009), Freeman et al. (2019) follow the second approach to examine household location choices across cities. They find that Chinese households take air quality into account in their location decisions and, on average, would pay about 22 USD for a one-unit reduction in annual $PM_{2.5}$ concentrations. This estimate is nearly an order of magnitude larger than the estimate of WTP for air quality in Ito and Zhang (2020).[28]

CONCLUSIONS AND PRIORITIES FOR FUTURE RESEARCH

This article has documented recent trends in environmental quality in China and reviewed recent studies on the consequences of environmental pollution and policy interventions that have taken advantage of more readily available data. These studies have deepened our understanding of environmental issues in China and also offer lessons for other developing countries. Some of this research has started to have an impact on China's environmental policies. For example, after the Chinese government learned that the coal-fired winter heating system resulted in disastrous health consequences, it launched a large-scale clean energy program to replace coal with natural gas as the main heating fuel.[29] As China continues its war on pollution, we are hopeful that environmental economics research will play an important role in the adoption of evidence-based environmental policy in China.

We conclude by highlighting several priorities for future research in this area. First, we believe that understanding the impacts of long-term pollution exposure remains the most important issue for both research and policy. However, most existing studies have focused on the short- and

[28] Although both studies use revealed preference approaches, the choices considered and the identification strategies are different, making it difficult to identify why these two estimates of WTP for air quality are so different.
[29] See for example: https://www.chinadialogue.net/article/show/single/ch/10285-Three-year-cut-to-life-expectancy-from-coal-heating-

medium-run variation in pollution due to data limitations. Future research should prioritize the identification of long-run quasi-experimental, or even experimental, variation in pollution.

Second, the evidence thus far suggests that the present health-focused quantification of pollution costs likely significantly underestimates the true costs of pollution (e.g., Ebenstein and Greenstone 2020). Thus, there is an urgent need for research on how air pollution affects long-run human capital acquisition, human cognition, and productivity. Further research is also needed on the extent to which compensatory behavior (e.g., avoidance expenditure, household sorting) can mitigate the negative impact of pollution.

Third, the estimated impacts of pollution on some key outcomes (e.g., health, productivity) vary greatly across studies, likely driven by factors that include differences in the sample coverage, identification strategies, and time horizons. However, we know very little about which factors are most important in explaining the differences in effect size. This discrepancy in the effect size across studies poses a challenge for the research community in their communications with policymakers and the public.

Fourth, research is needed on the causes and consequences of water pollution and effective policy options. Water pollution differs from air pollution in its dynamics and spatial patterns. Despite the improvement in air quality and surface water quality in China, groundwater quality has declined in the past decade; this trend is of particular concern, given that groundwater is the primary source of drinking water in many parts of the country.

Fifth, the economic research on soil pollution in China is limited. Anecdotal evidence suggests that soil pollution, primarily from industrial factories and farming practices, could be a widespread problem in China (Sun et al., 2019), posing health dangers to both local residents and consumers of food products from affected areas. However, public discussion has largely neglected this threat. An essential first step toward understanding and addressing this challenge is the systematic collection of data. The impact of plastic pollution is also an area of increasing concern, as plastic production and usage continue to grow and plastic waste flows into the ocean and enters natural habitats (Chu et al., 2020).

As China's environmental policies evolve and data access expands, there will be ample opportunity for the world to learn from China's practices and for scholars to conduct fruitful and exciting research on the country. When the next review of the literature on China's environmental challenges and policies is written, we will have a much clearer understanding of the complex linkages between human well-being and environmental quality and how government policies can influence these relationships.

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